Status and Future prospects for low k interconnect metrology

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Outline

- Background
  - **Low k material & integration challenges**
- Metrology challenges
  - **Research, Development or Production need?**
- Mechanical properties
- Porosimetry (incl. killer pores)
- Dielectric Constant
- Summary

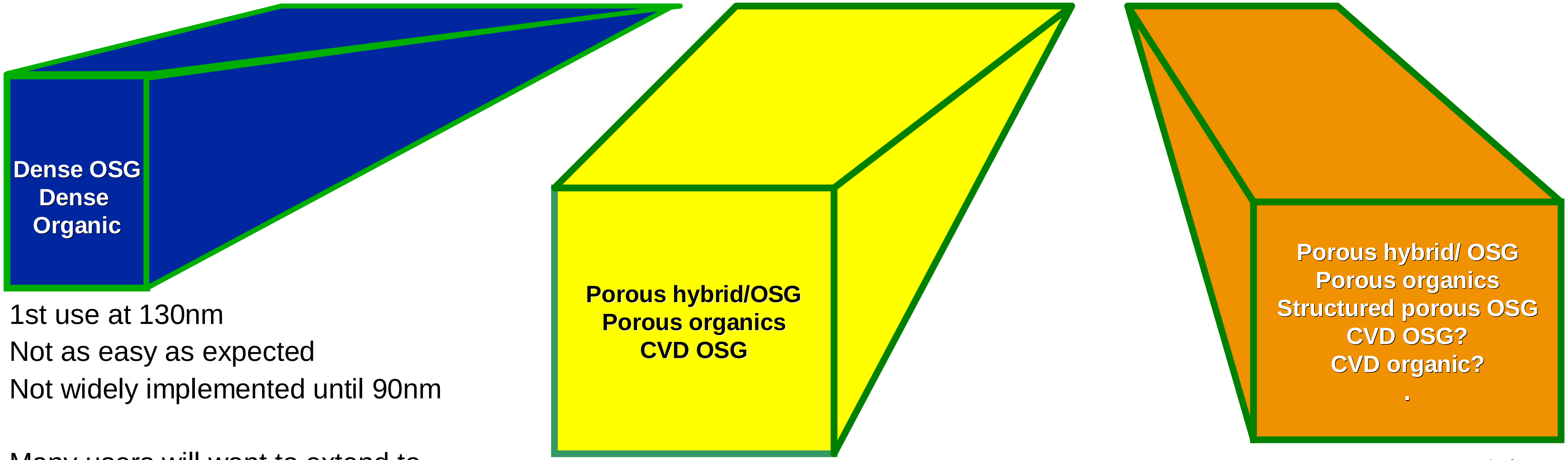
Purpose of this presentation
- **provide a different perspective on low k metrology needs**
- **elicit some discussion**

Please feel free to ask questions

Low k material evaluation activity

2002 ITRS Roadmap

Year of Production	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2010*	*2013*	*2016*
MPU 1/2 Metal One Pitch (nm)	150	130	107	90	80	70	65	45	32	22
Interlevel metal insulator (minimum expected) —bulk dielectric constant (k)	<2.7	<2.7	<2.7	**<2.4**	**<2.4**	**<2.4**	**<2.1**	**<1.9**	**<1.7**	**<1.6**
Interlevel metal insulator - effective dielectric constant (k)	3.0-3.6	3.0–3.6	3.0–3.6	**2.6–3.1**	**2.6–3.1**	**2.6–3.1**	**2.3–2.7**	**2.1**	**1.9**	**1.8**



Dense OSG
Dense
Organic

Porous hybrid/OSG
Porous organics
CVD OSG

Porous hybrid/ OSG
Porous organics
Structured porous OSG
CVD OSG?
CVD organic?
.

1st use at 130nm
Not as easy as expected
Not widely implemented until 90nm

Many users will want to extend to 65nm node

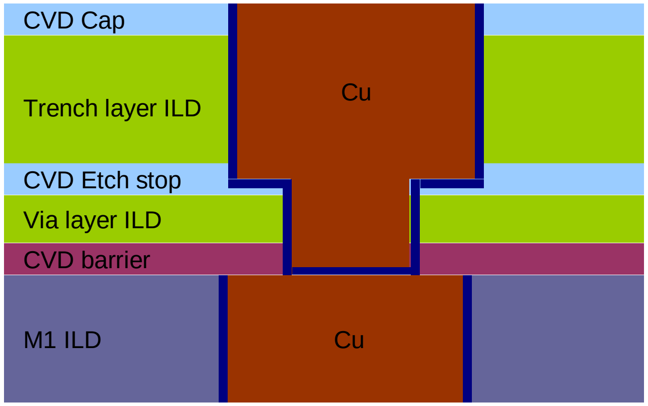
Many material candidates
Many new problems encountered
pore sealing, lower mechanical strength, etc.

Some consider the roadmap unrealistic

Most current materials are extensions of k > 2.2 versions

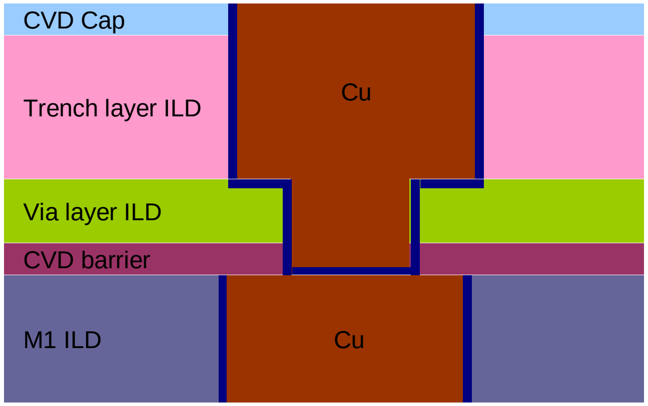
Outlook for k ~ 2.0 uncertain

Low k Integration Paths

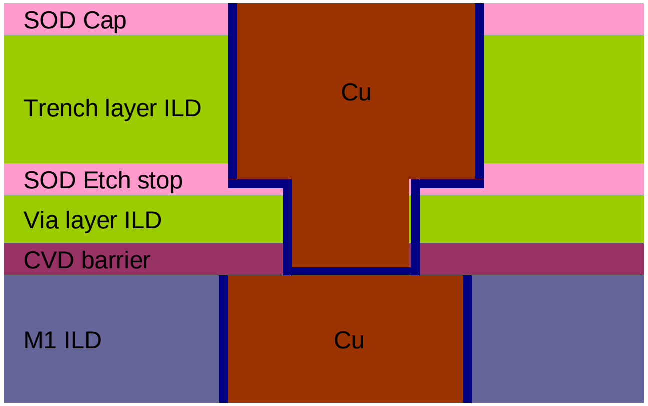


Conventional
SOD or CVD via & trench ILD
CVD barrier, etch stop & cap layers

Paths to lower k(eff)



Hybrid
CVD barrier & cap - middle etch stop layer eliminated
Dissimilar via & trench ILD layers (built in etch selectivity)
low k films could be SOD or CVD

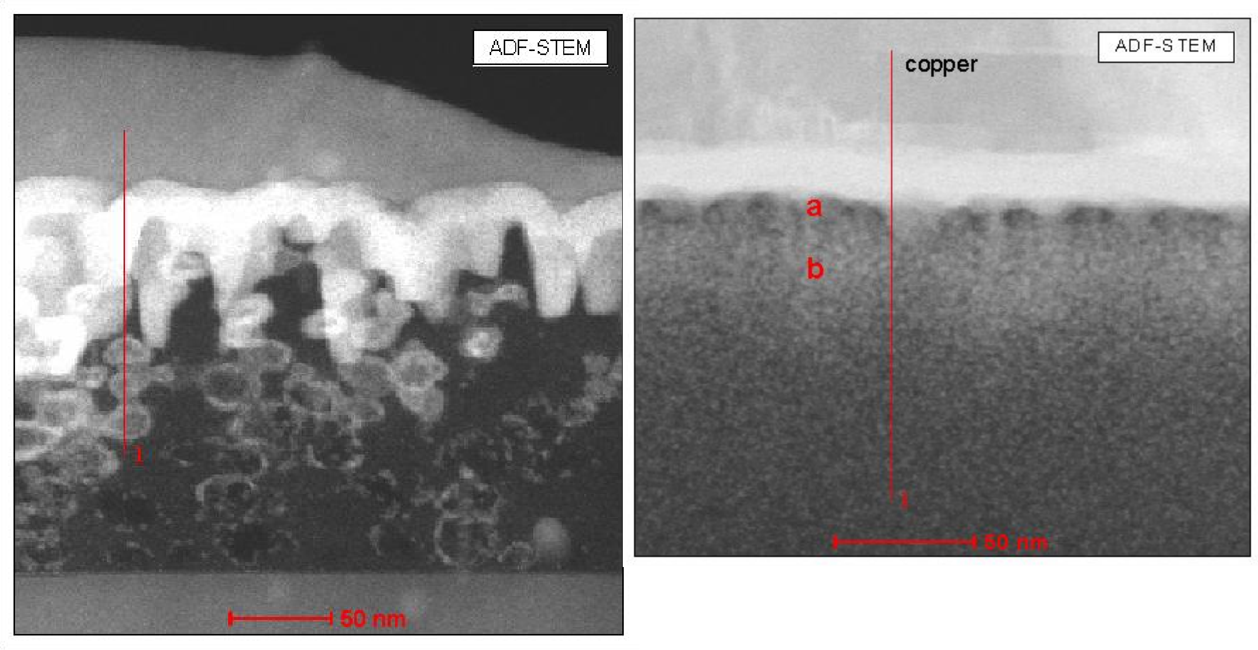


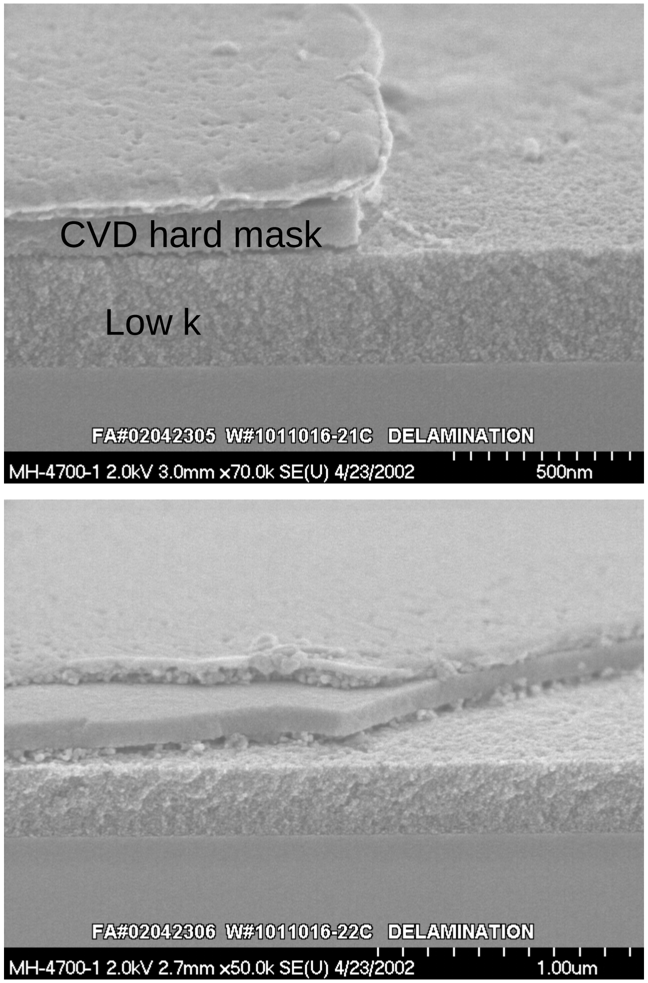
All spin-on
CVD barrier (critical for M1 Cu reliability)
SOD via ILD, etch stop, trench ILD, cap layers

