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Metrology and Characterization for Extending Silicon CMOS

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Contents

- 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

Gate depletion

Doped poly- Si ⇨ Metal

Size variation
Side wall roughness

CD & LER

Dopant fluctuation

Dopant distribution

Gate leakage

SiON ⇨ High-k

S/D resistance

Doped Si ⇨ Metal

Source

Drain

Carrier velocity saturation

Si ⇨ Strained Si, SiGe

Strain distribution

Short channel effects

Bulk planer Si ⇨UTB, multi-gate

Major Issues

•Simple scaling no more works well.

⇨Technology boosters (New materials) : I_{on} ↗ I_{off} ↘

•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

ΔLg

ΔW

Physical dimensions of 3D structures

Source

Drain

BOX

Multi-gate FET

Process compatibility

In-line/in-situ

Production

Optical (X-ray)

scatterometry

SEM

CD-SEM

Scanning probe

CD-AFM

TEM

TEM

R&D

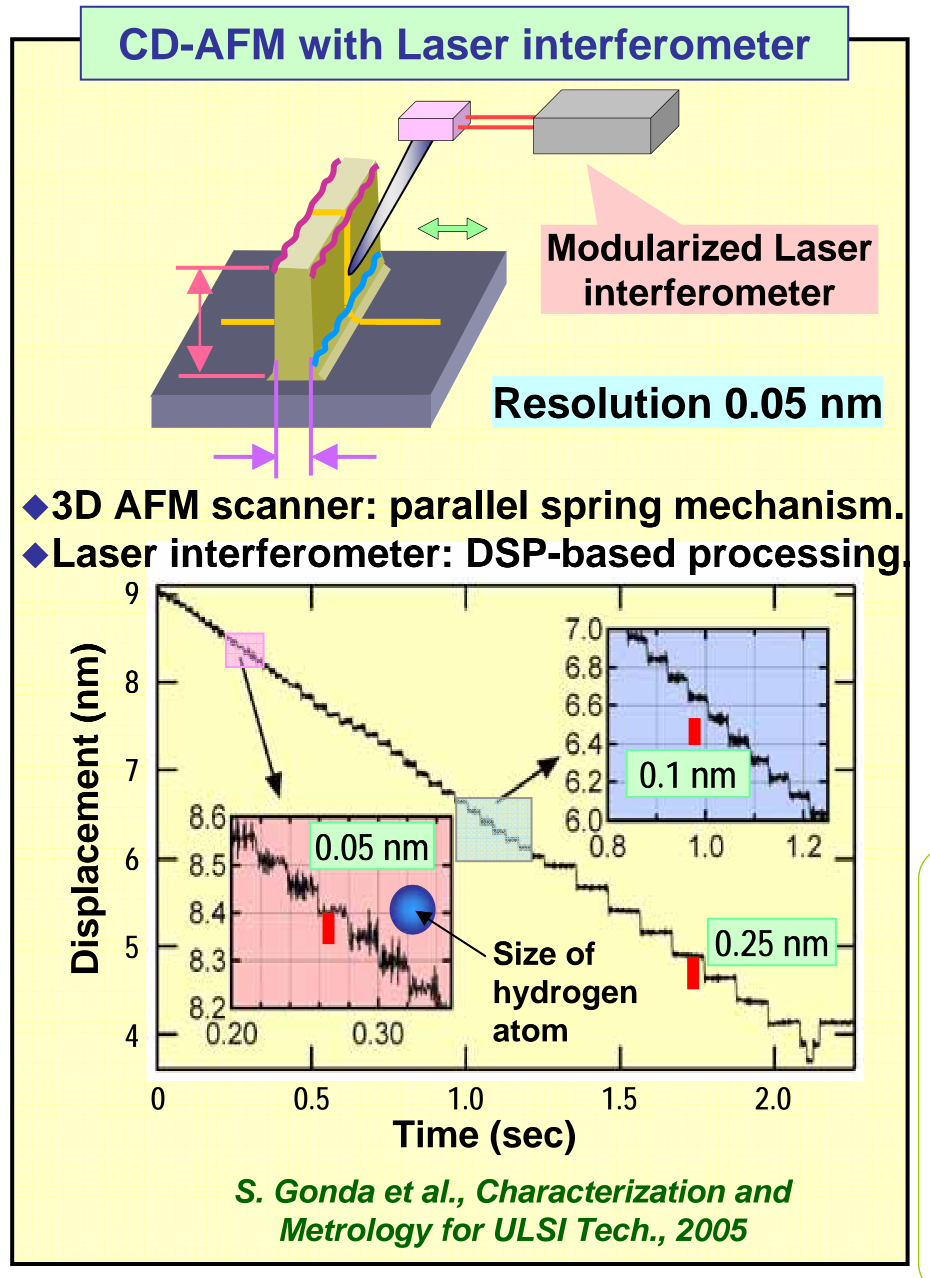
Off-line

Low

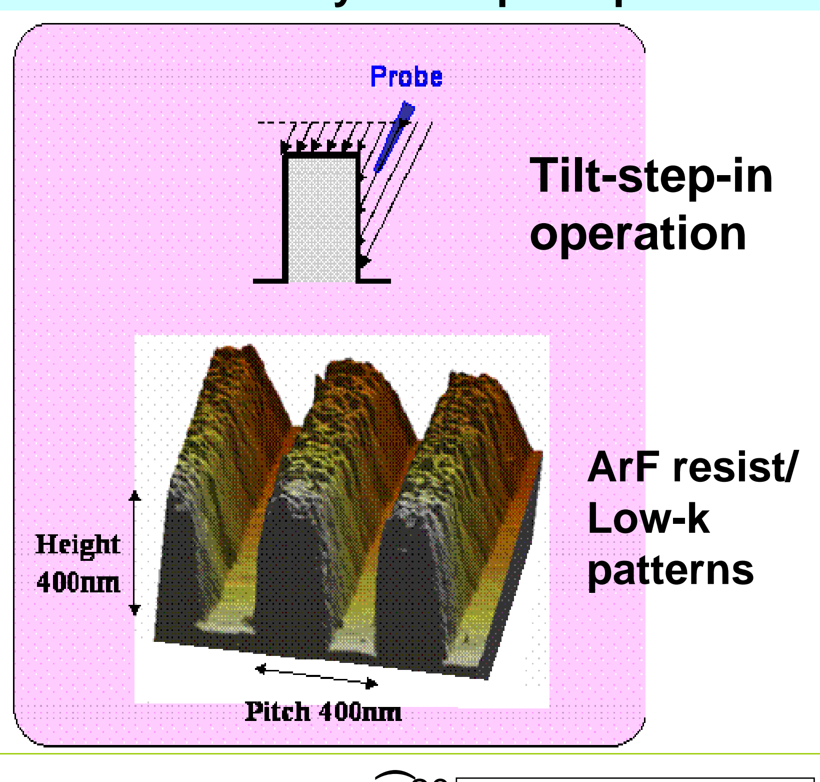
High

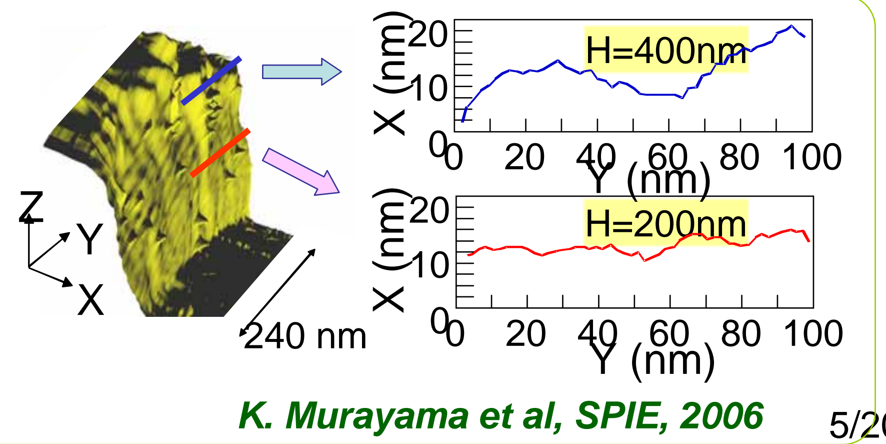
Inherent Spatial Resolution

High-Precision CD Metrology by AFM



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





Strain distribution

Mobility enhancement by

local strain

SiGe SiGe

pMOS

High Stress Film

nMOS

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

global strain

36nm

Strained-Si

SiGe SiGe

Buried Oxide

Strained Si layer

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

Process compatibility

Optical (X-ray)

UV Raman scattering

SEM

Scanning probe

Near-field Raman scattering

TEM

CBED, Nano-beam diffraction

Low High

Inherent Spatial Resolution

