Metrology for Nanoelectronics

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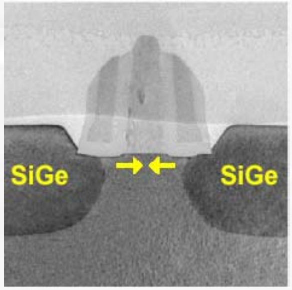
"This is an AMRC Project presentation made possible, in part, by funding provided by SEMATECH."

AGENDA

- Evolution of Micro to Nanoelectronics
- Lithography Metrology Challenges
- Transistor (FEP) Metrology Challenges
- Interconnect Metrology Challenges
- The Future of Materials Characterization
- Nano - Characterization and Metrology
- Trends & Conclusions

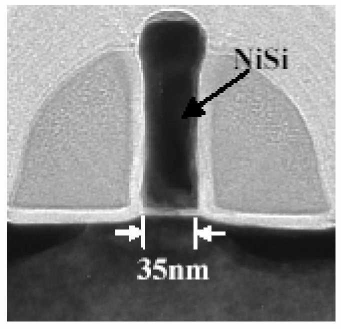
Transistor Evolution

Today
90 nm Node
Lg ~ 45 nm



Strain
Enhanced Mobility

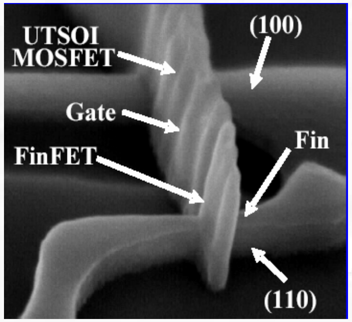
Tomorrow



New Materials

45 nm Node
Lg < 25 nm

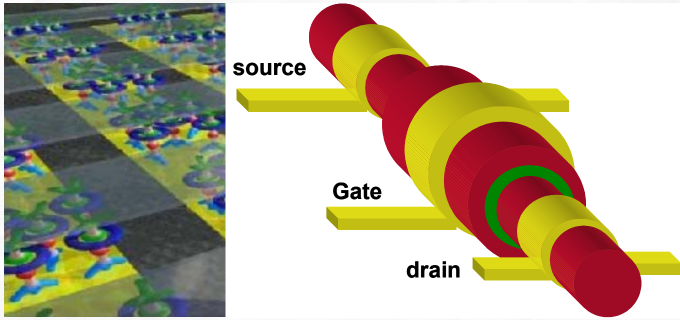
Future
15 years
Non-classical CMOS



CMOS
pMOS FINFET

16 nm Node
Lg ~ 6 nm

Beyond CMOS

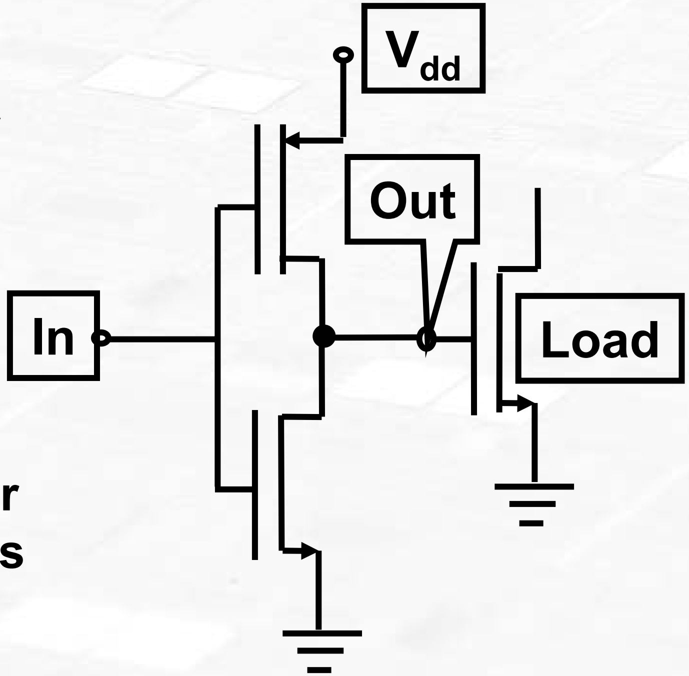


Molecular Switches ?
Nanowire Transistor ?

CMOS Switching Speed $\tau \sim 1/I_{dsat}$

Role of Saturation Drive Current

P Channel Transistor
- **Carriers = holes**



CMOS Inverter

N Channel Transistor
- **Carriers = electrons**

$$\tau = C_{load} V_{DD} / I_{dsat}$$

Switching Speed of Long Channel Transistor - The Old Days

$$I_{dsat} \propto (\ 1/Lg\ )\ (\ \mu_{Carrier\ \ Mobility}\ )\ (\ 1/EOT\ )$$

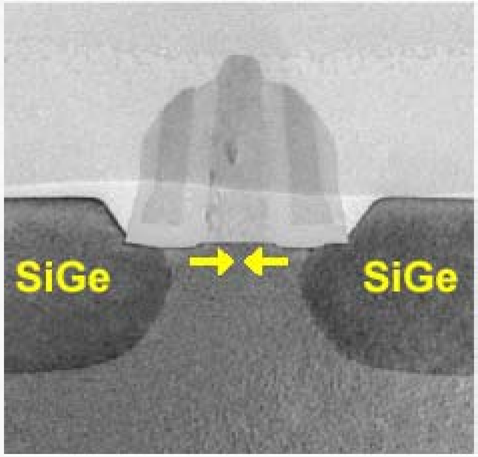
Transistor Gate Delay, τ, decreases as CD decreases but Gate Dielectric must also decrease in thickness.

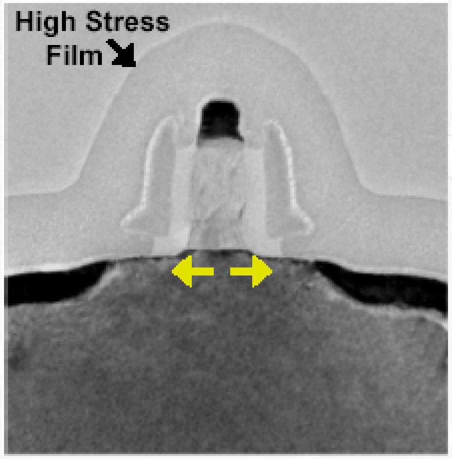
Idsat ⇧ as Lg gate length ⇩

Sounds Easy
- Just decrease the Gate length &/or increase mobility

TROUBLE As dielectric thickness decreases leakage current increases

High Volume ICs use CMOS w/ Locally Strained Si Strained Si substrates not used





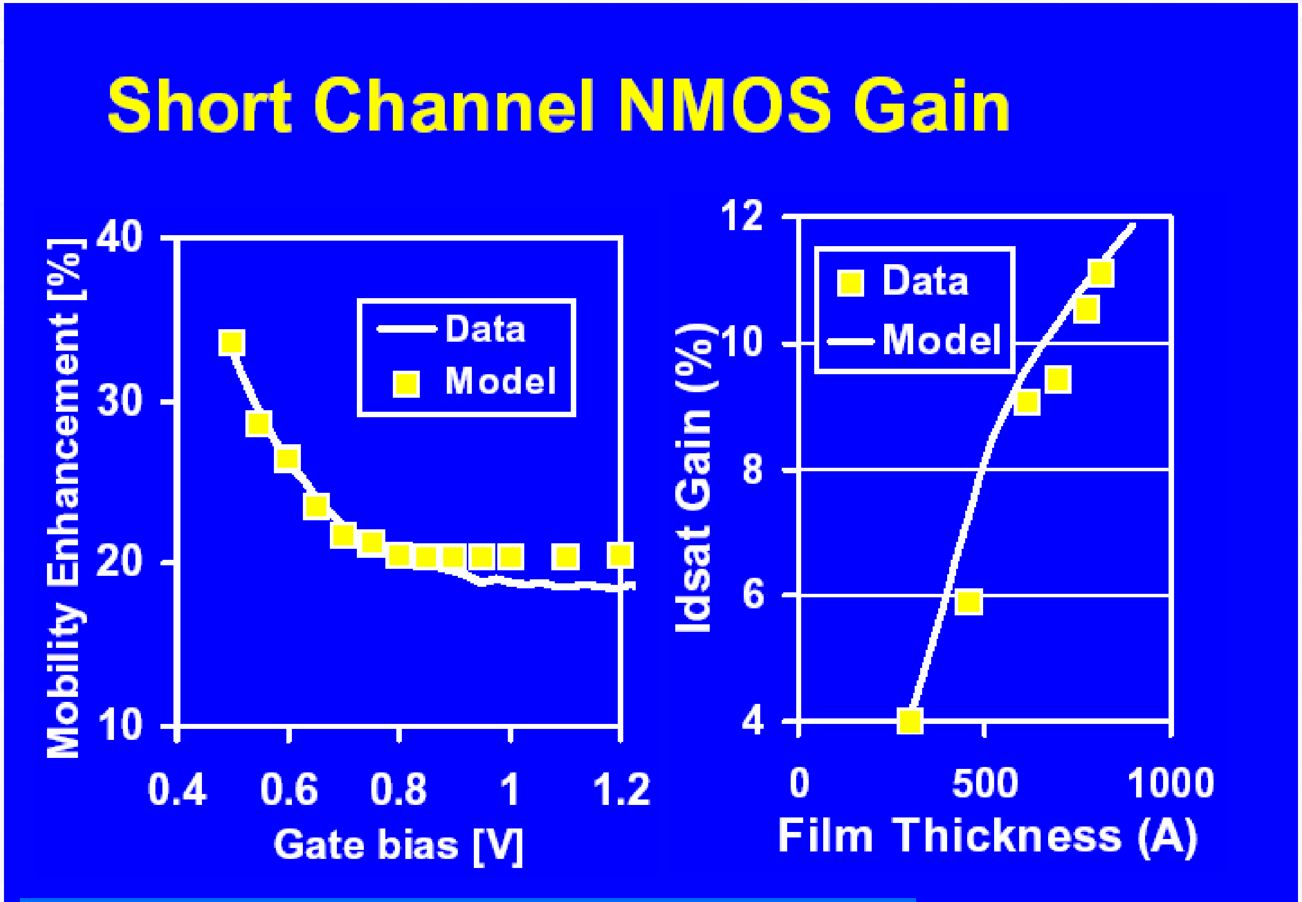
45 nm CD PMOS
Compressive Strain
increased hole mobility

45 nm CD NMOS
Tensile Stress SiN Layer
increased electron mobility

From T. Ghani, et al., IEDM 2003, p 978.
Courtesy Intel

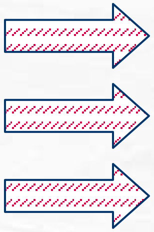
Trend : Use Modeling to connect what you want to measure with what you need to know

Example: Metrology of Strained Channel Devices

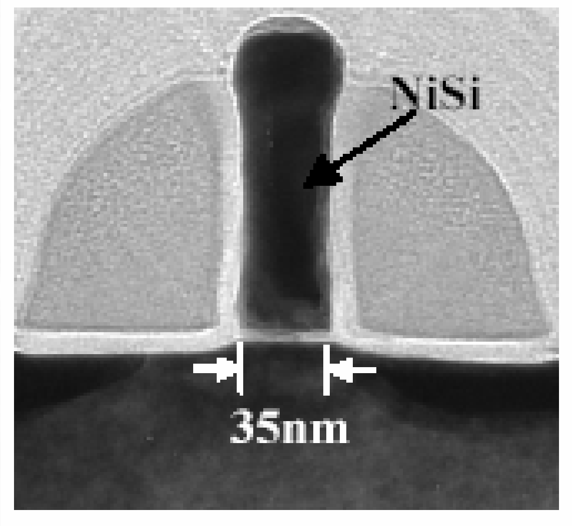


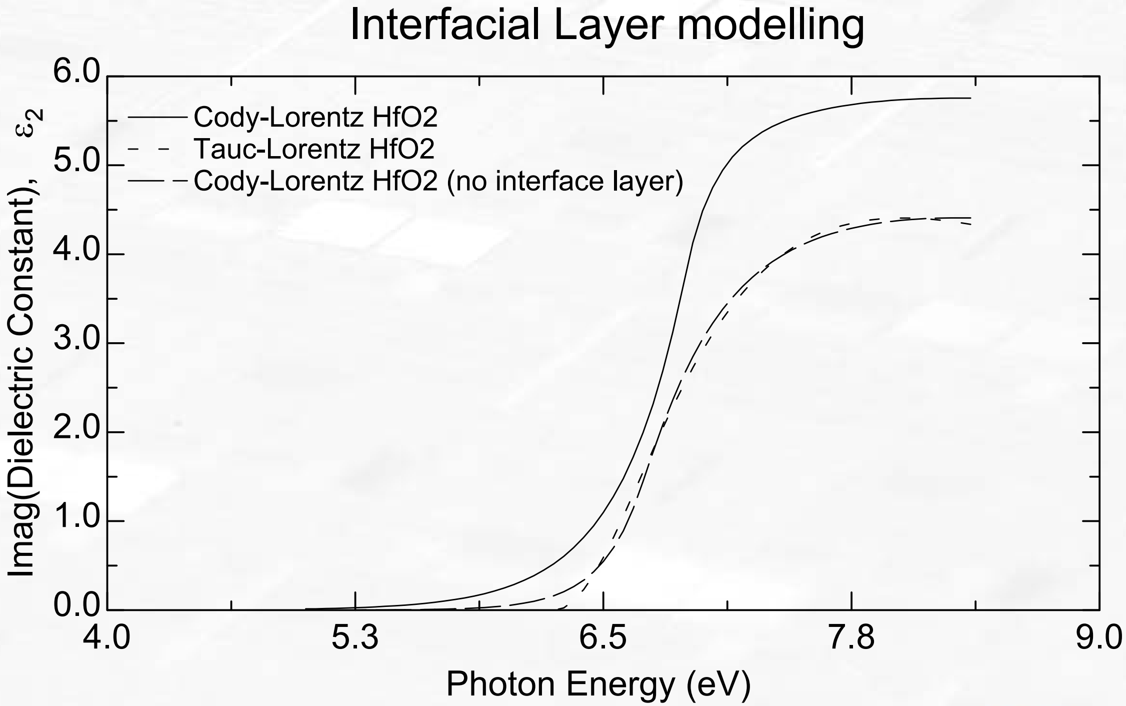
MD Giles, et al, VLSI Symposium 2004

Near Term Solution New Materials



Dielectric Material → **High k**
Poly Si Gate → **Metal Gate**
Transistor Channel → **Strained Si**





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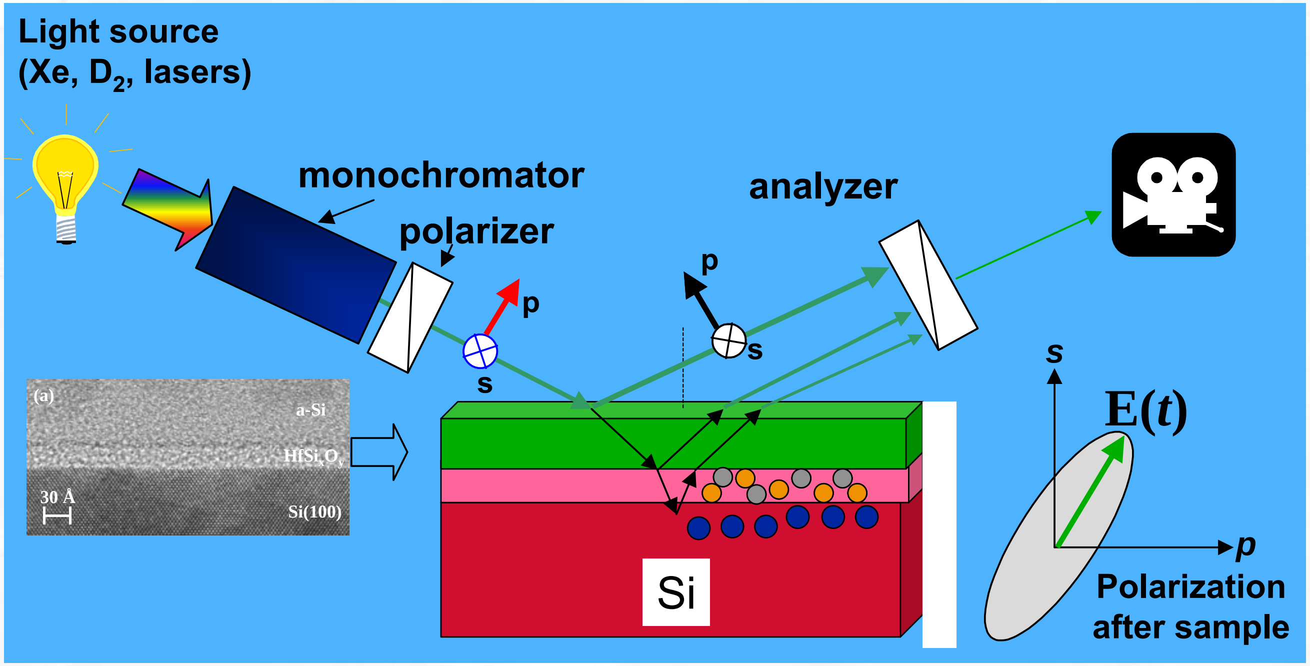
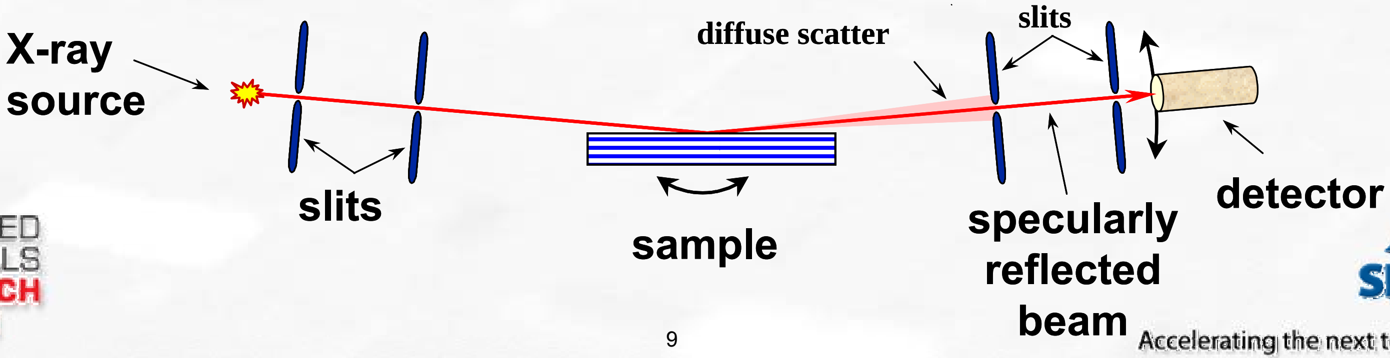
Trend: Interfacial Measurement is Increasing in Difficulty & Importance

Are Ellipsometry and XRR limited??





