SPM applications for advanced semiconductor manufacturing

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Since the utilization of AFM technology at IBM in 1986, it has been used for profile measurement in semiconductor devices. The virtue of its high resolution of more than 1000 times over optical microscope prompts the technical consideration as in-line metrology. To this day, the main applications are the surface roughness and step measurement after film treatments as chemical mechanical polishing (CMP), film deposition, and etching process. However, the inherent slow speed of measurement limits the wide range of employment for in-line metrology. Nevertheless, 3D stacking technology is emerging as a solution of high density device, and requires the ultra-flatness and the film adhesion force measurement which highlights the merit of SPM technology. In this session, I would like to mention the possibility of SPM technology in FEOL, MEOL, and BEOL process and discuss the application requirements for the next generation devices.

Context microscopy and spectroscopy to advance semiconductor devices – conductive AFM linked to a wealth of other analytical techniques via nanoGPS technology

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The design complexity of electronic components and the heterogeneity of new materials constantly increase with decreasing device sizes even down to the nanometer scale. Engineering of novel devices will account for a high level of reliability, sustainability, and longevity as part of quality standards which have to be met. In the related device optimization endeavor the detection and classification of nanoscale material imperfections as well as scale bridging material and device properties will be success critical and require the use of complementing analytical methods.
Here, the true correlation of electron- ion-, optical- and x-ray microscopy and complementing spectroscopies (optical, mass) is constantly emerging including the use of atom probe techniques in this analytical context. To account for truly correlative analytics, the application of the nanoGPS technology is an enabler when rigorously be applied for the aforementioned analytical modalities.

We will demonstrate the use of the nanoGPS technology to correlate analytical and imaging modalities for selected examples of silicon based ASICs. The underlying preparative and consecutive analytical workflows will be demonstrated. In addition, we will show the application of machine learning strategies to aforementioned heterogeneous data to further improve efficient material and device optimization.

Enabling electrical scanning probe microscopy for investigating GaN-based heterostructures and devices

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GaN has emerged as a material of high importance for key future applications related to light emission and power conversion [1-2]. In the absence of suitable substrates, it is typically grown on mismatched substrates (Al2O3, SiC and Si), which consequently results in the formation of extended defects such as threading dislocations [3]. Depending on the substrate used, their density can lie within the range 108-109 cm-2 in the active layer. Even with the continuous improvement in the quality of GaN epitaxy and henceforth, the device performance, these defects are persistently present and there is a huge interest in understanding what their role is and how they impact devices of different types (e.g., vertical and lateral transistors for high power application). Despite several findings made using various methodologies [4-7], a clear insight on their electrical activity, in terms of their trap-like behavior, recombination behavior and conductivity, remains a puzzle. Besides, due to strong polarization in GaN and its alloys, some of the analysis techniques made on as grown surface (0001) are also prone to effects of polarization discontinuity at the surface.
In this context, we have investigated properties of threading dislocations at the nanoscale by combining several scanning probe microscopy (SPM) techniques with sensitivities to different aspects of the electrical properties including space charge, recombination, and surface potential. These techniques include scanning capacitance microscopy, cathodoluminescence and kelvin probe force microscopy. This study was carried out on GaN heterostructures and GaN p-n diodes. A one-to-one correlation was eventually identified between the structural property of dislocations (i.e., the type of dislocations) and their electrical property. Lastly, this study was extended to externally produced non-polar surfaces to overcome effect of polarization, which makes our analysis depth-resolved and far more reliable than conventional plane-view SPM-based characterization.

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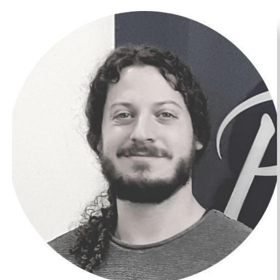

The "Swiss Army Knife" of microscopy: Atomic Force Microscopy as a versatile tool to image electronic and mechanic properties on a nanometer range

