## Spectroscopic Ellipsometry Focus Topic
## Room 202A - Session EL+EM-MoA

### Spectroscopic Ellipsometry: Novel Applications and Theoretical Approaches

**Moderators:** Vanya DarakchievaStefan Zollner, New Mexico State University,

1:20pm **EL+EM-MoA-1 The Physics of Low Symmetry Metal Oxides with Special Attention to Phonons, Plasmons and Excitons and their Potential for Uses in Power Electronics and Quantum Technologies***, **Mathias Schubert,*** University of Nebraska - Lincoln, Linköping University, Sweden, Leibniz Institute for Polymer Research, Dresden, Germany*; A Mock, R Korlacki, S Knight,* University of Nebraska - Lincoln*; V Darakchieva,* Linköping University, Sweden*; B Monemar,* Linköping University, Sweden, Tokyo University of Agriculture and Tech., Japan*; H Murakami, Y Kumagai,* Tokyo University of Agriculture and Technology, Japan*; K Goto,* Tokyo University of Agriculture and Technology, Tamura Corporation, Japan*; M Higashiwaki,* National Institute of Information and Communications Technology, Japan **INVITED**

We discuss analysis of the dielectric function tensor for monoclinic metal oxides. We derive the dispersions of transverse, longitudinal and plasmon coupled modes in gallium oxide [M. Schubert et al., Phys. Rev. B 93, 125209 (1-18) (2016); Editors' Suggestion], the Lyddane-Sachs-Teller relation for monoclinic and triclinic semiconductors [M. Schubert, Phys. Rev. Lett. 117, 215502 (2016)], the identification of transverse and longitudinal phonons in scintillator material cadmium tungstate [A. Mock, M. Schubert et al., Phys. Rev. B 95, 165202 (1-15) (2017)], the band-to-band transitions and excitons and their eigenvectors in gallia [A. Mock, M. Schubert et al., Phys. Rev. B 96, 245205 (1-12) (2017)], the effective electron mass tensor measurement using the optical Hall effect in gallium oxide [S. Knight, A. Mock, M. Schubert et al., Appl. Phys. Lett. 112, 012103 (2018); Editors' Pick], the temperature dependence of band-to-band transitions energies in gallium oxide [A. Mock, M. Schubert et al., Appl. Phys. Lett. 112, 041905 (2018)], and the dielectric and inverse dielectric tensor analysis method for transverse and longitudinal phonon mode dispersion characterization in high-power laser material yttrium silicon oxide [A. Mock, M. Schubert et al., Phys. Rev. B, 97 165203 (1-17) (2018)].

2:00pm **EL+EM-MoA-3 Mueller Matrix Spectroscopic Ellipsometry Based Scatterometry of Nanowire Gate-All-Around (GAA) Transistor Structures***, M Korde, **Alain C. Diebold,*** SUNY Polytechnic Institute

One of the most difficult measurement challenges facing semiconductor research and development is determining the feature dimensions and shape for complicated 3D structures. GAA transistors are fabricated from fins etched from a $Si/Si_{1-x}Ge_x/Si/\ Si_{1-x}Ge_x/Si$.. multilayer.(1, 2) At one point in the fabrication process, the nanowires used in GAA transistors have the nanowire transistor structures suspended between the source and drain. Considering the close spacing of neighboring transistors, measuring the nanowires is a significant challenge. In this talk, we present simulations aimed at understanding the sensitivity to changes in feature shape and dimension for the structures used to fabricate GAA transistors. Simulations of the multi-layer fins shown a clear sensitivity to fin shape and Si layer thickness which is enhanced by the use of the full Mueller Matrix capability vs traditional spectroscopic ellipsometry.