Nanotransistors – The Future

Short Channel Behavior

$$I_{dsat} \propto \left(\cancel{1/Lg} \right) \left(\mu_{Carrie} \; ? \; {}_{bility} \right) \left(\cancel{1/EOT} \right)$$

Nano Transistors

$$I_{dsat} \sim W\, C_{ox}\, (V_G - V_T)\, \nu_{sat}$$

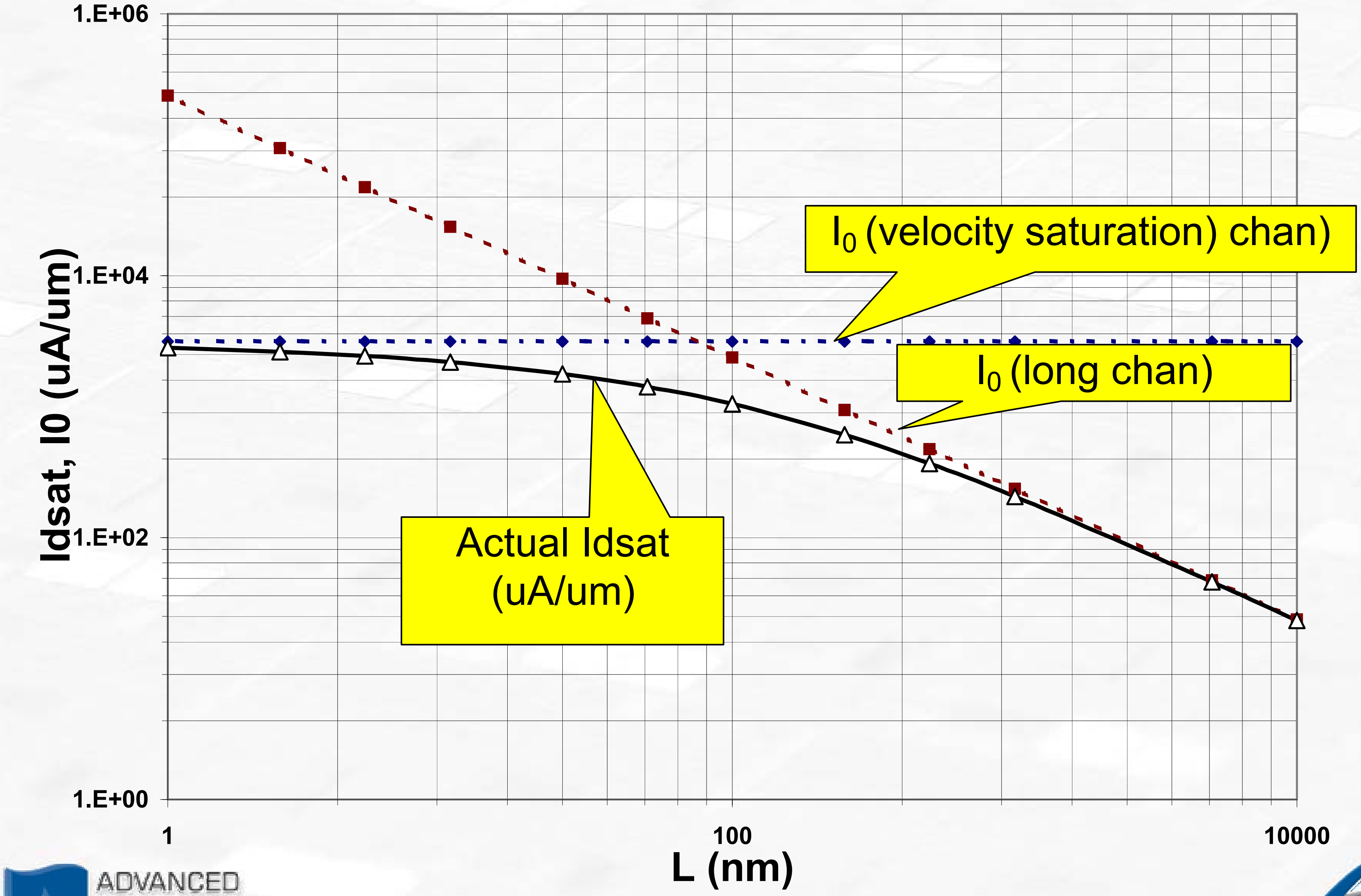
$$\tau = C_{load}\, V_{DD} / I_{dsat}$$

C dependence

A = Lg x W

Dopant Conc.

Change in Transistor Behavior



I_0 (velocity saturation) chan)

I_0 (long chan)

Actual Idsat (uA/um)

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Why measure CD for NanoTransistors

$$\tau = C_{load} V_{DD} / I_{dsat}$$

1. CD impacts Capacitance C

A = Lg x W

Dopant Conc.

2. CD impacts Threshold Voltage

Likharev has shown that below 10 nm CD,
Threshold Voltage is very sensitive to CD
At CD = 5 nm
Process range is 0.2 nm ~ 1 atom

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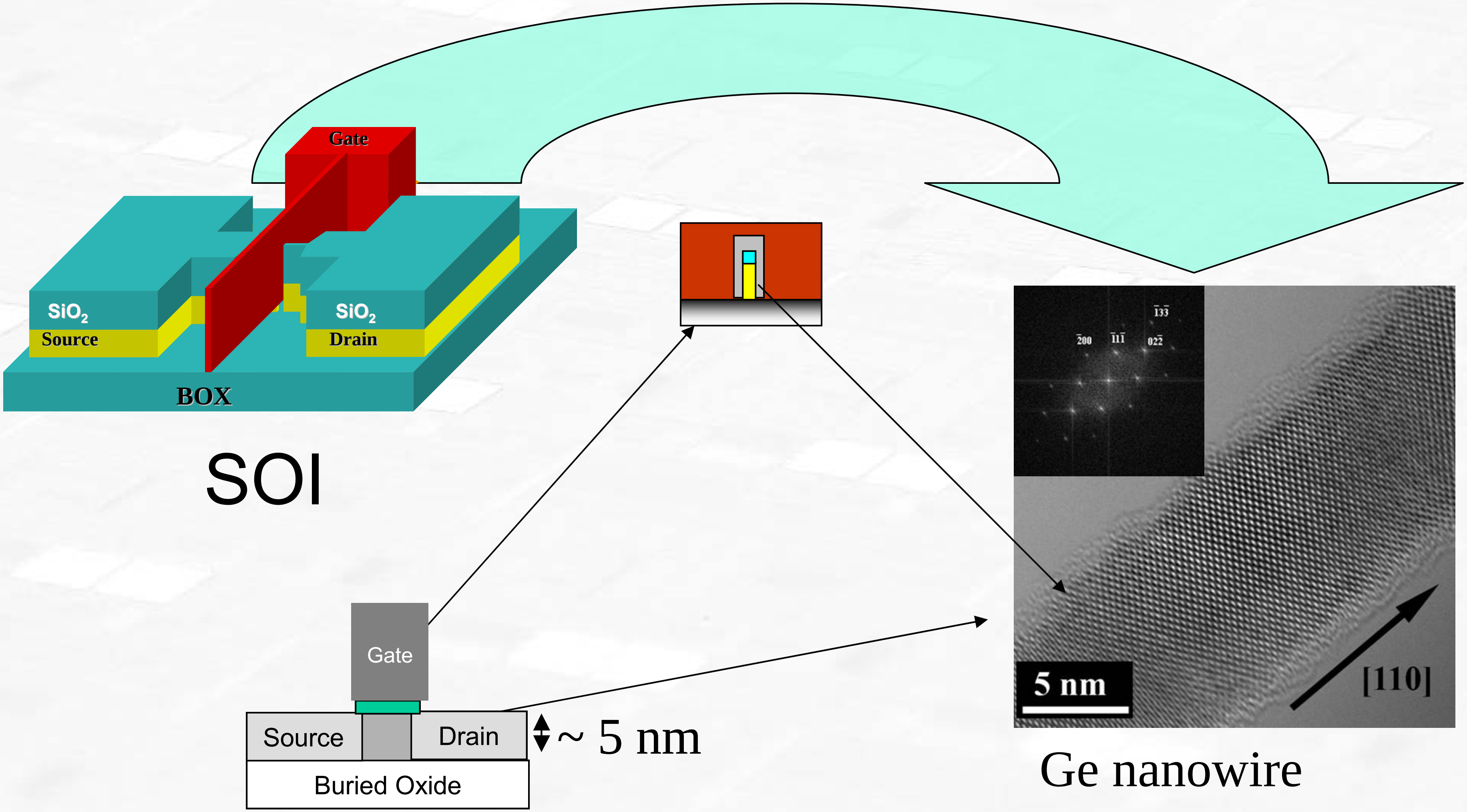
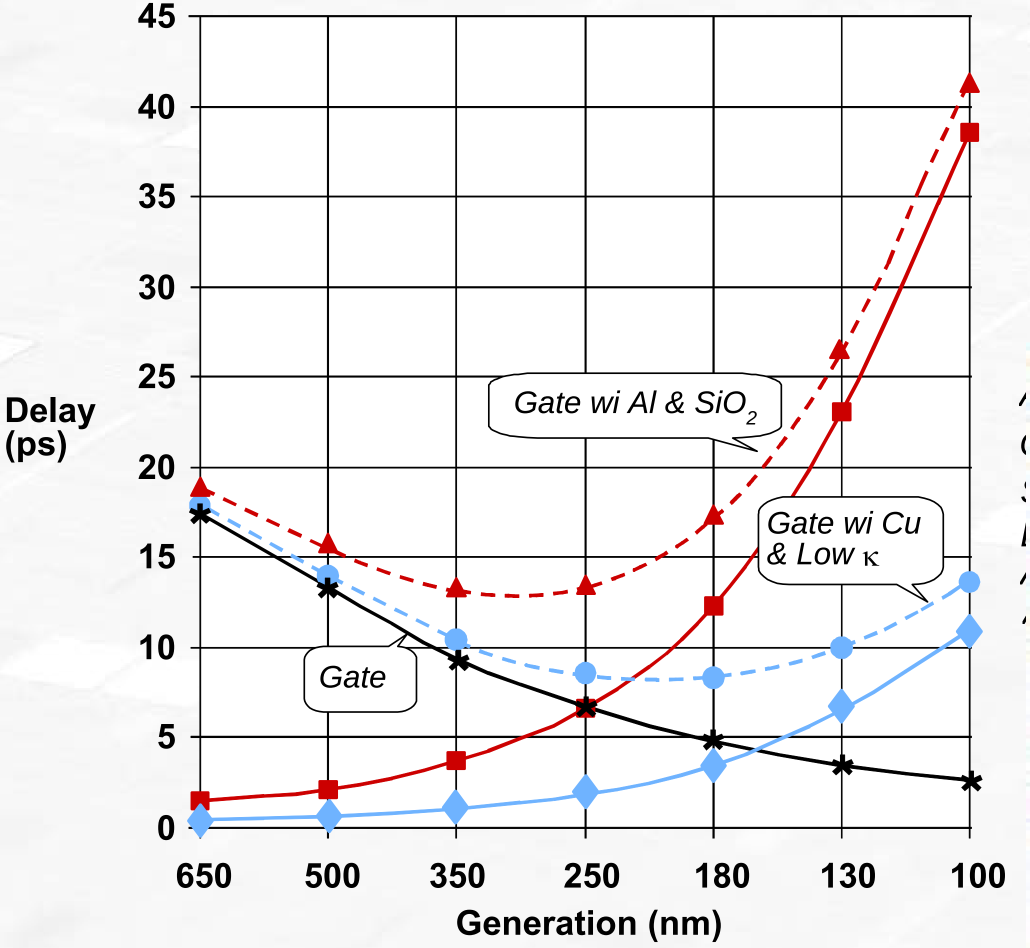
Nano-Sized Transistor Features

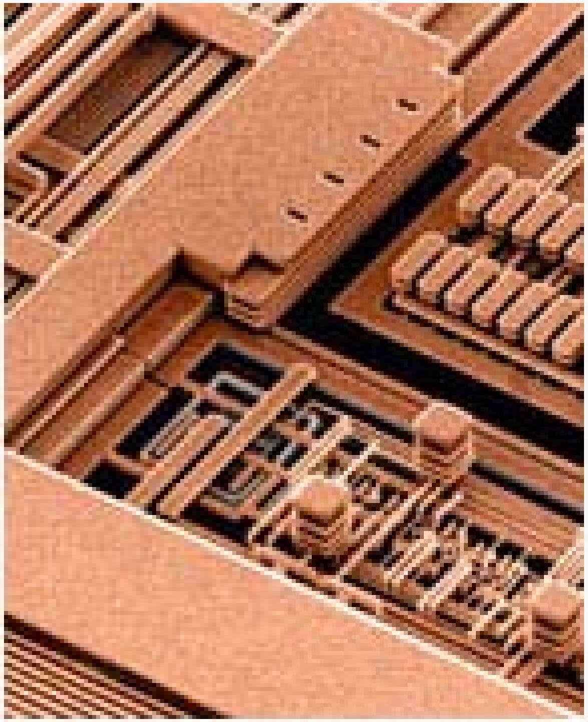


Nanowire Sized Si or Ge channel

Transistor and Interconnect Delays

SPEED / PERFORMANCE ISSUE *The Technical Problem*





From ITRS and Mark Bohr (Intel)
Figure from IBM

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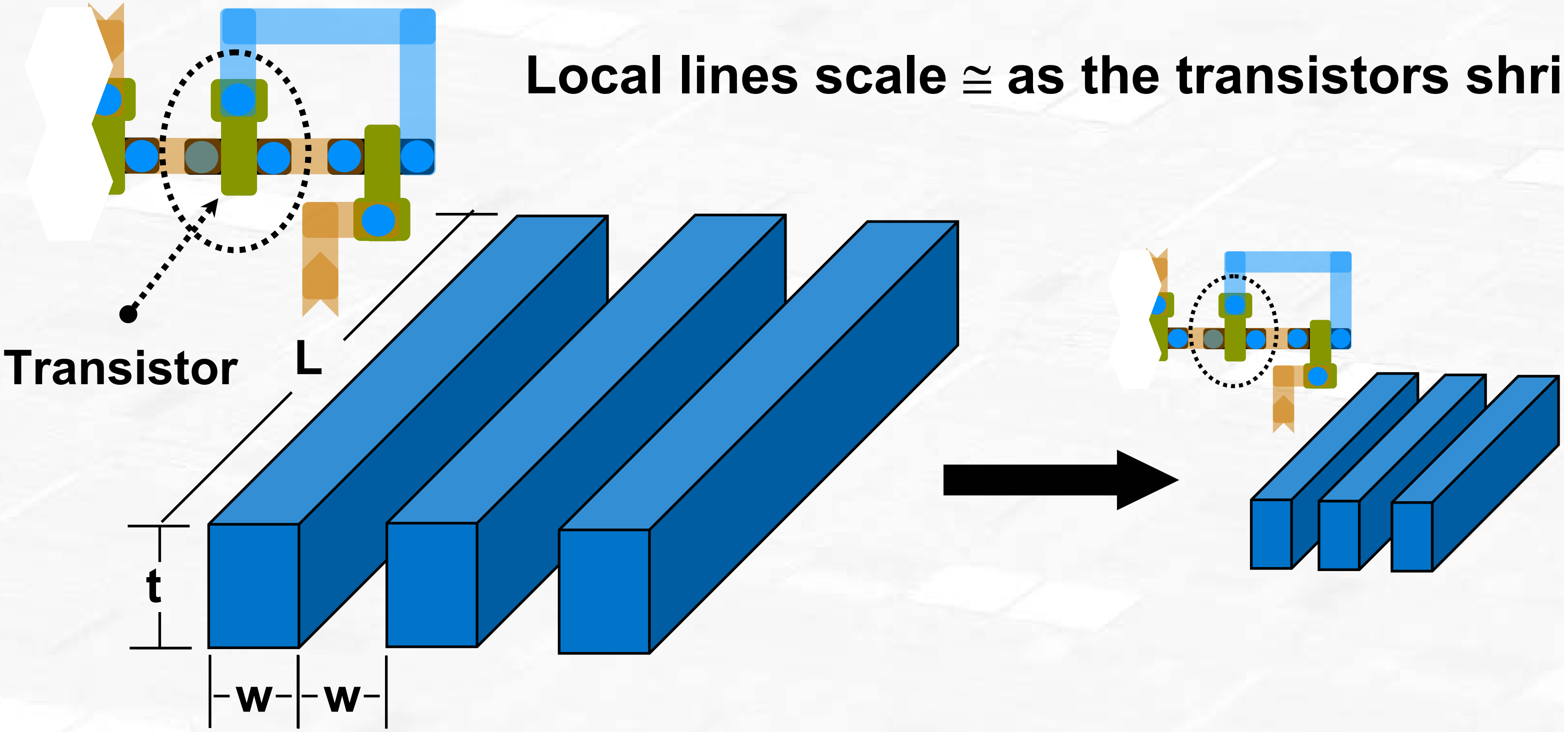
Interconnect Delay: LOCAL LINE SCALING

Local lines scale ≅ as the transistors shrink.