NBD (NanoBeam electron Diffraction)

Z-axis
X-axis
e^--beam

Strained
SiGe
17nm St-Si
35nm SiGe
100nm Box
Si sub.
70nm

Tensile strain

Z
X

St-Si
SiGe
Si

Si(x,z) =(5.474 Å,5.417 Å)

SiGe(x,z)=(5.469 Å,5.504 Å)

Si(x,z)=(5.433 Å,5.433 Å)

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

Poly-Si
Strained-Si
Relaxed-SiGe buffer layer
Lg=1.0
Lg=1 μm

Strain in a MOSFET channel

Compress <- Δ d/d -> Tensile
0.01
0.006
0.002
-0.002
-0.006
-0.01
x-axis
z-axis
Left
Center
Right
Position

Confocal/ probe-excited UV Raman microscope

Stress distribution in STI structures by confocal microscope

2D Raman mapping

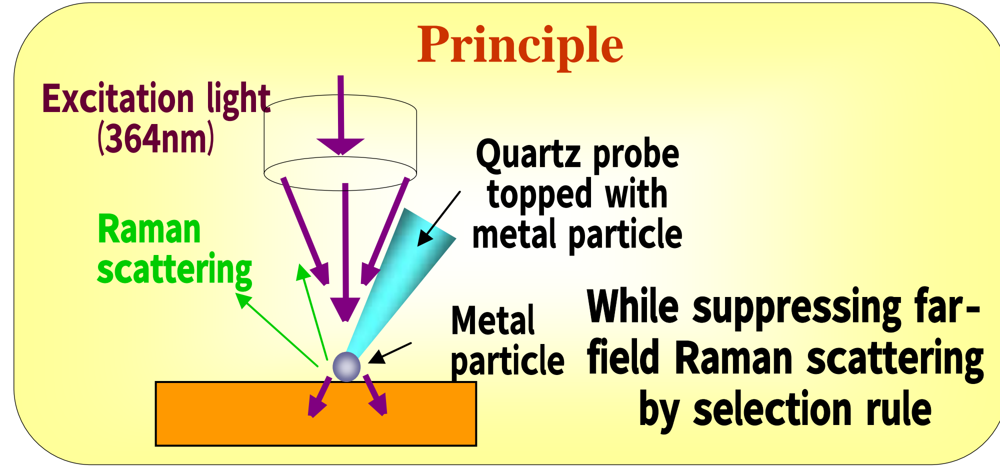
1D Raman maps across single Si stripes compressed by STI

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

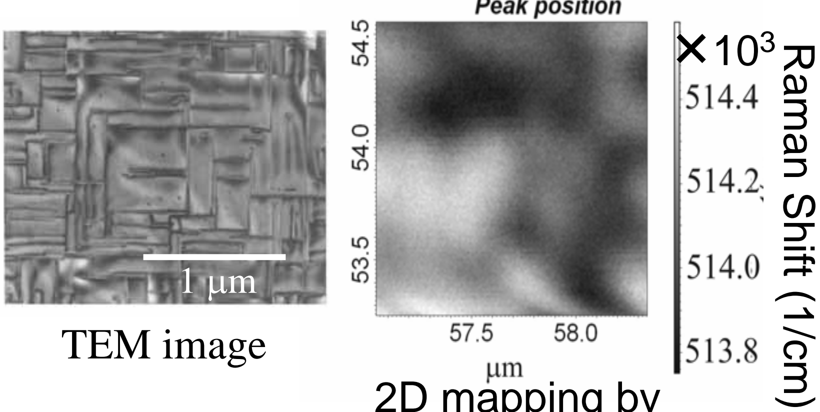
Analysis using polarization dependence of Raman scattering