1. Optical measurement of feature dimensions and shapes by scatterometry, A.C. Diebold, A. Antonelli, N. Keller, APL Mat., (2018), in press.
2. Muller matrix spectroscopic ellipsometry based scatterometry simulations of Si and $Si/Si_xGe_{1-x}/Si/Si_xGe_{1-x}/Si$ fins for sub 7-nm node gate-all-around transistor metrology, S. Dey, N. Keller, M. Korde, and Alain C. Diebold, SPIE, Metrology, Inspection, and Process Control for Microlithography XXXII, SPIE Advanced Lithography, San Jose, Feb 25-Mar. 1, 2018. To be published in conference proceedings.

2:20pm **EL+EM-MoA-4 Anomaly in the Optical Constants of Ni near the Curie Temperature***, **Farzin Abadizaman**, S Zollner,* New Mexico State University

Magnetized Ni demonstrates an anomaly in its optical constants near the Curie temperature ($T_c$ = 627 K). Experiment shows that this anomaly does not depend on the morphology of the sample. To investigate this feature, we have carried out a series of ellipsometry measurements in the energy range of 0.5 to 6.5 eV as a function of temperature from 80 to 800 K in 25 K steps. Furthermore, temperature dependent Mueller Matrix (MM) measurements have been performed on the magnetized Ni at a single energy of 1.97 eV as a series of four runs, up and down, between 300 and 800 K. The MM data of magnetized Ni reveal slight changes in the anisotropic portion of the MM while passing $T_c$. However, vast changes in the isotropic MM elements are found, indicating that the anomaly is not due to the induced anisotropy of the sample. The anomaly occurs only in the first run when the temperature passes $T_c$, which suggests that it stems from magnetization. On the other hand, magnetizing the sample again and repeating the experiment do not demonstrate any anomaly as passing $T_c$, which disproves our previous suggestion. In fact, the anomaly happens only once for each sample, regardless of its morphology.

No observable variation in the out-of-plane grain sizes were found in the XRD data before and after the temperature measurement. This and the fact that the anomaly occurs for a single crystalline sample as well as for a polycrystalline one indicate that it cannot be due to the grain growth. This turned our attention to the surface effects: Several experiments have been conducted to investigatehow the surface of sample changes around $T_c$ and how cleaning the surface affects the optical constants of Ni. The authors believe that the anomaly around $T_c$ originates from the surface changes. Yet the question of why it occurs near $T_c$ is still open. The same series of experiments have been performed on cobalt and the results are compared to Ni.

2:40pm **EL+EM-MoA-5 Phonon Confinement and Excitonic Absorption in the Optical Properties of ZnO Films***, **Nuwanjula Samarasingha,** S Zollner,* New Mexico State University*; D Pal, A Mathur, A Singh, R Singh, S Chattopadhyay,* Indian Institute of Technology Indore, India

Wide band gap materials like ZnO, which have drawn much attention for optoelectronic devices, have a large excitonic binding energy of 60 meV at room temperature. These excitons directly influence the dielectric function (**ε**) of ZnO. Hence investigation of excitonic absorption on the optical properties is very important. Wurtzite type ZnO shows three excitonic peaks in the ordinary dielectric function which are directly related to the electronic band structure. Due to the spin orbit and crystal field splitting the top valence band of ZnO is split into three sub bands . The corresponding free exciton transitions between these three valence bands and the lowest conduction band are denoted by A, C, and B. We also observe an exciton-phonon complex.

We explore the behavior of phonons and excitons in c-oriented ZnO thin films grown on Si (smaller band gap than ZnO) and $SiO_2$ (larger band gap than ZnO) using variable angle UV spectroscopic ellipsometry and FTIR ellipsometry. In order to characterize the structural properties of our ZnO films we performed X-ray diffraction (XRD), X-ray reflectivity (XRR), and atomic force microscopy (AFM) measurements.

According to the UV ellipsometry data the real and imaginary parts of **ε** in thin ZnO films on Si are much smaller than in bulk ZnO. We find that the excitonic enhancement decreases monotonically with decreasing film thickness. A similar behavior can be seen for ZnO films on $SiO_2$ as a function of thickness. The impact of this excitonic absorption on the **ε** was described by Tanguy [1]. We will fit our ellipsometric spectra by describing the dielectric function of ZnO using the Tanguy model. We will investigate the dependence of the excitonic Tanguy parameters on film thickness and substrate material.

