Failure Analysis of Semiconductors using Scanning Probe Microscopy (SPM)

Peter De Wolf Ph.D.
Veeco Metrology, Europe
dewolf@veeco.fr
Tutorial ESREF, Oct. 4, 2004

Purpose

- Help you understand why one should use an AFM for Failure Analysis
- Understand the function and application of all specific SPM-based FA techniques
- Specific Examples of Fault Isolation and Root Cause Analysis with AFM
- Convince you that AFM is the future of Nanoscale FA
Outline

• What is an AFM / SPM
• FA modes based on oscillating probe imaging
  – Electric fields, magnetic fields, surface potentials
• FA modes based on contact mode imaging
  – Resistance, capacitance, carrier profiling, thermal imaging,…
• Atomic Force Probing: extending probing to the nanoscale
  – Multiple probe setups

What is an AFM?

Three things common to all SPM’s:

• Sharp Probes
• Nano Positioning
• Force Feedback
**Force Feedback vs Deflection**

- AFM Retracts Z Piezo so that F is Constant
- Profiler drags tip over feature while measuring deflection. Deflection results in higher force at the top than the bottom: \( \Delta F = k \Delta z \)
- AFM probe can be oscillating or in contact, profiler always in contact

![Diagram showing force feedback vs deflection](image)

**Routine SPM applications for semiconductors**

- micro-structure of epi Si
- 0.3\(\mu\)m W plug after CMP showing recess.
- sub-0.1\(\mu\)m defect imaging
- Nano-lithography by anodic oxidation
- measurement of depth, width and sidewall angle
- 2D dopant profile of cross-sectioned leaky device
Tapping Mode Imaging example on epi Si

Zoom from 1 to 2µm scan size

Some useful FA SPM techniques

- **Based on Tapping mode**
  - Electric & Magnetic Field Microscopy (EFM, MFM)
  - Kelvin Probe Force Microscopy (KPM)
  - NSOM
- **Based on Contact mode**
  - Scanning Spreading Resistance Microscopy (SSRM)
  - Scanning Capacitance Microscopy (SCM)
  - Tunneling – AFM (TUNA)
  - Conductive – AFM (C-AFM)
  - 4-point-probe (4PP)
  - Scanning Thermal Microscopy (SThM)
- **Multiple probe techniques**
Part 1: Tapping-mode based methods

**Electric & Magnetic Force Microscopy**

**EFM:** Imaging of electric fields  
**MFM:** Imaging of magnetic domains & polarization

**Patented LiftMode:**  
- Separates topography from the electric/magnetic info  
- during liftmode, the oscillation amplitude, phase and/or frequency are measured
**EFM on Saturated Transistor**

- Main application: imaging of electric fields & potential distributions (for example: surface charges)
- Relative poor for dopant profiling

**Modified EFM**

- Tip scans above surface (liftmode or non-contact)
- AC+DC voltage between tip and sample $\rightarrow$ Force

\[ F_e = \frac{1}{2} \frac{dC}{dm} \left( V_{ac}^2 + 2V_{ac} V_{ac} \cos \omega t + \frac{1}{2} V_{ac}^2 (1 + \cos 2\omega t) \right) \]

- influenced by oxide thickness or surface charges
- $dC/dm$ is measured, not $dC/dV$
MFM example

MFM Image of magnetoresistive (MR) sensor

no magnetic bias

with bias 15 µm

Kelvin Probe Force Microscopy (KPM)

- Also called Surface Potential Microscopy
- When in liftmode a DC bias applied to the probe is matched to the surface potential thus minimizing the force on the probe
- Surface Potential is measured
Part 2: Contact-mode based methods
Scanning Thermal Microscopy (SThM)

- Measures temperature on sample surface
  - Detects resistance change in thin metal layer on the tip with a resistance bridge circuit

  - Small thermistor at end of tip
  - Temperature sensitivity <0.5°C
  - Tip scans in contact mode

SThM of ‘hot spot’
SThM on laser diode structure

Scansize: 10x10 µm

Topography

Temperature

Scanning Capacitance Microscopy (SCM)