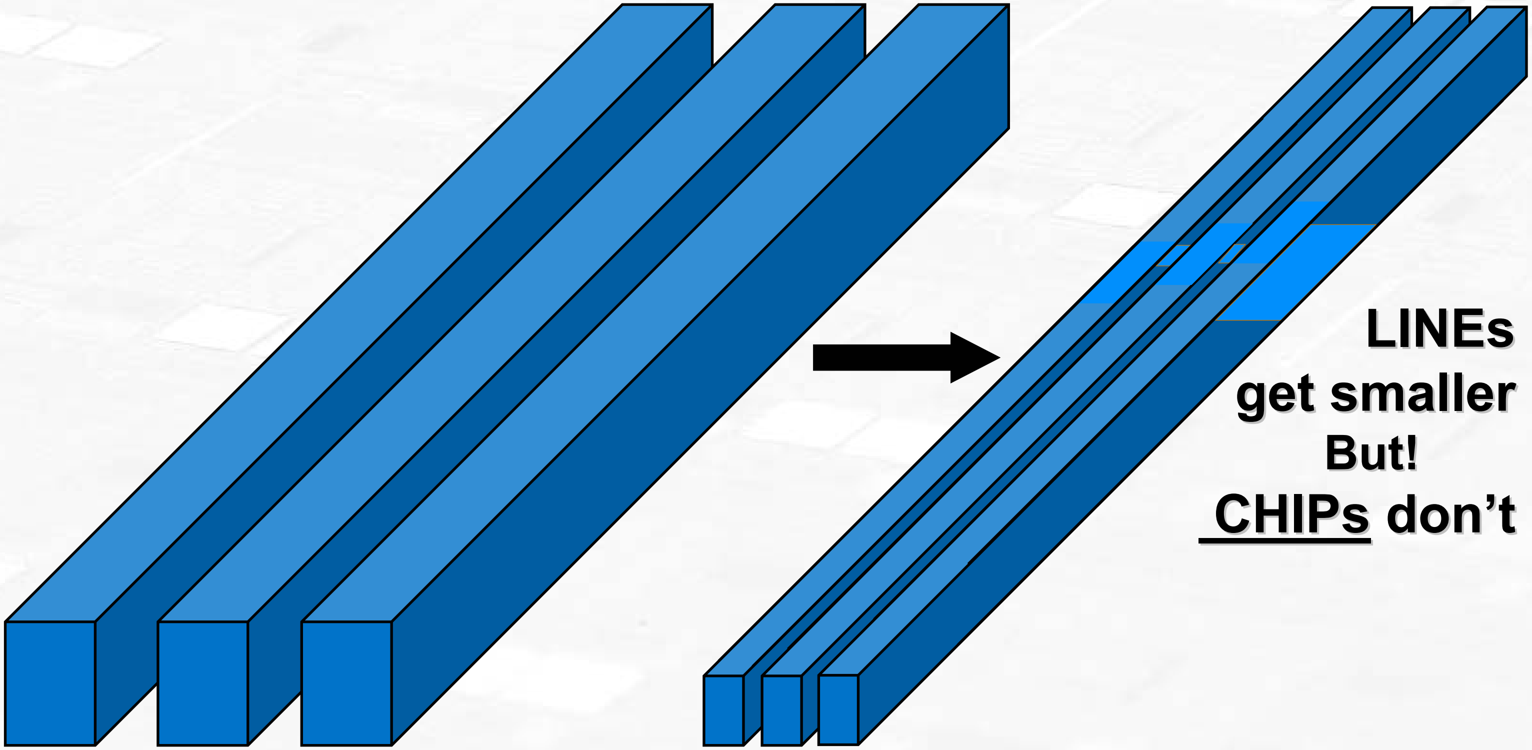
Local conductor lines get smaller in cross-section, spacing <u>& length</u>.

$$\text{RC Delay} \cong \rho\, \varepsilon \frac{L^2}{w^2}$$

Both L&W Scale
≅ the Same

Interconnect Delay: GLOBAL LINE SCALING

Global conductor lines getting smaller in cross-section but *NOT* in length. Signal delay is growing exponentially!



LINEs get smaller
But!
CHIPs don't

$$\text{RC Delay} \cong \rho\,\varepsilon\,\frac{L^2}{w^2}$$

L Stays Same

W ↓ Decreases

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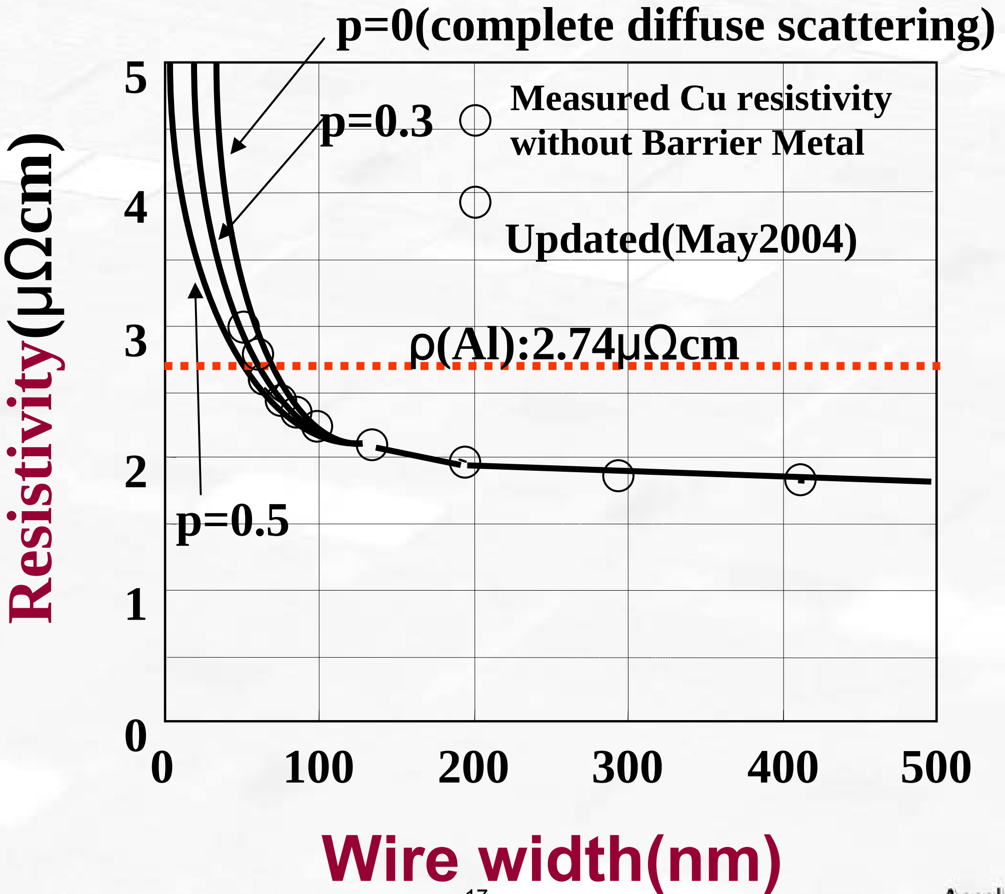
Trend: Sidewall Control will become more Important

Line Edge Roughness impacts Interconnect Resistance and Line Width Roughness impacts Transistor Leakage Current



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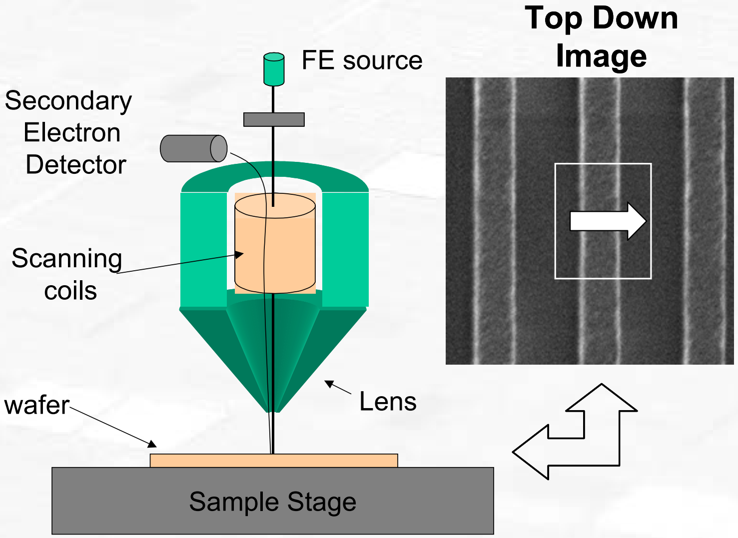
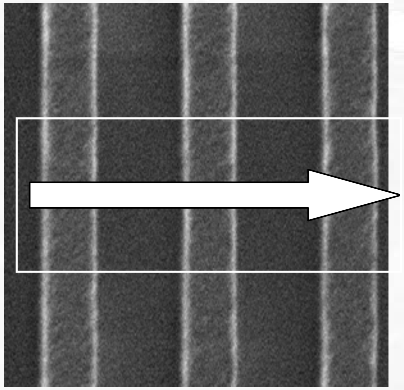
Evolution of CD-SEM

Today
90/65 nm Node
Lg < 45 nm

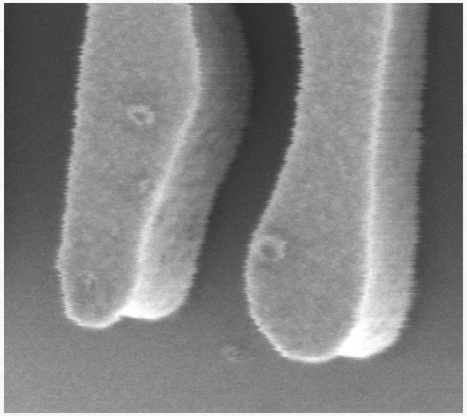
Old Way



New Way



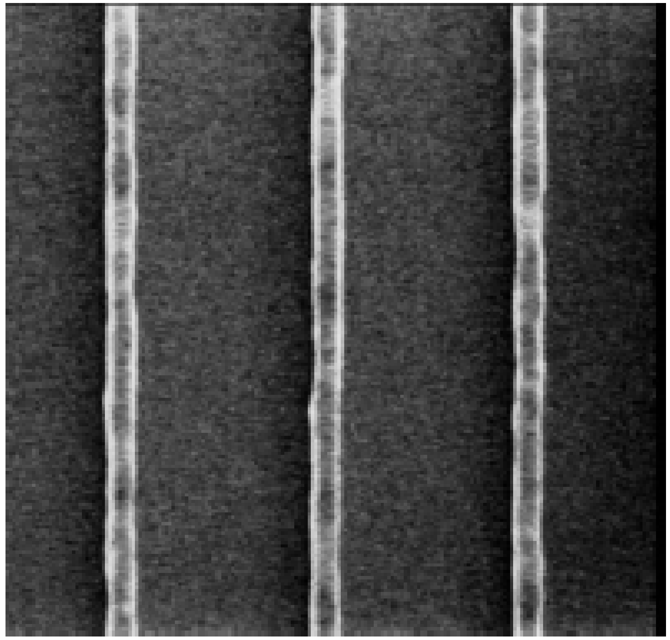
Measure several lines for local CD average



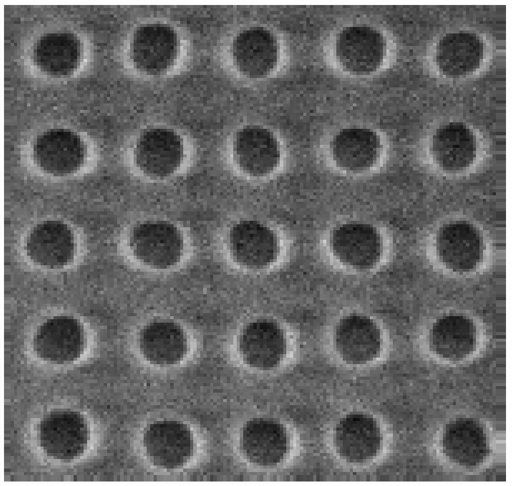
Tilt Beam for sidewall metrology

32 nm Node CD Evaluation

Bryan Rice (Intel), SPIE, 2004
CD-SEM and Scatterometry can reach 32 nm Node w/improvement – impact of SOI not tested



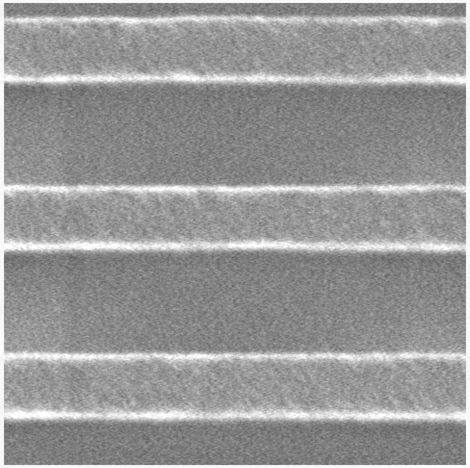
16 nm Lines -176 nm Pitch



45 nm contact Holes

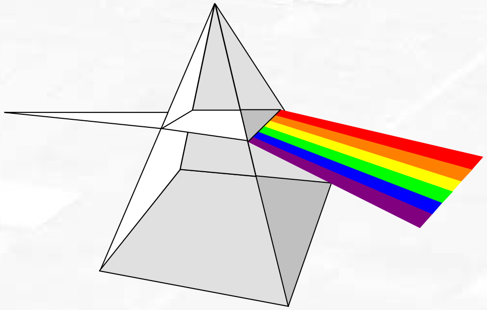
Recent Advances & Future Approaches

CD-SEM
Measure several lines for local CD average



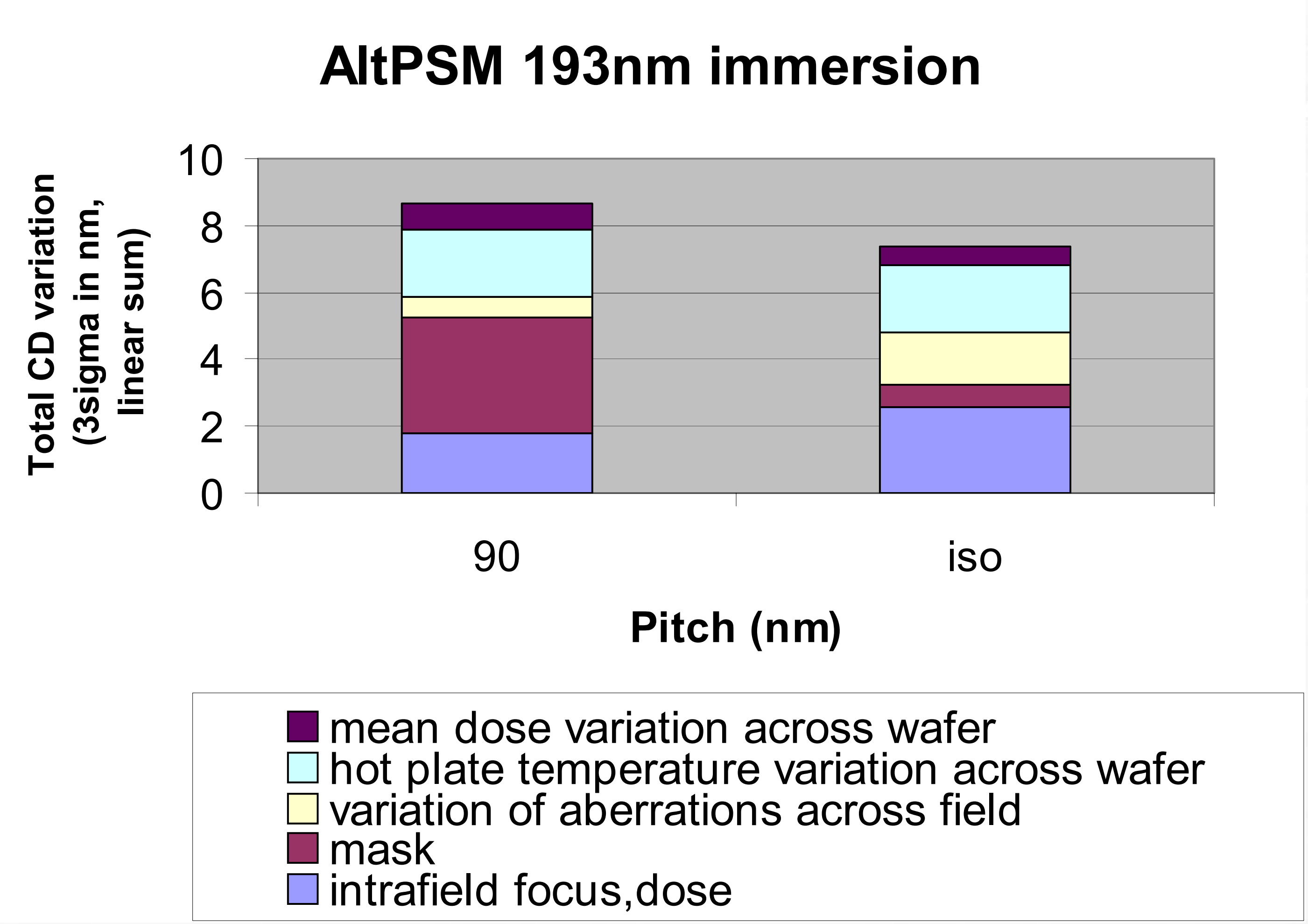
aberration corrected CD-SEM ?

Scatterometry
Add VUV to evolve toward sub 32 nm node : $L_g < 13$ nm



Add ?? to scatterometry to enable LER???

CD Variation for 193 nm Immersion Lithography



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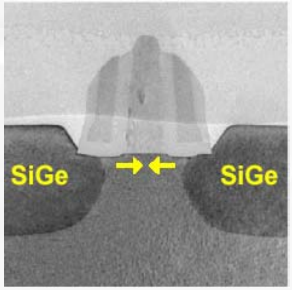
Transistor Metrology Evolution

Strain
Metrology

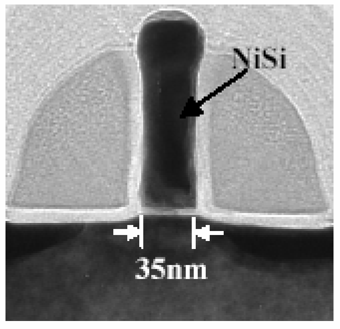
Today
90 nm Node



Strain
Enhanced Mobility

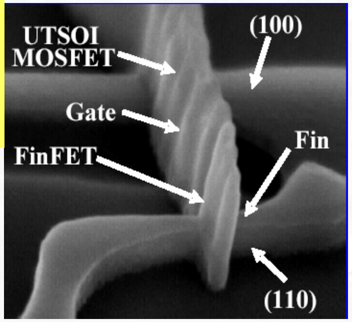
High κ/interface
& Metal Gate
Metrology

Tomorrow



New Materials

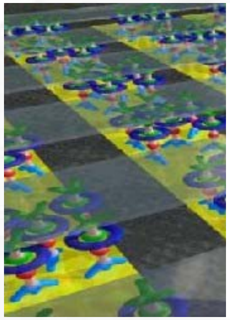
Future
15 years
Non-classical CMOS

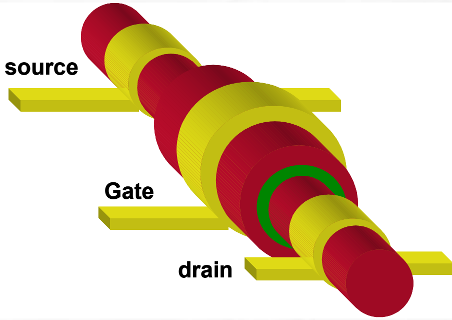


CMOS
pMOS FINFET

Metrology
For New
Structures

Beyond CMOS





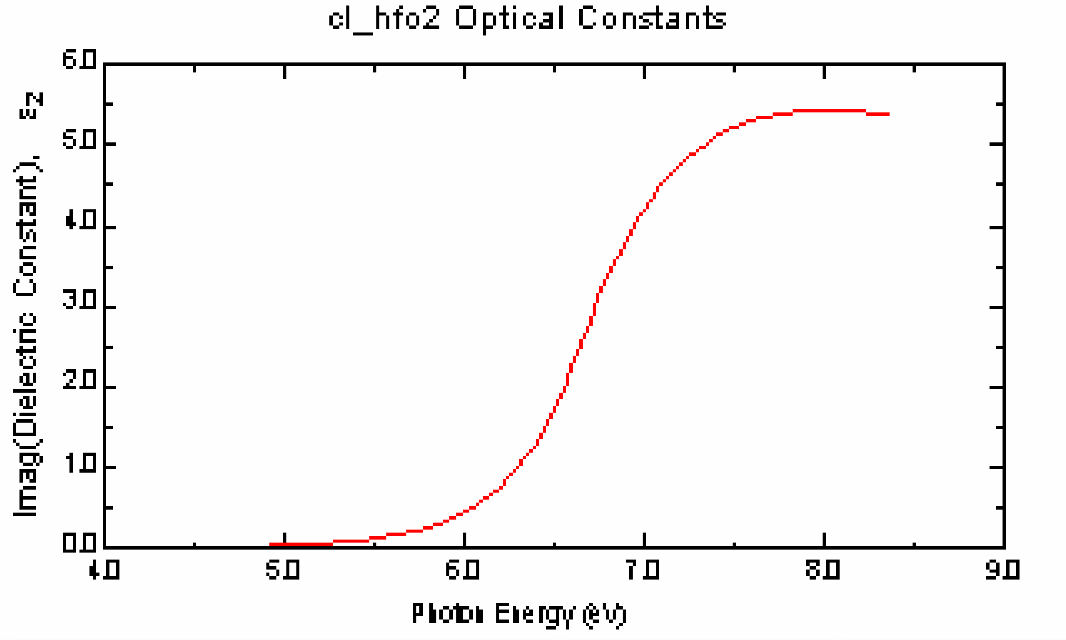
Molecular Switches ?
Nanowire Transistor ?

