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# Metrology and Characterization for Nanoelectronics

Toshihiko Kanayama
MIRAI-Advanced Semiconductor Research Center,
AIST, Japan

# Contents

- Why do we need measurement/characterization techniques for nanoelectronics?
- Characterization/metrology for local probing of material structures and properties
  - Physical dimensions
  - Local strain in Si
  - Dopant / potential distributions
- Conclusion

## Nanoelectronics: Exploitation of Nanostructures for Information Processing
## ⇒ Performance is sensitive to structures.

Source
Drain

6 nm
10 nm
Metal (FUSI) Gate
High-k ($HfAlO_x$)
SOI
$NiSi_2$
BOX
Region A
$NiSi_2$
Si
Region B
(111)
54.7°
$|I_d|$ ($\mu A/\mu m$)
$V_d$ (V)
$L_{phys}$=6 nm
$\Delta V_g$=0.2 V
$|V_g|$=1 V

G
S
D

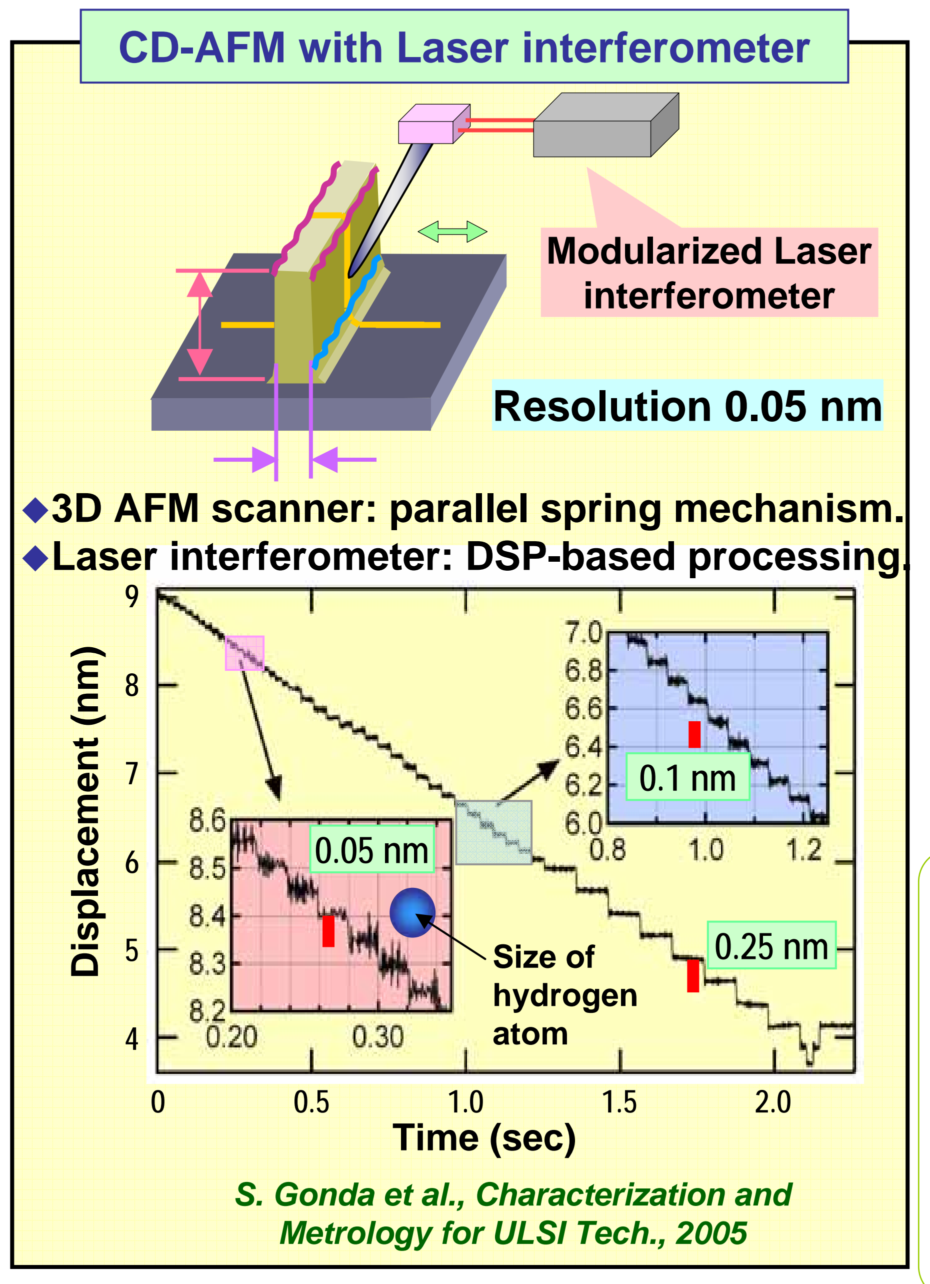
**Nano-wire transistors**

**Metal nano gap**

To understand and control nanoelectronics devices while minimizing variation,
Characterization and metrology of local properties and structures are needed.

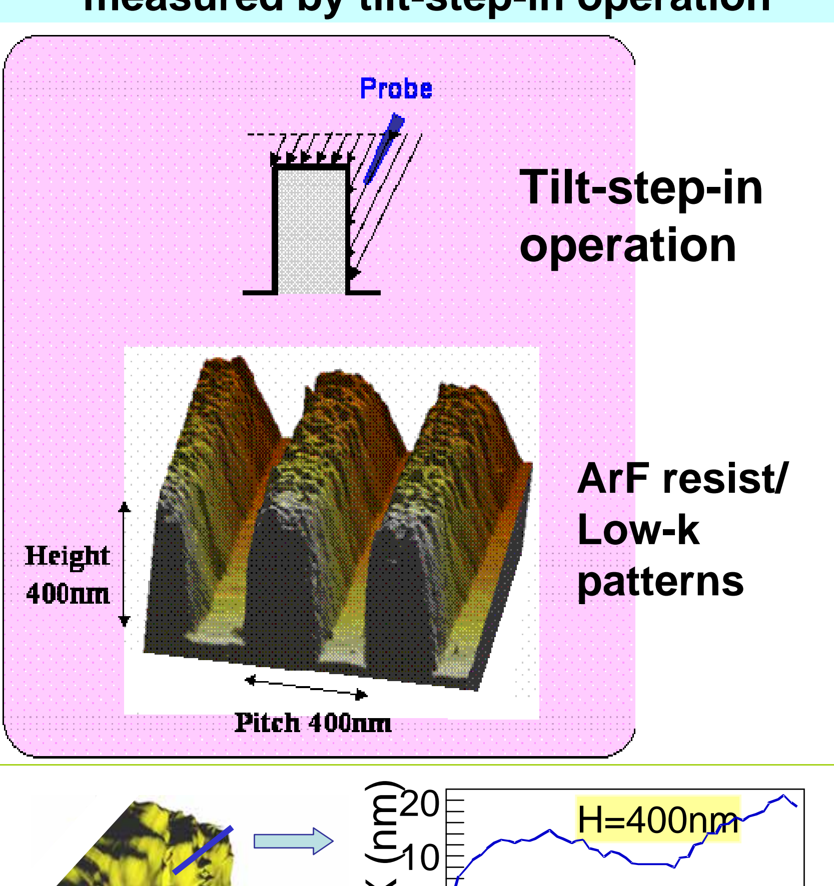
# Metrology and Characterization with High-spatial Resolution