- 3rd generation
- Several methods are referred to as SCM, but only one is an efficient carrier profiling tool
- measurement of C(V), not C(z)
SCM sensor

Gain & Filter

CTRL

VCO

dC/dV

Lock-In amplifier

detector

resonator

Sensitivity

$3 \times 10^{-22} \frac{F}{\sqrt{Hz}}$

Fly Lead

AC + DC Bias

sample

Oscillator

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SCM example: LOCOS isolation between bipolar transistors

topography

SCM dC/dV

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2 SCM modes (simultaneous)

Amplitude
Phase
always positive
n-type: negative
p-type: positive
Sample: SRAM memory

SCM resolution: example from Bell Labs

TEM
SCM

Courtesy: Rafi Kleiman, Bell Labs
Note: $10^{17}$ atoms/cm$^3$
In 50x50x50 nm there will be only 12 dopant atoms!
SCM on active device

Just like it is drawn in the Textbooks!

SCM spectroscopy: dC/dV curves

\( n \)-type Si
2x10^{17} \text{ at./cm}^3

\( p \)-type Si
3x10^{19} \text{ at./cm}^3

SCM can be used to measure the \( dC/dV \) curve in a fixed position.
SCM Failure Analysis example

![Good Device vs Failed Device](image)

- Good device
- Failed device with leakage path

SCM Failure Analysis example

![Good MOSFET vs Leaky MOSFET](image)

- Good MOSFET: P Channel MOSFET with LDD
- Leaky MOSFET: Implant Bridged Under Field Oxide
P-type region trapped by LOCOS causes leakage

One final case study: Trench Capacitor DRAM
DRAM Trench Capacitor Cross-Section

3 different depths

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SCM Summary

- Spatial resolution: 10-20 nm
- Clear difference between n and p-type
- Dynamic range: $10^{15}-10^{20}$ atoms/cm$^3$
- 2-D imaging and local C-V spectra
- Main application: 2-D dopant profiling in semiconductors: Si & compound

SSRM - principle of operation

- Conductive probe
- Contact resistance
- Spreading resistance
- $R = \frac{\rho}{4 \times \text{radius}}$
- Logarithmic scale
- $n$, $p$, Si
- DC voltage ($V_{DC}$)
- Current range: 10 pA - 0.1 mA
Resistance map on polished Si transistor

Scan size: 12x12 µm

Bipolar transistor (0.35 µm) : qualitative SSRM image
Instrumentation: probes

- stiff cantilever (3-100 N/m)
- high hardness (10-15 GPa)
- high electrical conductivity ($\rho < 10^{-3} \Omega \text{cm}$)
- small probe radius (10-20 nm)

Graph showing force (N) vs. resistance (a.u.) with AFM and SSRM.
SSRM on Si dopant staircase

SSRM on Si PMOSFET

Scan size: 5x5 \( \mu \text{m}^2 \)
SSRM on beveled surface

NMOS, vertical enlargement: 13.7x

- the structure must be sufficiently long
- 2-D carrier redistribution is unknown

SSRM on InP hetero-structure

Zn - doped layer

Zn - diffusion

Scan size: 5x5 µm²
SSRM on plugs

the missing plug

SSRM Summary

• SSRM can be used for
  – conductivity & resistivity imaging
  – 2-D carrier profiling in semiconductor devices
• current range: 10 pA - 100 µA
• spatial resolution: 10-25 nm

• carrier profiling
  – Resolution: down to 2 nm (in literature)
  – dynamic range: $10^{15}$-$10^{20}$ atoms/cm$^3$
  – junction localization is possible: resistance peak
**Comparison SCM & SSRM**

**SCM**
- Resolution: about 15nm (10nm in literature)
- Range: $10^{15}$-$10^{20}$ atoms/cm³
- Low-force contact mode
- Tips: metal-coated (PtIr, CoCr)
  - No signal on metals & insulators
- N-type and p-type result in different polarity
- Carrier concentration and $dC/dV$ have non-linear relation