Metrology
For New
Switches

Cody-Lorentz* optical model used for parametric modeling of gate dielectrics.

$$\varepsilon_2 \propto Exp\left[\frac{(E - E_t)}{\beta}\right], \; for E \le E_g.$$

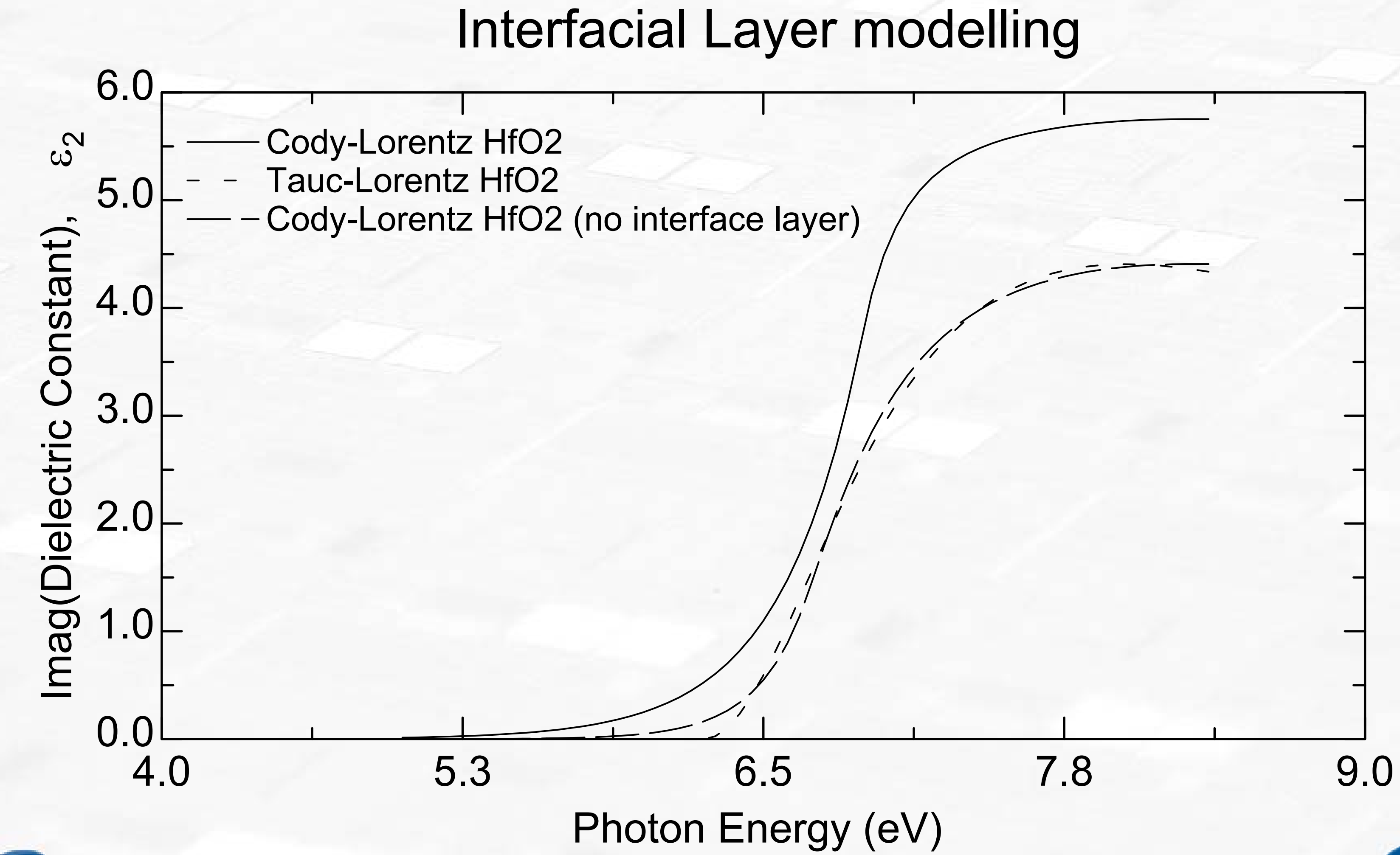
$$\varepsilon_2 \propto (E - E_g)^2, \; for E > E_g.$$



* A.S. Ferlauto, et. al., J. Appl. Phys., 92, 2424 (2002).

J. Price, et. al, Appl. Phys. Letters, 85, 1701 (2004).

Extend Ellipsometry by Optical Modeling



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Spectroscopic Ellipsometry Fundamentals:

For multiple films, use Abeles* matrix method to extract thickness and refractive index of each film:

$$r_p \propto \chi_{0,P}\left(\prod_{i=1}^{N} P_{i,p}\right)\chi_{sub,p}$$

$$r_s \propto \chi_{0,s}\left(\prod_{i=1}^{N} P_{i,s}\right)\chi_{sub,s}$$

X is the characteristic dielectric matrix for the ambient (0) or substrate (sub).

$$P_{j,p} = \begin{vmatrix} \cos(\beta_j) & -i\sin(\beta_j)\dfrac{\cos(\theta_j)}{\tilde{n}_j} \\ i\sin(\beta_j)\dfrac{\tilde{n}_j}{\cos(\theta_j)} & \cos(\beta_j) \end{vmatrix} \qquad P_{j,s} = \begin{vmatrix} \cos(\beta_j) & \dfrac{i\sin(\beta_j)}{\tilde{n}_j\cos(\theta_j)} \\ i\tilde{n}_j\sin(\beta_j)\cos(\theta_j) & \cos(\beta_j) \end{vmatrix}$$

$$\beta_i = \frac{4\pi d_i \tilde{n}_i \cos\theta_i}{\lambda}$$

d_i = thickness of ith film

$\tilde{n}_i$ = index of refraction of ith film

θ_i = incident angle

λ = incident wavelength

---

*F. Abeles, Ann de Physique 5:596, 1950.

Thin film limits for SE:

For the thin film limit:

- β<<1
- Small angle approximation ➡

$$Cos(\beta_j) \xrightarrow{\beta<<1} 1$$

$$Sin(\beta_j) \xrightarrow{\beta<<1} \beta_j$$

$$\lim_{\xrightarrow[\beta<<1]{}} = P_{j,s} = \begin{vmatrix} 1 & \dfrac{i\beta_j}{\tilde{n}_j \cos(\theta_j)} \\ i\,\tilde{n}_j\,\beta_j \cos(\theta_j) & 1 \end{vmatrix} \text{ and } P_{j,p} = \begin{vmatrix} 1 & -i\beta_j \dfrac{\cos(\theta_j)}{\tilde{n}_j} \\ \dfrac{i\tilde{n}_j\,\beta_j}{\cos(\theta_j)} & 1 \end{vmatrix}$$

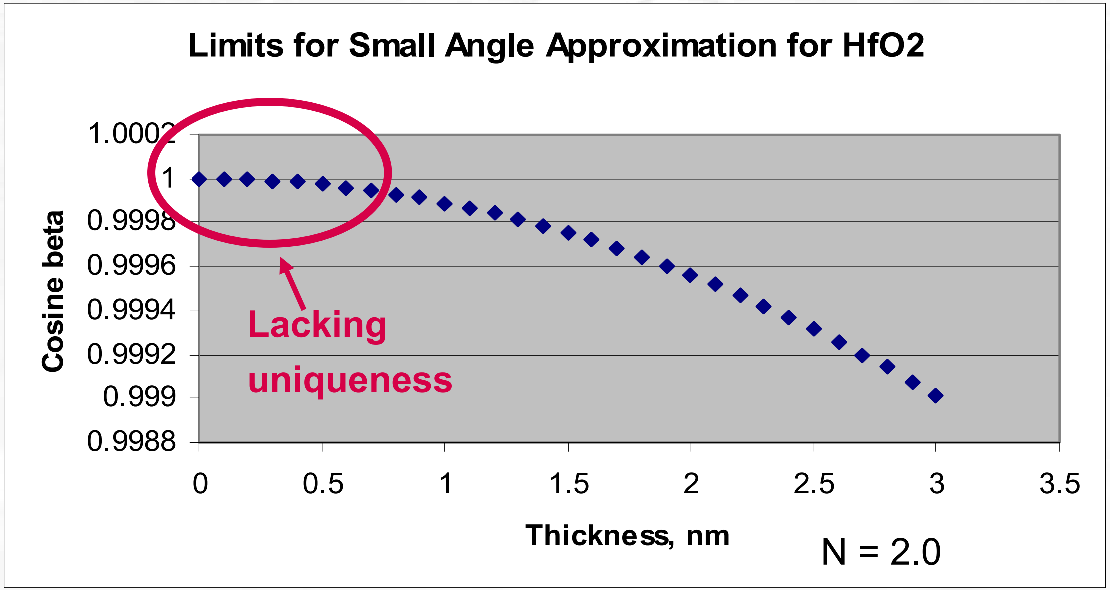
Is A above B or B above A??

Uniqueness and the need for complimentary techniques.

In order to separate the individual contributions, the characteristic phase factor, β, must be large enough:

$$\beta_i = \frac{4\pi d_i \tilde{n}_i \cos\theta_i}{\lambda}$$

1. Increase the thickness, d.
2. Decrease the wavelength, λ.



N = 2.0

Θ = 67 degrees

λ = 670nm

Otherwise, other complimentary techniques are needed (SHG,TEM,XRR, etc) in order to determine one of the variables, d or n

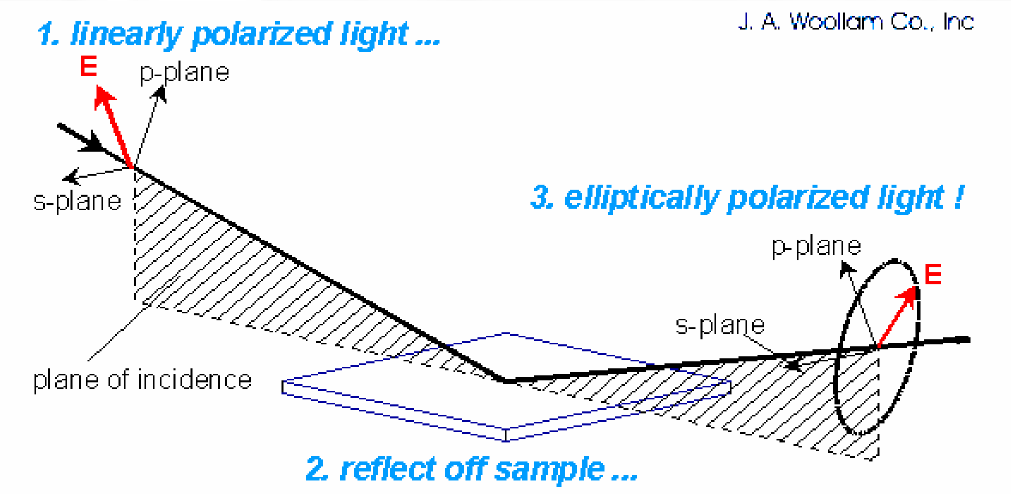
How thin a film can be measured with ellipsometry?

- Drude Approximation **In 1890, Drude observed that (for thin films) the change in the ellipsometric parameter Del, Δ, is linearly related to a change in film thickness*:**

$$\Delta - \Delta^0 = C_\Delta X$$

Here, C_Δ , is a constant of proportionality and is a function of the index of refraction, n, and X is the film thickness.

1. P. Drude, Ann. Phys. Chem., 36, 865 (1889).
2. A.N. Saxena, J. Opt. Soc. Am., 55, 1061 (1965).



J. A. Woollam Co., Inc

Del is the change in phase of the polarization after reflection.

$$\Delta = \delta_1 - \delta_2$$

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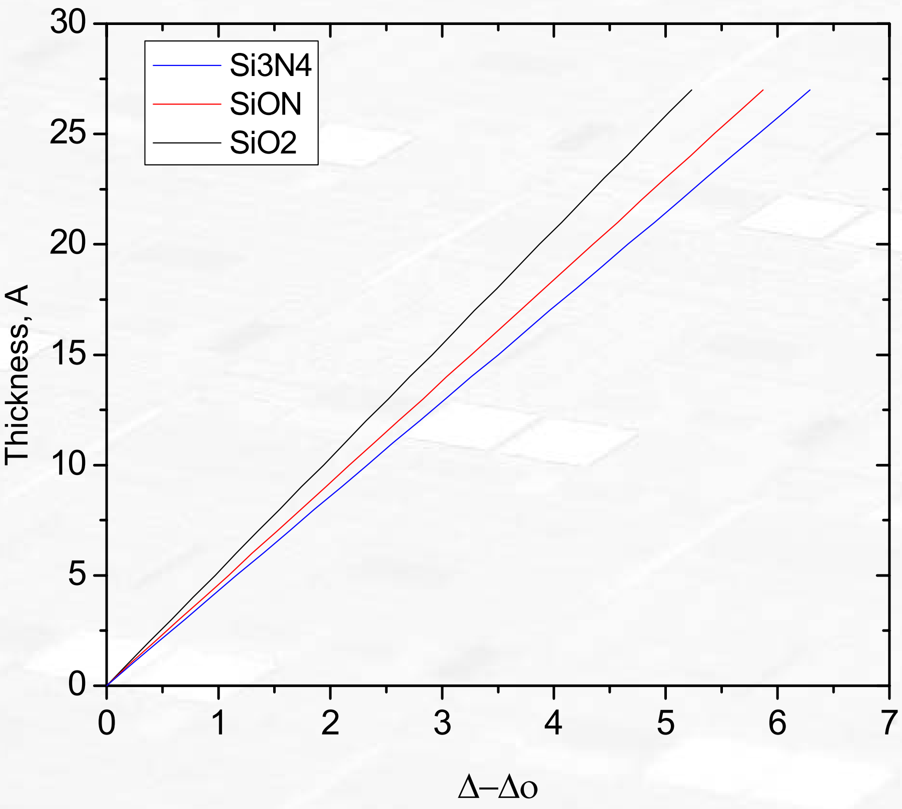
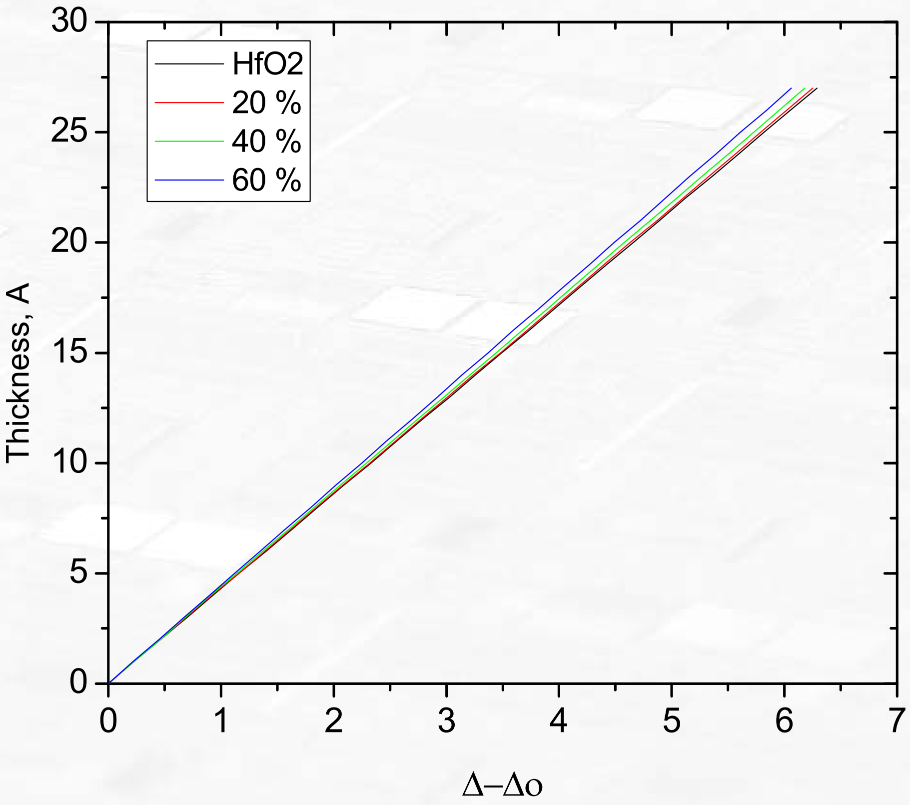
Ellipsometric sensitivity to changes in thickness.

