

## Introduction

**Scanning Microwave Impedance Microscopy (sMIM)** enables high resolution electrical characterization with Asylum Research **MFP-3D™** and **Cypher S™** atomic force microscopes (AFMs). sMIM distinguishes between changes in capacitance and resistance, allowing it to operate on a wide range of linear and non-linear materials including conductors, semiconductors, and insulators. sMIM provides higher lateral resolution (<50 nm) and superior signal-to-noise (>10X) while operating up to 80X faster and at lower power compared to competing technologies. sMIM is based on proprietary shielded AFM probes and electronics developed by PrimeNano, Inc. and is available integrated exclusively with Asylum AFMs.

## sMIM Technology and Capabilities

sMIM is a near-field technique that uses a microwave source coupled to a proprietary shielded AFM probe. As the tip scans the sample, local sample variations in permittivity ( $\epsilon$ ) and conductivity ( $\sigma$ ) affect the reflected microwaves. This is analyzed, distinguishing between changes in the measured capacitance (C) and resistance (R). A modulated bias can be applied to the sample to also measure the amplitude and phase of the dC/dV and dR/dV response.

On semiconductor materials, the dC/dV signal is highly sensitive to doping, with the phase indicating dopant type and the amplitude proportional to dopant concentration. On thin films, the sMIM capacitance can be related to the film thickness and dielectric constant. More generally, sMIM is useful on a wide range of nanomaterials where variations in permittivity and conductivity might help distinguish materials that show no contrast in topography.

### Common applications

- Semiconductors
- Dopant profiling
- Failure analysis
- Thin films
- Ferroelectrics
- Buried charge
- Graphene
- Carbon nanotubes



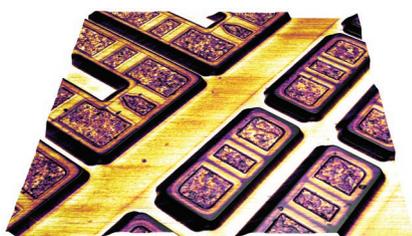
Topography



dC/dV Amplitude



dR/dV Amplitude



DC Capacitance



dC/dV Phase



dR/dV Phase

sMIM images of an SRAM sample (20  $\mu\text{m}$  scan size, ~400 nm tall features). These images demonstrate the variety of data types that sMIM can measure. DC Resistance can also be measured, but is not present in this data set. Note that although semiconductor samples like this one are a very common application area for sMIM, the technique is far more general and can be applied to most samples to help distinguish between different materials.

# Dramatically higher performance

## Higher sensitivity

sMIM delivers at least 10X higher signal-to-noise compared to scanning capacitance microscopy (SCM) and scanning microwave microscopy (SMM). When used for dopant profiling, this sensitivity enables differentiation of dopant concentrations  $<10^{14}$  atoms/cm<sup>3</sup>. For DC capacitance measurements, sMIM has demonstrated a  $<0.5$  aF noise floor.

## Higher lateral resolution

sMIM routinely achieves  $<50$  nm lateral resolution and has demonstrated  $<30$  nm, all under ambient conditions. sMIM uses proprietary shielded probes with solid metal tips for consistent high resolution results. Note that resolution is only a measure of the ability to resolve adjacent features and is not a limit on the smallest detectable feature, which can be much smaller.

## Faster imaging

sMIM has a much higher intrinsic bandwidth than competing techniques that require substantial averaging to achieve acceptable signal-to-noise, resulting in slow line scan rates ( $<1$  Hz). sMIM on the Asylum Cypher S routinely demonstrates high quality data at line scan rates  $>40$  Hz.

## Lower power

With optimized electronics and shielded probes, sMIM provides high sensitivity at low microwave source powers. It also measures the dC/dV response with low tip-sample modulation voltages, limiting the perturbation of the sample.

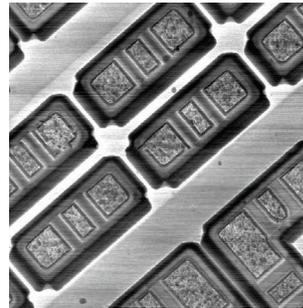
## Simplified data interpretation

SCM and SMM are highly susceptible to crosstalk due to topography. Proprietary sMIM shielded probes dramatically reduce these artifacts, simplifying data interpretation.

