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R. Schmidt-Grund (Ed.)
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Arbeitskreis Ellipsometrie (AKE) - Paul Drude e.V.
(German Association for Ellipsometry)

In 1999 a group of German ellipsometry enthusiasts established the “Arbeitskreis Ellipsometrie” with the aim of promoting ellipsometry in Germany. It was agreed to organize regular workshops to gather all ellipsometry protagonists: scientists, engineers, manufacturers, and students. In 2006 the conference language was changed to English in order to open the workshop to people from abroad.

In 2005 the non-profit association „Arbeitskreis Ellipsometrie (AKE) – Paul Drude e.V.” has been founded. The AKE PD e.V. supports the scientific and technical understanding of optical metrology, in particular of ellipsometry. It provides a platform for the dissemination of new scientific results and experience, and promotes young people working in this field.

Main Activities:
- Organization of the European Workshop Ellipsometry
- Paul Drude Award
- Ellipsometry Database
- Scientific Networking

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Unter den Eichen 87
12205 Berlin
www: http://www.ake-pdv.de
e-mail: vorstand@ake-pdv.org
Schedule

Monday, March 5

8:00 - 9:15  Registration

9:15 - 9:30  Opening

9:30 - 11:05  Magnetics and Metamaterials - MM 1
   Chair: H. Wormeester

9:30 - 10:15  B. Gompf, The effective dielectric response of complex materials

10:15 - 10:40  M. Schubert, New chemical, biochemical and biological sensing and separation principles based on highly ordered three-dimensional nanohybrid materials thin films

10:40 - 11:05  K. Hingerl, How realistic is modelling metamaterials with magnetic permeability?

11:05 - 11:25  Coffee break

11:25 - 12:41  Magnetics and Metamaterials - MM 2
   Chair: K. Hingerl

11:25 - 11:45  S. Burger et al., Numerical simulations for design and analysis of metamaterials and plasmonic structures

11:44 - 12:03  T. W. H. Oates et al., Characterizing periodic gratings and metamaterials using spectroscopic ellipsometry

12:03 - 12:22  N. Guth et al., Biaxiality in metamaterials near optical frequencies

12:22 - 12:41  K. Järrendahl et al., Polarization of Light Reflected from Chiral Structures - Calculations Compared with Mueller Matrix Ellipsometry Measurements on Natural and Synthetic Samples

12:41 - 13:50  Lunch

13:50 - 15:06  Magnetics and Metamaterials - MM 3
   Chair: B. Gompf

13:50 - 14:09  K. Mok et al., Magneto-optical coupling in ferromagnetic thin films investigated by vector-magneto-optical generalized ellipsometry

14:09 - 14:28  D. Schmidt et al., Vector-Magneto-Optical Generalized Ellipsometry on Ferromagnetic Sculptured Thin Films

14:28 - 14:47  K. Postava et al., Spectroscopic ellipsometry of magneto-optic garnet with in-plane anisotropy

14:47 - 15:06  M. Fronk et al., Characterization of metal oxide thin films and interfaces by spectroscopic ellipsometry and magneto-optical Kerr effect spectroscopy

15:06 - 15:25  Coffee break
### Rough and Structured Surfaces - RS 1

**Chair:** H. Arwin

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**Chair:** B. Bodermann

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### Industrial Applications - IA 1

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### New Developments and Miscellaneous Problems of Measurement and Data-Evolution - DP

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12:55 - 14:30 Electronic Properties - EP 1
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12:55 - 13:40 C. Bernhard, Electronic properties of strongly correlated electronic systems

13:40 - 14:05 M. Rübhausen, Spectroscopic Generalized Magneto-Optical Ellipsometry: Results on strongly correlated materials and new technology trends

14:05 - 14:30 R. Goldhahn, Nitride Semiconductors - a model system for demonstrating the influence of excitonic effects on the dielectric function

14:30 - 14:50 Coffee break

14:50 - 16:25 Electronic Properties - EP 2
Chair: C. Bernhard

14:50 - 15:09 D. Franta et al., Dispersion model of graphite: application of sum rule

15:09 - 15:28 S. Schöche et al., Spectroscopic Ellipsometry and optical Hall-Effect studies of free-charge carriers in p-type In-polar InN:Mg

15:28 - 15:47 A. Dejneka et al., Ellipsometry of ferroic phase transitions

15:47 - 16:06 A. Dejneka et al., Spectral Ellipsometry of TbMnO$_3$ Multiferroic

16:06 - 16:25 A. Charnukha et al., Universal microscopic description of the infrared conductivity of 122 iron arsenides

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8:30 - 9:40 Organics and Related - OR 1
Chair: K.-J. Eichhorn

8:30 - 9:15 K. Hinrichs, Ellipsometry for studying organic materials

9:15 - 9:40 S. Logothetidis, Intelligent optical sensing for Organic Electronics applications
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Acknowledgement

We gratefully acknowledge financial and logistic support by:

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Abstracts of the Talks
MM - Magnetics and Metamaterials
Maxwell’s equations in the presence of matter are incomplete in the sense that they have to be amended by constitutive relations of $\vec{D}$ and $\vec{B}$ to $\vec{E}$ and $\vec{H}$. Mathematically this is done by a tensor; from the physics point of view, one has to find the lowest-rank tensor that describes the material under investigation. Looking only on the linear, local, and quasistatic response the so-called bianisotropic constitutive relations exhibit the most general description:

$$\vec{D} = \epsilon \vec{E} + \xi \vec{H} \quad \text{and} \quad \vec{B} = \mu \vec{H} + \zeta \vec{E}.$$  

(1)

Neglecting symmetry considerations, one ends up with 36 complex material parameters, which all depend on frequency but – in this approach – not on the wavevector $\vec{k}$. Although challenging, in principle they can be calculated up-initio from the atomic structure. The best test for band-structure calculations, for example, is still the comparison of theoretically obtained $\epsilon(\omega)$ with the one determined by spectroscopy. The coupling parameters $\xi$ and $\zeta$ describe the magnetoelectric effects. Albeit known for more than hundred years, they have experienced a revival over the last 15 years. One has to stress that all experiments for retrieving magnetoelectric coefficients were done in the kHz- or MHz-range where the long wavelength limit is clearly fulfilled. Approaches explicitly including non-local effects (spatial dispersion) were developed for the visible and near-infrared region because here the typical size of the building blocks (atoms, lattice constants, artificial nanostructures) cannot be neglect compared to the wavelength of light. In this spectral range no distinction can be made between the magnetic induction $\vec{B}$ and the magnetic field intensity $\vec{H}$ because $\mu = 1$ at optical frequencies. Under this assumption the constitutive relations become rather simple:

$$\vec{D} = \epsilon_{ij}(\omega, \vec{k}) \vec{E} \quad \text{and} \quad \vec{B} = \vec{H}.$$  

(2)

For most nanostructures – dubbed metamaterials – the building blocks are in the range $\lambda/10 \leq P \leq \lambda$. To describe their effective optical behavior, a homogenization procedure has to be applied that yields well defined effective optical constants. Classical effective medium approximations, such as Bruggeman’s theory, are only valid in the long-wavelength limit and in general they yield physically unreasonable effective optical parameters; for instance, they usually provide effective permittivities that are not Kramers-Kronig consistent. The same is true for most retrieval procedures for effective permittivities and permeabilities from reflection and transmission measurements at normal incidence. During the last couple of years it became clear that it is not possible to define effective optical parameters for metamaterials, which are independent on the angle of incident of the probing light.

In the tutorial the question will be addressed which constitutive relations are appropriate for different kinds of complex materials.
New chemical, biochemical and biological sensing and separation principles based on highly ordered three-dimensional nanohybrid materials thin films

M. Schubert
University of Nebraska-Lincoln, Center for Nanohybrid Functional Materials, and Nebraska Center for Materials and Nanoscience
Email: schubert@engr.unl.edu

This talk reviews our efforts to combine unique physical properties of highly-ordered 3D-nanomaterials with chemical and biochemical recognition elements in order to develop new sensing and separation principles which will provide the basis for new and more powerful sensors and separation devices. Highly ordered three-dimensional nanohybrid materials thin films establish a new class of materials with magnetic, magnetooptic, optic, dielectric and magnetoelectric properties that can be tailored on the nanoscale. Generalized Ellipsometry is a suitable tool for accurate characterization of their new functional materials properties. New approaches include Vector-Magneto-Optic Generalized Ellipsometry (V-MOGE) where samples are investigated within magnetic fields freely variable within all three spatial coordinates, THz Optical Hall effect where free charge carrier excitations are studied without contacts, Mueller matrix microscopy where samples are studied in conoscopic imaging mode, and combined Quartz-Crystal-Microbalance and in-situ Ellipsometry where minute amounts of organic adsorbates can be quantified, for example. Highly-ordered 3D-nanomaterials can be made, for example, by physical deposition processes such as glancing angle deposition, or direct laser writing. Subsequent modification of surface chemical properties, for example by atomic layer deposition or self-assembly of organic surfactants, and functionalization, for example by crafting chemical and biochemical recognition elements, allows for implementation into new architectures of devices for application in medical and life sciences. Specific focus is directed onto the use of Spectroscopic Ellipsometry for characterization of magnetooptic and birefringence properties, from the Terahertz to Vacuum Ultra Violet spectral region. New model approaches for quantifying structural information, and related optical and magnetooptical properties are discussed. It is found that highly-ordered 3D-nanomaterials reveal coupled dielectric and magnetic properties, which are extremely sensitive to magnetic and dielectric materials attached to within the nanostructures, and which are exploited for design of new, flow-based or solution-based sensor and separation elements. Examples include aptamer-based DNA sensors, protein adsorption, monolayer self-assembly and dye-based analyte detection.

Figure 1: Highly-ordered 3D-nanomaterials with chemical and biochemical recognition elements (a) monolayer DNA aptamer sensor, (b) selective capsid (protein shell of virus) capturing in hollow-core nanohelices with matched dimensions, (c) viral attachment on bio-functionalized nanoscaled surfaces, for new sensing and separation principles
How realistic is modelling metamaterials with magnetic permeability?

K. Hingerl
Johannes Kepler University Linz
Email: Kurt.Hingerl@jku.at

Ab-initio calculations of the properties of split ring based metamaterials without assuming an effective or negative permeability. A two dimensional simulation model including split ring resonators embedded in a medium with a polaritonic permittivity, providing a low plasma frequency background, is introduced. Using the finite difference time domain (FDTD) method large scale simulations of these structures are presented. It was found from these ab-initio calculations that split ring resonators embedded in a polaritonic substrate material exhibit a negative refraction and backward waves and thus show a behaviour which can be modeled with a negative permeability. By constructing supercells it is possible to overcome anisotropy effects. However, for realistic material parameters, e.g. for Ag, for the chosen geometry the propagation length is of the order of one wavelength, jeopardizing applications. Despite the often used concept of “long wavelength limit” FDTD results show that this limit is seldom realized.

Spectroscopic ellipsometry holds great potential for the characterization of optical metamaterials, because the ratio of the Fresnel reflectances can be determined under oblique incidence, thereby providing the difference of the phases between p- and s-polarized light. We present ellipsometric spectra of a Fishnet metamaterial at different angles. The results show a good agreement between experimental and ab-initio calculated response of the structure, using the metallic and dielectric permittivities. By following the equivalent procedures derived independently by Menzel et al. [1], Berreman [2] and Rogers et al [3] we calculate the so called effective permeabilities and permittivities for anisotropic samples with orthorhombic symmetry. It is experimentally shown that spatial dispersion cannot be neglected for different angles of incidence, and more important that homogenization of a fishnet metamaterial assuming tensor relations for effective permeabilities and permittivities cannot be done without contradictions.

References
Numerical simulations for design and analysis of metamaterials and plasmonic structures

S. Burger\textsuperscript{1}, M. Blome\textsuperscript{1}, J. Pomplun\textsuperscript{2}, L. Zschiedrich\textsuperscript{2}, F. Schmidt\textsuperscript{2}

\textsuperscript{1}Zuse Institute Berlin, Berlin, Germany  
\textsuperscript{2}JCMwave, Berlin, Germany

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The spectral response of metamaterials and plasmonic structures critically depends on geometrical and material properties of the experimental arrangement. This allows for a broad variety of interesting applications. For understanding and designing properties of plasmonic resonators and metamaterials numerical simulations of Maxwell’s equations are very helpful. Rigorous simulations of such setups are challenging because (i) structures and field distributions are defined on multi-scale geometries (e.g., nanometer layers extending over microns), (ii) material properties (e.g., permittivity of silver) lead to high field enhancements or singularities at edges and corners of the objects, (iii) typical regions of interest are 3D and large in scales of cubic wavelengths, (iv) structures often are embedded into inhomogeneous exterior domains (e.g., plasmonic particles embedded into the material stack of a solar cell).

For approaching such simulation tasks we use finite-element methods (FEM solver JCMsuite) developed at JCMwave and ZIB. We discuss simulations of several metamaterial and plasmonic devices and effects, ranging from plasmonic nanoantennas for biomolecule detection to helix metamaterial as ultra-thin circular polarizer, photonic quasicrystals and plasmonic oligomers [1, 2, 3, 4, 5, 6].

References

Characterizing periodic gratings and metamaterials using spectroscopic ellipsometry

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The rapid expansion of the field of metamaterials has been facilitated by the development of new techniques to fabricate nanostructured metallic arrays. Simultaneous with fabrication advances, optical characterization of metamaterials has also developed, although progress in this endeavor has undoubtedly lagged, partly due to the dimensions of the samples fabricated thus far. The potential of ellipsometry was recognized in 2004 to characterize the magnetic resonances in terahertz metamaterials [1]. However the limited dimensions of fabricated samples in the IR and visible range hindered further investigation. The recent availability of relatively large area Vis-NIR metamaterials (cm²) now allows accurate optical measurements by well established plane-wave reflection and transmission techniques. In this work we use spectroscopic ellipsometry (SE) and transmission spectroscopy to characterize subwavelength periodic gratings and fishnet metamaterials with artificial magnetic resonances. The materials are fabricated by nanoimprint lithography (NIL). NIL allows the relatively fast and cost effective production of sub-100 nm structures over large areas [2]. Three samples are investigated, all with period of 365 nm; a single layer square silver grating on silicon; a 3 layer silver/SiO₂/silver grating on silicon; and an identical 3 layer grating on glass. VASE data is measured from 245 - 1700 nm. We will show that a comparative study of the same metamaterials on different substrates assists in mode identification, but changes the effective material parameters. Any ellipsometric investigation necessarily requires consideration of the angular-dependent optical response. We will show that this aids in the identification of the physical origin of the optical modes. On the question of parameter retrieval, SE is the method of choice for determining the permittivity of bulk and thin film materials, however the extension to materials with non-unity permeability, whilst logical, is not experimentally established. We will conclude by considering ellipsometry in the context of non-unity permeability and explore the potential of standard ellipsometric analysis to identify magnetic-type resonances and negative refraction.

References
2. Bergmair et al. Single and multilayer metamaterials fabricated by nanoimprint lithography, Nanotechnology 22, 325301 (2011)
Bianisotropy in metamaterials near optical frequencies

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Metamaterials are composed of arrays of plasmonic resonators engineered as to induce new optical properties. Near optical wavelength, the simplest structure proposed consists in square arrays of U shaped resonators. Generally, the medium is anisotropic and permittivity $\varepsilon$ and permeability $\mu$ must be described by tensors. The elements of the tensors can have different origins near the plasmonic resonances: electric dipole associated with plasmon resonances, magneto-electric coupling associated with current circulations [1] and spatial dispersion associated with non-local interactions among the currents [2]. Magneto-electric coupling and spatial dispersion lead to bianisotropy, which is described by an additional tensor $\kappa$. It is necessary to discriminate among these different origins and assess the relative contribution of each effect on the optical properties. The inspection of the Berreman's characteristic matrix of the metamaterial layers allows the sensitivity of measurements to elements of the tensors $\varepsilon$, $\mu$ and $\kappa$ to be assessed. Particular measurement conditions can then be defined to determine unambiguously the origins of the optical properties of metamaterials. We will illustrate this analysis in the case of U shaped resonators. Resonators made of gold were synthesized on a 320x320 nm$^2$ square lattice using e-beam lithography. The width of the arms was 20 nm with bottom arms 145 nm long and lateral arms 175 nm long. We show that measurements of the elements of the Mueller matrix are mandatory, even in this simple case, to provide comprehensive description of the optical properties of this metamaterial. The influence of magneto-electric coupling was evidenced by performing measurements of the three first rows of the Mueller matrix, along the bottom arm of the U. In these conditions, magneto-electric coupling induced transfer of polarization with $m_{13}=m_{31}$ and $m_{23}=m_{32}$ where $m_{ij}$ represents the element $(i,j)$ of the Mueller matrix (Fig. 1). By comparing measurements performed along different directions and incidences, we will discuss the relative magnitude of the different effects, present the spectral dependence of the different optical tensor elements and relate them to the resonant modes of the U shaped resonators.

![Figure 1: Spectral dependence of (a) $m_{13}$ and $m_{31}$ and (b) $m_{23}$ and $m_{32}$ elements of the Mueller matrix recorded at an incidence of 40\degree for light propagating along the bottom arm of the U shaped resonators.](image)

References

Polarization of Light Reflected from Chiral Structures - Calculations Compared with Mueller Matrix Ellipsometry Measurements on Natural and Synthetic Samples


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The Mueller matrix elements $m_{ij}$ representing the polarization response from a nanostructured material is determined by the constituent materials optical properties and the superstructure. Here, we investigate how chiral structures in form of helicoidally stacked uniaxial layers determine $m_{ij}$ as a function of polarization state, wavelength $\lambda$, incidence angle $\phi$ and azimuthal angle of the incoming light. The studied parameters include the layer materials ordinary/extraordinary optical properties, Euler angle values, and layer thickness as well as the thickness and pitch of the helicoidal superstructure. Sub- and superstructure inhomogeneity is also introduced. From the Fresnel-based calculations, $m_{ij}$ as well as the degree of polarization $P$, ellipticity and azimuth of the polarization ellipse are obtained and presented as contour and trace plots to give a complete view of the polarization behavior. The results from the calculations are compared with Mueller matrix spectroscopic ellipsometry measurements of both natural and synthesized helicoidal structures. The measurements were performed with a dual rotating compensator system (RC2, J.A. Woollam Co., Inc.) for wavelengths in the range from 245 to 1000 nm and incident angles from 20 to 75°. For some measurements the azimuthal angle of the incident light was varied. The investigated natural chiral structures were exoskeletons from several beetles in the scarab subfamilies Cetoniinae and Rutelinae. As predicted from the calculations it is observed that the reflection from these beetles can have a high degree of polarization and high ellipticity (near-circular polarization). Both left- and right-polarization was observed. The synthesized structures are helicoidal nanorods of Al$_{1-x}$In$_x$N grown on sapphire substrates with metal-nitride seed layers using UHV magnetron sputtering. Due to an internal composition gradient (a variation of $x$) in the crystalline structure, the nanorods will tilt away from the substrate normal. Helicoidal structures can thus be obtained by rotating the substrate around its normal during deposition. Samples with different pitch and layer thickness with right-handed as well as left-handed chirality were grown. Also for these structures both left and right near-circular polarized light is observed. By combining calculations, ellipsometry measurements and scanning electron microscopy characterization we get a good input to build layered models of the natural and synthetic samples. After regression fitting a good agreement between calculated and measured optical data were obtained.
Magneto-optical coupling in ferromagnetic thin films investigated by vector-magneto-optical generalized ellipsometry

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With the setup vector-magneto-optical generalized ellipsometer (VMOGE) [1], we performed Mueller matrix ellipsometry [2] measurements in a magnetic field of arbitrary orientation and magnitude up to 400 mT at room temperature. We probed the Mueller matrix elements of capped, ferromagnetic Fe, Ni₂₀Fe₈₀, Co, Ni₈₀Fe₂₀, and Ni thin films on ZnO substrates in the spectral range from 300 to 1100 nm [3]. We determined the off-diagonal elements in the magneto-optical dielectric tensor of the ferromagnetic thin films under saturated in-plane magnetization conditions via a model analysis. The off-diagonal elements depend on the net spin polarization and the electronic band structure of the ferromagnetic thin films. For pure ferromagnetic metals Fe, Co, and Ni, the converted off-diagonal elements agree well with the reported experimental optical conductivity data [4]. Mueller matrix ellipsometry also allows one to identify the magnetization orientations in the ferromagnetic sample. With additional measurements on the magnetization of the ferromagnetic thin films, we extracted the magneto-optical coupling constant Q, which is magnetic field and film thickness independent. Such material parameter Q is useful to model the magneto-optical response of magnetized thin films in layered sample systems in dependence of the incident angle of light, wavelength, and magnetization.

![Graph](image_url)

Figure 1: The real and imaginary part of experimental off-diagonal optical conductivity spectra $\omega\sigma_{xx}$ for (a) Fe, (b) Co, and (c) Ni. The white squares are the optical conductivity determined by VMOGE. Adapted from Ref. [3,4].

References

Sculptured thin films are self-organized and self-assembled three-dimensional nanostructures with tunable geometries. These artificial nanostructured thin films exhibit highly anisotropic physical properties, which mainly depend on their specific geometry. Understanding magnetic behavior and phenomena in nanostructures is of utmost importance with respect to utilizing magnetic nanowire thin films for next generation three-dimensional data storage devices, for example.

Slanted and spatially coherent columnar nanostructure samples from ferromagnetic permalloy (Ni$_{80}$Fe$_{20}$) were prepared by glancing angle electron-beam deposition. Subsequently, a thin conformal Al$_2$O$_3$ passivation layer was coated by atomic layer deposition to prevent sample oxidation.

We present and discuss the approach of vector-magneto-optical generalized ellipsometry on ferromagnetic permalloy nanostructured thin films carried out at room temperature. Investigations have shown that the highly porous anisotropic metal alloy thin films with approximately 100 nm film thickness are still transparent, reveal strong form-induced birefringence, and exhibit intriguing magneto-optical anisotropy. Spatial magnetization hysteresis loops are studied using a three-dimensional Helmholtz coil arrangement. This particular octupole setup allows for arbitrary magnetic field directions at the sample position with field strengths up to 200 mT while optical access is granted for focused reflection and transmission-type ellipsometry measurements. The determined magneto-optical coupling parameters, which are proportional to the sample magnetization M, reveal intriguing anisotropic magnetic behavior of the slanted columnar thin film. Three-dimensional graphs of the magneto-optical coupling parameters with respect to spatial hysteresis loops are representative for the sample magnetization. The graphs reveal strong azimuthal magnetization dependence and allow conclusions about magnetic switching behavior.

Figure 1: (left) Photograph of the vector magnet mounted onto the ellipsometer goniometer. (right) Three-dimensional graph of the magneto-optical coupling parameters (real-part) with respect to a spatial hysteresis loop within the xz-plane (PL, plane of incidence). The slanting plane of the columns is also parallel to the plane of incidence ($\lambda = 500$ nm, $\Phi_0 = 55^\circ$, $\mu_0H = 170$ mT).
Spectroscopic ellipsometry of magneto-optic garnet with in-plane anisotropy

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Bismuth and Cerium doped YIG with in-plane magnetic anisotropy is promising material for magnetophotonic crystal and magnetoplasmonic nonreciprocal devices [1]. Its low absorption together with magneto-optical activity in near-infrared and red spectral range gives possibility for application in telecommunication and optoelectronics. For the above application and precise modeling and optimization of magnetophotonic and magnetoplasmonic structures, there is a need for precise spectra of optical and magneto-optical parameters - the complete permittivity tensor.

In this paper we apply spectroscopic ellipsometry (0.6 - 6.5 eV), magneto-optical ellipsometry (0.77-2.5 eV), and infrared spectroscopy (7500-370 cm⁻¹) to obtain the spectral optical functions of the GGG substrate and Bi:YIG film. The magneto-optic films were produced using liquid phase epitaxy on both interfaces of the single crystal GGG substrate. Almost in-plane magnetic anisotropy was confirmed using magneto-optic vector magnetometry. Magneto-optic spectra were measured using a null magneto-optic ellipsometer with phase modulation by Photoelastic modulator (PEM) [2].