Silicon, Oxide, and Nitride



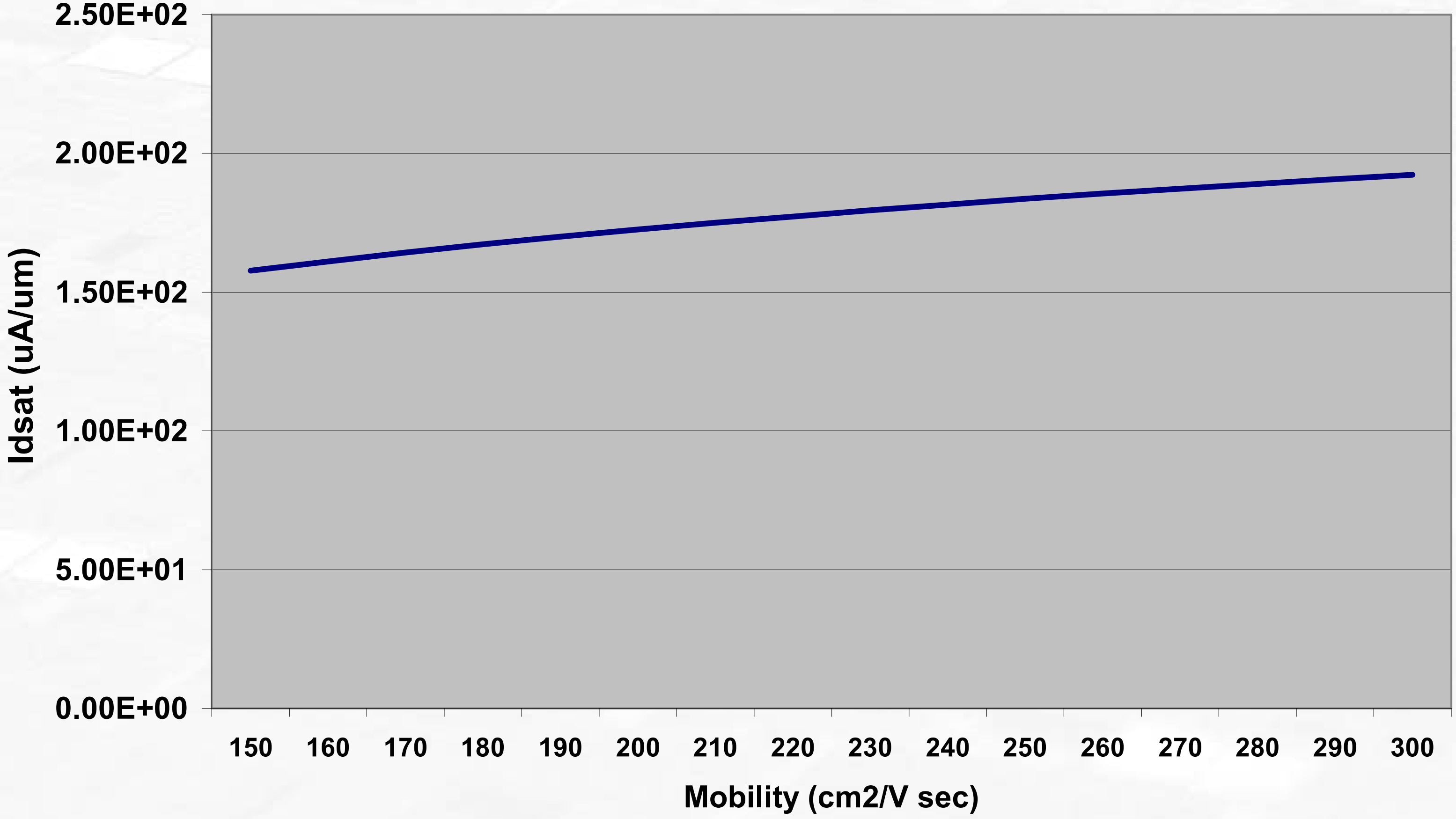
HfO2 and it's silicates



For accurate ellipsometers, we can measure Del with 0.01 degree resolution. Therefore, theoretically, we are capable of measuring 0.1nm films independent of a user-defined model…

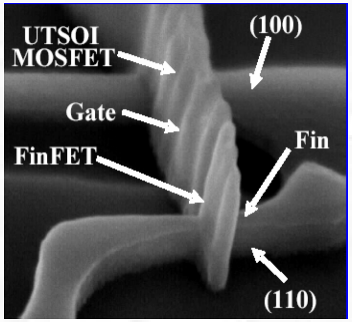
Mobility vs Transistor Drive Current

How sensitive is process to stress variation?

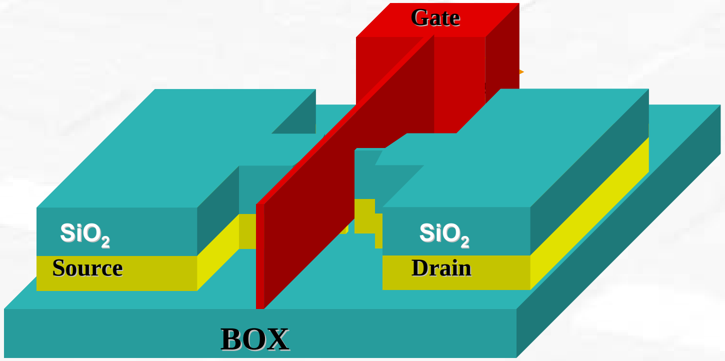


***Equation from Taur&Ning*, p. 151**

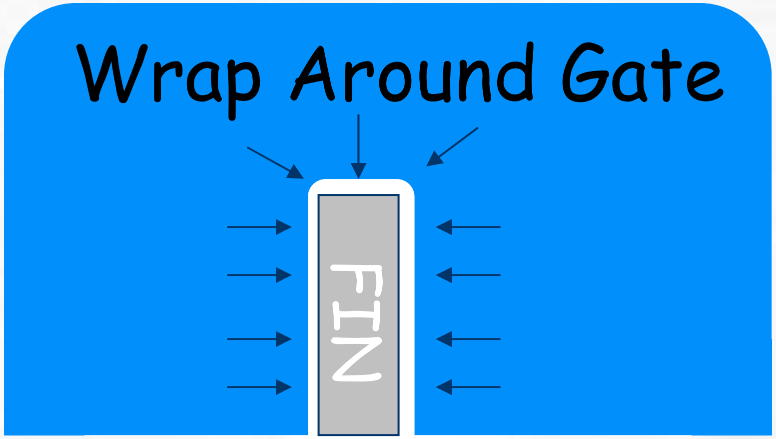
Wrap Around Gate Metrology



FINFET



Side Wall and Top Dielectric Thickness and Composition



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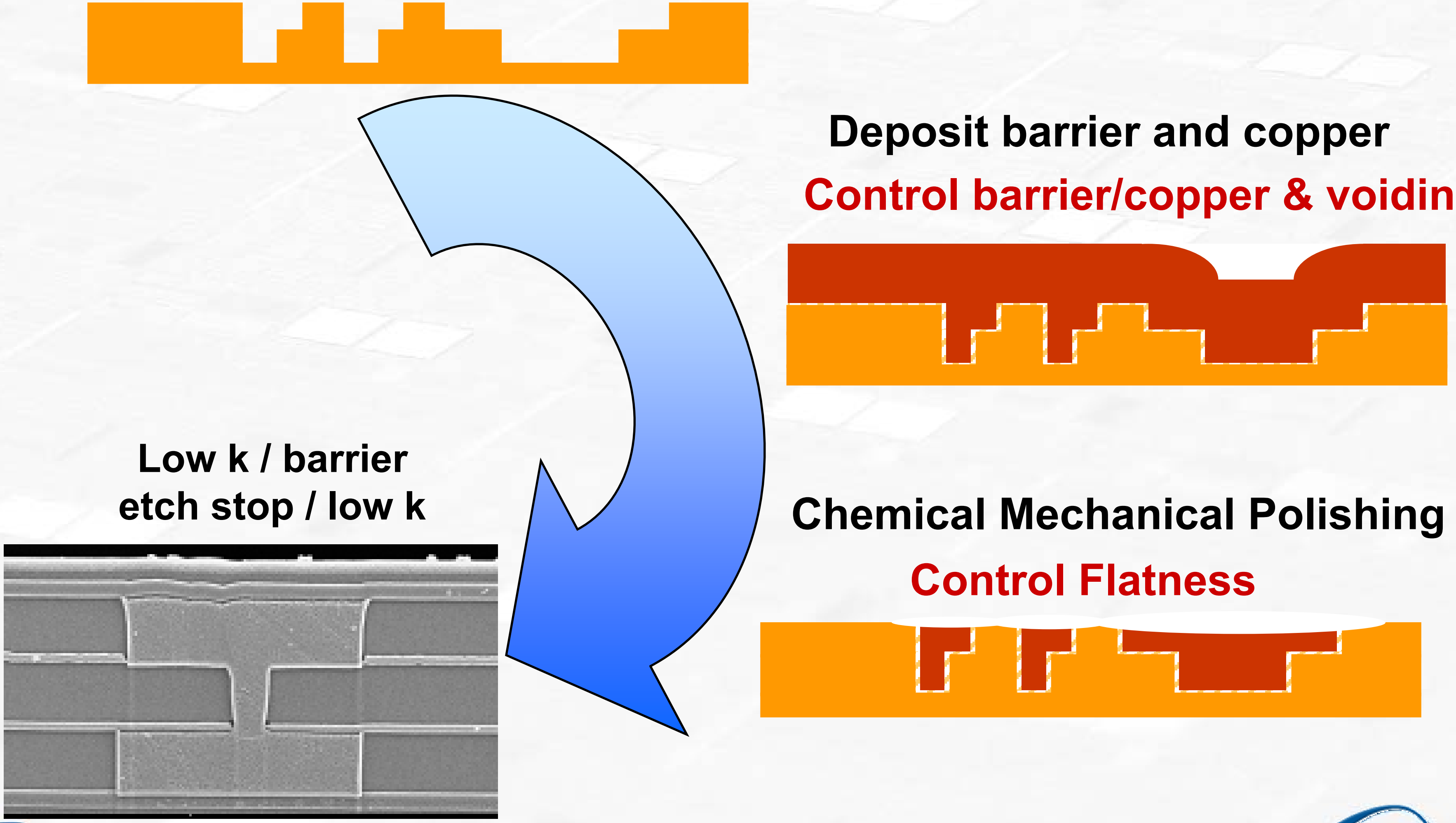
Interconnect Metrology



Pattern Low κ

Control Film Stack Thickness, Line width/depth and shape

Deposit barrier and copper

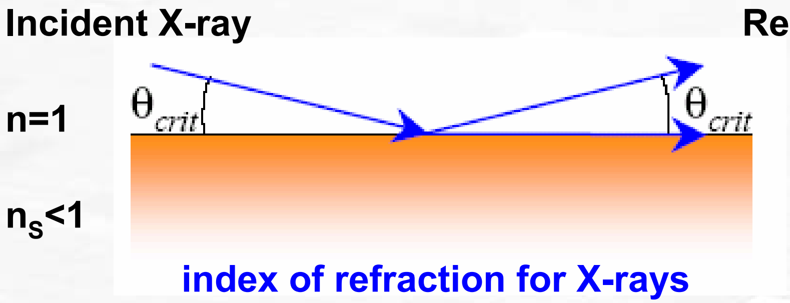
Control barrier/copper & voiding

Chemical Mechanical Polishing

Control Flatness

Low k / barrier etch stop / low k

Bulk X-ray Reflectivity

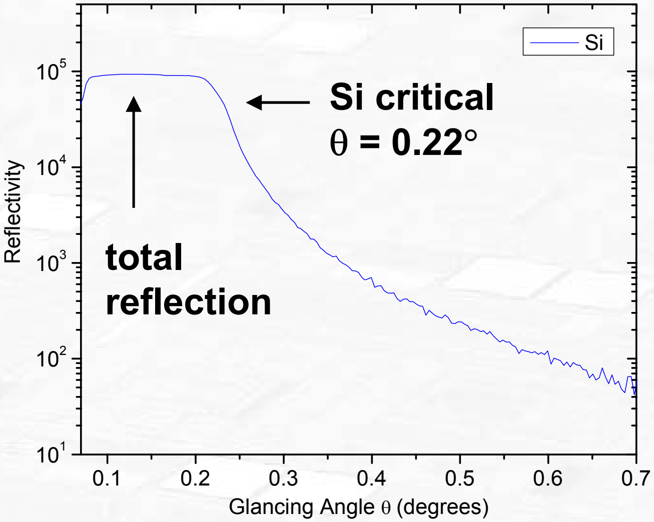


$$\theta_{crit} = \lambda\sqrt{r_o\rho_e/\pi}$$

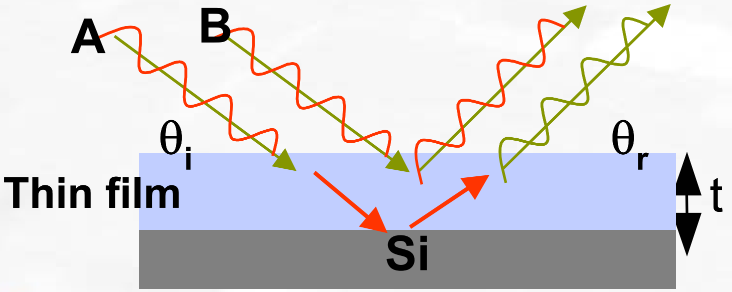
Si
D= 2.33 g/cm³

λ = X-ray wavelength= 1.5406 A
r_o = classical electron radius=2.8×10^{-15} m
ρ_e = electron density

XRR spectrum of Si



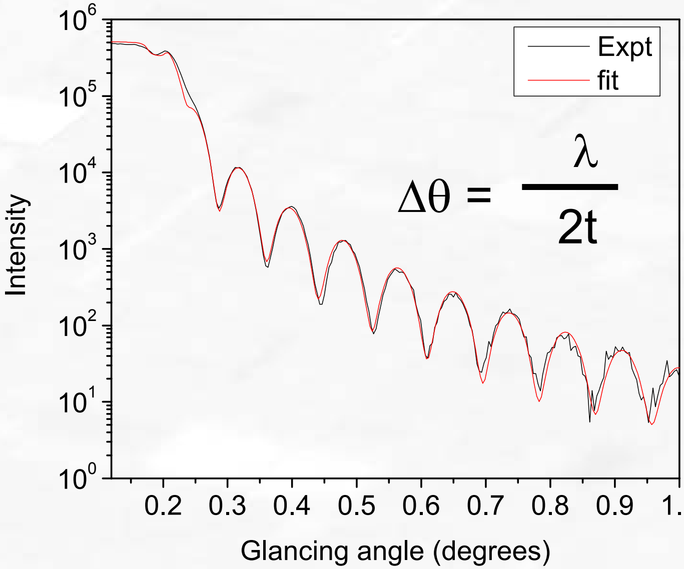
Thin film Thickness & Density



Bragg equation

$$2t\sin\theta = n\lambda$$

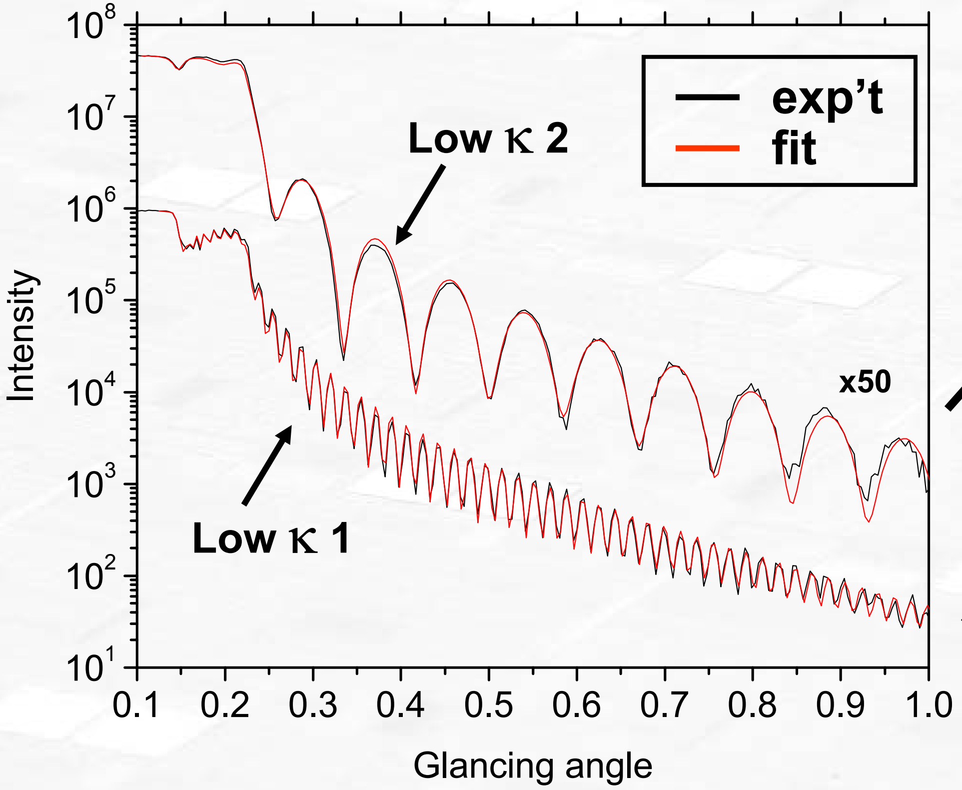
$$\lambda = 1.5406 \text{ A}$$



$$\Delta\theta = \frac{\lambda}{2t}$$

XRR spectra of porous Low κ 1 and Low κ 2

2 Layer Model



Porous low κ 2

T= 7.6 nm, D=0.956 g/cm3

T= 35.9 nm, D=0.73 g/cm3

T= 6.6 nm, D=0.979 g/cm3

Si with native oxide

Total thickness = 50.1 nm

Porous low κ 1

T=226 nm; D=0.931 g/cm3

T= 6.2 nm, D=1.01 g/cm3

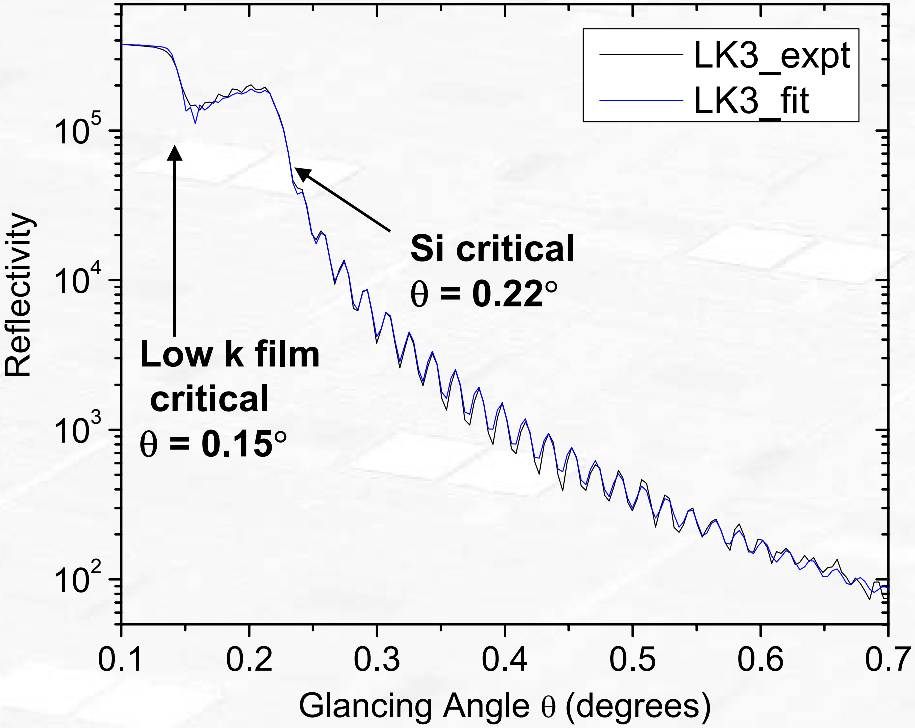
Si with native oxide

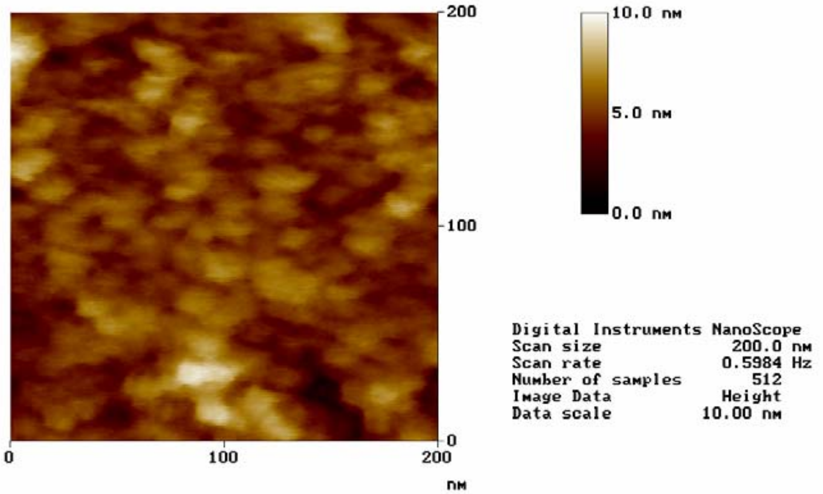
Total thickness= 232.2 nm

Models with additional interfaces are needed to adequately describe the envelope of the fringes for porous low κ 1 and low κ 2 films.

