Aggressive scaling of Cu/lowk: impact on metrology

Karen Maex

Sywert H. Brongerma, Francesca Iacopi, Kris Vanstreels, Youssef Travaly, Mikhail Baklanov, Jan D'Haen and Gerald Beyer

IMEC, KULeuven, LUC, IMOMEC

Introduction

-Performance is important:

Speed (RC), Energy (C), noise (C)

-How to measure R and C

-How to characterize Cu and low k in their narrow features

-Relevance of surface and interface characterization

Specifications for 32nm

	65nm	65nm	45nm	45nm	32nm	32nm
	2004	2003	2004	2003	2004	2003
Pitch local (nm)	152	152	108	108	76	76
Pitch intermediate (nm)	195	195	135	135	95	95
Barrier thickness M1 (nm)	5.4	7	4	5	2.8	3.5
Barrier thickness intermediate (nm)	7	7	4.9	5	3.6	3.5
Effective resistivity M1(uOhm.cm)	3.22	2.2	3.62	2.2	4.14	2.2
Effective resitivity intermediate (uOhmcm)	2.92		3.19		3.58	
Erosion local (nm)	13	13	10	10	7	7
Erosion intermediate (nm)	18	18	12	12	9	9
Dishing global (nm)	19	19	14	14	10	10
Jmax-intermediate MA/cm2	1.4	1.0	1.44	2.5	4.3	3.5
keff	2.7-3.0	2.7-3.1	2.3-2.6	2.3-2.6	2.0-2.4	2.0-2.4
k	<2.4	<2.5	<2.1	<2.2	<1.9	< 1.1
Equivalent sidewall damage (nm)						

Outline

-Electrical performance on R and C

-Low k dielectrics:

- k value
- pore sealing
- mechanical properties

-Cu wires

-Grain growth

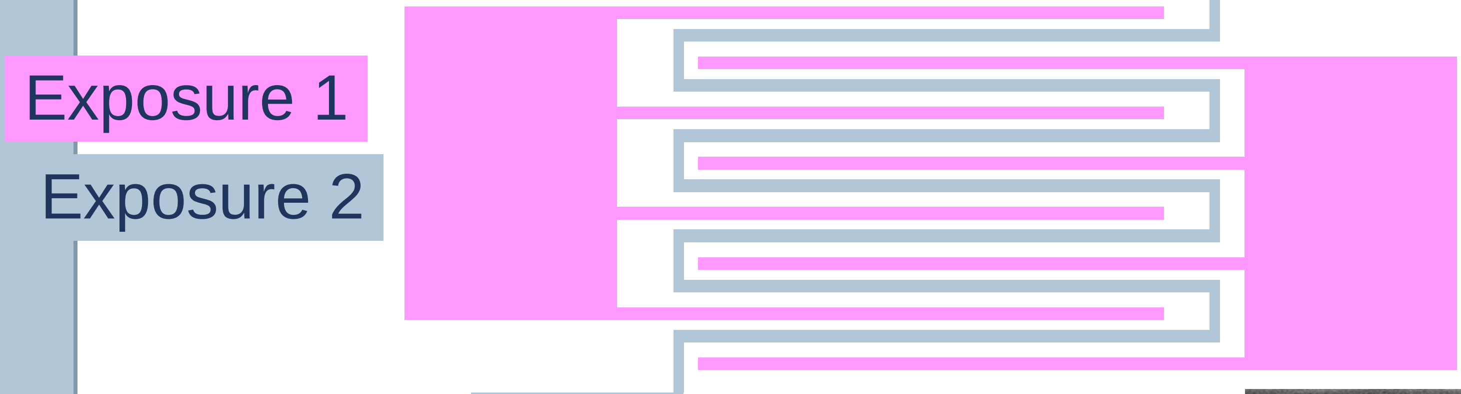
-Surface scattering

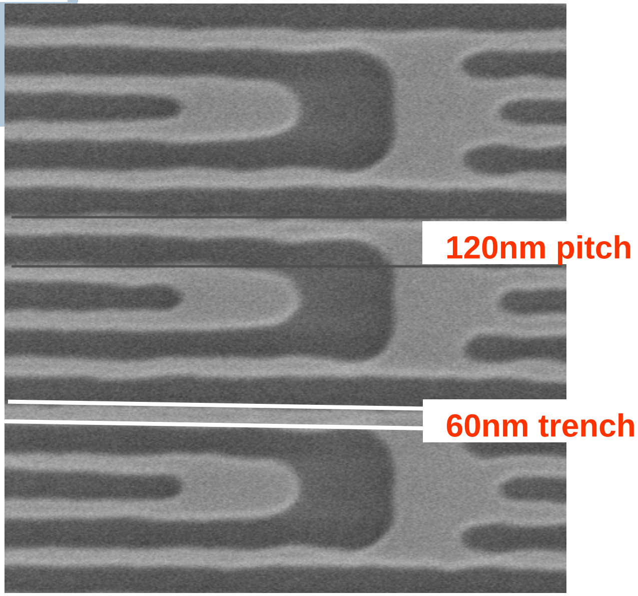
-Conclusion

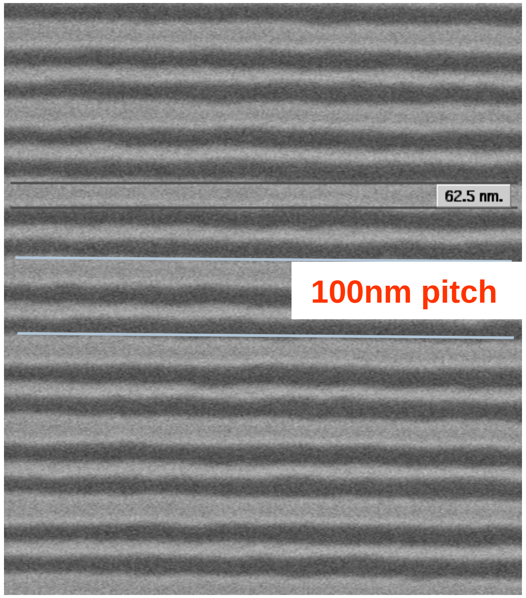
Scaling dimensions:SD50

M1 pitch for 45nm node: 108 nm

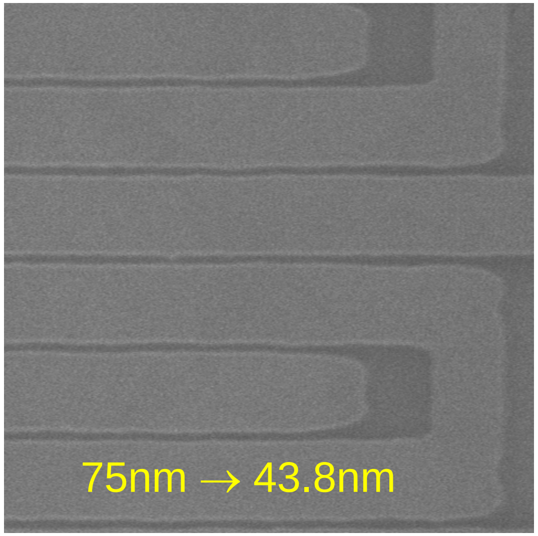
- Impossible on 193nm, 0.75 NA scanner (ASML /1100)
- Split design (2 masks, 2 exposures)→ more relaxed pitch