**SSRM**
- Resolution: about 15nm (2nm in literature)
- Range: $10^{15}$-$10^{20}$ atoms/cm³
- High-force contact mode
- Tips: diamond-coated
  - Signal on metals
- N-type and p-type result in same polarity
- Sample resistivity and resistance are proportional

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**Tunneling AFM (TUNA) - principle of operation**

- Conductive AFM probe
- Thin dielectric film
- DC bias voltage (-50V - +50V)
- 1pA / V gain
- 40 fA RMS noise

- Extra gain + filter
- To ADC

- Closed loop
TUNA on 5 nm gate oxide

Scan size: 1x1 \( \mu \text{m}^2 \)

- current increases exponentially with voltage

\[ t_{ox} = \begin{cases} 8 \text{ nm} & \text{for } 8 \text{ V} \leq V \leq 9 \text{ V} \\ 5 \text{ nm} & \text{for } 6 \text{ V} < V < 8 \text{ V} \end{cases} \]
Breakdown measurement

At +3V  + 6V  +1V

TUNA on SiO₂ - trench isolation

field-oxide (no current)
defect (high current)

topography  Voltage for 1 pA current
Voltage at 1 pA and TEM section

TUNA

TEM

Oxide thinning

50 nm

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TUNA Summary

- Spatial resolution: 2-10 nm
- Current range: 50 fA-120 pA
- 2-D imaging and local I-V spectra
- TUNA can be used for:
  - Current imaging in thin dielectric films: gate-oxides, Al-oxide,...
  - Dielectric film thickness uniformity
  - Oxide defect localization, imaging and characterization
  - Oxide breakdown measurement, reliability tests

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Conductive AFM case study:

- Provided by Any Ericsson (MultiProbe)
- Localisation of faulty contacts
- Precisely isolate defects for contact micro-leakage or higher contact resistance
- Local I/V measurements from contacts to substrate

Fault examples:
- Gate Oxide Rupture
- Gate poly short to P+ contact
- CoSi induced junction leakage
- High contact resistance
- Stacking fault induced leakage

Cl-AFM Locates a Gate Oxide Defect

- Very easy to spot the leaking gate
- Current Image gives a quantitative leakage current
- Simplest Defect to Localize, Similar to PVC
- Do you see the W via seam?
**CI-AFM compared to Passive Voltage Contrast**

- Sample Parallel Lapped to Contact Level
- BW Image is SEM Voltage Contrast
- Yellow Inset is AFM Current Imaging
- Current Image was acquired with -2V on the sample stage
- SEM VC relies on charging effect due to beam current

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**Both PVC & CI show the effect of a poly-bridge short**

- Sample Parallel Lapped to Contact Level
- Techniques are roughly equivalent for opens and shorts
CoSi induced junction leakage

- SEM PVC shows no abnormality
- AFM CI contrast contacts A, B and C
- Local IV curves show reverse breakdown
- Microstructure shows abnormal CoSi formation

High contact resistance

- Site A is High Resistance Contact
- Site B is an Open Contact
- Local IV curves show Contact B
- Microstructure shows abnormal CoSi formation
Stacking fault induced leakage

- Current Image Shows failing Bit Line Contact
- Microstructure shows a stacking fault in the CoSi

Fault localization hit rate

- A comparison of the “hit rate” between PVC and CI-AFM used a total of 33 samples.
- The hit rate of defect identification by PVC was 30% (10/33) and CI-AFM 90% (30/33).
- Detection for junction leakage or resistive contacts is much higher using Current Imaging
- Both biases can be used to check both forward and reverse currents
- Local IV curves can be acquired to characterize the failure and far higher detail can be obtained
- Normal Probes Limit currents to nA, tungsten or diamond probes can reach μA - mA
Summary: Useful FA SPM techniques (1 probe)

- Based on Tapping mode
  - Electric & Magnetic Field Microscopy
  - Kelvin Probe Force Microscopy
  - NSOM

- Based on Contact mode
  - Scanning Spreading Resistance Microscopy
  - Scanning Capacitance Microscopy
  - Tunneling – AFM
  - Conductive – AFM
  - Scanning Thermal Microscopy
  - 4-point-probe

Why do Four-Point-Probe on an SPM?