XRR analysis: surface roughness

Porous Low κ 3





```
Digital Instruments NanoScope
Scan size               200.0 nm
Scan rate             0.5984 Hz
Number of samples          512
Image Data              Height
Data scale            10.00 nm
```

The magnitude of the roughness from XRR is ~2x greater than from the AFM data

XRR				AFM	
				200 nm scan	20 micron scan
Formula	**thickness(nm)**	**Density(g/cm3)**	**Rrms (nm)**	**Rrms (nm)**	**Rrms (nm)**
SiCOH	**226.7**	**0.952**	**2.3**	**1.07**	**0.89**
Si	**thick**	**2.33**	**0.25**	**0.2**	**0.1**

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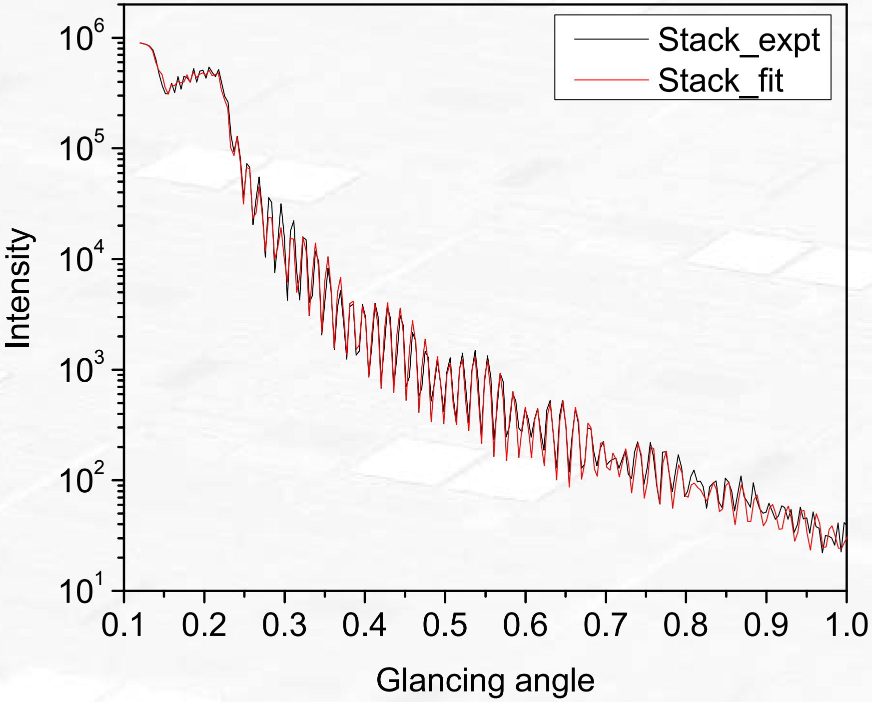
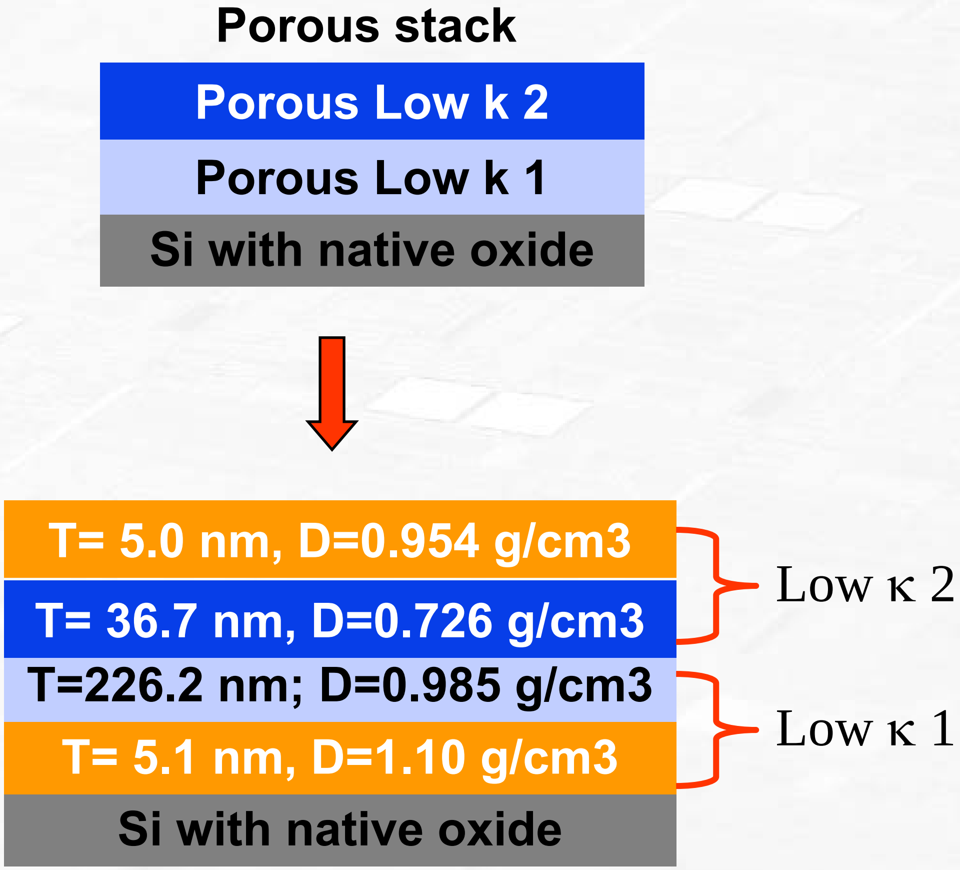
XRR spectrum of porous stack: Low κ 1 and Low κ 2





Porous stack

Porous Low k 2

Porous Low k 1

Si with native oxide

T= 5.0 nm, D=0.954 g/cm3

T= 36.7 nm, D=0.726 g/cm3

T=226.2 nm; D=0.985 g/cm3

T= 5.1 nm, D=1.10 g/cm3

Si with native oxide

Low κ 2

Low κ 1

<u>Multi-layered model is</u> also needed to measure the properties of the film stack composed of the porous Low κ 1 and Low κ 2 films

AGENDA

- Evolution of Micro to Nanoelectronics
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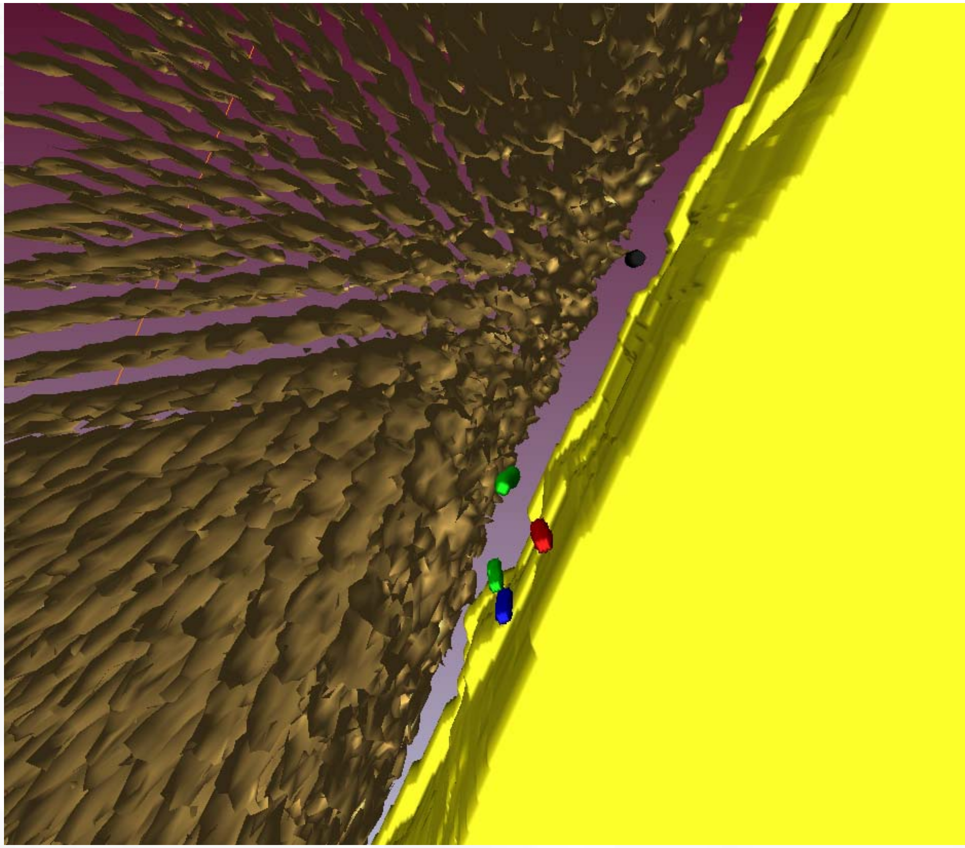
- Transistor (FEP) Metrology Challenges
- Interconnect Metrology Challenges
- The Future of Materials Characterization
- Nano - Characterization and Metrology
- Trends & Conclusions

The Future of Materials Characterization

Trend : 3D Atomic Imaging

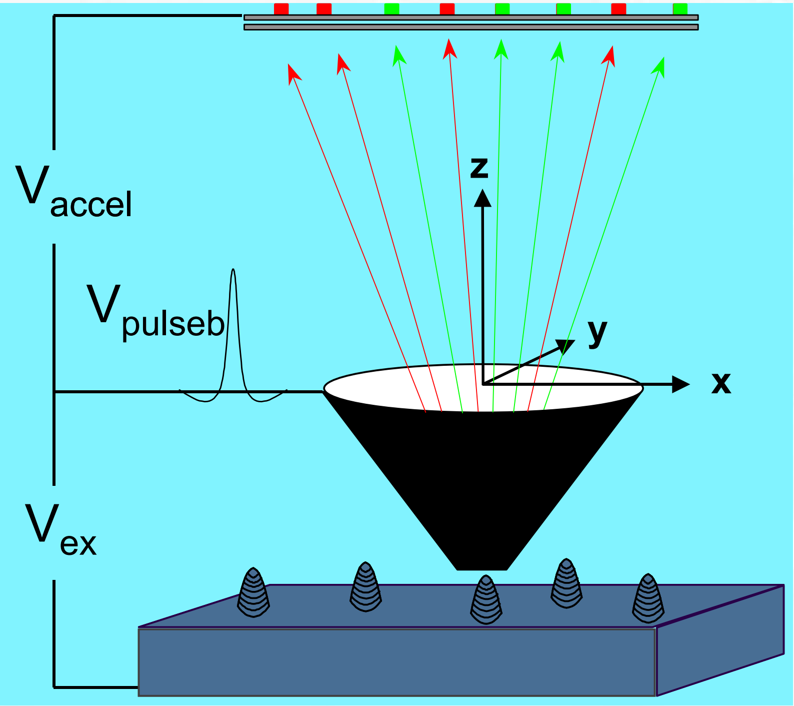
Pennycook, et al, Aberration Corrected STEM
Hf atoms in High K – Si Interface

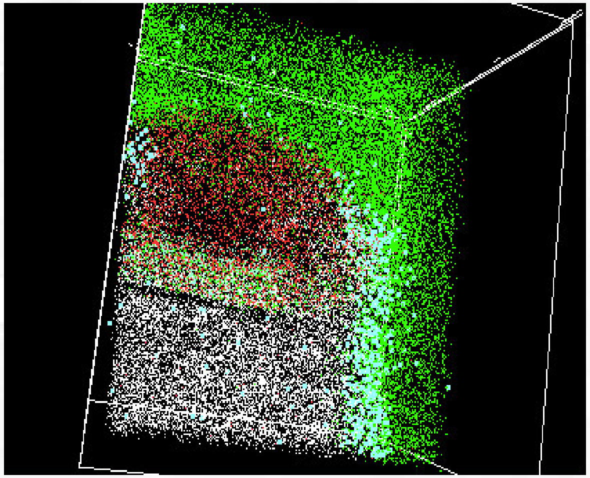


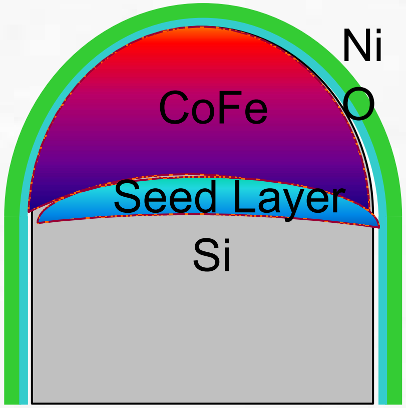
The Future of Materials Characterization

Trend : 3D Atomic Imaging

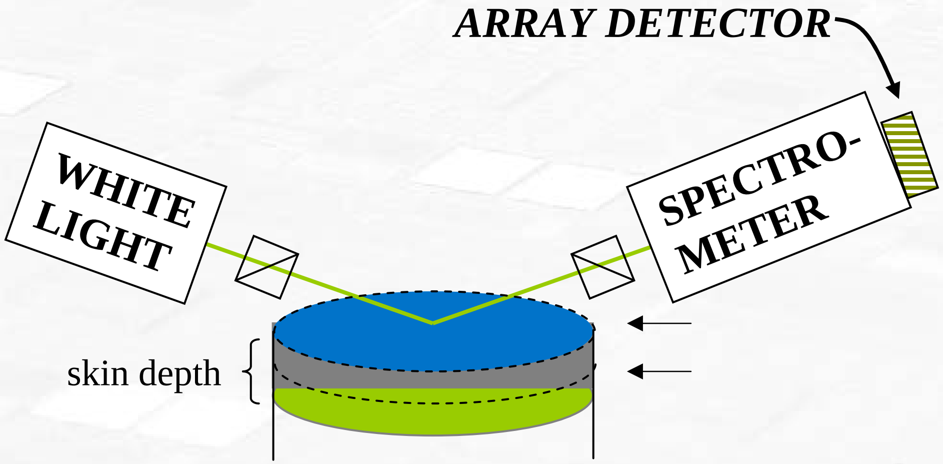
Kelly, et al, Local Electrode Atom Probe

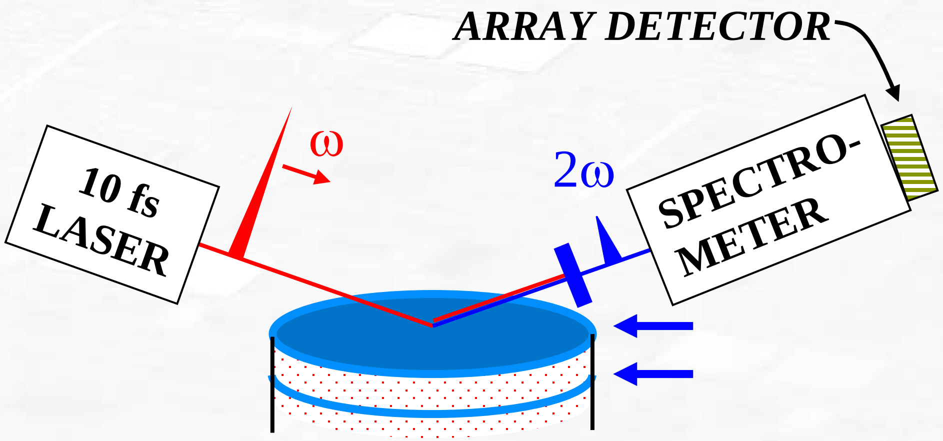






The Future of Materials Characterization
Trend : New Problems often require New Methods such as Optical Second Harmonic Generation





SPECTROSCOPIC ELLIPSOMETRY:
surfaces & buried interfaces are perturbations to the bulk response

SH SPECTROSOPY:
surfaces & buried interfaces are the primary source regions

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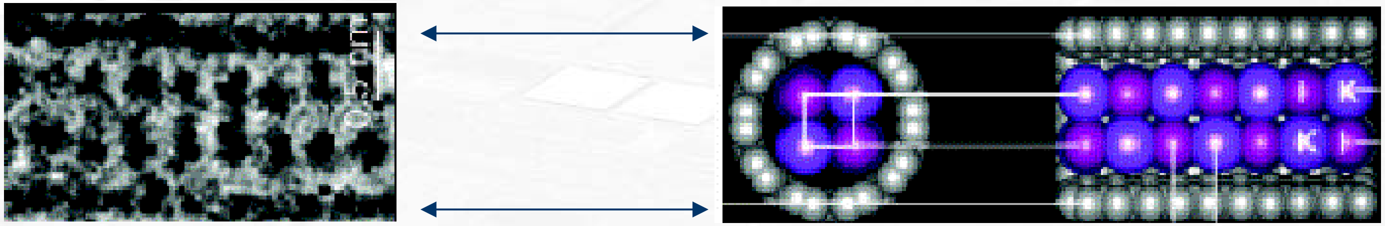
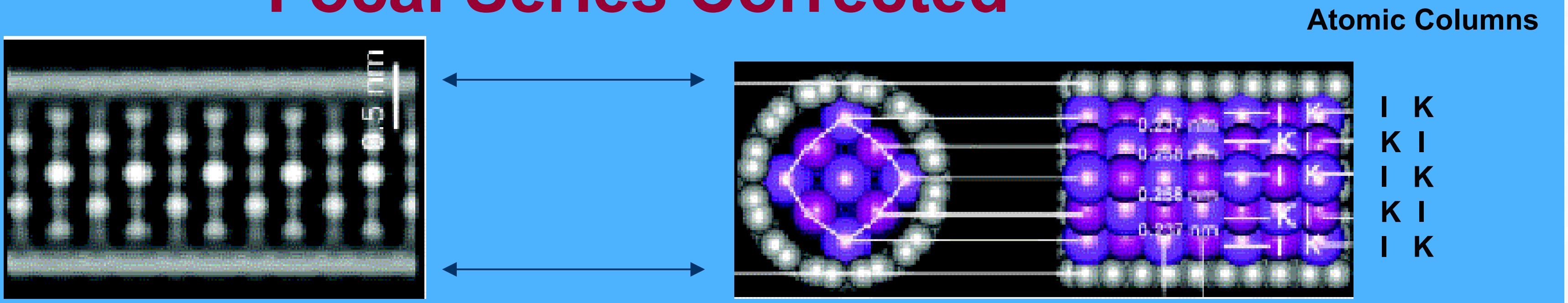
NanoCharacterization of Nanotubes
Aberration Corrected TEM Imaging