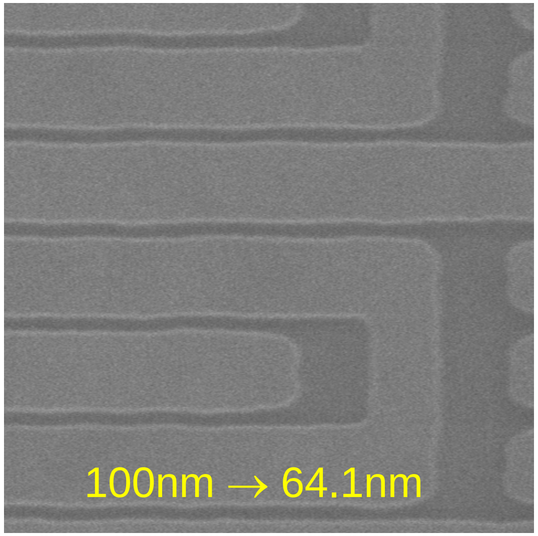


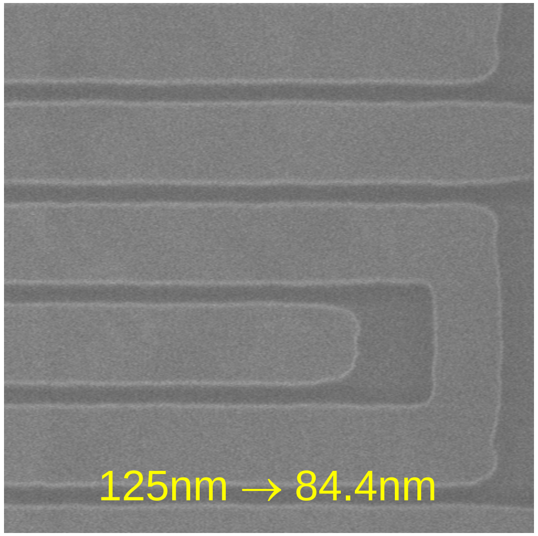


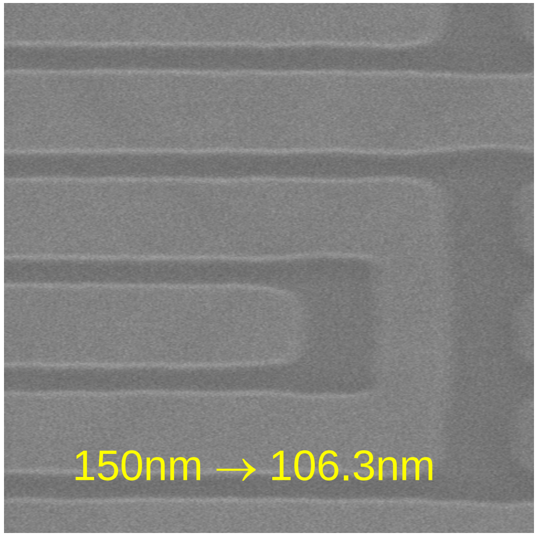


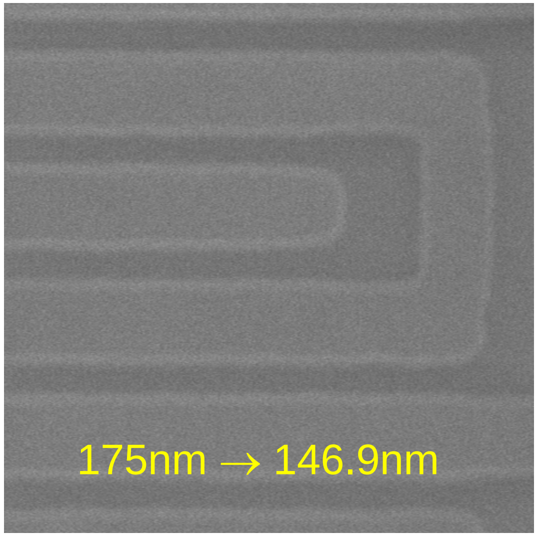
Scaling dimensions: spacings

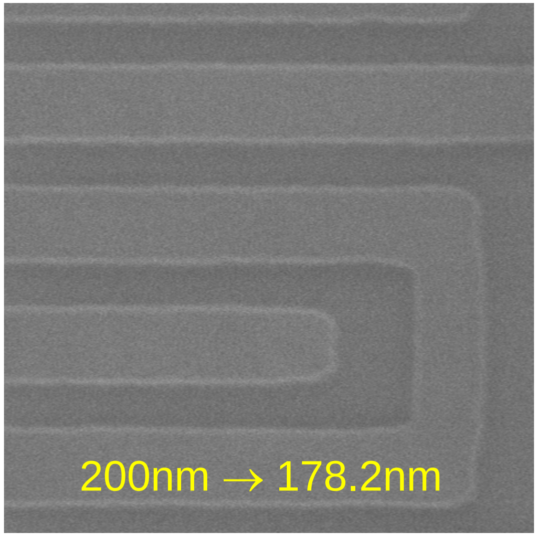

75nm → 43.8nm


100nm → 64.1nm


125nm → 84.4nm

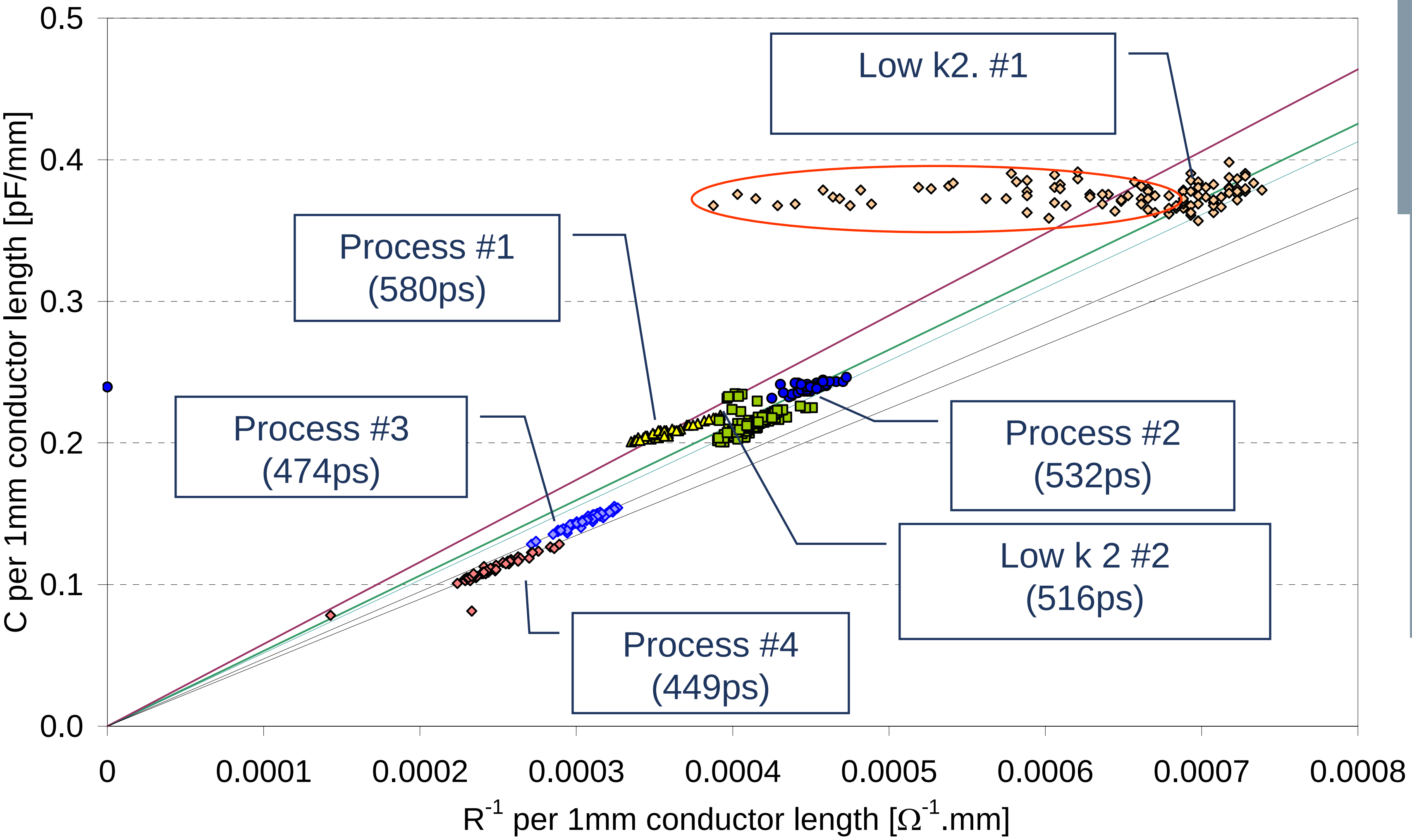

150nm → 106.3nm


175nm → 146.9nm

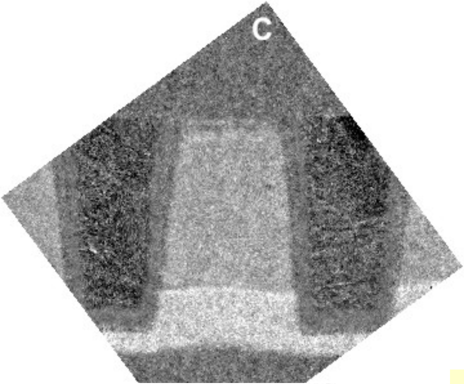

200nm → 178.2nm

Motivation

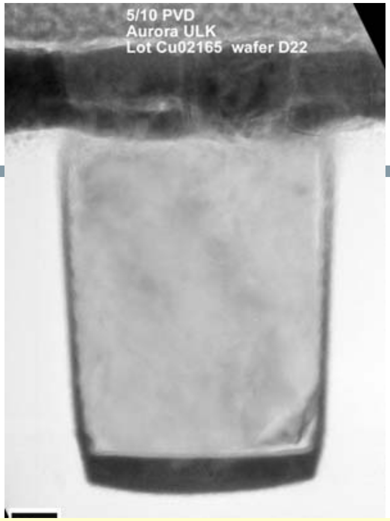
Interconnects are complex structures for which RC is easy to derive …



Motivation

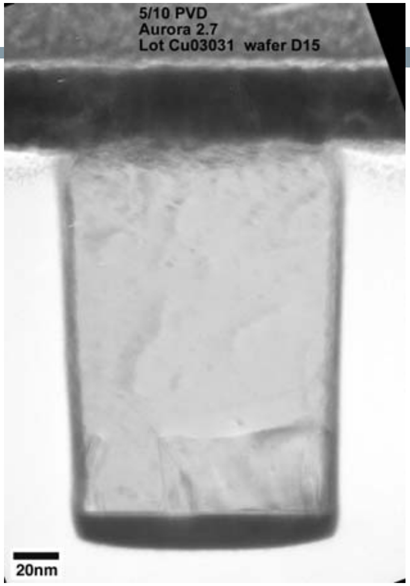


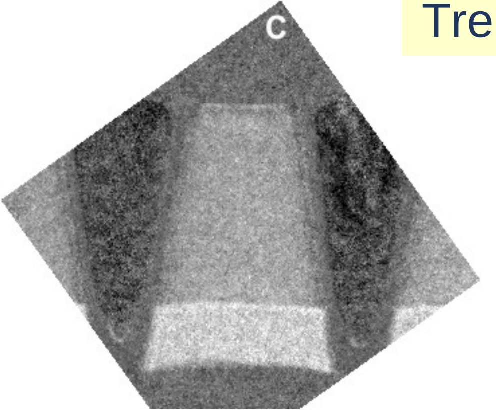
Trench profile

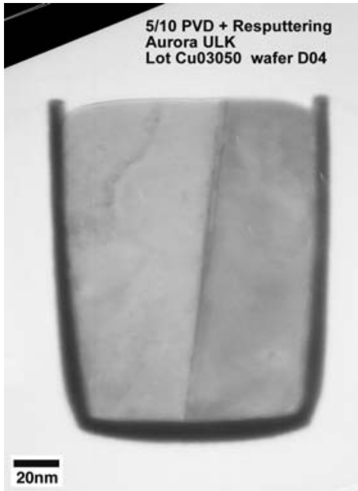


Non conformal barrier

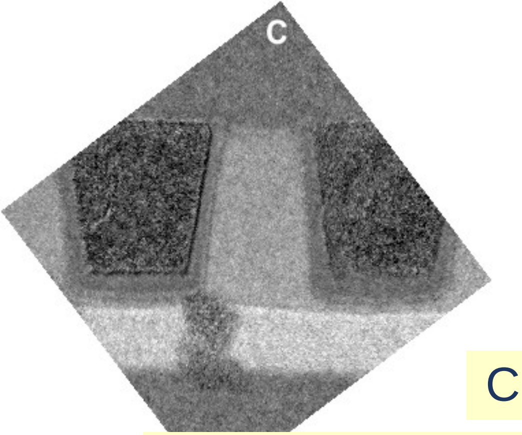
Dielectric height



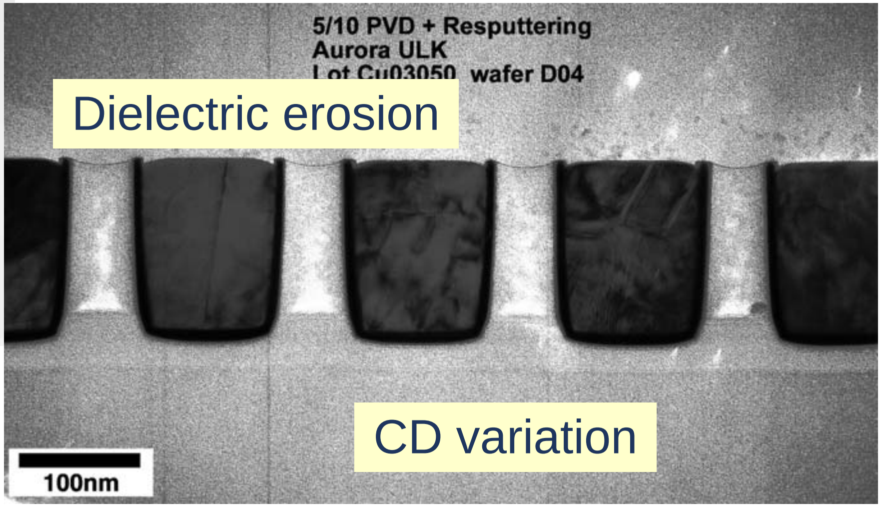




Conformal barrier



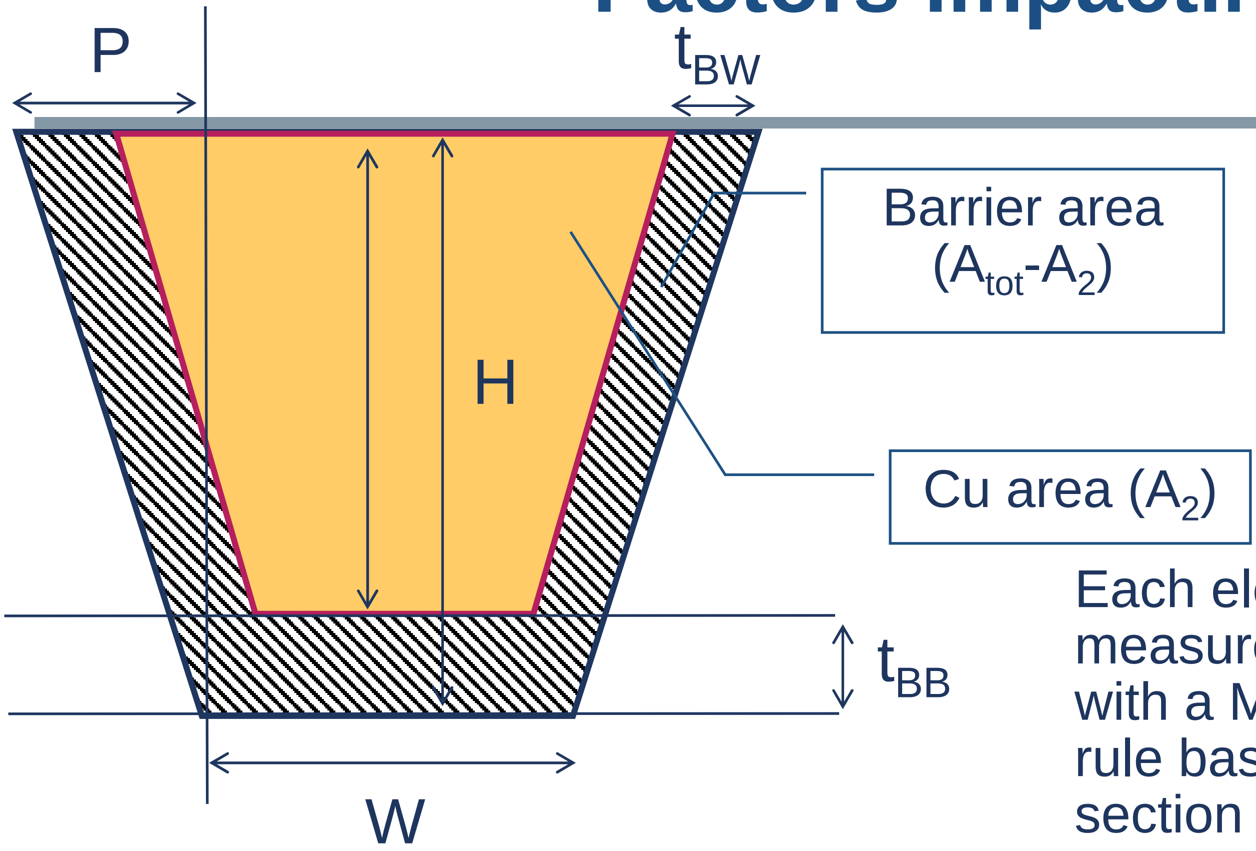
Bottom SiC opening



Dielectric erosion

CD variation

Factors impacting Cu area



Each electrical measurement starts with a Mathiessen's rule based cross-section measurement

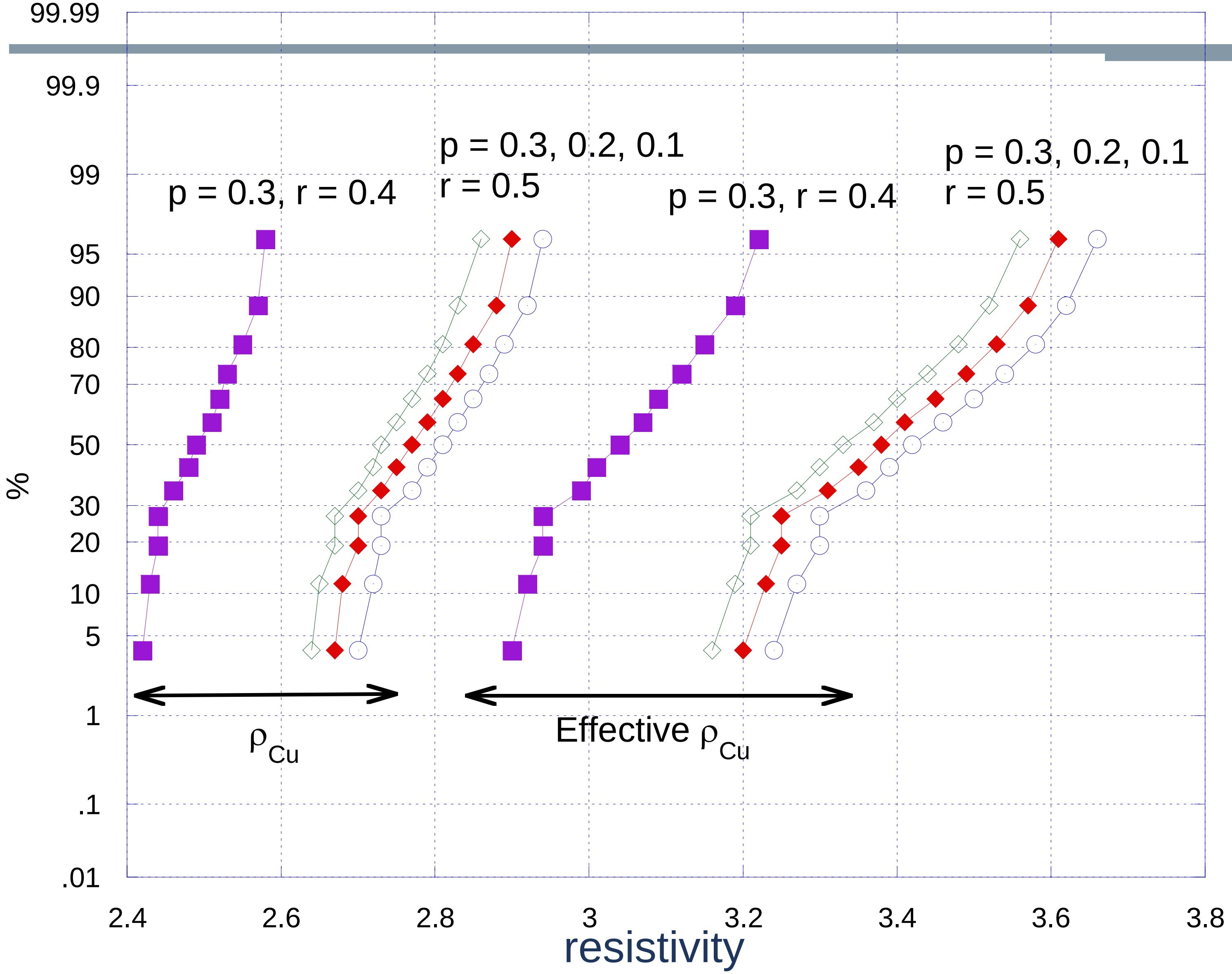
$$A_2 = \frac{(W - 2*t_{BW} + W + 2*P - 2*t_{BW})*(H - t_{BB})}{2}$$

