Metrology and Characterization for Extending Silicon CMOS

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• Requirements for measurement/characterization technology
• Characterization/metrology for local probing of material structures and properties
  – Physical dimensions (CD & LER)
  – Local strain in Si
  – Dopant / potential distributions
• Conclusion
Problems and solutions for CMOS evolution

Major Issues
• Simple scaling no more works well.

Technology boosters (New materials): $I_{on} \uparrow I_{off} \downarrow$
• Variability increases.

To understand, predict, design and control new technologies while minimizing variation, Characterization and metrology of local properties and structures are needed.
Metrology and Characterization with High-spatial Resolution

Process compatibility

Production

R&D

Low
Inherent Spatial Resolution
High

Physical dimensions of 3D structures

scatterometry

CD-SEM

CD-AFM

TEM

Source
Drain

BOX

Multi-gate FET
High-Precision CD Metrology by AFM

CD-AFM with Laser interferometer

- Resolution 0.05 nm
- Modularized Laser interferometer
- 3D AFM scanner: parallel spring mechanism.
- Laser interferometer: DSP-based processing

Sidewall and line edge roughness measured by tilt-step-in operation

- Tilt-step-in operation
- ArF resist/ Low-k patterns

S. Gonda et al., Characterization and Metrology for ULSI Tech., 2005

K. Murayama et al, SPIE, 2006
Strain distribution

Mobility enhancement by

- **Local strain**
  - T. Ghani et al., IEDM (2003) 978
  - pMOS
  - nMOS

- **Global strain**
  - T. Numata et al., MIRAI, IEDM (2004) 177
  - Strained Si layer

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- UV Raman scattering
- Near-field Raman scattering
- CBED, Nano-beam diffraction

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Process compatibility

Inherent Spatial Resolution

- Low
- High
NBD (NanoBeam electron Diffraction)

Si(x,z) = (5.474 \, \overline{\text{Å}}, 5.417 \, \overline{\text{Å}})

SiGe(x,z) = (5.469 \, \overline{\text{Å}}, 5.504 \, \overline{\text{Å}})

Si(x,z) = (5.433 \, \overline{\text{Å}}, 5.433 \, \overline{\text{Å}})


Strain in a MOSFET channel

Poly-Si

Strained-Si

Relaxed-SiGe buffer layer

Z-axis

X-axis

Tensile strain

X-axis

Z-axis

Lg=1 \, \mu m

Comp. res. < \Delta d/> Tensile

0.01

0.006

0.002

-0.002

-0.006

-0.01

Left

Center

Right

Position

Confocal/probe-excited UV Raman microscope

- **AFM** probe
  - AFM probe with position-sensitive detector
  - **λ** = 675 nm for AFM

- **Spectrometer**
  - **λ** = 364 nm

- **Strained Si**
  - Raman Intensity (arb. units)
  - Si substrate
  - Si-Ge

- **Raman Shift (cm⁻¹)**: 490, 500, 510, 520, 530, 540
  - 364 nm
  - 514 nm

- **SiO₂**
  - 400 nm

- **Int intensity cross section**
  - 125 nm
  - NA 1.3 immersion
  - 10% / 90%

- **Fitting resolution**
  - Intensity cross section.
Stress distribution in STI structures by confocal microscope

1D Raman maps across single Si stripes compressed by STI

Analysis using polarization dependence of Raman scattering

Raman Intensity (a.u.)

aa-configuration

cc-pol. (parallel to stripe)

cc-pol. (parallel to stripe)

aa-pol. (perpendicular to stripe)

aa-pol. (perpendicular to stripe)

Raman Shift (cm⁻¹)

STI bottom corner 515.0

middle of stripe 523.5

side wall 521.1

100 nm

300 nm

300 nm

400 nm

SiO₂

Si(001)

Si

SiO₂

SiO₂

1.4 µm

1.4 µm

330 MPa

330 MPa

180 MPa

180 MPa

E // [110]

E // [110]

E \ [110]

E \ [110]