Not Corrected



Heavy atom (Iodine) atomic columns are imaged

Focal Series Corrected



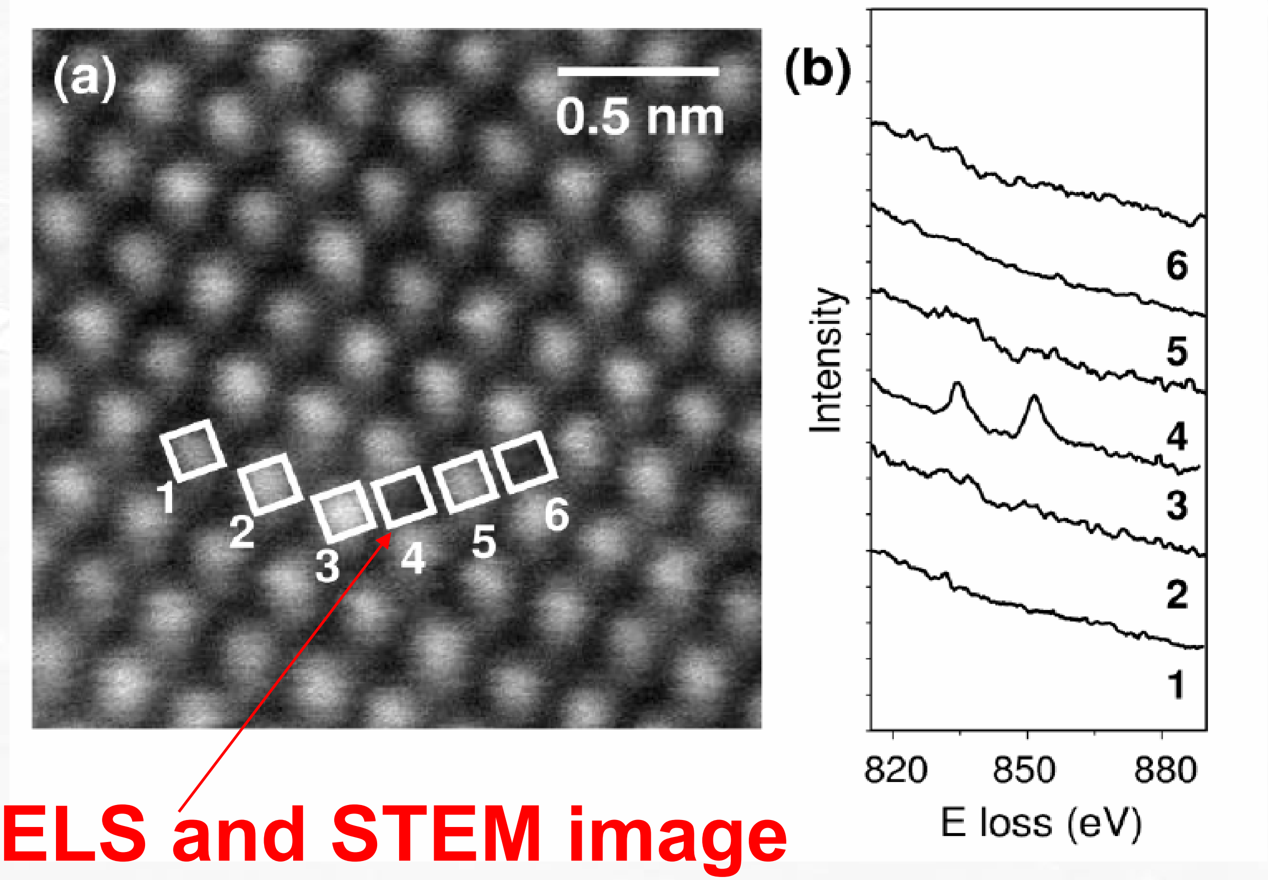
Both K and I atomic columns are imaged

Sloan, et al, MRS Bulletin, April 2004

Imaging atomic columns & spectroscopy of one atom in column

Requirement

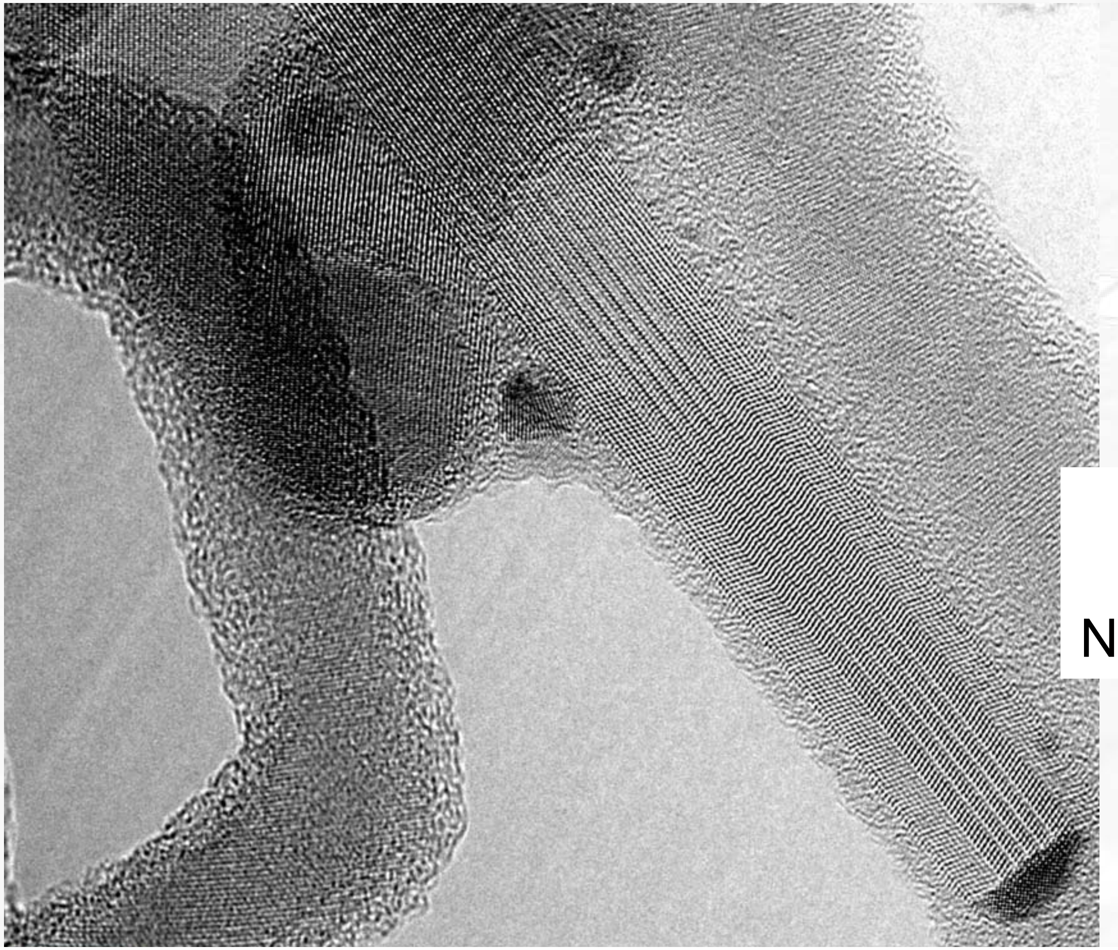
Aberration Corrected TEM/STEM



La seen in ELS and STEM image of $CaTiO_3$

Varela, et al, PRL 92, 2004, p 106802

Aberration Corrected HR-TEM Korgel Group Si Nanowire



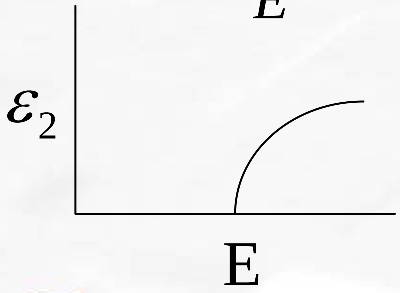
Au dot structure
&
Nanowire Twinning

NanoMetrology & Optical Methods

Trend : Metrology Models MUST INCLUDE OPTICAL RESPONSE DUE TO DIMENSIONAL CONFINEMENT:

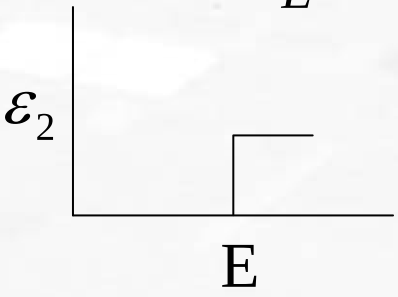
3D: Bulk Film

$$\varepsilon_2 \propto \frac{(E-E_g)^{\frac{1}{2}}}{E^2}$$

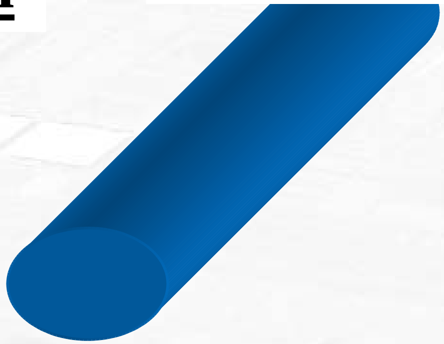


2D: QuantumWell

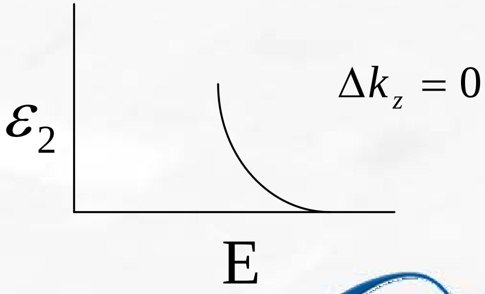
$$\varepsilon_2 \propto \frac{\Theta(E-E_g)}{E^2}$$



1D: NanoWire



$$\varepsilon_2 \propto \frac{(E-E_g)^{\frac{-1}{2}}}{E^2}$$



Imaginary part of the dielectric function at the direct band-edge

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Trends and Conclusions

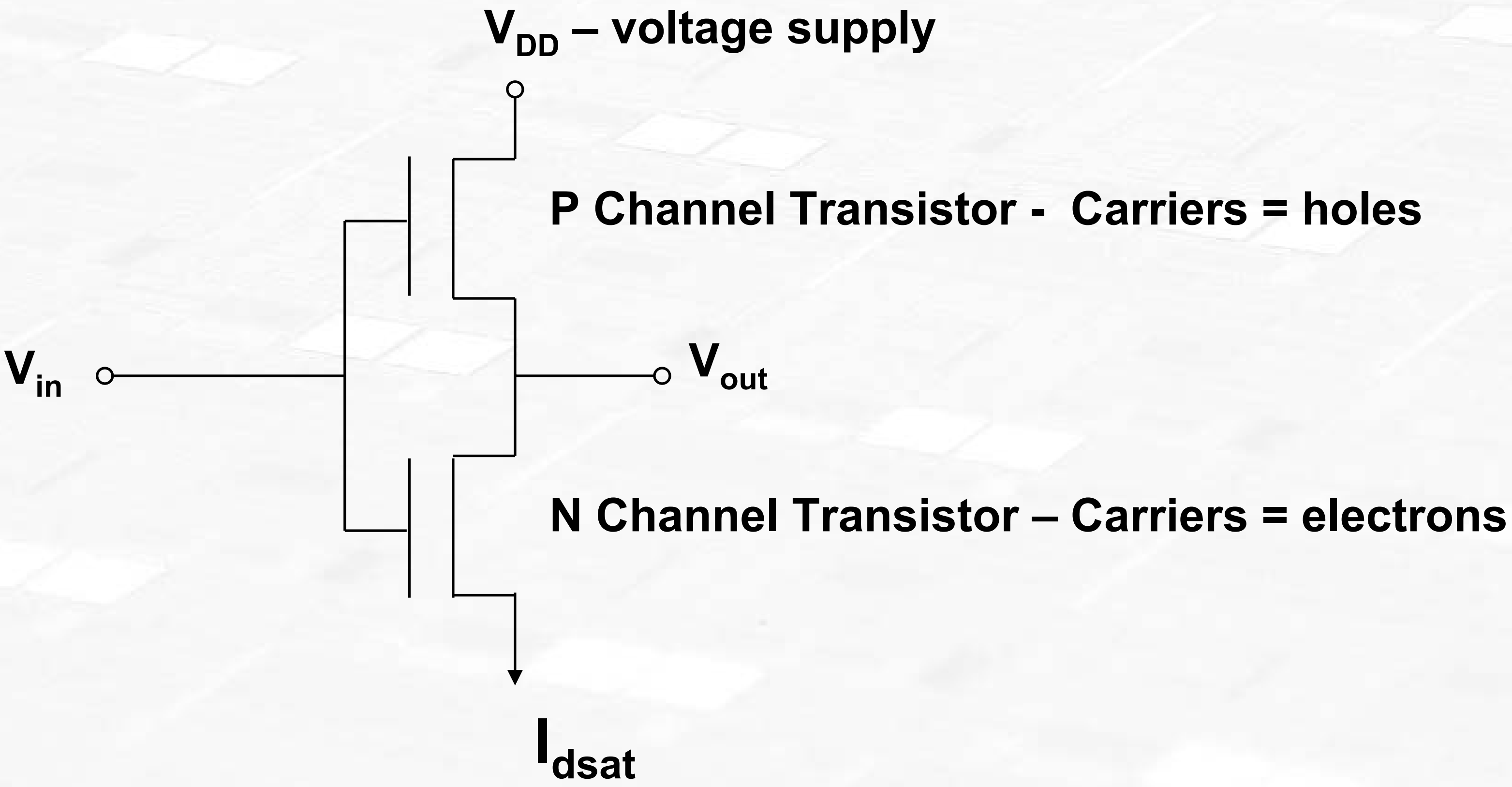
- Use Modeling to connect what you want to measure with what you need to know
- Interfacial Measurement is Increasing in Difficulty & Importance
- Sidewall Control will become more important
- 3D Atomic Imaging
- New Problems often require New Methods such as Optical Second Harmonic Generation
- Trend : Dimensional Confinement and Surface State Effects must be included in Optical Modeling

Acknowledgements

- PY Hung, Jimmy Price, Hugo Celio
- Peter Zeitzoff + Howard Huff
- Ken Monnig
- TEM Community – Brendan Foran, Christian Kisielowski, Dave Muller, Steve Pennycook, John Silcox, Suzanne Stemmer
- Dan Wack – KLA-Tencor

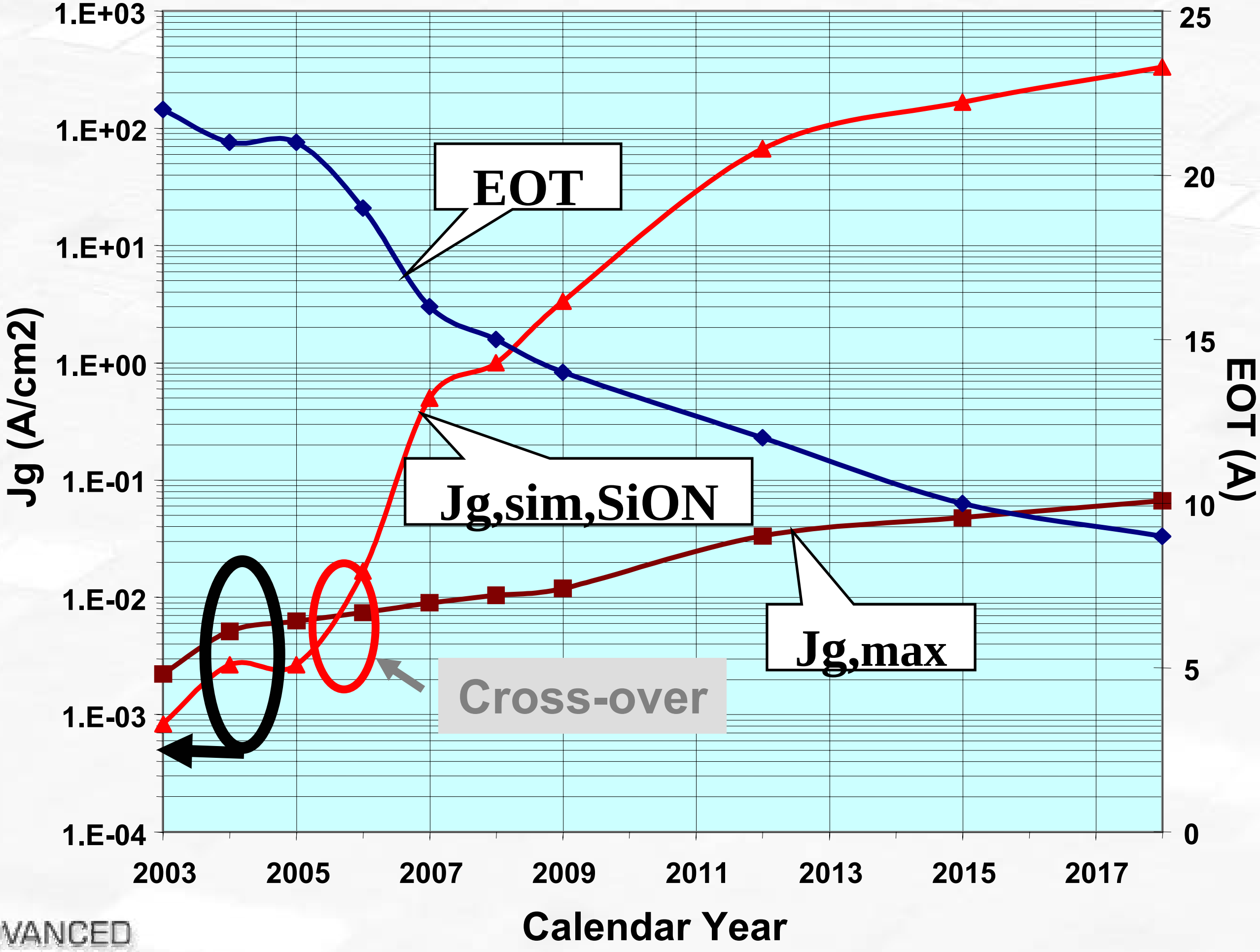
CMOS Switching Speed $\tau \sim 1/I_{dsat}$