Low k dielectric

integration challenges

- Mechanical strength
  - – (low k voiding, adhesion, packaging, etc)
- Pore sealing
- K(eff)
- System reliability

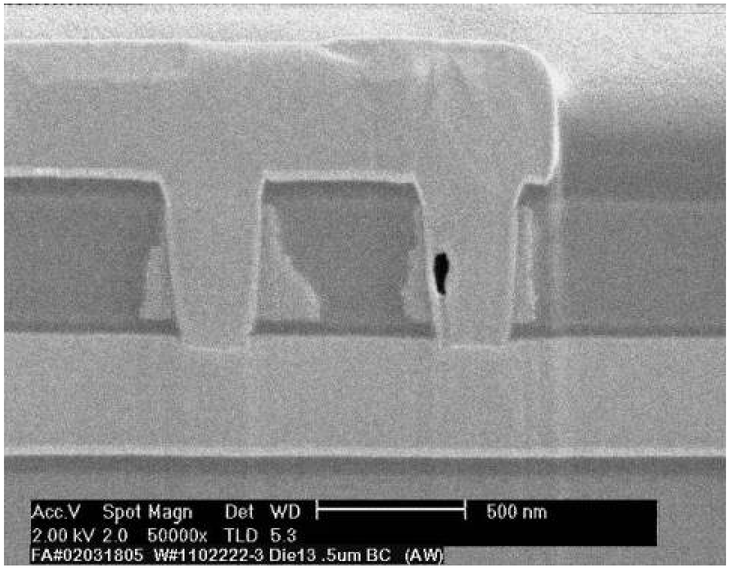

CVD barrier penetration into pores



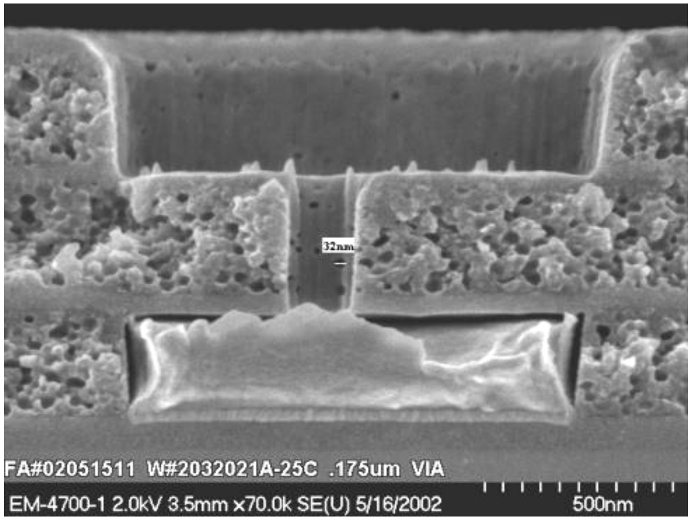
delamination

Low k dielectric

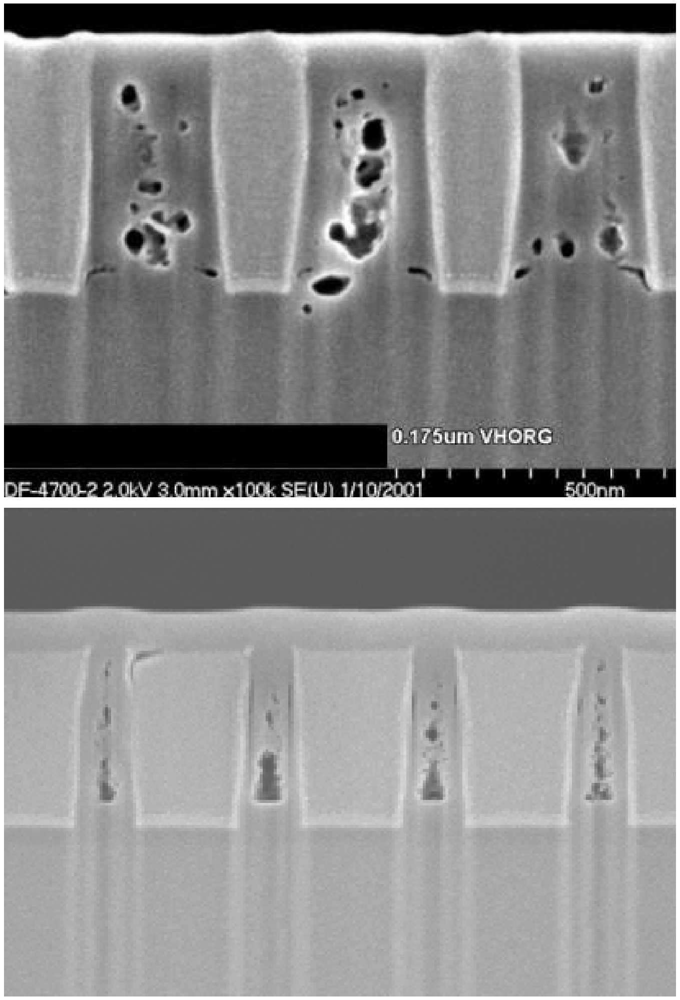
integration challenges



System reliability



Large pore structure



Low k voiding

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Low k integration summary

- Unique properties of porous low k materials make integration challenging

Metrology techniques are needed that help:

RESEARCH & DEVELOPMENT ENGINEERS

A) understand/improve the materials they are working with

B) solve integration challenges

PRODUCTION FABS

C) monitor production processes

D) keep production in control

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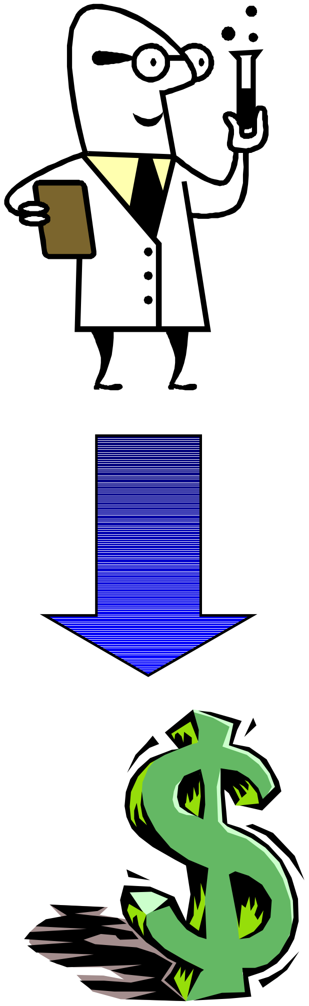
Research, Development, or Production

- Metrology needs vary greatly depending on when and where they are used

- Research
  - **Fundamental material property evaluations. May or may not be used once a material is selected for mainstream integration**

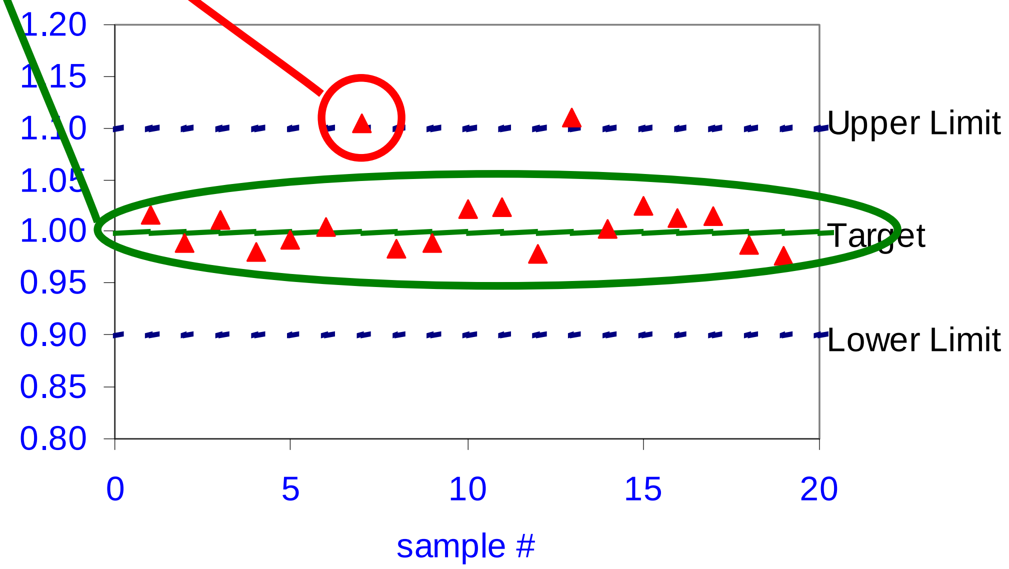
- Development
  - **Full technology development and qualification phase (may incl. some material research as well)**

- Production
  - **Likely to be used on a production floor for process control & monitoring**



Production Needs

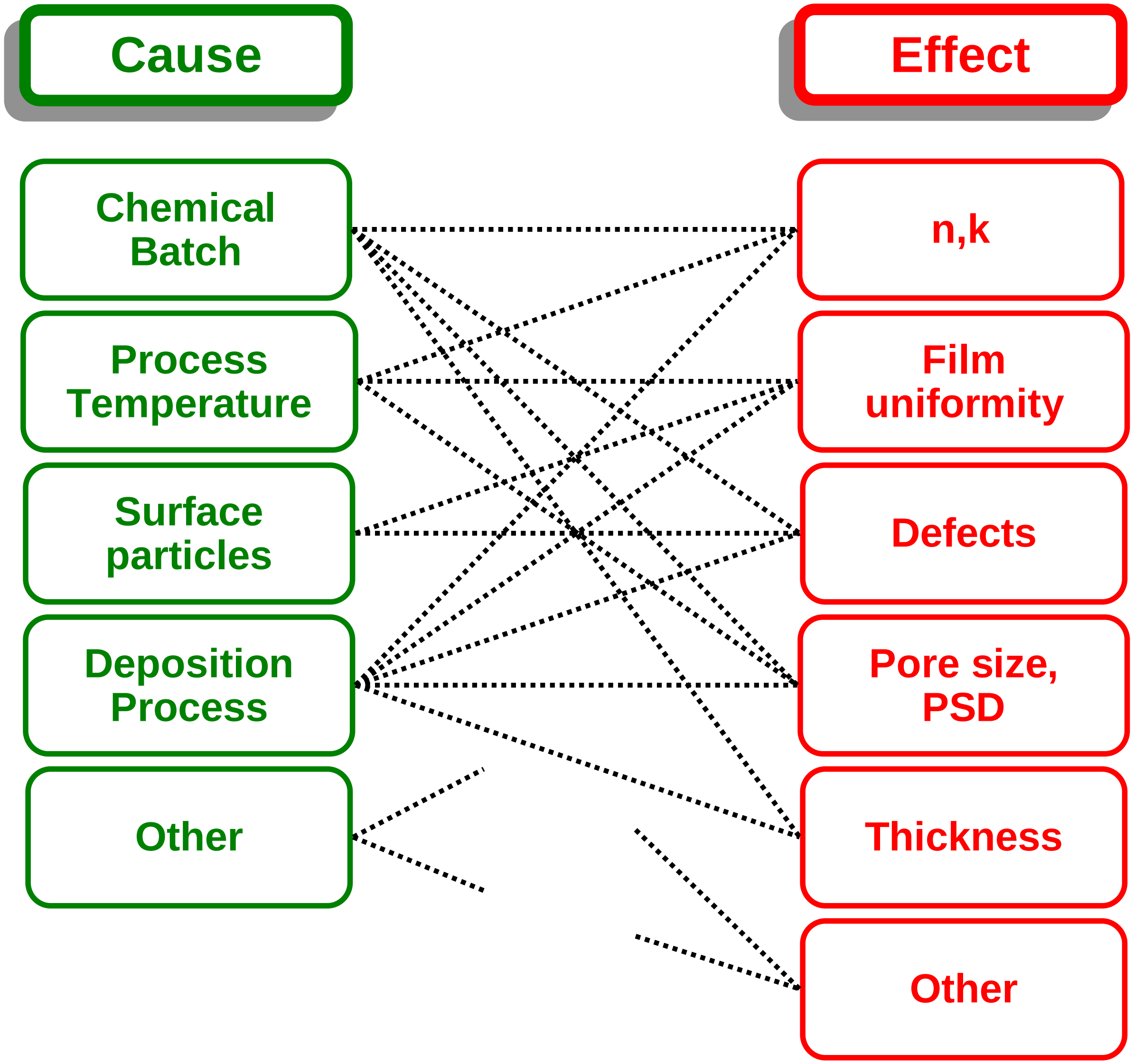
- Results need to be available in <u>real time</u> (not necessarily true for R&D)
- <u>S</u>tatistical <u>P</u>rocess <u>C</u>ontrol (SPC)
  - Is the metrology <u>sensitive</u> to process changes or drifts?
  - Is my process stable?
- Process Tuning - when process drift occurs
  - Does the metrology help me figure out what went wrong?
    - Direct measurements usually preferable (i.e. thickness, composition, etc)
    - Indirect measurements can also be valuable if a correlation exists
      - (i.e. Rs, FTIR, etc)