References

Characterization of metal oxide thin films and interfaces by spectroscopic ellipsometry and magneto-optical Kerr effect spectroscopy

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In this contribution we will present the spectroscopic ellipsometry and magneto-optical Kerr effect spectroscopy (MOKE) characterization of Cu₂O bulk crystals as well as ultra-thin films prepared by atomic layer deposition (ALD). Cu₂O was already used as injection material in metal-based transistors [1] going into the direction of spin injection and as base material for diluted ferromagnetic semiconductors [2]. On the other hand, thin films of Lanthanum Strontium Manganate (LSMO) were investigated as potential ferromagnetic substrate/electrode for organic semiconductor barrier layers. Therefore, in addition to the optical constants which can be extracted from traditional spectroscopic ellipsometry, also the information about the magnetically induced off-diagonal elements of the dielectric tensor is of interest. In order to access these tensor elements polar MOKE spectroscopy is applied in this work. In the case of the Cu₂O single crystal the surface roughness has to be taken into account in order to avoid an artificial absorption tail into the band gap region in the dielectric function [3]. The optical constants determined from the ellipsometry and the MOKE spectrum were used to calculate the magneto-optical Voigt parameter Q of the Cu₂O bulk and the off-diagonal elements of the dielectric tensor. The ALD films show different dielectric behaviour compared to the bulk crystal, mainly due to imperfect substrate coverage. However, the Voigt constant of the bulk was used to predict the MOKE-spectra of the ALD films [4]. The differences between the simulated and the experimental data can be attributed to the film roughness and presence of other species such as Cu(OH)ₓ. The LSMO (magneto-)optical properties were found to vary significantly with the film thickness. Furthermore, the deposition of an organic semiconductor layer, copper phthalocyanine (CuPc) on top of LSMO yields a change in the magneto-optical properties of the LSMO. An optical layer model was applied in order to calculate separately the MOKE responses of the dominating ferromagnetic substrate and the paramagnetic organic top layer. The simulation results were compared to the experimental separation of the two contributions.

References

RS - Rough and Structured Surfaces
Ellipsometric characterisation of rough and structured surfaces

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Surface roughness is routinely quantified with real space image methods like AFM in quantities like the root mean square (rms) roughness and the correlation length. In the analysis of ellipsometric spectra, surface roughness is modelled by introducing an additional layer between the topmost material layer and the ambient. The dielectric properties of this additional layer is modelled as an effective medium of the two materials, while its thickness is considered to reflect the rms roughness. Aspnes and Theeten considered several Effective Medium Approximations (EMA) to model surface roughness and concluded that Bruggemans EMA is the most appropriate [1]. The interpretation of the layer thickness remained however questionable.

A different approach to the influence of surface roughness on the optical response is the Rayleigh Rice (RR) approximation [2]. The RR approach is a perturbation of the Fresnel equation, that relates the actual power spectral density of the surface morphology to a modification of the reflection and refraction coefficient. Very recently a detailed analysis of the RR approach considered a surface showing self-affine roughness [3]. AFM measurements have shown that this is an appropriate model for roughness as a result of for instance the growth of a thin film. The roughness is characterized by the rms value $w$, the correlation length $\xi$ and a critical exponent $\alpha$. The analysis with the Rayleigh Rice approach showed that the change in the reflectivity scales with $w^2/\xi^\alpha$. This finding allowed to interpret the thickness of the traditionally used EMA layer in terms of the rms roughness and the correlation length. This implies that a small correlation length strongly enhances the ellipsometric perception of roughness. In this presentation the implications of the RR analysis will be discussed.

For semiconductors, the traditional EMA approach provides a reasonable fit of the measured spectra of a rough surface. However, a reasonable fit is no longer observed for roughness on metal surfaces like silver and gold. This breakdown is illustrated with the inability to model the optical response of shallow ripples on a Ag(001) surface. The plasmonic effects of such a structured surface is well described with the RR approach, providing ripple amplitude and average spacing.

References

Invited

Dimensional characterisation of nanostructured surfaces using scatterometry and ellipsometry.

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Many current and future technologies in different fields like optics, semiconductor industry or nanotechnologies require a highly accurate and reproducible metrology of micro- and nanostructures. Currently, especially the semiconductor industry greatly pushes the metrological requirements. Although sophisticated ultra-high resolution microscopic techniques like SEM and AFM are available, optical methods are of interest and are important because they are non-destructive, fast and have a good in-line capability. Scatterometry, the analysis of optical radiation scattered or diffracted at a structured or unstructured surface, is already known as an important metrology in this context and is a promising candidate to solve future challenges in dimensional nanometrology.

Scatterometry gave access to a fast and non-destructive characterisation of the structures, avoiding the constraints of imaging (microscopic) methods particularly by Abbe’s diffraction limit. Thus, e.g. the width of structures well below the optical wavelength is measurable. However, the evaluation of the measured data requires a quite complex, time- and memory-consuming mathematical treatment, the solution of the inverse diffraction problem. Many different methods are applied and discussed in literature, like e.g. diffractometry, reflectometry, ellipsometry, Mueller polarimetry and scatterometry in the actual sense, which may be summarised under the generic term "scatterometry". We shortly discuss the grading of scatterometry in the application range between stochastically structured (rough) surfaces and few (or single) structure scattering.

A short overview about the different methods and their applications will be given, including an overview of the commonly used inverse analysis methods. Some aspects concerning the potential of these different methods, their sensitivity, the approximations used in the analysis and the limits of these methods will be discussed. Finally a short overview of the experimental and numerical methods currently used and on future developments at PTB will be given.
Ellipsometric Porosimetry (EP) for the Characterization of Nanostructured Sol-Gel Thin Films

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The performance of thin oxide films critically depends on their microstructure. Porosity, which is a common feature of sol-gel derived materials is highly detrimental for some applications, whereas in other cases it is the basis for the desired function. For nanoscaled films, however, it is very difficult to obtain reliable quantitative information about porosity and pore size distribution using, for example, electron microscopy or conventional spectroscopic methods. When spectroscopic ellipsometry is performed in atmospheres with controlled humidity, the measurements allow a monitoring of the successive filling of pores with water by capillary condensation: Ellipsometric porosimetry (EP) thus is able to provide data regarding open porosity, pore size distribution, and refractive index of the solid backbone material of thin films. Examples of the application of EP to different film systems will be given ranging from standard problems to elaborate and challenging questions. Additionally, limitations and possible pitfalls of the method will be discussed.
Ellipsometry on metals and alloys in the solid and liquid state

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Motivation
For understanding and optimizing laser processing of metals and alloys the optical properties, especially the absorption in function of the temperature of the work piece up to the liquid phase have to be known. Unfortunately to best of our knowledge only few experimental data of optical properties is published for metals which are used in industrial applications. Therefore an ellipsometer has been set up in order to measure the optical properties of samples up to about 1500°C. At this temperature many metals used in industrial applications, like aluminium, copper and different kind of steel, are in the liquid phase.

Experimental
A standard Rotating Compensator Ellipsometer (RCE) configuration has been used, where the compensator is placed after the sample and before the analyzer (PSCA-setup). A Superluminescent Light Emitting Diode (SLED) with a centre wavelength at 1070nm and a bandwidth of 100nm as a light source and a spectrometer as a detector have been chosen. The ellipsometer is mounted to a vacuum chamber allowing measurements at 10-5 mbar as well as under an inert gas atmosphere. With the current configuration angles of incidence of 80°, 70°, 45° and 40° for the ellipsometer can be chosen. The samples can be heated in two ways: firstly with a translatable and tiltable heating stage, on which the sample is positioned and with which temperature up to 1000°C could be achieved. Secondly the light of a fibre coupled high power diode laser is focused onto the surface of the sample. By using both heating methods amongst others aluminium, copper and steel can be heated above their melting point.

Results and Discussion
The main focus of this work will not be the ellipsometer itself and the data-analysis, where a standard approach has been chosen, but the difficulties that emerge when doing ellipsometry at high temperature and in the liquid state, respectively. Several problems such as curved surface of the sample in the liquid state, surface roughness changes with temperature, material evaporation, temperature measurements and metallurgic effects have to be addressed, which will be discussed in more detail.

One specific challenge is the influence of a curved sample surface. When melting the metal samples they take a curved, convex or concave shape. Therefore the influence of curved surfaces on the ellipsometry measurements has been studied by doing ellipsometry on steel metal rods and ball bearing of different diameters. Results of successfully managing this effect will be reported along with the investigations concerning the right crucible material in order to influence the wetting behaviour of the liquid metal sample and to minimize the metallurgic reaction between the sample and the crucible material.

Another important topic is the influence of the evaporation of material from metals and alloys at high temperatures, respectively. In order to avoid strong deposition inside the vacuum chamber walls and the viewports for the ellipsometer and the heating laser, a series of experiments at different pressures of argon have been conducted.

An additional issue is the formation of a contamination layer on the liquid samples. This layer probably formed by impurities of the samples diffusing to the surface may strongly influence the ellipsometer data and has to be avoided. Several strategies to minimize these layers will be presented.
Reflexions on the Electromagnetic Waves: their limits and perspectives

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Introduction:
During the last years several new discoveries attacked the models on which our understanding of the physical laws of the universe are based. Recently the OPERA experiment claimed that the speed of light can be challenged by neutrinos. The measure of the background of the universe and the acceleration of the expansion lead to a balance of 75% of mater that we cannot see directly but feel. We live in a time which is similar to Galileo, Newton, Descartes, etc. We anticipate that new discoveries and new theory will come soon. This paper will summarize this feeling, based on experiments including our field of light analysis of our environment.

Experiment:
From Ptolemaus to Ticho Brah, the observation of the universe was with the eye, Galileo revolutionized the astronomy with his lunette and Keppler changed the model to Helio-centric. In the same time the optical microscope invented by Janssen, or Gallileo, enables to see the invisible world at small size. Up to now, the electromagnetic waves are the major tool for the observation of the sky, we can reach the 400 000 years after the big bang where the limit stands. For the small world, electron beam and AFM have completed the optics. Will the speed of light stay as the limit after the Gran-Sasso experiment? Will the LHC give us the confirmation of the model of interaction, today no signal has been seen, and shall we need a new model?

Modeling:
We can feel that we are in a period of uncertainties and that our models should be revised. In our field, the complete measure of the complex reflectance of light on the natural materials, as beetle’s wings, versus angle and wavelength and polarization with a complete Muller matrix analysis demonstrate the full understanding of the electromagnetic waves propagation. In addition, based upon this model, bio-mimetic, it was possible to nearly re-make the same coatings. This opens the field to new development, calculation a priori of materials and coatings, which do not exist in the nature, as meta-materials with new behaviors. The realization for visible range remains difficult but we may see such layers soon. It has been made down to NIR. Perspectives: there are already new means to explore the laws of the universe, the giant LHC, the gravitational wave interferometers and the neutrinos which may lead to new concept and models. The progress of the limit of detection of the Virgo interferometer will be displayed.
IA - Industrial Applications
Although ellipsometry as phase-sensitive effect was discovered by Paul Drude almost 120 years ago, the first industrial applications came up not earlier than 70 years later. In the mid-sixties of the last century, single-wavelength ellipsometry enabled the determination of the thickness of thin oxide films in the emerging planar technology with accuracy in the range of one nanometer. In fact, thin film technology was nanotechnology on an industrial scale from the beginning. Nowadays, ellipsometry has a vast variety of applications in academic research, testing laboratories, industrial quality assurance, and process monitoring and control. As model-based technique, the conversion of ellipsometric quantities $\Psi$ and $\Delta$ into real physical quantities, among them optical and dielectric functions and thickness, is usually required. The selection of appropriate models also depends on the pre-knowledge of surface properties and modification features such as materials and the layer or stack design. Sometimes, this can be very sophisticated and time-consuming. In academic research, the time-effort for model selection, adaption and validation is not as crucial. In general, there is a huge variety of new materials and advanced surface designs, sometimes investigated by ellipsometry for the first time. In case of testing labs, the materials involved and the basic sample structure are usually known, frequently just deviations of the physical quantities have to be explained. In at-line quality assurance, the materials involved and the sample structure are well-defined. However, a fast decision whether the sample is “within limits” is needed. For on-line process monitoring and control, the same criteria may just apply to the raw data $\Psi$ and/or $\Delta$ on even much shorter time scales. This tutorial addresses a number of practical aspects of measurement and data evaluation with regard to these different application scenarios: first, sample-correlated features such as inhomogeneous samples vs. lateral resolution and mapping/imaging, thickness inhomogeneity vs. mapping/modelling, anisotropic samples vs. sample orientation, graded samples vs. vertical sensitivity/modelling, rough samples vs. depolarisation/modelling, specific sample features (native and degradation films), surface contamination and adsorption phenomena, and backside reflection, second, measurement-correlated aspects such as single wavelength vs. multiple wavelength, angles of incidence vs. Brewster angle, laser coherence length, and third, model-dependent issues such as fingerprints vs. model-based data evaluation, parameter coupling for very thin and thick thin films, available models and limits of validity. Besides a microscopic or SEM-inspection of an unknown sample, sometimes, the use of thickness standards and reference materials is also recommended as shown in several inter-laboratory comparisons or even required for accredited testing labs according to DIN EN ISO/IEC 17025. Prior to measurement, verified knowledge on the sample structure is a must. Real sample are treated as ideal and hence models do not correspond to physical reality. Thus, the development of standard operating procedures (SOPs) is recommended for all fields of application.
Optical metrology plays a fundamental role for the technology control and process development. The manufacture process requires high throughput measurements performed for monitor and process wafers with a pattern recognition alignment. Spectroscopic ellipsometry (SE) at fixed angle in the wavelength range of 190-800 nm as well as normal incidence reflectometry (R) are powerful technology control inline techniques. In this presentation examples of application of SE and/or R preferentially for the 0.25 and 0.13 µm BiCMOS technologies will be demonstrated. Each technology requires about 50 SE and/or R measurements performed in front end and back end of line. The most applicable dispersion models used for describing the optical constants of materials will be reviewed. They can be implemented as recipes for inline control. An example of gate SiO2 thickness monitoring and influence of airborne molecular contamination surface layer will be considered. In-line thickness and composition control of graded SiGe:C heterojunction bipolar transistors will be shown. It will be presented the typical examples of complex multilayer stacks, in particular for metallization module characterization, where the combination of SE with R in one measurement cycle is a best choice. The optical characterization of new high-k materials will be demonstrated. Special attention will be given application of ellipsometry for characterization of nanostructured layers. The extraction of geometrical structure parameters is performed by using RCWA in comparison with effective medium approximation. It will be shown how the regular process and tool control is performed and analyzed statistically (SPC). Finally, the importance of thin film metrology in Si technologies will be demonstrated by considering a correlation between layer thickness and electrical parameters.
Standardisation in the analysis of complex thin film systems with ellipsometry

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Along with the development of computing power in the last decades, ellipsometry has become one of the most versatile surface analysis techniques. Its biggest advantages are its use of optical radiation which is non-destructive to almost all samples and the fact that it can be employed in laboratory air in most cases. Measurement as well as analysis of the samples are possible in a very short time.

Despite the measurement itself being background-free, i.e. requiring no measurement of absolute light intensity, there is still the need for traceable calibration of the ellipsometric measurement and analysis process. Usually, standardised surfaces as well as film thickness standards are employed for the calibration of ellipsometers. These are, however, simple idealised samples in most cases which don’t seem fit for the more complex analysis tasks of today. Furthermore, film thickness standards still require the use of additional measurement methods for calibration. Tactile step height measurements and X-ray reflectometry are used for this task.

In this presentation a new type of reference samples is introduced in the range of several µm film thickness. These samples require the simultaneous characterisation of film thickness and of the dielectric function as the layer material is not a standard thermal silica. Therefore, a new approach is taken to study these samples which uses exclusively non-destructive methods (X-ray reflectometry and X-ray fluorescence along with ellipsometry). A European project on the metrology of thin films used in optoelectronics is introduced. One of the tasks of this project is the proof of concept for the new multi-µm thick reference sample. Other goals include the measurement of complex layer systems (as used in PV systems and OLEDs), the traceable study of laterally structured and curved samples with imaging methods and the development of a reference large-area mapping system for ellipsometric measurement of samples as big as photovoltaic panels. The combination of optical methods and X-ray methods is shown to be useful for all of these goals.

Figure 1: Reference sample (6.3 µm silicon dioxide on silicon) and its ellipsometric evaluation.
In-Line optical monitoring of quality of r2r gravure printed nano-materials for organic electronics applications

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A major factor for the achievement of the required performance, efficiency and lifetime of flexible organic electronics is the optimization of the quality of the printed materials (organic semiconductors, transparent electrodes, etc.) onto the flexible polymer substrates. Another important factor is the in-line and in-situ monitoring of the quality of materials that produced by roll-to-roll (r2r) printing processes.

In this work, in-line and real-time Spectroscopic Ellipsometry (SE) has been implemented in order to investigate the optical response, thickness uniformity and structural composition of r2r gravure printed nanomaterials onto moving flexible rolls of corona treated Polyethylene Terephthalate (PET). These nanomaterials include inorganic and hybrid barrier layers, PEDOT:PSS electrodes, P3HT:PCBM blends in single and multi-layered structures in both machine and transverse directions.

The results of the in-line monitoring were correlated with the printing conditions as well as with other functional properties such as conductivity, morphology and barrier performance. Finally, the results show that the adaptation of the in-line SE exhibits very good stability, and it can provide significant information of the r2r printed materials and it can be used as a robust quality control tool for the r2r fabrication of flexible organic electronic devices.
Ellipsometrical study of orange peel on highly polished metallic surfaces

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Finishing processes of metallic surfaces such as polishing could yield typical topographic features which could be detrimental for their functionality. The quality of polished metallic surfaces is commonly estimated upon their visual appearance, which frequently leads to very subjective classifications of their topographic features. Current industrial requirements, however, needs nowadays a high-quality process monitoring to reduce production costs and time, i.e., extremely accurate surface analysis techniques. In this contribution, a detailed study of highly polished metallic surfaces by means of Spectroscopic Ellipsometry (SE) is presented. In particular, an attempt is made to identify orange peel on steel samples. In this manner, it is shown that the ellipsometrical parameters as a function of the azimuthal angle reveal isotropic optical properties for all investigated samples. In addition, it is also shown that the pseudo-dielectric function in the range 1.5 eV to 2.5 eV can be correlated to the surface topography of samples. Therefore it is concluded that the SE is enough sensitive to qualitatively detect orange peel on highly polished metallic surfaces.
A fast imaging ellipsometer for in-situ measurements

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Imaging ellipsometry has, until now, found limited application for in-situ monitoring, predominantly due to the relatively low measurement speed. This has been limited both by measurement methods and the necessity of scanning the focus in order to obtain sharply focussed images at the large angles of incidence encountered in ellipsometry. A rapid imaging ellipsometer has been developed which overcomes these limitations and allows $\Psi - \Delta$ maps to be captured in just a few seconds, making it well suited for in-situ applications.

The focus problem has been overcome by applying the Scheimpflug principle to the camera system and introducing tilts to both the lens and detector [1]. In this way focus is achieved and distortion corrected simultaneously over the whole field of view. This is possible over a range of magnifications from approximately 0.5-2, at typical angles of incidence used in ellipsometry. By capturing sharp images in a single exposure, significant improvements in measurement speed and efficiency have been achieved over the focus stacking method. The perspective distortion is corrected optically hence images taken at different angles of incidence cover the same field of view and so multiple angle of incidence ellipsometry can be used obtain additional degrees of freedom for data analysis [2].

In order to take measurements quickly a polarisation state generator based on liquid crystal variable polarising optics has been built which allows very rapid switching between polarisation states. This is used in combination with a Fourier series measurement algorithm based on the Dynamic Imaging Microellipsometry method [3]. With this method, $\Psi - \Delta$ maps can be obtained with 10 polarisation states in just 2.5 seconds, the measurement rate currently being limited by the control computer and software. More polarisation states and multiple frames can be measured to obtain more accurate data and greater dynamic range at a trade-off for measurement speed.

The imaging ellipsometer has been used in a combined technique (imaging ellipsometry and grazing incidence small angle x-ray scattering) in-situ experiment to monitor the compaction and calcination of sol-gel ceramic thin films on a silicon substrate during heating at temperatures from 400 to 1000°C. Both techniques were applied simultaneously on the 7T-MPW-SAXS beamline at BESSY. Preliminary results from these experiments will be presented as a demonstration of the instrument.

Figure 1: The prototype Scheimpflug geometry imaging ellipsometer

References
DP - New Developments and Miscellaneous Problems of Measurement and Data-Evolution
We report on the progress of the development of variable angle of incidence terahertz ellipsometer using time-domain detection scheme. Our setup operates in range 0.1 - 2 THz (app. 0.5 - 1 meV) and is powered with NIR femtosecond pulsed laser providing excitation for emitter and detector photoconductive antennas. The time-domain detection allows one to obtain both amplitude and phase of the light at the detector and by combining this approach with simple rotating analyzer ellipsometry (RAE) configuration it is possible to detect ellipsometric Delta in full range of 360 degrees (i.e. comparable performance to rotating compensator ellipsometry with continuous waves). The ellipsometric signal analysis (including the necessary polarizer and analyzer offset calibration) differs from standard RAE and will be discussed in our contribution.

While time-domain THz spectroscopy can access real and imaginary part of dielectric function easily for transparent samples, ellipsometric configuration brings benefit for opaque samples, as it is reference free measurement of reflected light. Nevertheless, by adding a reference measurement, the complete Jones matrix is made available. It can be shown that by knowing all complex elements of the Jones matrix one can determine independently both dielectric permittivity and magnetic permeability as frequency dependent quantities.

Our THz ellipsometer is equipped with optical cryostat for measurements at temperatures between 8 K and 450 K. The instrument is still in development phase and its actual status and performance will be demonstrated on the example of SrTiO$_3$ spectra.
Spectroscopic ellipsometry measurements on nano-granular TiO$_2$ thin films

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We have investigated the optical, morphologic and electronic properties of nanogranular TiO$_2$ films deposited onto silicon substrates by means of supersonic cluster beam deposition (SCBD)\cite{1, 2, 3}, using spectroscopic ellipsometry (SE), Atomic Force Microscopy (AFM) and X-ray Photoelectron Spectroscopy (XPS). Nanogranular (and nanoporous) TiO$_2$ films are promising for biological and gas-sensing applications \cite{4, 5} and may even be exploited for applications in hybrid photovoltaic devices.

Detailed knowledge of the surface and inner structure of nanogranular TiO$_2$ is a pre-requisite for the investigation of their response to the deposition of selected molecules in liquid environment. AFM images revealed a characteristic surface roughness arising from the random stacking of the spheroidal nanoparticles during the low-energy deposition from the supersonic beam. High-resolution XPS measurements showed the presence of a good oxide stoichiometry with only a small fraction ($<3\%$ typ.) of non-stoichiometric oxide species. Previous Raman and TEM measurements indicated an amorphous cluster structure with embedded rutile, anatase and brookite nano-crystals \cite{3}.

SE investigations in the wavelength range 245-1700 nm were performed on various films in the 20-150 nm thickness range. The mixed amorphous/crystalline structure and the complex morphology of these nanogranular films introduce some drastic changes in the optical properties of these films with respect to crystalline TiO$_2$ thereby making the modeling of these systems a particularly challenging task. Initial efforts were focused on simple models based on the rutile and anatase optical properties found in literature. Bruggeman Effective Medium Approximation (B-EMA) was used in order to model the complex film morphology (e.g. presence of nano-voids in the porous structure), in analogy with our recent works on gold nanoclusters films \cite{6, 7, 8}. Improved agreement, with a fair qualitative description of the SE data, was obtained modeling the optical properties of the TiO$_2$ fraction by means of the so-called P-Semi approach. The relatively high mean squared error of these fits calls for further refinements of the model, especially in the absorption-edge region and towards the infrared, where a relevant absorption is observed. To this end, transmission measurements on transparent samples are planned. In situ SE spectra of nanoporous TiO$_2$ films immersed in ethanol will be also presented.

