Failure Analysis of Semiconductors using Scanning Probe Microscopy (SPM)

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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**

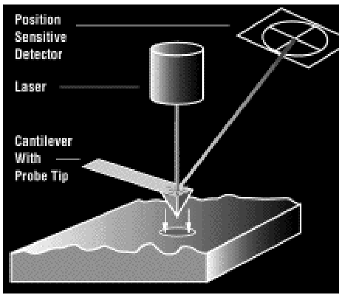
Outline

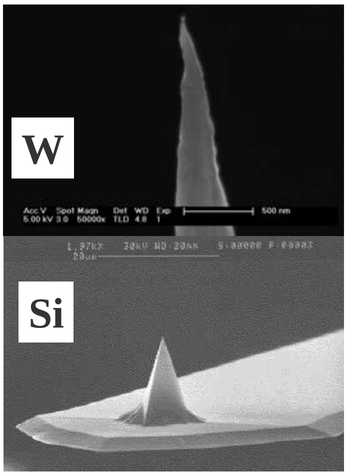
- **What is an AFM / SPM**
- **FA modes based on oscillating probe imaging**
  - **Electric fields, magnetic fields, surface potentials**
- **FA modes based on contact mode imaging**
  - **Resistance, capacitance, carrier profiling, thermal imaging,…**
- **Atomic Force Probing: extending probing to the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

What is an AFM?

Three things common to all SPM's:

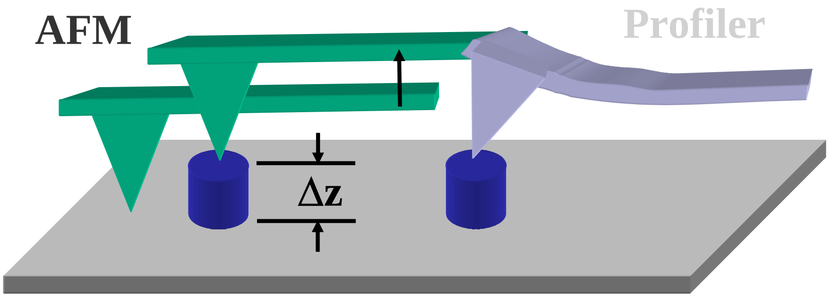
- **Sharp Probes**
- **Nano Positioning**
- **Force Feedback**



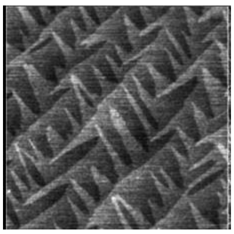


Force Feedback vs Deflection

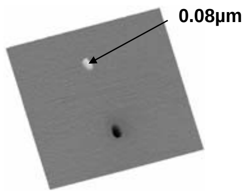
- AFM Retracts Z Piezo so that F is Constant
- Profiler drags tip over feature while measuring deflection. Deflection results in higher force at the top than the bottom: $\Delta F = k\,\Delta z$
- AFM probe can be oscillating or in contact, profiler always in contact



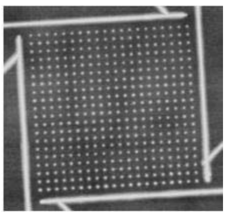
Routine SPM applications for semiconductors

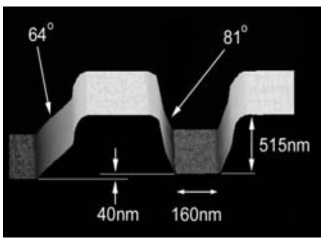

micro-structure of epi Si


0.3µm W plug after CMP showing recess.



sub-0.1µm defect imaging

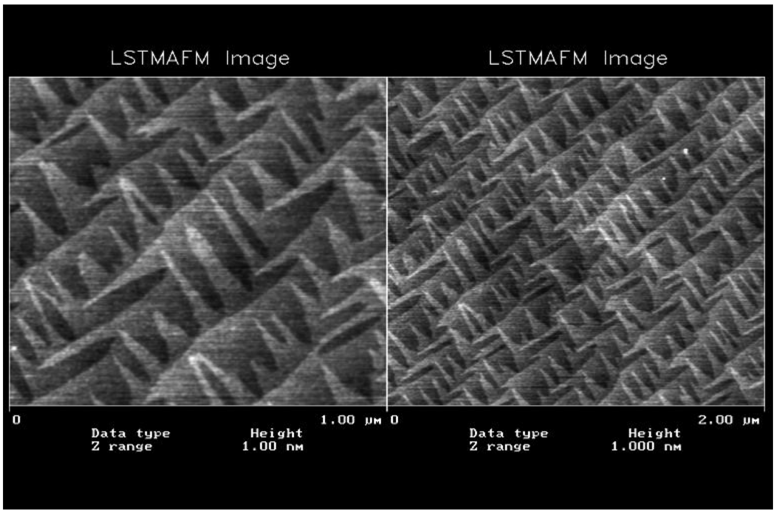

Nano-lithography by anodic oxidation



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

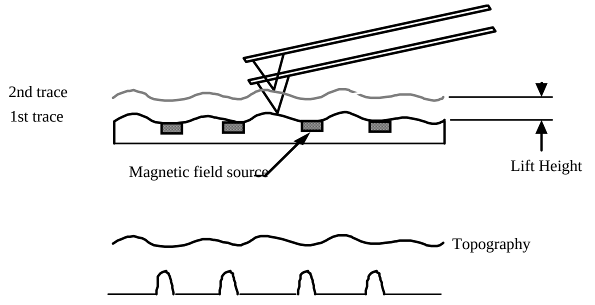
Some useful FA SPM techniques

- **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

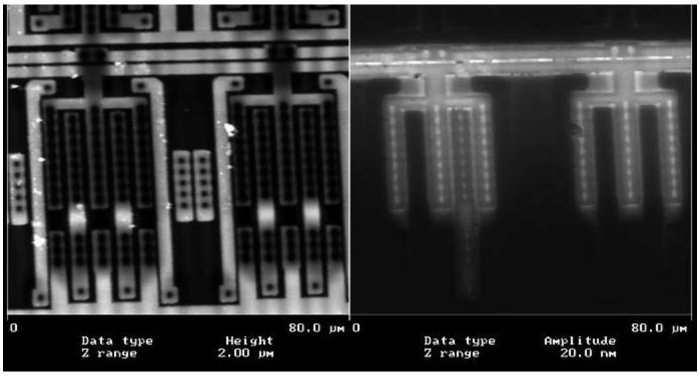
EFM: Imaging of electric fields
MFM: Imaging of magnetic domains & polarizationg



Pattented 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**



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Modified EFM

– **Tip scans above surface (liftmode or non-contact)**
– **AC+DC voltage between tip and sample -> Force**

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

– **influenced by oxide thickness or surface charges**
– **dC/dm is measured, not dC/dV**

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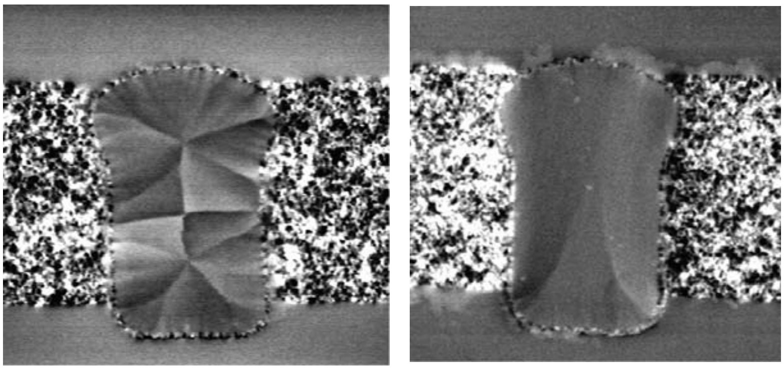
MFM example