NOTE:

- Production metrology needs to show a <u>relevant correlation</u> but does not need 100% scientific certainty

Process control issues



Cause

- Chemical Batch
- Process Temperature
- Surface particles
- Deposition Process
- Other

Effect

- n,k
- Film uniformity
- Defects
- Pore size, PSD
- Thickness
- Other

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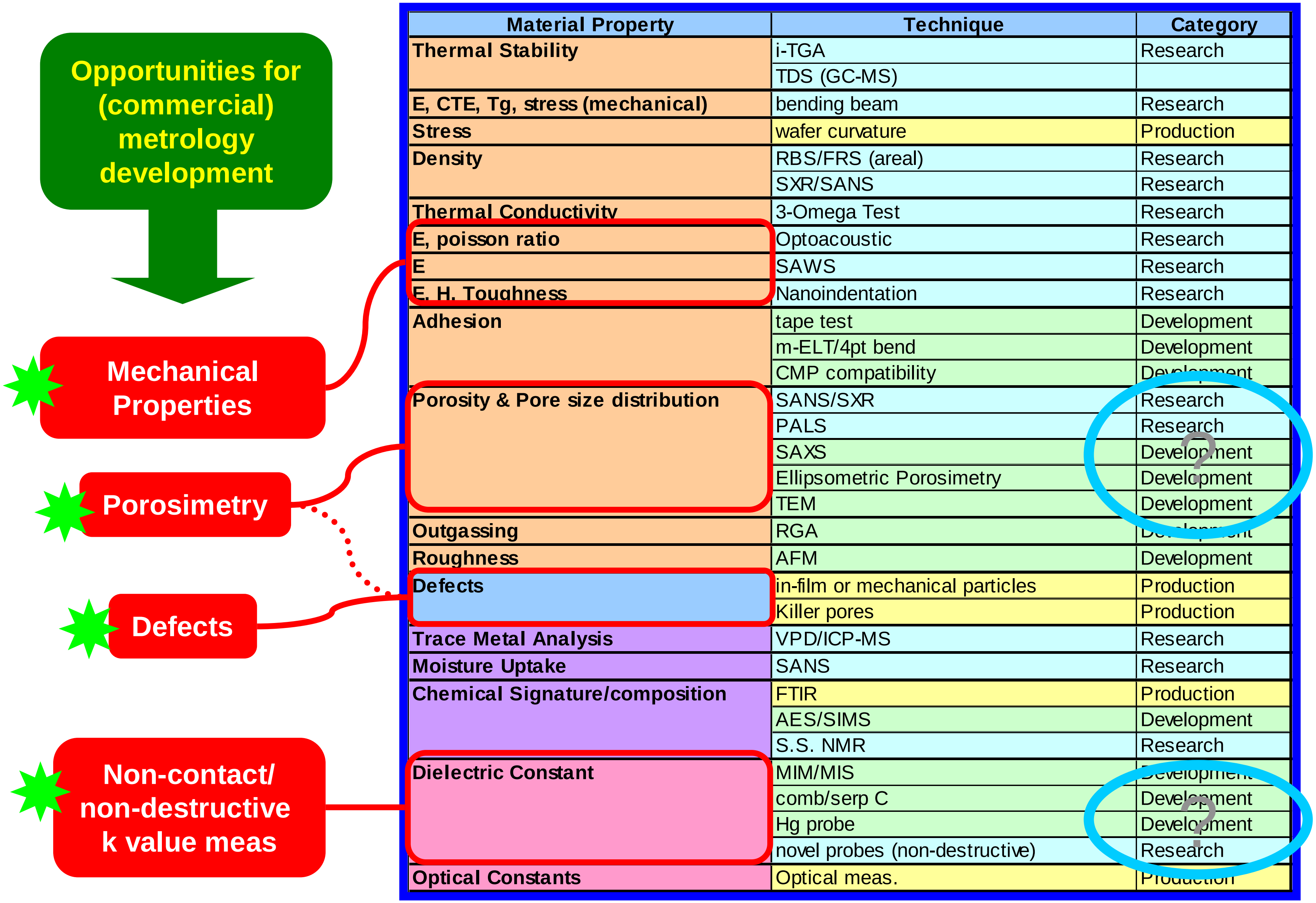
Low k film metrology – R&D or production?



Opportunities for (commercial) metrology development

Mechanical Properties

Porosimetry

Defects

Non-contact/ non-destructive k value meas

Material Property	Technique	Category
Thermal Stability	i-TGA	Research
	TDS (GC-MS)	
E, CTE, Tg, stress (mechanical)	bending beam	Research
Stress	wafer curvature	Production
Density	RBS/FRS (areal)	Research
	SXR/SANS	Research
Thermal Conductivity	3-Omega Test	Research
E, poisson ratio	Optoacoustic	Research
E	SAWS	Research
E, H, Toughness	Nanoindentation	Research
Adhesion	tape test	Development
	m-ELT/4pt bend	Development
	CMP compatibility	Development
Porosity & Pore size distribution	SANS/SXR	Research
	PALS	Research
	SAXS	Development
	Ellipsometric Porosimetry	Development
	TEM	Development
Outgassing	RGA	Development
Roughness	AFM	Development
Defects	in-film or mechanical particles	Production
	Killer pores	Production
Trace Metal Analysis	VPD/ICP-MS	Research
Moisture Uptake	SANS	Research
Chemical Signature/composition	FTIR	Production
	AES/SIMS	Development
	S.S. NMR	Research
Dielectric Constant	MIM/MIS	Development
	comb/serp C	Development
	Hg probe	Development
	novel probes (non-destructive)	Research
Optical Constants	Optical meas.	Production

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Thermal/Mechanical properties

Material Property	Technique	Category
Thermal Stability	i-TGA	Research
	TDS (GC-MS)	
E, CTE, Tg, stress	bending beam	Research
Stress	wafer curvature	Production
Density	RBS/FRS (areal)	Research
	SXR/SANS	Research
Thermal Conductivity	3-Omega Test	Research
E, poisson ratio	Optoacoustic	Research
E	SAWS	Research
E, H, Toughness	Nanoindentation	Research
Adhesion	tape test	Development
	m-ELT/4pt bend	Development
	CMP compatibility	Development
Porosity & Pore size distribution	SANS/SXR	Research
	PALS	Research
	SAXS	Development
	Ellipsometric Porosimetry	Development
	TEM	Development
Outgassing	RGA	Development
Roughness	AFM	Development

?

Analysis category definitions (for the sake of this discussion)	
Research	Fundamental material property evaluations. May or may not be used once a material is selected for integ.
Development	Full technology development and qualification phase (may incl. some material research as well)
Production	Likely to be used on a production floor for process control & monitoring

Chemical & Optical properties
Defects

Material Property	Technique	Category
Defects	in-film or mechanical particles	Production
	Killer pores	Production
Trace Metal Analysis	VPD/ICP-MS	Research
Moisture Uptake	SANS	Research
Chemical Signature/composition	FTIR	Production
	AES/SIMS	Development
	S.S. NMR	Research
Dielectric Constant	MIM/MIS	Development
	comb/serp C	Development
	Hg probe	Development ?
	novel probes (non-destructive)	Research

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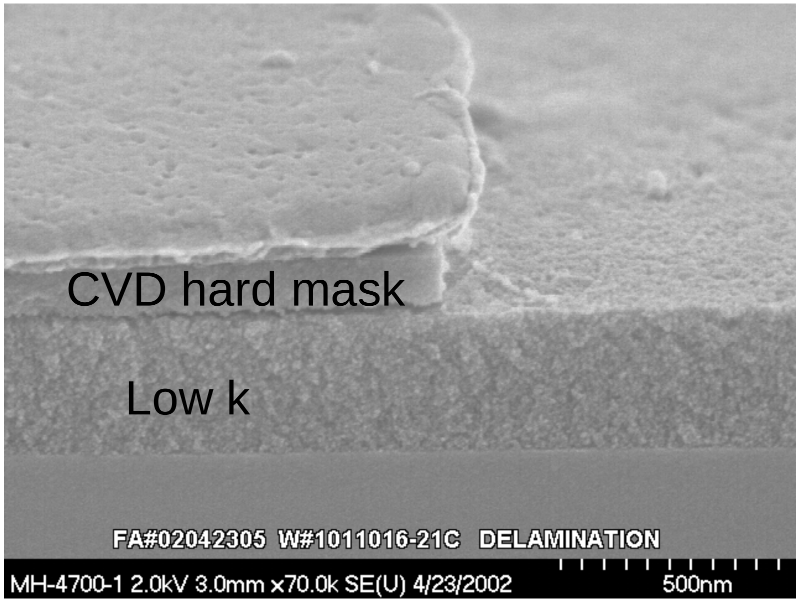
Mechanical properties

Research

Development

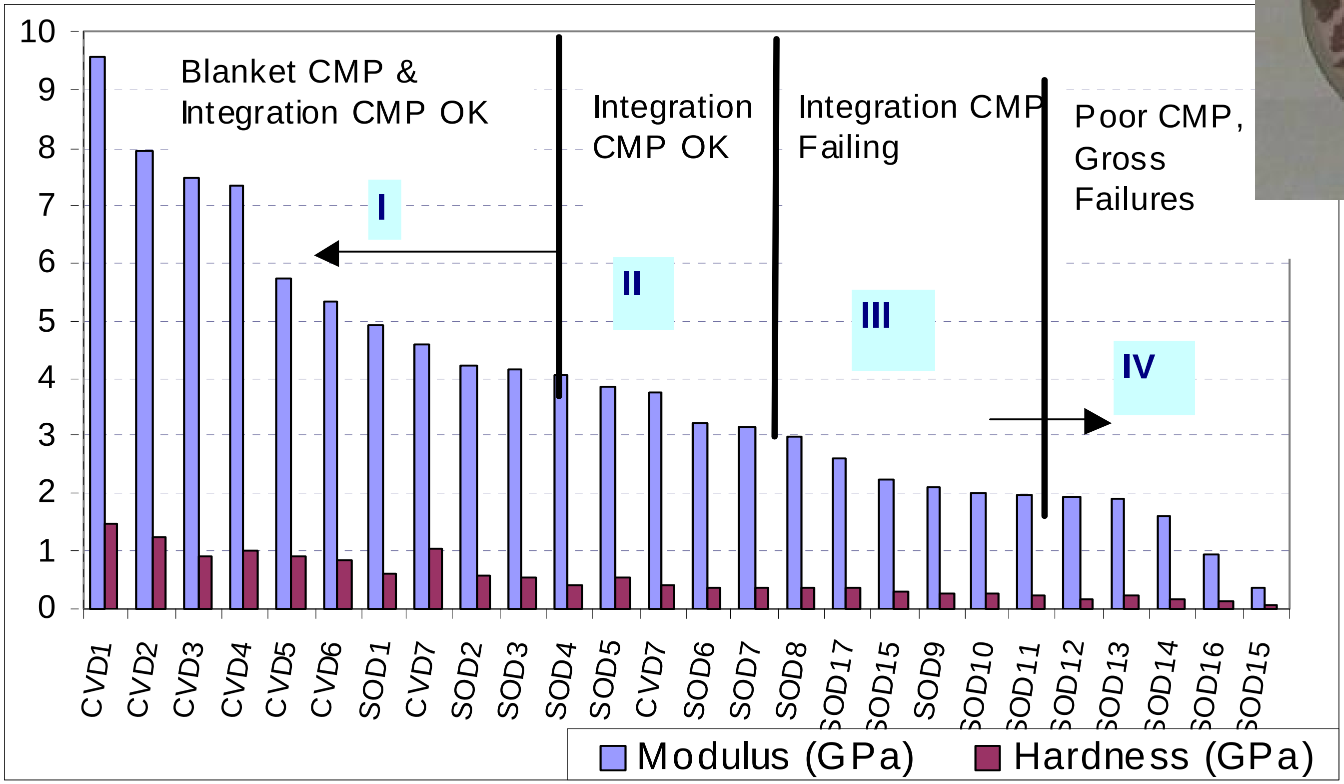
- For low k materials, mechanical “strength” is a major concern
  - Cohesive failure
  - Interface delamination
  - Mechanical confinement of Cu (EM, stress migration)
- Modulus, Hardness, Toughness, Adhesion are all of interest