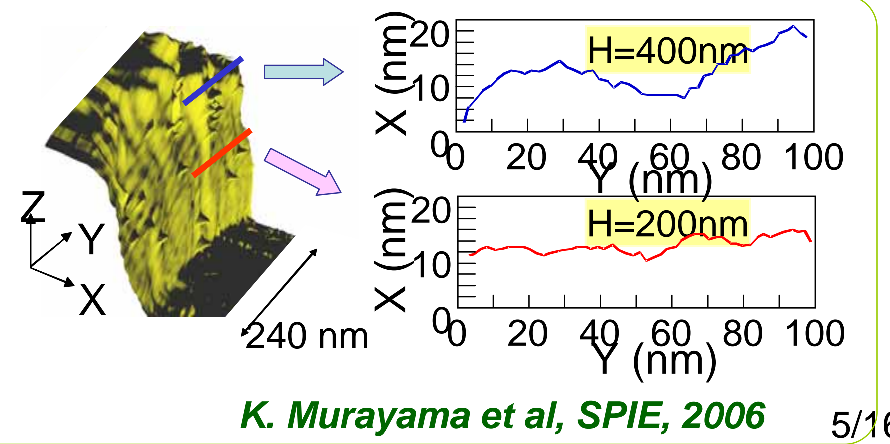
# High-Precision CD Metrology by AFM




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

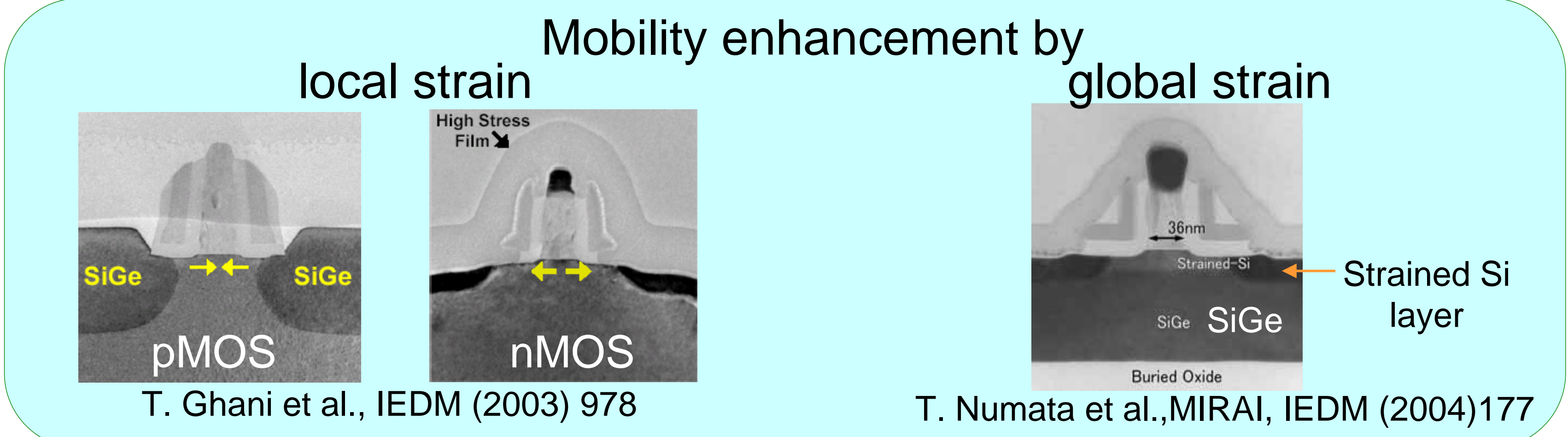
## Sidewall and line edge roughness measured by tilt-step-in operation