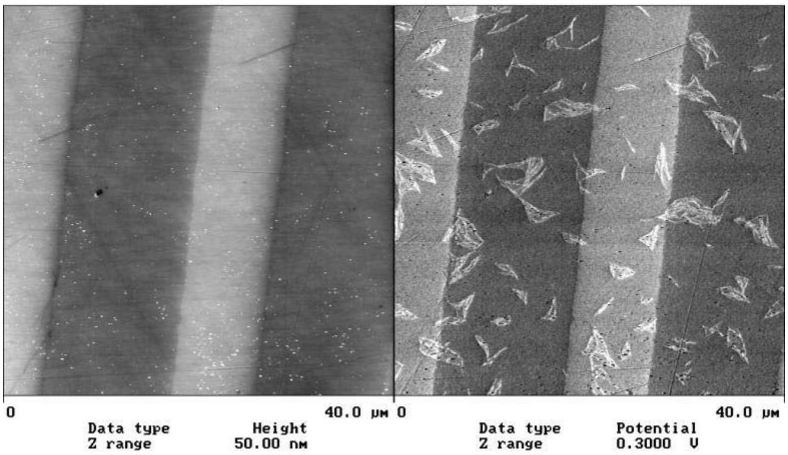
no magnetic bias with bias 15 µm

MFM Image of magnetoresistive (MR) sensor

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**

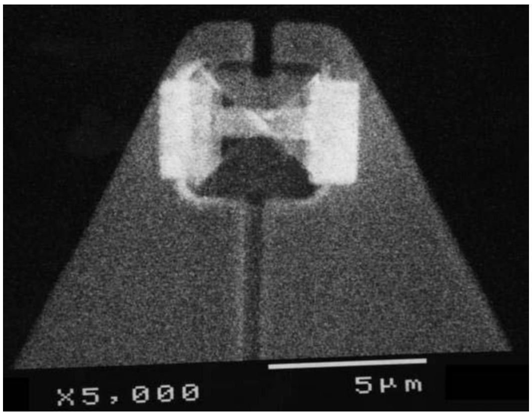
KPM of TiO_2 Lines on SiO_2



Part 2: Contact-mode based methods

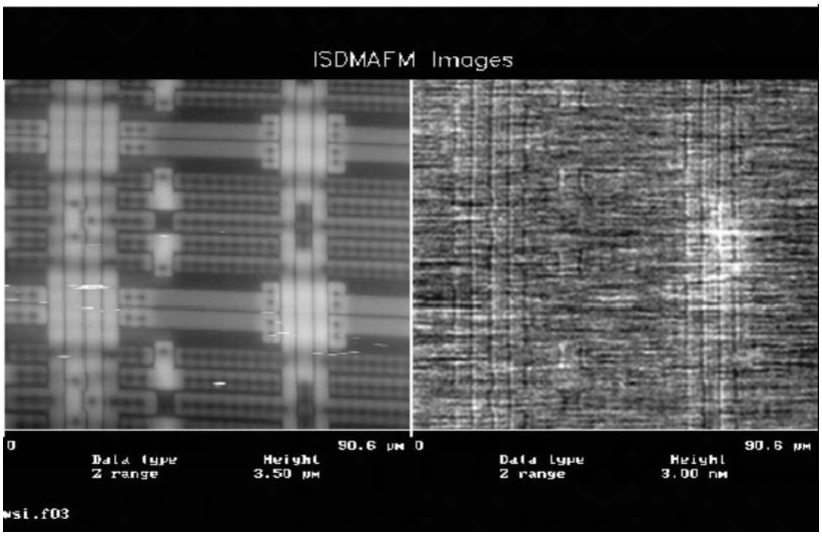
Scanning Thermal Microscopy (SThM)

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

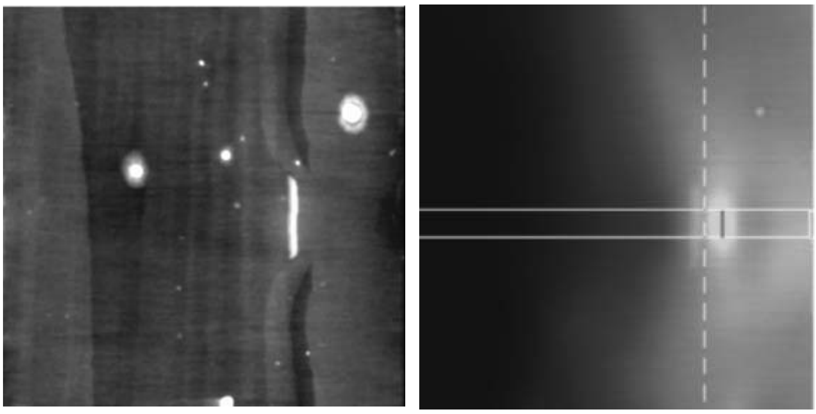


- **Small thermistor at end of tip**
- **Temperature sensitivity <0.5C**
- **Tip scans in contact mode**

SThM of 'hot spot'



SThM on laser diode structure

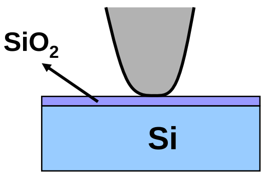


Topography **Temperature**

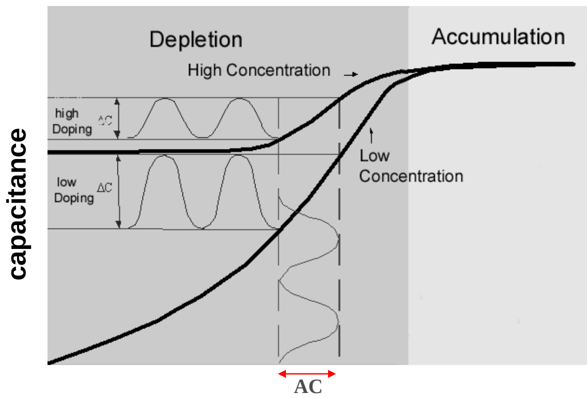
Scansize: 10x10 μm

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)**

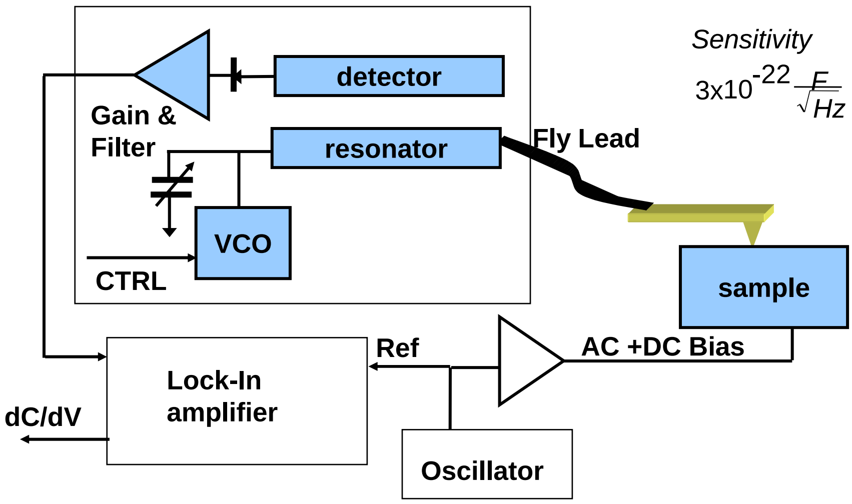


= MIS capacitor

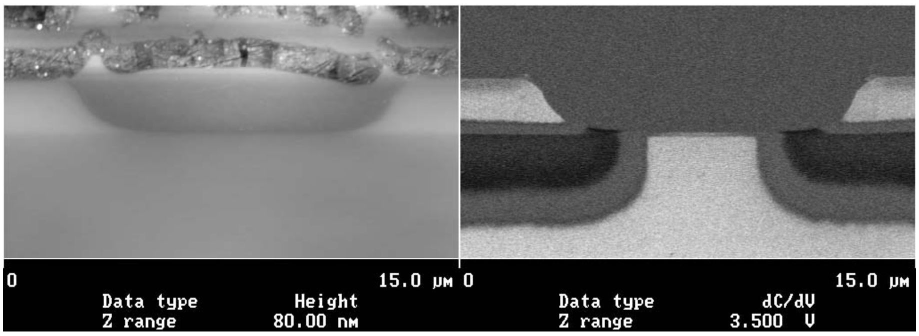


voltage

SCM sensor



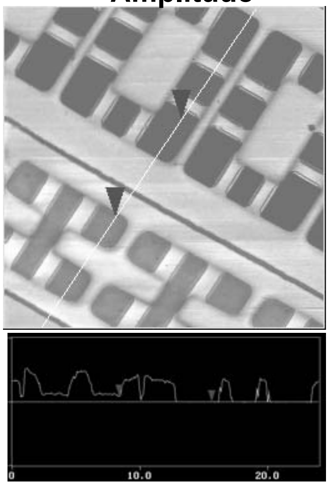
SCM example: LOCOS isolation between bipolar transistors



topography **SCM dC/dV**

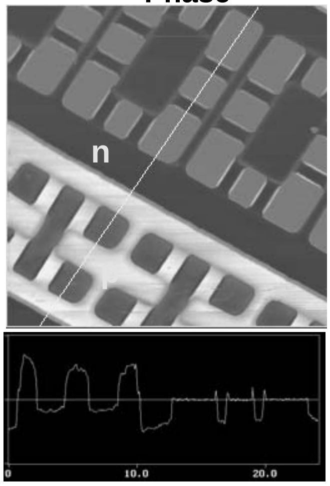
2 SCM modes (simultaneous)

Amplitude



always positive

Phase

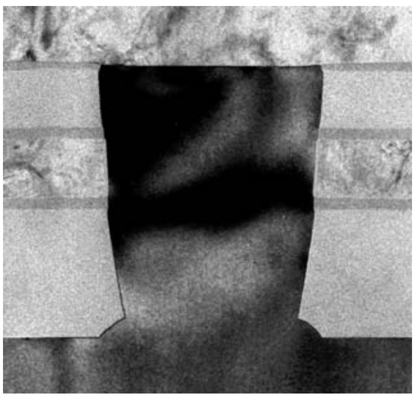


n-type: negative
p-type: positive

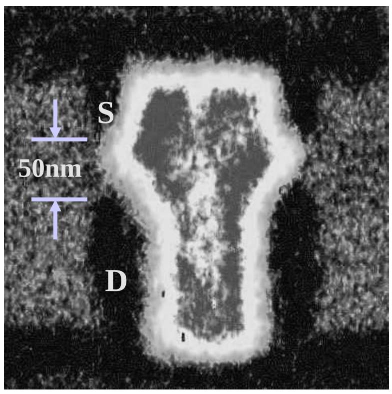
Sample: SRAM memory

SCM resolution: example from Bell Labs

TEM

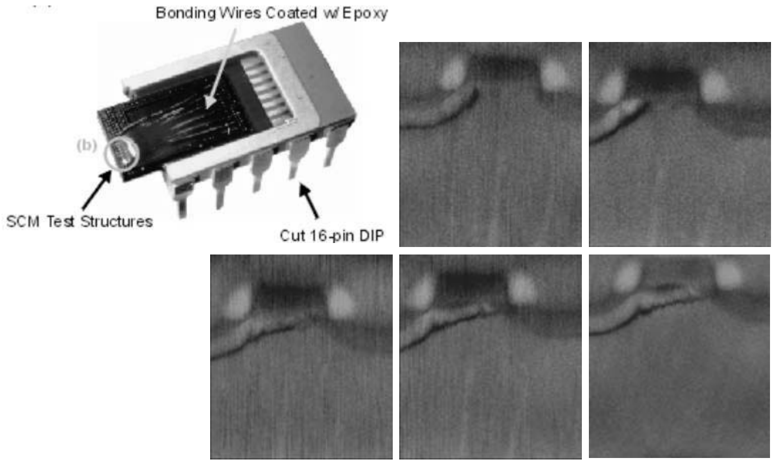


SCM



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

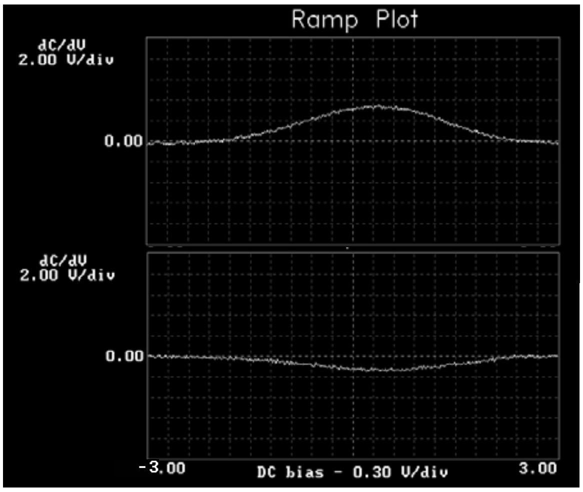


Just like it is drawn in the Textbooks!