References

5. R. Carbone et al., Biomaterials 27, 3221 (2006)
Opportunities and challenges of ellipsometry for process monitoring in atomic layer deposition

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Ellipsometry has widely served as a powerful non-invasive technique to monitor time-continuous as well as time-discrete deposition or etch processes at exactly the place where they occur (in situ) and even in real-time. As an example for coating ultra-thin films, we investigated atomic layer deposition (ALD), where the film growth ideally proceeds in a layer-by-layer manner.[1]

We utilized a spectroscopic ellipsometer with rotating compensator (M 2000® Fl by J. A. Woollam Co., Inc.) which was mounted on top of an ALD reactor (FHR Anlagenbau GmbH) as we have previously described in Ref. [2] and [3]. Prior to the deposition processes, we corrected the actual surface temperatures, which based on the temperature-dependent dielectric response function of silicon,[4] with respect to the set-point of a heater’s electrical control loop. Throughout the entire ALD process time, full ellipsometric spectra were acquired within a photon energy range from 0.73 eV to 4.96 eV, which was automatically triggered to the purging pulses after every ALD half-cycle and thus was synchronized to the ALD process under investigation.

Even without optical modeling, we described the ALD film growth in both the initial and the homogeneous linear film growth regime.[2] After applying appropriate optical models, the ellipsometric spectra were translated into one-dimensional film properties, and important process characteristics (like a film thickness increment per time interval) were quantified.[3, 5]

However, some critical issues still remained: A first issue regarded the time-continuous real-time acquisition of ellipsometric spectra in the range of milliseconds providing a sufficient signal-to-noise ratio. Although the employment of a single-wavelength ellipsometer has already achieved picosecond resolution,[6] a spectral information would typically support the physical interpretation of ellipsometric data that were acquired during deposition or etch processes, especially during the initial stage. A second issue concerned the temperature-dependent optical material parameters for a variety of insulators, semiconductors and metals following the example of silicon from Ref. [4]. These temperature-dependent parameters would facilitate a reliable translation of ellipsometric spectra that were acquired during deposition or etch processes under a specific temperature into one-dimensional film properties (like a film thickness, surface roughness or electrical conductivity). A third issue covered the optical parameters of conductors which have been reported to depend on the film thickness once the nanometer range is reached.[7] Up to now, the constitution of appropriate optical models for these ultra-thin (< 3 nm) films and even more for nano-sized wires or dots is still lacking.

References
Ellipsometric study of nano patterned surfaces for structural investigation

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We have investigated nano patterned surfaces using spectroscopic ellipsometry with the goal to assess the structural quality of the patterns. Nanoscale ripple patterns on SiO₂ and Al₂O₃ surfaces were formed with low-energy ion beam erosion (E_{ion} 2 keV) at oblique ion incidence angles. Depending on process parameters (ion species, erosion time, ion energy,) ripple patterns with different wavelengths λ_{R} and amplitudes are formed. For fused silica ripple patterns wavelength and amplitude are around 100 nm and 10 nm, respectively. This introduces anisotropy in the dielectric function with respect to the in-plane orientation. This anisotropy is only visible if the wavelength of the light is on the same scale λ_{R}. The anisotropy follows the orientation of the ripple pattern but also shows distinct features that cannot be accounted for by a perfect ripple pattern. Hence we attribute this to imperfect pattern formation. However, the analysis lacks a suitable model to directly relate the imperfections in a pattern to changes in the dielectric function. In the case of Al₂O₃ the emerging structures have a period and amplitude of approximately 20 nm and 1 nm, respectively. This periodicity could not be measured directly by ellipsometry in the standard spectral range. However, by coating the surface with a thin Au film occurring plasmon resonances can be exploited to probe the induced anisotropy. The resonances often lie in the visible spectral range and are thus measurable using standard ellipsometers. While the substrate dielectric function is susceptible to the ripple pattern only close to the λ_{R} the plasmon resonance is strongly affected by the nanoscale pattern even if the resonance is far away from λ_{R}. For Au plasmonic structures deposited on patterned surfaces we found a distinct resonance frequency for k parallel and perpendicular to the ripple pattern. This anisotropy can be described with an effective medium approximation taking a mix of two spectra measured parallel and perpendicular to the wave vector of the pattern. For patterns with a λ_{R} of ~100 nm only a very weak anisotropy is observed whereas the anisotropy is much stronger for patterns with a shorter wavelength. This illustrates the fact that the size and formation of the gold particles is responsible for the strength and position of the plasmon resonance. This opens up the possibility to investigate structures that are much smaller than the wavelength of light used for the investigation.
EP - Electronic Properties
Electronic properties of strongly correlated electronic systems

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I will start with an overview of the relevant materials, like the cuprate and pnictide high temperature superconductors, the CMR manganites, the multiferroics, or the 2D electron gases which form at the interface between insulating oxides.

I will then briefly discuss some very simple models for describing the optical response of metals and superconductors (like the Drude-model and the extended Drude-model). I will also recall some important tools like the optical sum rules and the KK relationship and discuss general strategies to analyze the optical data.

Finally, I will present some relevant examples like the gap spectroscopy in superconductors, the unusual metal-to-insulator transition in the CMR manganites, electromagnons in multiferroics, or the plasma modes of 2D electron gases at oxide-interfaces. The emphasis will be on showing how information about the relevant electronic properties can be obtained from optical spectroscopy and ellipsometry in particular.
Spectroscopic Generalized Magneto-Optical Ellipsometry: Results on strongly correlated materials and new technology trends

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tba
Nitride Semiconductors - a model system for demonstrating the influence of excitonic effects on the dielectric function

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The application of semiconductors in optoelectronic devices requires precise knowledge on the dispersion of the complex dielectric function (DF) or the refractive index allowing the optimisation of e.g. wave guides or distributed Bragg reflectors. Beside the application aspect, the DF is of fundamental interest because its spectral dependence is closely related to the band structure of the materials, i.e. it shows peculiarities in the vicinity of the critical points (CP), the so-called van Hove singularities. It is usually assumed that the experimentally determined transition energies can be directly compared to the theoretical results. The group-III nitride semiconductors InN, GaN, and AlN exhibit two particular interesting properties. At first, the spectral range of interband transitions is much larger as for example arsenides or phosphides. Therefore, deviations between theory and experiment appear become better visible. At second, the wide-band gap materials are characterized by high exciton binding energies leading to a pronounced redistribution of oscillator strength between transitions.

The talk provides an overview on recent experimental data for the nitrides. The use of synchrotron radiation at BESSY II allowed to expand the studied spectral range up to 20 eV, i.e. not only the band-gap region but also the high-energy DF were investigated in detail. The experimental results are compared to the results of theoretical calculations.

For the hexagonal compounds, at least dielectric tensor components have to be determined. The ordinary and extraordinary DFs describe the optical response of a semiconductor to an electromagnetic wave with electric field polarization perpendicular and parallel to the optic axis (c-axis), respectively. Data of a- and m-plane InN, GaN, and AlN evidence a strong anisotropy over the whole range. For the band-gap region, it is related to the valence band ordering at the center of the Brillouin zone and the corresponding selection rules. For a very accurate determination of the band gaps and the valence band splittings from the DF, it is essential to take in the analysis the contributions from free excitons and the exciton continuum as well as from exciton-phonon complexes into account. The impact of the band reversal for AlN on the properties of the InAlN and AlGaN alloys is discussed. Based on these results, the studies of alloys provide in addition reliable values of the bowing parameters.

The comparison of the experimental data in the high-energy part to recent theoretical calculations evidences characteristic deviations in both the peak positions and the spectral shape. The origin will be discussed in detail as well as the consequences for determining the transition energies for van Hove singularities from experimental data. In brief, calculations of the DF based on the band structure derived from density-functional theory in local density approximation (DFT-LDA) underestimate the transition energies while the application of quasi-particle corrections within a perturbation approach alone leads to an overestimation. Good agreement between theory and experiment can only be achieved by taking into account the electron-hole interaction (excitonic effects) by solving the Bethe-Salpeter equation.
Dispersion model of graphite: application of sum rule

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We have developed dispersion model for graphite that is based on modern understanding of solids and fulfills three general conditions for dielectric function: (i) Kramers-Kronig relations; (ii) time reversal symmetry and (iii) f-sum rule. The sum rule has been formulated for the transition strength function defined as a continuous condensed-matter equivalent of the oscillator strength known for discrete transitions in atomic spectra. Therefore, the dispersion model is constructed as the parametrization of the transition strength function that is proportional to the conductivity. The advantage of the f-sum rule application consists in the combination of dispersion parameters related to the electronic structure with the material density in one model. The model separates dielectric response of individual absorption processes such as interband transitions, core level excitations and high energy electron excitations. Moreover, the structure of graphite requires to consider anisotropic response along and perpendicular to the optical axis.

The dispersion model was applied to the evaluation of experimental data obtained on highly oriented pyrolytic graphite (HOPG) from ellipsometry (Jobin-Yvon UVISEL) in the range 0.6-6.5 eV. Since the measurement range did not cover the spectral range of $\sigma \rightarrow \sigma^*$ the spectral distribution of transition strength function in this range was taken from the tabulated data [1]. Comparison of the transition strength function obtained from the measurement and the transition strength function calculated from the tabulated data are in Figure 1.

![Figure 1: Ordinary and extraordinary transition strength functions of HOPG. The points represent the tabulated data [1].](image)

References

Spectroscopic Ellipsometry and optical Hall-Effect studies of free-charge carriers in p-type In-polar InN:Mg

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Preparation and control of p-type conduction is still a challenge towards fabrication of InN-based photonic devices. Several authors have demonstrated that p-type conductivity in InN can be achieved by introduction of Mg as acceptor impurity. However, it is known that p-type regions in InN are embedded as buried channels in between high-density electron layers that form on the surface and at the interface between the InN and its substrate (or buffer layer) due to intrinsic defects and elements such as oxygen or hydrogen which act as shallow donors. This behavior affects the confirmation of conduction type and impedes the characterization of the p-type region by conventional electrical methods like electrical Hall-effect or hot probe measurements. This difficulty is not only attributed to the high sheet charge density on the surface but also to the large difference between electron (1000-2500 cm\(^2\)/Vs) and hole mobility (20-75 cm\(^2\)/Vs).

Electrolyte capacitance-voltage measurement (ECV) is commonly applied for the determination of hole concentrations while mobility values are estimated by fitting sheet conductivities from Hall-measurements of samples with different thicknesses.

We have studied a sample set of Mg-doped In-polar InN samples of about 400 nm thickness grown on c-GaN-buffer/sapphire by molecular beam epitaxy. In this set, the Mg-concentration was systematically increased from 1.2x10\(^{16}\) cm\(^{-3}\) to 3.9x10\(^{21}\) cm\(^{-3}\) in order to achieve and control p-type doping. It was demonstrated by Yoshikawa et al. [1], by applying ECV that p-type conductivity was achieved for a Mg-concentration range between 1.1x10\(^{18}\) cm\(^{-3}\) and 2.9x10\(^{19}\) cm\(^{-3}\).

We applied spectroscopic ellipsometry (SE) in the spectral range THz, FIR, MIR and NIR-VIS-VUV for characterization of electronic, vibrational and optical properties. By using a unique optical Hall-Effect setup (THz-FIR SE in magnetic field) the free-charge carrier induced birefringence is investigated to characterize surface electron accumulation, interface electron accumulation and volume free-charge carriers. By analyzing the phonon-plasmon coupling clear evidence for volume p-type conductivity in the MIR-SE data is found. The free-charge carrier parameters concentration and mobility are determined and the limitations towards the accessibility of the hole mass by optical Hall-effect are discussed.

References
1. A. Yoshikawa et al., phys. stat. sol. (a) 207, 1011 (2010).
Ellipsometry of ferroic phase transitions

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In the last years, interest to ferroic (ferro-electric, -magnetic, and mutiferroic) materials has experienced a steep rise. Mainly, this is due to high potential of such materials for numerous emerging devices, especially for spintronic and memory applications. A key to controlling unique properties of these materials is understanding nature of ferroic phase transitions. Such transitions from the high-temperature para-phases (e.g. para-electric, -magnetic) to the low-temperature ferro-phases take place on cooling, and they are accompanied by changes in optical properties. Studies of optical properties as a function of temperature can contribute considerably to understanding ferroics. Since often the materials under investigation are in the form of non-transparent ceramics, thin films, or multilayer structures, it is difficult to assess their optical properties using conventional interferometry and spectrophotometry. In ellipsometry, the optical constants of a material can be evaluated from the direct measurements of the main ellipsometric angles $\Psi$ and $\Delta$, thus removing restrictions to sample transparence and thickness. Here we demonstrate application of ellipsometric spectroscopy to investigations of ferroic phase transitions in single-crystal, ceramic, and thin-film epitaxial materials. The measurements were performed using variable-angle J.A. Woollam spectroscopic ellipsometer equipped with continuous flow UHV cryostat system that allows operation in the 0.75-9.0 eV spectral range and 5-800 K temperature region. Examples of ferroelectric, magnetic, and strain-induced phase transitions manifested in temperature evolution of refractive index and as the Kern-Harbeke effect in absorption spectra [1, 2] are presented.

References

Spectral Ellipsometry of TbMnO₃ Multiferroic

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We present the results of a detailed spectral ellipsometry experiments in which the complex dielectric function of a stoichiometric untwinned TbMnO₃ single crystals accurately monitored within the temperature region 10-300 K. Ellipsometric spectra were collected with J. A. Woollam variable-angle spectroscopic ellipsometer assembled with continuous flow UHV cryostat system and operating in the 1700-148 nm (0.73-9.0 eV) spectral region. The dielectric response along b and c axis (i.e. along and perpendicular to the ferromagnetic ab plane) was found to be highly anisotropic, confirming thereby that our crystal is detwinned to a substantial degree. Plate’s faces were optically polished with the resulting surface roughness less than ~ 2 nm. To eliminate depolarizing effects of back-surface reflection, the back surface of specimens was mechanically roughened. The size of the analyzed light spot was around 2 mm. All data were taken from the center of the samples. In this study we focus on the analysis of excitations observed at high energy ~ 3.5-6.0 eV and at the lowest 1.8-3.2 eV energy excitation. A special attention was paid to evaluation of the magnitude and role of electronic contribution into ferroelectric polarization and phase transition taking place at TC ~28 K at which sinusoidal spin structure of TbMnO₃ changes into a magnetic spiral structure. Estimation of the magnitude of the static electronic dielectric constant was based on the generalized multioscillator model, parameters of which were obtained from fitting of the dielectric response with sum of n independent damped harmonic oscillators.
Universal microscopic description of the infrared conductivity of 122 iron arsenides

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We report the full complex dielectric function of high-purity Ba\textsubscript{0.68}K\textsubscript{0.32}Fe\textsubscript{2}As\textsubscript{2} single crystals with $T_c = 38.5$ K determined by wide-band spectroscopic ellipsometry at temperatures $10 \leq T \leq 300$ K. We discuss the microscopic origin of superconductivity-induced infrared optical anomalies in the framework of a multiband Eliashberg theory with two distinct superconducting gap energies $2\Delta_A \approx 6k_B T_c$ and $2\Delta_B \approx 2.2k_B T_c$. The observed unusual suppression of the optical conductivity in the superconducting state at energies up to $14k_B T_c$ can be ascribed to spin-fluctuation-assisted processes in the clean limit of the strong-coupling regime. We further demonstrate that the same model provides a good description of the infrared conductivity of electron-doped compounds in this class of superconductors.
OR - Organics and Related
Ellipsometry for studying organic materials

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Organic materials and thin organic films are of increasing technological interest, e.g., in the development of functional surfaces as for example self assembling monolayers (SAMs) or polymer brushes, optical devices, organic light-emitting diodes (OLEDs), solar cells and biosensors. Ellipsometry is not only a sensitive in-situ method for growth studies and process analysis, but it can also be a versatile tool for identification, structural analysis, electronic characterization and determination of quantitative optical properties. Related research fields are often interdisciplinary and range from physics, physical chemistry towards biochemistry and biotechnology.

Depending on the spectral range from infrared (IR) to vacuum ultra violet (VUV), ellipsometry can probe conducting, structural, molecular and electronic properties of organic compounds. Some applications are reviewed in Ref. [1]-[5]. Due to the absorption of light, vibrations of free carriers, phonons, molecular vibrations and electronic transitions are excited. In the linear optics approach, the corresponding dielectric function can be described as a sum of these fundamental excitations. Interpretation of the optical response in this approach and an optical model can reversely deliver information on the sample and film properties. By exploring the anisotropic optical properties of vibrational and electronic bands, also molecular orientations can be determined. Thereby the detection limit of ellipsometry is dependent on the spectral range and the material properties and can reach submonolayers.

References

Invited

Intelligent optical sensing for Organic Electronics applications

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Spectroscopic Ellipsometry (SE) is proven to be a powerful optical sensing technique that can be implemented in a wide variety of nano-structured materials (inorganic, organic, hybrid, biomaterials) for state-of-the-art applications. Its flexibility for in-situ adaptation to thin film fabrication processes (either vacuum or printing in roll-to-roll configuration) in combination to its advanced methodologies for the interpretation of the measured spectra give a significant advantage over other conventional techniques. In this talk, we will discuss the latest results on the implementation of optical sensing on the characterization of state-of-the-art materials (inorganic, organic, hybrid) for applications in Organic Electronics, such as in Organic Photovoltaics (OPVs) and Organic Thin Film Transistors (OTFTs).

Organic Electronics is one of the most rapidly evolving sectors in the modern science & industry and involves several applications. In the case of OPVs, there is a significant amount of research in the structure of the donor-acceptor blend which defines the overall OPV efficiency and performance. The evolution of the blend film morphology and the distribution of donor and acceptor materials during post-deposition thermal annealing can dramatically affect the OPV functionality. Therefore, it is essential to understand the mechanisms for the distribution of the polymer and fullerene constituents and the kinetics of the molecular rearrangement. It will be shown how SE can provide information on the blend morphology of mixtures of organic semiconductors (such as P3HT and PCBM), and transparent conductors (such as PEDOT:PSS) that are fabricated by wet and printing processes onto flexible polymer substrates.

Also, we will report on the latest advances of the optical characterization of small molecule organic semiconductors that are deposited by solution methods towards the fabrication of OTFT devices. These include the bis(triisopropylsilylethynyl)-pentacene (TIPS-pentacene) that has been investigated in terms of its optical anisotropic behavior that affects the underlying charge carrier mechanism. Furthermore, we have examined the annealing temperature effects on the molecular ordering and morphology and in order to correlate it with the induced optoelectronic properties.
Analysis of photonic structures in beetles using Mueller-matrix data

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Since one hundred years it is known that some scarab beetles reflect elliptically polarized light as demonstrated by Michelson (Phil. Mag. 21(1911)544) for the beetle Chrysina resplendens. The handedness of the polarization is in a majority of cases left-handed but also right-handed polarization has been found. The polarization and color effects are generated in the outer part of the exoskeleton, the so called cuticle. Our objective is here to demonstrate that structural parameters and materials optical functions of these photonic structures can be extracted by advanced modeling of spectral multi-angle Mueller-matrix data recorded from beetle cuticles.

A dual rotating compensator ellipsometer (RC2, J. A. Woollam Co., Inc.) is used to record normalized Mueller-matrix elements $m_{ij}$ ($i, j = 1..4$) in the spectral range 300–900 nm at angles of incidence in the range 20–75°. All measurements are performed on the scutellum (a small triangular part on the dorsal side of the beetles) with focusing optics resulting in a spot size of the order of 0.05 – 0.1 mm. The software CompleteEASE (J. A. Woollam Co., Inc.) is used for regression analysis. Analysis of data measured on Cetonia aurata will be presented in detail and data from other beetles in the Cetoniinae and Rutelinae subfamilies will be briefly discussed.

A contour plot of Mueller-matrix data measured on Cetonia aurata (Fig. 1) is shown below. This beetle has a metallic shine and if illuminated with unpolarized white light it reflects left-handed polarized green light as revealed by the non-zero Mueller-matrix elements $m_{14}$ and $m_{41}$ in the green spectral region for angles of incidence below about 45°. This is detailed in the graph to the right which shows a spectrum for Mueller-matrix element $m_{41}$ at 20° as well as fitted model data. The model used for the chiral nanostructure is based on a twisted lamella structure, also called Bouligand structure. Given the complexity of the nanostructure, an excellent model fit is achieved. The obtained model parameters are the spectral variation of the refractive index of the birefringent lamellas and the pitch. Limitations and development of the model will be discussed as well as its applicability to more complex beetle cuticle structures.

In addition, Mueller-matrix spectra are very rich in information about reflection properties and allow parameterization of polarization parameters of the reflected light, e.g. in terms of azimuth and ellipticity of the polarization ellipse and the degree of polarization (see abstract by Järrendahl (p. 28)).
Generalized ellipsometry in-situ monitoring of fibronectin protein infiltration of sculptured thin films


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Sensor technologies are being developed to detect the presence of analytes including specific DNA sequences [1] and contraband [2]. Sculptured thin films (STFs) produced by electron-beam glancing angle deposition (GLAD) are promising scaffolding materials for such sensors. STFs offer increased surface area and are thus expected to increase the per area efficiency of sensors. Many applications necessitate real-time in-situ measurements under native liquid ambient. Generalized ellipsometry (GE) is sensitive to the anisotropic properties of STFs. Therefore, GE analysis should further improve the detection limits for analytes that infiltrate a STF.

We introduced a fibronectin protein solution over a Ti-TiO2 STF and monitored adsorption and rinsing processes with simultaneous, in-situ GE and quartz crystal microbalance with dissipation (QCM-D) techniques. An anisotropic Bruggeman effective medium approximation was applied to our optical model to determine the volume fraction of fibronectin present within the STF.

We find that anisotropic Mueller matrix elements are sensitive to fibronectin adsorption, implying that the protein infiltrates the STF and does not simply form an additional isotropic layer on top. Additionally, the GE and QCM-D dynamic measurements show good agreement on the amount and rate of fibronectin adsorption, which we relate via geometry calculations.

Figure 1: GE (left axes) and QCM-D (right axes) dynamic results for fibronectin adsorption into a Ti-TiO2 STF.

References
In-situ Infrared spectroscopic ellipsometry and PL studies during electrochemical deposition of polypyrrole layers on Si surfaces

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Conducting polymers offer a unique combination of properties, which are interesting for microelectronics, sensors, and photovoltaic applications. The possibility to obtain these polymers in a conducting state or as semiconductor depending on the oxidation state of the respective polymer makes these polymers to a promising material for optoelectronic applications. A low recombination rate at the silicon/polypyrrole (Si/PPy) interface is important for electronic devices, especially for solar cells. We investigated the change in Si surface recombination behaviour during the electrodeposition of ultrathin PPy films onto Si surfaces by means of in-situ photoluminescence (PL) measurements and inspected the surface coverage by in-situ infrared spectroscopic ellipsometry (IRSE). The electrodeposition was performed in aqueous electrolyte solutions utilising anodic potential pulses. Dependent on the potential thin, adhesive, uniform oxidized and non-oxidized PPy films were successfully deposited on Si electrodes. Very small amounts of interfacial silicon oxides have been found at the Si/PPy interface. PL measurements (see fig. 1, left) lead to the assumption that electrodeposition of PPy onto the Si electrodes generate only very few additional non-radiative recombination-active defects. Hence, polypyrrole is an excellent passivation layer of such defects at the Si surface. The in-situ measured IRSE spectra show the development of the PPy related specific signatures due to N-H and C-H vibrations (see fig. 1, right).

References
**Effect of the anodic potential on the rate of growth and electrochromism of polypyrrole membranes doped with dodecylsulphate.**

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Electrodeposited polypyrrole, Ppy, is increasingly used in sensors, microelectronic mechanical systems MEMS, drug release, actuators and analytical displays. The kinetics of growth and the final structure of the Ppy layers depend on the potential, electrodeposition programme, the anodic potential limit and the cycling time. The presence of different ions in the electrolyte modifies the layer growth rate, the voltammetric response and the interface capacity indicating variations in both the structure and the initial size of the oligomers that stick on to the surface, the partial water exchange taking place together with ions uptake processes into the membrane as well as the relaxation processes of the network that allows different redox reaction yields. The properties of these membranes can be modified by doping the Ppy with large and bulky shaped annions such as dodecylsulphate achieved by electrooxidation in solutions containing these large anions which are thereby incorporated into the film as fixed charges. The adsorption of dodecyl sulphate also hinder the growth of the oxide monolayer on the gold electrode. These membranes offer good selectivity and high stability during prolonged switching conditions. Ellipsometry has been applied in situ to characterise the layer structure. Recent work has investigated the characteristics of electrodeposited Ppy on gold in both buffer phosphate and in dodecylsulphate solutions 1-2. The fitting procedure minimises the error function G that corresponds to the measured and calculated optical data at different wavelengths and to different thicknesses d. The optimisation method converges after m iterations to theoretical optical values. The convergence is fulfilled after m interactions when the Euclidean norm of the each arrangement and the partial derivatives of G tends to 0. For a sequential set of thicknesses the fitting of the n, k and d values allows to check variations in the compactness of the film as a function of the distance to the electrode.

