Overcoming the challenges of the Micro and nano scale materials and devices characterization and measurement.

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**Metrology & Surface Analysis**

- AFM / STM (Agilent Technologies)
- Profilers (KLA-Tencor)
- Interferometer (IDE-KLA / Sensofar)
- SNOM/AFM/Raman (Nanonics)
- Nano-Indenter (MTS - Agilent)
Show Room

Dark Room
Richard Feynman

“There is Plenty of Room at the Bottom”

The Scale of Things – Nanometers and More

Things Natural
- Ant ~ 5 mm
- Human hair ~ 60-120 μm wide
- Red blood cell ~ 2-5 μm
- Duct mile ~ 200 μm
- ATP synthase ~ 10 nm diameter
- DNA ~ 2.12 nm diameter
- Atom of silicon spacing ~ tenths of nm

Things Manmade
- Head of a pin 1-2 mm
- Microelectromechanical (MEMS) device 10-100 μm wide
- Pollen grain
- Red blood cell
- Zone plate array “lens” outer ring spacing ~ 50 nm
- Self-assembled, nature-inspired structure many 10s of nm
- Nanotube electrode ~ 10 nm diameter
- Carbon nanotube ~ 1.3 nm diameter
- Quantum dot on a silicon surface positioned in a 5 nm gap with an STM tip, canal diameter 14 nm

The Challenge
- Fabrication and growth of nanoscale devices, e.g., synthesizing carbon nanotubes with internal semiconductor doping.
Outline

• STM
• Contact AFM
• Non Contact AFM
• Phase Measurements
• Vector Network Analyzer (VNA)
• VNA and AFM coupling
  – Technical Solutions
  – Results
• Next generation
History

• STM (*Scanning Tunneling Microscope*)
  • Developed in 1981 by Gerd Binnig et Heinrich Rohrer (Nobel Price in 1986)

– And then Contact AFM, SNOM, Non Contact AFM, MFM, EFM...
Scanning Probe Microscope
Basic Principles

Tip/Probe/Cantilever – Responds to a particular surface property as it is scanned over the surface.

Feedback – Z position controlled to keep particular property constant.

STM – Current
AFM - Deflection
AC Mode – Amplitude

Applications limited mostly by experimenter’s imagination.
Basic Principles - STM

Measures Tunneling Current
- Exponentially relation between separation and current.
- At low bias the image reflects the local electronic structure of the sample surface.

Imaging Modes
- Constant Height
- Constant Current

Spectroscopy
- I/V, I/S
Basic Principles - AFM

- Tip motion is monitored by the laser spot reflected into the photo detector.

- Topography signal derived from voltage applied to piezo to keep tip deflection constant times piezo sensitivity parameter.

- Contact mode force (≈0.1 to 1000nN) controlled by cantilever stiffness and deflection.
Schematic - Feedback Loop

\[ V_z(t) = P \times e(t) + I \int e(t) dt \]

**Photo-diode**

**Hybrid Servo**

**ADC In**

**ADC Topo**

**DAC Out**

Deflection (AFM)

Amplitude (AC Mode)

Setpoint

Servo Gain Settings (Software)
Contact Mode

• Advantages
  – Easy set up
  – Fast imaging
  – Friction signal
  – Force vs. distance measurements

• Disadvantages
  – Lower resolution
  – Possible tip and/or sample damage

• Mode choice usually dictated by sample.
Current Sensing AFM (CSAFM™)

**Principle:**

- A bias is applied to the sample; current flows through the conducting cantilever to preamp.

- Allows simultaneous probing of conductivity and topography.

- Preamplifiers with different sensitivities are available:
  - 10 nA/V (noise ≈ 30 pA rms)
  - 1.0 nA/V (noise ≈ 3 pA rms)
AC Methods - Acoustic Drive (AAC)

- A piezoelectric transducer shakes the cantilever holder at or near the resonant frequency of the cantilever (100 - 400 kHz typically).

- Interaction with the sample reduces the oscillation amplitude. This reduced amplitude is used as the feedback signal.
The cantilever is coated on the top side with a proprietary magnetic film.

A solenoid applies an oscillating magnetic field which is used to vibrate the cantilever.

Since only the cantilever is oscillating, fewer resonances are excited.
Advantages of AC modes

- Soft surfaces stiffened by viscoelastic response
- Impact predominantly vertical
- Pull-off from sticky (contaminated) surfaces
- Instrumental advantage (1/f noise)
Higher Resolution

- Gentler contact preserves asperities - same tip gives better resolution
- Functionalized tips survive
- More control of interactions

Plasmid DNA in water. (a) MAC (b) Contact - same tip
Polymers

Phase imaging

• Topography / Phase

Topography

Phase Measurement
Magnetic Fields

1st scan (Topography)

2nd scan (Magnetic field Measurement)

30 µm scan – MFM measurement - Hard disk
Electric Fields

1st scan (Topography)

2nd scan (Electric field Measurement)

2 µm scan – EFM measurement - Squares made by electric charge deposition on SiO2, only revealed by EFM
Electric Field Measurements (EFM)

EFM measurement on active circuit
Nanoscale Electronic Devices Characterization

All MW measurement system have 50 Ohms characteristic impedance.

Classical nano devices impedances can conveniently be expressed as multiples of the resistance quantum,

\[ R_0 \equiv \frac{h}{2e^2} = 12.96k\Omega. \]
Traditional SCM

- Scanning only
- Qualitative
- Poor sensitivity
- Limited $10^{15}-10^{20}$ Atoms/cm$^3$
- No Conductors/Insulators

$dV$

$dC$

VCO

Detector
Network Analyzer Basics
What is a Vector Network Analyzer?

Vector network analyzers (VNAs)...