SCM spectroscopy: dC/dV curves

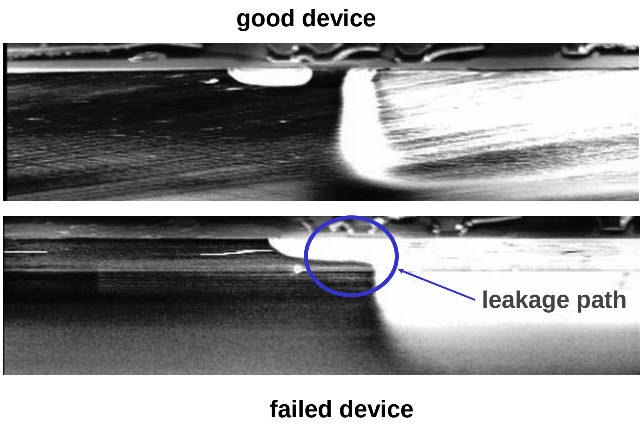
***n*-type Si**
2x10^{17} at./cm^{3}

***p*-type Si**
3x10^{19} at./cm^{3}



SCM can be used to measure the *dC/dV* curve in a fixed position.

SCM Failure Analysis example



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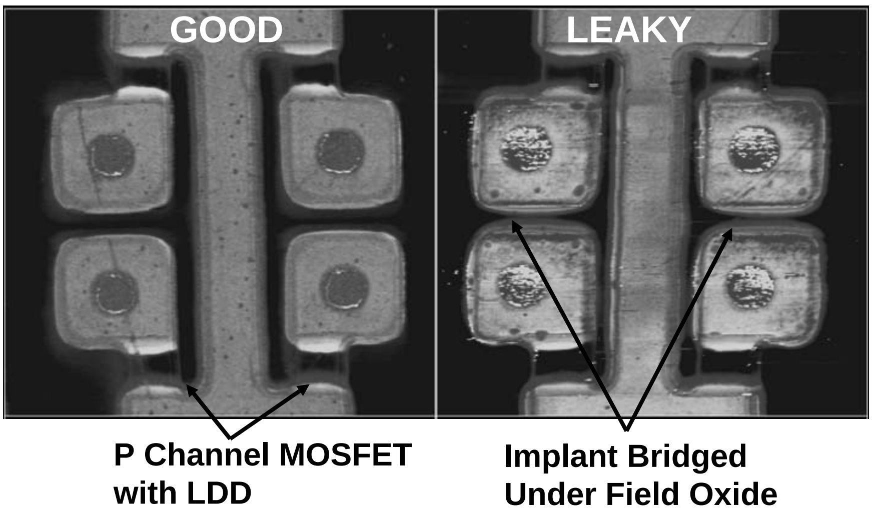
SCM Failure Analysis example



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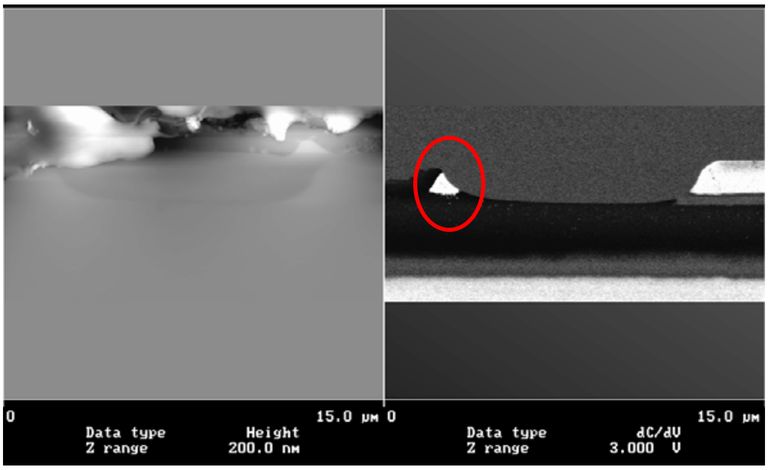
P-type region trapped by LOCOS causes leakage



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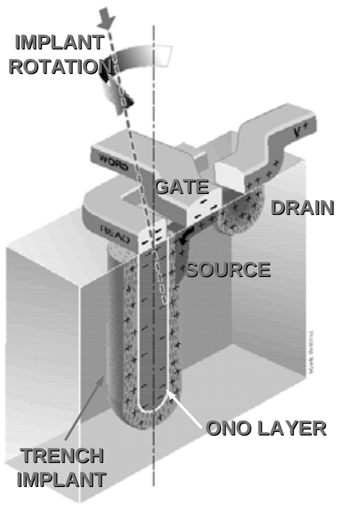
One final case study: Trench Capacitor DRAM



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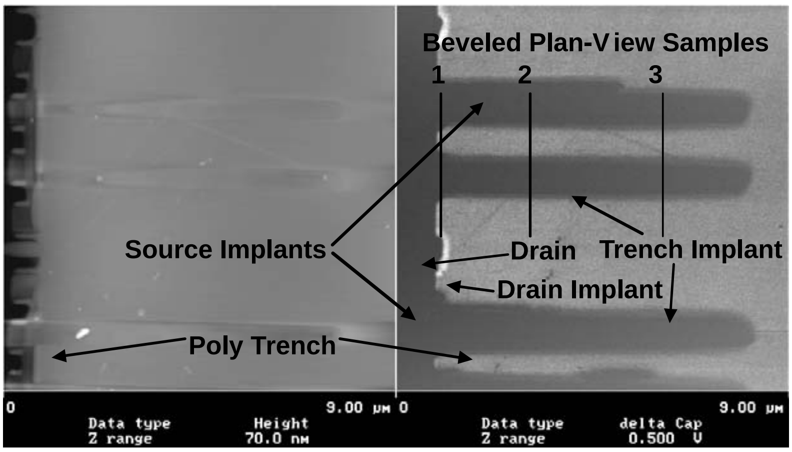
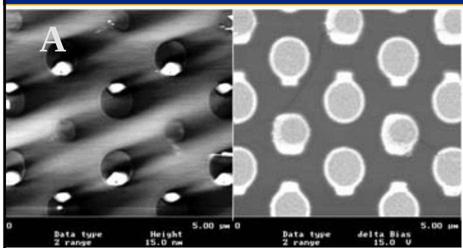
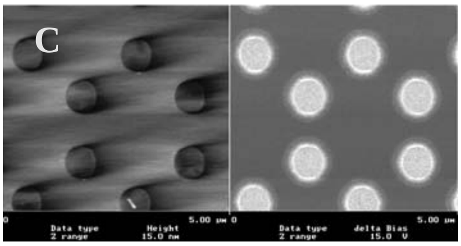
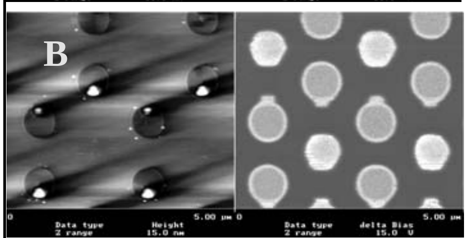
DRAM Trench Capacitor Cross-Section