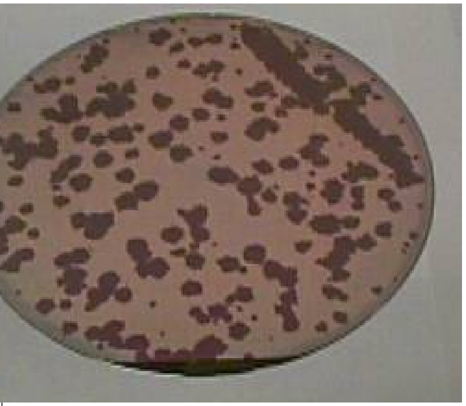


Typical cap delamination failure

CMP Performance and Modulus

historical trends

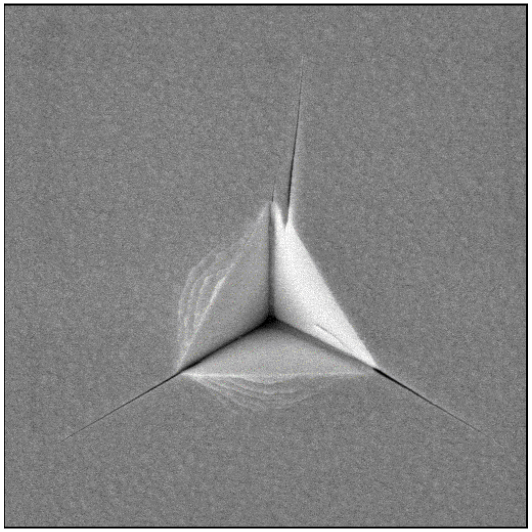




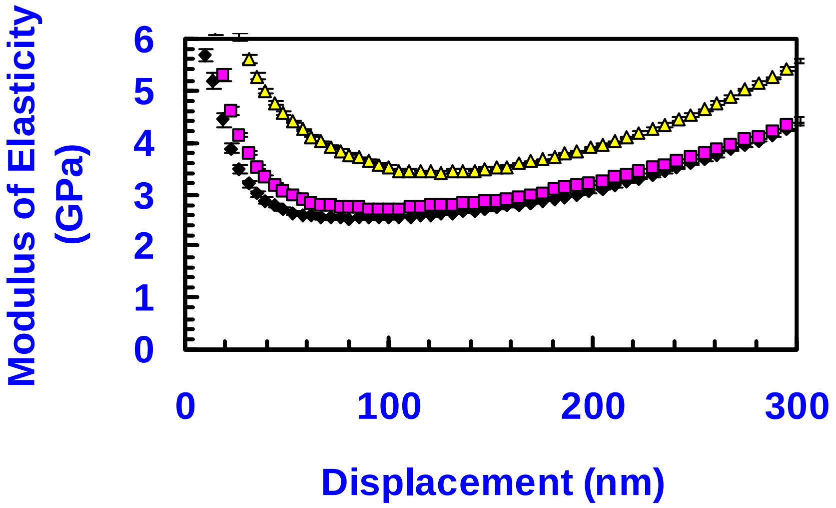
- Modulus ≥4 GPa, patterned structures have high yield
- Modulus <4GPa, yield is lower; addition of dummy metal fill provides “acceptable” yields for testable structures.
- Other properties (i.e. toughness) may be more important for different classes of materials
- No clear answer whether Modulus ≥4 GPa is <u>sufficient</u> for full chip integration and packaging. Some people suggest ≥6-8 GPa may be required.

Nano-indentation

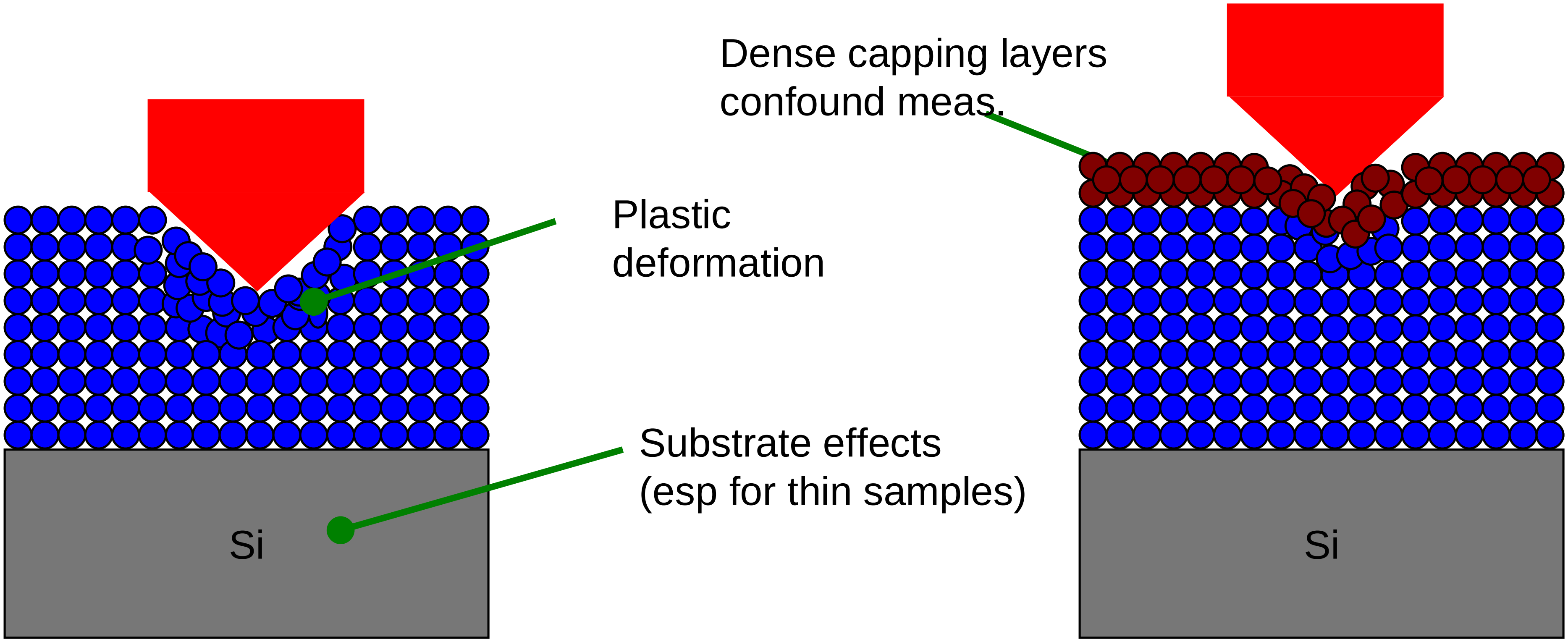
- Well established technique for dense, non-crushable materials
- Very commonly used to measure low k material modulus & hardness - everybody reports nano-indentation results
- Being evaluated for fracture toughness
- Questions arise about the applicability/accuracy of nano-indentation for porous low k materials



Typical Nanoindentation Plot



Questions about nano-indentation with porous low k materials



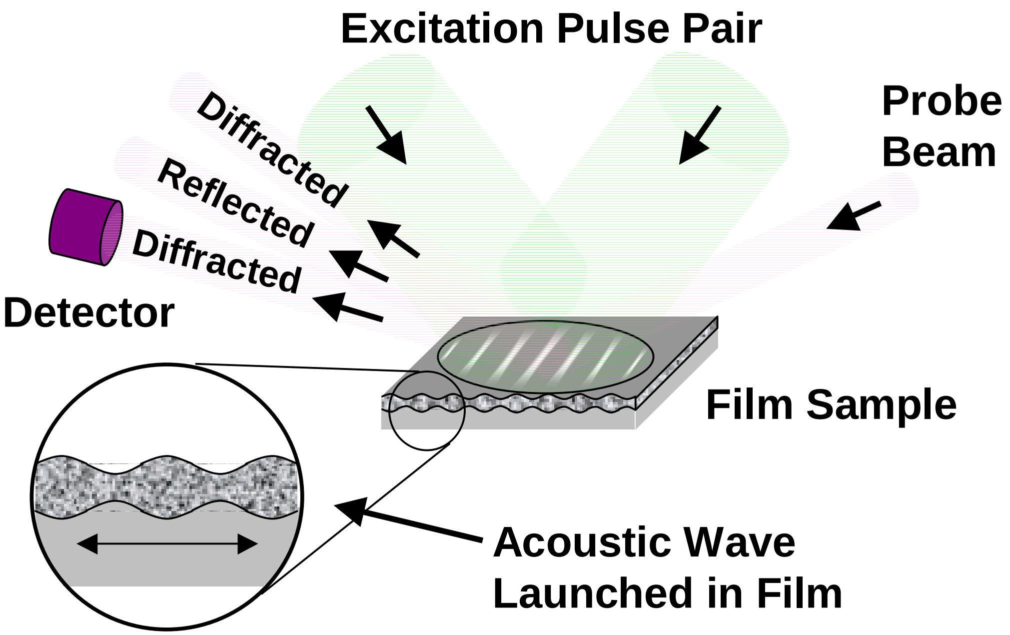
Dense capping layers confound meas.

Plastic deformation

Substrate effects (esp for thin samples)

Other techniques may give more “accurate” modulus numbers

Schematic Diagram of Philips Impulse Technique



Stripe pattern imaged by excitation laser launches an acoustic wave in the film. Wave is detected by diffraction of probe laser from the film surface.

Program models Velocity Vs. Wave Vector data to determine the Longitudinal Velocity (V_L) and Transverse Velocity (V_T) for the film.

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

$$\nu = \{1-1/2 \cdot (V_L/V_T)^2\}/\{1-(V_L/V_T)^2\}$$

Figures courtesy Philips Analytical.