**References**

Spectroscopic ellipsometry as a versatile tool to investigate properties of responsive poly(N-isopropylacrylamide) systems with incorporated magnetic nanoparticles

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Responsive polymer systems designed by using polymer brushes or hydrogels are interesting systems, which can exhibit reversible or irreversible changes in their physical and structural properties to special environmental conditions (e.g. temperature or magnetic fields). The temperature responsive poly(N-isopropylacrylamide) (PNiPAAm) is one of such polymers. It undergoes a phase transition in aqueous solution at its lower critical solution temperature (LCST) of 32°C and induce an increase in hydrophobicity. Combined with the properties of magnetic nanoparticles (NP) (e.g. Fe₃O₄ or CoFe₂O₄) these systems can lead to new surface functionalities with new interesting properties for many applications, as sensing, wettability or (bio)adhesion.

For the design of such thin film systems (Fig. 1) a basic knowledge of the film characteristics is essential. Therefore it is first necessary to know how much nanoparticles are inside or attached to the system. With spectroscopic Vis-Ellipsometry (SE) it is not only possible to investigate optical properties of these films but also the composition of it, e.g. volume fraction of Fe₃O₄-NP.

We studied two types of films and present results for a thin NP-composite film prepared by pre-mixing of the PNiPAAm with hydrophobic Fe₃O₄-NP, spin-coated and grafted to a silicon substrate (System 1) and a film prepared by adsorption of hydrophilic functionalized Fe₃O₄-NP onto PNiPAAm brushes (System 2). The former system was chosen to develop an optical model starting from a simple two component effective-medium-approach (Maxwell-Garnett-EMA) using the optical constants of the pure polymer measured by SE and of Fe₃O₄ with averaged data taken from three different publications. The SE best fit-results were validated with scanning electron microscopy (SEM), atomic force microscopy (AFM) and X-ray photoelectron spectroscopy (XPS). After transferring this optical model to System 2, the adsorption of hydrophilic functionalized Fe₃O₄-NP onto PNiPAAm brushes was investigated and will be discussed with additional results obtained from contact angle (CA) and phase transition (LCST) measurements.

Figure 1: Measured Fe₃O₄-NP fraction (SE) in comparison with data from SEM and XPS analysis
Orientation of Non-Planar Molecules in thin Polycrystalline Layers from Infrared Ellipsometry Spectra – OFET and OPV materials

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The determination and control of molecular ordering within organic thin films is of particular interest for designing and improving production processes for organic field effect transistors (OFET) and organic photovoltaic (OPV) devices. By enhancing the molecular ordering in the conducting film performance of OFETs can be significantly improved [1]. Whereas by heat treatments of merocyanine/C60 PHJ solar cells the fill factor could be considerably increased [2]. We showed that the preferred orientation of the dye molecules in the donor film changes upon post-annealing resulting in a higher exciton dissociation efficiency at the donor acceptor hetero-interface.

In this talk we show how to reliably conclude on the predominant molecular orientation in a thin film by a computation based comparison of infrared (IR) ellipsometric measurements with density functional theory calculations (BP86 level of theory) [3] of vibrational eigenvalues and eigenvectors for a single molecule. To proof this concept we determined the anisotropic dielectric functions of two organic semiconductor thin films, ID583 and NDI-F, in the spectral range of 350 to 5000cm⁻¹ with high precision[2],[4]. The approach is especially advantageous if applied to molecules with an anisotropic and non-planar structure forming X-ray amorphous layers with a preferred molecular orientation but an insufficient degree of long-range order for diffraction based methods (Fig.1). In such cases our analysis yields more accurate and significant results than achievable by only comparing ordinary and extraordinary refractive indices in the visible range.[5]

In addition, we show how a thorough comparison between DFT and IR spectroscopic data can help identifying effects of intermolecular interactions.

This work is part of the German leading-edge cluster "Forum Organic Electronics". Our group is involved in the project POLYTOS in which new organic materials for printed electronics are being developed.

Figure 1: Height (left) and phase (right) plots from tapping mode AFM measurements showing the dimensions of the grain sizes of the NDI-F layer. The scan area was 1 x 1µm².

References
4. R. Lovrincic et al., unpublished.
Superimposed effects of nano-scale confinement and penetrant on behavior of ultra-thin glassy polymer membranes

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Ultra-thin polymer membranes have been widely used in technological processes such as flue gas treatment or natural gas purification where they provide advantages due to high fluxes. The gaseous streams involved are known to contain highly pressurized penetrants (CO₂, methane, olefins) which may cause unwanted plasticization effects that affect membrane properties over its lifetime. Reduction of the thickness of a glassy polymer to nanometer scale (ultra-thin films) is known to have strong effects on its materials properties, such as a reduction in the glass transition temperature [1], a reduction of the Young’s modulus [2], and an enhanced rate of densification (physical aging) [3]. The knowledge of the superposition of the nano-confinement and penetrant effects is therefore important for the purpose of understanding membrane behavior and predicting its long term performance.

The research presented involves new and complementary experimental approaches applied in order to quantify and understand the superimposed phenomena in ultra-thin polystyrene (PS) films. PS is selected as a base material which serves as a model macromolecular system. The studies focus mainly on sorption, permeation and plasticization mechanisms as a function of polymer film thickness utilizing high pressure Spectroscopic Ellipsometry.

Figure 1 presents an in-situ SE experiment where sorption behavior of 100 nm polystyrene film in different liquid penetrants under ambient pressure is investigated. Difference in the diffusion character of the penetrant in polymer material is well signified and explained in terms of the polymer-penetrant affinity difference. In the range below 100 nm the lengthscale effects for the case II non-fickian diffusion of n-hexane in PS are shown to be much weaker than the influence of the sample thermal history.

Figure 1: Liquid penetrant sorptive dilation of a 100 nm polystyrene film normalized to the initial film thickness

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Aging Effects of As-deposited and Passivated Cobalt Slanted Columnar Thin Films

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The fabrication of three-dimensional metal nanostructures with tailored geometry is one of the central challenges of nanotechnology because geometrical and material parameters are responsible for the optical, electrical, mechanical, chemical, or magnetic properties of such nanostructured thin films. Engineered artificial sculptured thin films (STFs) with designed anisotropies are potential candidates for applications in various fields such as optics, magneto-optics, as well as chemical and biological sensing and detection. However, in order to utilize metallic nanostructures for novel applications their size-, structure-, and material-driven physical properties and possible aging effects have to be understood and quantified.

We utilize glancing angle electron-beam deposition, which exploits physical atomic-scale shadowing and dynamically varying particle flux azimuth for fabrication of three-dimensional spatially coherent STFs with different morphologies. Subsequently, nanostructures are coated with a thin conformal passivation layer by means of atomic layer deposition (ALD). The ALD process is monitored with in-situ generalized ellipsometry.

We will present the fabrication processes as well as structural and optical properties of highly anisotropic ALD coated metal STFs determined by generalized spectroscopic ellipsometry in the visible and near-infrared spectral region. In particular, aging effects of as-deposited and passivated slanted columnar thin films from cobalt will be discussed. An anisotropic Bruggeman effective medium approximation developed for highly ordered three-dimensional metal nanostructures is employed to analyze spectroscopic Mueller matrix ellipsometry data. Our model approach allows for determination of biaxial (monoclinic) optical and structural properties as well as fractions of multiple film constituents. While the optical properties of the uncoated film change over time, the alumina passivation layer prevents oxidation in air and therefore aging effects; however, it affects the intrinsic bulk-like Co optical properties.

Figure 1: Schematic drawing of a core-shell Co SCTF coated with an Al₂O₃ passivation layer (3 ALD cycles depicted, a). High-resolution cross-section SEM micrographs reveal the structural equivalence before (b) and after (c) the ALD passivation process.
Metal slanted columnar thin film THz optical sensors

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Sculptured thin films (STFs) are artificially made materials with three-dimensional, highly spatially coherent arrangements of nanostructures. Contemporary interest in materials for terahertz (THz) electronic, optoelectronic, and optical applications is redrawing attention to STFs that may enable designed optical properties for the THz frequency region.

We report on the anisotropic optical dielectric functions of a metal (cobalt) slanted columnar thin film deposited by electron-beam glancing angle deposition for the THz frequency domain using generalized spectroscopic ellipsometry. A simple anisotropic Bruggeman effective medium dielectric function homogenization approach is successfully employed to describe the observed optical response. This approach describes isolated, electrically conductive columns which render the thin film biaxial (orthorhombic) [1].

Furthermore, we demonstrate that the anisotropic optical response of metal (cobalt) slanted STFs at THz frequencies strongly depends on the dielectric properties of the dielectric ambient surrounding the STF (see Fig. 1). An effective medium dielectric function approach is used to describe the combined optical response of metal STF and dielectric ambient. Our observations indicate that metal (cobalt) STFs can be used as sensors which will enable detection and characterization of minute amounts of dielectrics at THz frequencies, such as for flow-based detection of liquid chemical constituents. The anisotropic Bruggeman effective medium approach predicts upon slight modifications of Drude, fraction and/or depolarization parameters that targeted optical properties of STFs in the THz range can be achieved by variation of slanting angle, lateral column density, and material.

Figure 1: Experimental (dotted lines) and best-model calculated (solid lines) Mueller matrix spectra $M_{12}$ and $M_{21}$ obtained for a Co STF in air and immersed in water in comparison. b) shows the Mueller matrix spectra $M_{33}$.

References

Anisotropy and magneto-dielectric effects in monoclinic Wolframite

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Wolframite, (Fe,Mn)WO₄, is an iron manganese tungstate mineral that is the intermediate between ferberite (Fe²⁺ rich) and huebernite (Mn²⁺ rich). Along with scheelite, the wolframite series are the most important tungsten ore minerals. Despite the industrial importance of wolframite, minor knowledge exists about the physical properties. Wolframite is pseudo-orthorhombic. The locations of all the atoms in wolframite deviate only very slightly from orthorhombic symmetry, which is why the monoclinic angle, beta is so close to 90°. However, the ordering of the metal atoms, which occurs to produce appropriate charge balance on the oxygen atoms, reduces the symmetry of wolframite to monoclinic.

We present and discuss the results of a generalized ellipsometry study of natural-ore wolframite for two different surface cuts, for the spectral range from the near Infrared to the vacuum ultra violet. While Wolframite is birefringent throughout the investigated spectral region, strong dichroism is obtained in the VUV spectral range where wolframite is absorbing. We construct a dielectric model tensor description for which the three principal orthogonal polarization axes are additionally tilted by introducing a sheer matrix to account for the monoclinicity of the crystal axis system. In our optical model analysis we further observe that a pure dielectric monoclinic model system is not sufficient to completely describe the line shape of the off-diagonal Mueller-matrix elements. The introduction of magnetoelectric polarizability functions rendering a general bianisotropic material response was necessary to achieve a good agreement between experimental and model data. We discuss possible origins of the observed magnetoelectric properties of wolframite, the appropriateness of implementing 3 instead of 4 dielectric major polarizability functions as well as 3 additional magnetoelectric polarizability functions.
The Optical-Hall Effect

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The optical Hall-effect allows the unambiguous, contact-free determination of charge carrier density, their type, mobility, and effective mass including their anisotropies in conducting or semiconducting multilayer or nanoscopically inhomogeneous structures [1]. This technique utilizes generalized ellipsometry to determine the anisotropic magneto-optical response of free charge carriers of samples exposed to a magnetic field. So far experiments demonstrated only for limited spectral range (0.1-1.5 THz and 50-650 cm\textsuperscript{-1}), temperature (300 K and 10 K), and magnetic field (up to 4.5 T).

However, high fields and low temperature are important for systems with low carrier density, high effective mass, correlated electron systems, and systems with quantum confinement. Here we report on the design and implementation of an ultra wide spectral range low temperature high field optical Hall-effect system. The new instrument consists of a frequency domain THz, an FTIR-FIR and an FTIR-MIR ellipsometer granting access to an extremely wide spectral range from 0.1 THz to 225 THz (3-7500 cm\textsuperscript{-1}). A closed cycle cryogenic system is employed for the superconducting magnet (field up to 8 T) and provides sample temperatures of 300 K-1.5 K at low operation cost. We demonstrate recent applications of the optical Hall-effect for Si [2], III-V semiconductors structures[3] and graphene [4].

![Figure 1: Technical drawings and photo of partially constructed optical Hall-effect setup (September 2011)](image)

References

Optical, magnetic, and magneto-optical properties of layered and embedded Fe₃O₄-nanoparticles

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Superparamagnetic Fe₃O₄-nanoparticles (NP) with diameter of 6.7 nm have been layered on PNiPAAm polymer brushes and embedded into a NP-PNiPAAm composite system with the number of NPs 3.6E11 and 0.5E11, respectively. The effect of the surrounding and stabilization on the optical, magnetic [1], and magneto-optical properties of the samples has been investigated. Such hybrid materials are useful for biological engineering, for example to design a magnetic biosensor. We studied the optical properties by spectroscopic ellipsometry and extracted effective optical constants and thickness. In our optical dispersion model, a Bruggemann-EMA layer is used to analyze the Fe₃O₄-NP layer, while the polymer brush is described by a Cauchy layer. Secondary electron microscopy and atomic force microscopy were used to study the surface topography of the samples, and more than 95% coverage of the layered NPs on the polymer brush was observed. SQUID measurements revealed a superparamagnetic behaviour from the Fe₃O₄-NPs in both systems. The saturation magnetization amounts to 0.000072 emu/cm² and to 0.000033 emu/cm² for the layered and embedded Fe₃O₄-NP, respectively. From magneto-optical generalized ellipsometry, we observed that certain Mueller matrix elements from the polymer brush sample with layered or the composite with embedded Fe₃O₄-NPs depend quadratically on magnetic field in polar geometry. This is a second-order magneto-optical effect so far, while first order magneto-optical effects have not been observed.

References
Ellipsometric and magneto-optic measurements on thin permalloy films

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Magnetic materials are widely used for data storage applications. Especially thin films are important. Film structure and magnetic properties must be well known for such applications. Spectral generalized magneto-optical ellipsometry is very well suited to analyze both properties.[1]

Thin permalloy films of 20 and 30 nm were sputtered on silicon dioxide and silicon substrates. Additionally, one sample was thermally treated at 100°C. The ellipsometric measurements were done using a SENTECH SENresearch ellipsometer with the magneto-optical extension to measure the fractional intensity change of the transversal magneto-optical Kerr effect.

The ellipsometric spectra could be fitted well assuming oxidation of the permalloy films. The thickness of the oxides was between 4-6 nm. The optical parameters of the different films are all slightly different. The fractional intensity change curves show clearly the expected magnetic behavior of the thin films. The effect depends on the sample structure. Permalloy films deposited on 100 nm SiO2 on silicon show larger effects. There was no influence on the magneto-optical behavior of the heat treatment at 100°C.

Based on the height of the FIC effect we expect a thickness of 1-2 nm as detection limit of the applied method for magnetic properties of permalloy films.

References

Characterization of manganese and iron silicides by in situ spectral generalized magneto-optical ellipsometry

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Dilute magnetic semiconductors (DMS) combine the electronic transport properties of semiconductors and memory characteristics of magnetic materials. The complementary properties of semiconductor and ferromagnetic material can manipulate both degrees of freedoms of electrons’ spins and charges for spintronic devices. In recent years, group IV(Ge, Si)-based DMSs attract considerable experimental effort due to the compatibility with mainstream silicon technology. In our work we present the investigation of structural, magnetic and optical properties of manganese and iron silicides thin films on Si (100) substrate by in situ spectral generalized magneto-optical ellipsometry. The measurements were performed by spectral and laser ellipsometers (“Spectroscan” and “LEF-71” respectively by Institute Semiconductors Physics SB RAS), optimized to measure not only traditional ellipsometric parameters, but also magneto-optical response of the sample. The magnetoellipsometers were integrated into the ultrahigh vacuum chambers of molecular beam epitaxy setup, which allowed to control the optical and magnetic properties of thin films directly in the growth process. As a result of the magneto-optical response analysis, it was found that iron and manganese silicides in magnetic phase were formed on the Si surface and by analysis of the ellipsometric parameters dependence on evaporation time the silicide nanoclusters were identified and their structural properties were found.

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Polarimetric Characterization of Porous Anodic Alumina quasi-Random nanostructures

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Porous Anodic Alumina (PAA) is a nanostructured material obtained in a cost-effective self-organising electrochemical process. Given these characteristics, is gaining increasing interest as a template in several nanotechnology fields such as organic photovoltaic applications [1], biological sensing [2], nanotechnology manufacturing [3], magneto-optics [4].

PAA show a quasi-random structure, this is: a triangular lattice of vertical straight pores perpendicular to the alumina surface, but with the lattice periodicity broken into domains of random orientation and with a dispersion in size. This structure confers the material photonic properties close to those of Photonic Crystals and Quasicrystals [5]. Several works have attempted to determine the optical properties of the alumina host material [6, 7] and several examples of multilayer interferential devices have been reported [8]. However, in order to enable efficient design of devices a precise optical characterisation method of the material would be desirable.

The objective of this work is to develop a reliable characterisation method for PAA single layers on the aluminium substrate. This poses a particular problem since, in the fabrication process the aluminium/alumina interface is not flat but it appears patterned as a hemispherical concavity at the bottom of each pore. This non-uniformity together with the porous nature of the samples gives rise to a certain amount of scattering that the classical multilayer models cannot take into account. To this aim, simulations of the amount of scattered light with the help of an S-Matrix formalism will be performed in order to assess its influence on polarimetric measurements. These calculations will be compared against spectroscopic polarimetry and reflectivity measurements on actual samples.

References

Plasmonic response in 2D self-organized Au/LiF nanoparticle arrays

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We report the optical response of 2-dimensional self-organized arrays of Au nanoparticles (NPs) with flexibly tunable shape and arrangement, realized by deposition onto self-organized ridge-valley structures at the LiF(110) surface. Tuning the array fabrication conditions, the NP mean size, spacing, and aspect ratio could be controllably varied, allowing to tune the plasmonic response of the arrays. The optical response has been modeled by an effective-medium model, achieving good agreement between experiment and theory. In particular, the remarkably narrow width of the plasmonic resonance in these arrays is shown to arise as a consequence of the partial compensation of the dipolar coupling fields between neighboring nanoparticles, characteristic of the 2D array geometry [1].

The plasmonic arrays were employed as substrates for the deposition of magneto-optically active magnetite (Fe₃O₄) nanocrystals (NC). The magneto-optical (MO) spectral response of the Fe₃O₄/Au system exhibits the characteristic resonances of magnetite nanocrystals, accompanied by a clear enhancement of the Kerr rotation angle in correspondence of the SPR. The occurrence of plasmon-enhanced MO response in the system is discussed based on the MO spectra and on magnetic measurements performed under resonant or off-resonant plasmonic excitation.

References

In transmission or reflection experiments small isolated metal clusters exhibit particle plasmon resonances, their energy depends on size and shape of the particles and the dielectric properties of the surrounding media. In closed metal films plasmons can only be exited when an additional periodic structure helps to match the $k$-vectors of the incident light to the one of the surface plasmon polariton. In this case the optical response becomes strongly $k$-dependent and can therefore no longer be described by an effective $\varepsilon(\omega)$ [1]. On this background the question arises whether disordered and therefore isotropic but strongly interacting metal clusters also exhibit a $k$-dependent optical response. To answer this question we perform a systematic study on disordered gold nano-discs on glass substrates with different densities of the clusters. They were fabricated via the so-called hole-mask colloidal lithography (HCL) process [2]. Additional AFM investigations confirm that they have no long range order, although the samples exhibit a preferred next neighbor distance. Transmission intensity and Mueller-Matrix ellipsometry measurements at various angles of incidence were performed in the range of 8000 – 20000 cm$^{-1}$ utilizing a Woollam VASE spectroscopic ellipsometer on samples with three different densities.

In Figure 1 the AFM image and the transmission spectra of different incident angles for the sample with the highest density are shown. The particle plasmon of the gold nano-discs at about 12500 cm$^{-1}$ exhibit a clear red-shift with increasing angle of incidence i.e towards higher $k$-values. Additionally to the main particle plasmon peak, a peak around 6000 cm$^{-1}$ appears, which is not present in the spectra of samples with a lower disc density. This peak correspond to disc dimers. Therefore this peak show no dispersion with increasing angle of incidence. In the Mueller-Matrix ellipsometry measurements the samples exhibit at oblique incidence large off-diagonal elements indicating a strong mixing of polarization states. This behavior is unexpected for an amorphous sample and is a strong hint that spatial dispersion cannot be neglected in the description of these sample.

Figure 1: a) AFM image, b) Transmission spectra. Disordered high density gold nano-discs exhibit a strong red-shift of the particle plasmon with increasing angle of incidence.

References
Reflectance investigation of Si photonic crystals by polarization ellipsometry

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The characterization of nano structure surfaces in many applications such as solar cells and photodetector is an interesting subject for many investigators [1]. This is especially important for silicon-based devices which have a high refractive index and thus high reflectance. One way to reduce the reflectance of these devices is using porous to produce intermediate antireflection layers with suitable refractive index matching between air and substrate. Also the photonic crystals also have been utilized in reducing the reflectance of these devices [2].

In this study, Polarization ellipsometry used to investigate the reflection of one and two dimensional Si photonic crystals (PCs). The PCs have been fabricated by interference lithography and reactive ion etching (RIE) techniques. To do the interference lithography, a He-Cd laser of wavelength 325 nm has been used. We have measured the reflectance spectra (R) of PCs by using a Horiba Jubin Yvon Ellipsometer. We have found significant enhancement on the reduction of reflectance. Also we show that increasing the etch depth and FF reduce the reflectance. This reduction in reflectance is significantly lower than the corresponding one in bare Si which is more than 30.

Fig.1a shows the reflectance spectra of 1D sample for both P and S polarization. It can be seen that crystal modes exist in the reflection spectrum of S polarization but they are not appear in the P polarization. That is because of non-periodically of sample in corresponding direction. Fig.1b shows the reflectance spectra of 2D sample for both P and S polarization by same period and depth. This figure shows that the reflectance decreases to less than 5% in the wavelength range of 400 nm to 1500 nm for both polarizations.

Figure 1: Image and reflectance spectra of 1D sample (a) and 2D sample (b).

References
Optical properties and stress minimization of multilayer optical coatings grown by dual ion beam deposition (DIBD)

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The demand for thin films with improved properties is rapidly growing. For instance, highly reflective coatings with low intrinsic stress are needed for advanced applications, such as micro mirrors for laser scanners or endoscopes. In the present paper the optical and stress properties of multilayer optical coatings consisting of a metal layer and a Bragg structure made of SiO$_2$ and TiO$_2$ layers are studied. The thin films are grown by dual ion beam deposition (DIBD). DIBD uses two low-energy ion beam sources: a sputter source for sputtering the target and an assist source for simultaneous bombardment of the growing film. Thereupon, a non-thermal energy contribution is introduced which can be used to tailor thin film properties, such as the layer stress [1].

It is shown that the assisting ion bombardment reduces the layer stress of SiO$_2$ and TiO$_2$ single layers considerably and affects the index of refraction [2]. Based on the results obtained for single layers, the film structure is optimized with a reflectivity maximum at a wavelength of 1064 nm and the influence of the assisting ion bombardment is modeled. Subsequently, mirror structures are deposited on Si substrates, and the optical and stress properties are investigated. A maximum reflectivity of 98.8% is found for a mirror structure consisting of an Ag layer and three SiO$_2$/TiO$_2$ Bragg-pairs. Theoretically, a maximum reflectivity of 99.7% should be obtained, but the dielectric layers within the multilayer structure show absorption caused by contamination. Still, the stress of the mirror structures could be reduced by a factor of three upon assisting ion bombardment.