$$\Rightarrow A_2 = (W - 2*T_{BW} + P)*(H - T_{BB})$$

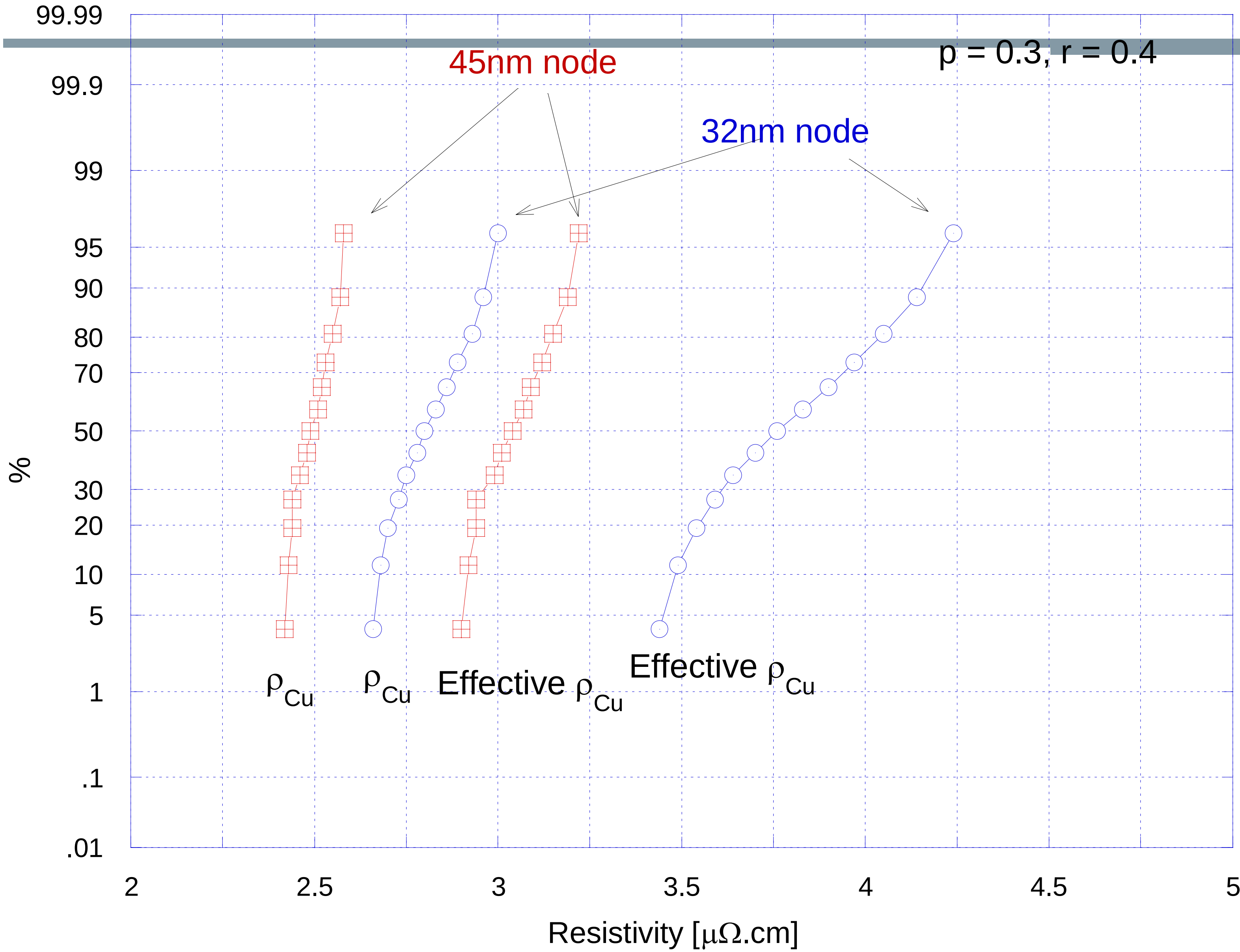
$$\Rightarrow A_2 = H*W - 2*H*t_{BW} + H*P - W*t_{BB} + 2*t_{BW}*t_{BB} - P*t_{BB}$$

$$\Rightarrow A_2 = F(H, W, t_{BW}, t_{BB}, P)$$

Resistivity measurements and model



Y. Travaly, M. Bama, L. Carbonel, V.Sutcliffe, F. Iacopi, M. Stucchi, M. Vanhove , K. Maex
Submitted to IEEE. Trans. El. dev


p = 0.3, r = 0.4
45nm node
32nm node
ρ_{Cu}
ρ_{Cu}
Effective ρ_{Cu}
Effective ρ_{Cu}
%
99.99
99.9
99
95
90
80
70
50
30
20
10
5
1
.1
.01
2
2.5
3
3.5
4
4.5
5
Resistivity [μΩ.cm]

Low k dielectric: current status

Process compatibility

- Adhesion
- Wet cleans
- Plasma chemistry
- Barrier compatibility (reliability)
- CMP slurries
- Post-CMP clean
- CMP & Bonding

Controlled surface engineering

- Minimize surface modification
- Barrier continuity
- Barrier conformality
- Stable Barrier/Low-k interface

Low-k properties

- k-value
- Porosity
- Pore size (micro vs. meso-)
- Pore connectivity & distribution
- Composition & structure
- Density (ρ)
- Polarizability (α)
- Pore wall density (ρ_{wall})
- Mechanical properties
- Stress
- Thermal conductivity
- Coefficient of thermal expansion

Low-k = $F(k, n, \rho, \rho_{wall}, P, E, H, PS, \alpha)$

Low k dielectric: current status

Methodology & Convention

$$\begin{array}{c|cccccccc}
 & \text{k-value} & \text{Porosity} & \text{Pore size} & \text{Density} & \text{Pore wall density} & \text{Elastic modulus} & \text{Hardness} & \text{Refractive index} \\
\hline
 & k_{11} & P_{12} & PS_{13} & \rho_{14} & \rho wall_{15} & E_{16} & H_{17} & RI_{18} \\
 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\text{Low-k (j)} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
 & k_{n1} & P_{n2} & PS_{n3} & \rho_{n4} & \rho wall_{n5} & E_{n6} & H_{n7} & RI_{n8}
\end{array}$$

$$\boxed{r_{14} = \frac{\sigma_{14}}{\sigma_1 * \sigma_4}}$$

correlation coefficient between (k, ρ)

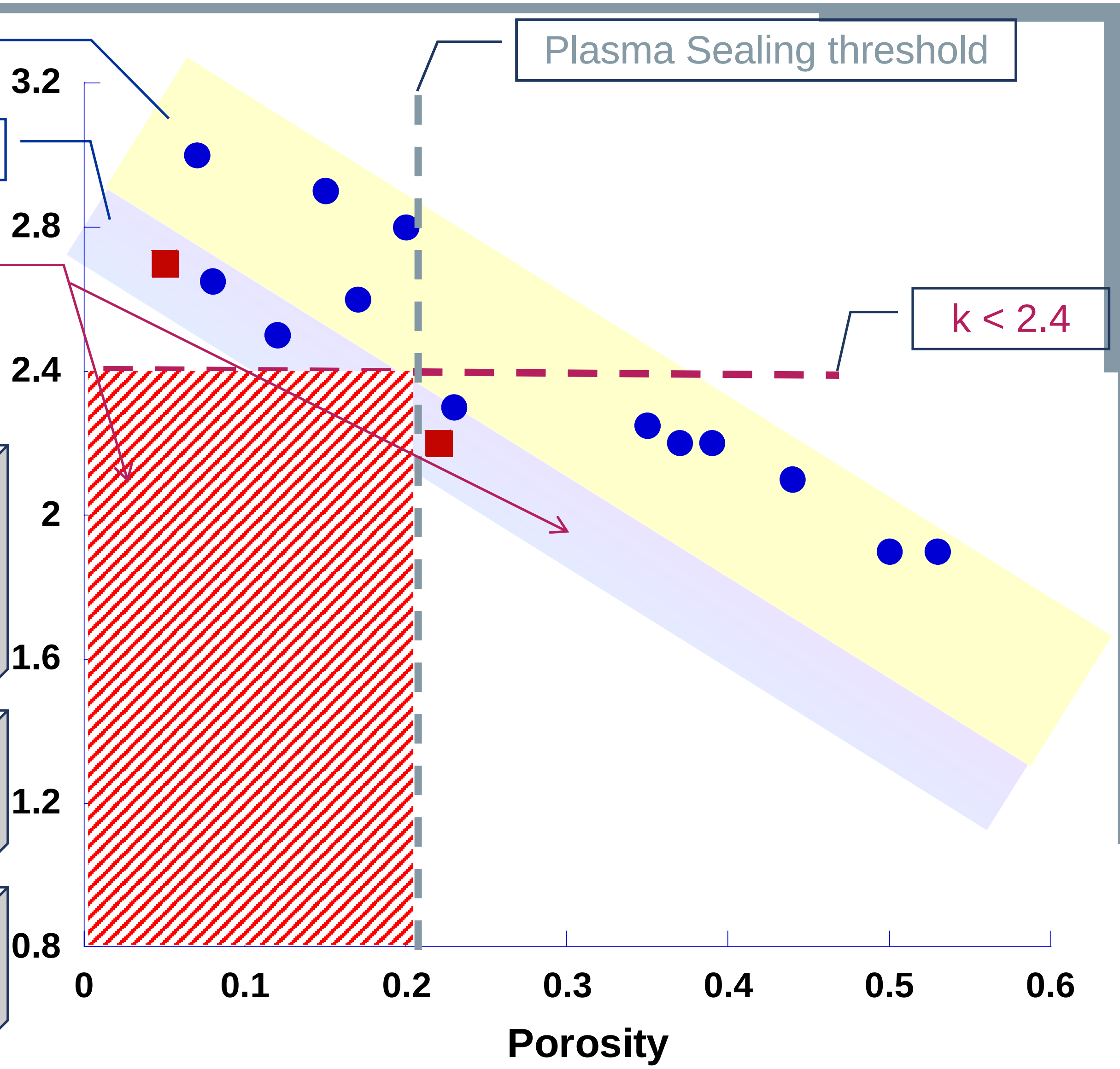
Low k dielectric: current status

Silicon containing LKs

Organic polymer

No available Low-k solution

Conventional integration scheme fail



Revolutionary sealing methods:
+ seal large pores
+ thickness controllable
+ chemical composition tunable

Revolutionary integration scheme:
+ post process porosity creation

Revolutionary low-k processes:
+ mechanical stability

Scaling dimensions

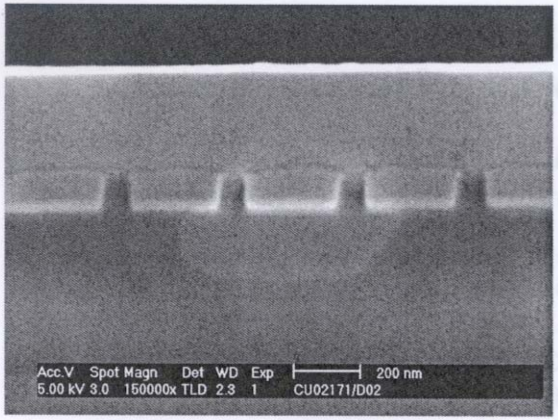


Fig.1 Cross-sectional micrograph of 75nm spaced meander-forks.

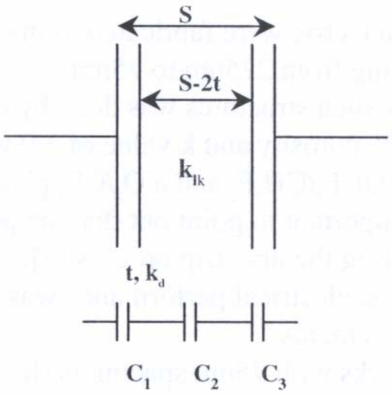


Fig.3 Scheme of the damage induced at the sidewalls of a dielectric space upon patterning.