FDTD simulation

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

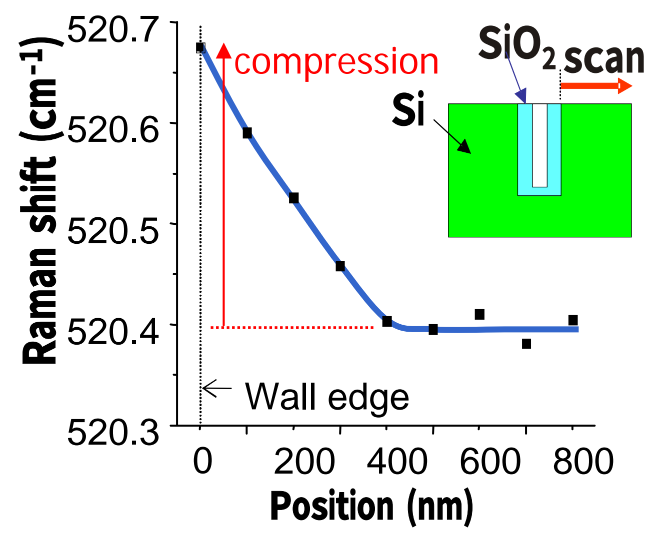


25nm –thick Strained Si on
27nm-thick $Si_{0.7}Ge_{0.3}$



TEM image

2D mapping by
confocal microscope



Stress distribution around a oxidized hole

516
515
514
513
Raman Shift (cm^{-1})
Probe-excited Raman scattering
0
1
2
3
Position (µm)

Strain Mosaic in strained Si layer

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

Local Strain Metrologies

method	sensitivity	Spatial resolution	feature
Probe excited Raman scattering	**0.05 cm^{-1} (ε～ 0.005%)**	**～50-100 nm**	**Non-destructive**
UV Raman scattering	**0.05 cm^{-1} (ε～ 0.005%)**	**～130 nm**	**Non-destructive Non-contact**
CBED (Convergent beam electron diffraction)	**Δd/d= 0.02%**	**～20 nm**	**High precision**
NBD (Nano-beam electron diffraction)	**Δd/d = 0.1%**	**～ 10 nm**	**High spatial resolution**

ε：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)