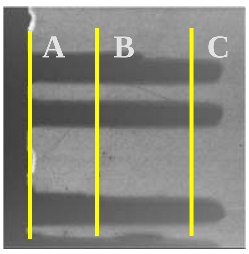


3 different depths





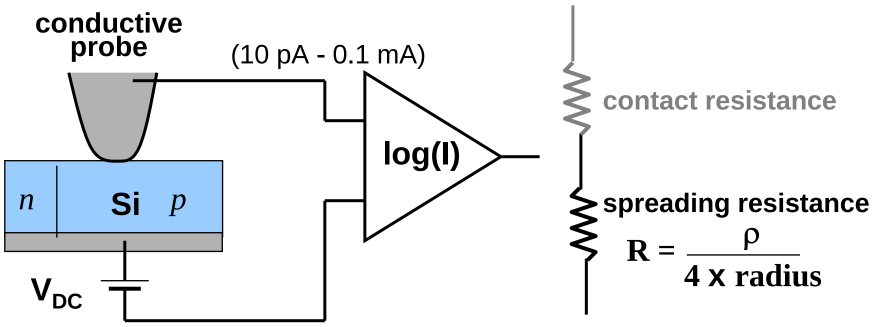




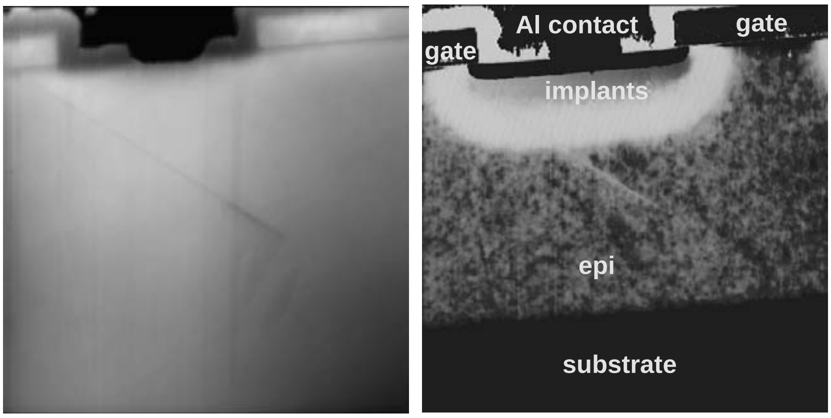
SCM Summary

- **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



Resistance map on polished Si transistor



topography **resistivity**

scan size: 12x12 µm

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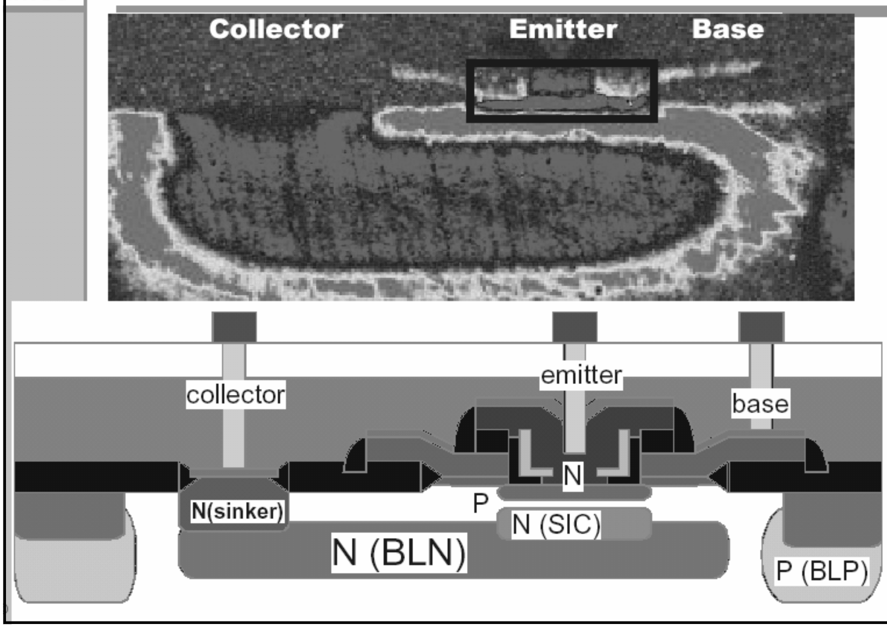
Bipolar transistor (0.35 µm) : qualitative SSRM image



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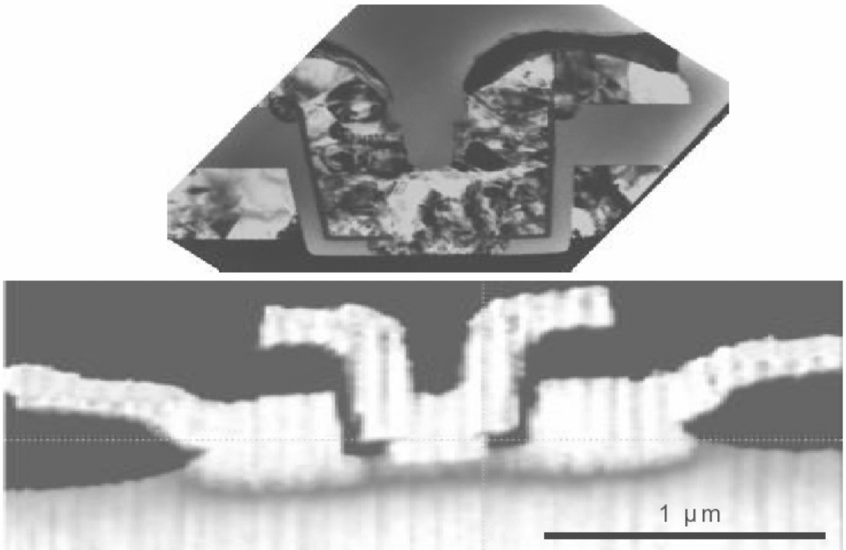
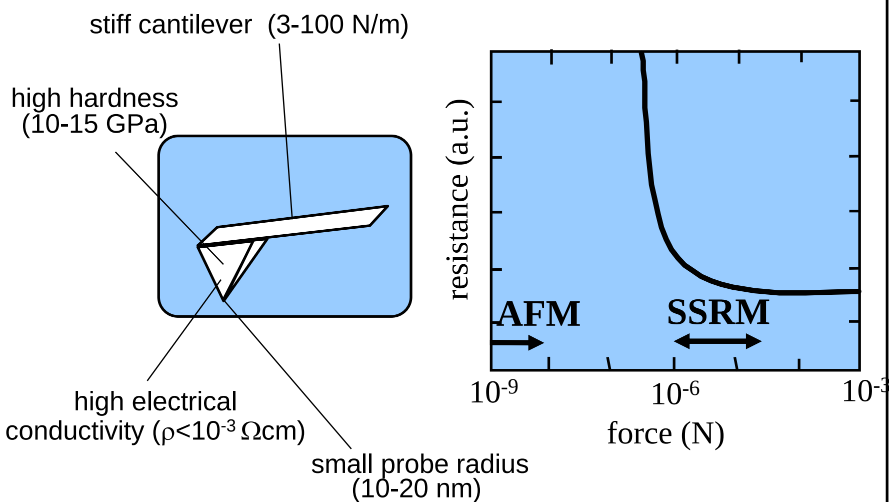
Bipolar transistor (0.35 µm) : qualitative SSRM image



© 14

Instrumentation: probes



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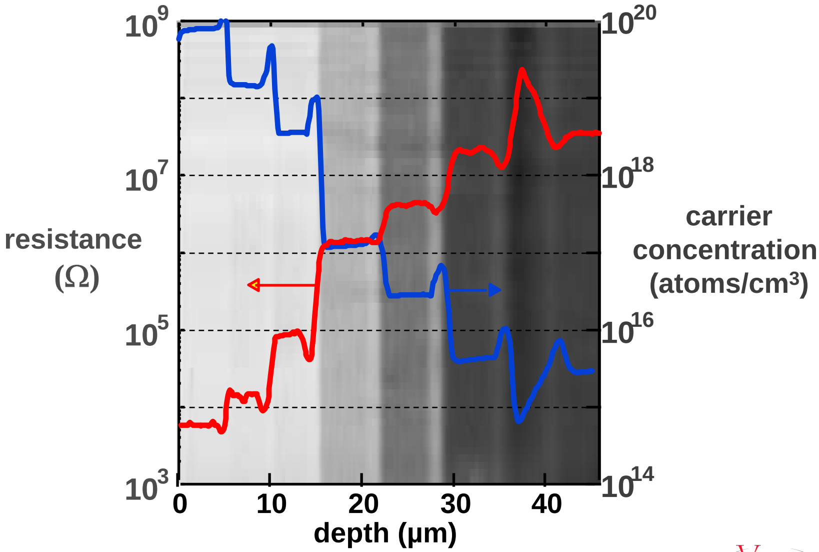
SSRM on Si dopant staircase



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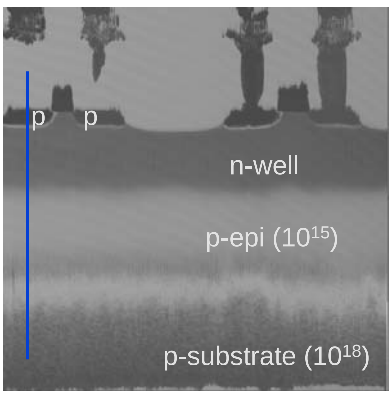
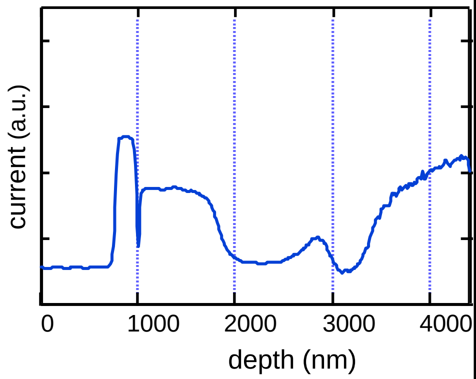
SSRM on Si PMOSFET



Scan size: 5x5 µm^2



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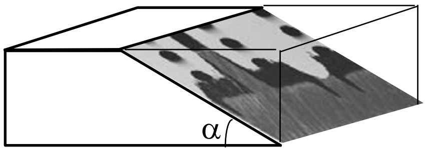
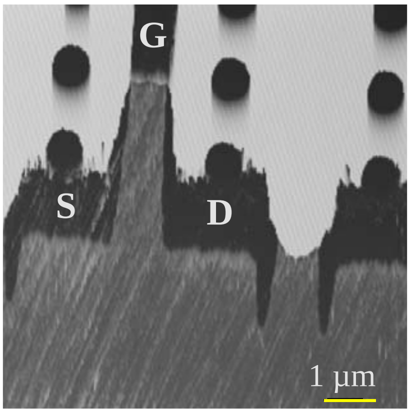
SSRM on beveled surface