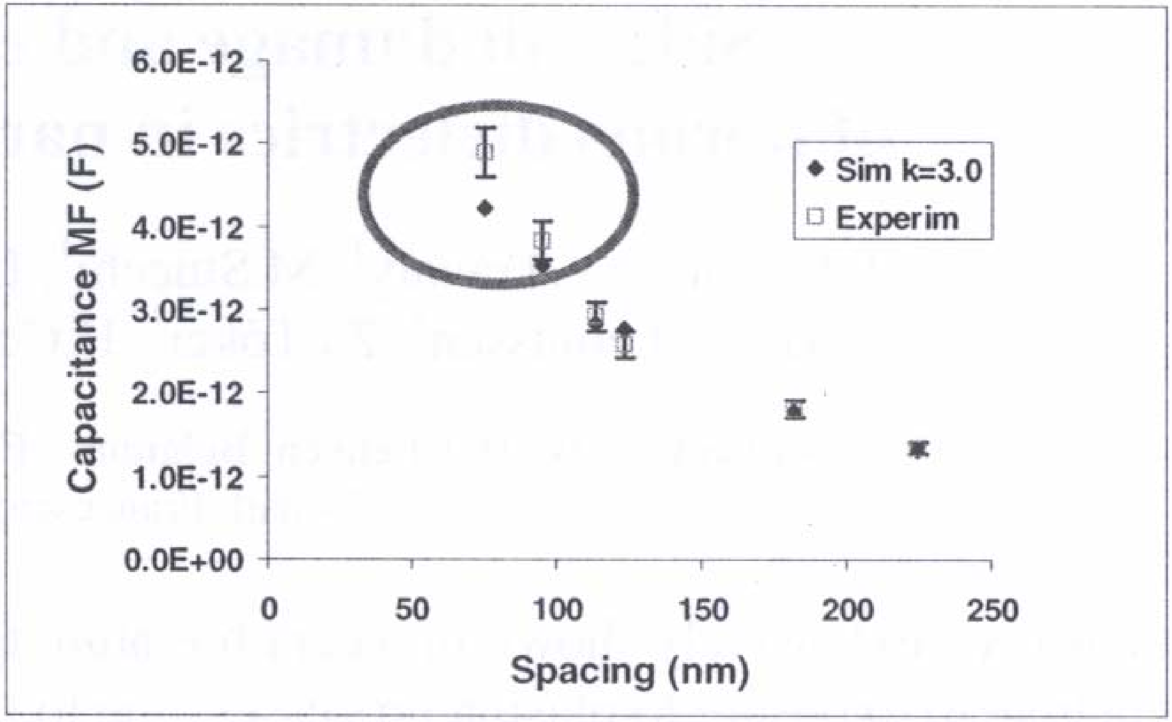
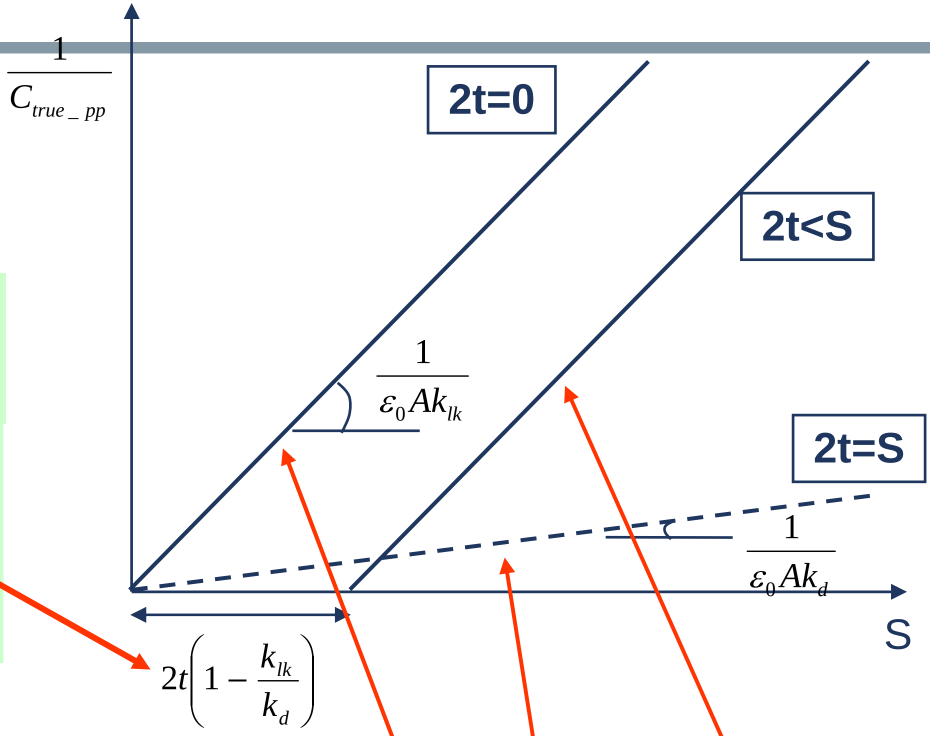


Fig.2 Experimental interline capacitance values are compared versus spacing to the ones calculated assuming a k=3.0 for the integrated dielectric.

Scaling dimensions



'Electrical equivalent sidewall damage':

$$S' = 2t\left(1-\frac{k_{lk}}{k_d}\right)$$

1) 2t<S (general case)

$$\frac{1}{C_{true\_pp}}=\frac{2}{C_{1\_pp}}+\frac{1}{C_{2\_pp}}=\frac{1}{\varepsilon_0 A}\left(\frac{2t}{k_d}+\frac{S}{k_{lk}}-\frac{2t}{k_{lk}}\right)$$

2) 2t≥S (full modification)

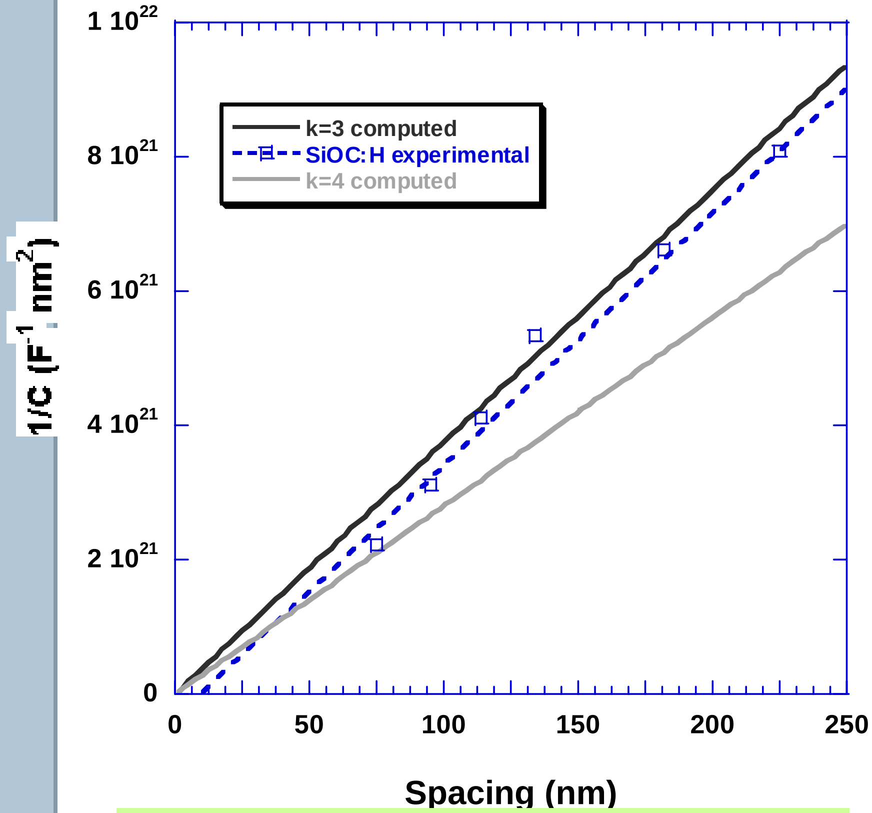
$$\frac{1}{C_{true\_pp}}=\frac{1}{\varepsilon_0 A}\left(\frac{S}{k_d}\right)$$

3) t=0 (no modification)

$$\frac{1}{C_{true\_pp}}=\frac{1}{\varepsilon_0 A}\left(\frac{S}{k_{lk}}\right)$$

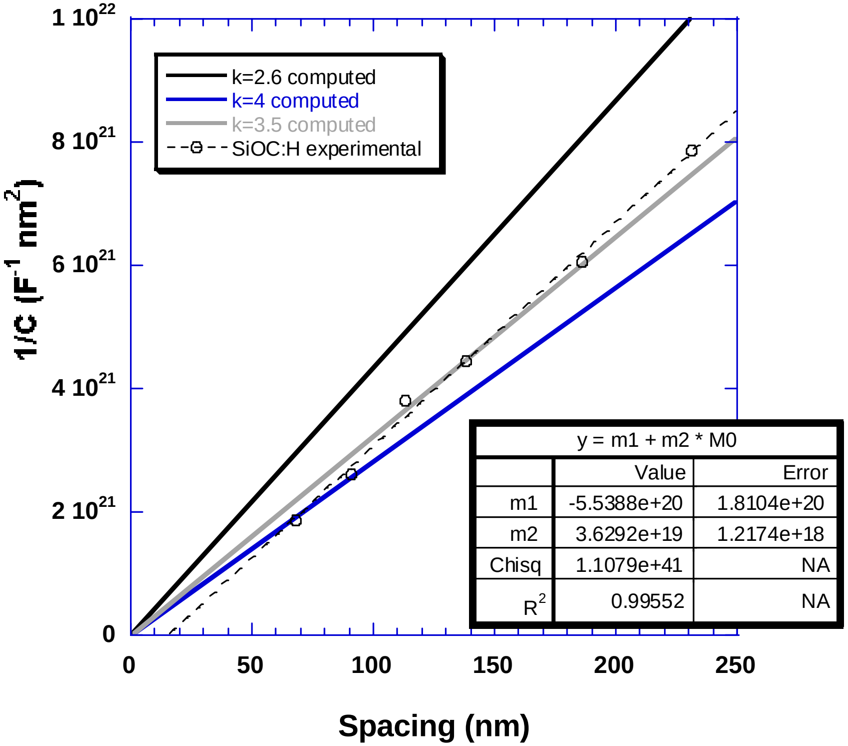
F. Iacopi, K. Maex, M. Stucchi, O. Richard, Electrochem. And Solid State Letters 7(4) G79-82, 2004

Scaling dimensions



Fitting slope:same as pristine

Intercept with S axis: ‘Electrical equivalent sidewall damage’ = 10nm



y = m1 + m2 * M0

	Value	Error
m1	-5.5388e+20	1.8104e+20
m2	3.6292e+19	1.2174e+18
Chisq	1.1079e+41	NA
R^2	0.99552	NA