Wurtzite type ZnO has 12 phonon branches, 9 optical and 3 acoustic modes. Among these 9 optical modes, only $1A_1$ and $1E_1$ polar phonon modes are IR active. According to the IR ellipsometry data these IR active phonon mode frequencies of ZnO films are consistent with bulk ZnO. We find a small redshift and increasing broadening with decreasing ZnO film thickness on a Si substrate. We will analyze the thickness dependence of the phonon oscillator strength of ZnO films on Si and $SiO_2$ substrates..

Reference:

[1] C. Tanguy, Phys. Rev. Lett. **75**, 4090 (1995).

Supported by NSF (DMR - 1505172).

3:00pm **EL+EM-MoA-6 High Aspect Ratio Etch Tilt Detection with Full 4x4 Mueller Matrix Spectroscopic Ellipsometry and Its Application to 3DNAND Channel Hole Etch Process and Chamber Monitoring***, **Peilin Ong**,* Micron Semiconductor Asia Pte. Ltd., Singapore*; S Ng,* Nanometrics Incorporated*; G Chu,* Micron Semiconductor Asia Pte. Ltd., Singapore*; P Murphy,* Nanometrics Incorporated*; L Liong, W Fu,* Micron Semiconductor Asia Pte. Ltd., Singapore*; Y Wen,* Nanometrics Incorporated, Nanometrics Incorporated*; L Ho,* Micron Semiconductor Asia Pte. Ltd., Singapore

Full 4x4 Mueller Matrix Spectroscopic Ellipsometry (MMSE)[1] is a widely-used technique for measuring cross-sectional profile, critical dimensions (CD) and material thicknesses of repeating structures created as part of microelectronic device manufacturing processes. In this paper, it will be shown that its application can be extended to measuring asymmetries in such structures with off-diagonal Mueller Matrix Elements[2]. These asymmetries, such as tilt of etched holes, and lines or trenches, are typically caused by inhomogeneity in the etch plasma sheath at the wafer edge. This paper will focus on one of the most important use-cases: tilt of high aspect ratio (HAR) etched 3D-NAND channel holes. Full 4x4 MMSE can be used to provide fast, accurate, non-destructive measurements of the channel hole tilt, both in direction and magnitude.

Furthermore, in contrast to CD and thickness measurements which are typically done in metrology test keys, this tilt measurement is in-die and on-device. This allows us to characterize the tilt at all locations on the wafer edge, as well as the variation in tilt as the wafer edge is approached. In addition, we also show how the measurements can be used to monitor the condition of the etch chamber for equipment control and/or to trigger preventive chamber maintenance.

3:40pm **EL+EM-MoA-8 Ultra-High-Speed Spectroscopic Ellipsometry and its Applications***, **Gai Chin**,* ULVAC Inc., Japan

As a comprehensive manufacturer of metrology tools and deposition tools, ULVAC developed an innovative high-speed spectroscopic ellipsometer for some thin-film deposition applications, such as PVD, CVD, ALD and others.

This novel spectroscopic ellipsometry can measure the thickness and optical constants of thin films at a dramatically fast speed. Its data acquisition time is as short as 10ms. It does not require any active components for polarization-control, such as a rotating compensator or an electro-optical modulator. The Fourier analysis of channeled spectrum obtained from the spectrometer allows determining the four spectroscopic ellipsometry parameters of the samples simultaneously.

It created great opportunities for new applications of the spectroscopic ellipsometry in which the compactness, the simplicity and the rapid response are extremely important. It can be integrated into the deposition tool and successfully measured thin films in-situ to realize the Advanced Process Control (APC). Obviously, those from PVD, CVD and ALD are some promising applications for this novel spectroscopic ellipsometry.