With a macro-spacing between the probe points the current lines goes deep into the sample.

With a micro-spacing the current runs close to the surface. Only the surface layer is characterised.

Ultra-thin film characterization
Why do FPP on an SPM?

- Lower forces allow to measure softer materials
- Lower forces allow to have less (or no) penetration
- Non-destructive probing technology
- Small geometry allows more localized measurements: 1,000x smaller than conventional probes

The Microscopic Four-Point Probe

- AFM
- 4PP
- Gold
- Cantilever
- Under cut support
- Silicon
Four-Point Probe

- Cr/Au coated SiO$_2$ cantilevers.
- In plane tapered tips.
- Contact diameter 10-100 nm.
- Contact force $10^{-4}$ - $10^{-6}$ N
- 4-Point Probes are available in 5, 10, 15, 20, 25 and 30 $\mu$m spacing.
Conductivity Measurements

Four-point-probe measuring on metallic surface

Bending of four-point-probe cantilevers

Part 3: Multiple Probe probing

Acknowledgements; Andy Ericson – MultiProbe (andy@multiprobe.com)
Gate Oxide Defect, Revisited

- With more than one probe we can localize to device with damage
- Measure leakages between Source/Drain to the Gate

Using the IV Spectra to Localize and Characterize

- With two probes there is little need for a TEM micrograph
- If cross section is desired, the target is unambiguous
- Extent and character of oxide failure is understood
Deep Submicron Probing

- Optical Probing is impossible below 0.25µm node.
- Typical Solution is to use the FIB mill to create pads for probing
- Pads are straightforward, but ion beam damage shifts threshold voltages
- You have to decide which cell is the problem for single bit fails
- Can’t get reference data from adjacent cells
- FIB mill can rupture thin gate oxide, especially SOI transistors.

FIB Pad Probing at M1

- Almost impossible to rework for another transistor in the cell
- Limited to two transistors at 90nm and below
- Hard-stop for sub-100nm lines and contacts
- Yield for samples is ~50%
- FIB micro probing pads deposition shifts the threshold voltage of MOS transistors
- This effect is even at sub pC/µm exposure
- Data from A Campbell et al. 1999 ISTFA
FIB contacts deposited on 0.13µm SRAM transistors at Contact Level

- Internal cache transistors are more susceptible to FIB damage at contact level
- Must probe at contact to access the individual transistors
- Sample prep is a ½ day process plus baking to lower ∆Vt
- Sample goes from PFA to EFA and back again creating long waits

Atomic Force Probing

- Probing needs to have sharp tips, nano-positioning, and force control for ohmic contacting.
- Probes need to be brought to within a few hundred nanometers of each other
- Probes must be robust to contact metal repetitively
- Image map automatically registers the probes to contact points
### Atomic Force Probing SRAM Cell Requirements

<table>
<thead>
<tr>
<th>Technology Node</th>
<th>SRAM cell area</th>
<th>Req’d Probe Spacing</th>
<th>S/D/G triangle area</th>
<th>Best Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>180nm</td>
<td>2.0µm</td>
<td>.5µm</td>
<td>.13 µm²</td>
<td>250nm</td>
</tr>
<tr>
<td>130nm</td>
<td>1.5µm</td>
<td>.38µm</td>
<td>.07 µm²</td>
<td>100nm</td>
</tr>
<tr>
<td>90nm</td>
<td>1µm</td>
<td>.25µm</td>
<td>.03 µm²</td>
<td>50nm</td>
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<tr>
<td>65nm</td>
<td>.8µm</td>
<td>.19µm</td>
<td>.018 µm²</td>
<td></td>
</tr>
<tr>
<td>45nm</td>
<td>.6µm</td>
<td>.13µm</td>
<td>.009 µm²</td>
<td></td>
</tr>
</tbody>
</table>