Fitting slope: k: 2.6→3.11

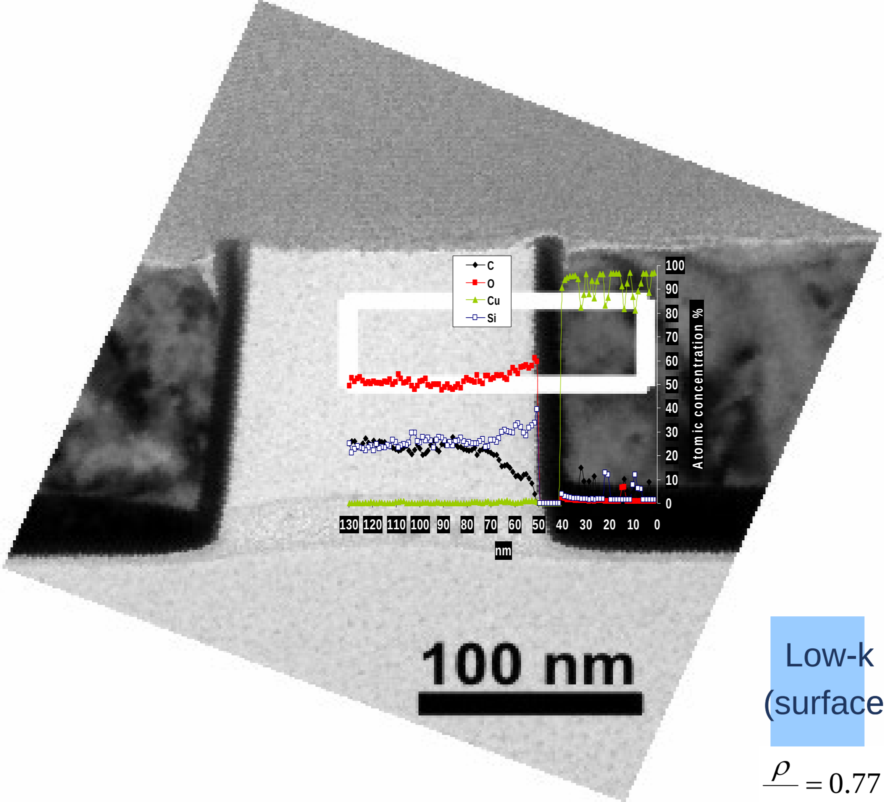
➔ Combined Field

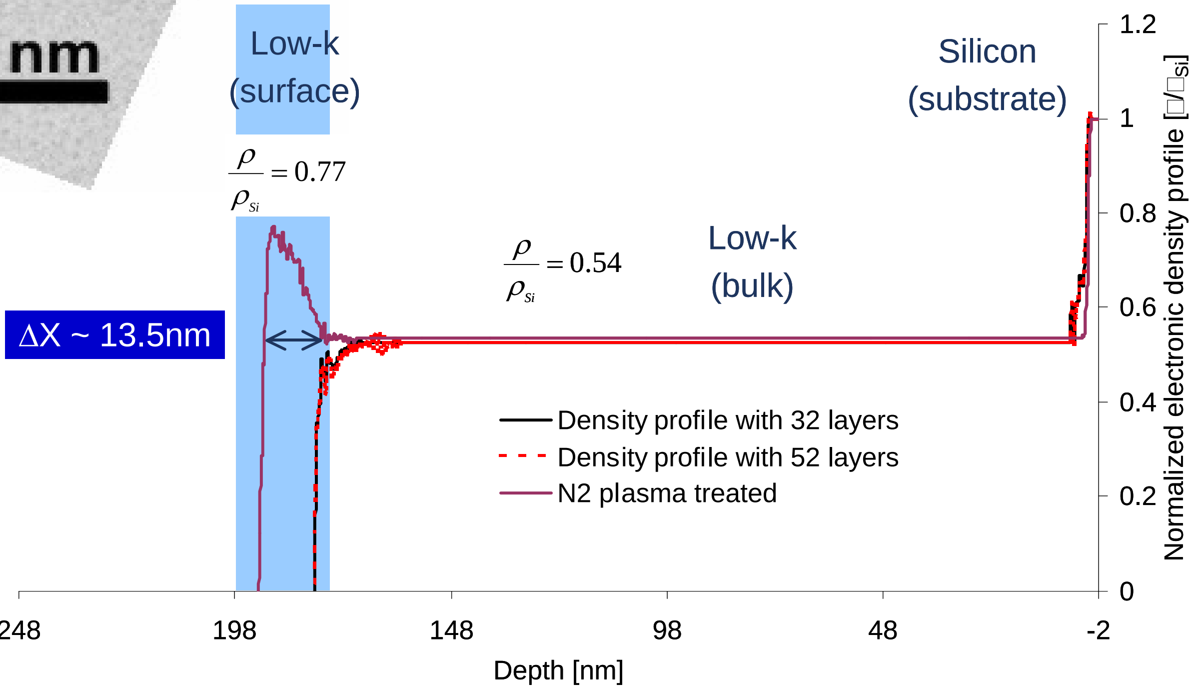
+ sidewall damage = 15nm

Scaling dimensions plasma damage

…about 20nm modified region

For S'=10nm ➔ $k_d=(k_{eq})\cong 4.0$

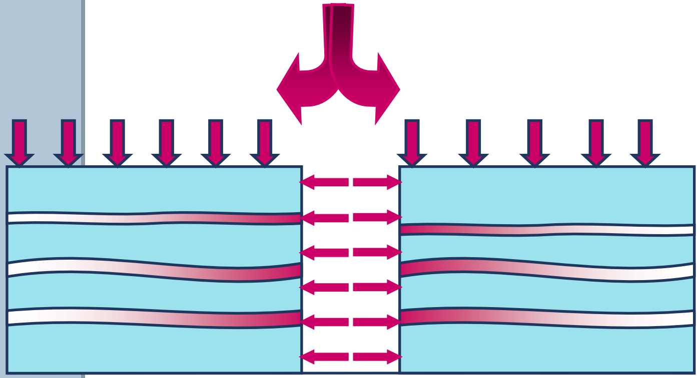




Plasma-induced modifications can be quantified

Scaling the k-value: sealing methodology

Absorption of chemicals and moisture



Current sealing method by plasma

-only workable for microporous materials

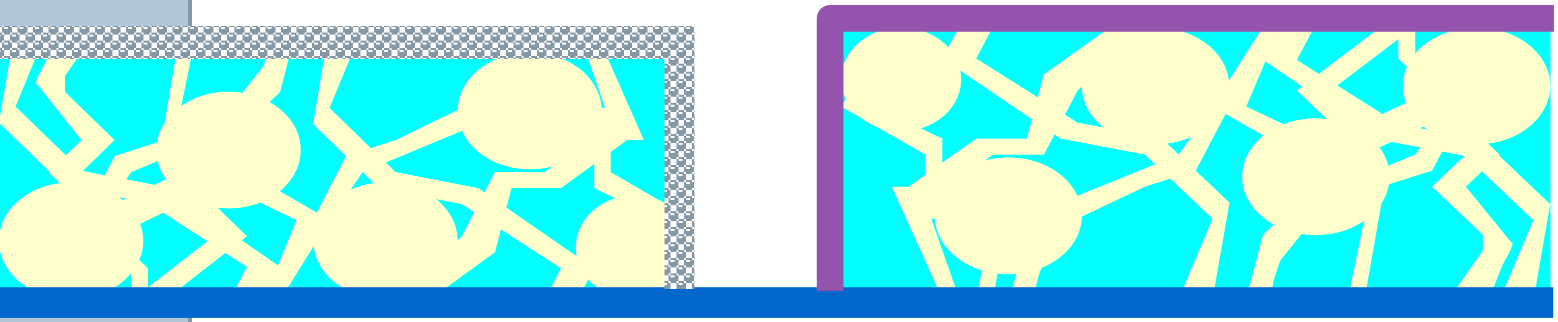
(k>2.6)

-What to do for mesoporous materials with lower k-values?

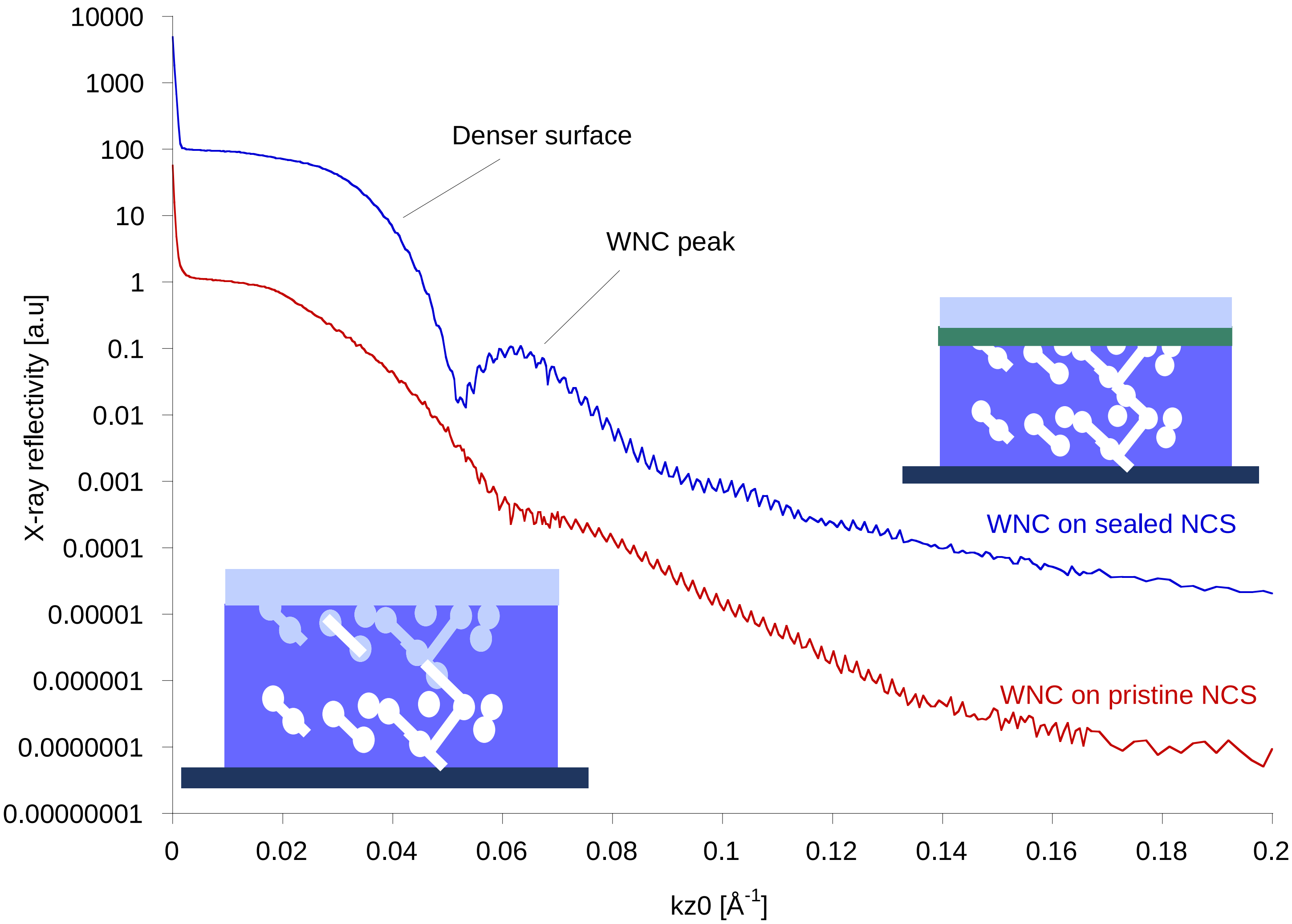
Sealing is needed

Surface modification

Deposition of sealing layer

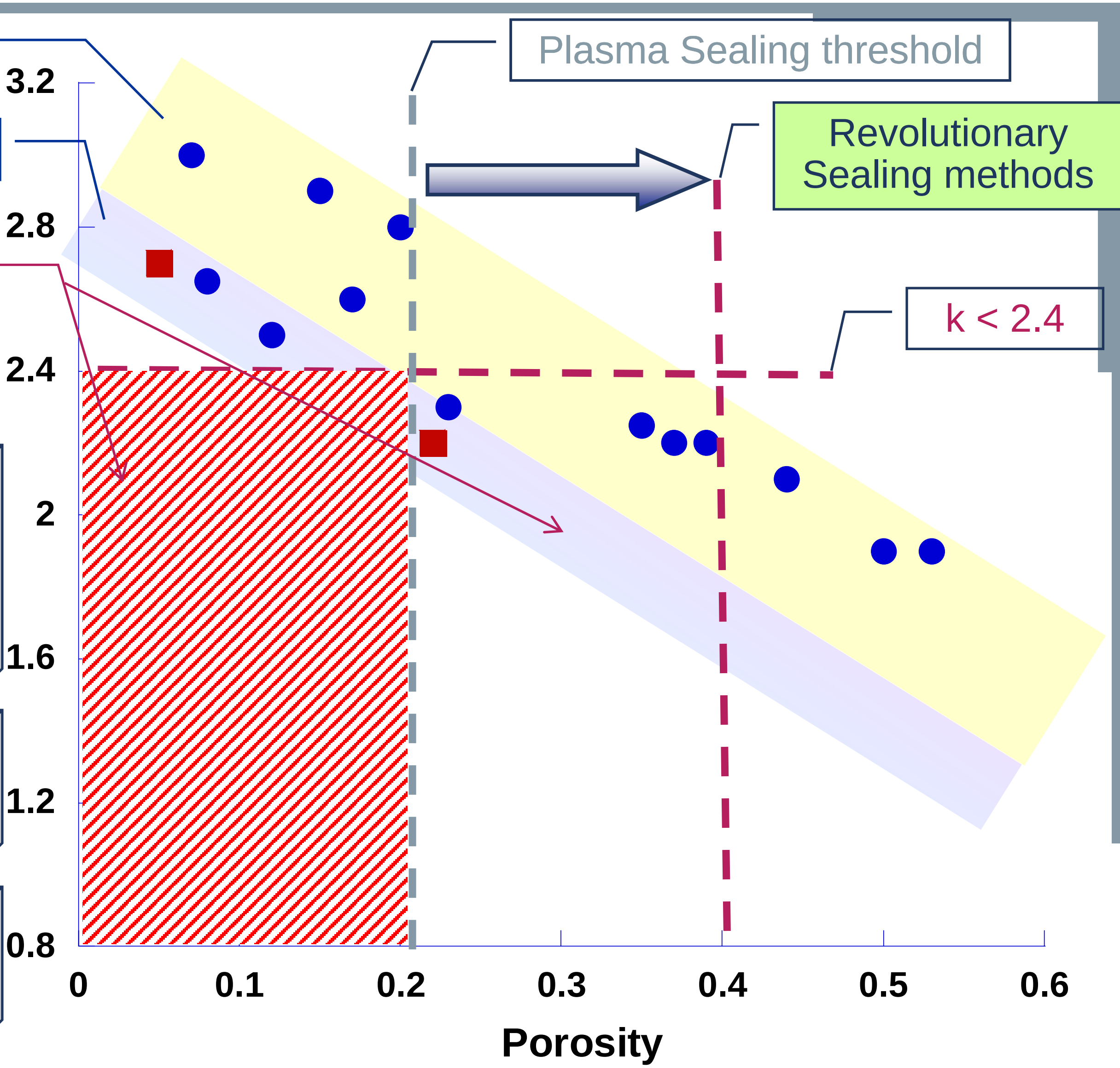


XRR
ALD on porous vs. sealed dielectric surface



Y. Travaly, J. Schuhmacher, A.M. Hoyas, T. Abell, V. Sutcliffe, M. Van Hove K. Maex
JAP 97 (2005) in press

Scaling the k-value: sealing methodology



Silicon containing LKs

Organic polymer

Plasma Sealing threshold

Revolutionary Sealing methods

k < 2.4

No available Low-k solution

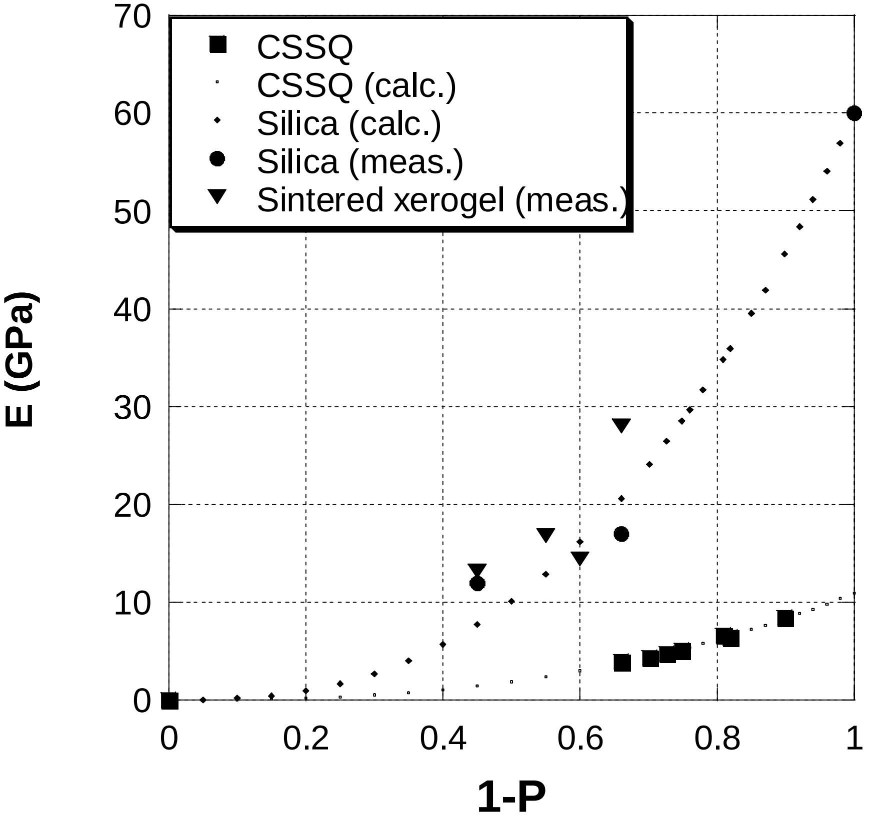
Conventional integration scheme fail

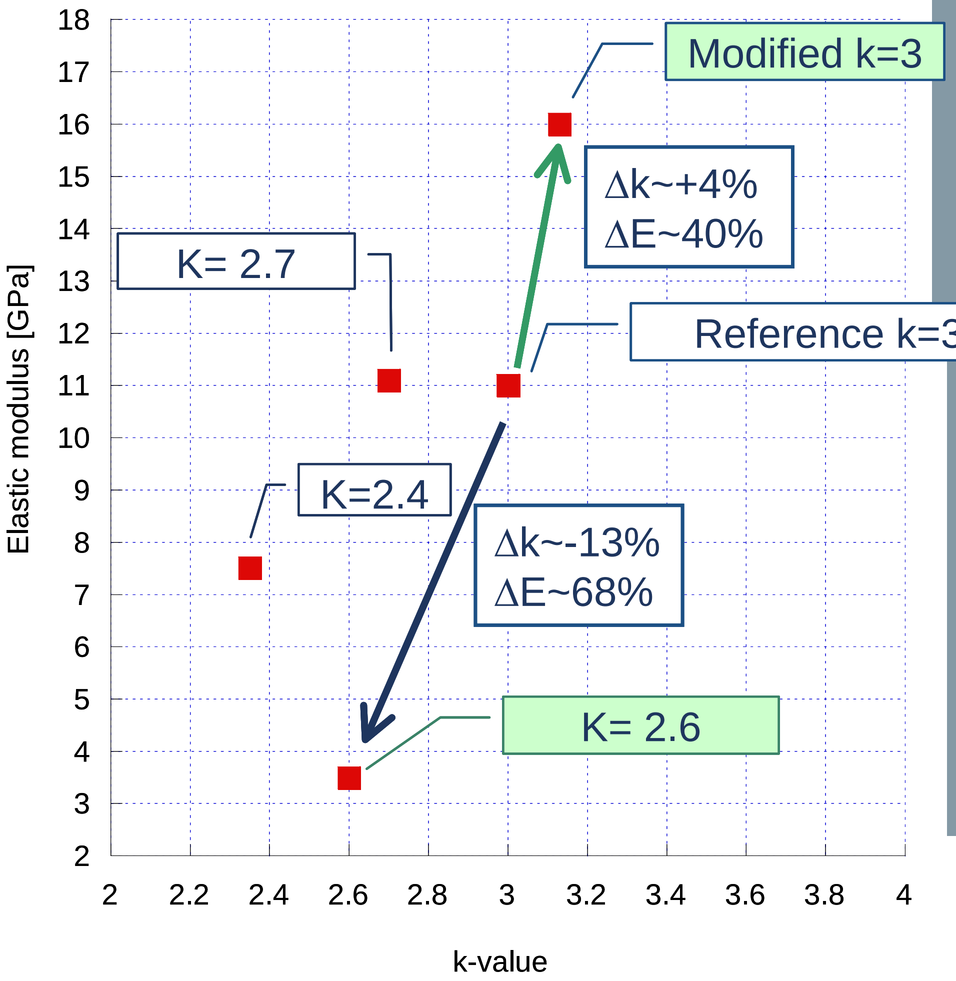
<u>Revolutionary sealing methods:</u>
+ seal large pores
+ thickness controllable
+ chemical composition tunable