NMOS, vertical enlargement: 13.7x

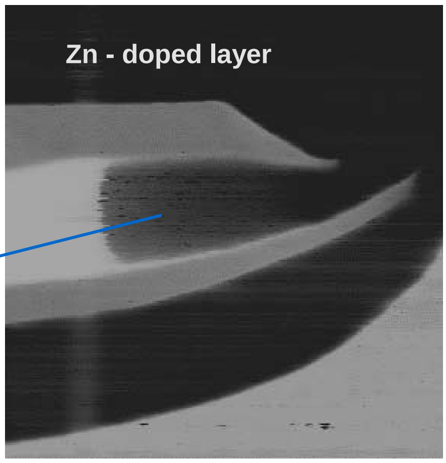




!
- **the structure must be sufficiently long**
- **2-D carrier redistribution is unknown**

SSRM on InP hetero-structure

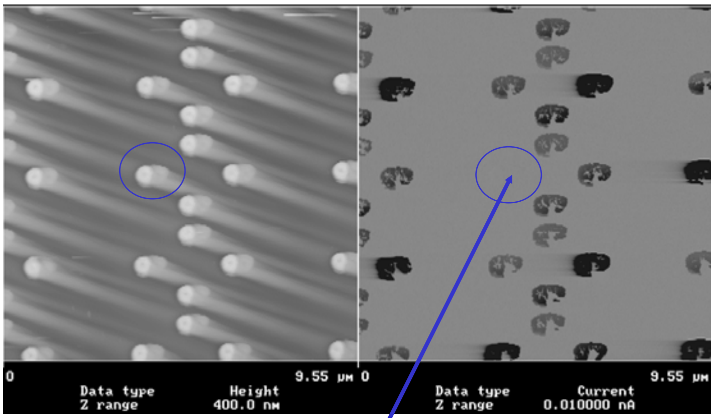
(Cross-section)



Zn - diffusion

Scan size: 5x5 µm^2

SSRM on plugs



the missing plug

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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

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Comparison SCM & SSRM

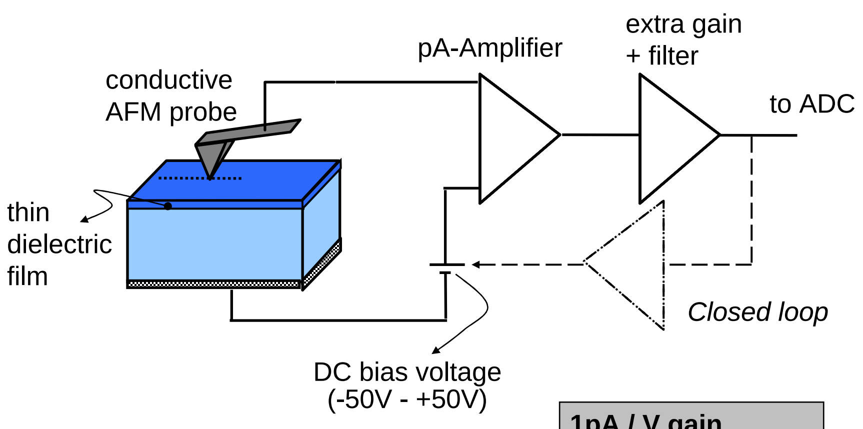
SCM

- \+ resolution: about 15nm (10nm in literature)
- \+ range: 10^{15}-10^{20} atoms/cm^3
- \+ 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

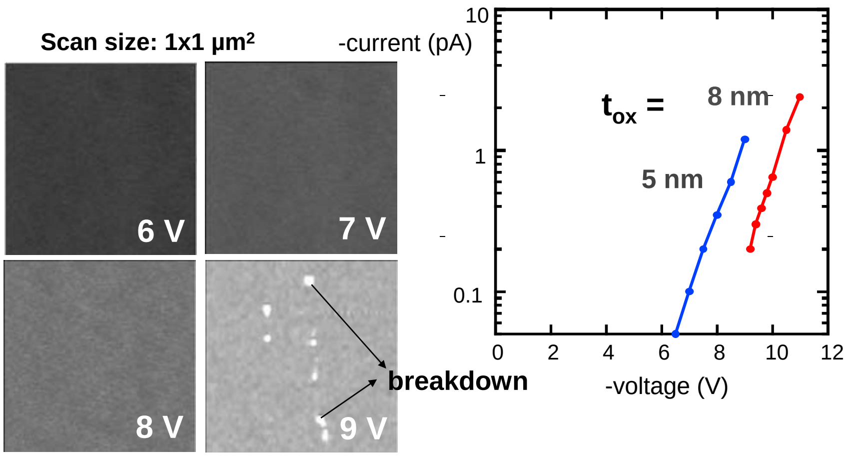
- \+ resolution: about 15nm (2nm in literature)
- \+ range: 10^{15}-10^{20} atoms/cm^3
- – high-force contact mode
- ± Tips: diamond-coated
- \+ Signal on metals
- – n-type and p-type result in same polarity
- \+ sample resistivity and resistance are proportional

Tunneling AFM (TUNA) - principle of operation



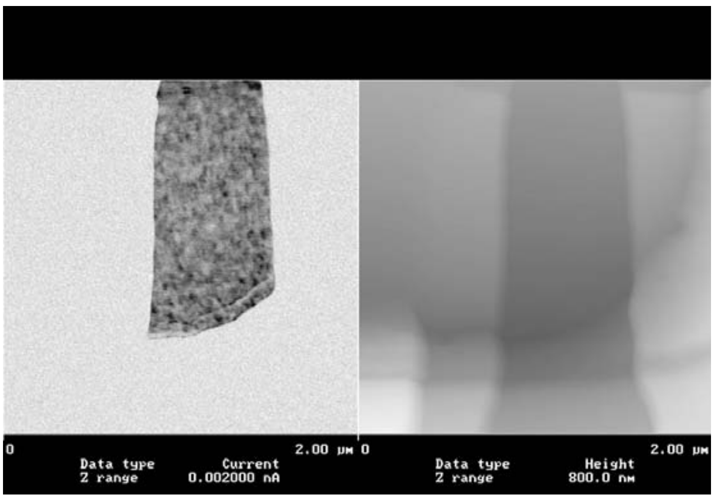
1pA / V gain
40 fA RMS noise

TUNA on 5 nm gate oxide

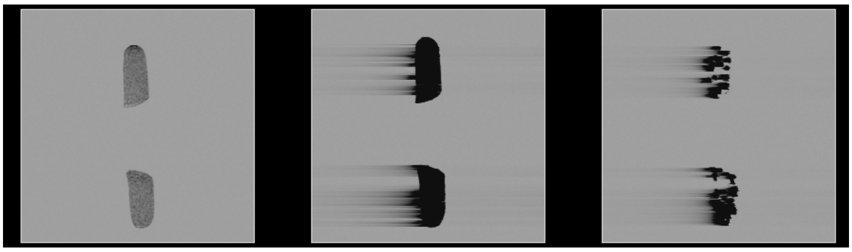


current increases exponentially with voltage

TUNA on gate oxide



Breakdown measurement



At +3V   + 6V   +1V

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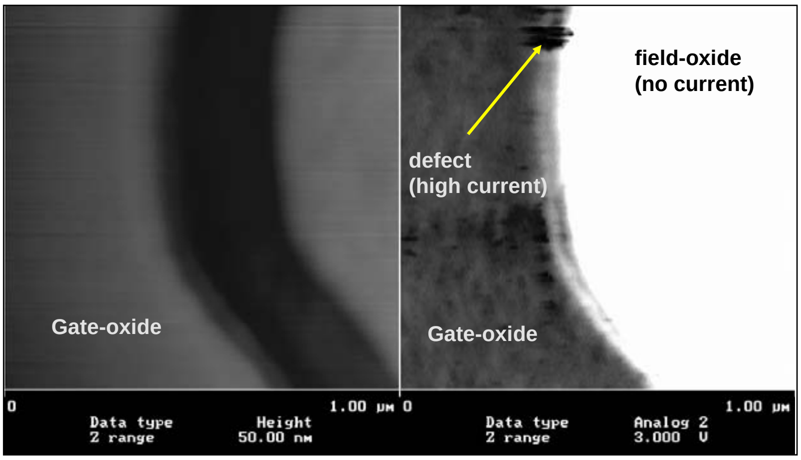
TUNA on SiO_2 - trench isolation



topography   Voltage for 1 pA current

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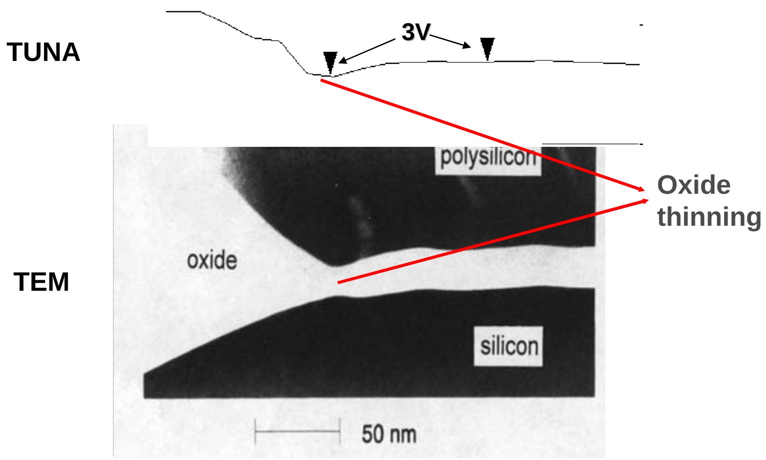
Voltage at 1 pA and TEM section



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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)**