This paper describes the principle, system configuration and creative efforts on developing a series of high-speed spectroscopic ellipsometers. Some of its new applications will be also introduced, such as the PVD, CVD, ALD, EUV, OLED, MEMS and some measurement data of thin films from the semiconductor, flat panel display and other industries.

4:00pm **EL+EM-MoA-9 Use of Ellipsometry to Monitor Implant Damage in Methane Plasma Implant***, **Nicholas Bateman**,* Varian Semiconductor Equipment, Applied Materials

The Applied Materials PLAD tool consists of an inductively couple plasma source and a pulsed direct current (DC) bias coupled to a platen upon which a wafer is e-chucked. This tool architecture enables high throughput for high dose implants. Unlike a standard beamline implant, which will not lead to any deposition on the wafer, the plasma implant process directly exposes the wafer to the plasma leading to both deposition and implant damage. Standard industrial metrologies like Thermawave [1] are sensitive only to the implant damage. Process control could be enhanced if both the implant damage and the deposition thickness could be monitored online.

Ellipsometry is extensively used in the semiconductor industry to measure and monitor film thickness and optical properties [2]. It would be the ideal industrial technique to measure the deposition left by a plasma implant process, but has not been used to evaluate the damage caused by ion implant.

This work presents the development of an ellipsometry model that can be used to simultaneously monitor the deposited layer thickness and the implant damage caused by a methane plasma implant. The dispersion function for the deposited layer was determined by fitting multi-angle, broad wavelength ellipsometry data for different process times and bias conditions. The extracted thickness of the damage layer is shown to be well correlated to Thermawave across a wide range of process parameters, and through an extended ‘marathon’ test. As the implant voltage is reduced to zero the model trends continuously to match the results of a ‘deposition only’ ellipsometry model that matches SEM thickness measurements.

These results suggest that for plasma doping applications, ellipsometry can be used to monitor both implant damage and deposition simultaneously to allow improved process control.

**References:**

[1] J Opsal, US Patent 5,074,669, Method and apparatus for evaluating ion implant dosage levels in semiconductors (1989)

[2] DE Aspnes, Journal of Vacuum Science & Technology A, **31**, 058502 (2013)

4:20pm **EL+EM-MoA-10 Study of the Thickness-dependent Optical Constants of Metallic Thin Films based on Ellipsometry and Reflectivity***, **Jiamin Liu**, H Jiang, S Liu,* Huazhong University of Science and Technology, China

Metallic thin films have been widely used in various plasmonic and nanophotonic applications, such as bio-chemical sensors, meta-materials and nanolasers, benefiting by their size-dependent optical constants which are different from that of bulk materials. Considering that the performances of these films are sensitive to their thicknesses and optical constants, it is highly desirable to precisely characterize the thicknesses and the optical constants of such thin films for better applications.

In this work, a synergic analysis method based on ellipsometric parameters and reflectivity has been proposed, which enables the simultaneous determination of both the thickness and the optical constants for the metallic thin film. Both the ellipsometric parameters, including the amplitude ratio tan($\psi$) and the phase difference $\Delta$ between p- and s-components, as well as the reflectivity are acquired using one ellipsometer. The proposed method consists of a point-by-point synergic regression analysis on the reflectivity and the ellipsometric parameters as well as an oscillator-parametrization regression analysis on the ellipsometric parameters. The former analysis allows for the accurate determination of the thickness of metallic thin films, while the latter enables the acquisition of the optical constants. Both virtual and practical experiments of measuring a series of Cu thin films deposited on Si substrates have been sequentially carried out for demonstration. The results clearly show the coupling effect between the thickness and optical constants of these samples. And by comparing with the thicknessses reported by AFM and TEM, the validity and the accuracy of the proposed method have been verified. Further analysis on the optical constants of Cu thin films has been carried out using the oscillator-parametrization we proposed, in which the thickness dependency of the Drude term, the plasma energy and the relaxation time has also been analyzed.

# Author Index

## Bold page numbers indicate presenter