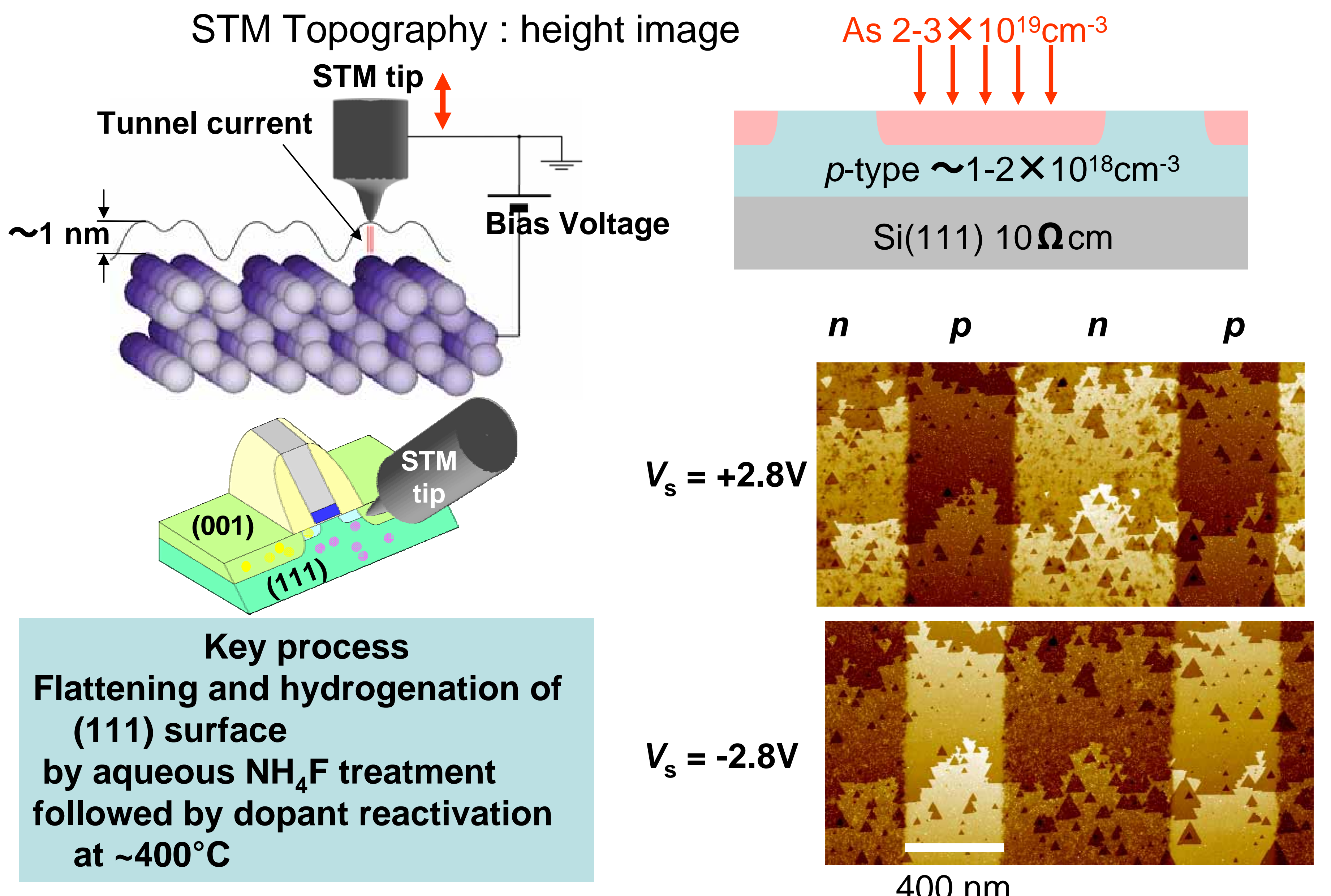
Bolotov, poster No.098, this conference

STM Features

- atomic resolution
- ability to measure

atomic and electronic structure, surface potential, and individual dopant atoms through various measurement modes: topography, *I-V*, d*I*/dz

STM observation on atomically flat and hydrogenated surface



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 negative charge	donor positive charge
$V_s>0$		
$V_s<0$		

Quantitative potential profiling by *I-V* measurements

Potential simulation

vacuum
surface
p: $1\times10^{17}cm^{-3}$
n: $1\times10^{17}cm^{-3}$
junction
Z (μm)
X (μm)

Si
probe
Band Bending V_{BB}
e^-
CBM
E_{fs}
E_{ft}
V_{gap}
V_s
VBM
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: $2\times10^{19}cm^{-3}$
p: $1\times10^{18}cm^{-3}$
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

Resonance energy vs. Substrate Fermi level

Potential profile in a pn junction region

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

Two-dimensional dopant profiling methods

method	principle	Spatial resolution
STM	**Surface potential/ Dopant detection**	**atomic ～1 nm**
SCM **(Scanning Capacitance Microscope)**	**Capacitance (C-V)**	～10～20 nm
SSRM **(Scanning Spreading Resistance Microscope)**	**Spreading resistance**	～5 ～10 nm
Kelvin Force Microscope	**Surface potential**	～100 nm
Electron holography	Internal potential	～1 nm
TEM *Z* **-contrast**	Dopant atom contrast	～ 1 nm

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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