*K. Murayama et al, SPIE, 2006*

# Strain distribution

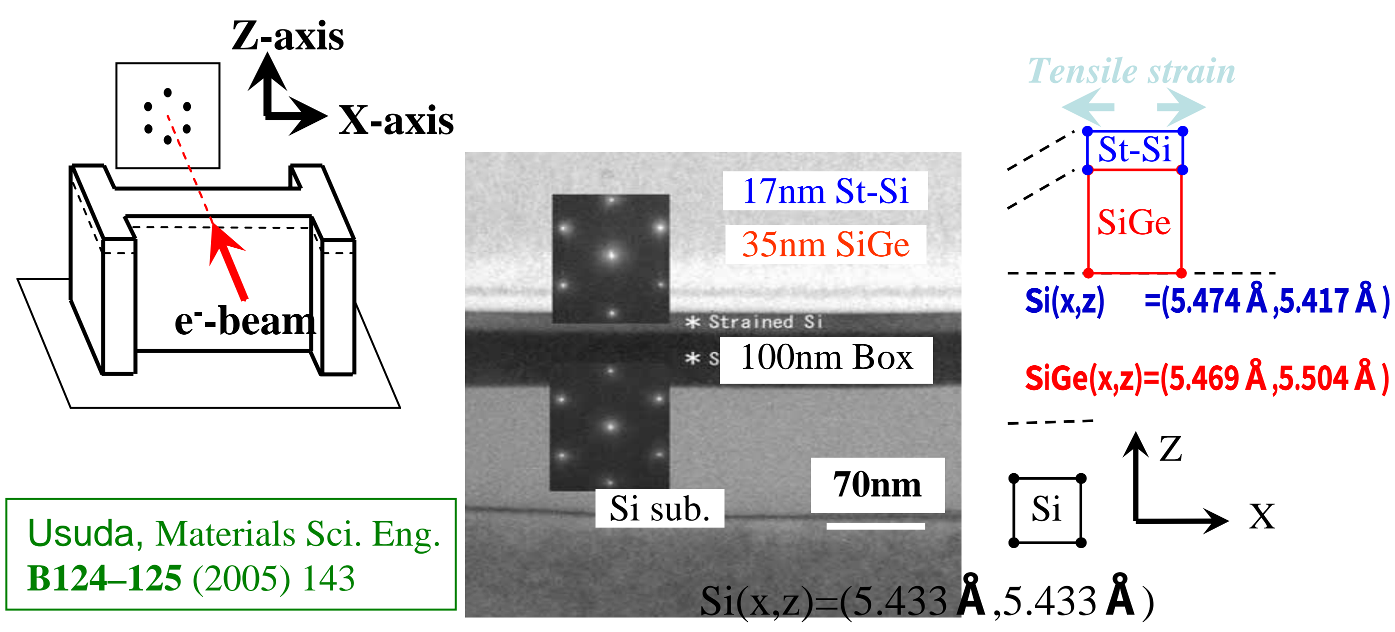



T. Ghani et al., IEDM (2003) 978

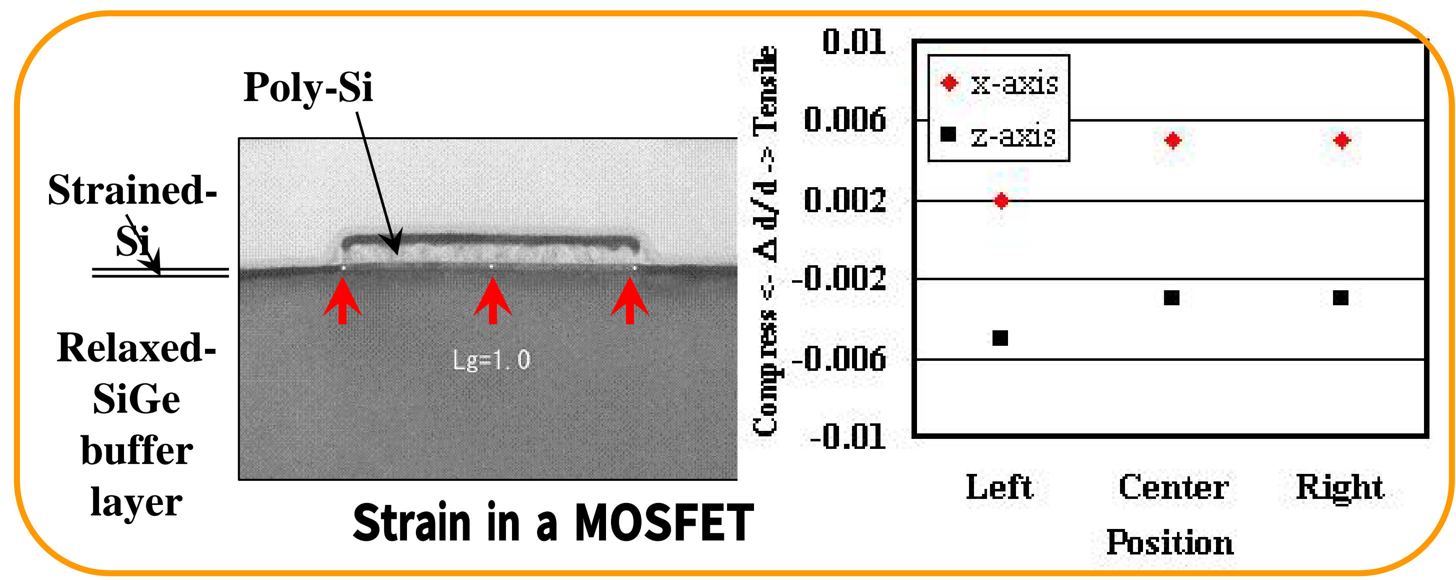
T. Numata et al.,MIRAI, IEDM (2004)177

# Local strain measurement by electron beam diffraction

## NBD (NanoBeam electron Diffraction)




Usuda, Materials Sci. Eng. **B124–125** (2005) 143