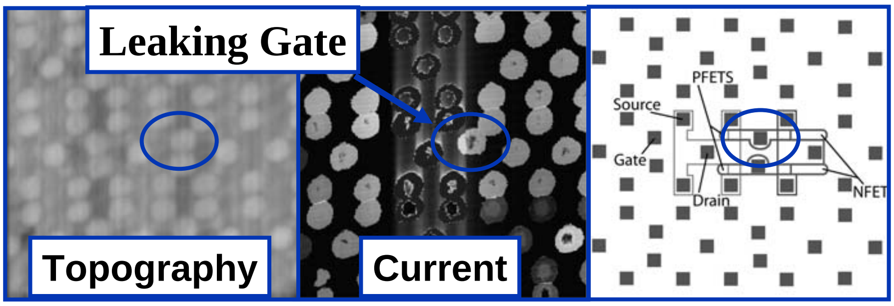
- **Localisation of faulty contacts**
- **Precisely isolate defects for contact micro-leakage or higher contact resistance**
- **Local I/V measurements from contacts to substrate**

Fault examples:

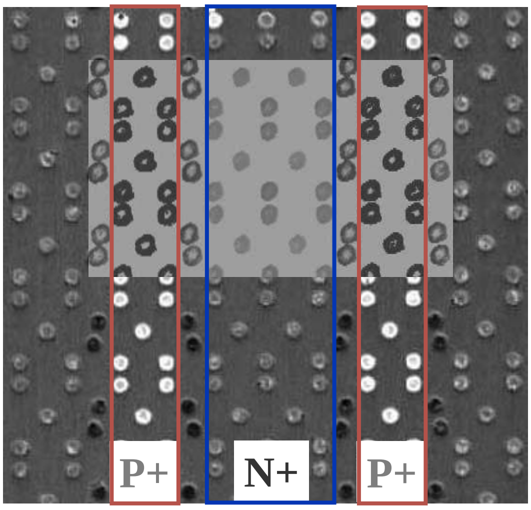
- Gate Oxide Rupture
- Gate poly short to P+ contact
- CoSi induced junction leakage
- High contact resistance
- Stacking fault induced leakage

CI-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?**



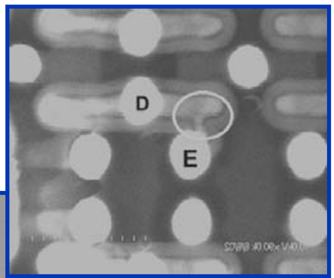
CI-AFM compared to Passive Voltage Contrast

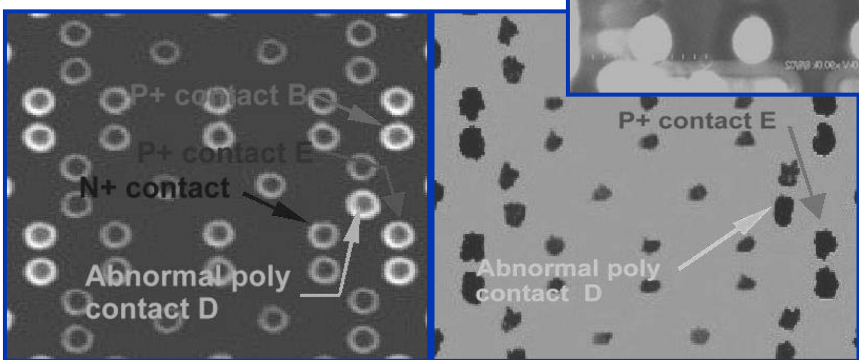


- Sample Parallel Lapped to Contact Level
- BW Image is SEM Voltage Contrast
- Yellow Inset is AFM Current Imaging
- Current Image was acquired with -2V on the sample stage
- SEM VC relies on charging effect due to beam current

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

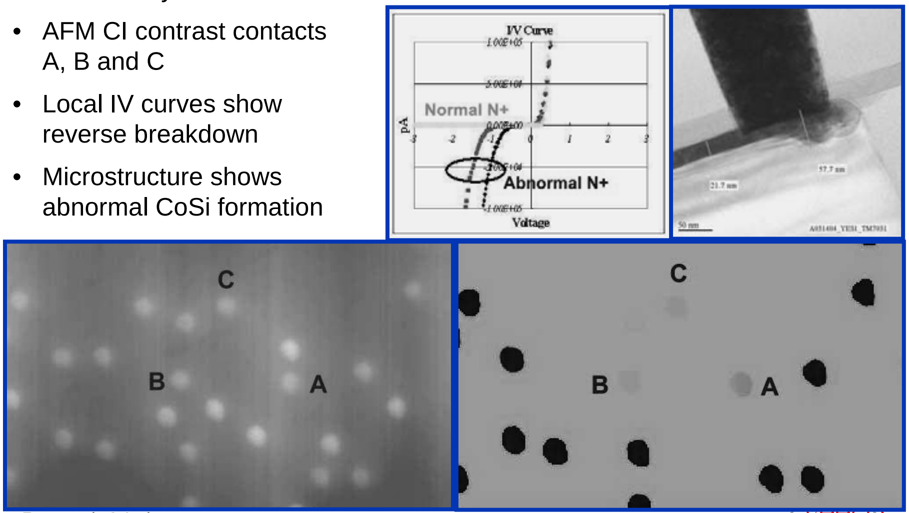
- Sample Parallel Lapped to Contact Level
- Techniques are roughly equivalent for opens and shorts





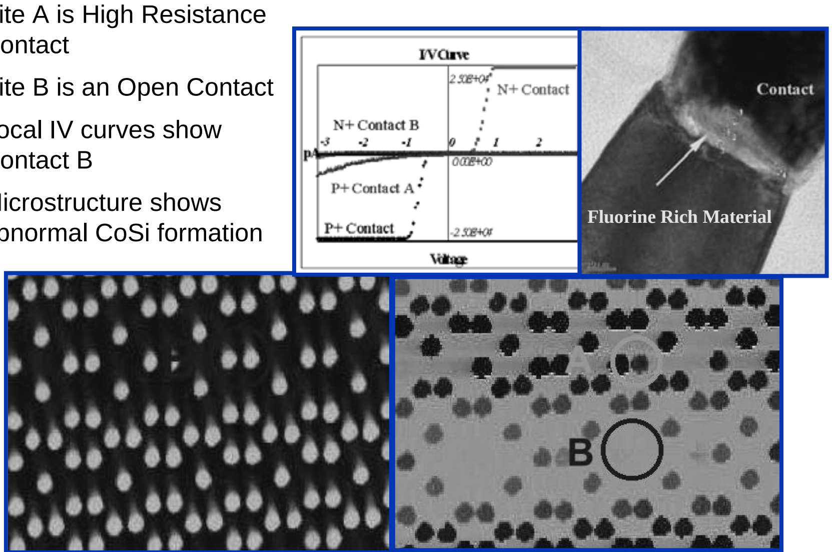
CoSi induced junction leakage

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



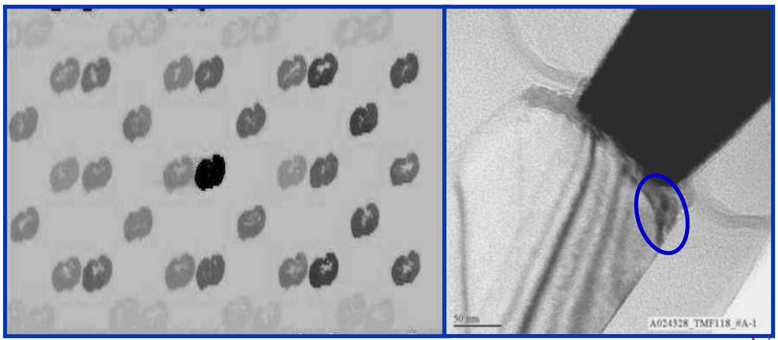
High contact resistance

- 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



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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**

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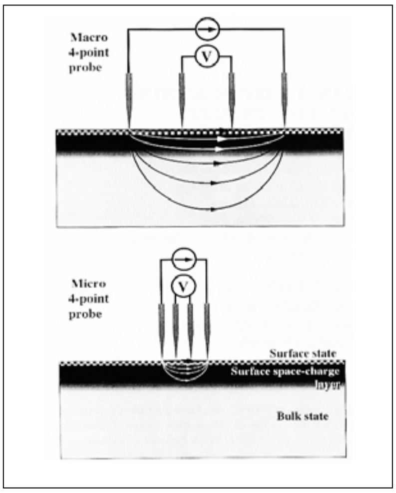
Summary: Useful FA SPM techniques (1 probe)

- **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 ?



Hasegawa and Grey, Surf. Sci. 500 84 (2002).

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

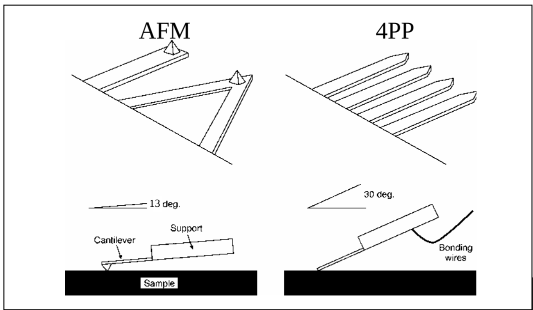
With a micro-spacing the current runs close to the surface. Only the surface layer is characterised.

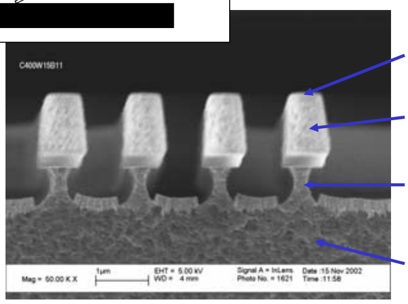
Ultra-thin film characterization

Why do FPP on an SPM ?