### Adapting an AFM for Probing

- Positioning vs imaging = AC vs DC (piezo hysteresis, creep)
- Probing Geometry Definitions
- Multiple Probes in close proximity
- Probes for Probing
- Synchronized scanning
- Optical Access
- Low Noise
Ultra-Fine W Needles

- Tungsten needles are a great material for electrical AFM applications
- They don’t wear out, no semiconductor junctions, 100X harder than typical AFM tip coatings
- Much better tip geometries as seen below:
  - Probe Radius \( R = 50-250\text{nm} \)
  - Probe Length \( L = 50-200\text{mm} \)
  - Entrant Angle \( b = >a/2 \)
  - Taper Angle \( a = 6-50\text{ Deg} \)
  - Spring Constant \( k = 1-1000\text{N/m} \) Stiff!

Optical Access for Gross Positioning

- AFP Probes are mounted on a special thick platen
- Room between probes for optical microscope
- Use positioner screw to bring the probes to within a few microns of the target.
- Low Magnification Optical View over SRAM
Tall M1 Lines and Section

- Probe is capable of scanning over tall structures
- Extended topography can be probed such as multiple metal layers
- Poly and silicide is also possible to probe

Optical View Low and High Mag

- When probing ~100nm lines, the space between the probes is not visible
- AFP image is required for probing
Using CAD navigation

- AFP Image of SRAM cell polishing to MC1
- Cad Layout for Comparison and navigation

AFP Transistor Measurements

- Probing examples from different nodes
- Methods for verifying contacts
- Good and Bad curve examples
130nm Process Technology

- This part has 90nm gate length making it a 130nm node part
- Notice the Plug Seam! This will come up later

SRAM Cache Layout

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**Ids vs Vds @ Vg = -0.5 to 2.0V**

![Graph showing Ids vs Vds for different Vg values.](image)

- **Vg=0.5**
  - 68µA
- **Vg=1.0**
  - 122µA
- **Vg=1.5**
- **Vg=2.0**

**AFP Imaging of a 90nm part**

- Part Lapped (by hand quickly) using diamond film
- 15, 8, 3, 1, 0.1µm
- Scratches are left over from 8µm film since I wasn’t patient enough
- Sample was oxide recessed in 20:1 dilute HF for about 10 sec to expose about 30-40nm of tungsten via
- HF etch back is necessary for good ohmic contacts
90nm Probing Example

- Probes used are 100nm
- Minimum Pitch = .25µm
- Probes A, B, & D in a triangular area = 1/32nd µm²
- Drag color coded cursors in each image to desired node
- Increase force to contact.

Diode Check to verify contact

- Nfet Source/Drain Diode Check is easiest since it is just a diode to backside
- For sub 100ohm contacts you should get tens of microamps
- Sometimes substrate is resistive and diode check needs two probes
- For Pfet Diode Check it requires light to get a single probe backside contact.
- If you place an Nwell contact then you get diode independent of light
**Contact Resistance Effects**

- Part at 90nm should give ~100µA drive current from my experience
- Slope of Saturation should be flat
- Low drain resistance gives spacing in the linear region
- All contacts ~20-30Ω
- Drain Resistance Dominated the linear region
- If Source Resistance will look like better curves (flatter in saturation) but very low drive
- Gate Contact typically draws no current

![Contact Resistance Effects Diagram](image1.png)

**65nm Probing Requirements**

- Minimum pitch of 180nm between probes
- 65nm probing requires 3 of 4 probes in a triangular area of 1/50th µm² !!
- The probe radius must be <50nm
- The CI-AFM image of the 65nm SRAM array shows a leaky contact to Vss.
65nm SRAM Transistor

- Nfet and Pfet family of curves are the curves for one inverter
- This technique is capable of measuring all 6 of the transistors in the bit cell
- Not limited to target cell, can measure neighbor cells

Atomic Force Probing Summary

- Technique is capable at the latest technology node and should be functional for 45nm
- Positioning accuracy (closed loop), hard metal probes are necessary for probing.
- AFP allows sharp probe to stay relatively undamaged for hours of probing.
- There is no measurable damage or threshold shifting with AFP probing.
- FIB pads method will be replaced by AFP.