References
Anisotropic response from a textured fourfold symmetric substrate: when Fresnel meets Bragg

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Periodic metal - dielectric structures with a characteristic length scale similar to the wavelength of light have attracted large attention for future photonic applications. New effective dielectric properties may arise from these artificially structured materials. We analyzed the optical response of a nanotextured silicon surface containing fourfold symmetric pyramids with a separation of 224 nm. This surface was covered with a 70 nm Au layer. Mueller matrix ellipsometry was used for a thorough experimental characterisation of the optical properties of such periodic structures. We found that despite the fourfold symmetry of the surface, the optical response changes substantially at oblique incidence when the sample is rotated around its normal. When the light beam is incident along the high symmetry direction, the anisotropic Mueller elements are negligible whereas a 30° rotation to the left or right leads to significant anisotropic Mueller elements of opposite sign, see figure below. This observation shows that the optical response of this nanotextured surface does not comply with the morphological symmetry. A similar response is also found for the bare Si pyramids, i.e. without the presence of the gold layer. A first explanation of these observations is provided by considering diffraction. With diffraction, not only the intensity, but also the polarization of the specular light beam can be strongly altered. This leads to an optical response of a surface that at a first glance mimics chiral behaviour.

![Figure 1: Azimuthal dependence of the M13 Mueller matrix component of a fourfold symmetric nanostructure.](image)

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A Mueller Matrix Spectroscopic Ellipsometry Study of Scarab Beetles of the Chrysina Genus

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The attractive shiny metallic colour of jewel scarabs is originating from the structure of the exoskeleton. For some directions and wavelengths of the incident light this structure will also cause the reflected light to have a large ellipticity (near-circular polarization). This is due to that the exoskeleton is a helicoidal structure, formed by layers of chitin molecules. The reflected light is most commonly left-handed polarized but right-handed polarization is also observed. In this work six species of Scarab beetles from the Chrysina genus are investigated. The complete Mueller-matrix is measured with a dual rotating compensator ellipsometer (RC2, J.A.Woollam Co., Inc.). The results are presented as contour plots where we represent different parameters as a function of incidence angle $\phi \in [25; 75]^\circ$ and wavelength $\lambda \in [240; 1000]$nm of the incident beam. Parameters of particular interest are the $m_{41}$ element of the Mueller-matrix, which is related to the circular polarization behaviour, the degree of polarization, the ellipticity and the absolute value of the azimuth angle. From ocular observations through left- and right-circularly polarizing filters all specimens showed clear polarization effects in terms of colour changes. However, the Mueller matrix ellipsometry measurements showed two general types of polarization behaviour depending on the studied species. *Chrysina macropus* and *Chrysina peruviana* had a smaller range of $m_{41}$ values around zero. Much larger $m_{41}$ variations were observed for *Chrysina argenteola*, *Chrysina chrysargyrea* and *Chrysina resplendens*. *Chrysina gloriosa* had both types of polarization behaviour depending on if the measurements were made on the green or golden parts of this striped beetle. Comparisons among samples of beetles from the same species were conducted. For instance, different specimens of *Chrysina resplendens* show rather large differences in the polarization response whereas specimens of *Chrysina chrysargyrea* showed very similar polarization behaviour. All studied specimens did in some sense reflect both right- and left-handed polarized light. In many cases very high ellipticities (near-circular polarization states) were observed. Models of structures generating the observed polarization effects as well as biological aspects will also be discussed.

Figure 1: Three pictures of *C. chrysargyrea* from left to right taken with a left-circular polarizer, no filters and with a right-circular polarizer in front of the camera. Two contour plots of $m_{41}$ for *C. chrysargyrea* showing a large region with left-handed near-circular polarization and *C. resplendens* showing a large region with right-handed near-circular polarization.
Simulation of light scattering from biological helicoidal structures

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The present work is devoted to analysis of models describing light scattering from beetles exhibiting structural colours. In some beetles, preferably from the Rutelinae and Cetoniinae subfamilies, such beautiful and well saturated colours originates from periodical helicoidal structures. By studying the spectral and polarization characteristics of specularly reflected light, it is possible to determine pitch and optical constants of these structures.

The scattering characteristics varies among beetles but for those with near-specular reflection, collimated light after interaction with the surface of the beetle shows moderate scattering as illustrated in Fig.1 (a). Such scattering is here modelled and compared using four models: (1) an ideal helicoidal structure with a rough surface as shown in Fig.1 (b); (2) a scattering medium with an ensemble of domains of ideal helicoidal structures with domains differing by their orientation of the helical axes and with a planar interface as shown in Fig.1 (c); (3) A structure with helical axes perpendicular to a planar interface and with irregularities in the structure as illustrated in Fig. 1(d); and (4) an ensemble of structures with helical axes normal to a curved interface as shown in Fig. 1(e). These four models are here studied in order to determine which is most appropriate for implementation in simulation of the observed scattering and, at the same time, being useful for interpretation of ellipsometric measurements.

Figure 1: Four models for describing scattering from helicoidal structures.
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Investigation of depolarization in zinc oxide films

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In this work, sources of depolarization and their separation in the depolarization spectrum were investigated. To achieve this goal, zinc oxide thin films with various morphology and thickness-distribution were prepared by pulsed laser deposition. Investigations were made on 1) smooth samples with non-homogenus film thickness, 2) rough or crystalline samples, where the film thickness is uniform, and 3) samples, where both features appear. The samples were studied by measuring not only the ellipsometric angles but also the depolarization. The morphology of the films was characterized with atomic force microscopy, scanning electron microscopy and profilometry. It was shown that an interference structure appeared in the depolarization spectrum in the transparent range of zinc oxide on samples with non-uniform film thickness. Scattering due to surface roughness and crystallites caused a depolarization depending also on the wavelength. In the absorbing region the depolarization caused by scattering is decoupled from depolarization induced by the film thickness non-uniformity since reflection from the film-substrate surface is eliminated.
Ellipsometric Investigation of the Effect of Cleaning by Ar-Ion Sputtering on Semiconductor Surfaces

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Ar-Ion sputtering is a common technique to clean off contaminations from semiconductor surfaces. The Ar-ions are accelerated towards the sample with high energy to sputter the surface. The high energy of the ions causes the intended cleaning but additional damage of the crystalline structure of the semiconductor occurs. The figure shows the optical constants of Ar-ion-damaged Si in comparison with crystalline Si. The typical interband critical points of Si have vanished for the Ar-ion-damaged Si. The dispersion more resembles characteristics of amorphous materials. We systematically investigated the influence of variations of sputtering parameters like ion energy and sputtering angle on the optical constants of the damaged Si.

Figure 1: Comparison of the dispersion of n and k of crystalline Si and Ar-ion-damaged Si
Determination of optical constants of GeO$_x$ films modified by thermal annealing and ion irradiation

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We report on spectroscopic ellipsometric (SE) investigations on GeO$_x$ films fabricated by electron-beam evaporation method and subjected to two post-deposition treatments, namely, shift heavy ion irradiation and thermal annealing. One set of films were irradiated with 100 MeV Ag$^{7+}$ ions at fluences between $1 \times 10^{12}$ and $1 \times 10^{14}$ ion-cm$^{-2}$. Another set of films were annealed at temperatures 500 $^\circ$C and 600 $^\circ$C in an Ar atmosphere. For the first set, line shapes of the dielectric function obtained from SE measurements were fitted by the Tauc-Lorentz model. The refractive index (at 633 nm) of the pristine GeO$_x$ film was estimated to be 1.860 and decreased to 1.823 for films irradiated at an ion fluence of $1 \times 10^{14}$ ion-cm$^{-2}$ as shown in Fig.1(A). The change in refractive index with ion fluence is attributed to a stochiometric change and structural transformation represented by GeO$_x$ $\rightarrow$ Ge + GeO$_y$ ($y > x$) occurring due to a thermal spike induced by ion irradiation [1]. In the second set, XRD and TEM measurements show the formation of Ge nanocrystal embedded in a GeO$_x$ matrix after thermal annealing. The particle sizes calculated from TEM micrograph were in the range of 2-9 nm. The line shapes of the dielectric function of annealed films were fitted by the Bruggemann effective medium approximation by taking the fraction of inclusion of nc-Ge ($f_{Ge} = 0.5$) in GeO$_x$ matrix. A marked reduction in the refractive index function was obtained for Ge nanocrystals with respect to bulk c-Ge. For example, at the $E_1$ critical point (2.12 eV) of bulk c-Ge, the real and imaginary parts of the refractive index function of Ge nanocrystals are lower than that of bulk c-Ge by approximately 60% and 90% as shown in Fig. 1(B). The reduction of the dielectric function due to the size effect in Si nanocrystals has been reported [2]. The band gap of Ge nanocrystals was also estimated from the SE measurements and compared with the band gap calculated from the quantum confinement model. The changes in the optical constants and bandgap in nanocrystalline Ge vis-a-vis bulk Ge will be discussed.

Figure 1: (A) Refractive index of GeO$_x$ films as a function of ion fluence. (B) Spectral dependence of the real part of refractive index functions of thermally annealed samples and comparison with the bulk Ge.

References
Influence of ion implantation on optical properties of native oxide films on GaAs

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Ion implantation process is one of the most popular methods used in electronic devices fabrication. The aim of the study is to determine the effect of ion implantation fluence on the dielectric function of native oxide. Implantation processes with In⁺, Al⁺, Ne⁺ and Ar⁺ ions have been performed at room temperature. In the investigations of optical properties of ion-implanted GaAs layers, the spectroscopic ellipsometry SE [1] method, with a VASE ellipsometer of J.A Woollam Company was used.

Our samples were described by three- and four-phase models before and after implantation, respectively [2]. Based on the analysis of experimental results, it was found that with a growing fluence, the thickness of natural oxide increases and saturates at a certain value. We determined the spectra of dielectric function of natural oxides and values of the thickness d_{ox} using the MAIE [2] method and Cauchy approximations to model the oxides layers. For native oxides, the refractive n_{ox} and extinction k_{ox} coefficients as a function of the wavelength were described by Cauchy equations [3]. Next, for the samples after the implantation process, the minimalization method with the Point by Point procedure, proposed in the VASE software [3] was applied. The bands were observed in the spectra of the imaginary part of dielectric function, which can be attributed to three-elemental compounds formed in the implanted subsurface layers.

References

3. J.A. Woollam Co. Inc. VWASE 32 program v 3.386, tabulated at UNL (Lincoln University, Nebraska, USA)
In the paper, we report the results of spectroscopic ellipsometry investigations of subsurface GaAs layers before and after hot implantation with Al ions. It is well known that one of the most important fabrication methods in semiconductor industry is ion implantation [1]. Nowadays the technique is used, i.a. for synthesis of A3-B5 compound nanostructures in silicon matrices [2]. Implantation into hot targets allows to decrease the disorder level in subsurface layers to avoid amorphization [3]. In our work, semi-insulating single crystalline (100) GaAs substrate was doubly implanted at different temperature in the range of 250-500 °C by 250 keV and 100 keV Al ions with fluences: 3.5x10^{16} cm^{-2} and 9.6x10^{15} cm^{-2}, respectively. Native oxide layer thicknesses and optical properties were studied using the Rutherford Backscattering Spectrometry/Nuclear Reaction (RBS/NR) [4] and spectroscopic ellipsometry methods. The Cauchy model of optical coefficients spectral dependences was used in the ellipsometric analyses. The thickness growth of native oxide with an increase of the implantation temperature was observed in hot-implanted GaAs. The spectra of refraction index and extinction coefficient of the oxide layers in the 250 to 900 nm wavelength range were determined. For the same samples, the increases in oxygen concentrations as determined by NR and decreases of As obtained by the RBS technique were observed. Simultaneously, the increase in Ga concentration in the subsurface layers was also detected. These effects can be attributed to creation of the (Ga,Al)As alloys in the near surface layers of hot implanted samples.

References
Optical characterization of textured industrial steel back reflectors for photovoltaic applications

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Nowadays solar cell research is mainly concentrated on improving energy conversion efficiency while decreasing production costs, in order to offer lower cents per kilowatt hour ratio for solar energy. One way to improve energy conversion efficiency without the need to improve or change active material(s) is to improve light trapping properties. There are multiple ways to improve trapping of the light inside the active region of a solar cell, but many of them rely on expensive technologies based on the production of ordered nanostructures. Therefore, it is important to find cost effective methods such as texturing of top transparent conductive oxides and/or back reflectors.

In this work we concentrate on industrial nickel-iron steel materials which have potential to be cost effective substrates for thin film solar cells. In particular, we are studying a Fe-41Ni alloy (industrial name N42) which is textured using ferric chloride solution (FeCl₃). The level of texturation and optical properties of such substrates can be optimized by adjusting chemical etching time, temperature, and Baume degree. For solar cell applications, the best performing textured substrate should have the maximum total reflectance and maximized haze factor. We have observed that those two properties are not compatible with each other; therefore, an optimization for real solar cell structures is needed.

As a main tool providing primary characteristics of textured substrates (total reflectance and haze factor) we use a spectral reflectometer with an integration sphere. Our textured substrates don’t have a perfect Lambertian surface and still have sufficient specular reflectance for studying samples using a spectroscopic ellipsometer. Ellipsometry can possibly provide information about surface roughness (which can be compared with AFM), but also about the cortical layer present on our substrates. Analysis of the total reflectance and haze factors allows us to model expected light trapping enhancement for particular thin film solar cells and find optimal substrate for achieving maximal energy conversion efficiency.

Figure 1: Scanning electron microscopy image of textured N42 substrate.
Ellipsometric demonstration of the deficiency of the standard models of the effective medium approximation for nanostructured layers and the new approach with the account of interparticle interactions.

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Application of standard models of the effective medium approximation for nanostructured layers like nanoparticles on a surface is problematic as: these models do not account intrinsically anisotropic environment for particles in layers; they don’t account direct interparticle interaction, as it is zero in average for 3D case. In contrary to the approximation of nanocomposite properties in the case of bulk, the geometrical anisotropy of 2D layers results in the line splitting for transversal and longitudinal polarizations. At the same time the account of direct interparticle interaction reflects in the additional shift of plasmon resonances with the particle concentration, which is bigger than in the standard Maxwell-Garnett model. Spectroscopic ellipsometry of such layers demonstrates the dependence of the plasmon resonance on the particle concentration. The application of Maxwell-Garnett model for the description of such films gives smaller shift of the resonance then it is measured and inconsistent film parameters in spite of the mass thickness is reasonable. On the base of self-consisted approach with the use of Green functions we developed the model of the optical response of the layer of nanoparticles randomly distributed on the surface [1]. In contrary to the standard models of the effective medium approximation the direct electromagnetic interaction between the particles was taken into account in this model by the Lipman-Shwinger [2] equation. The solution of this equation in the Fourier space in the so-called k-z approximation allows to determine the average polarizability of the layer on the base of parameters of constituting particles and their concentration. Such an analogue of the effective medium approximation intrinsically includes the geometrical anisotropy of the layer as well as interparticle interactions demonstrating both the anisotropy in the optical parameters and the dependence of the resonance of the system on the particle concentration. Such polarizability can be used in calculations of different optical response of systems with nanostructured layers.

References
In-situ spectroscopic ellipsometry for surface control in PLD Growth

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We present detailed measurements of the surface condition of typical substrates used in the growth of oxides. Surface quality plays an important role for epitaxial growth as it determines the possible relations between the substrate and the epilayer. Thus in situ information about the surface condition is of importance. Investigated are two different situations that are of importance for epitaxial growth. On the one hand many single crystal substrates can be treated to exhibit atomically flat terraces with a unit cell height providing a perfect surface for homo- and heteroepitaxy. The challenge is however to preserve this surface even under growth conditions. We have employed in-situ SE accompanied by ex-situ AFM measurements to study the surface of ZnO single crystal substrates. The SE spectra clearly reveal a change in $\Delta$ when the ZnO is exposed to typical growth conditions (e.g. low oxygen partial pressure and elevated temperatures). AFM measurements confirm the reorganization of the surface and the formation of aggregates. On the other hand substrates often have adsorbates on the surface that impede on epitaxial growth. As an example we have studied MgO substrates. These substrates usually show a large $\Delta$ even on a smooth surface indicating the presence of a thin surface layer. Using in-situ SE it is shown that this layer can be removed if proper pretreatment temperature and pressure conditions are chose. This work was supported by Deutsche Forschungsgemeinschaft in the framework of Sonderforschungsbereich 762 "Functionality of Oxidic Interfaces"
Optical characterization of PLD deposited oxides thin films: comparison of Ellipsometry and AFM roughness measurement on YSZ and Ni-YSZ thin films

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Spectroellipsometry is a non destructive technique which allows the optical characterization of thin films for a wide range of wavelengths. The surface roughness can be also estimated using appropriate fitting models for the recorded data. In this paper on report on optical and morphological characterization of transparent thin films oxides like ZrO₂, HfO₂, Ta₂O₅, ZnO, YSZ and Ni-YSZ deposited by Pulsed laser Deposition and Radiofrequency Assisted Pulsed Laser Deposition. The refractive index of the layers was obtained using a VASE spectroellipsometer in the range of 250-1700 nm. Measurements have been performed at three incident angles; a Cauchy model for dispersion of refractive index in transparent region (ε₂ ≈ 0) was used. For YSZ and Ni-YSZ thin films deposited on Si(100) substrates, roughness data measured by two techniques, Atomic Force Microscopy and Spectroellipsometry were correlated.
Application of the Combined Method of Spectroscopic Ellipsometry, Spectroscopic Reflectometry and Imaging Spectroscopic Reflectometry to Characterizing Rough Non-Uniform Thin Films

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Thin films exhibiting various defects are frequently encountered in practice. Roughness of the boundaries and thickness non-uniformity are common defects present in many films prepared by miscellaneous technologies. They can have a substantial influence on various thin film properties including their optical properties. Moreover, these two defects affect results of the optical characterization of the thin films in a considerable way especially when they occur simultaneously in these films. Therefore it is necessary to develop suitable methods enabling us to perform the optical characterization of the films containing both the defects in a correct way.

In this contribution a new efficient method of the complete optical characterization of the thin films exhibiting randomly rough boundaries and non-uniformity in thickness will be presented. This method is the combined method of variable angle spectroscopic ellipsometry (VASE), spectroscopic reflectometry (SR) and imaging spectroscopic reflectometry (ISR). Formulae for the ellipsometric quantities and reflectance measured within VASE and SR take into account the existence of both the mentioned defects above. Into these formulae the influence of the thickness non-uniformity is included by using the local thickness distribution density in integrals expressing the mean values of the ellipsometric and reflectometric quantities. The influence of the randomly rough boundaries is taken into account by means of the perturbation Rayleigh-Rice theory (RRT) in these formulae. Within ISR the spectral dependences of the local reflectance measured by individual pixels of CCD camera serving as the detector of the imaging spectroscopic reflectometer are calculated using the reflectance formula corresponding to the uniform thin film with randomly rough boundaries. Local areas onto the films corresponding to the individual pixels are sufficiently small so that the films can be considered to be uniform in thickness within these areas (the RRT is again used for including roughness).

VASE and SR are used to determine the spectral dependences of the thin film optical constants and parameters describing thickness non-uniformity (mean thickness and the rms value of the local thickness) and roughness of the boundaries (the rms value of the heights of the irregularities and autocorrelation length). The film optical constants can be determined separately in individual wavelengths selected by means of simultaneous treating ellipsometric and reflectometric data obtained for these individual wavelengths or using a suitable dispersion model. The experimental data of ISR are used to determine the area distributions (maps) of local thickness and the rms values of the height irregularities of the films. Within treating the ISR data the values of the optical constants of the films characterized are fixed in values determined using VASE and SR. The method described was utilized for the optical characterization of ZnSe films prepared by molecular beam epitaxy onto GaAs single crystal substrates whose optical constants are known in the literature. In the contribution the results of the optical characterization of one selected sample of the ZnSe films achieved within the spectral region 190–1000 nm will be presented for illustration.
Modeling of periodic and non-periodic surfaces by means of rigorous modal
diffraction methods

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Rigorous diffraction methods attain more and more importance for the ellipsometric modeling. As opposed to the so-called optical scatterometry which is widely applied in the semiconductor industry in order to retrieve profile parameters from periodic patterns, the prevalent samples in surface ellipsometry are mostly stochastic rather than deterministic. Nevertheless, there is a strong trend in semiconductor metrology also to cover stochastic sample characteristics such as line edge roughness. Moreover, the spot size reduction greatly helps to reduce Si real estate costs and enables the possibility to measure real non-periodic in chip structures instead of periodic reference patterns in the scribe lane.

The rigorous coupled wave approach (RCWA) [1] is a viable, robust and widely used method in optical scatterometry. Another less widespread simulation method is the Chandezon Coordinate Transformation Method (CCTM a.k.a. C-method) [1]. Both methods fall in the category modal methods and are closely related to each other. This paper shall discuss advantages and drawbacks of both methods by means of some examples. It turns out that both methods supplement each other in an almost ideal way. Furthermore, it will be shown how both methods can be derived by the same basic procedure and the basic outline of a joint C-RCWA method [3] will be given. It combines the advantages of both methods into a powerful simulation method for patterned multilayer samples. Finally, some suggestions are made how non-periodic or statistical surfaces can be modeled by means of this C-RCWA method.

References

Profile and material characterization of sine-like surface relief gratings by spectroscopic ellipsometry

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Sinusoidally modulated surface relief gratings are of high interest for various optical devices. Their optical response have been widely studied by means of calculations employing many theoretical approaches. Optical experiments on sinusoidal gratings, on the other hand, have mostly been carried out by means of power reflectance measurements and has not received considerable attention by spectroscopic ellipsometry (SE). Nevertheless, SE measured in a wide spectral range can be effectively used to investigate the quality of fabrication by optical lithography combined with material deposition and grating replication.

We apply SE to analyze geometric and material properties of sinusoidal gratings patterned on either opaque aluminium or transparent polymer [1]. Due to various imperfections in the fabrication process, the gratings are not perfectly sinusoidal. For this reason we monitor not only the geometrical dimensions (period and depth), but also the actual sine-like relief shape. Employing measurements in several angles of incidence increases the sensitivity, which helps to determine material properties such as the refractive index and the thickness of the native oxide overlayer.

To analyze the SE experimental data, we apply simulations employing the rigorous coupled wave analysis using the correct Fourier factorization rules, which enables fast convergence. As an example, Figure 1 shows the ellipsometric parameter Delta measured and simulated on a sinusoidal relief grating patterned on the top of an aluminium surface with the period of 278 nm, depth of 70 nm, thickness of native AlO overlayer of 2 nm, and with the angle of incidence being 70 degrees.

Figure 1: Ellipsometric parameter measured and simulated on an Al grating.

References

Characterization of Polyelectrolyte Coatings on structured substrates

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The functionalization of substrates with polyelectrolytes is a well-known method based on the attraction of opposite charges of alternatingly applied polyelectrolytes, commonly denote as layer-by-layer technique.[1] The thickness and architecture of the multilayer film can be manipulated by the used polyelectrolytes, pH value, ionic strength, temperature and various other factors.[2] Due to the technical challenges of characterizing nano-scaled, thin, soft textured films on rough structures we combined the strengths of different analytic methodologies to access the characteristics of the coatings. To examine the influence of structured surfaces on the layer-stacks the well-established system poly(L-lysine) / poly(L-glutamic acid) was applied to smooth as well as rough surfaces in form of linear periodic grooves (fig.1). The derived information is used to emulate the texture of natural templates. To further fine-tune generated surfaces the use of other electrolyte combinations is under investigation and characterization of obtained coatings are completed by spectroscopic and electrochemical methods.