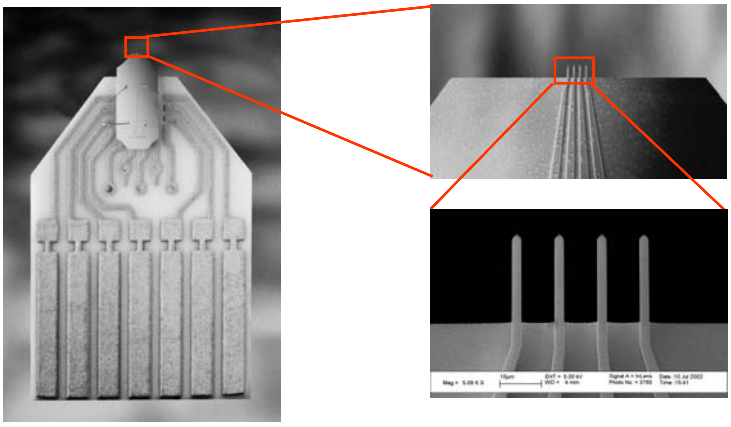
- Lower forces allow to measure softer materials
- Lower forces allow to have less (or no) penetration
- Non-destructive probing technology
- Small geometry allows more localized measurements: 1,000x smaller than conventional probes

The Microscopic Four-Point Probe

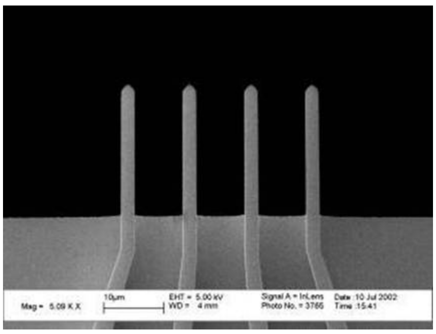




Four-Point Probe

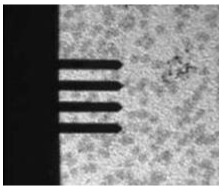


Four-Point Probe

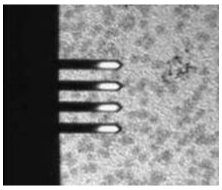


- Cr/Au coated SiO_2 cantilevers.
- In plane tapered tips.
- Contact diameter 10-100 nm.
- Contact force 10^{-4} - 10^{-6} N
- 4-Point Probes are available in 5, 10, 15, 20, 25 and 30 μm spacing.

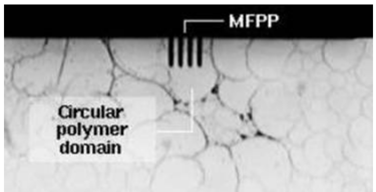
Conductivity Measurements

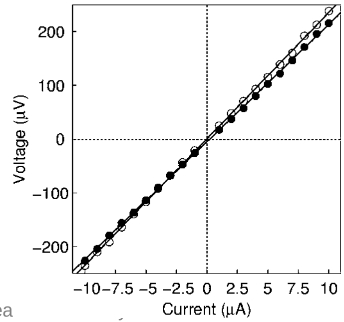


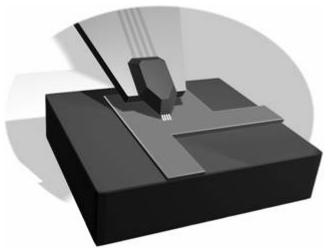
Four-point-probe measuring on metallic surface



Bending of four-point-probe cantilevers





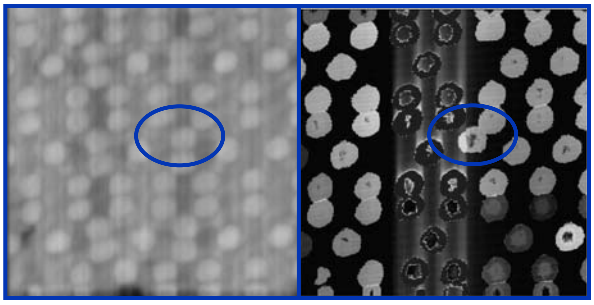


Part 3: Multiple Probe probing

Acknowledgements; Andy Ericson – MultiProbe (andy@multiprobe.com)

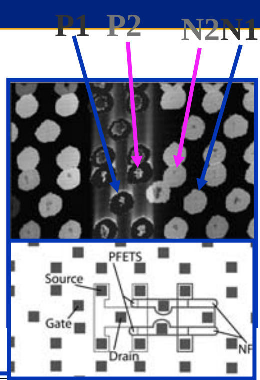
Gate Oxide Defect, Revisited

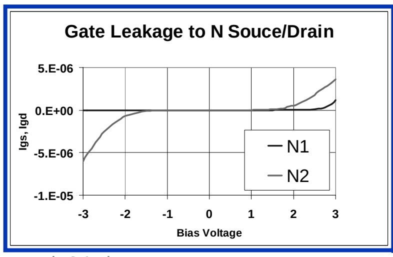
- With more than one probe we can localize to device with damage
- Measure leakages between Source/Drain to the Gate

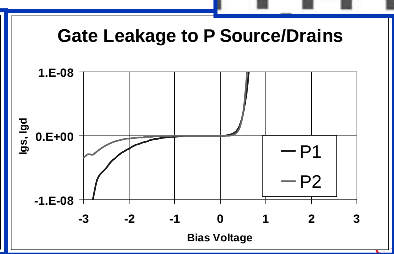


Using the IV Spectra to Localize *and* Characterize

- 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





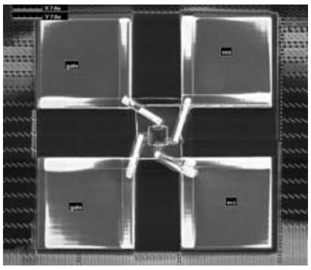


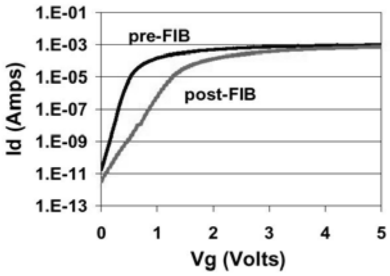
Deep Submicron Probing

- **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.**

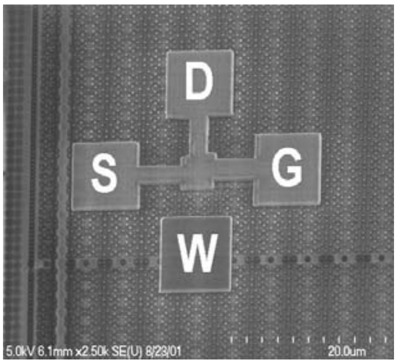
FIB Pad Probing at M1

- **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/um exposure**
- **Data from A Campbell et al. 1999 ISTFA**





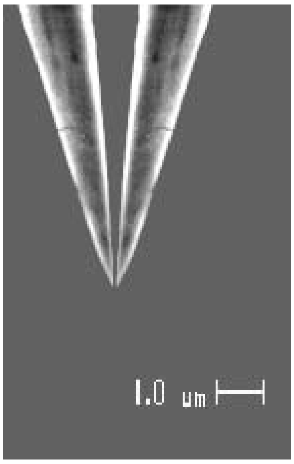
FIB contacts deposited on 0.13μm SRAM transistors at Contact Level



- 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 ΔVt
- 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

Technolog y Node	SRAM cell area	Req'd Probe Spacing	S/D/G triangle area	Best Probe
180nm	2.0μm	.5μm	.13 μm^2	250nm
130nm	1.5μm	.38μm	.07 μm^2	100nm
90nm	1μm	.25μm	.03 μm^2	
65nm	.8μm	.19μm	.018 μm^2	50nm
45nm	.6μm	.13μm	.009 μm^2	

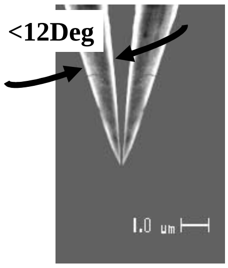
Adapting an AFM for Probing

- 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 = 50-250nm**
- **Probe Length L = 50-200mm**
- **Entrant Angle b = >a/2**
- **Taper Angle a = 6-50 Deg**
- **Spring Constant k = 1-1000N/m Stiff!**



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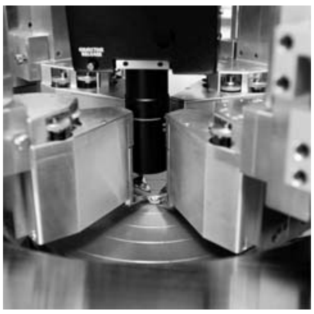
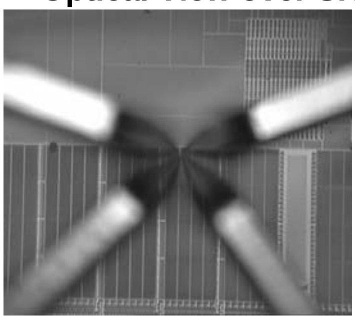
Optical Access for Gross Positioning

- **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**





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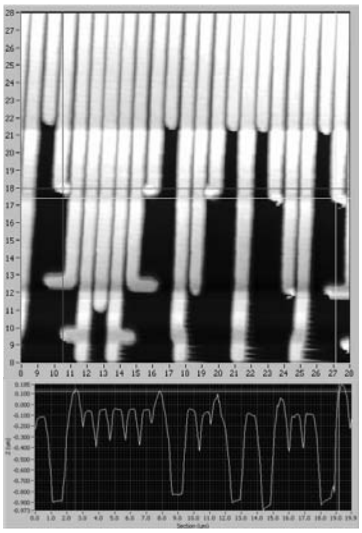
Tall M1 Lines and Section