Determination of Young Modulus from EP data

Fundamentals:

$$\Delta P = 2\gamma / r \quad (Young - Laplace\ equation);$$

$$\ln\frac{p}{p_0} = -\frac{2\gamma V_L}{RT}\cdot\frac{1}{r};$$

$$\Rightarrow \quad \Delta P = \ln\frac{p}{p_0}\cdot\frac{RT}{V_L};$$

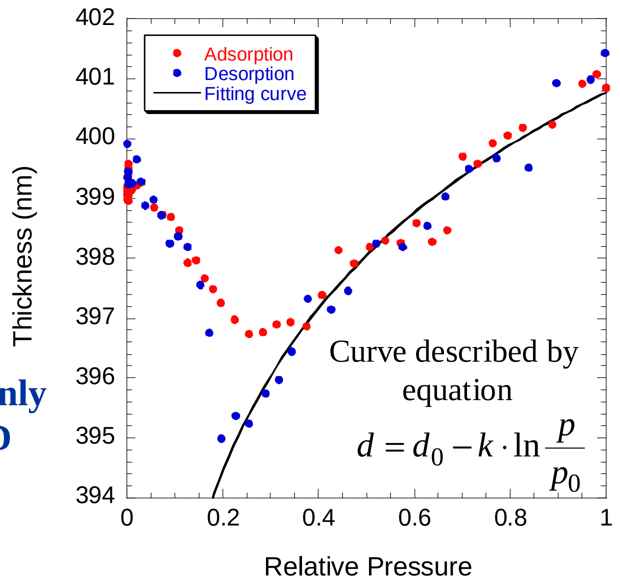
Change of the film thickness due to capillary forces is equal to

$$d = d_0(1-\Delta P/G) = d_0 - k\cdot\ln\frac{p}{p_0},$$

$$and\ G = \frac{\Delta P\cdot d_0}{k}$$

where G is Young Modulus.

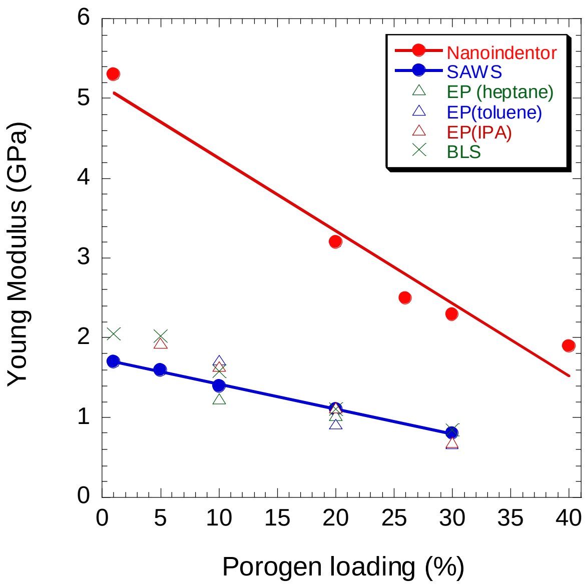
Change of thickness is only 1.5% (negligible for PSD calculation)



Curve described by equation

$$d = d_0 - k\cdot\ln\frac{p}{p_0}$$

EP Young Modulus is close to SAWS and BLS values but about 3 times less than values obtained by Nanoindentor.



Courtesy M.R.Baklanov.

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Modulus/Hardness Summary

- Questions often arise about the applicability/accuracy of nano-indentation to report modulus for porous low k materials
- Other techniques exist but are not as widely tested or utilized
- Accurate reporting of modulus is probably very important question from a fundamental material perspective

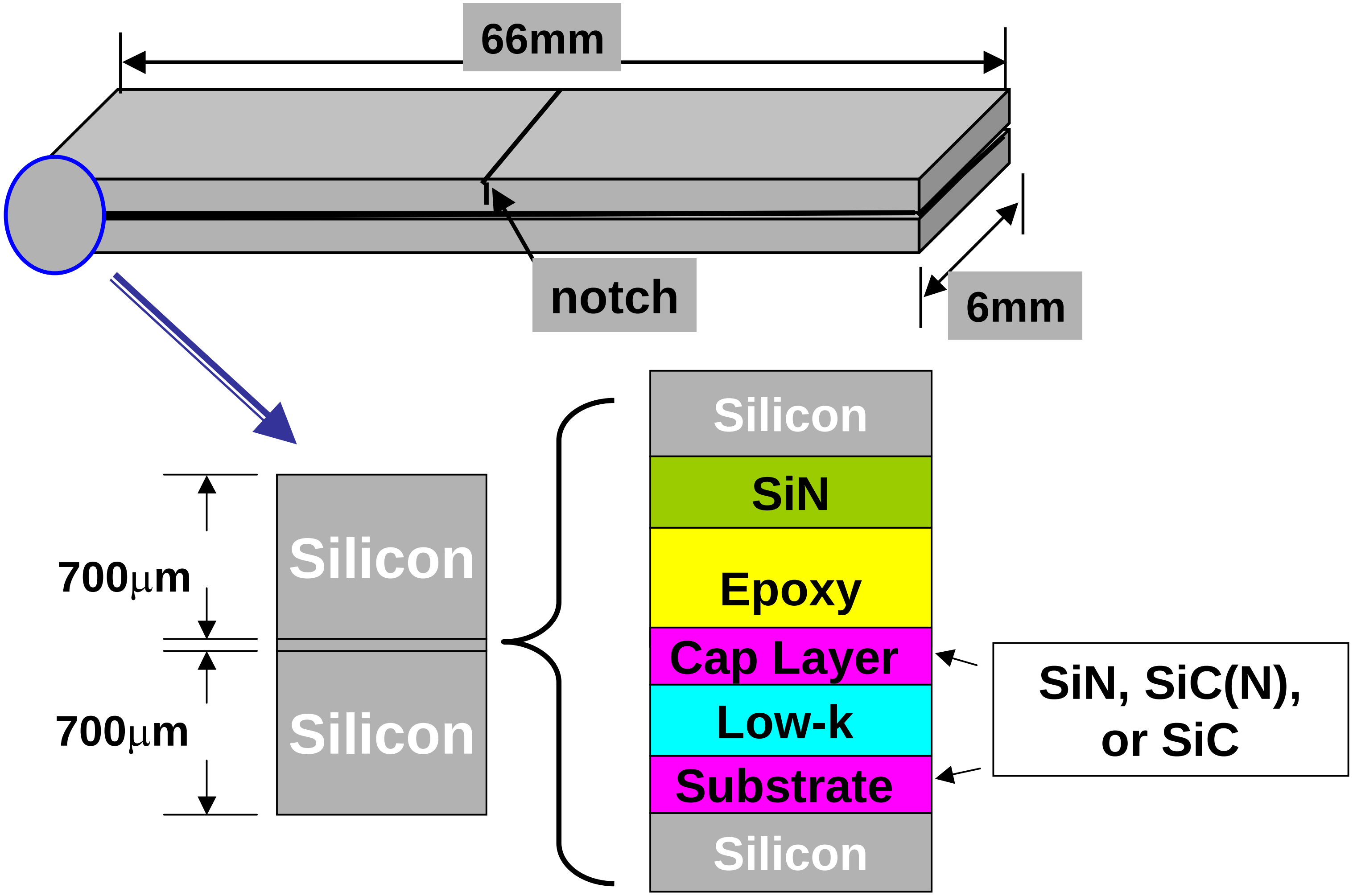
but

- Relatively unimportant from an engineering perspective
  - The true acid test is on-chip integration and packaging

- Challenges to the industry:
  - Utilize modulus/hardness testing for relative comparison but be careful predicting success/failure based on #'s alone
  - Establish correlation between fundamental material properties and integration success

Adhesion testing

Sample Configuration for 4-point Bending Test



66mm

notch

6mm

700μm

700μm

Silicon

Silicon

Silicon

SiN

Epoxy

Cap Layer

Low-k

Substrate

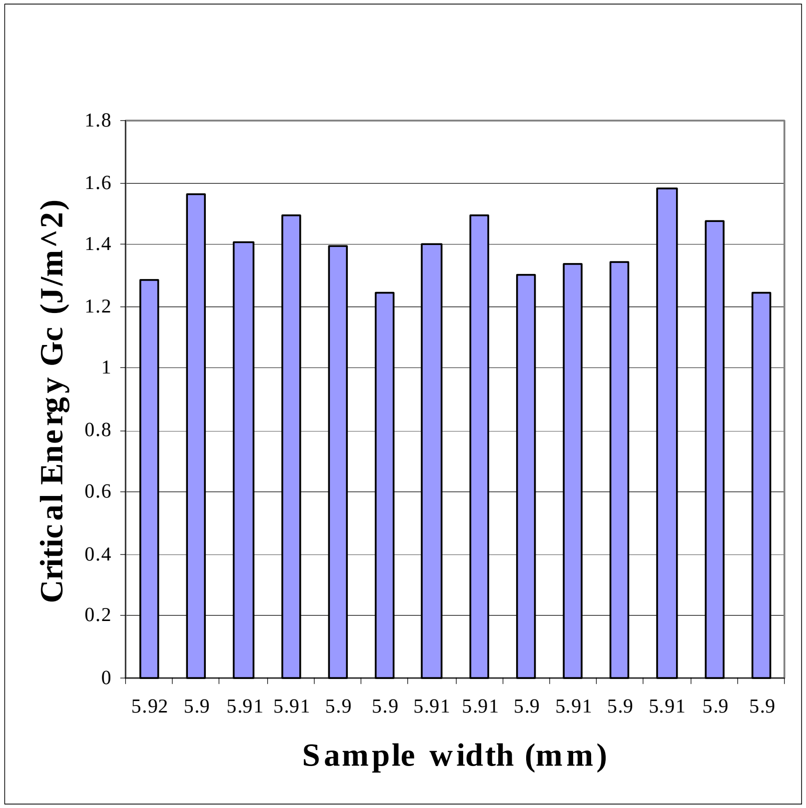
Silicon

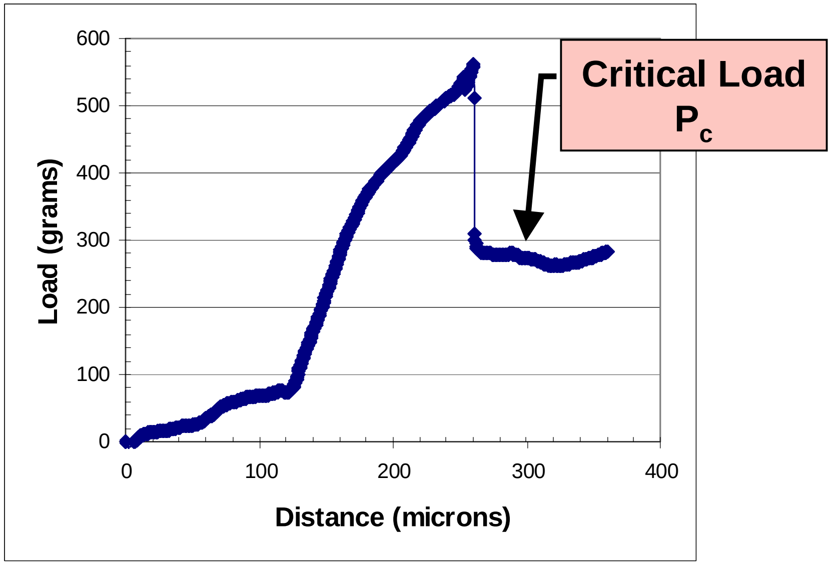
SiN, SiC(N),
or SiC

Courtesy UT

Experimental Results

Si/SiC/low k/SiC





Average Critical Energy Release: 1.396 J/m^2
Standard Deviation: +/- 0.112
Error: 0.080