![Figure 1: A Δ-map of (PLL/PGA)₈ coating on a flat glass (left) compared to periodic (100µm period, 0.9µm height of profile) structured glass (right). AFM-images of (PLL/PGA)₈ coated periodically structured glass B error signal 0mV (brown) - 940mV (yellow) C height profile of the cross section (red line in B) D detail of the higher sides in height signal mode and E enlargement of the valley in height signal mode.](image)

References

3. The authors thank the DFG for funding (HO 4200/3-1), the Laser-Laboratorium Göttingen e.V. for manufacturing the structured substrates and H. Rothe and A. Mirhamed for many pleasant and stimulating discussions.
Spectroscopic ellipsometry study of Ta2O5 films on SiO2 substrates for gravitational wave detectors mirrors

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A stack of Ta2O5/SiO2 layers is presently used as coating layer of mirrors in interferometric detectors for gravitational waves at the VIRGO and LIGO laboratories. The sensitivity of the second generation of this type of detectors will be limited in the 50÷300 Hz frequency range by the mirror thermal noise, and it was suggested that mechanical losses in the Ta2O5 layers are the dominant source of noise. We focus here on Spectroscopic Ellipsometry (SE) results (in the 0.75÷5 eV spectral range) obtained on high quality Ta2O5 films deposited on SiO2 substrates (at 100 C in \(\sim 2 \times 10^{-4}\) mbar background oxygen pressure) by a Veeco-IonTech Spector Dual Ion Beam Sputtering System \(\copyright\) at CSIRO (www.acpo.csiro.au). Information on optical properties and thickness of films has been correlated with accurate absorption measurements (Photo Thermal Common-Path Interferometry) at 1064 nm performed at LIGO. Data obtained on films with different nominal thickness (40 vs 500 nm) and subjected to different thermal treatments have been analyzed in terms of several 4-phases models (substrate/interface/film/surface) applying several approaches (Cody-Lorentz, so-called PSEMI approximation) to describe the tantala layer. Regarding the interface we tested simple intermixing and a more refined and realistic model considering a graded nanoporosity inside the tantala layer [1]. The good agreement between data and simulations over the whole spectral range allowed a fair description of optical properties and an accurate evaluation of film thickness, in terms of a slowly varying density of spherical pores degrading from the substrate/film interface (about 6÷7 %) to the film/ambient interface. The surface roughness of all films is always below 1 nm. Regarding the IR spectral region and in particular the 1064 nm wavelength, the model gave virtually null values of the extinction coefficient, largely below the instrument sensitivity, in consistence with the interferometric measurements (absorption at 1064 nm in the 1÷900 ppm range).

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Refractive index measurement and analysis of wet and dry thermal oxide layer on Silicon by using spectroscopy ellipsometry

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Optical properties of Silicon dioxide SiO2 have been studied in the last years and Si thermal oxidation is interesting because of its significant properties over than other SiO2 layer deposition and growth methods such as high quality, low impurity and low defects. Also these layer can be etched more easily than other SiO2 which produced by other methods. Most application of Silicon dioxide is used as the gate oxide in the semiconductor devices [1]. On the other hand periodic gradient refractive index structures are important because of their ability to use in photonic application such as Photonic Crystals and waveguide. Several methods have been used to determine optical properties of thin film and most of them are spectroscopy ellipsometry [2]. In this work by using spectroscopic ellipsometry, we measure and analyze variation of refractive index profile for five thermal oxide samples at the temperature rang of 1000 – 1050 K in different condition such as exposing time of Silicon substrate to an oxidizing environment of O2, injection rate of O2 and Ar in the ambient. Also we studied effect of water vapor which is known as wet thermal oxidation technique in the refractive index profile of SiO2. Our ellipsometric measurement cover spectral range between 250 and 830 nm and the data were taken at the incident angle of 70 deg near the Brewster angle of SiO2. The figure shows refractive index of samples versus wavelength for exposing time of Silicon substrate to an oxidizing environment of O2 (sample A & B), increasing injection rate of O2 in the ambient (B & C) and refractive index of wet oxidation sample (D & E). It can be seen in figure refractive index varies from 1.45 to 1.47 by average. Also we have shown that refractive index in wet oxidation is independent of injection rate of O2 and the effect of exposing time of sample to oxidizing environment of O2 in refractive index variation is less than dry method.

Figure 1: Refractive index profile for different condition of fabrication methods

References
Spectroscopic Ellipsometry as complementary method to determine electrical properties of ZnO:Al films

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ZnO:Al layers, which are employed as TCOs in Si thin film solar cells, need to provide high transparency of >80% in the relevant spectral region and a sufficiently low sheet resistance of <15 Ω. Moreover, a small thickness of the ZnO:Al layer is desired to reduce overall costs of the solar cell. Optimising all properties is a complex undertaking, as all parameters are interrelated.

In this study, measurement methods are compared to find a reliable procedure for assessing the quality of DC magnetron sputtered ZnO:Al layers. Therefore, the influences of the film thickness and post deposition annealing temperature are investigated via four point probe, Hall measurements and spectroscopic ellipsometry (SE). Furthermore, the well known spatial resistance inhomogeneity of DC magnetron sputtered ZnO:Al films is analysed by SE.

The SE measurements suggest that the decrease of specific resistance with increasing thickness for samples with a thickness of >200 nm is mainly caused by an increase in carrier concentration, due to less trapping of charge carriers. The spatial sheet resistance inhomogeneity, which is presumably caused by high energetic impinging O\(^{-}\) ions that lead to a crystal structure with higher strain and more defects, can also be identified in SE measurements. Furthermore, Hall and SE measurements show a similar trend of decreasing carrier concentration for high post deposition annealing temperatures towards 600°C, which is accompanied by a significant increase in IR transmission.
The stability of the ITO sputtering films by thermal treatment in N2 atmosphere

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ITO and ITON thin films are materials with high technological impact due to the significant applications in different optoelectronic devices such as flat panel displays, solar cells or its use in ohmic contacts [1, 2]. There are a big number of papers related with this topic but very few cover the time stability of these films. For this reason the aim of this work is to asses the process of stabilization of the film (prepared by rf sputtering) surface, by using thermal treatment in N2 atmosphere. The changes of the chemical and of the optical properties were controlled by XPS, AFM and UV-VIS-NIR & IR ellipsometry. The optical properties of these films are known to be complicated due to the graded microstructure which leads to variations of the refractive index in the film thickness [3]. In consequence, for the modeling of ellipsometric data it was used the Function-Based Graded Layer which allowed the variation of the optical constants at the top and bottom of the films. In order to improve the fitting model, the surface roughness was also modeled and further compared with the roughness obtained by means of Atomic Force Microscopy. The XPS analysis showed the elemental composition of surfaces and their chemical environment and together with IR ellipsometry have been demonstrated the stability of ITO films after thermal treatment under N2.

References
In-line measurement of ARC coatings

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Thickness and refractive index are primary quality control parameters for antireflective coatings on silicon wafers in PV applications. In order to increase the productivity it is essential to measure these parameters in in-line mode. By using in-line approach there are several challenges due to moving wafer. In this work, sources of harmful effect were separated from the signal using Fourier analysis. The well known method to measure ARC layers is laser ellipsometer with He-Ne laser. Considered a single point measurement the Psi and Delta values depend only thickness and refractive index of the layer. In-line measurement on the fly generates harmful effect during collection of data. During measurement the moving sample adds so called signal modulation in function of wafer speed and surface morphology. We investigated a signal processing method to filter out the harmful intensity modulation generated by surface roughness and morphology. Our laser ellipsometer based on rotating compensator concept using quarter wave plate. Only half turn of compensator is enough to reconstruct the layer information. Half turn time is typically 50 ms. The measured intensity is over sampled per half turn getting detailed polarization and reflectivity information. The over sampling of the signal can be separated for time invariant and time dependent parts using Fourier decomposition. After separating the collected information we can measure the layer properties without moving effect. Based on the novel signal processing method the thickness values and thickness variations (also refractive index) point by point on the samples were the same as off-line single point measurements.
Ellipsometric Optimization of MIR Antireflection Coatings for Use in Gas Sensors Based on an External-Cavity Quantum Cascade Laser and a Photoacoustic Detector

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We demonstrate the versatility of an external-cavity quantum cascade laser (QCL) in the Littrow configuration with photoacoustic detection. We have successfully used the cavity with QCL active regions emitting at wavelengths centered both at $\lambda_1 = 11.3 \, \mu m$ and $\lambda_2 = 4.35 \, \mu m$ with tuning ranges of 67 cm$^{-1}$ and 48 cm$^{-1}$, respectively. These configurations were used for ammonia detection near 11.3 $\mu m$ and CO$_2$ isotopologue recognition in human breath near 4.35 $\mu m$.

The standard approach to compensate for intensity fluctuations due to mode-hopping is to actively vary the temperature of the QCL, although this severely limits the scanning speed. Thus, our approach is to use anti-reflection coatings of the intra-cavity QCL facet with sufficiently low residual reflectivities to eliminate mode-hopping altogether. For this, residual reflectivities of less than $10^{-3}$ need to be achieved over the entire tuning range. Since optical constants of films in the mid-infrared are not tabulated systematically with sufficient accuracy for this task, we have characterized 4 sputtered oxides and 2 nitrides using spectroscopic MIR ellipsometry, including their response to variation of the deposition parameters.

![Figure 1: MIR optical properties $n$ and $k$ in the range of 700...2000 cm$^{-1}$ of sub-stoichiometric silicon nitride deposited at different flow rates of the reactive sputter gas, i.e. nitrogen. Clearly visible is the absorption peak ($k$) at the TO-phonon energy rising in amplitude with increased nitrogen content and the associated decrease in the value of $n$.](image-url)
Ellipsometric and Raman studies on mechanical stress in MOS devices

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The characteristic dome like shape distribution of the parameters (with the biggest values in the middle and the lowest values in the corners of the gate) has been observed in our investigations [1, 2]. Such parameters are flat band voltage, and the effective contact difference potential. Taking our results into account [3, 4], the following hypothesis was drawn: irregular shape distribution of electrical parameters have been caused by the irregular shape of stress distribution under the metal gate. To prove or deny the assumed hypothesis, the investigations of stresses and strains occurred in MOS structures are performed. The fractional derivative spectrum (FDS) model [5] in connection with spectroscopic ellipsometry was used for both optical and stress analyses of semiconductor substrate (silicon). The FDS is especially promising technique when the limitations of the standard treatment by Lorentz shape line analysis occur and it is very helpful to extract basic information on relevant physical quantities from the observed \( \varepsilon(E)^{2}(E) \) spectra determined by spectroscopic ellipsometry [6]. This method enabled us to extract the critical points (CP) parameters efficiently with one consent [7]. In particular, using spectroscopic ellipsometry and FDS, the critical points \( E_1 \) and \( E_2 \) observed in the \( \varepsilon(E)^{2}(E) \) spectra in the silicon substrate and its interface have been investigated. On the basis of formulae given in [8] and extracted values of Van Hove critical points mechanical stress in Si substrate have been determined. Additionally, in our studies, Raman Spectroscopy as a complementary technique has been applied. Particularly, in this work, primary results of stress distribution in dielectric layer (SiO\(_2\)) measured by Raman Spectroscopy in the vicinity of the metal gate (Al, AlSiCu) and under the gate were presented. At the edges of the gate and under the gate, tensile and compressive stresses were observed, respectively. The results of mechanical stress investigations determined by both mentioned methods for semiconductor substrate were comparable.

References

Detection of outliers in spectroscopic ellipsometry maps: a multivariate approach based on Mahalanobis distance

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End-products in steel industry are usually protected by a lubricant layer coated by electrospray technique. As the metal substrates are rough, measuring the thickness of the lubricant layer and more specifically identifying spots that correspond to an excess of lubricant remains a challenge: the usual thickness of the lubricant layer is much smaller (about 4-10 nm) than the roughness of the metal substrate (about 1 µm for tinplate steel). Spectroscopic ellipsometry (SE) can contribute to such an identification. Using a statistical method based on the Mahalanobis distance which generalizes the Euclidean distance for non-diagonal covariance matrices [1], robust estimates of the principal components were used to identify the multivariate outliers and therefore the excess of lubricant. After identification of the outliers, statistical distributions of the Cos $\Delta$ values in the near-infrared region were estimated and their mean value linearly decreases as a function of the lubricant weight, according to the Drude’s approximation [2]. A local calibration of the lubricant film thickness is therefore readily possible without having to explicitly solve the ellipsometric equations [3].

References

Ellipsometry and Polarimetry for Research and Quality Control of Thin Coatings on Flexible Substrates

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Polymer sheets are used worldwide in a wide range of applications like packaging, display and photovoltaic technology. The manufacturing process of these sheets involves extruding machines that stretch the material in both lateral and longitudinal directions with respect to the machine direction, thus inducing birefringence. In most cases, the sheets obtained are optically biaxial. To achieve the final functionality the polymer sheets are often coated with thin films. An analysis of both the flexible substrate and the films are important for the development of new applications and for quality control in industrial processes. In this work we show analyses of functional films on different polymer sheets used in packaging, display and photovoltaic technology. Depending on the nature of the film and the flexible substrate ellipsometric, polarimetric or both techniques are used for the analysis. In the simplest case ellipsometric data are used in the UV where the polymer sheet is not transparent and thus anisotropy can be neglected. In more complicated cases the measurements and modeling are done using polarimetric data acquired in both reflection and transmission configuration. The model gives, as a main result, the dielectric tensor of the polymer sheet as well as thickness and optical constants of the coatings.
SPR gas monitoring with ellipsometric read-out on thin inorganic layers

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A gas sensor based on the surface plasmon resonance (SPR) effect with ellipsometric read-out (Δ as measured quantity) was studied. Thin gold layers were used as plasmon material and as already shown, sensor stability as well as sensitivity against low gas concentrations could be enhanced by top-coating the gold layer [1]. As top-coating layers, 5-10 nm inorganic materials (TiO₂, ZrO₂, MgF₂) were applied. All materials show similar sensitivity, e.g. 50 ppm propane gas could be detected. An outstanding characteristic of the top-coating material Fe:SnO₂ was observed: It shows a significant sensitivity towards the toxic gas carbon monoxide. Compared to the other top-coating materials, the sensitivity is improved by three orders of magnitude. In Figure 1, the result is presented for different concentrations of carbon monoxide with air as reference gas. The average value of the basic line is depicted as solid line. A gas concentration is detected, when the response in Δ is above 3 σ (standard deviation of the average value), depicted as dashed line in Figure 1. These results are considered as a first step towards selectivity, which is an important requirement to gas sensors in industry.

Figure 1: Detection of different concentrations of carbon monoxide in air on Fe:SnO₂; air as reference gas. Solid line: arithmetic average; dashed line: 3 σ.

References
1. A.Nookë et al., Thin Solid Films 519 (2011) 2659-2663
Optical Bandgap and Aging Effect of Ultra-Thin High-k Films Grown by Atomic Layer Deposition


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High-k dielectrics [1] have been intensively studied in order to replace the conventionally used SiO$_2$ as gate dielectrics to minimize leakage currents when further scaling down microelectronic devices. Hafnium dioxide (HfO$_2$) is one of the candidates due to a high k value of 25, a wide bandgap of around 5.8 eV, and a good thermal stability. HfO$_2$ films are often crystalline, but amorphous films are preferred to minimize leakage currents through dielectric layers. It is possible to obtain amorphous films by growing HfO$_2$ together with another compound, such as Al$_2$O$_3$ (k value: 9), which stays amorphous at much higher temperatures.

Two series of ultra-thin high-k samples (mixed layers Hf$_x$Al$_y$O$_z$ and bilayers HfO$_2$ on Al$_2$O$_3$) were investigated using spectroscopic ellipsometry (SE) in the energy range of 0.7-10.0 eV. The bandgap of mixed layers is linearly dependent on the Hf fraction from 5.77 eV for HfO$_2$ to 6.71 eV for Al$_2$O$_3$ as shown in Fig. 1. The effective bandgap of bilayers is lower than that of mixed layers with a comparable Hf fraction. The optical properties of bilayers are dominated by the top layer. In addition, an increase in film thickness as well as a decrease in bandgap energy and refractive index was observed after sample storage for two months in atmosphere and the mechanism is discussed.

Figure 1: The dependence of (effective) bandgap ($E_g$) and refractive index (n) on Hf fraction for mixed layers (a-b) and bilayers (c-d).

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Increasing sensitivity to optical functions of thin absorbing films by combining TIR ellipsometry with standard ellipsometry and reflectometry

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Spectroscopic ellipsometry and reflectometry are widely used techniques used for the characterization of thin films or stacks. The sensitivity of these techniques to the thickness of the films relies on a simple interferometric effect. The light coming from the bottom side of a given thin film interferes with the light reflected by the upper side, thus creating a modification in the intensity and the polarization state of the emerging wave. However, when the layers absorb a noticeable fraction of the light coming from their bottom side, the interferometric effect fades and the sensitivity of SE or reflectivity is decreased. In those situations a problem arises: what to do when optical metrology is of interest? In this communication we propose a solution well adapted for cases when absorption is caused by metallic layers made of noble metals. We propose to use total internal reflection (TIR) ellipsometry to excite a surface longitudinal wave. This wave is created because of the excitation of plasmons in the surface of the metal film which propagates along film interface. The electrical field associated to the plasmon wave can penetrate inside the metal film and below and is therefore sensible to the materials below the metallic film. When the resonance condition is achieved, the optical effects of the plasmon wave are magnified. They show-up as a sharp spectral minimum in the intensity of reflected light, which is explained by a drastic reduction (or even a suppression) of the ‘p’ component of the polarized light. The position and the value of this minimum are strongly dependent on the thickness of the thin metallic film as well as the refractive index of the material under it. This dependence makes combination of TIR ellipsometry with standard methods more sensitive to thickness of absorbing films.

We have measured a set of samples consisting on a stack of three films deposited on a glass substrate. The upper and bottom films were made of a transparent dielectric, zinc oxide (ZnO). The film in the middle was made of silver (Ag) of varying thicknesses. We performed measurements with a phase-modulated ellipsometer working in the ultraviolet-visible-near infrared range, a spectroscopic Mueller-matrix polarimeter working in the middle infrared range and a conventional reflectometer working in the ultraviolet-visible-near infrared range. TIR measurements were performed with the spectroscopic ellipsometer coupled with a prism in the Otto configuration. We used a multi-layer optical model to fit the data and to determine the parameters defining the samples (thickness and optical functions). The dielectric function of the ZnO layers was determined from previous measurements on monolayers deposited under the same conditions. The variance-covariance matrix of the fitted parameters was used as criterion to evaluate the advantages of combining TIR ellipsometry with standard ellipsometry and reflectometry as compared with standard techniques alone.
A global search method using parameter analysis in a broad range for silicon nanocrystals

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A significant part of ellipsometric investigations is directed towards the analysis of samples with increasing complexity. Not only the choice of proper optical models, but also the use of global parameter search is getting more and more important. The final iterative gradient algorithm of the fitting process finds a minimum in most cases, but assuring that it is the global one is a crucial issue. In this work we propose a method that can be used more or less automatically. In the first step a broad range is defined for the parameters and the mean squared error (MSE) is calculated for a number of randomly selected parameter sets. Next, the range of parameters is adjusted automatically, based on the sensitivity of the parameters that can be measured by the change of MSE as a function of the parameter value. The ranges are decreased for sensitive (unique) parameters, whereas they are held broad for non-sensitive ones. For the latter case, fixing or coupling non-sensitive parameters may be considered. Using this approach may help significantly to move towards the global minimum of the system. This method is also useful when the initial values of the parameters are not well defined. It can be run automatically and simultaneously on different CPUs. We demonstrate the method on nanocrystalline silicon thin films deposited by low pressure chemical vapor deposition (LPCVD) of Si on quartz. This work was supported by the National Development Agency grant TÁMOP-4.2.2/B-10/1-2010-0025 and OTKA grant Nr. K81842.
Characterisation of Silicon Nanoparticles Sprayed Films by Means of Ellipsometry and Raman Techniques

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In this work thin films of silicon nanoparticles (Si NP) having nominal sizes of around 6 nm and 40 nm were deposited by spray coating onto 0.1 mm thick molybdenum foils in a glove box under nitrogen atmosphere. The specially designed glove box system (SonoTek, figure 1) allows, additionally to thin film preparation by spray coating, also an in situ treatment of the film via flashing with a Xenon lamp (DTF - Dresden Thin Film Technology) as well as its characterisation with a Horiba UVISEL spectroscopic ellipsometer. Therefore, spectroscopic ellipsometry allows the freshly prepared Si NP thin films to be compared with the flashed treated ones. Additionally, ex situ (ambient atmosphere) ellipsometry, Raman spectroscopy and Atomic Force Microscopy measurements were performed for such films, before and after flashing in order to better understand the in situ ellipsometry spectra. Further results as well as correlations between the three used techniques of investigation will be presented and discussed.

Figure 1: Glove box with spray coater, flash lamp, and spectroscopic ellipsometer.
Overall focused imaging, improved spectral resolution and spectral range broadening for high-resolution Imaging Spectroscopic Ellipsometry

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A variety of technical improvements have been achieved in Imaging Ellipsometry since the 6th ellipsometry workshop.

From the point of view of imaging a very important breakthrough is the development of a new generation of objectives that allow for real-time overall focused images at the oblique observation direction in ellipsometry. This novel imaging approach was successfully implemented for the first time in Brewster Angle Microscopes, replacing the time-consuming focus scanning method, which is prone to artifacts. Besides the obvious imaging advantage, this improvement at the same time allows for a drastic 10-100 reduction in measurement times for high-resolution maps of $\Delta$ and $\Psi$. Now this method becomes available also for Imaging Ellipsometry. A spectroscopic imaging ellipsometer at the BAM, Berlin has been upgraded recently with an interchangeable objective unit. The working principle of the objective as well as experimental results and a comparison with previous methods will be presented.

Achieving high spectral resolution in an Imaging Spectroscopic Ellipsometer is a challenge because of the splitting-up of the available light onto the 106 detector elements of a camera. A dedicated, continuously tunable UV-VIS-NIR light source has been developed. Additionally, the detection range has been broadened into the NIR using a sensitive InGaAs-camera. Together, these improvements strengthen the analytical capabilities of Imaging Spectroscopic Ellipsometry. Some technical issues and first results will be discussed.

A major advantage of imaging ellipsometry is the fast recording of ellipsometric contrast micrographs with a high contrast for thin layers. From this point of view, the integration of other analytical techniques into the setup of an imaging ellipsometer is promising synergetic effects. We will present recent developments of such combined instruments integrating THz-Spectroscopy or quartz-crystal microbalance (QCM-D).

Finally, we will present new flow cell designs that allow for in situ ellipsometry at the solid/liquid interface, addressing specific requirements in biological and biochemical applications of ellipsometry.
Development of a new sensitive SE using “white laser” and multiple pass cavity


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Introduction:
The ellipsometry technique is very sensitive to thin layers, but the two parameters: tan(Ψ) and cos(Δ) measured, can only give two information; Thickness and refractive index, for one wavelength. In the case of very thin films, below 3 nm, it becomes quasi impossible to separate T from N with precision, one gets an optical thickness. We present a multi-pass ellipsometry technique which can multiply the sensitivity of the technique by adding the phase shift with the number of pass n, thus enabling the extraction of T and N separately. In addition, as the absorption is also enhanced by en, it becomes possible to assess the k in the same measurement.

Experiment:
We describe two different approaches to use several pass on the sample. First one is based upon the cavity ring down technique (CRDE) where we use a short laser pulse between two high reflexion concave mirrors; the sample is placed in the cavity. This can lead to hundreds of pass on the sample, in this case, a total reflexion sample in order to keep a good enough signal. The absorption reduces the intensity at each pulse, the slope is proportional to the absorption. Second one is based upon a Herriot multiple pass cavity mounting where the successive pass are not exactly at the same point. This mounting does not require a pulsed laser. In this case the low reflexion of the sample limits the number of passes, but it can be adapted on existing instruments as it will be shown. Taking into account a reference on bare substrate, one can measure a very low k.

Modeling:
The modeling is simple, rp and rs are power n, the phase is multiplied by n if the mirrors used are not adding any phase shift. The mounting is achromatic and up to 7 pass have been demonstrated. The tan(Ψ) power n can have a large value, our record is 400! The basis and limitations of the two different mountings will be developed as well as preliminary results taken on SiO₂ on Si and Al₂O₃ on Al and liquid on prisms. Perspectives and potential new application will be discussed.