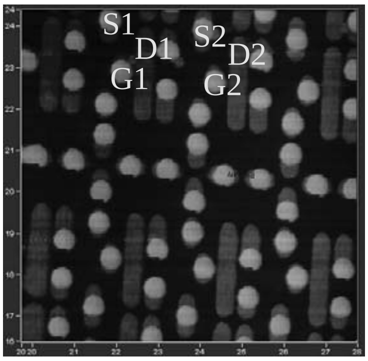
- **Probe is capable of scanning over tall structures**
- **Extended topography can be probed such as multiple metal layers**
- **Poly and silicide is also possible to probe**

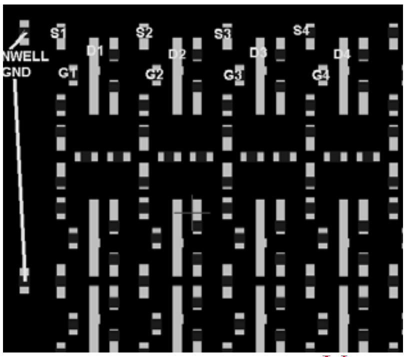
Optical View Low and High Mag

- **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**

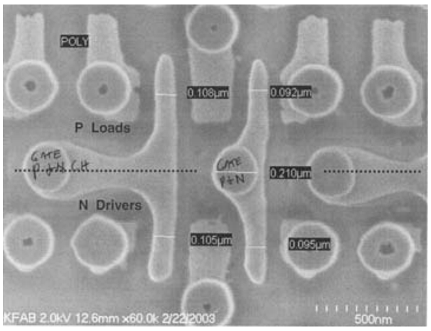




AFP Transistor Measurements

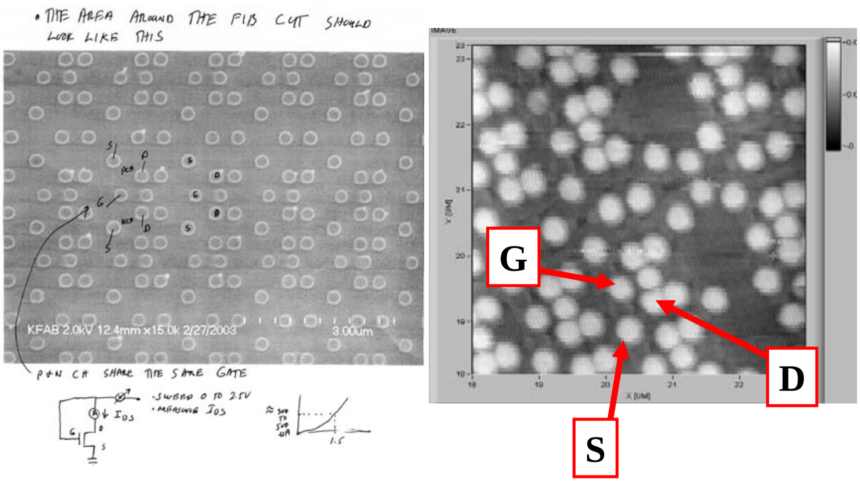
- **Probing examples from different nodes**
- **Methods for verifying contacts**
- **Good and Bad curve examples**

130nm Process Technology

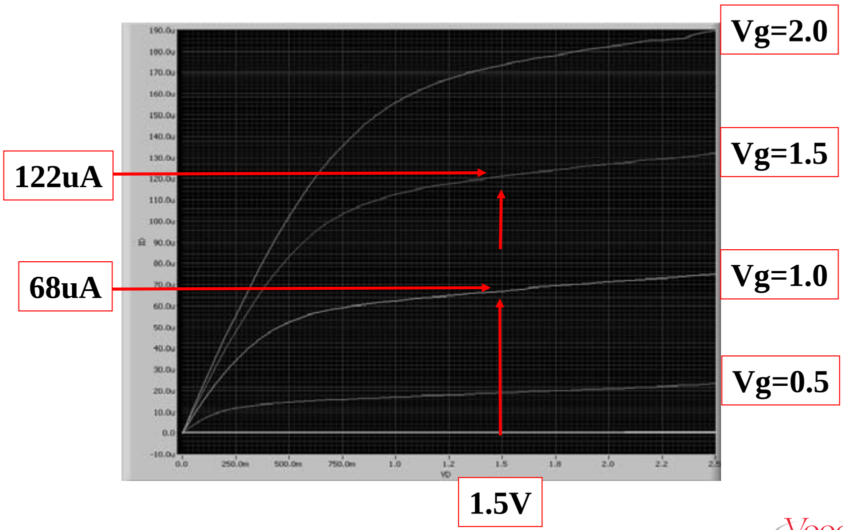


- This part has 90nm gate length making it a 130nm node part
- Notice the Plug Seam! This will come up later

SRAM Cache Layout



Ids vs Vds @ Vg = -0.5 to 2.0V



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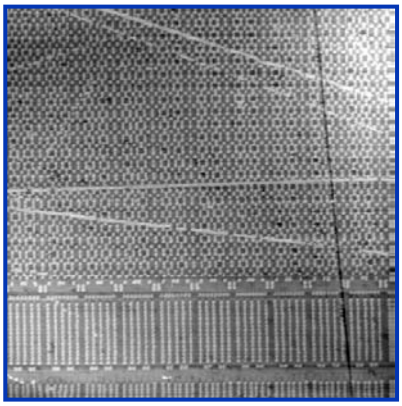
AFP Imaging of a 90nm part



- **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**

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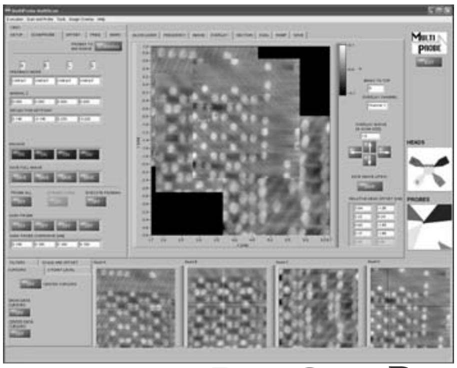
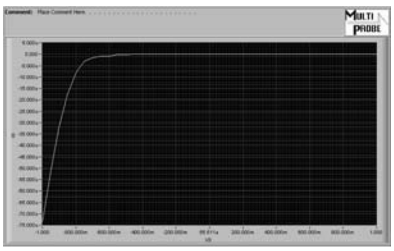
90nm Probing Example

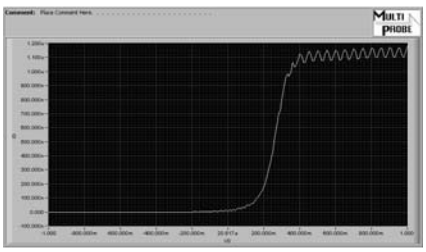


- Probes used are 100nm
- Minimum Pitch = .25µm
- Probes A, B, & D in a triangular area = 1/32nd μm^2
- Drag color coded cursors in each image to desired node
- Increase force to contact.

Diode Check to verify contact

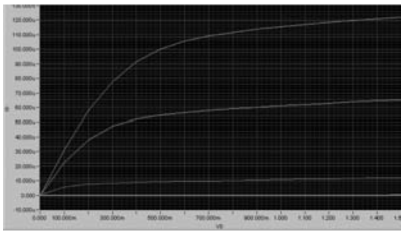
- Nfet Source/Drain Diode Check is easiest since it is just a diode to backside
- For sub 100ohm contacts you should get tens of microamps
- Sometimes substrate is resistive and diode check needs two probes
- For Pfet Diode Check it requires light to get a single probe backside contact.
- If you place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

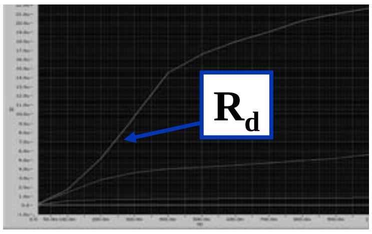




Contact Resistance Effects

- 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





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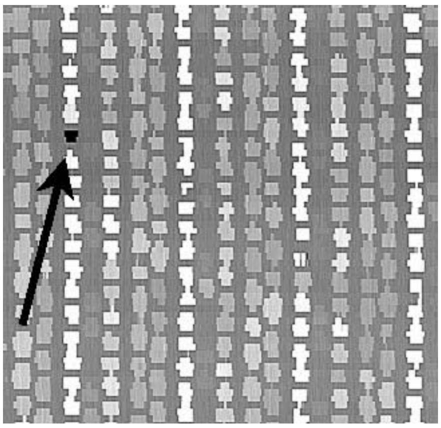
65nm Probing Requirements



- 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.

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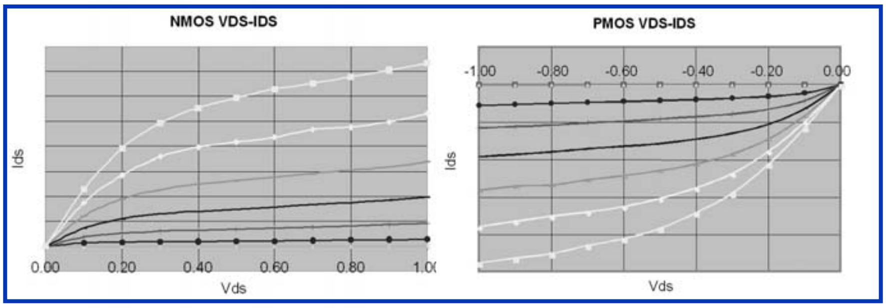
65nm SRAM Transistor

- **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**



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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.**

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