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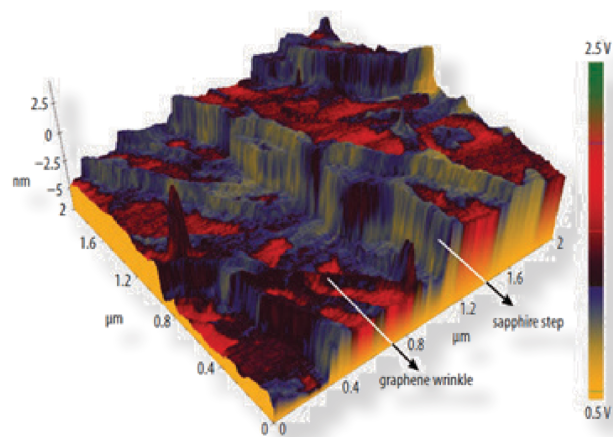
Present and future high-end devices require a combination of functional properties on progressively miniaturized structures. It becomes crucial being able to probe these properties, such as the local piezo-response of wearable electronics or the surface potential of 2D heterostructures, on the nanometer-sized architecture of microchips. Defects reduce or inhibit the performance of such devices. The detection of structural defects which go beyond mere, visible cracks calls for versatile methods that allow imaging diverse properties on a local scale. In this talk, we demonstrate the use of several state-of-the-art modes of the broad family of Atomic Force Microscopy (AFM) for such applications. Among them, Conductive AFM is a well-suited tool for analyzing electronic shunts, and we will present a study on the bias- and illumination-dependent current flow through silicon/perovskite tandem solar cells as an example. Moreover, it will be explained how Kelvin Probe Force Microscopy (KPFM) is a valuable tool e.g. to study local perturbances in the electronic structure of 2D materials, depending on topographic features on the underlying substrate. Lastly, we exhibit how Piezoelectric Force Microscopy (PFM) allows for both studying and manipulating the local domains in piezo-responsive materials like P(VDF-TrFE) films. All these electronic measurements can be combined with nanomechanical probing to investigate features like stiffness and adhesion on a nanometer range, emphasizing the versatility of AFM-based techniques to provide a comprehensive analytical toolbox.



Scanning Microwave Impedance Microscopy (sMIM) for FA and Characterization of Electronic Materials

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Failure analysis and Characterization of semiconductor devices has to keep pace with the ever-increasing complexity and decreasing feature size being introduced at each new node. We introduce here scanning Microwave Impedance Microscopy (sMIM), a technology that can measure critical material properties such as capacitance, resistivity and free carrier density all at the nanoscale [1], [2]. sMIM is a near field technique that uses an AFM cantilever as a microwave source to measure the electrical properties of materials at nanometer scale. Recent developments in this area have produced ultra-sensitive systems that can detect sub attofarad (<10^(-18) Farad) variations in the capacitance of films. An additional advantage of this technique is that it does not require an electrical path through the sample since it is the reflected microwave signal that provides the sample's electrical properties being measured. This further simplifies the setup but it also allows direct measurement of insulating films with no grounding needed. If the sample is non-linear, an AC bias can be applied between the tip and the sample to measure dC/dV and dR/dV. Therefore, sMIM can be applied to a wide variety of material systems ranging from insulators to doped semiconductors with a sub-10 nm spatial resolution. Since microwaves can penetrate into a sample, sMIM can image sub-surface layers as well. The penetration depth of this measurement can be as high as a few hundred nanometers, an example of this is shown in figure 1. Recently, the ability

