Ultra-High Resolution Nano-Electrical Measurements for Semiconductors (Part 1)
Peter De Wolf
Dec. 3, 2014

Atomic Force Microscopy
3D Optical Microscopy
Fluorescence Microscopy
Tribology
Stylus Profilometry
Nanoindentation

Innovation with Integrity
AFM-based Nano-Electrical Modes

- Conductivity / Resistivity: C-AFM, TUNA, Peakforce-TUNA, SSRM
- Electric Field: EFM
- Charge: EFM, SCM
- Surface Potential / Workfunction: KPFM, Peakforce-KPFM
- Carrier Density: SCM, SSRM
- Piezoelectric Properties: PFM
- Specialty Modes: Scanning Gate, Pyro-electric AFM, Photoconductive-AFM, 4-Point Probe, Non-linear Dielectric Microscopy…
AFM-based Nano-Electrical Modes
Some examples

SSRM on cross-sectioned MOS transistors
1.2x0.6 µm scan, log scale

Tunneling-AFM (TUNA) on carbon nanotubes
4x2 µm scan, 4pA scale

Peakforce-TUNA on PP/EPDM polymer blend
3x3 µm scan

Modulus

Adhesion

Height

Current
AFM-based Nano-Electrical Modes
Some examples

**KPFM**, 2x1 µm scan, potential map on InP nanowire with 3V electrical bias between contacts

**SCM**, 4x2 µm scan, carrier diffusion of cross-sectioned double-diffused SiC MOSFET
Practical Aspects:
The Electrical AFM Probe

- The electrical AFM tip should be: Conductive, Hard, Wear-resistant & Sharp. Good materials are Diamond, Pt, PtIr, Pt-Silicide.

Practical Aspects: Environment

- Many samples alter properties when exposed to Oxygen or Water
- At ambient conditions, a thin water layer on the sample can degrade the spatial resolution & influence electrical properties
- When applying voltages on some samples (metals, semiconductors,..), local anodic oxidation can take place and strongly influence the measurements

SSRM on ITO layer, 10x10 µm scan
Practical Aspects:
Environment - Glovebox

Dimension Icon AFM inside Glovebox

O$_2$ ~ 0.1ppm
H$_2$O ~ 0.1ppm
Practical Aspects: Environment - Glovebox

- Under ambient conditions, the conductivity map cannot observe the oxide layer.
- Under a controlled environment of < 1 ppm O₂ & H₂O the layer can clearly be observed.

SSRM on thin oxide layer
Nano-Electrical Characterization of Semiconductor Devices

- Lateral dimension of transistors continue to shrink
- New architectures (SOI, FinFET, TFETS,..) and materials (SiGe, Ge, III-V,..) are introduced
- ‘Classic’ 1D dopant profiling methods (SRP, SIMS,..) reach their limits

AFM-based 2D & 3D techniques with nm-resolution are needed
Ultra-high resolution nanoelectrical measurements for semiconductor applications. (Part 2)

P. Eyben, K. Paredis, A. Schulze, A. Nazir, U. Celano, R. Chintala, T. Hantschel and W. Vandervorst
Established by state government of Flandres in 1984 with initial staff: ~70

Imec’s staff has grown to 2,086 people in 2013. Of these, 383 are residents - visiting researchers from partner companies & institutes and 289 are PhD researchers.
OUR MISSION

- World-leading research in nanoelectronics
- Scientific knowledge with innovative power of global partnerships in ICT, healthcare and energy
- Industry-relevant technology solutions
- International top talent in a unique high-tech environment committed to provide building blocks for a better life in a sustainable society
MCA DEPARTMENT AT A GLANCE

Materials & Components Analysis department

MCA: ~50 people
Researchers: ~15  R&D support: ~20
PhD students: ~10 MSc students: ~5

MCA-CA
SIMS
RBS/ERD
APT

MCA-CSA
TOFSIMS
XPS

MCA-NP
Nanoprober, Raman,
Conductive diamond

MCA-SA
TEM
FIB

CAMS

MCA-SPM
SSRM
KPFM
C-AFM
STM
RESEARCH IN THE SPM TEAM

TCAD CALIBRATION (SSRM)

DEVELOPMENT OF NEW AFM MODES (FFT-SSRM,...)

TOMOGRAPHY (SSRM, C-AFM,...)