- **Test 22 Samples**
- **Typically G_c ± 10%**
- **FA on 2 samples**

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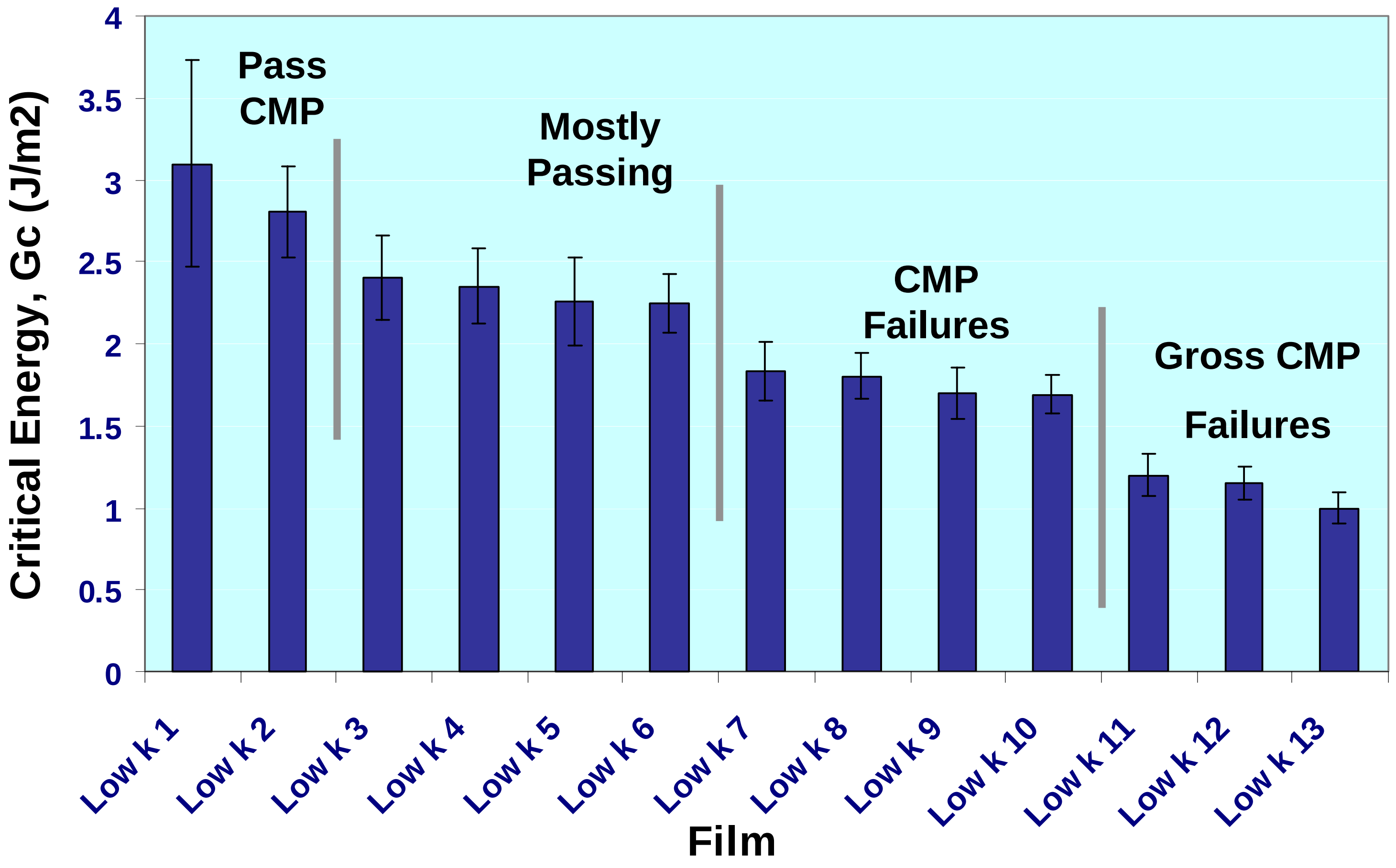
CMP Performance and critical energy

historical trends



- Typically films with $G_c > 2.25$ J/m^2 have no issues with ISMT blanket or patterned wafer CMP. (for 2LM structures)

Critical Energy (Gc)

- Several techniques are used (MELT, 4pt bend)
- Questions often arise about the technique used, sample preparation, repeatability, etc.
- Measuring Gc can be of aid to explain trends (success/failure)
    - Difficult to predict total success based on good Gc

- Accurate reporting of Gc is probably very important question from a fundamental material perspective

but

- Relatively unimportant from an engineering perspective
    - The true acid test is on-chip integration and packaging

- Challenge to the industry:
    - Utilize adhesion testing as an analysis tool, but be careful predicting success/failure based on #'s alone

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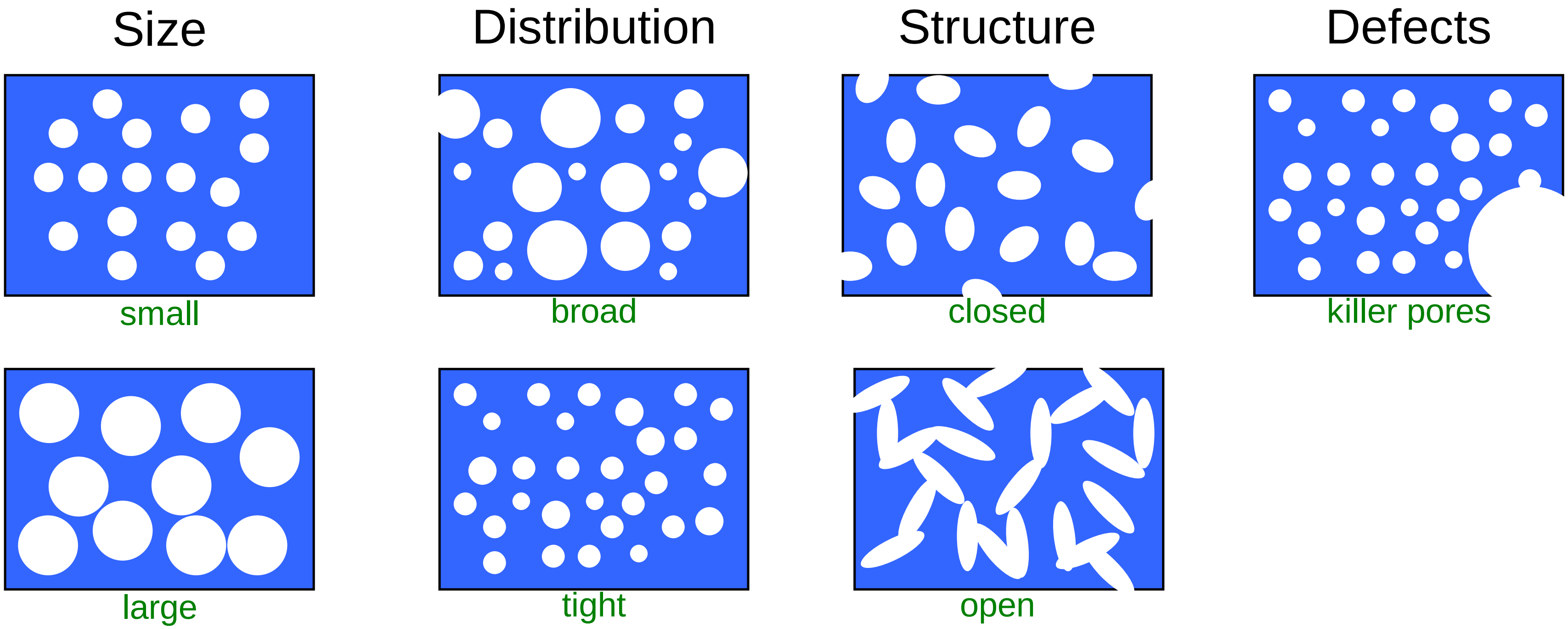
Porosimetry

Research
Development
Production?

- Different materials have different pore properties
- What information do we want to know?



TEM

Sample thinned to <20 nm thickness

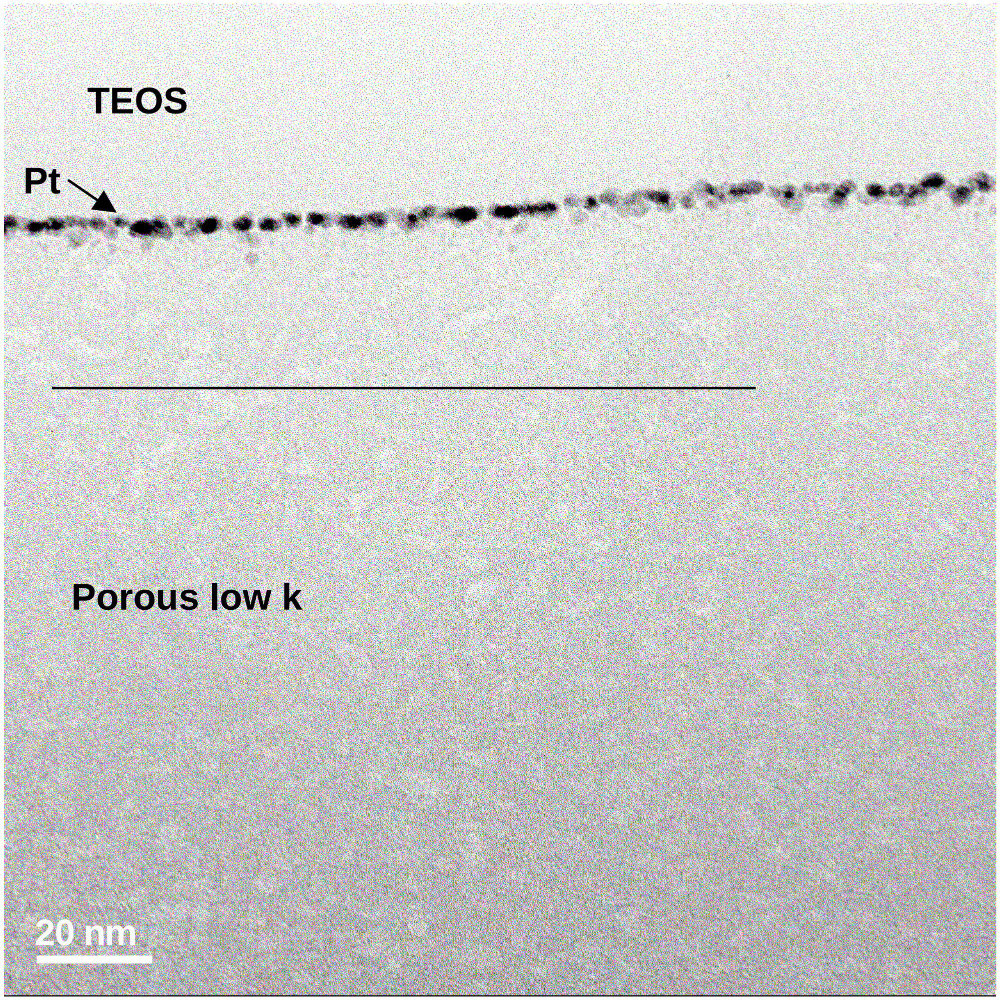
Pores with diameter >0.8 nm are resolved, smaller pores not visible due to sample thickness.

Observations:

- **maximum pore dimension 6.8 nm**
- **average pore size 2.86 nm**

- **good correlation to PALS for this sample**

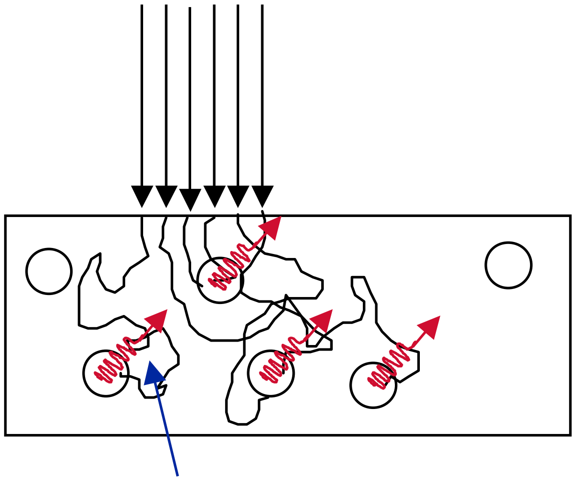
Good technique for “seeing” pore structure



TEM courtesy Brendan Foran (ISMT)

Positron Annihilation Lifetime Spectroscopy (PALS)

Incident Low-energy Positron Beam from a ^{22}Na source. Energy can be varied for depth profiling.



The Ps will annihilate into 3 γ-rays with a vacuum lifetime of 142 ns. In a porous material, the annihilation lifetime is proportional to the collision frequency. Thus, the Ps lifetime is related to the pore size.