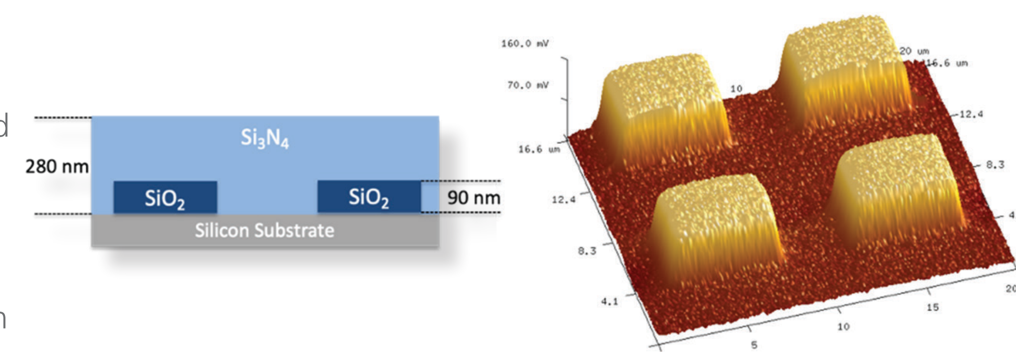

Figure 1. Subsurface imaging of dielectric films

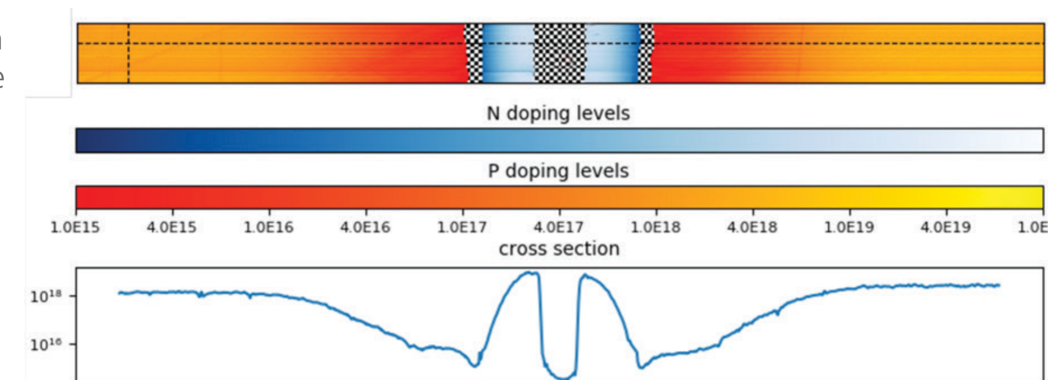

Figure 2. Carrier density distribution, polarity and depth profile of doped epitaxial films

to automatically quantify images of carrier concentration in silicon has been introduced to the market [3], [4]. Quantified carrier profiles can be easily created on cross sectional samples as shown in figure 2.
Types of measurements to be presented include C-V for dielectric quality/integrity, mapping of dopant concentration in silicon and image sensors. The application of sMIM in the FA of complex devices will also be covered.

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Identification of sub-20 nm EUV defects with Nano-IR PiFM

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With the advent of 45nm and below technology nodes and advanced processes such as atomic layer deposition and EUV lithography, the need to identify the chemical composition of defects and ultrathin films is of paramount importance. The defects and residues of concern range from 10 nm to 500 nm in size and monolayer in thickness, which the current batch of molecular analytical tools cannot address due to the lack of sensitivity and/or spatial resolution. A relatively new nanoscale technique called infrared photo-induced force microscopy (IR PiFM), which combines atomic force microscopy (AFM) and infrared (IR) spectroscopy with ~ 5 nm spatial resolution, is introduced. By utilizing a state-of-the-art tunable broadband IR laser (tunable from ~550 to > 4000 cm-1 with ~ 3 cm-1 spectral width over the entire range), truly nanoscale PiF-IR spectra that agree with bulk FTIR spectra can be acquired; PiF-IR spectra can be used to search the existing IR database to unambiguously identify the different chemical species (both organic and inorganic molecules) of sub-20 nm defects and monolayer residues via their IR signatures. PiFM images at fixed wavenumbers associated with the different chemical species provide chemical mapping in real space with ~ 5 nm spatial resolution, clearly illuminating multi-component defects and existence of residues. The talk will show how the nanoscale hyperspectral PiFM data can provide unambiguous and quick feedback to process engineers engaged in advanced semiconductor processes.

Keynote Talks Abstracts
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Lifetime Testing of Power Semiconductors – Electrical and thermo-mechanic evaluation

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Power semiconductors find themselves in a booming environment. However, their performance, reliability and lifetime play an important role for their contribution to sustainability. In the presentation, we will discuss typical reliability tests for power semiconductor modules used e.g. in automotive application and their special requirements compare to other microelectronics. "Macroscopic" Scanning acoustic microscopy and lock-in thermography play an important role to identify failures, as well as Focused-Ion-Beam (FIB) and SEM analysis for the "Microscopic" – also being used for material characterization and modelling.

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