Role of Saturation Drive Current



$$\tau = C_{load} V_{DD} / I_{dsat}$$

Leakage Current Increases as SiO_2 Gate Dielectric Thickness Decreases



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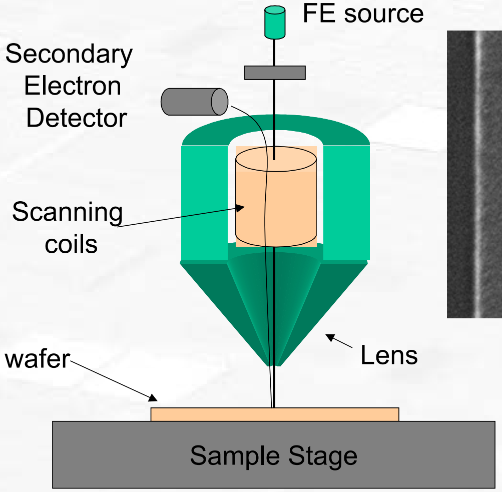
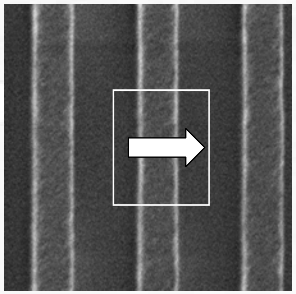
Evolution CD-SEM
Applied Materials CD-SEM

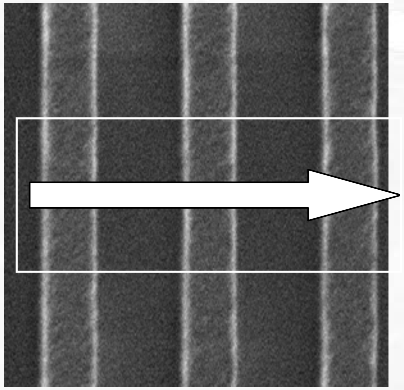
Old Way

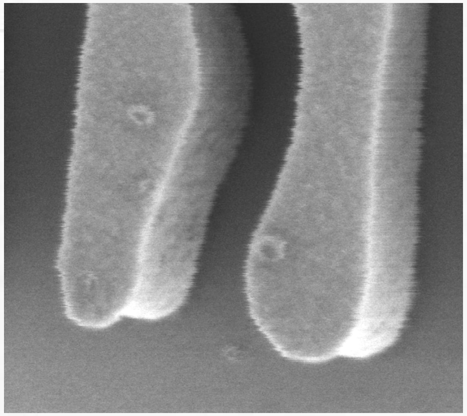


Top Down Image



New Way





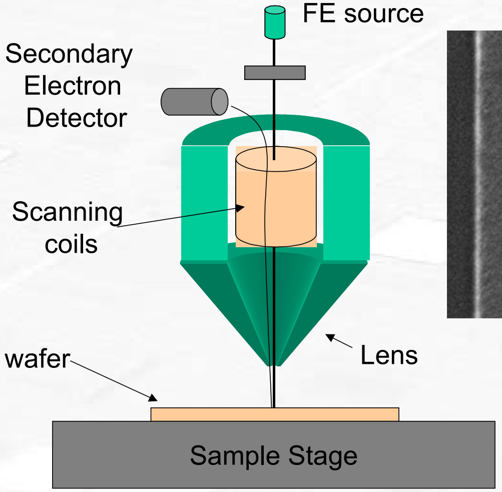
Measure several lines for local CD average

Tilt Beam for sidewall metrology

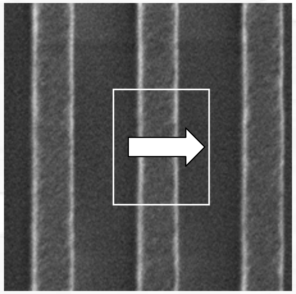
The CD-SEM of the Future???

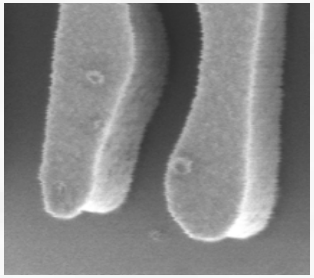
Migration of TEM LENS Technology to SEM

Today



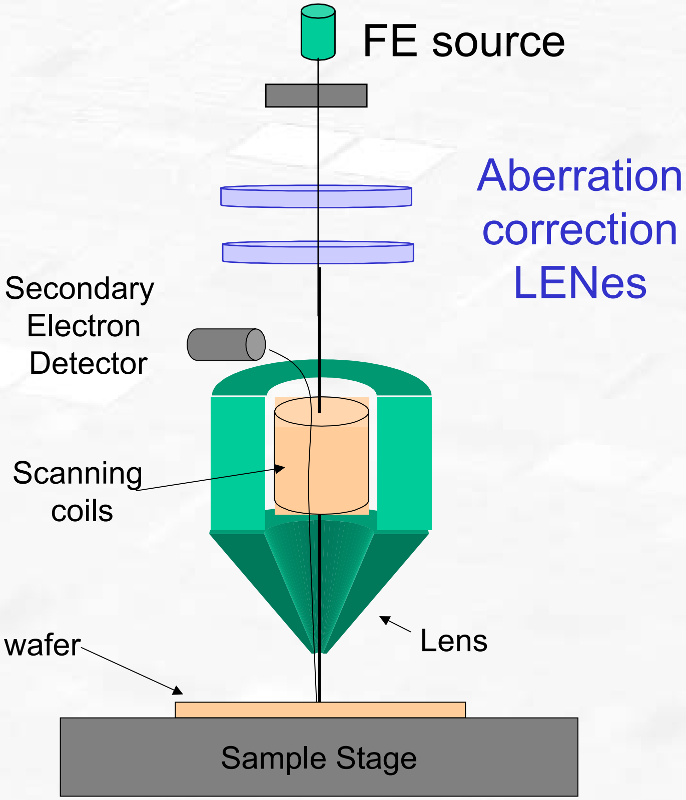
Top Down Image



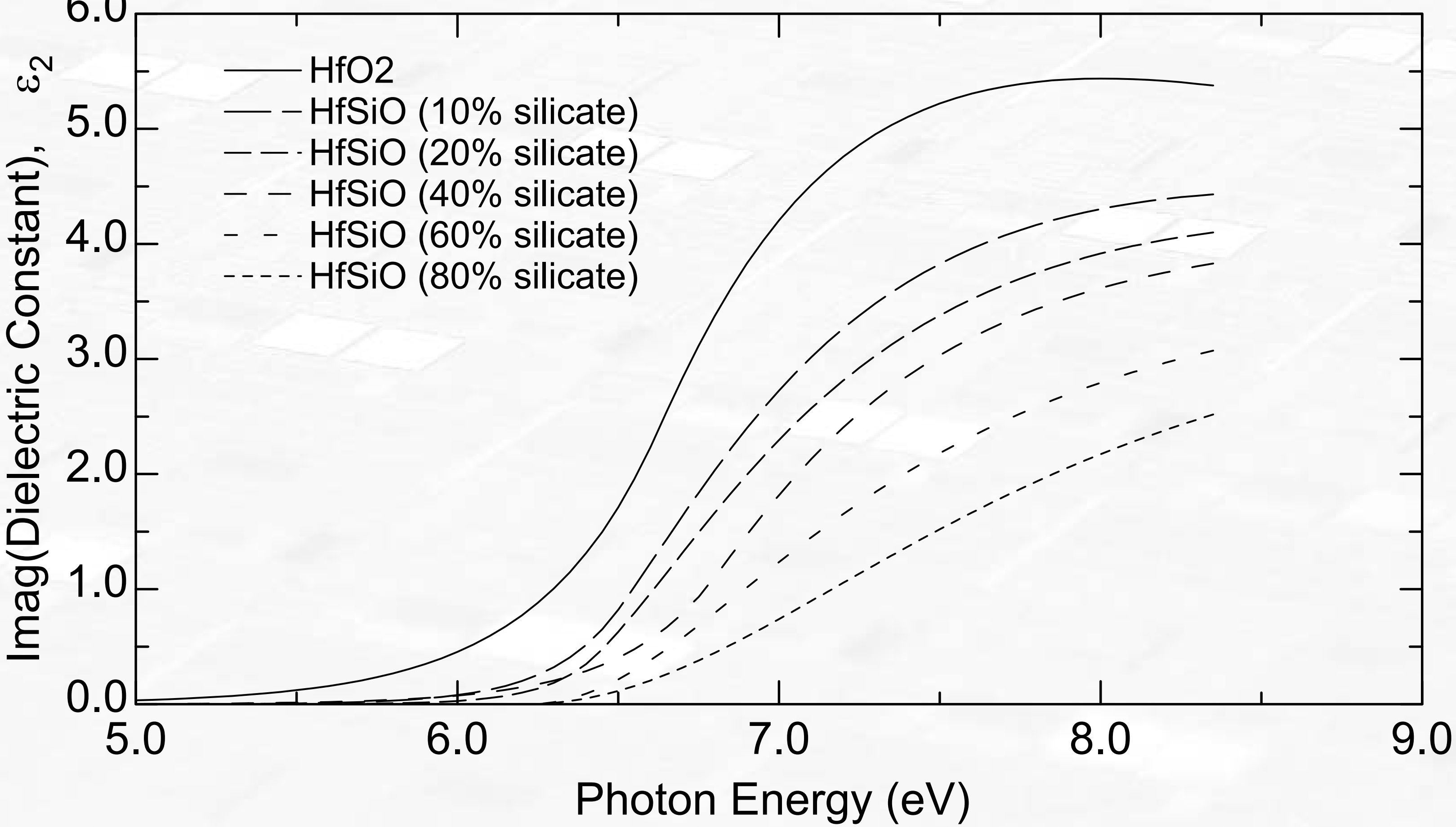


Tilt Beam for sidewall metrology

Tomorrow



Optical Constants



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Spectroscopic Ellipsometry Fundamentals:

-> SE extracts the thickness and index of refraction from a film stack using the Fresnel reflection coefficients:

$$r_p = \frac{r_{01,p} + r_{12,p} e^{-i\beta}}{1 + r_{01,p} r_{12,p} e^{-i\beta}}$$

$$r_s = \frac{r_{01,s} + r_{12,s} e^{-i\beta}}{1 + r_{01,s} r_{12,s} e^{-i\beta}}$$

Where, $\beta_i = \frac{4\pi d_i \tilde{n}_i \cos\theta_i}{\lambda}$

- Here, the first indices is the incident medium, and the second indices is the subsequent medium (e.g. 0 = air, 1 = top film).
- P and S are the polarization states parallel and perpendicular to the plane of incidence.
- β is the phase factor for the ith layer.

d_i = thickness of ith film
n_i = index of refraction of ith film
θ_i = incident angle
λ = incident wavelength

For multiple films, this can become very complicated…

Spectroscopic Ellipsometry Fundamentals:

- For multiple films, use Abeles* matrix method:

$$r_p \propto \chi_{0,P} \left(\prod_{i=1}^{N} P_{i,p} \right) \chi_{sub,p}$$

$$r_s \propto \chi_{0,s} \left(\prod_{i=1}^{N} P_{i,s} \right) \chi_{sub,s}$$

X is the characteristic dielectric matrix for the ambient (0) or substrate (sub).

Where,

$$P_{j,p} = \begin{vmatrix} \cos(\beta_j) & -i\sin(\beta_j)\dfrac{\cos(\theta_j)}{\tilde{n}_j} \\ i\sin(\beta_j)\dfrac{\tilde{n}_j}{\cos(\theta_j)} & \cos(\beta_j) \end{vmatrix} \qquad P_{j,s} = \begin{vmatrix} \cos(\beta_j) & \dfrac{i\sin(\beta_j)}{\tilde{n}_j\cos(\theta_j)} \\ i\tilde{n}_j\sin(\beta_j)\cos(\theta_j) & \cos(\beta_j) \end{vmatrix}$$

*F. Abeles, Ann de Physique 5:596, 1950.

THE PROBLEM IS RC - HOW FAR CAN YOU GO?

A Theoretical Ideal

Aluminum (alloy) >>> Copper, R reduction of

	Aluminum (alloy)	Copper	R reduction of
Resistivity	**3.2**	**1.8**	**1.8 x**

SiO2 >>>>>>>>>>>>> Air, C reduction of

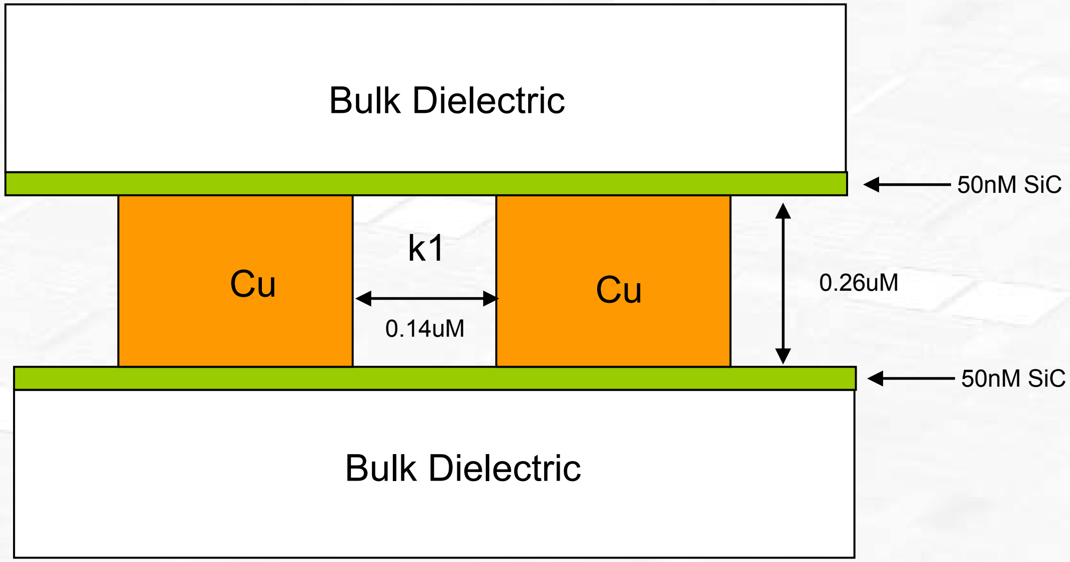
	SiO2	Air	C reduction of
Dielectric Constant	**4.2**	**1.0**	**4.2 x**

RC Reduction of

7.5

Thanks to Navjot Chhabra

MODELED EFFECTIVE DIELECTRIC CONSTANTS

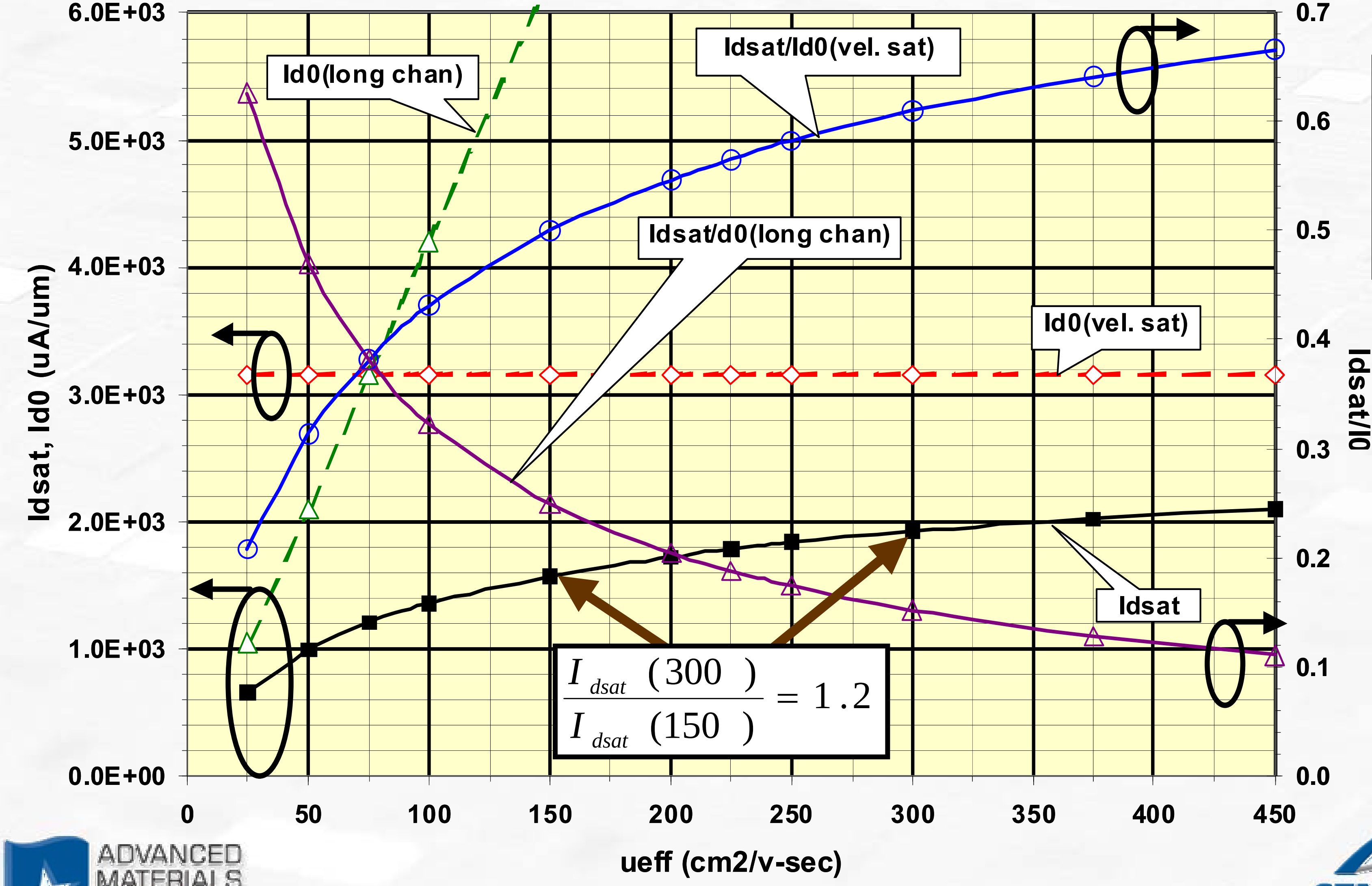


If bulk dielectric = 2.6 (SiLK*) then k_{eff} = 2.94
If bulk dielectric = 2.2 then k_{eff} = 2.57
If bulk dielectric = 1.5 then k_{eff} = 1.96
If bulk dielectric = 1.0 (Air) then k_{eff} = 1.5

* SiLK Semiconductor Dielectric, Trademark of the Dow Chemical Company

Thanks to Navjot Chhabra

Drive current response to strain uniformity



$$\frac{I_{dsat}(300)}{I_{dsat}(150)} = 1.2$$

-L=25nm
-Vg=1.0V
-Vt=0.2V
-Tox=0.7nm
-m=1.5
-vsat=8E6