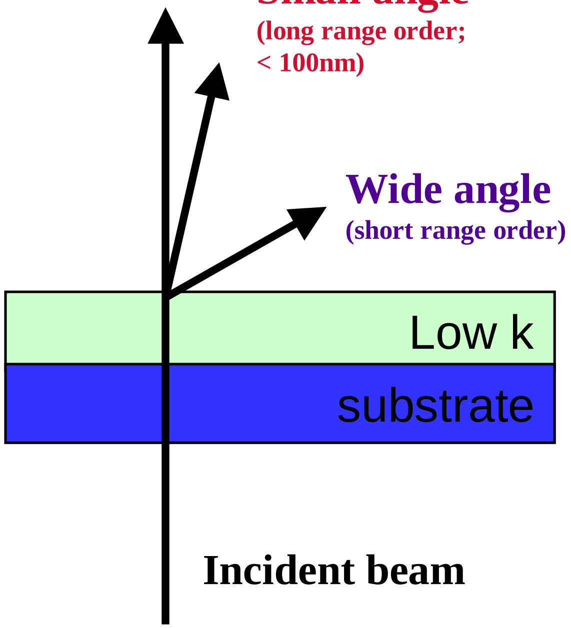
PALS yields information about

Average pore size (related to Ps lifetime)

Pore connectivity

Courtesy D. Gidley - U. Michigan

Small Angle Neutron Scattering (SANS)



Small angle

(long range order; < 100nm)

Wide angle

(short range order)

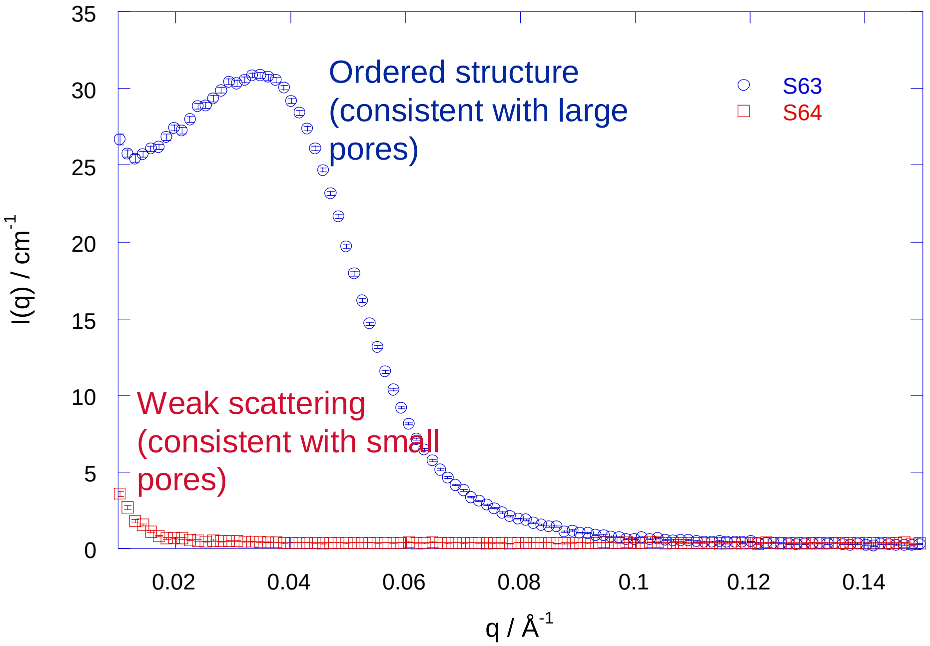
Low k

substrate

Incident beam

SANS can provide:

- Average pore size
- Pore shape info.
- Relative moisture uptake info. (using D_2O)

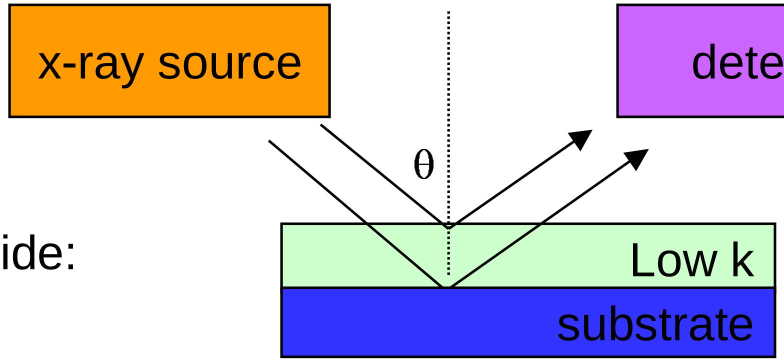


Ordered structure (consistent with large pores)

Weak scattering (consistent with small pores)

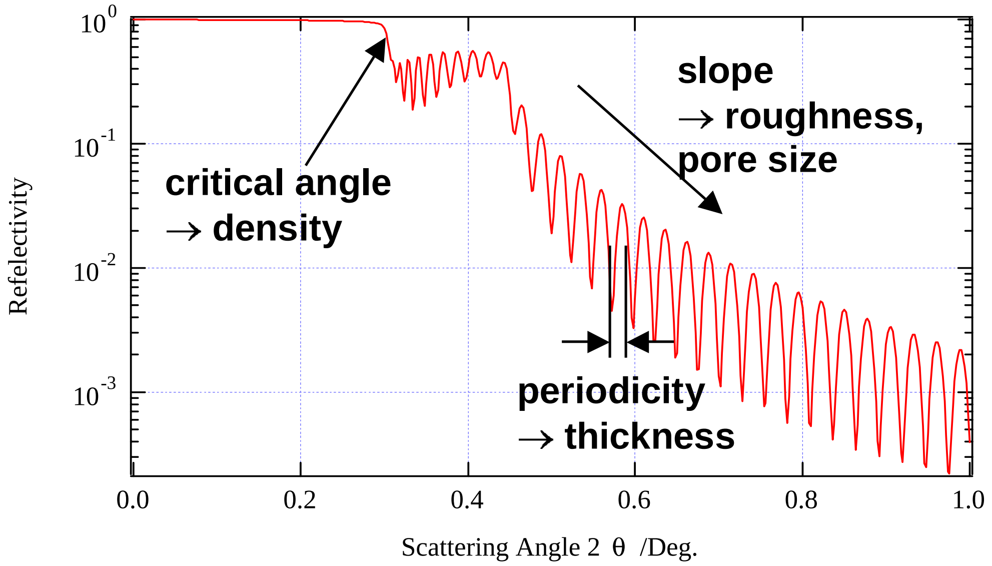
Courtesy W. Wu, NIST

Porosimetry techniques – XRR/SAXS



X-ray techniques provide:

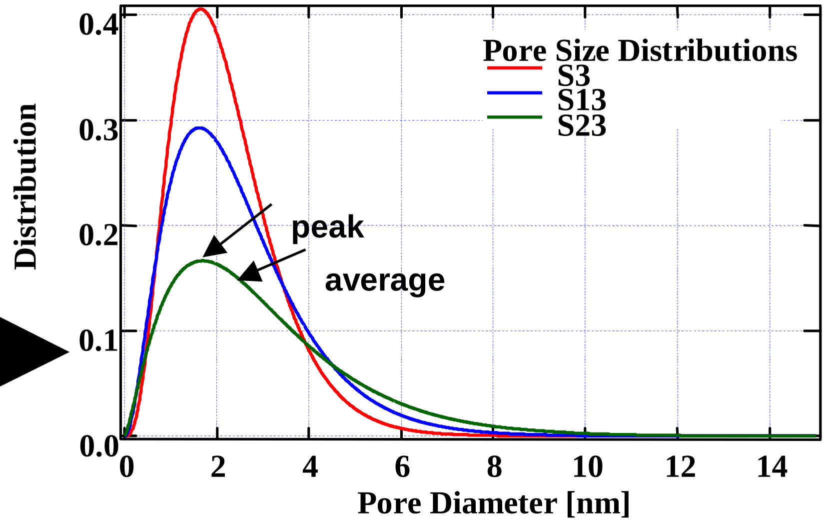
- XRR: density and thickness
- SAXS: PSD



critical angle → density

slope → roughness, pore size

periodicity → thickness



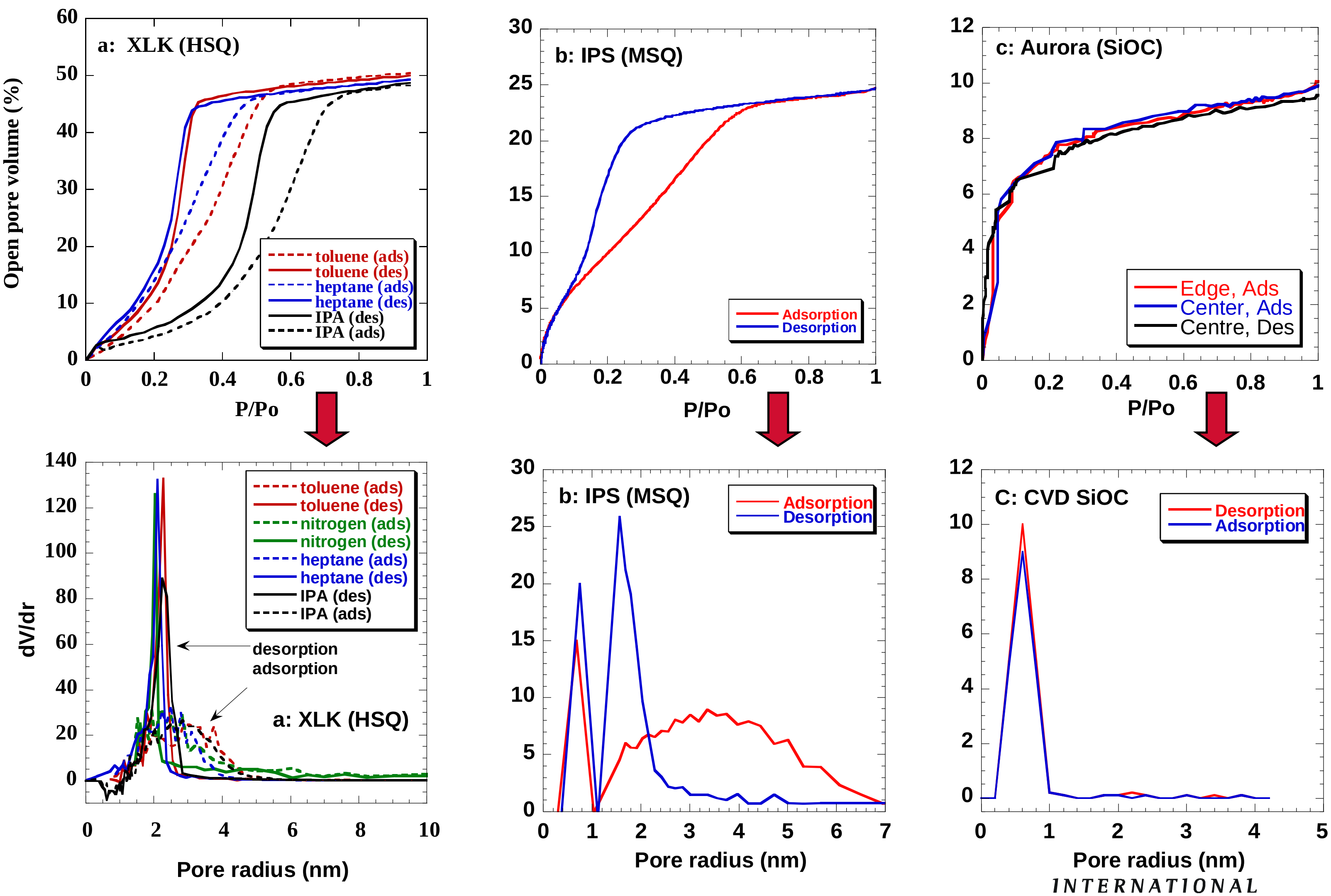
peak

average

Ellipsometric Porosimetry

Adsorption and PSD in meso- and microporous films

Mesopores: - hysteresis loop; condensation at P/Po = 0.2 - 1.
Micropores: - no hysteresis loop; condensation at P/Po < 0.2.



