Transmission Electron Microscopy for metrology and characterization of semiconductor devices

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Trends in Semiconductors Industry

Device scaling ("More Moore"), today's technology challenges:

**New 3D device structures**

**New materials & chemistry**

Complex, marginal processes .... Critical dimensions in 3D, < 10 nm
Trends in Semiconductors Industry

TEM Microscopy for two use cases: analytics & metrology

**Analytics & Defect analysis**
*(EDX, EELS, Diffraction)*

**Metrology**: CD’s, pitch, LER, OL,...

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1. TEM Microscopy with images of various samples, including Ni2Si, NiSi, Si, and a graph showing energy loss vs. energy.
2. Images of SiGe and SiGe CD’s with different measurements indicating LER: a check mark for good and an X for bad.

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Trends in Semiconductors Industry

TEM demand explodes to meet 3D transistor and litho challenges

- **Faster** TEM data and **more** TEM data:

- TEM transition: *from Lab to Fab*

> TEM microscopy needs to be fast, automated and easy to use

*(and sensitive, accurate & reproducible for metrology)*

Information source: Intel, SPIE 2016
A new STEM metrology workflow

TEM microscopy requires a workflow with different tools to
• Prepare thin TEM lamellas from full wafers
• Extract TEM lamellas from wafer, return wafers in manufacturing line
• Measure TEM lamellas in TEM microscope

From wafer to Microscopy data
FEI’s TEM workflow developments in EU projects
A “TEM metrology box” with FEI technology inside

What Newly developed Technologies are inside?

• **Phase 1: new METRIOS TEM platform**
  – Automated microscope alignments, active drift control
  – Automated image acquisition
  – Automated STEM and TEM metrology

• **Phase 2: extended capabilities**
  – Software Embedded spherical aberration Corrector
  – Software Embedded EDX acquisition

• **Phase 3: improved capabilities**
  – New EDX detector
  – Automated EDX metrology
  – Improved accuracy: calibration and distortion corrections
Probes}\textsuperscript{Cs} correctors, ease-of-use!

Corrector Technology is not new, but the important innovation is that

\textit{Abberation correction has become a simple push button operation!}

- operators can use it instantaneously, automatically; it works and provides consistent, excellent results
- Example: 14 nm device using OptiSTEM

Starting Point:

\begin{itemize}
  \item 1\textsuperscript{st} order
  \item focus + stigmatism
\end{itemize}

C1A1 correction at ‘low’ mag:
(STEM) Probe Cs correctors

Corrector Technology is not new, but the important innovation is that

*Abberation correction has become a simple push button operation!*

- operators can use it instantaneously, automatically; it works and provides consistent, excellent results
- **Example: 14 nm device using OptiSTEM**
  Zoom in on silicon after 1\(^{st}\) order:

  ![Image of first-order correction](image1)

  Once per day, A2B2 correction:

  ![Image of second-order correction](image2)

  2\(^{nd}\) order

  Axial coma + 3fold stigmatism
The (demonstrated) benefits of automation

**Manual STEM metrology**
- High Resolution (~ 1.1 Å)
- Accurate (~ 1 %)
- CD info in 3D
- Image based, No modeling

| CD, Profile, LWR, any | Any structure | Slow & No Statistics | Accurate | Destructive |

**Automated STEM metrology**
- Slow
- No Statistical data
- Poor precision: (3% 3 σ)
- Fast (~ 10 x faster)

![Graph comparing time per sample for automated and manual methods](image)
The (demonstrated) benefits of automation

**Manual STEM metrology**
- High Resolution (~ 1.1 Å)
- Accurate (~ 1 %)
- CD info in 3D
- Image based, No modeling

25 nm

**Automated STEM metrology**
- Fast (~ 10 x faster)
- Statistical Data (10 x more)

21 samples/wfr
45 devices/sample
5 CD’s / device
~ 5000 data / 10 hrs
The (demonstrated) benefits of automation

<table>
<thead>
<tr>
<th>Manual STEM metrology</th>
<th>Automated STEM metrology</th>
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<tbody>
<tr>
<td><strong>CD, Profile, LWR, any</strong></td>
<td><strong>STEM Metrology Dynamic Precision</strong></td>
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<tr>
<td><strong>Any structure</strong></td>
<td><img src="chart.png" alt="STEM Metrology Dynamic Precision Chart" /></td>
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<tr>
<td><strong>Slow &amp; No Statistics</strong></td>
<td>Manual Metrology</td>
</tr>
<tr>
<td><strong>Accurate</strong></td>
<td>Automated Metrology</td>
</tr>
<tr>
<td><strong>Destructive</strong></td>
<td>TopWidth</td>
</tr>
<tr>
<td><strong>Slow</strong></td>
<td>Fast (~ 10 x faster)</td>
</tr>
<tr>
<td><strong>No Statistical data</strong></td>
<td><strong>Statistical Data</strong> (10 x more)</td>
</tr>
<tr>
<td><strong>Poor precision: (3% 3σ)</strong></td>
<td><strong>Adequate precision</strong> (1% 3σ, 3x better)</td>
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<tr>
<td><strong>High Resolution (~ 1.1 A)</strong></td>
<td><strong>Accurate (~ 0.4 %, 2x better)</strong></td>
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<tr>
<td><strong>Accurate (~ 1 %)</strong></td>
<td></td>
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<tr>
<td><strong>CD info in 3D</strong></td>
<td></td>
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<td><strong>Image based, No modeling</strong></td>
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Metrios analytical STEM application examples
EDX based metrology of 3D VNAND memory

\[ \text{Difficult (diffraction) contrast in direct STEM images for ONO metrology} \]
EDX based metrology of 3D VNAND memory