Acknowledgments: FP7 SOFORT project.
Application of envelope function method for Fabry-Perot interference extremums to the ellipsometry of monolayered coatings

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The physical principles of application of the envelope function for multi beam interference spectra extremums to the ellipsometry of light reflection for plane wave incidence on transparent and absorptive mono layered structures were for the first time established. Analysing by the method of computer simulation showed that taking into consideration the peculiarities of Fabry-Perot interferometry [1], functions $\tan \Psi$ for minimum and $\tan \Psi$ for maximum and phase of wave $\psi$- and $p$-polarization in the general case describe the envelope functions of extremum of oblique spectra of Fabry-Perot contours interference

References

1. Kosobutskyy P.S. 2006 Opticheskii Zhurnal Vol.73 (12) P.73-76
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*In-polar InN:Mg*
The technology for the growth of ultrathin oxide films or heterostructures is approaching the same level of atomic control as in the case of semiconductors. Yet, in contrast to semiconductors, high electron densities lead to novel and sometimes exotic states at the interface. One of the most prominent examples is the formation of a two-dimensional electron liquid (2DEL) at the interface between two textbook band insulators, LaAlO$_3$ (LAO) and SrTiO$_3$ (STO), with surprising properties such as bistable conductivity, magnetic order, and tunable superconductivity. The design of nanoelectronic circuits based on these effects demonstrate a high application potential. However, in spite of intense research efforts, key properties of the 2DEL like the microscopic mechanisms driving it and the distribution of charges around the interface are still controversially discussed. We propose an optical characterization of high correlated system by variable angle spectroscopic ellipsometry (VASE) and second harmonic generation (SHG). The use of a standard linear-optical characterization like the former and a second order one like the latter can provide a wide optical characterization of these materials. Samples were first analyzed with a VASE from J. A. Woollam Company, in the wavelength range from near UV to near IR (300-1700nm), in order to measure optical constants. Ellipsometric data were then used to fit SHG spectra [1], which can provide information on interfaces phenomena. In this work we present our recent results on the study of interfaces between various transition-metal oxides with a Perovskitic structure, including LAO/STO, LaGaO$_3$ (LGO)/STO and NdGaO$_3$ (NGO)/STO interfaces.

References

Ellipsometric phase identification in ultrathin perovskite-structure ferroelectric films

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Perovskite-type oxide ferroelectric (FE) films represent a large field of fundamental and application-oriented research. Special interest is attracted to ultrathin epitaxial films, where presence of substrate imposed strain and film-substrate interface can lead to intriguing novel electronic and ferroic properties. Structure of such films is usually analysed using x-ray diffraction, and functional polarization response is inspected using electrical measurements. With decreasing films thickness to a few nanometers, these studies require more sophisticated techniques employing, e.g. synchrotron radiation, contactless methods, etc. Since optical absorption spectra and temperature evolutions of the refractive index can be uniquely ascribed to a definite FE state and phase transition, correspondingly, the optical studies may be used for express-identification of FE state. In ultrathin films, this can be realized using ellipsometric spectroscopy. This method allows inspecting films with very small thickness, and deposited on almost arbitrary substrate. By comparing crystal structure, FE, and optical properties of bulk single-crystal FEs and FE thin films, it is turned out to be possible to create reference data sets for optical properties of the phases which are possible in ultrathin films. Based on this, the phase state in a newly prepared ultrathin film can be express-identified using ellipsometry. As an example, identification of perovskite-structure and/or pyrochlore-structure, epitaxially strained, non-polar, and polar phases in ultrathin KTaO₃ films are presented.
Temperature variation of PbTiO3 bandgap at ferroelectric phase transition

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Ferroelectric perovskite such as PbTiO3 (PT) have many attractive properties for technical applications. In its low temperature phase, (PT) has tetragonal symmetry and is ferroelectric. It belongs to the P4mm space group and lattice parameters are: \(a = 3.904 \text{ Å}\) and \(c = 4.152 \text{ Å}\) \((c/a = 1.064)\). At 763 K it undergoes a transition to a cubic and paraelectric state having space group Pm3m with lattice parameter \(a = 3.865 \text{ Å}\). The temperature variation of lattice parameters was recorded by x-ray diffraction. The analysis was performed by means of Rietveld type refinement. PbTiO3 thin films for our study were prepared by chemical solution deposition (CSD) technique on sapphire (\(\text{Al}_2\text{O}_3\)) substrate using lead acetate trihydrate and Ti-isopropoxide. Pyrolysis was done at 450-500°C and final annealing of the film was at 600-700°C. Optical properties of the PbTiO3 thin films have been measured with variable angle spectroscopic ellipsometry in the spectral range of 1 to 6 eV and in the temperature interval from room temperature up to 600°C. The corresponding optical response functions were calculated and their temperature dependence determined. The electronic band gap was estimated using the Tauc plots in both phases. The temperature dependence of band gap was compared with that of the lattice parameters measured by x-ray diffraction. A strong correlation in the behavior of structural and optical properties was found. The experimental data clearly demonstrate influence of structural changes on electronic structure and optical properties of thin films. The experimental values obtained in this way are in good agreement with those calculated by Density Functional Theory (DFT). The relatively small difference between the theoretical and experimental results is consequence of the methodology employed, the DFT methodology underestimates band gap results.

We acknowledge Yu Hong Huang and Nava Setter (EPFL) for the supply of the films. This work was partially supported by the Grant Agency of the Czech Republic under Contract No. P204/11/1011.
Point by point ellipsometry data inversion techniques. Application to the extraction of thickness, refractive index and extinction coefficient of sol-gel derived ZnO

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Ellipsometry is a technique of great interest to characterize thin films. Information of different kinds can be extracted from measurements. However, because of the highly non-linear character of optical equations, data inversion remains a challenging task in many cases. General process of spectroscopic ellipsometry data interpretation consists in building a parametric representative model of the sample where unknown materials are represented by dispersion laws and fitting generated to experimental data by varying some of the parameters. However materials cannot always be represented by theoretical laws. Fitting procedure furthermore requires the knowledge of estimates values of the parameters as a starting point. Alternatively numerical procedures referred as point by point methods can be used to extract some parameters of interest from each point of the spectrum considered as an independent data point.

This work is focussed on the techniques of point by point data extraction concerning the problem of extraction of thickness and refractive index of transparent layers (n-d case) and the problem of extraction of refractive index and extinction coefficient when thickness is known (n-k case). Concerning n-d case, numerical procedures related to McCrackin algorithm have been known for some time. An extension of this method based on the study of sensitivity of the technique to the different parameters of the sample is proposed to extract thickness with great confidence. Concerning n-k case, knowing the thickness, refractive index and extinction coefficient can be extracted by considering them as variables to fit ellipsometric function to experimental data for each point of the spectrum. However the result depends on guess value and can lead to erroneous results. A method is proposed, based on the determination of contours of the ellipsometric function. It accurately provides all solutions in an as extended as wanted range of complex refractive index values without using minimization techniques and without requiring guess values. Errors relative to any of the parameters used in the sample model are calculated and discussed.

The proposed methods are used to extract parameters of sol-gel synthesized ZnO layers. The samples are obtained after deposition of precursor solution on a silicon substrate, high speed spin coating and thermal treatment. Thickness is first confidently extracted in the transparency range of materials and then complex refractive index is extracted over the whole spectral range. Because of the elaboration process that leads to materials with defects, extracted refractive index and extinction coefficients have features that can hardly be represented by the standard model dielectric functions and the proposed methods are of great interest. The observed features are correlated to other experimental such as luminescence.
The optical properties of ZnTe, ZnS and Mn-doped zinc sulfide (ZnS:Mn) nanocrystals embedded in SiO$_2$ matrix are studied by spectroscopic ellipsometry (SE). The nanocrystals are obtained by sequential multi-energy ion implantation of Te, Zn, S, and Mn into a silica layer with a 206 nm and 250 nm thick grown on Si(111) followed by a subsequent annealing for 30 min at 700°C for ZnTe and at 900°C for ZnS and ZnS:Mn. The formation of the nanocrystals is observed by transmission electron microscopy. Variable angle ellipsometric measurements are performed in air at room temperature at angles of incidence of 55°, 60°, 65° and 70°. The Critical Points (CPs) dispersion model [1] is used to extract optical properties of the samples. The optical responses are determined by taking into account the oxygen-deficiency defects in SiO$_2$ matrix. The optical properties such as dielectric function and second derivative of the dielectric function are presented and analyzed. The determined dielectric function spectra reveals distinct structures attributed to band gap and optical transitions at higher energy. The nanocrystals ZnS:Mn exhibit a reduction in the dielectric function in comparison with the bulk ZnS. The correlation between optical responses and the size of the nanocrystals are also given.

References

Anisotropic dielectric properties of MgZnO in the energy range from 2 to 25 eV

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An accurate determination of the complex dielectric function (DF) of ZnO is of great interest for the fundamental understanding of its electronic properties and is a key to optimize optoelectronic devices. Especially in the band gap region the DF is strongly affected by the coulomb interaction and the polar character of the material. Even at room temperature this leads to characteristic features connected to free excitons and exciton-phonon complexes (EPC), which have to be included when determining fundamental material parameters like the exciton binding energy or the band gap position. The appropriate analysis yields finally a valuable parameterization of the DF which is mandatory for further investigations and developments. Using a home-made VUV ellipsometer at the Berlin synchrotron radiation facility BESSY II, nonpolar MgZnO samples were investigated with very high spectral resolution at temperatures between 10 and 300 K and photon energies ranging from 2 to 25 eV. In the case of ZnO a strain free sample with atomically smooth surface was prepared by annealing in oxygen atmosphere, whereas the MgZnO samples were grown epitaxially. We present the ordinary and extra ordinary DFs of the dielectric tensor obtained by employing an anisotropic model. The results are in remarkable agreement to novel ab-initio calculations and confirm the importance of excitonic effects in the entire VUV DF of MgZnO. The high resolution of around 0.5 meV allows us to extract all free band gap excitons (n = 1 and n = 2) and to elucidate the fine structure of the accompanying EPCs.
Infrared spectroscopic ellipsometry study of the iron based high temperature superconductor $K_{0.8}Fe_{1.6}Se_2$

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The newly discovered iron chalcogenide superconductor $K_{0.8}Fe_{1.6}Se_2$ from the iron based superconductor family also attracts much attention recently for exhibiting the nature of intrinsic phase separation. We will report our infrared ellipsometry measurement on its single crystal as well as the single crystal of the corresponding insulating phase. We will demonstrate by using the effective medium approximation (EMA) approach, it is possible to refine the optical dielectric function of the single superconducting phase and the measured optical response can be reproduced.
Broadband Ellipsometry on the Iron-Based Superconductor Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$

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Using broad-band infrared ellipsometry, we have determined the dielectric response function of single crystals of the iron arsenide high temperature superconductor Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$. In particular, we have investigated how the spin density wave (SDW) in the magnetic state and the energy gap(s) and the condensate density in the superconducting state evolve as a function of Co-doping. Unlike the undoped parent compounds of the cuprate HTSC, the undoped BaFe$_2$As$_2$ is metallic and exhibits clear signatures of itinerant magnetism with a pronounced SDW gap. By combining the optical spectra with data obtained by $\mu$SR we are able to track the phase diagram and the clear competition between the magnetic and superconducting order parameter.
Optical Properties of Graphene on SiC Polytypes Determined by Spectroscopic Ellipsometry from the Terahertz to the VUV

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Wafer-scale production of high quality epitaxial graphene is required for graphene device fabrication [1]. It has been observed, however, that the highest quality graphene is achieved from exfoliation, while epitaxial graphene exhibits less desirable electronic and optical characteristics [2]. Identifying substrate effects on epitaxial graphene is of paramount interest for future device production. We report on the optical properties of graphene determined over an extremely wide spectral range from terahertz (0.65 THz, 0.28 meV) to the VUV (9.5 eV) using spectroscopic ellipsometry. The samples studied here include graphene grown on SiC by thermal sublimation of silicon from the substrate at high temperature. Several different SiC polytypes, including 4H, 3C, and 6H SiC were studied. The terahertz and infrared ellipsometry and THz-IR optical Hall-effect investigations provide detailed information on the free-charge carrier properties of graphene. The analysis reveals multiple carrier channels with strongly varying mobility, effective mass, and density parameters and their dependence on the substrate. The ellipsometric data obtained in the visible and VUV spectral range show distinct differences in the complex dielectric function of graphene as the underlying substrate differs in material composition and polytype.

The ellipsometric data obtained in the THz and infrared spectral ranges allow the identification of multiple, parallel sheet carrier densities within the single-to-few monolayer thick graphene layers, and which crucially depend on substrate orientation and growth condition. Analysis of the multiple two-dimensional carrier sheet densities reveals their extreme yet strongly varying mobility, effective mass, and density parameters as well as the vertical carrier sheet profile [2]. Our findings reveal striking influences of the substrate. We discuss the physical mechanisms of the substrate that influence the free charge carrier properties in epitaxial graphene such as surface polarity, dopant incorporation, surface roughness, and defects.

The ellipsometric data obtained in the visible and VUV spectral range were fit to a Model Dielectric Function (MDF) which employs traditional physical model lineshape analysis procedures, and provides quantitative model parameters for the band-to-band transition characteristics of graphene in the ultra violet region. Distinct differences in the complex dielectric function of graphene are observed as the underlying substrate differs in material composition and polytype. In particular in the spectral region of the band-to-band transition the complex dielectric function is sensitive to both substrate and growth parameters. We compare our results with those of recent publications of graphene grown by CVD on SiO\(_2\) [3].

References

1. A.K. Geim and K.S. Novoselov, Nat. Mater. 6, 183 (2007)
Ellipsometric studies of $E_1$ and $E_1+\Delta$ interband transitions in (Ga,Mn)As diluted magnetic semiconductor

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Diluted magnetic semiconductor (Ga,Mn)As is the most promising material for future spintronic devices [1]. Manganese atoms substituted for Ga provide holes and oriented spins to the system. Mn$^{2+}$ ions polarize hole spins which results in ferromagnetic order of other Mn ions due to Ruderman-Kittel-Kasuya-Yoshida (RKKY) interaction. Ordering occurs below the magnetic transition temperature $T_C$. (Ga,Mn)As is usually grown by Low Temperature Molecular Beam Epitaxy (LT-MBE) technique. There are two main theories concerning band structure of (Ga,Mn)As: the sp-d hybridization Zener model [1] and the valence band anticrossing model [2]. Although this material has been investigated for more than decade the band structure with increasing Mn atoms concentration is not clear up to now [3, 4]. One can notice red shift of $E_1$ and $E_1+\Delta$ transitions in [3], and blue shift with simultaneous vanishing $E_1$ transition with increasing Mn content [4]. In our earlier photoreflectance study [5] we observed the increasing value of optical gap energy in the vicinity of the $\Gamma$ point up to 4% Mn atoms in GaAs matrix. Sample which contained 6% revealed a red shift in reference to the 4% sample what indicates that the Fermi level energy is raising. In this paper we present additional new results of ellipsometric study of (Ga,Mn)As. The Woollam VASE ellipsometer was applied to investigate the $E_1$ and $E_1+\Delta$ interband transitions with increasing Mn content in (Ga,Mn)As samples in reference to LT-GaAs substrate. Our findings are in a good agreement with the previous photoreflectance study.

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References
Influence of thermal annealing on optical spectra of subsurface GaAs layers implanted by indium and xenon ions

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In order to modify the optical and electrical properties of subsurface layers of solids the process of ion implantation and thermal annealing of doped semiconductors is used [1].

In this work the results of studies of the optical properties of the subsurface layers GaAs after In⁺ and Xe⁺ ions implantation and thermal annealing are presented. Two series of SI GaAs (100) were exposed to In⁺ and Xe⁺ ions beams with energies 250 keV and 100 keV, respectively. In both cases fluences were equal 3·10¹⁶ cm⁻². After implantation process the material was exposed to isobaric thermal annealing at 600°C and 800°C [1].

In the purpose of determination of the thickness of the subsurface layers exposed to ions the RBS method was used [2]. Optical properties (spectra of dielectric function) were investigated in the range of wavelength from 250 nm to 1000 nm by applying spectroscopic ellipsometry (SE). To describe investigated materials, basing on the SE measurements, two-, three- and four-phase models were applied [2]. Changes of dielectric function spectra for doped layers were verified by using the Kramers-Kronig analysis [3].

It was observed that thermal annealing at 600°C yields rebuilding the crystalline structure of doped materials. Likewise it was noticed the growth of oxides thickness on surfaces after implantation and thermal annealing as well as optical constants changes in comparison with unimplanted material. Additionally, the modification of dielectric function was observed near the critical point E₁ for the subsurface GaAs layer implanted by indium ions and annealed at 800°C. The following effects can be interpreted as a result of diffusion process and formation of a three-element GaInAs alloy in ion doped layer enriched in In atoms.

References
Isovalent substitution on the iron site in pnictides - an optical study

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Here we report on a comprehensive study on the full complex dielectric function $\varepsilon(\omega)$ in the $ab$ plane of Ba(Fe\textsubscript{1-x}Ru\textsubscript{x})\textsubscript{2}As\textsubscript{2} by applying spectroscopic ellipsometry in the broad range of 60 meV to 6 eV. The investigated set of samples grown out of self flux spans the whole range from the well studied parent compound BaFe\textsubscript{2}As\textsubscript{2} ($x=0$) deep into the overdoped regime ($x=0.74$), not reported so far, showing superconductivity in a broad range with $T_c$ up to 20 K at optimally doping ($x=0.35$).

By applying a classical dispersion analysis of a Drude term and a minimal set of Lorentz oscillators we detect an increase in the bare plasma frequency $\omega_p$, associated with the free carrier response, and a significant decrease of the low-energy dielectric permittivity $\varepsilon_\infty$ upon doping.

The main contribution to $\varepsilon_\infty$ arises from the lowest lying interband transitions at $\sim 0.5$ eV, which assigned to be from Fe(Ru)-d/As-p to Fe(Ru)-d hybrid states \cite{1}. This contribution gives rise to anomalously high $\varepsilon_\infty \approx 60 - 80$ among all other high-$T_c$ superconductors with, e.g., $\varepsilon_\infty \approx 5$ in YBCO \cite{2}. This, in conjunction with increased Fe(Ru)-d bandwidth with $x$ due to stronger hybridization with As-p states \cite{3}, hints to a strong decrease in the high polarizability of Fe-As bonds, which is thought to play a crucial role in establishing and controlling superconductivity in iron pnictides.

References

1. A. Charnukha et al., Nature Communications 2 (2011), 219
2. A. V. Boris et al., Science 304 (2004), 708
Application of FDS method in spectroscopic ellipsometry studies of semiconductors with direct and indirect band gaps

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Determination of critical point (CP) energy refers to calculating the fractional derivative order [1] of the function $E^2 \varepsilon(E)$, where $E$ is the photon energy and $\varepsilon(E)$ is the dielectric function of a crystal.

The spectra of dielectric function $\varepsilon(E)$ were determined using the spectroscopic ellipsometry (SE) technique [2]. The measurements were carried out in the range from 1.24 eV to 4.96 eV for single crystals of Cz Si and SI GaAs, semiconductors with indirect and direct band gap, respectively. There were used two models for description of the examined samples. The first one: two-phase model (ambient, substrate) assumes that both media are homogeneous and isotropic and there is no layer between them (this model assumes that the layer of native oxide is absent). The three-phase model (isotropic media: an ambient, a thin, flat and parallel layer and a substrate) assumes the existence of thin layer of native oxide at the surface of solids.

Using the above models the spectra of the real and imaginary parts of the dielectric function ($\varepsilon_1$ and $\varepsilon_2$, respectively) were evaluated from the SE measurements. Fractional Derivative Spectra (FDS) method was applied to extract the CP energies in Cz Si and SI GaAs in the vicinity of the $E_1$ transition.

The results of the SE investigation and FDS calculation allow to draw conclusion that the position of CP corresponding to $E_1$ in both semiconductors is shifted to lower energies when the two-phase model was used in calculations.

This effect is connected with the fact of lowering of the effective atomic density of crystal, due to recognizing the oxide layer as a part of substrate. Furthermore, the use of sequential computation increases the sensitivity of the FDS method, allowing to determine the energy position of CP with an accuracy of 1 meV [3]. Moreover, the FDS algorithm is more convenient than the Kramers-Kröning relations in the CP investigation because the FDS does not require knowledge of so many parameters [4].

References
1. Xing-Fei He, Phys. Rev. B 42 (1990) 11751
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Characterization of molecular orientation in vacuum-deposited organic films used in solar cells: new results from UV-Vis-NIR VASE

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Meanwhile, vacuum deposited organic films are widely applied in organic electronic and opto-electronic devices. Advantages like accurate thickness control, high material purity, stacking of multi-layer systems, and the opportunity of using flexible substrates make them attractive for a wide range of applications and large scale fabrication. Although the electrical and optical properties of organic materials have been widely investigated to improve the performance of organic electronic devices, these properties are most often not fully clarified due to the large number of substances, complexity of materials, effects of impurities, molecular conformation and aggregation. In particular the molecular order is often found to strongly influence properties like e.g. charge transport. As example, organic solar cells (OSC) work most efficiently when high mobility in vertical direction is achieved, i.e. when flat lying molecules provide overlapping of their electron systems perpendicular to the substrate plane. Additionally, in OSCs flat lying molecules also enable good interaction of the transition dipole with the incident electromagnetic light wave and can thus achieve high absorption. Consequently, the investigation and understanding of molecular orientation is essential for further improving the performance of OSC as well as other organic devices. For this reason, we apply Variable Angle Spectroscopic Ellipsometry (VASE) to determine the optical properties of several small molecular organic materials that are used in the current best performing vacuum deposited OSCs. With this technique, optical anisotropy of the organic thin films can be characterized and reveals possible preferential molecular orientations, i.e. preferential orientation of the molecular transition dipole. As already shown by previous works VASE can even be applied for amorphous layers. In contrast to the common assumption that amorphous layers are fully isotropic, it appears that preferential molecular orientation can be present nonetheless [Yokoyma et al., Org. El. 10 (2009), 127-137]. We present VASE measurements of neat donor layers as well as layers of the donor materials mixed with C\textsubscript{60}. The optical constants and the optical anisotropy are evaluated in the spectral range from 245 to 1680nm and discussed in respect of molecular orientation, thereby addressing the question: What makes these materials good absorbers for OSC? Furthermore, we study with VASE the effects of post-annealing and deposition onto heated substrates, two methods which are usually applied to improve the solar cell performance.
Determination of optical constants and phase transition temperatures in polymer fullerene thin films for polymer solar cells

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Plastic photovoltaics combining semiconducting polymers with fullerene derivatives have the potential to become the first cost efficient solar cells able to compete with fossil fuels. The maximum power conversion efficiency is already 8.3%[1], and new polymers arrive frequently in the search for efficiencies of 10%. As a first step in the screening of candidate materials, the optical constants of the pure polymer as well as the polymer blend with fullerenes are determined from Variable Angle Spectroscopic Ellipsometry (VASE), using Tauc-Lorentz oscillator models, throughout the solar spectrum. These models are then used to predict the upper limits to photocurrent generation in devices, in transfer matrix simulations of the multilayer thin film photovoltaic devices. This forms an essential step in the choice of materials for optimization in devices.

Materials optics measurements are also used to deduce the phase diagram of polymer and polymer blend films. The glass transition temperature is very important for plastic solar cells and must be higher than the 80°C a device can reach to avoid degradation during operation. Temperature dependent ellipsometric measurements has proven to be a feasible way to determine phase transitions in polymer thin films[2]. These transitions are displayed as a sudden change of the volumetric expansion coefficient, and are manifested by an abrupt increase of thickness at the phase transition temperature. For thickness determination a Cauchy model is applied to the transparent infrared part of the spectra.