# Confocal/probe-excited UV Raman microscope for local strain analysis



Raman shift: $1/\lambda_{out} - 1/\lambda_{in}$ = phonon vibration

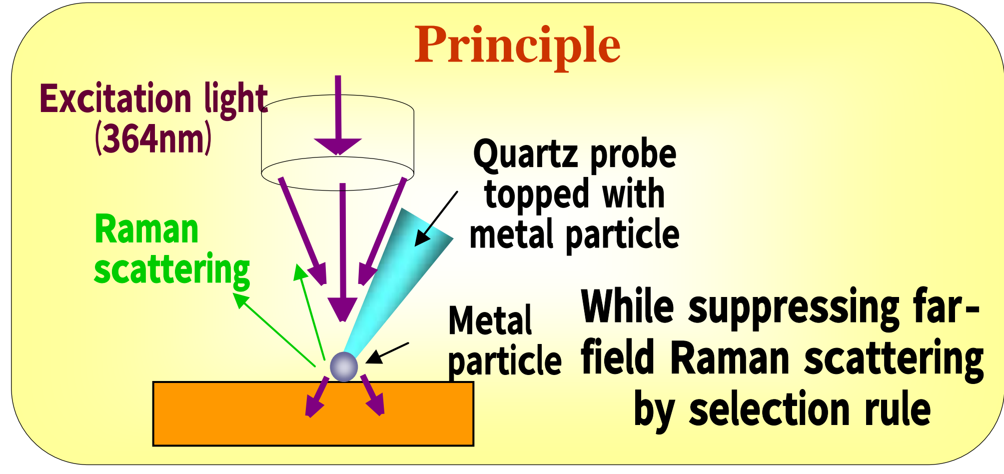
For strain $\varepsilon$ in Si: $\Delta(1/\lambda) = 723\ \varepsilon\ \mathrm{cm}^{-1}$

2D Raman mapping

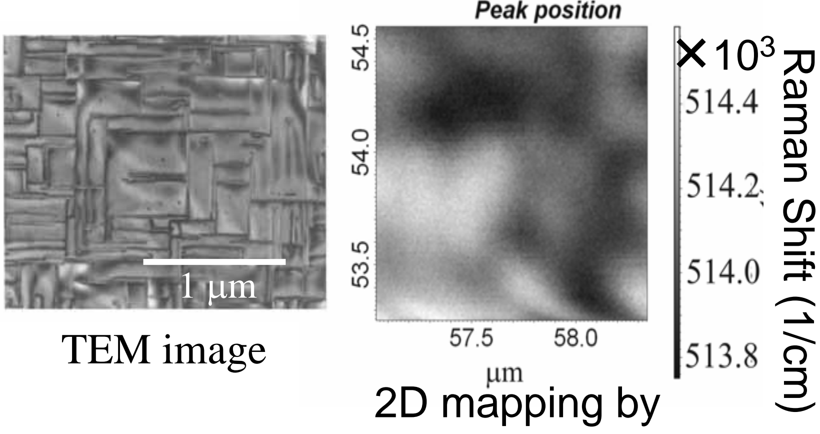
Poborchii, Appl. Phys. Lett. **89** (2006) 233505