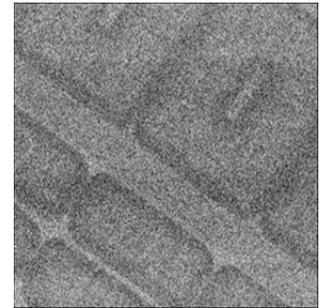
## Simple operation

sMIM requires minimal sample preparation and very few parameter adjustments. Though clean, polished samples will produce the best data, sMIM is far more forgiving than SCM. Parameter adjustments are few and very simple, not like the highly sensitive and complex SCM optimization. The hardware setup is also very straightforward, unlike the myriad of settings present on the network analyzers used with SMM.

sMIM

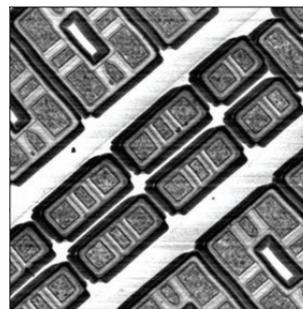


SMM

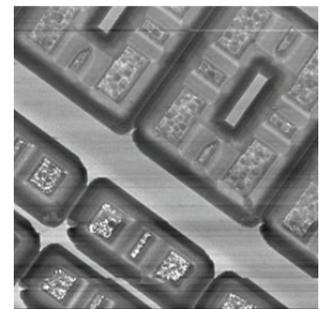


*Under equivalent conditions (1 Hz line scan rate, -15 dBm source power), the signal-to-noise of sMIM images is dramatically better than SMM.*

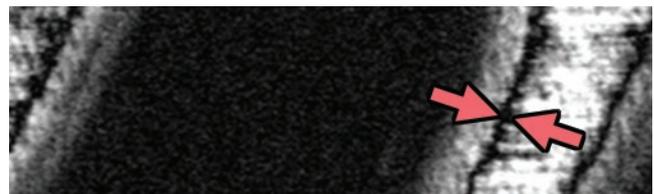
sMIM



SMM

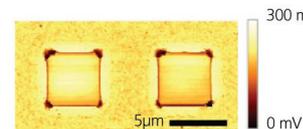


*Even scanning 80X faster (20 Hz vs. 0.25 Hz line scan rates) and at 1000X lower source power (-15 dBm vs. 15 dBm), the signal-to-noise of sMIM images is still much better than SMM.*

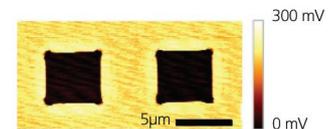


*Here, sMIM demonstrates a feature in the SRAM sample that measures 30.5 nm in width.*

Shielded Probe



Unshielded Probe



*Capacitance images of an etched silicon sample with 40 nm high square pillars. The entire sample is silicon, so the capacitance on top of the pillars should be the same as the surrounding area. Using a shielded probe this is what we observe, with only small artifacts at the step edges. Using an unshielded probe, however, we see a very large capacitance difference between the top of the pillars and the surrounding lower level. Exclusive PrimeNano shielded sMIM probes localize the capacitance measurement to the tip compared to unshielded probes where the entire cantilever contributes to the measurement.*

# New, unique capabilities

## Compatible with most sample types

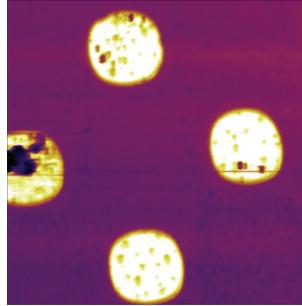
sMIM operates on almost any material, including conductors, semiconductors, and insulators. It does not require an oxide layer. SCM is limited to non-linear semiconductor materials.

## Measure C and R simultaneously

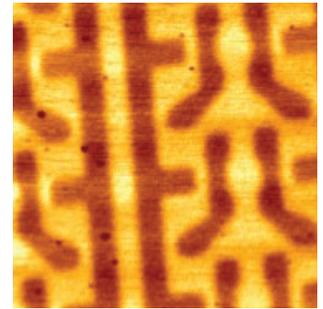
sMIM can measure both capacitance and resistance simultaneously. There's no need to switch modes or probe holders and try to find the same area of the sample. This additional information assists in understanding complex microelectronic structures.

## Detect buried structures

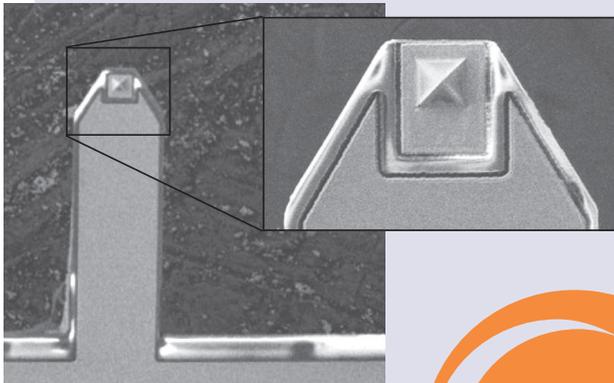
sMIM is sensitive to sub-surface features, readily imaging detailed sample features even under insulating or dielectric films >100 nm thick.



DC capacitance image of oxidized Al dots on a SiO<sub>2</sub> substrate, 15 μm scan.



SiO<sub>2</sub> pattern on Si imaged under a 100 nm Al<sub>2</sub>O<sub>3</sub> film, 5 μm scan.



## Exclusive technology enables superior sMIM performance

### Shielded probes

PrimeNano's patented sMIM probes are fully shielded all the way to the tip to improve sensitivity and resolution and reduce topography crosstalk. The tips are solid metal, eliminating inconsistent results that occur due to wear of metal-coated tips.