<u>Revolutionary integration scheme:</u>
+ post process porosity creation

<u>Revolutionary low-k processes:</u>
+ mechanical stability

Scaling the k-value: mechanical strength





Modulus => porosity

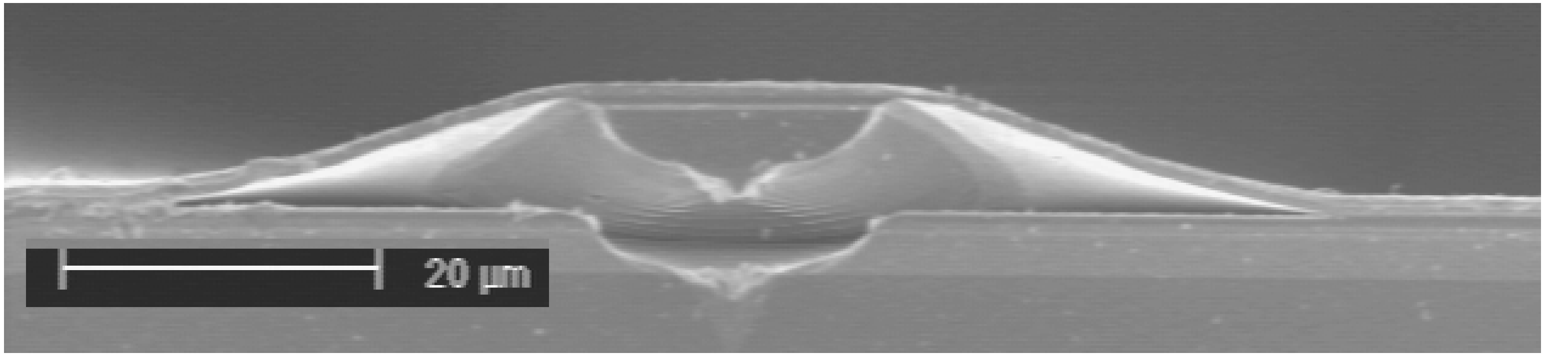
=> wall material

M. Baklanov and K. Maex

Philosophical Transactions, in press

Post treatment changes the wall material (confirmed by NMR)

Scaling k-value: mechanical properties

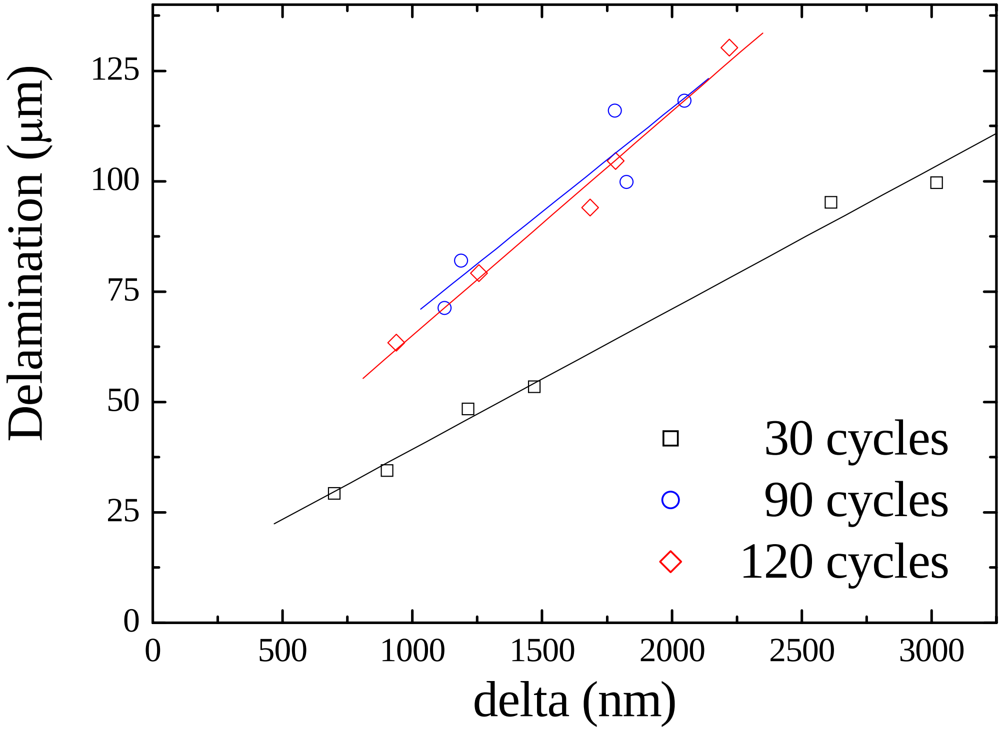


Sample:

thin barrier film

on dielectric

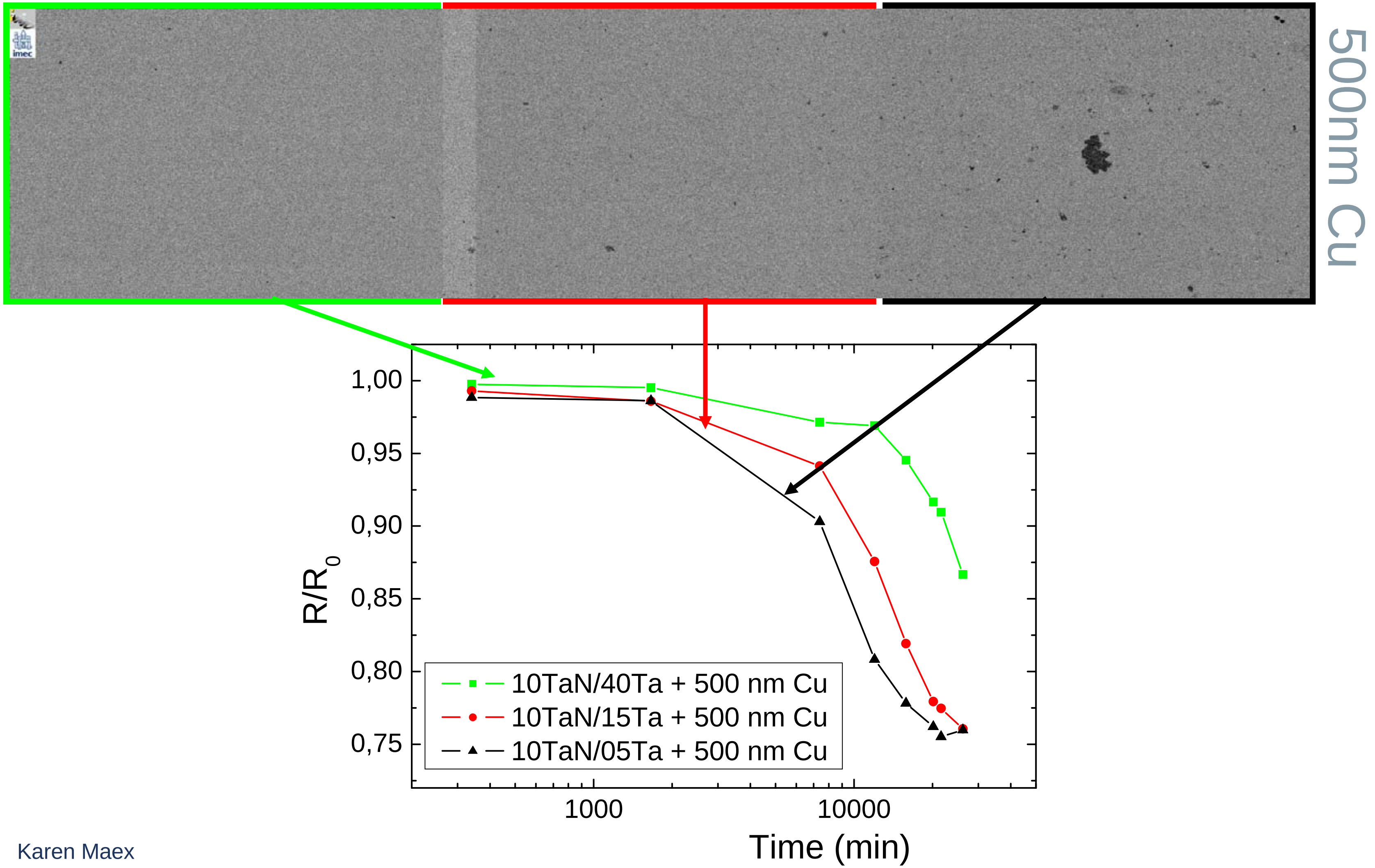
Consistent with 4Point bending



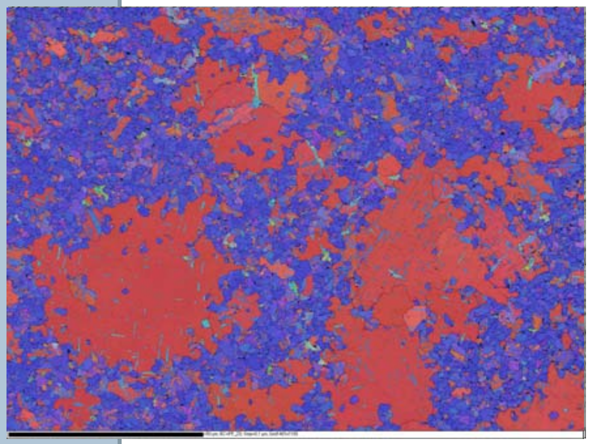
S.H. Brongersma, D. Degryse, J.souiller, B. Vandevelde K.Maex MRS Proc 812 (2004)