References
Anisotropic characterization of polymers film for OPV

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Organic Materials for photovoltaic applications are studied for several years already and become extremely promising for the fabrication of solar cells. The high sensitivity of Spectroscopic Ellipsometry, which is a well-established technique to determine the optical properties and thicknesses of thin layers, can be used to characterize the OPV layers, in this field of application. Due to the long chains of atoms, such polymer molecular films easily exhibit uni-axial anisotropy. Usually such anisotropy is addressed by what is called “generalized ellipsometry”. Following this approach it is necessary to determine the 2 off diagonal elements of the Jones Matrix and this requests to perform multiple acquisitions for different azimuth positions of the sample. An alternative to this approach is to consider the Mueller Matrix formulation which consists to describe the sample by a $4 \times 4$ matrix. This approach requests the determination of 16 parameters but no rotation of sample is necessary. In the case of anisotropic sample, the upper right block ($2 \times 2$ elements) of the Mueller matrix becomes different from 0 as it is the case for isotropic samples. Moreover using this approach it is possible to evaluate simultaneously the degree of polarization of the reflected beam which give useful information about the non ideality of the ellipsometer tool itself or the loss of polarization of the beam due to some diffusion coming from the sample itself. In this paper, after a short presentation of the acquisition technique, the 4 specific Mueller coefficients for anisotropic samples will be presented and a suitable modelisation will be proposed. This approach will be illustrated by different organic polymer layers dedicated to photovoltaic applications. Limitations and perspectives will also be discussed.
Characterization of bulk-heterojunction layers for solar cell application with spectroscopic imaging ellipsometry

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Organic solar cell research has attracted increasingly scientific and economic interest in the last decade. Flexible and cheap OPVs are promising but the power conversion efficiencies is still an issue. To overcome this, different approaches like new materials, improved materials engineering, and more sophisticated device needed to be combined and a better understanding of structure-morphology/function-optical properties relation in the microscopic scale are required.

The first plastic solar cell devices were based on conductive polymers like Poly(2-methoxy-5-(2-ethylhexyl oxy)-1,4-phenylen-vinylen) (MEH-PPV) but higher performing organic solar cell designs are based on a blend of an electron-donating and accepting material, also refereed to as a bulk-heterojunction. One such example was MEH-PPV intimately blended with the soluble fullerene derivative [6,6]-phenyl C$_{61}$-butyric acid methyl ester (PCBM). The external quantum efficiency (EQE) of the corresponding solar cell is increased due to the large interfacial area between the electron-donating and accepting phases of the photo-active blend. Hence, controlling the blend morphology at the nanoscopic scale is essential for optimizing the power conversion efficiency of plastic solar cells when employing a bulk-heterojunction as the photo-active layer. Recent advances in polymer based solar cells has mainly been achieved with poly(3-hexyl-thiophene) (P3HT) and derivative here of as the electron-donating component of the photo-active blend.

Variable-angle imaging spectroscopic ellipsometry is a non-invasive optical probe technique that monitors changes in the polarization state of light on reflection from a sample. It can be seen as the link inbetween macroscopic ellipsometry, optical microscopy and scanning probe techniques. Ellipsometric contrast pictures offer assess the film homogeneity with a lateral resolution comparable to an optical microscope and a thickness contrast comparable to AFM. The ellipsometric parameter $\Delta$- and $\Psi$ were recorded by mapping and by measuring with defined regions of interest (ROI)s. Backside reflections are generally undesirable in ellipsometry. In general, imaging ellipsometry offers a straightforward approach to eliminate reflected light from the backside of the substrate, even for thin transparent substrates.

The investigation of silk-printed and spin-coated bulk-heterojunction layers as well as the bare substrate were performed with a Spectroscopic Imaging Ellipsometer nanofilm_ep3se incl. EP3View Software, 20x and 2x objectives and a beam cutter.

Ellipsometric contrast pictures were taken using different magnifications. The contrast was increased by the use of a polarizer and an analyser. An area of $\approx$1 mm$^2$ in the centre of each sample was investigated in ellipsometric micrographs. At least two-zone measurements of $\Delta$ and $\Psi$ were performed in the wavelength range between 360 and 1000 nm. The region of interest was located in the shadow of the beam cutter, ensuring only a single reflection from the sample. Spectra were recorded for the bare substrate as well as for the layer systems based on it. Different optical modells are discussed. For high resolution small scale inspection, $\Delta/\Psi$ maps were recorded and the data were transferred into map of thickness and map of refractive index.
In-situ monitoring of the growth of polypyrrole at the liquid/silicon interface by combining infrared spectroscopic ellipsometry (IRSE) and reflectance anisotropy spectroscopy (RAS)

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In this work, the electrochemical polymerization of a polypyrrole (PPy) film on a Si(110) wedge in aqueous solution was in-situ investigated by a combination of infrared spectroscopic ellipsometry (IRSE) [1] and reflectance anisotropy spectroscopic (RAS) techniques. The electrochemical deposition was performed on Si(110) substrates using the potentiostatic pulse method [2]. The deposition process and the development of the optical properties of the PPy film with time was characterized and the chemical components of the deposited film were identified by their specific infrared signature. Additionally, the morphology of the PPy film was inspected by atomic force microscopy (AFM).

References

Spectroscopic Ellipsometry study of temperature-induced phase transitions in hybrid inorganic-organic perovskites

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Two dimensional hybrid organic-inorganic perovskite compounds have attracted much attention due to their electrical and optical properties which make them a promising material for potential application in optoelectronics devices. In fact, these compounds form natural self-assembled organic-inorganic hybrid quantum-well structure consisting of corner sharing PbI₆ octahedra, forming 2D semiconductor layers and intercalated inorganic chains, which play the role of barrier layers. Moreover, it has been shown that they exhibit many phase transitions [1, 2]. Most of them consist in order-disorder phase transitions governed by rotational and/or orientational ordering of organic molecules. The correlation between the photoluminescence properties and the thermally induced phase transitions represents an interesting area of study in the way of the thermal control of the photoluminescence properties of materials. The understanding of these correlations may also open new applications of these compounds as sensors of temperature, pressure or other physical functions. We report here on the first ellipsometric study, to our knowledge, of the temperature induced phase transitions in hybrid organic-inorganic perovskite. Spectroscopic ellipsometry (SE) of PbI [3] based perovskite, with different organic chains, has been performed as a function of temperature and evidenced the presence of first order phase transitions with an associated hysteresis loop. These measurements were correlated with photoluminescence spectroscopy. The structural transitions were confirmed by heat capacity measurements which yield the entropy change at the transition. Raman spectroscopy and X-ray diffraction were used to investigate the mechanism of the transition.

References
Optical anisotropy in total internal reflection ellipsometry of thin molecular layers

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Total internal reflection ellipsometry (TIRE) [1] is a technique combining spectroscopic ellipsometry and SPR. The sensitivity of this method is higher in comparison to conventional ellipsometry or SPR [2]. In fact, TIRE utilizes the analytical power of ellipsometry and increases the sensitivity by introducing the SPR effect into the operation scheme of ellipsometer. A large sensitivity of TIRE enables one to analyze in more details the structure and properties of thin organic layers [3]. It is well known [4] that the molecules of organic compounds generate most frequently an anisotropic optical response, when external electromagnetic field is applied. However, the optical anisotropy is masked in liquids. This phenomenon is neglected in the analysis performed by means of commercially available SPR-based biosensors, though the optical anisotropy is supposed to manifest itself due to a partially regular arrangement of molecules on substrate. Therefore, some important features of biologically active monolayers are lost, and, as a result, the structural aspects of investigated molecules are not completely characterized. In the case of immunosensors, the appropriate site-specific orientation of antibodies on the sensors surface is important for their sensitivity and ability to interact with antigen [5]. Summarizing, the structural and optical parameters determined from regression analysis of ellipsometric data of uniaxial anisotropic model provide the important information about the molecular monolayer, such as orientation of biomolecules with respect to the substrate surface, the distance of active sites of biological object from the surface.

References

Optical properties of thin ZnTPP-films on Si

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In this study the optical properties of Zn-tetraphenylporphyrine (ZnTPP) films on Silicon (111) surfaces covered with native oxide were determined. The films prepared with organic molecular beam deposition were analysed by IR-spectroscopic ellipsometry and reflectance anisotropy spectroscopy (RAS). The observed anisotropy is discussed as well as the correlation of the vibrational frequencies with the film thickness. For different modes the dependence on the symmetries of the vibrational modes of the ZnTPP molecules will be discussed.

Figure 1: Dielectric function of ZnTPP-film
Phase separation investigation of roll-to-roll gravure printed P3HT:PCBM thin films by Spectroscopic Ellipsometry

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Among the traditional industrial printing methods, gravure printing exhibits significant advantages, such as high resolution and throughput. Roll-to-roll (r2r) processing, which is widely used in the printing industry (e.g. packaging) is a cost-effective technology that can be successfully implemented for the fabrication of Flexible Organic Electronics Applications, such as Organic PhotoVoltaics (OPVs).

In this work, Poly-(3-hexylthiophene-2,5-diyl):C_{61}-butyric-acidmethyl-ester (P3HT:PCBM) films were r2r gravure printed onto flexible polymer rolls of Polyethylene Terephthalate (PET) for the fabrication of OPVs. Spectroscopic Ellipsometry (SE) in the NIR-Vis-fUV spectral region (0.7-6.5 eV) combined by sophisticated analysis methodologies has been employed in order to investigate and determine the effect of the gravure printing conditions and thermal treatment on the optical and compositional characteristics of P3HT:PCBM blend films printed onto flexible PET substrates. The findings were correlated with results from Atomic Force Microscopy and Grazing Incidence X-Ray Diffraction methods.

The investigation and understanding of the vertical phase separation of P3HT and PCBM phases in the blend films by SE, has led to the optimization of the printing/thermal treatment conditions which indicates the significant usability of SE as precise characterization quality control tool in printing mechanisms and optimization processes for OPVs.
Responsive polymer brushes are functional materials which offer a wide range of applications. Due to the possibility of changing the surface properties by external stimuli such as pH, solvent, temperature or electric field, polymer brushes can control protein adsorption, wettability or adhesion of surfaces.

As a method for optical, chemical and structural analysis of ultra-thin organic films, infrared spectroscopic ellipsometry (IRSE) is a well-established method. A special in-situ cell allows to perform IRSE measurements of ultra-thin organic films in aqueous environments and therefore enables measurements of responsive polymer brushes in aqueous solutions.

This in-situ method was successfully used to perform comprehensive in-situ-studies on polyelectrolyte brushes. Different brush systems based on materials such as PAA (poly(acrylic acid)) [1] or P2VP (poly(2-vinyl-pyridine)) [2] were intensively studied with respect to their pH-dependent switching behavior. Monitoring of the characteristic vibrational bands during change of the pH enabled the detection of chemical and structural changes in the brush layer. The investigation of the switching behavior of pure PAA polyelectrolyte brushes in combination with additional methods such as in-situ-XSW (X-Ray Standing Waves) allowed to suggest a model of the processes inside the brush layer during the switching process. [3]

Additional to the investigations of the switching process, it was possible to monitor the controlled ad- and desorption of proteins (HSA) on polyelectrolyte brushes made from PAA.

References


Investigating small molecule detection by aptamer thin films using combinatorial spectroscopic ellipsometry and quartz crystal microbalance

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The study of interactions between small molecules and biological recognition layers faces the inherent challenge of low sensitivity due to the size mismatch between the biological sensing element and its target. Thus, an amplifying factor must be associated with small molecule binding to allow for the use of conventional techniques of investigating surface-confined intermolecular interactions. DNA-based conformational switches provide an opportunity to couple small molecule binding to a large-scale reorganization of a surface-confined layer. As a model system, we investigate condensed layers of a DNA aptamer switch that undergoes a large-scale conformational change in the presence of procaine, a cocaine analog, forming a three-way junction. We investigate the morphology of a switchable DNA thin film using combinatorial spectroscopic ellipsometry and quartz crystal microbalance (SE-QCM). While SE reports a film thickness proportional only to the changes in the organic content of the thin film, QCM thickness is also affected by the contribution from the solvent coupled to the DNA film upon the introduction of the small molecule target. Simultaneously monitoring changes in film thickness given by each technique allows for the real-time quantification of bioactive layer porosity—a parameter that is inaccessible via either technique alone.
The study bio-molecular films using total internal reflection ellipsometry

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Biological thin films may form on the gold surface as a result of specific molecular interaction. Bio-molecular films were investigated by the Total Internal Reflection Ellipsometry (TIRE) technique, which is a combination of internal reflection and ellipsometry, enhanced with the Kretschmann type Surface Plasmon Resonance (SPR) \cite{1}. The TIRE experimental set-up used in our work was built on the basis of commercial SE 800 SENTECH spectroscopic ellipsometer operating in spectral range of 280-850 nm, and the home-built flow cell connected to syringe pump to control the liquid flow rate. The interaction of rabbit antibodies with bacterial endotoxin (lipolysaccharides LPS) were studied. Proteus mirabilis O3 S1959 (0.5mg/ml) reacted at 37\(\degree\)C with anti-O3 rabbit antibodies (1/200 diluted in PBS). The prepared solution were injected into the fluid cell through syringe pump and on to the gold surface. Due to the adsorption of bio-molecules on the gold surface the film is formed. The measurements were carried out to obtain ellipsometric parameters \(\Psi(\lambda)\) and \(\Delta(\lambda)\) for different incident wavelength in a spectral range between 400 and 850 nm. The ellipsometric angles permits to determine the thickness and the index refraction of the biomolecular film for the solution used. We observed that time evolution of bio-film thickness created on gold surface. The measurements demonstrate wavelength shift in the TIRE. It indicate on binding of antigen LPS O3 with anti O3 rabbit antibodies.

This work was partially supported by grant no. 8.2.1/POKL/2009, for J. Glen

References

In-situ and Real-Time Ellipsometry for the Monitoring and Evaluation of Protein Adsorption on Organic and Inorganic Thin Films

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Protein adsorption is an important aspect for the improvement of many applications, such as medical implants and biosensor design [1]. The density, orientation and conformation of the adsorbed proteins are believed to be key factors in controlling subsequent cellular adhesion [2]. As for the haemocompatibility of artificial implants, two basic blood plasma proteins, human serum albumin (HSA) and fibrinogen (Fib) are of great importance. The aim of this work is to study in-situ and real-time protein adsorption on inorganic carbon-based (such as amorphous hydrogenated carbon (a-C:H) and carbon nitride (CNx)) and organic (such as poly(3,4-ethylene dioxythiophene)-poly(styrene sulfonate) PEDOT-PSS) thin films. Carbon-based thin films are considered as excellent candidates for use as biocompatible coatings on biomedical implants [3] and were developed by rf reactive magnetron sputtering under different deposition conditions. On the other hand, PEDOT-PSS thin films, which belong to the category of conducting polymers, could be suitable for several biomedical applications and devices [4]. The latter were developed with spin coating technique using a variety of different forms of starting materials in terms of their polymerization. For the analysis of the optical, compositional and structural properties of the thin films, in-situ Spectroscopic Ellipsometry (SE) in the Vis-UV spectral region was used. The adsorbed protein layers were evaluated during their dipping in protein solutions using a liquid cell. In addition, real-time Multi-Wavelength Ellipsometric (MWE) measurements were carried out for the dynamic evaluation of the adsorption mechanisms of the HSA and Fib proteins onto carbon-based and PEDOT-PSS films. Suitable ellipsometric models are proposed and used for the analysis interpretation of the experimental data, taking into account the surface topography and wettability of the films.

References

2. K.K. Chittur, Biomaterials 19, 301 (1998)
Ellipsometric investigation of photochromic transition in ultrathin films of diarylethene polymers

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The light-triggered conversion of a thermally irreversible photochromic polymer has been studied by means of spectroscopic ellipsometry. The photochromic material under investigation is a polyester containing diarylethene units in the main chain, which has been obtained by polymerization of 1,2-bis-(2-methyl-4-(p-hydroxymethylphenyl)-3-thienyl)perfluorocyclopentene with adipoyl chloride. The presence of an aliphatic spacer guarantees a good solubility of the polymer in common organic solvents and interrupts the $\pi$-conjugation over the polymer backbone in order to not strongly affect the photochromism of the diarylethene moiety. By irradiation with UV light the uncolored material turns blue and a strong absorption band centered at 586 nm appears. The colored state is thermally stable and, accordingly, the backward reaction is only light-triggered with visible light. Absorption spectra in chloroform solution at different irradiation times show the presence of an isosbestic point at 318 nm, which is a clear indication of the absence of relevant side reactions.

In this work, very thin films (20-40 nm thickness), spin cast on SiO$_2$/Si substrates, have been investigated by spectroscopic ellipsometry (SE) in the 245-1700 nm wavelength range. Dynamic scans allowed to monitor with great accuracy the transition from the transparent form to the blue one, during UV irradiation ($\lambda$=311 nm, 9W); the reverse transition has been also investigated while irradiating with a laser at 655 nm wavelength. Spectroscopic features related to the blue form are clearly visible in $\Psi$ and $\Delta$ data and are emphasized in difference spectra calculated with respect to the transparent form data. In order to determine the dispersion of the optical constants and film thickness we analyzed the ellipsometric data in both transparent and absorbing regions. The transparent layer has been modeled in the VIS-near IR using simple dispersion rules (Cauchy, Sellmeyer), yielding satisfactory fit results. A convenient multi-peak absorbing layer was employed for the blue form, to model the absorption band in the visible and other neat absorptions in the near UV. The experimental data and the model indicate a variation of the refractive index (about 2 %) between the two forms. We are also investigating a possible slight reduction of film thickness which may occur during the light-induced cyclization that converts the polymer from the transparent to the blue form.
Temperature-sensitive swelling behavior of poly(N-isopropylacrylamide) brushes characterized by in-situ infrared spectroscopic ellipsometry

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Polymer brushes are very attractive material systems for biophysics and biochemistry. They react to external stimuli like temperature, pH, or solvent by changes in their surface properties. The brushes thereby represent functionalized surfaces important for applications like controlled protein and cell adsorption.

Infrared spectroscopic ellipsometry (IR-SE) in combination with a special in-situ cell is a suitable method for studying the film properties at the solid-liquid interface and therefore allows to investigate the structural and chemical properties of polymer layers in aqueous environment [1], [2].

An important representative for temperature-sensitive polymer brushes is poly(N-isopropylacrylamide) [PNIPAAm], which is of great technological interest owing to the phase transition at its lower critical solution temperature of 32°C. The swelling behavior of PNIPAAm brushes was investigated in neutral water at different temperatures around 32°C using in-situ IR-SE.

References
GLAD Sculptured Thin Films Functionalized with Polymer Brushes

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The development of stimuli-responsive surface coatings has been the subject of many investigations in the recent past [1]. Polymer brushes, consisting of polymeric macromolecules tethered on one end to an underlying substrate, are regarded as very promising candidates because these systems are capable of responding to external stimuli such as temperature or pH, generally by reversible swelling-deswelling behavior. Another focus of modern material science and engineering lies on the fabrication of three-dimensional nanostructures possessing tunable intricate features such as porosity, surface roughness, and surface chemistry [2]. In this study, nanostructures with slanted columnar surface morphologies were functionalized with polymer brushes to fabricate a dual featured surface in which the intercolumnar spaces of the nanostructures are filled with polymer brushes (Fig. 1). Specifically, the nanostructures were fabricated by glancing angle deposition (GLAD) of silicon onto gold. Guiselin polymer brushes, consisting of polyacrylic acid were reacted to the slanted columns by a grafting-to approach using a poly(glycidylmethacrylate) anchoring layer. Generalized ellipsometry (GE) was employed to characterize the fabrication of the GLAD sculptured thin film (STF) as well as the step-wise reaction of polymer brushes to the GLAD nanostructures. Furthermore, in-situ combinatorial spectroscopic ellipsometry and quartz crystal microbalance with dissipation studies were conducted to evaluate the reversible swelling characteristics of functional polymer brushes. This study demonstrates that GLAD STF are capable of withstanding the grafting-to process. GE was also shown to be an accurate probe of monitoring hybridization of materials within complex nanostructures. Together with post-fabrication analysis, GE demonstrates that polymer brushes are successfully immobilized within the GLAD STF and that the brushes exhibit reversible swelling characteristics. These complex and tunable hybrid nanostructures with stimuli-responsive characteristics provide novel material surfaces for nanoelectronics, biotechnology, and a variety of other advanced material applications. We acknowledge funding from DFG and BMBF for this work.

Figure 1: Schematic of GLAD sculptured thin film functionalized with PAA Guiselin brushes

References
Optical behavior of thick and thin dielectric films embedding noble metal nanoparticles

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The stabilization of metal nanoparticles (NPs) against aggregation in solution and their dispersion in the matrix are the main challenges that have to be encountered when composite films made of NPs and of a dielectric matrix (e.g. a polymer film) have to be prepared. In situ synthesis methods exist, in which the chemical reduction of a noble metal salt is achieved either by thermal annealing or by photoreduction, the polymer matrix acting as a reducing agent. Such methods are usually simple (one-pot synthesis), but their mechanism is today not fully understood although being the subject of an increasing number of publications. The optical properties of such composite films can be probed by spectroscopic ellipsometry (SE) [1]. They are characterized by the presence of an absorption peak due to the plasmon resonance [2]. In the case of silver NPs, the resonance occurs at about 415 nm and the films appear yellowish-brown in color. We showed, using AFM analysis and SE, that increasing the annealing time of thick films (d > 500 nm) contributed to the onset of more particles whose area decreased and that the intensity of the absorption peak, modeled as a Lorentzian absorption line, was strongly correlated to the density of NPs [3]. In the mid-infrared spectral domain, the presence of additional peaks located at 1134 cm⁻¹ and 1036 cm⁻¹ also suggested the presence of bonds between Ag and the polymer matrix [4]. In this study, the optical properties of Ag-doped polymer films were studied using SE as a function of the thickness of the film. 20nm-thick and 300nm-thick films with a high Ag content were considered. The topography of the films was studied by atomic force microscopy and the roughness parameters of the thin films were found to be larger than those of the thicker ones. The parameters of the surface plasmon polariton resonance are also thickness-dependent: in the case of thin films, the amplitude of the resonance is higher, the position of the resonance smaller and the peaks wider than in thicker ones [5].

Acknowledgements: This work is supported by the National Fund for Scientific Research of Belgium (FRFC project 1926111).

References

Informations

Information for presenters

Talks

Please provide a ppt(x), odp, or pdf file to the technical staff at the workshop office (SR 224) right now during your registration and subsequently check together with the technical staff whether your presentation works properly. Session chairs and speakers are expected to appear in the lecture hall (Großer Hörsaal, Room 205) at least 10 min before the start of their session. Please strictly keep in time! The allotted time (talk/discussion in min.) is for tutorials 45/0, invited talks 20/5, contributed talks, topics: MM, RS, EP, OR 15/4; topic: IA 10/5, and topic DP 8/7

Please note, that at the beginning of the first session of a respective topic a tutorial and invited talks will be given to introduce the topic. Therefore, it will not be necessary to show too much basic details in your presentation. If you like, you can contact the respective speakers.

Posters

Poster sessions take place in the first floor (SR 218, SR 221, SR 224, SR 225). Please attach your poster right now at your arrival. All posters will be presented for the entire workshop duration. The authors of odd numbers should be present at their poster during the first poster session (Mo) and those of even numbers during the second poster session (Tu). The code of each poster - given in the abstract book - is shown on the board. Please prepare your poster in A0 portrait format.

Workshop CD

Please provide a copy (or ready-for-publish version) of your Talk/Poster for publication on the Workshop CD to the technical staff at the workshop office (SR 224) right now during your registration where you are asked to sign for approval. This CD will be published electronically, accessible for the workshop participants only via their log-in account.

Social event

The conference dinner will take place on Tuesday night at "Schalterhalle" in the restaurant "Bayrischer Bahnhof" (address: Bayrischer Platz 1; www.bayerischer-bahnhof.de). The musical ambience will be provided by the "Guitarolas". We will meet at 19:15 directly at the "Bayrischer Bahnhof" or at 19:00 in front of the physics building for guided walk.

Board

During the breaks and the poster sessions, snacks will be served. Lunch takes place in the cafeteria ("Mensa", c.f. the map). You received the vouchers for lunch in the cafeteria together with your abstract book.

Public transport

A ticket for the Leipzig public transport (LVB) is included in the conference package and is printed on your conference badge, which you are supposed to carry by your side (for the ticket inspector). You can take the trams, buses, and S-Bahn in the Zone 110 of the MDV.
Informations

Internet

WLAN will be available during the workshop, please find below the settings for the access.

- name: UniLeipzig-Event
- password(PSK): Quali-2012
- security encryption: WPA2/AES
- IP address: getting automatically (DHCP)

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Award

The Paul Drude Medal will be given to a young scientist for exceptional contributions to the field of ellipsometric metrology or spectroscopy. Another award will be given to the best poster. The price-winner will be selected at the workshop by the members of the international advisory board and the program committee.
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