### Optimized electronics

PrimeNano's sMIM electronics have been designed to do exactly one thing very well – sMIM. They were purpose-built for this application and the impedance carefully matched to optimize performance at 3 GHz. General purpose network analyzers are not optimized for scanning microwave measurements.

### Asylum Research AFMs

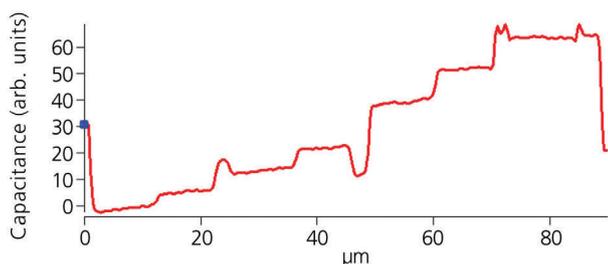
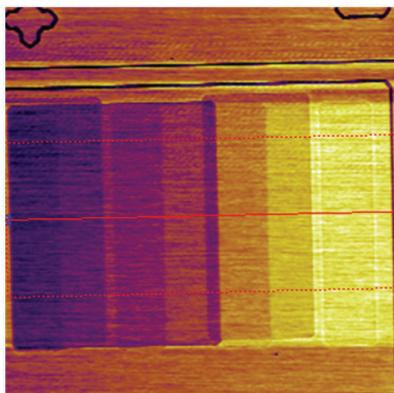
Asylum Research, the technology leader in AFM, builds the world's highest performance AFMs. sMIM benefits from numerous features, including sample scanning, low-noise lock-in amplifiers, low-noise / high resolution scanners, and the fast scanning capability of the Cypher S AFM.

PrimeNano  
ScanWave™ sMIM  
Technology



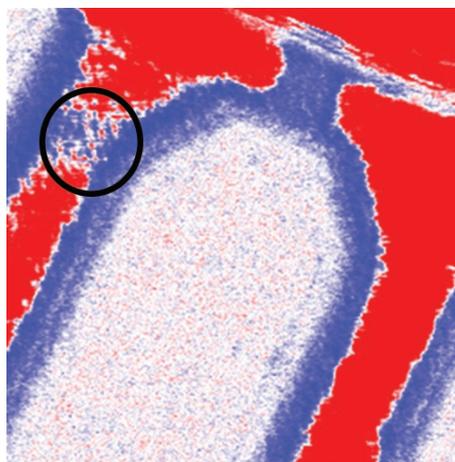
## Dopant profiling

sMIM enables high sensitivity dopant profiling in the range of  $10^{14}$  to  $10^{20}$  atoms/cm<sup>3</sup>. Below, the DC capacitance image of a dopant staircase sample demonstrates sensitivity better than  $0.5 \times 10^{15}$  atoms/cm<sup>3</sup>.



## Failure analysis

sMIM is a powerful tool for semiconductor failure analysis. The ability to image all materials in the device, including metals and dielectrics, provides a more complete view and assists in navigating to the region of interest. The high sensitivity of sMIM gives it the potential to find challenging defects. Below, an apparent defect was found in an SRAM device, an unexpected dopant variation revealed in the phase channel of the dC/dV measurement.



dC/dV phase image of an SRAM device. The region circled shows a possible failure, 2.5 μm scan.

## Specifications

**Compatibility:** sMIM is available integrated exclusively with the Asylum Research MFP-3D and Cypher S AFMs

**Measurement capabilities:** DC capacitance, DC resistance, dC/dV (amplitude and phase), dR/dV (amplitude and phase)

**Microwave source:** 3 GHz at -45 to -15 dBm power

**Lateral resolution:** <50 nm typical, <30 nm has been demonstrated

**Noise floor (capacitance):** 0.5 aF

**Dynamic range (dopant level):**  $10^{14}$  to  $10^{20}$  atoms/cm<sup>3</sup>

**Probes:** Fully shielded, hardened solid metal tip probes (patented)

Visit [www.AsylumResearch.com](http://www.AsylumResearch.com) for more information

The foregoing datasheet is copyrighted by Oxford Instruments Asylum Research, Inc. Oxford Instruments Asylum Research, Inc. does not intend the datasheet or any part thereof to form part of any order or contract or regarded as a representation relating to the products or service concerned, but it may, with acknowledgement to Oxford Instruments Asylum Research, Inc., be used, applied or reproduced for any purpose. Oxford Instruments Asylum Research, Inc. reserves the right to alter, without notice the specification, design or conditions of supply of any product or service. Application Note 31 – 6/2014.

6310 Hollister Avenue  
Santa Barbara, CA 93117  
Voice +1 (805) 696-6466  
Toll free +1 (888) 472-2795  
Fax +1 (805) 696-6444

[www.AsylumResearch.com](http://www.AsylumResearch.com)  
[info@AsylumResearch.com](mailto:info@AsylumResearch.com)  
[sales@AsylumResearch.com](mailto:sales@AsylumResearch.com)



The Business of Science®