Expanding Impedance Measurement to Nanoscale:

Coupling the Power of Scanning Probe Microscopy with Performance Network Analyzer (PNA)

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Outline

• SCM Basics.
• Microwave Network Analyzer Basics (VNA).
• Challenges of VNA as a SMM measurement engine.
• Addressing the measurement challenge.
• Electromechanical coupling challenge and solution
• Mechanical design.
• DPMM (Dopant Profile Measurement Module)
• System overview.
• Some interesting images.
Traditional SCM

- Scanning only
- qualitative
- poor sensitivity
- limited $10^{15}-10^{20}$ Atoms/cm$^3$
- No Conductors/Insulators
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 → Lightwave → Reflected

Transmitted

DUT → RF
Transmission Line Terminated with Zo

Zs = Zo

Zo = characteristic impedance of transmission line

V_{inc} \rightarrow \text{V} \rightarrow \text{V} \rightarrow \text{V} \leftarrow \text{V}

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

For reflection, a transmission line terminated in Zo behaves like an infinitely long transmission line
Transmission Line Terminated with Short, Open

For reflection, a transmission line terminated in a short or open reflects all power back to source.

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$Z_s = Z_0$

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In-phase (0°) for open, out-of-phase (180°) for short

\[ V_{inc} \rightarrow V_{refl} \]
Transmission Line Terminated with 25 Ω

$Z_s = Z_o$

$Z_L = 25 \Omega$

$V_{inc} \rightarrow$ 

$V_{refl}$

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

**REFLECTION**

\[
\frac{\text{Reflected}}{\text{Incident}} = \frac{A}{R}
\]

- SWR
- S-Parameters \( S_{11}, S_{22} \)
- Reflection Coefficient \( \Gamma, \rho \)
- Return Loss
- Impedance
- Gain / Loss

**TRANSMISSION**

\[
\frac{\text{Transmitted}}{\text{Incident}} = \frac{B}{R}
\]

- Transmission Coefficient \( T, \tau \)
- Insertion Delay
- Group Delay
- S-Parameters \( S_{21}, S_{12} \)
Standard Vector Network Analyzer as a reflectometer

\[
S_{11} = \frac{Z_L - Z_0}{Z_L + Z_0}
\]

Figure 1: reflection coefficient vs. impedance

Low resistive load
High SNR
Low Resolution

Highly resistive load
High SNR
Low Resolution

Load close to 50 Ohms
Low SNR
High Resolution

Very small capacitor
High SNR
Low Resolution

Source

A/D

A

LO

A/D

B

LO

Probe
Proposed solutions

Cancellation (Nulling) of the reflected wave can be done either in the RF front end or the IF stage:

**RF techniques:** 1) Balun and amp 2) Differential Amp
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.
Simplified Single Frequency Solution

Source

A

LO

B

LO

A/D

Half wave length
Coaxial resonator

50 Ohm

Probe

freq = S(1,1) = 0.001 / -90.076

1.910GHz

impedance = Z0 * (1.000 - j0.003)

-40

-20

0

-40

-60

freq (500.0MHz to 3.000GHz)

m1 freq = 1.910GHz

S(1,1) = 0.001 / -90.076

impedance = 20 * (1.000 - j0.003)

m2 freq = 1.910GHz

dB(S(1,1)) = -57.550

dB(S(1,1)) vs freq, GHz
Electromechanical coupling
Balanced Pendulum: How Does It Work

- Laser tracking spot remains fixed relative to Z-piezo & AFM cantilever
- Z-piezo does not bend
Early Design Suffers from Abrupt Localized Bend of Coax Connecting TIP to Diplexer

Load Diplexer

RF to PNA

Coax from the Tip to diplexer

Scanner head With Conductive Tip
Distribution of Electromechanical Coupling Through Coaxial Loop

Diffusion of electrical/mechanical coupling with integration of enhanced VNA and Precision Machining
Speedy Conductive Tip Replacement

- Pt/Rb Cantilever
- Alumina Carrier
- RF Connection
- Conductive Tip
- Magnetic Jaw
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.
DPMM Block Diagram/Physical Realization
DPMM Internal Structure and as an add on Module to PNA

DPMM Internal MIC detail

DPMM as an add measurement module to PNA
### System Overview

- **Photodetector**
- **Coaxial cable**
- **Coaxial Resonator**
- **Sample**
- **Network Analyzer**
- **Ground/Shield**

Sample scanning AFM in X and Y and Z (closed loop)

- Network analyzer sends an incident RF signal to the tip through the diplexer.
- RF signal is reflected from the tip and measured by the Analyzer.
- The magnitude and the phase of the ratio between the incident and reflected are calculated.
- Apply a model to calculate the electrical properties.
- AFM scans.
- AFM moves tip to specific locations to do point probing.
SRAM Image

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)
Review: SCM 2D Dopant Profiling

MOS capacitor

1D MOS High Frequency C-V Curve
Relation between capacitance / dopant concentration

\( \Delta C \) dependence on dopant density

- Scanning only
- qualitative
- poor sensitivity
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SCM System diagram - (\( \Delta C \)) mode.

- Capacitance Sensor
- Pre-amp
- AFM
- Lock-in amplifier
- Controller/Computer

Sample Voltage (V)

Capacitance (F)