ANALYSIS OF CBRAM (C-AFM)

DEFECTS IN III-V SC (NC-AFM, STM, KPFM)

ELECTRICAL PROPERTIES OF ORGANIC SC (C-AFM, KPFM)
SSRM CONCEPT

\[ R_{\text{meas}} = R_{\text{probe}} + R_{\text{spreading}} + R_{\text{sample}} + R_{\text{bc}} \]

\[ R_{\text{spreading}} = \frac{\rho}{4a} \]

\[ \rho = \frac{1}{e\mu_n n} \quad \text{or} \quad \rho = \frac{1}{e\mu_p p} \rightarrow n \quad \text{or} \quad p = \frac{1}{4ae\mu R} \]
DEDICATED DIAMOND TIPS FOR SSRM

Tips made of (boron) doped diamond in order to withstand the large pressures (and shear stresses) involved during SSRM.

Two tip technologies available:
- Coated diamond tips (CDT)
- Full (molded) diamond tips (FDT)

Nano-protrusions at the tip apex:
→ Reduced contact size
→ Possible multiple nano-contacts

FDT present a lower aspect ratio vs. CDT → no tip breakage
FDT are sharper and present smaller diamond grains at their outer surface vs. CDT → leading to better resolution

SSRM NANOCONTACT

Ref.: K. Mylvaganam et al. @ Nanotechnology 20 (30) p. 305705 (2009)
LIMITATIONS OF SSRM IN AIR

• Commercial Coated Diamond Tips (CDT) can not be used for high resolution SSRM

• Percentage of working home-made Full Diamond Tips (FDT) that can be used for high resolution SSRM is too low

• Signal to noise ratio is too low

• Repeatability and reproducibility are too low (Sample and tip damaged relatively quickly)

<table>
<thead>
<tr>
<th></th>
<th>SSRM</th>
<th>ITRS 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral/vertical steepness of dopant profile (nm/decade)</td>
<td>1 - 2</td>
<td>1.6</td>
</tr>
<tr>
<td>Lateral/depth spatial resolution for 2D dopant profile (nm)</td>
<td>1 - 3</td>
<td>1</td>
</tr>
<tr>
<td>Dopant profile concentration precision across concentration range (%)</td>
<td>5-20%</td>
<td>2%</td>
</tr>
<tr>
<td>Dynamic range (at/cm³)</td>
<td>10¹⁵ - 10²⁰</td>
<td>10¹⁴ - 10²¹</td>
</tr>
</tbody>
</table>
IMPACT OF HUMIDITY

In the presence of water, the growth of b-Si (6 coord.) is retarded
→ Need to push more

In the presence of water, the volume of transformed silicon is higher
→ Lower resolution

Ref.: C.Y. Tang et al. @ Nanotechnology 16, p.15 (2005)
IMPROVED SSRM PERFORMANCES

- Quantified SSRM profile matches with SIMS
- Improved resolution (0.6-1 nm)
- Improved signal to noise level ratio (noise <10%)

<table>
<thead>
<tr>
<th></th>
<th>SSRM</th>
<th>ICON-GB</th>
<th>ITRS2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral/vertical steepness of dopant profile (nm/decade)</td>
<td>1 - 2</td>
<td>1 - 1.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Lateral/depth spatial resolution for 2D dopant profile (nm)</td>
<td>1 - 3</td>
<td>0.6 - 1</td>
<td>1</td>
</tr>
<tr>
<td>Dopant profile concentration precision across concentration range (%)</td>
<td>5-20%</td>
<td>3-5%</td>
<td>2%</td>
</tr>
<tr>
<td>Dynamic range (at/cm³⁻³)</td>
<td>10¹⁵ - 10²¹</td>
<td>10¹⁵ - 10²¹</td>
<td>10¹⁴ - 10²¹</td>
</tr>
</tbody>
</table>

Diagram 1: 0.3-0.5 nm oxide

Diagram 2: Average repeatability (%) for Air, ICON-GB, and UHV

Diagram 3: Dopant carrier concentration (cm⁻³) vs. Depth (nm)
SAMPLE PREPARATION FOR SSRM

- Most measurements performed on cross-sections (XS)

- Protective SiO$_2$ and Si/glass dummy used to protect the XS edge

- Back-contact (BC) employed to collect the spreading current:
  - Performed manually using GaIn eutectic covered with Ag-paint
  - On shorter structures FIB used to place local BC down to 1 µm from the XS edge (= distance to avoid Ga contamination on the XS)
ADVANCED SAMPLE PREPARATION

- Cross-section:
  - **Polishing** using diamond and Al₂O₃ foils (RMS roughness < 0.6nm).
  - **Micro-cleavage** SELA MC600. (Position XS determine with 300nm accuracy, less defects and extrinsic SS, RMS roughness < 0.4nm).
  - **Ga FIB lapping** @ low incidence angle (1deg) and energy (3-5keV). (<10nm accuracy)

- FIB can also be used to **mark area(s)** of interest and/or to generate local BC pads.
APPLICATION: PROCESS CALIBRATION (DRAM)

Processing: implantation (dose, energy,...), annealing (diffusion, activation,...)