# Analysis using polarization dependence of Raman scattering

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

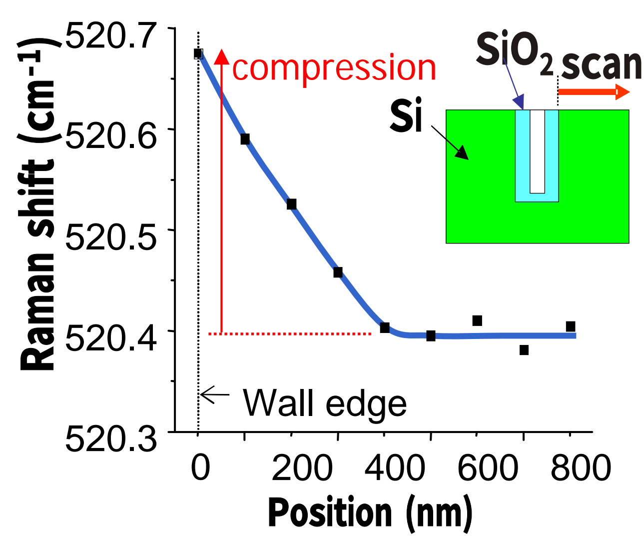



25nm –thick Strained Si on
27nm-thick $Si_{0.7}Ge_{0.3}$




TEM image

2D mapping by
confocal microscope




Stress distribution around a oxidized hole

Raman Shift ($cm^{-1}$)

516
515
514
513

Probe-excited Raman scattering

0 1 2 3

**Position (μm)**

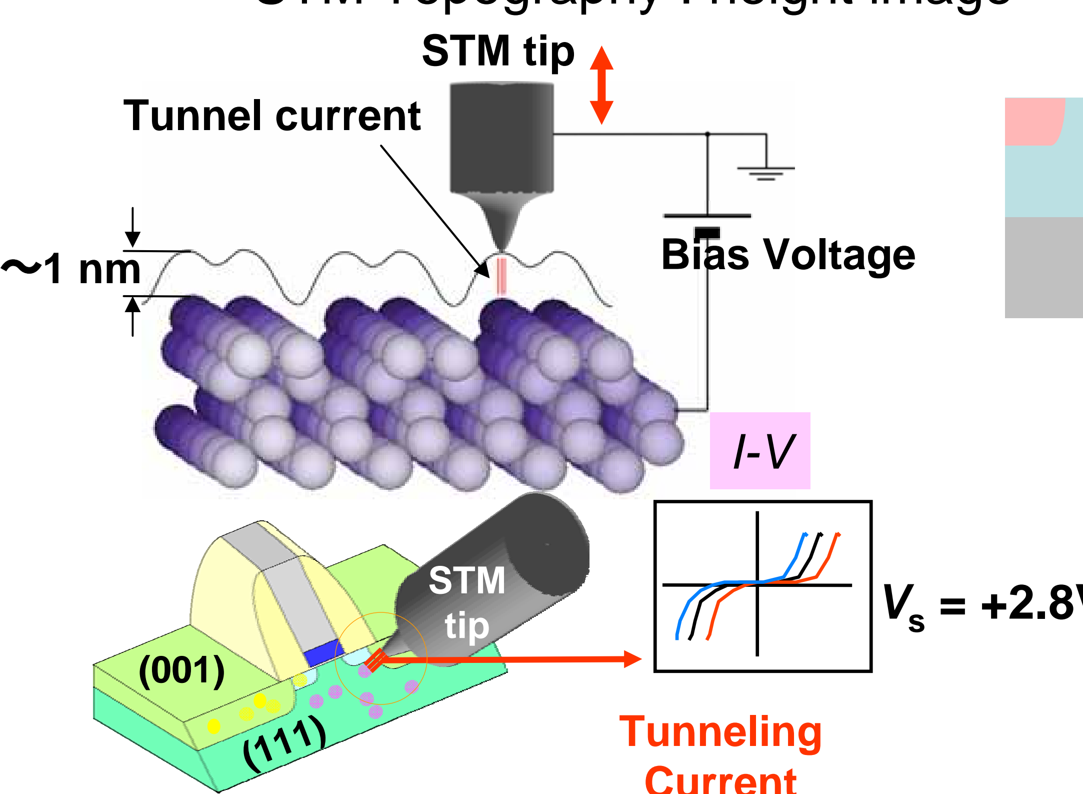
Strain Mosaic in strained Si layer

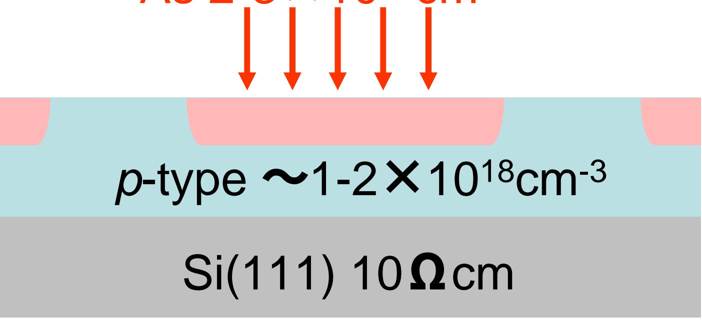
Poborchii, JJAP Exp Lett. **44** (2005) L202