- Are stimulus-response test systems
- Characterize forward and reverse reflection and transmission responses (S-parameters) of RF and microwave components
- Quantify linear magnitude and phase
- Are very fast for swept measurements
- Provide the highest level of measurement accuracy
Lightwave Analogy to RF Energy

- Incident
- Reflected
- Transmitted
- Lightwave
- DUT
- RF
Transmission Line Terminated with Zo

$Z_s = Z_o$

$Z_o = \text{characteristic impedance of transmission line}$

$V_{\text{inc}} \rightarrow \text{wave}$

$V_{\text{refl}} = 0! \text{ (all the incident power is absorbed in the load)}$

For reflection, a transmission line terminated in Zo behaves like an infinitely long transmission line.
For reflection, a transmission line terminated in a short or open reflects all power back to source.
Transmission Line Terminated with 25 Ω

Zs = Zo

V_{inc} \rightarrow \bigcirc \rightarrow V_{refl}

Standing wave pattern does not go to zero as with short or open
High-Frequency Device Characterization

**REFLECTION**

\[
\begin{align*}
\text{Incident:} & \quad R \\
\text{Reflected:} & \quad A \quad \text{with} \quad A = R \\
\text{SWR} & \quad \text{S-Parameters} \quad S_{11}, S_{22} \\
\text{Reflection Coefficient} & \quad \Gamma, \rho \\
\text{Impedance, Admittance} & \quad R+jX, G+jB \\
\text{Return Loss} & \\
\end{align*}
\]

**TRANSMISSION**

\[
\begin{align*}
\text{Incident:} & \quad R \\
\text{Transmitted:} & \quad B \\
\text{Gain / Loss} & \quad \text{S-Parameters} \quad S_{21}, S_{12} \\
\text{Impedance, Admittance} & \quad R+jX, G+jB \\
\text{Transmission Coefficient} & \quad T, \tau \\
\text{Group Delay} & \\
\text{Insertion Phase} & \\
\end{align*}
\]
Standard Vector Network Analyzer as a reflectometer

$$s_{11} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Figure 1: reflection coefficient vs. impedance

- Highly resistive load: High SNR, Low Resolution
- Low resistive load: High SNR, Low Resolution
- Load close to 50 Ohms: Low SNR, High Resolution
Fully Automated Proposal

- System drift correction via ECAL
- Phase shifting and Attenuation are done through DSP
- Low IF frequency, and High speed ADC are chosen to minimize the computational round off error in DSP.
How do we measure small things?

- SMM is a near field system. The resolution is determined by the Electric field interaction area with the sample. This is on the order of 5-10 nm
- SMM uses a network analyzer to measure the vector reflection coefficient caused by the tip-sample interaction; this gives information about the material properties (dielectric properties)
- While an AFM needs “contact” to make a measurement the SMM can measure without contact. You can be 1-10 nm away from the sample and still have good sensitivity
Electromechanical coupling
Balanced Pendulum: How Does It Work

- Laser tracking spot remains fixed relative to Z-piezo & AFM cantilever
- Z-piezo does not bend

Tube Design
Pendulum Design

deformation stress

Y scan
Early Design Suffers from Abrupt Localized Bend of

Scanner head
With Conductive Tip

Load Diplexer
RF to PNA
Coax from the Tip to diplexer
**Distribution of Electromechanical Coupling Through Coaxial Loop**

- Conductive Tip
- Diplexer 50 Ohm CKT
- Looped cable
- Extraction tool
- Conductive Tip
- Looped cable
- Half-Wavelength Cable

**Diffusion of electrical/mechanical coupling with integration of enhanced VNA and Precision Machining**
How to Interpret the Measurement Tip and cantilever impedance

C (measured Cap)= C1 II (C2 in series C3)
C1 nominal=3.18 fF with 100 nm change gives 3.18 af change in capacitance.
C2 nominal=5.3 aF and tip capacitance of 2 nm dielectric over a conductor.
The tip over a silicon substrate has .53 aF effective capacitance.
How to Interpret the Measurement Tip and Cantileverer
DPMM approach:

Use the Flatband transfer function that is function of dopant density (variable capacitor) that can be used as an AM mixer to modulate the reflected MW signal at the rate of Flatband drive frequency (<100 KHz). The said AM modulation index is function of the dopant density.
IMEC p-type after CO2 snowjet cleaning RH~23.5% T~71.4 F
Beautiful SMM channels
Life Science Examples

AFM
Cell
SMM

AFM
Virus
SMM
Topography (A), dopant concentration (B), and capacitance (C) images of the 0.25 um polished SRAM sample. In the dopant image (B), bright color represents n-type carriers, and dark color is p-type. Alternating lightly doped p and n wells are clearly resolved. Looking at the connection areas between the labeled transistors and their neighbor n wells, as marked by the rectangles, it is very noticeable that the dark (p) carriers seen in the connection areas of all good transistors (blue marked) does not appear for the 48th transistor (red rectangle). In stead, the area is fully filled with bright (n) carriers, indicating a short between that transistor and its neighbor n well. In the capacitance image (C), some difference of that transistor area (red) from other good (blue) ones is also visible. The topography image (A) does not show any difference. (W. Han, 7/10/2008, for Freescale)
Available SPM-based techniques to probe materials electric properties:

- Scanning near-field microwave microscopy (SNMM)
- Scanning capacitance microscopy (SCM)
- Scanning spreading resistance microscopy (SSRM)
- Electrostatic force microscopy (EFM)
- Current-sensing (or conductive) AFM (CSAFM)
- Kelvin force microscopy (KFM)
- More …

Nanoscale Materials Electronic Measurements

Vector network analyzer + AFM
Scanning Microwave Microscopy (SMM)

Absolute measurements for:

impedance
capacitance
dopant density
more …
Merci