330 MPa 180 MPa

~900 MPa

Compression

300 nm ~ 1650 MPa

Tension

FDTD simulation
Raman scattering excited by metal-particle-topped AFM-probe

Principle

25 nm-thick Strained Si on 27 nm-thick Si$_{0.7}$Ge$_{0.3}$

TEM image

2D mapping by confocal microscope

Raman scattering excited by metal-particle-topped AFM-probe

Stress distribution around a oxidized hole

Probe-excited Raman scattering

## Local Strain Metrologies

<table>
<thead>
<tr>
<th>method</th>
<th>sensitivity</th>
<th>Spatial resolution</th>
<th>feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe excited Raman scattering</td>
<td>0.05 cm⁻¹</td>
<td>~50-100 nm</td>
<td>Non-destructive</td>
</tr>
<tr>
<td></td>
<td>(Δ ~ 0.005%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UV Raman scattering</td>
<td>0.05 cm⁻¹</td>
<td>~130 nm</td>
<td>Non-destructive</td>
</tr>
<tr>
<td></td>
<td>(Δ ~ 0.005%)</td>
<td></td>
<td>Non-contact</td>
</tr>
<tr>
<td>CBED (Convergent beam electron diffraction)</td>
<td>△ d/d = 0.02%</td>
<td>~20 nm</td>
<td>High precision</td>
</tr>
<tr>
<td>NBD (Nano-beam electron diffraction)</td>
<td>△ d/d = 0.1%</td>
<td>~10 nm</td>
<td>High spatial resolution</td>
</tr>
</tbody>
</table>

△ strain
STM for dopant profiling

Spatial resolution for 2D/3D dopant profile better than 2.8 nm by 2007 (ITRS 2005)

Scanning Tunneling Microscopy (STM)

Cross section of FET

STM Features

- atomic resolution
- ability to measure atomic and electronic structure, surface potential, and individual dopant atoms through various measurement modes: topography, I-V, dI/dz

Vacuum-Gap Modulation

- local work function

Direct counting of dopant atoms

Hydrogen passivation

Bolotov, poster No.098, this conference
STM observation on atomically flat and hydrogenated surface

STM Topography: height image

Key process
Flattening and hydrogenation of (111) surface by aqueous NH₄F treatment followed by dopant reactivation at ~400°C

Simultaneous measurement of potential and dopant atom

- **Potential Fluctuation and Charge Distribution**
  - Substrate bias voltage: $V_s$
  - Donor distribution correlates with the potential fluctuation.

### Imaging of dopant atoms

<table>
<thead>
<tr>
<th>$V_s$</th>
<th>acceptor negative charge</th>
<th>donor positive charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_s &gt; 0$</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>$V_s &lt; 0$</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>

- **Sample Image**
  - $V_s = +1.7 \text{ V}$, $I_t = 6 \text{ pA}$
  - 40 nm scale
  - Red spots: Donors
  - Blue spots: Acceptors
Quantitative potential profiling by $I$-$V$ measurements

Potential simulation

$V_s = +1.7 \, \text{V}, \, I_t = 6 \, \text{pA}$

$I$-$V$ measurement

STS
(scanning tunneling spectroscopy)

Issues

- Potential distortion by STM bias
- $V_s = V_{gap} + V_{BB}$ unknown

Potential simulation

abrupt junction

$n$: 2 $\times$ $10^{19}$ cm$^{-3}$
$p$: 1 $\times$ $10^{18}$ cm$^{-3}$

Sample Bias Voltage (V)

Distance (nm)

Sample Bias Voltage (V)

Tunnel Current (nA)

Position

CBM = $E_F$tip

VBM = $E_F$tip

CBM

VBM

Depletion~50 nm

$\sim 0.9 \, \text{V}$

M. Nishizawa et al, to be published in APL 2007
Resonance energy vs. Substrate Fermi level

### Two-dimensional dopant profiling methods

<table>
<thead>
<tr>
<th>Principle</th>
<th>Spatial resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic contrast</td>
<td>atomic $\sim 1$ nm</td>
</tr>
<tr>
<td>Internal potential</td>
<td>$\sim 5$ $\sim 10$ nm</td>
</tr>
<tr>
<td>Kelvin Force Microscope</td>
<td>$\sim 100$ nm</td>
</tr>
<tr>
<td>TEM Z</td>
<td>$\sim 1$ nm</td>
</tr>
</tbody>
</table>
Conclusion

For further extension of CMOS evolution
- To implement new booster technologies and to minimize variation, characterization and metrology of local properties and structures are needed.
  - e.g., CD & LER, Local strain in Si, Dopant distributions

- Various methods must be comprehensively used;
  - Optical, SEM/TEM, Scanning probe in conjunction with Simulations (TCAD), because no single method can give complete information in nm regions.
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Sample preparation
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  H. Fukutome of Fujitsu Laboratory Ltd. for the $p$-$n$ junction samples.

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