# STM for potential and dopant profiling

## Scanning Tunneling Microscopy (STM)

STM Topography : height image

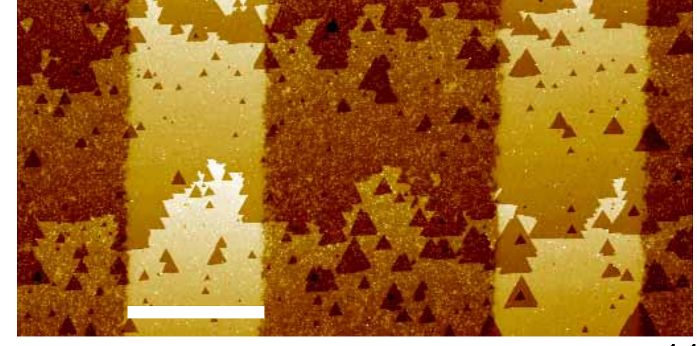





$V_s$ = +2.8V

$V_s$ = -2.8V




**Key process**

**Flattening and hydrogenation of (111) surface by aqueous $NH_4F$ treatment followed by dopant reactivation at ~400°C**

Nishizawa, J. Vac. Sci. Technol. **B24** (2006) 365

# Simultaneous measurement of potential and dopant atom

*n* *p*

$V_s$ = +1.7 V, $I_t$ = 6 pA

40 nm

Donor distribution correlates with the potential fluctuation.

donors (red spot)

acceptors (blue spot)

40 nm

**Imaging of dopant atoms**

**Substrate bias voltage: $V_s$**

| $V_s$ | acceptor<br>negative charge | donor<br>positive charge |
|---|---|---|
| $V_s>0$ | | |
| $V_s<0$ | | |

# Quantitative potential profiling by *I-V* measurements

**Potential simulation**

vacuum
surface
p: 1×10^17cm^-3
n: 1×10^17cm^-3
junction
Z (μm)
X (μm)

Si
probe
Band Bending $V_{BB}$
CBM
$E_{fs}$
VBM
$e^-$
$E_{ft}$
$V_{gap}$
$V_s$
Vacuum gap

**Issues**

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

*unknown*

*I-V* measurement
STS
(scanning tunneling spectroscopy)

$V_s$ = +1.7 V, $I_t$ = 6 pA

40 nm
*n*
*p*

**abrupt junction**

*n*: 2×10^19cm^-3
*p*: 1×10^18cm^-3
CBM = $E_F$tip
VBM = $E_F$tip
~0.9 eV
Sample Bias Voltage (V)
Distance (nm)

Sample Bias Voltage (V)
Tunnel Current (nA)
CBM
VBM
~0.9 V
Depletion~50 nm
Position
Sample Bias Voltage (V)

*M. Nishizawa et al, to be published in APL 2007*

# Resonant Tunneling Measurement of Local Potential

Energy
E
$V_B$
STM Probe
Marker molecule
Mono-layer $C_{60}$
HOMO
LUMO
~0.3 nm
Thin oxide
Si
$E_F$
z
Resonance Tunneling (RET) Current

200 nm
20 nm
Oxidized at 500°C～
1 ML $C_{60}$ deposition

Differential conductance dI/dV (nS)
$3\times10^{18}$ cm$^{-3}$
substrate Hole density
$4\times10^{15}$cm$^{-3}$
without $C_{60}$
Substrate Bias [V]

Resonance peak energy [eV]
CBM
VBM
$(E_F-E_i)$ [eV]

Resonance energy vs. Substrate Fermi level

$E_F-E_i$ (eV)
p
depletion
n+
Position [nm]