Plan view EDX map with line scan

EDX line scan

EDX provides chemical contrast and is well adapted for ONO metrology

- TiN = 2.5 nm, $\text{AlO}_x = 3.0$ nm
- Si = 12.2 nm
- NONO = 2.6/4.2/4.3/9.7 nm
Plasma doping of FINFET (damage and profile)

Plasma doping does not create significant damage in the FIN silicon lattice
Plasma doping of FINFET (damage and profile)

EDX shows As doping accumulation at Si-SiO₂ interfaces
iDPC
a new STEM imaging technique
Imperfection of (S)TEM imaging techniques

GaN [110]
(schematic)

ABF-STEM

HAADF-STEM

Ga
N
Ga
N
New technique: iDPC-STEM

GaN [110]

Titan FEI: iDPC-STEM of GaN [110]

- High tension: 300 keV
- Opening angle: 21 mrad
- Cs corrected
**iDPC How does it work? GaN**

**4 Segment Detector**

- $E_x = \frac{\partial V}{\partial x} = Q_1 - Q_3$
- $E_y = \frac{\partial V}{\partial y} = Q_2 - Q_4$

$$\mathcal{F}\{i^{DPC}\} = \frac{1}{2\pi} \mathcal{F}\{|\psi_{in}|^2\} \cdot \mathcal{F}\{\varphi\}$$

$i^{DPC}$ (represents $\varphi$)

$$\varphi = \sigma V$$

Integration (electric field is conservative)

**Patent:**
- US 9,312,098 B2
- Lazić et al.


**Calculation:**

$$\overrightarrow{I^{DPC}}(\vec{r}_p) = \nabla \cdot \overrightarrow{I^{DPC}}(\vec{r}_p)$$
Why do(n’t) we see Nitrogen?

GaN $[1\overline{1}20]$ (experiment)

Periodic system of elements (simulation)

ABF$^{[2]}$

iDPC (object $\varphi)^{[1]}$

ADF (object $\varphi^2)^{[2]}$


Examples on GaN[211] zeolite interfaces LiTi2O4 Semicon devices
Ultimate lateral resolution
Comparison iDPC with HAADF on GaN [211]

More information accessible
Light and heavy elements imaged at the same time
with sub Angstrom resolution
Low-dose imaging with iDPC: Zeolite

• Zeolite imaged at 300 keV

• Dose: 961 e⁻/Å²

• Sample damages at dose of 5000 e⁻/Å²

• Not possible to focus using ADF image

Imaging of extremely sensitive materials possible
Interface termination: iDPC-STEM images of ZrO$_2$/Ni interface

HAADF

Sample: courtesy of Prof. Dr. Wayne Kaplan, Israel Institute of Technology Technion

| Titan Themis 300 STEM at 300kV |
|-------------------------------|-----------------|
| Image size: 512x512            | Frame time: 6 s |
| Detector: DF4/iDPC            | Converg. angle: 21 mrad |

Imaging of atomic configuration of the interface and the termination of the substrate
Extremely light element imaging
Simultaneous ADF-STEM vs. iDPC-STEM

Li clearly visible within LiTi$_2$O$_4$ using iDPC-STEM
Extremely light element imaging iDPC-STEM: Experiment vs. simulation

Observation from comparison with simulations:

- Li is visible if beam best focus is inside sample
- In top-right corner Li is visible: Sample is probably thicker than 20 nm
- Defocus change consistent with thickness change
Contrast enhancement on semicon devices: STEM – EDS

STEM EELS in Talos

<table>
<thead>
<tr>
<th></th>
<th>200kV</th>
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<tbody>
<tr>
<td>Acquisition:</td>
<td>17 min</td>
</tr>
<tr>
<td>System mag.:</td>
<td>910 kx</td>
</tr>
<tr>
<td>Current</td>
<td>250 pA</td>
</tr>
<tr>
<td>Drift corr.:</td>
<td>On</td>
</tr>
<tr>
<td>Map size:</td>
<td>406x384</td>
</tr>
<tr>
<td>Display:</td>
<td>Raw counts, smoothed</td>
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</tbody>
</table>
Contrast enhancement on semicon devices

STEM & iDPC @ low dose

Contrast enhancement at only ~1000pe/pixel electron dose
Conclusions

• The newly developed automated Metrios Metrology TEM microscope combines ease of use with excellent metrology capabilities now adequate for 10 nm device technology:
  - precision ~ 0.2 nm 3σ, accuracy ~ 0.4%

• Automated and sensitive STEM-EDX allows for fast chemical characterization (dopants, stoichiometry,..) but also complements STEM metrology for low contrast materials (e.g. ONO layer stacks)

• Statistically relevant (S)TEM data provide new solutions for process control of advanced devices: Line roughness analysis (LWR and LER), Hybrid (reference) metrology for e.g. OCD or CD-SEM

• iDPC-STEM is direct and linear imaging electrostatic potential of the sample.

• It is capable of imaging light and heavy elements together.

• It is a low dose technique with superior contrast, which enables to handle sensitive materials in metrology applications.
Thank you!