SSRM: measurement and quantification

Device simulations

Predict the device performance and compare them to measured electrical data

Processing:
- Implantation (dose, energy,...)
- Annealing (diffusion, activation,...)

SSRM:
- Measurement
- Quantification

Device simulations:
- Predict the device performance
- Compare to measured electrical data
APPLICATION: CMOS IMAGE SENSOR

Individual Pixels of Image Sensors

SSRM provides high resolution 2D carrier distributions inside the individual pixels of a CMOS image sensor.

SSRM image with courtesy of www.imec.be/cams
APPLICATION : DRAM TRENCHES

Implant out-diffusion at the top and bottom of the DRAM trenches.

SSRM image with courtesy of www.imec.be/cams
APPLICATION: POWER MOSFET

Dopant concentrations inside an integrated Schottky diode in a power MOSFET device.

SSRM image with courtesy of www.imec.be/cams
APPLICATION : InP/InGaAs FINFET

InP(Mg)/InGaAs(Si) in V-STI trenches

- A large in-diffusion of P into the Si substrate is measured.
APPLICATION : Ge FINFET

SiGe / strained Ge in STI trenches

- P-doping level in SiGe and P diffusion into strained Ge
- Higher P concentration noticed in Ge
APPLICATION: Vertical hetero TFET
Tomography: How to realize 3D-SSRM?

- Use of dedicated staggered test-structures (implemented on FinFETs)
- Use of slice and view concept (implemented on CNT interconnects)

**COMPARATIVE STUDY**

<table>
<thead>
<tr>
<th></th>
<th>Staggering</th>
<th>Digging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution in 3rd direction</td>
<td>2-3nm</td>
<td>3-5nm</td>
</tr>
<tr>
<td>Dedicated test-structure needed</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Versatility (different materials present,..)</td>
<td>YES</td>
<td>More limited</td>
</tr>
</tbody>
</table>

© IMEC 2014 / CONFIDENTIAL
3D-SSRM ON NW-TFET
3D-SSM ON CNT-BASED INTERCONNECTS:
Tomogram of individual CNTs in contact hole

Ref: A. Schulze et al., Nanotechnology 23 (2012) 305707
3D-SSRM ON FINFET

Possible short between gate and plug due to poor alignment

Possible leaky junction of the drain

Fin under gate

30nm < 10nm

15nm
3D C-AFM ON CBRAM

Filament evolution from top to bottom electrode

(Rem. Rate 0.7 nm/scan)

Conductive (filament) Bridging Device

U. Celano et al., Nanoletters, 2014, 14, 5, 2401

[Schindler et al., APL 2009, 94, 072109]
C-AFM ON ORGANIC SOLAR CELLS

P3HT:PC[60]BM

P3HT:PCBM

PEDOT:PSS

ITO

Cross section view of spray coated P3HT:PCBM (1:1) BHJ solar cell

Operation principle

- P3HT:PCBM 1:1 ratio
- 200 nm active layer
- η~4%

- Craters with varying depth were made using Ar cluster beam
- Depth profile using SPM techniques based on electrical properties of P3HT and PCBM
C-AFM-BASED DEPTH PROFILING:
Vertical phase segregation & efficiency of exciton dissociation

On degraded sample, no more P3HT plateau → poorer efficiency

Hypothesis:
- 100% optical absorption
- Equal absorption for P3HT and PCBM
- 10 nm exciton diffusion length

\[ \eta_{\text{fresh}} = (87 \pm 3)\% \]

\[ \eta_{\text{degraded}} = (65 \pm 5)\% \]
QUESTIONS?

Ultra-high resolution nanoelectrical measurements for semiconductor applications.

P. EYBEN, J. MODY, A. NAZIR, K. PAREDIS, A. SCHULZE, T. HANTSCHEL AND W. VANDERVORST