Potential profile in a pn junction region

Bolotov, Appl. Phys. Lett. **87** (2005) 133107

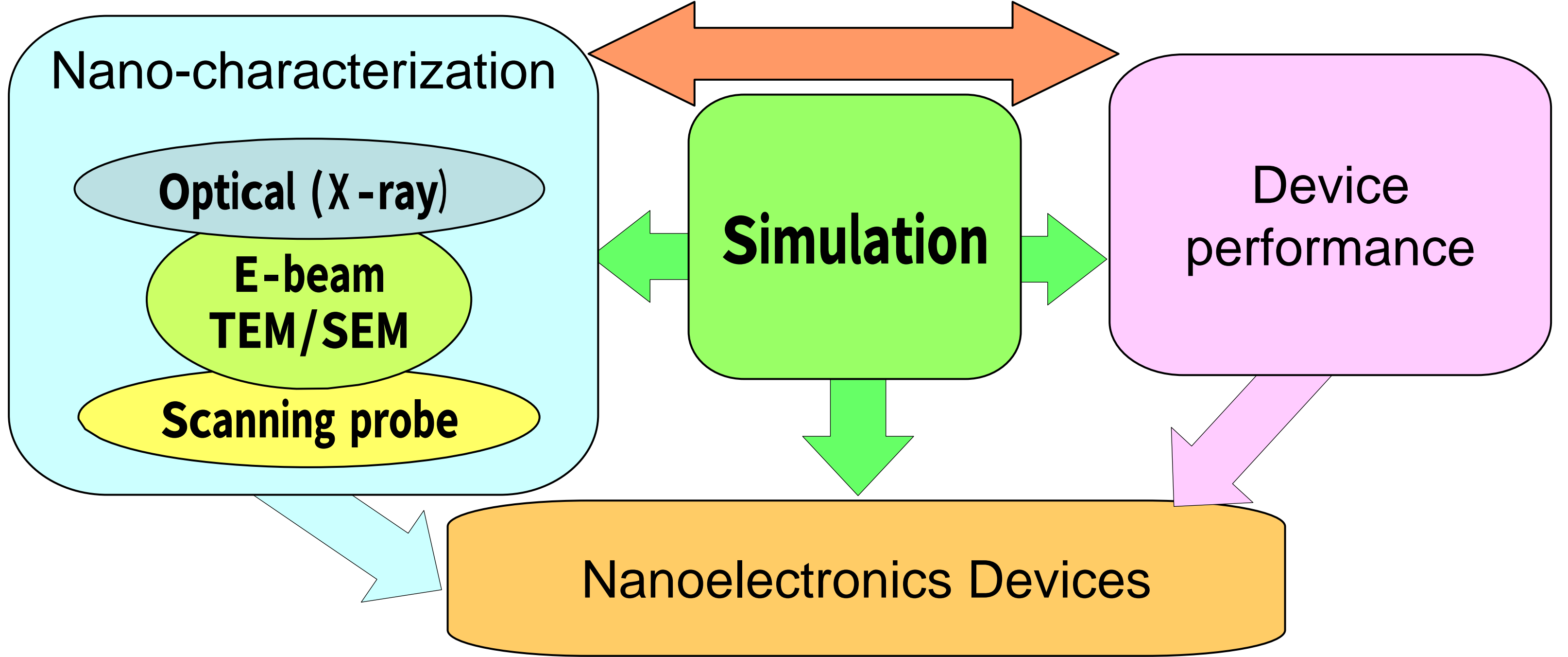
# Conclusion

For R&D of Nanoelectronics Devices

- Characterization and metrology of local properties and structures are needed.
  - e.g., CD & LER, Local strain in Si, Potential distributions

- Various methods must be comprehensively used;
  - Optical, SEM/TEM, Scanning probe

in conjunction with Simulations,
because no single method can give complete information in nm regions.



# Acknowledgments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- T. Tada and V.V. Porochii for UV Raman measurements
- L. Bolotov and M. Nishizawa for STM measurements
- K. Usuda for Nano-beam diffraction
- S. Gonda for CD-AFM
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## Sample preparation

- N. Hattori of Renesas Technology for strained STI structures
- H. Fukutome of Fujitsu Laboratory Ltd. for the *p-n* junction samples.

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