Influence of α-Ta thickness

10TaN/**40Ta** 10TaN/**15Ta** 10TaN/**5Ta**

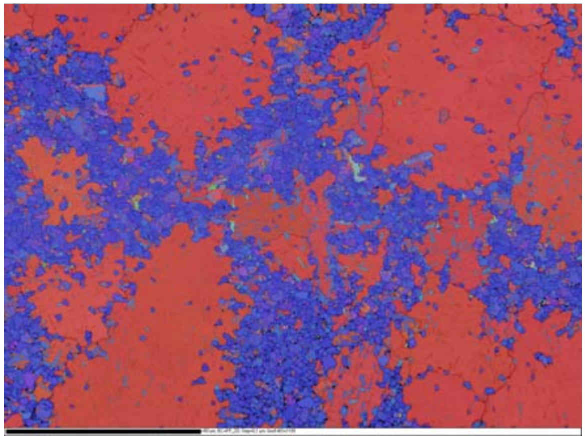


EBSD: Super Secondary Grain Growth



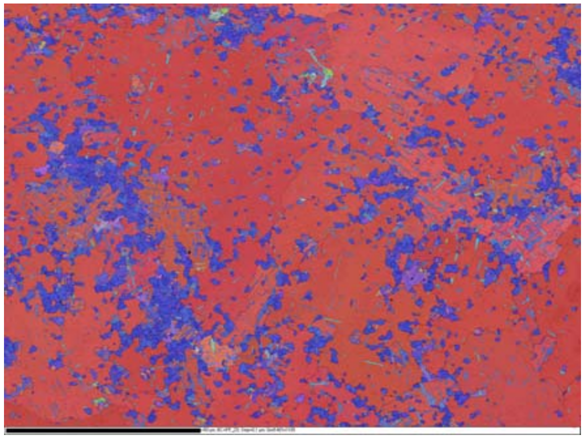
10TaN/40Ta

500Cu



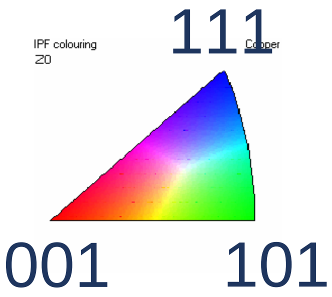
10TaN/15Ta

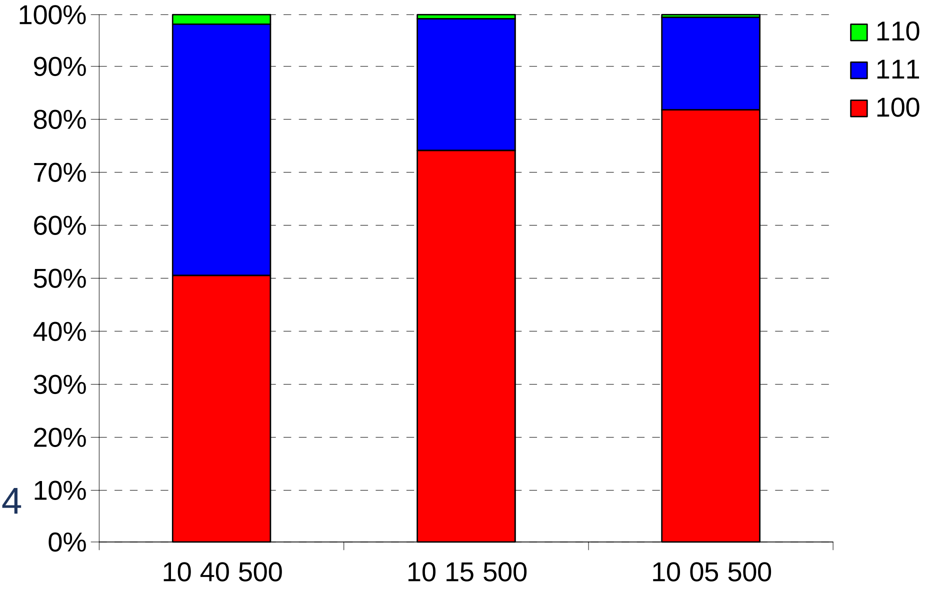
500Cu



10TaN/5Ta

500Cu

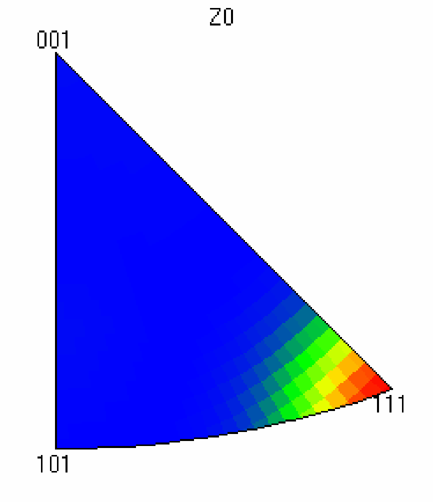


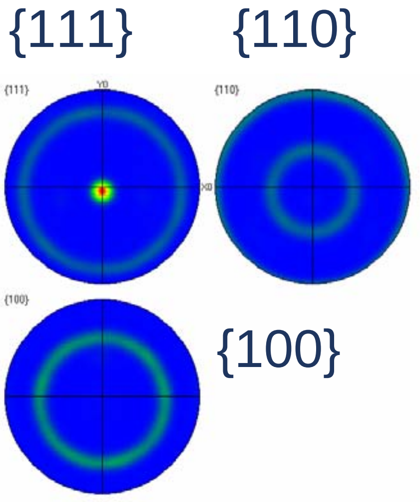


K. Vanstreels et al, proc. AMC 2004

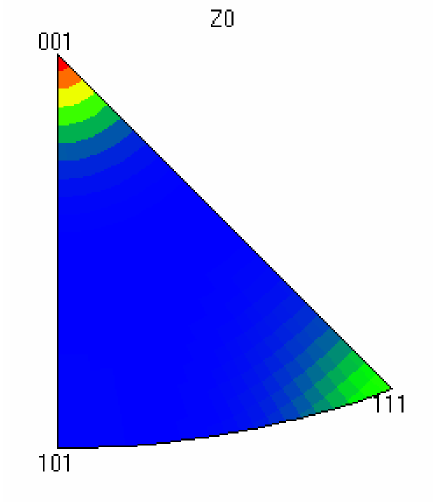
Narrow wires

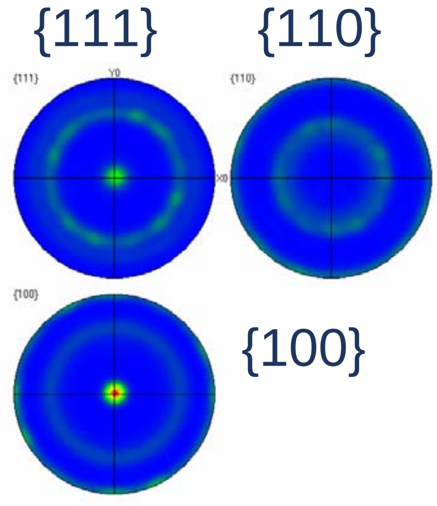
No SSGG



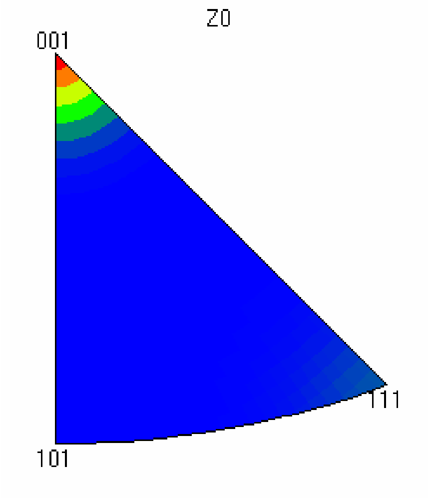


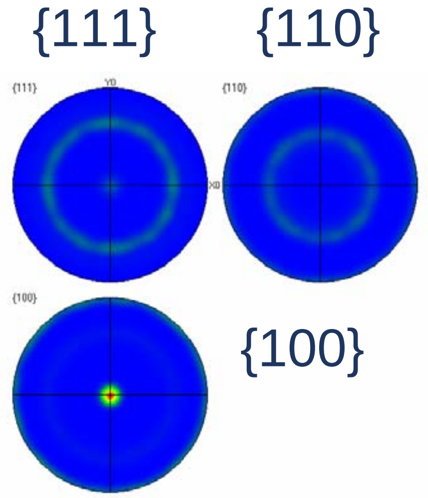
Partial SSGG



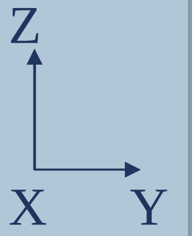


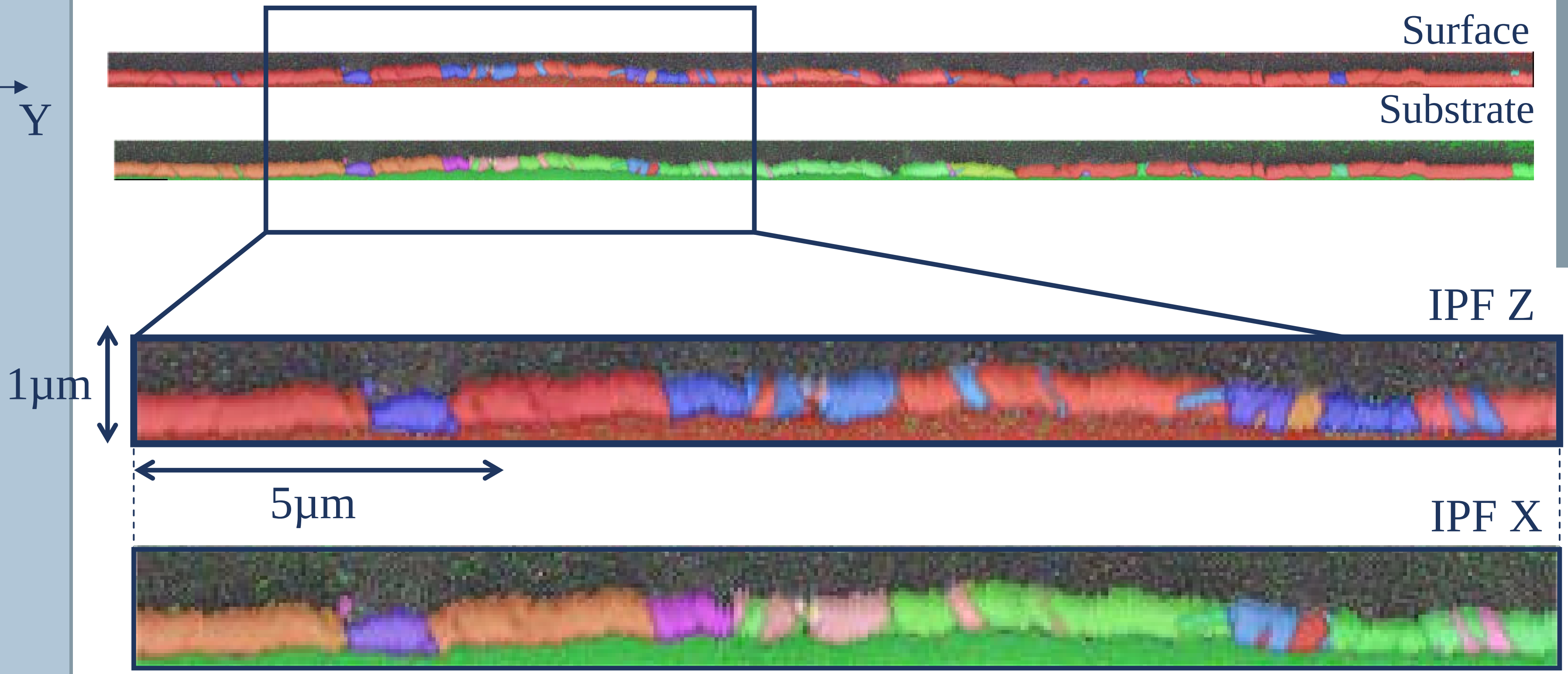
Full SSGG

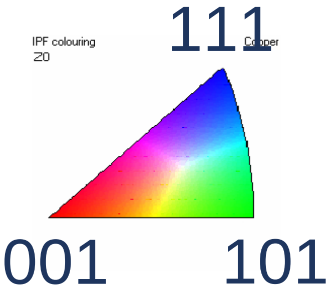




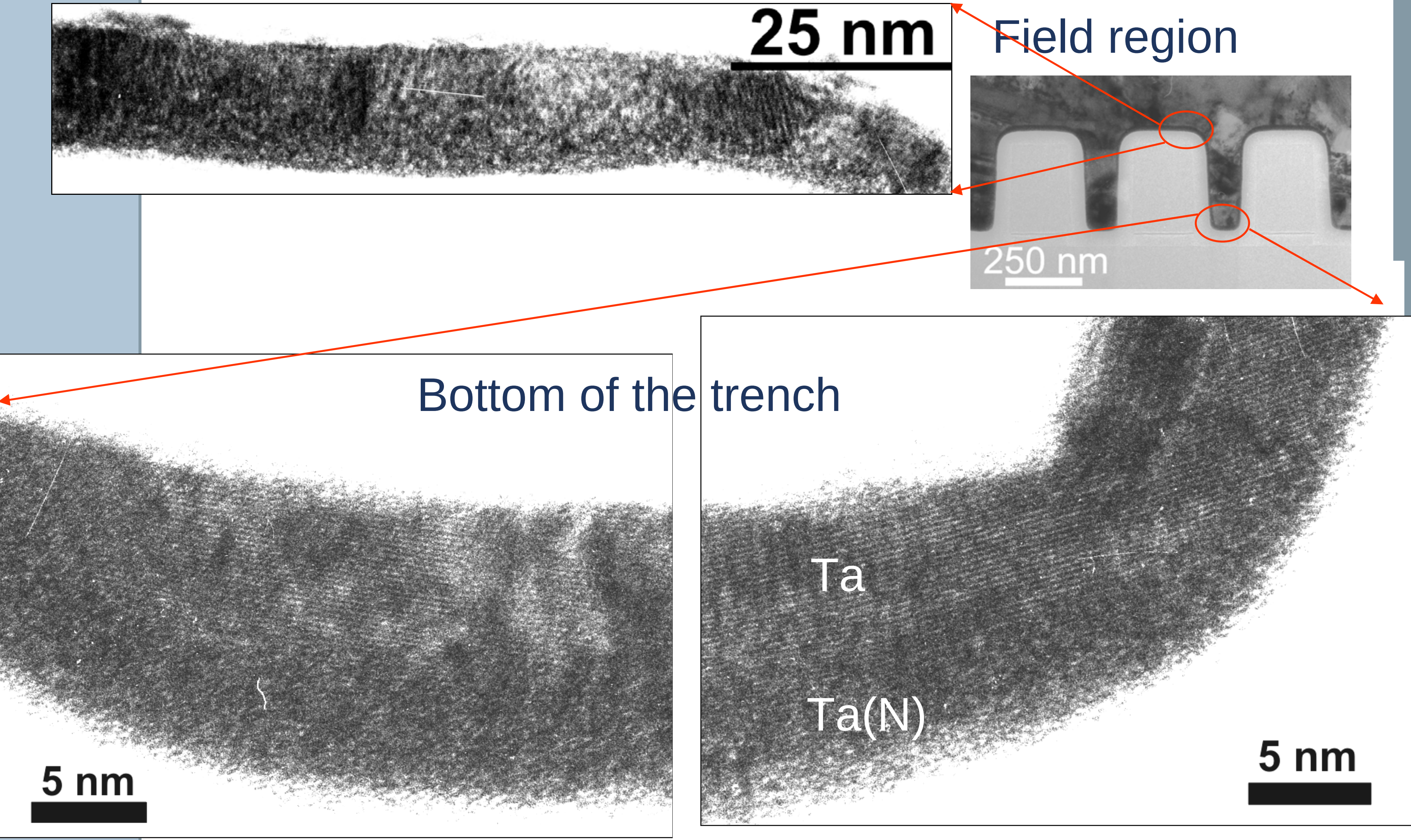
EBSD: Cross section







Crystal phase determination
5/10 Ta(N)/Ta+RESP



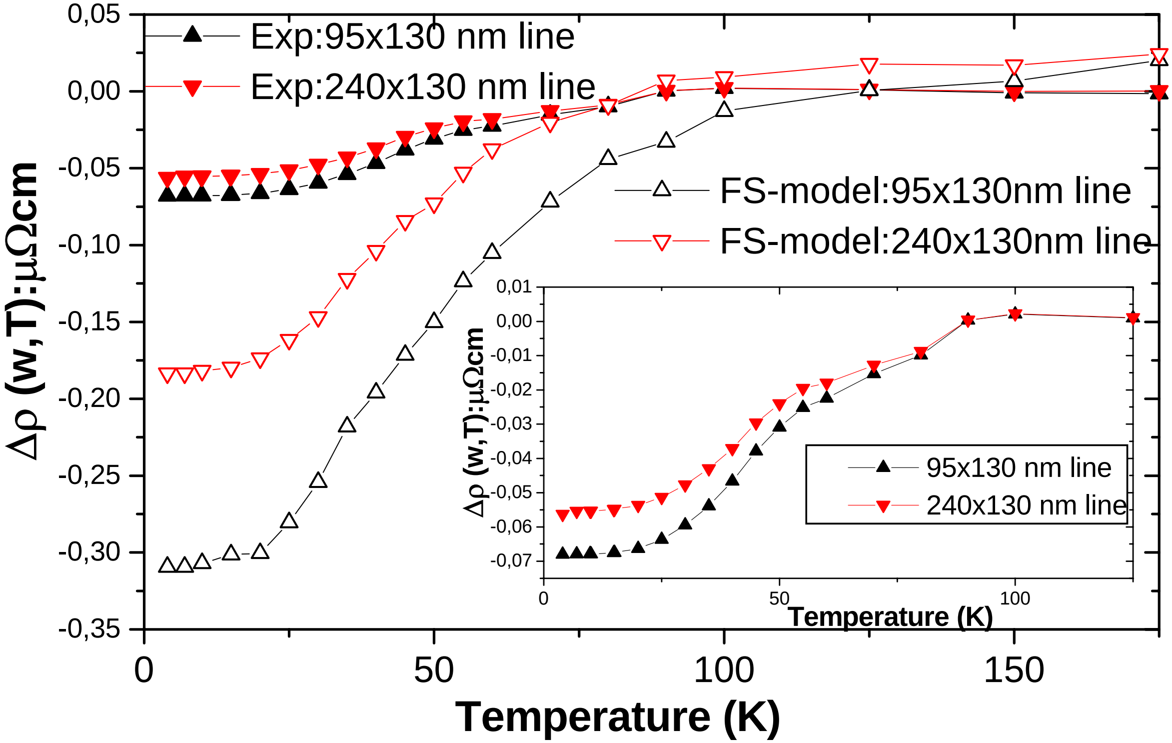
Influence of impurity incorporation on DMR induced by Surface scattering

