# Electrical Scanning Probe Microscopes to Address Industrial Nano-Metrology Needs of Integrated Circuits and Nanoelectronic Devices

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***Abstract* — Electrical modes of scanning probe microscopes have found considerable metrology applications in integrated circuits and emerging nano-electronic devices. This paper will review the critical metrology needs that electrical SPMs have addressed in the integrated circuit industry and further applications for the characterization of nano-electronic devices. Solutions to metrology problems addressed by electrical SPM modes including the scanning capacitance microscope (SCM), scanning Kelvin force microscope (SKFM), scanning microwave microscope (SMM), scanning spreading resistance microscope (SSRM), conductive-AFM (c-AFM), and magnetic force microscopy (MFM) will be reviewed.**

***Index Terms* — Metrology, scanning probe microscopy, semiconductor device doping, semiconductor-insulator interfaces, semiconductor-metal interfaces, three-dimensional integrated circuits, III-V semiconductor materials, through silicon vias.**

## I. Introduction

Scanning probe microscopes have become a significant set of metrology tools for the integrated circuit industry. Variants of the atomic force microscope are commonly used for critical dimensional metrology, surface topography characterization, and trench and sidewall roughness metrology. Microscopes based on the AFM and sensitive to various electrical properties have also found many metrology applications. While the scanning tunneling microscope can probe the density of states of semiconductors with atomic resolution, the electrical modes of AFM often have considerably poorer spatial resolution. Measurements that depend on capacitive coupling of the probe to the surface under examination will have spatial resolution governed by the electrical field's inverse square dependence with distance. In practice this means that not only does the terminal tip contribute to the signal, but also the tip sidewall, the cantilever, and any unshielded part of the tip electrode. [Contact modes such as scanning spreading resistance microscope (SSRM) and the conductive AFM (c-AFM) have spatial resolution related to the physical tip contact area.] Sophisticated data acquisition techniques and high aspect ratio tips or coaxial tips have been developed to improve the spatial resolution of electrical AFM modes. While the inverse square dependence of electrical field can reduce spatial resolution, it can also be employed to produce three-dimensional or subsurface images.

Highly utilized electrical modes include the scanning capacitance microscope (SCM), scanning Kelvin force microscope (SKFM), scanning microwave microscope (SMM), scanning spreading resistance microscope (SSRM), conductive-AFM (c-AFM), also known as tunneling AFM (TUNA[1]), magnetic force microscopy (MFM), scanning SQUID microscopy, and scanning giant magneto-resistance (GMR). Several of these techniques can be extended through optical pumping which allows the generation and recombination dynamics of photo-generated charge carriers to be studied. These microscopes have found applications to some critical metrology problems for the integrated circuit industry and to emerging nano-electronic devices.

## II. SCM and SSRM for Dopant Profiling

The quantitative measurement of the two-dimensional dopant profiles of the source-drain regions of MOSFETs with ultra-shallow junctions was an early metrology goal and driver for the development of SCM. SCM uses a capacitance sensor connected to the tip to measure the differential capacitance between the tip and sample [1]. For a semiconductor sample, a small ac voltage is used to modulate the depletion layer in the semiconductor beneath the tip. Since quantitative information is required, considerable effort was spent on developing software tools to relate the measured dC/dV signal to local dopant concentration. The SMM can also be operated in a dC/dV mode, providing essential the same information as the SCM [2]. The required accuracy and spatial resolution of dopant profiles of state-of-the-art transistors is running away from the capabilities of SCM, but applications to devices with larger dimensions, such as SiC power devices and as a failure analysis tool for detecting the existence (or lack) of doped regions remain.

SSRM uses a diamond coated tip making high pressure contact to silicon and a logarithmic current amplifier to measure the tip to sample spreading resistance over many

[1]Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the materials or equipment used are necessarily the best available for the purpose.

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orders of magnitude [3]. SSRM has been applied to image extremely abrupt dopant profiles in FINFETs and other nanoelectronic devices.

## III. SCANNING KELVIN FORCE MICROSOCPY FOR WORK FUNCTION IMAGING

SKFM is an AFM based technique which uses an applied ac potential to induce oscillations of the cantilevered tip through capacitive forces [4]. A feedback loop is employed to null the oscillations and thereby provide a measure of tip-to-sample contact potential difference. If the work function of the tip is known, the work function or surface potential of the surface under examination can be deduced. Various SKFM data acquisition modes exist, including double pass amplitude modulation, single pass AM, and frequency modulation. Numerous applications to nanoelectronics exist including identification of the work function of different grains in a metal film and differentiating single, double, and multiple layer graphene.

## IV. CONDUCTIVE ATOMIC FORCE MICRSOCOPY FOR DEFECT CHARACTERIZATION

Conductive AFM measures the current at a constant voltage of the contact between the tip and sample in parallel with an AFM measurement of surface topography. C-AFM is similar to SSRM, though it is tuned to a narrower range of sample conductivity. Tunneling AFM (or TUNA) is a C-AFM technique from Bruker Corp. optimized to lower current densities for characterizing tunneling through thin dielectric films. C-AFM can also be used to measure the current-voltage characteristics of the tip-to-sample contact at a single tip location. The measured current can be a strong function of contact pressure, surface condition and tip size. C-AFM has been employed to locate defects in insulating layers, filament formation in memresistor memories, and defects in III-V layers grown on silicon substrates.

## V. SCANNING MICROWAVE MICRSOSCOPY FOR SUBSURFACE IMAGING

A new implementation of scanning microwave microscopy (SMM) has recently been introduced by Agilent. SMM measures the magnitude and phase of the S11 reflected high frequency signal (incident signal minus signal transmitted through the tip into the sample) through use of a vector network analyzer. Shielding and coupling of the tip to the sample is essential to functional SMM. The input to the VNA is a transmission line terminated by the tip-to-sample impedance. With additional electronics the SMM can also measure the dC/dV signal between the tip and sample, allowing it to function in SCM mode for semiconductor dopant profiling.

Two distinct sub surface imaging modes with applications to integrated circuit metrology should be possible with SMM. Through the capacitive coupling of the tip to conductive structures in an insulating matrix it should be possible to measure the dimensions and integrity of metallization within low-k dielectrics for back end of the line (BEOL) metrology. A second distinct subsurface imaging mechanism utilizes the skin depth as a function of frequency. Here images are acquired at different frequencies, with the primary component of the signal arising from a depth within the sample determined by the skin depth at that frequency. This imaging technique may be useful to characterize defects and voids within (metallic) through silicon vias (TSVs).

## V. FAILURE ANALYSIS WITH ELECTROMAGNETIC MODES

A significant metrology application for SPM is the detection of opens and shorts within BEOL metallization. The magnetic fields of current carrying conductors have been detected via magnetic force microscopy (MFM), scanning SQUID microscopy (SSM), and scanning giant Magneto-resistance (GMR). MFM has been used for magnetic characterization of nanomaterials as well as detecting the magnetic field from buried current carrying conductors [5]. SSM has been used to localize open defects in interconnects by imaging the RF magnetic field produced by feeding the defective part with an RF probing current, under the name Space Domain Reflectometry [6]. SKFM can image the potential of sub-surface metallization, potentially also providing open fault detection.

## VI. CONCLUSION

SPMs have found multiple and significant applications to the metrology of semiconductors, integrated circuits and nano-electronic devices. Significant improvements in performance and in number of applications can be expected in the future.

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