	95x130 nm	240x130 nm
R	0.57	0.62
λ	~23 nm	~29 nm

*R is calculated by Mayadas-Shatzkes model

*λ is estimated by assuming *(ρλ)* as a constant, 0.66 x 10^{-15} Ω M^2

A.F. Mayadas Appl. Phys. Lett., 14, 345 (1969)



$$\Delta\rho(w,T) = [\rho(w,T) - \rho(\infty,T)] - [\rho(w,293K) - \rho(\infty,293K)]$$
$$= \Delta\rho(T) - \Delta\rho(293K)$$

Reduced λ & SSDMR due to impurity incorporation

W. Zhang. S. Brongersma, K. Maex et al, accepted for Electrochem Solid State Letters 2005

Conclusion

-Aggressive scaling of Cu/ low k wire has implications on metrology

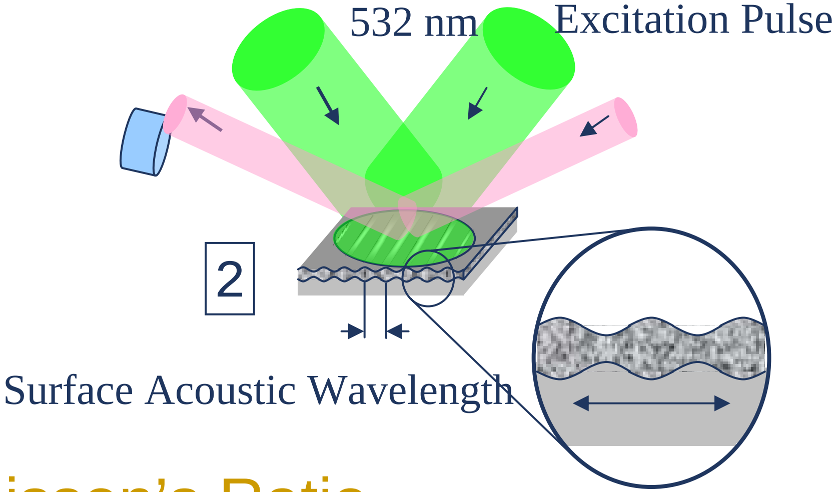
- low k value has to be extracted from the small features

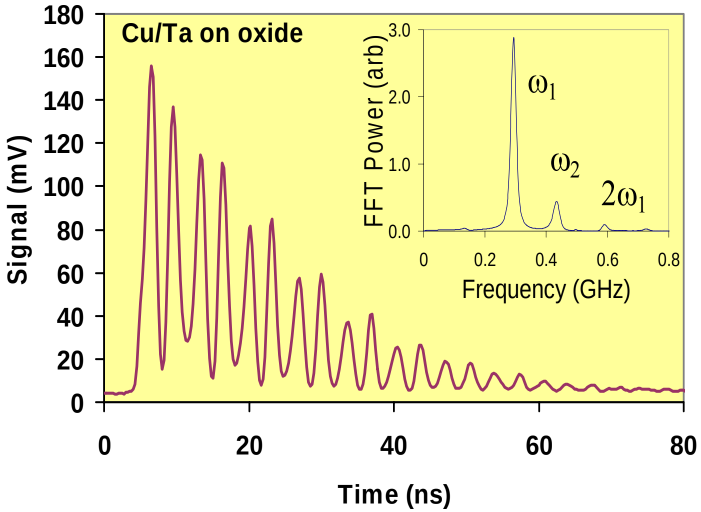
- interfaces and surfaces are as important as bulk values

-super grain growth has been observed in Cu

-Mean free path of Cu has an (indirect) linewidth dependency

Scaling k-vlaue: mechanical properties



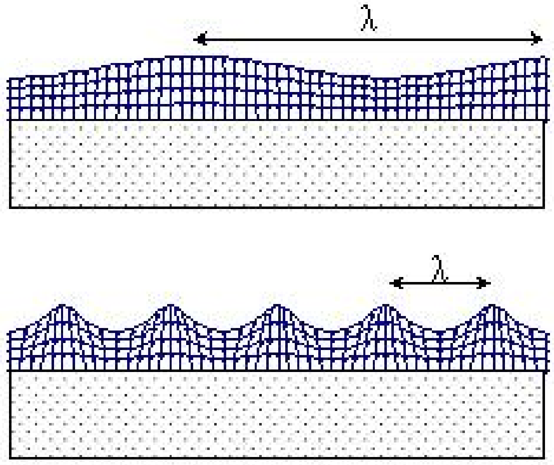


Poisson’s Ratio

$$\nu = \frac{1-\frac{1}{2}\left({V_L}/{V_T}\right)^2}{1-\left({V_L}/{V_T}\right)^2}$$

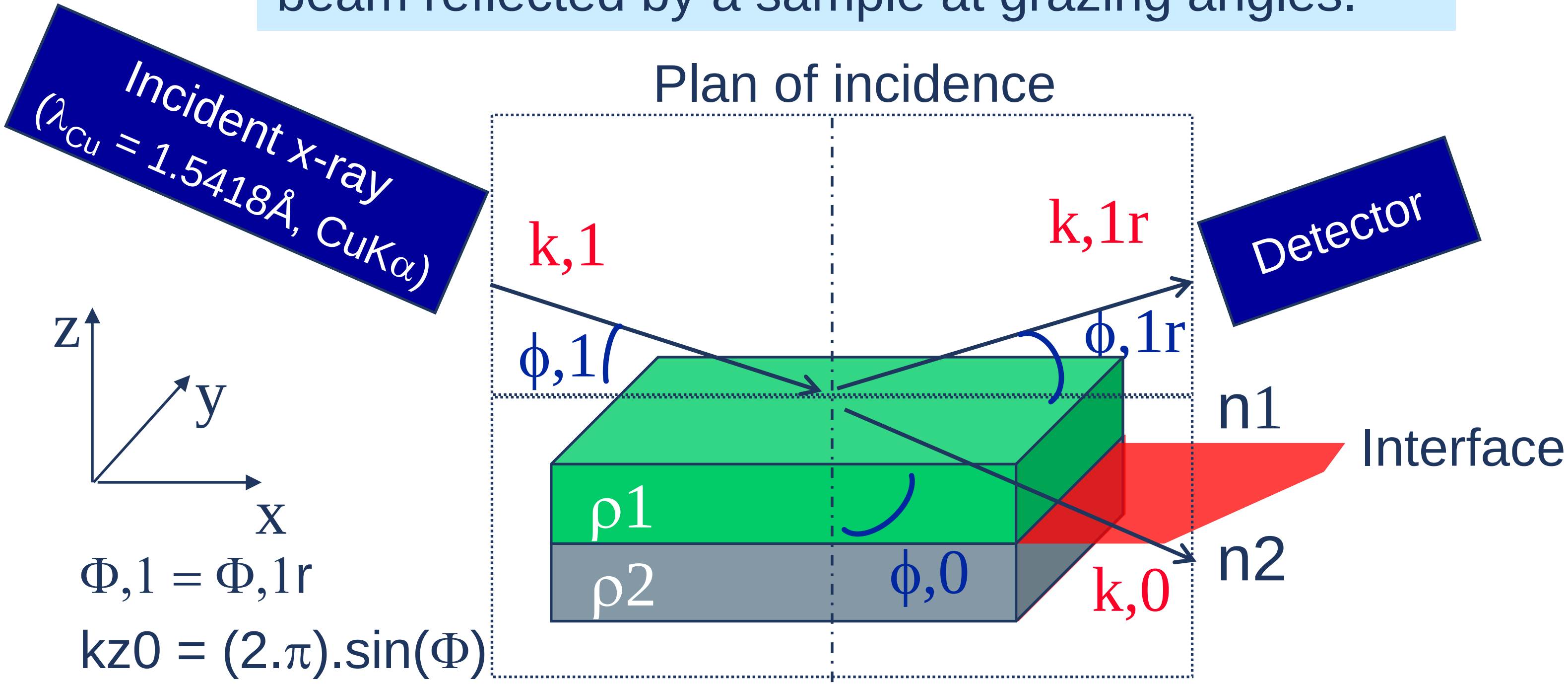
Young’s Modulus

$$E = 2(\nu+1)\cdot V_T^2\rho$$



Principles

XRR involves monitoring the intensity of the x-ray beam reflected by a sample at grazing angles.



$\Phi,1 = \Phi,1r$

$kz0 = (2.\pi).\sin(\Phi)$

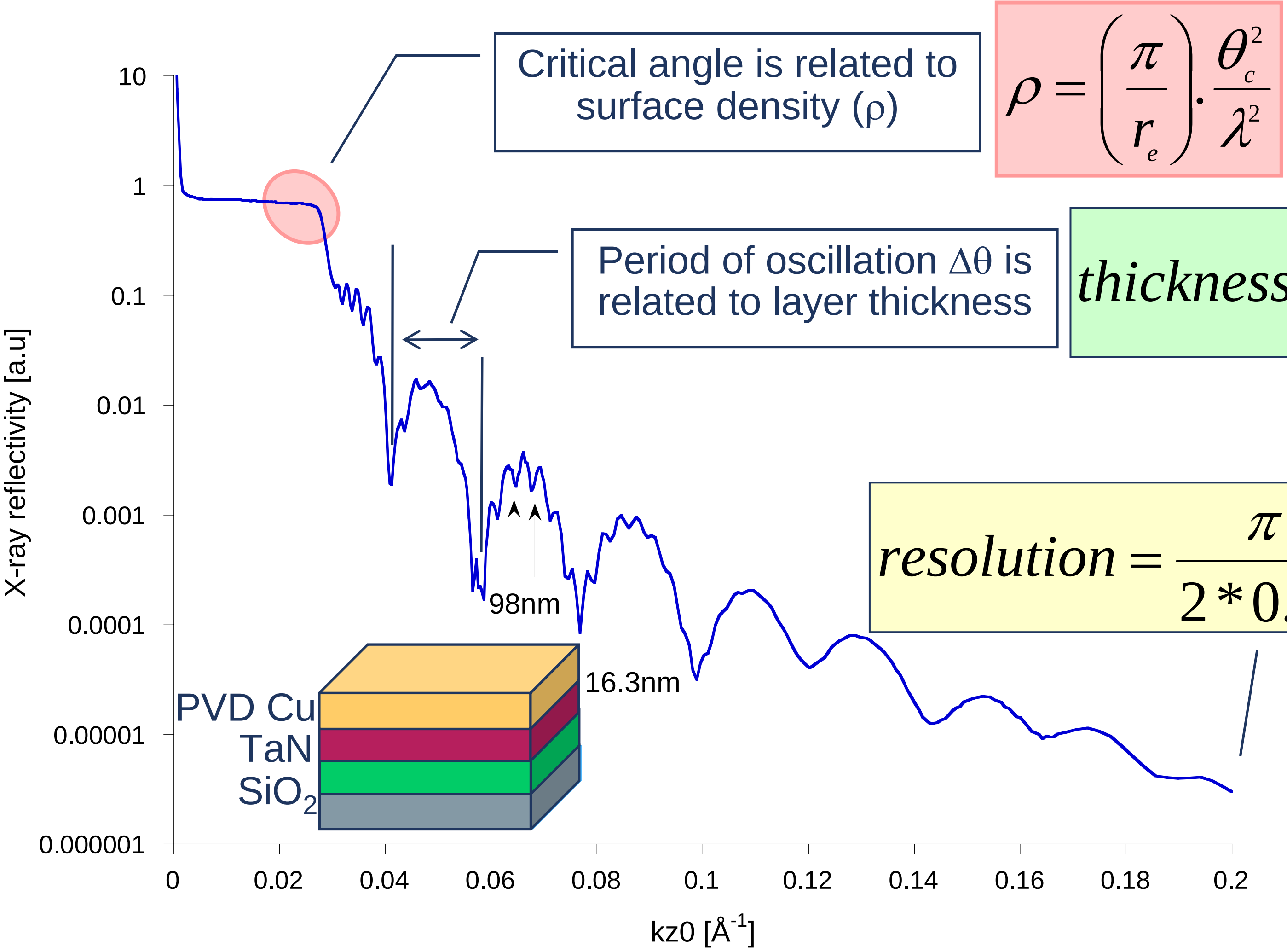
Refractive index of matter for x-rays of wavelength λ:

$$n(z) = 1 - \rho\frac{\lambda^2 r_0}{2\pi} + i\frac{\lambda}{4\pi}.\frac{1}{\mu}$$

Reflectivity from real surface:

$$R(kz) \propto \int \left\langle \frac{d\rho}{dz} \right\rangle e^{2ikz}\,dz$$

Features of XRR spectra



Critical angle is related to surface density (ρ)

$$\rho = \left(\frac{\pi}{r_e}\right) \cdot \frac{\theta_c^2}{\lambda^2}$$

Period of oscillation Δθ is related to layer thickness

$$thickness = \frac{\pi}{\Delta kz0}$$

$$resolution = \frac{\pi}{2 * 0.35} \approx 5\text{Å}$$

At least 2 periods are visible, presence of a multi-layer stack