Ref. M.R.Baklanov and K.P.Mogilnikov. Semic.Fabtech, 2001

Porosimetry Summary

Research
Development
Production?

- Powerful scientific techniques exist
- Techniques currently being used
  - **TEM**
    - **Excellent for "seeing" pore structure**
    - **Requires TEM sample prep, only observes small area, Not sensitive to very small pores**
  - **PALS**
    - **Established scientific technique, requires Ps source and γ-ray detector**
  - **SAXS**
    - **Powerful laboratory technique - showing promise as commercial tool**
  - **SANS**
    - **Powerful laboratory technique**
  - **Ellipsometric porosimetry**
    - **Shows promise as analytical lab tool, especially for inorganic films**

Porosimetry

Research
Development or
Production

Research
Development
Production?

- **Development engineers will say pore size & PSD should be measured in production**

- **Production engineers will say “if pore size needs to be measured in production, then the film is not production worthy”**

- **True answer is probably somewhere in between**

  It is important to have the ability to monitor pore size and PSD in a fab.

  Can be direct or indirect measurement

  Measurement frequency will only be determined after SPC charts are created

Yield Enhancement Roadmap

2002 ITRS Roadmap

Year of Production	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2010*	*2013*	*2016*
MPU 1/2 Metal One Pitch (nm)	150	130	107	90	80	70	65	45	32	22
Critical Defect Size (nm)	75	65	54	45	40	35	33	23	16	11
Random D_0 (faults/m^2)	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356
Random D (faults/300mm wafer)	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100
Random Particles Per Wafer Pass (PWP) (defects/m^2) SOD track	308	232	157	111	99	62	54	26	12	6

Total # killer defects on a 300mm wafer (through the entire process)

Assume killer pore size = critical defect size

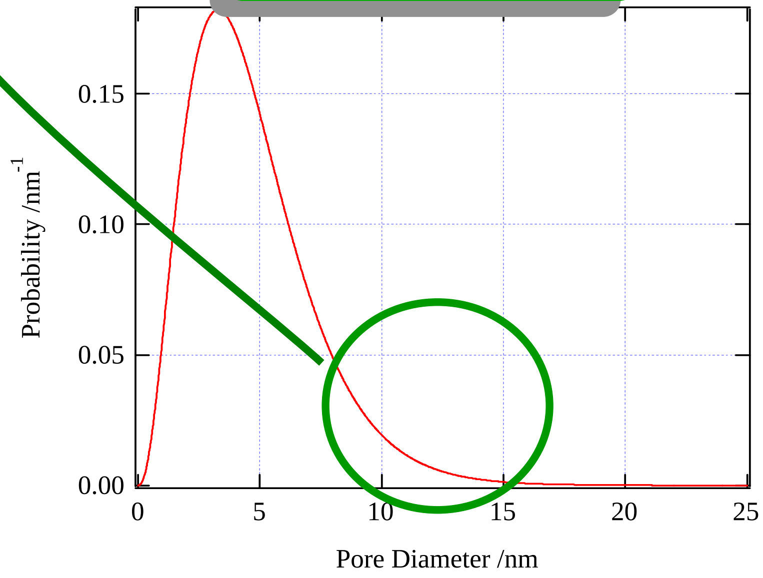
Average pore size ~ 2 to 8 nm (depending upon material

So we can think of a killer pore size ~ 5-10X average pore size

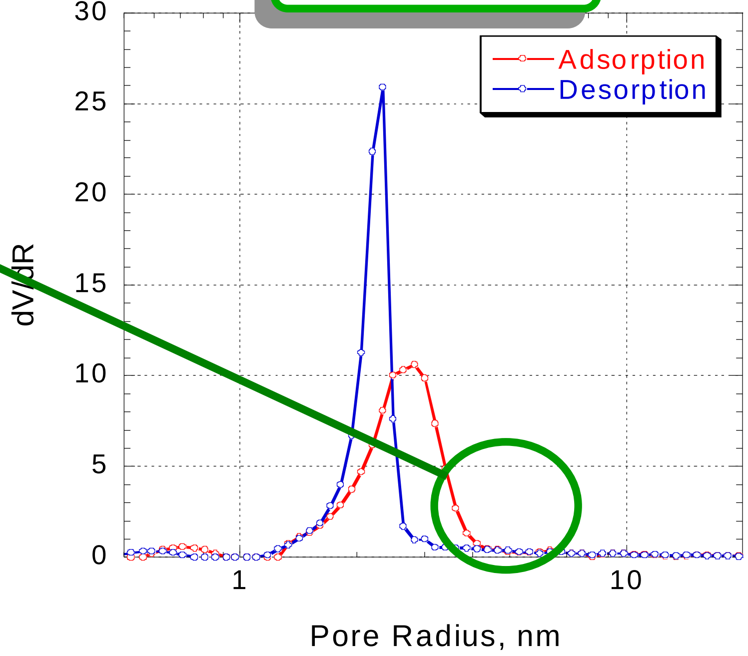
Killer pore detection

- Looking for a very small number of pores, >5-10X average pore size
- Killer pores not = tail or shoulder of a distribution

PSD from SAXS



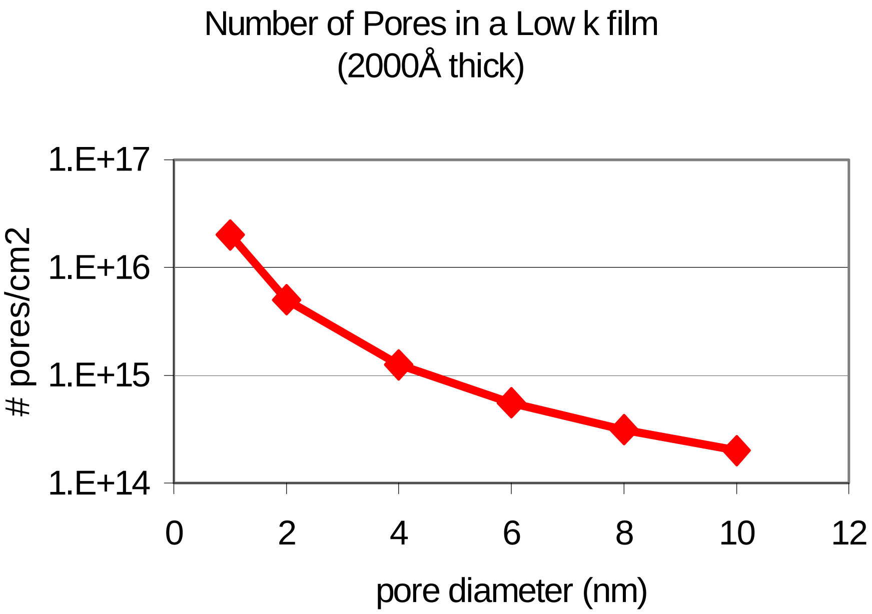
PSD from EP

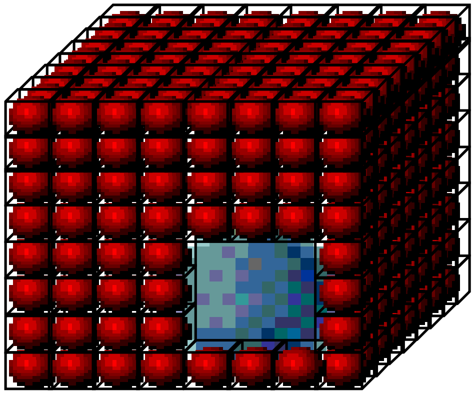


Killer pore detection

Production

- Let’s run the numbers
  - ~ 1E15 pores/cm^2 (per low k layer)
  - < 0.1 defect/cm^2 allowed (for all processing)
- Statistical approaches will not work





Need defect detection techniques that do <u>NOT</u> see average pores (signal to noise ratio)

<u>There is no clear solution available</u>

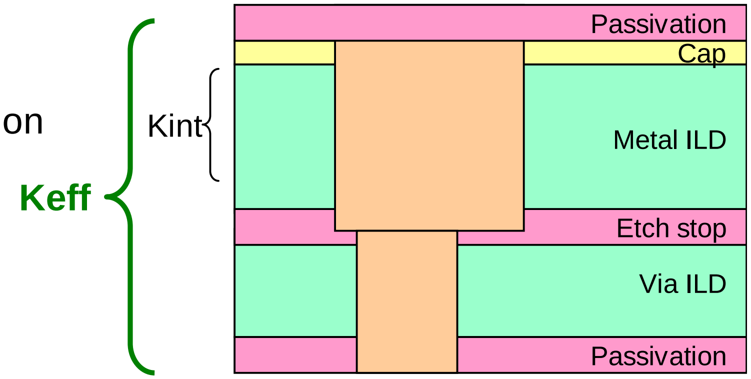
Outline

- Background
  - **Low k material & integration challenges**
- Metrology challenges
  - **Research, Development or Production need?**
- Mechanical properties
- Porosimetry (incl. killer pores)
- Dielectric Constant
- Summary

Dielectric Constant

- **We need to be careful when discussing k-value?**
  - Are we talking about as-deposited k, Keff, Kint, etc?
  - **As-deposited k value** - most often quoted by suppliers
    - does not include processing such as etch, ash, etc.
  - **Kint (integrated k value)**
    - typically means extracted k value of the film after integration
  - **Keff (effective k value)**
    - usually refers to the k value of the full stack, assuming a homogeneous film
    - function of (Kint)
    - **stronger** function of (thickness, cap, & passivation)
    - Downstream processing can have a significant effect
      - Etch, ash, cleans, ambient exposure, thermal cycling, etc
    - is the most important, but also the most misinterpreted representation on roadmaps

ILD stack is composed of many discrete layers



$$RC = \rho\varepsilon\frac{l^2}{td}$$

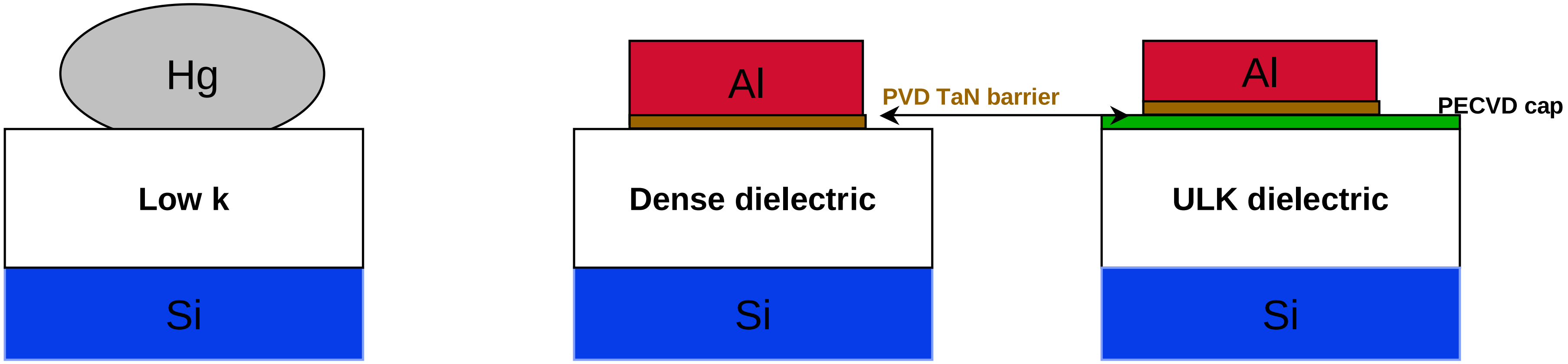
ρ = metal resistivity
ε = dielectric permitivity (k)
l = line length
t = dielectric thickness
d = line thickness

Hg probe & MISCAP

Hg probe
- k, C-V

Type 1
MISCAP
- k, C-V
- I-V, Vbd

Type 2
MISCAP
- k vs.. Chemical Compatibility
- I-V, Vbd
- PECVD cap required for Al etch, cleans



Hg probe - good for initial k estimate

questions about probe area (error on k value); can’t be used on product

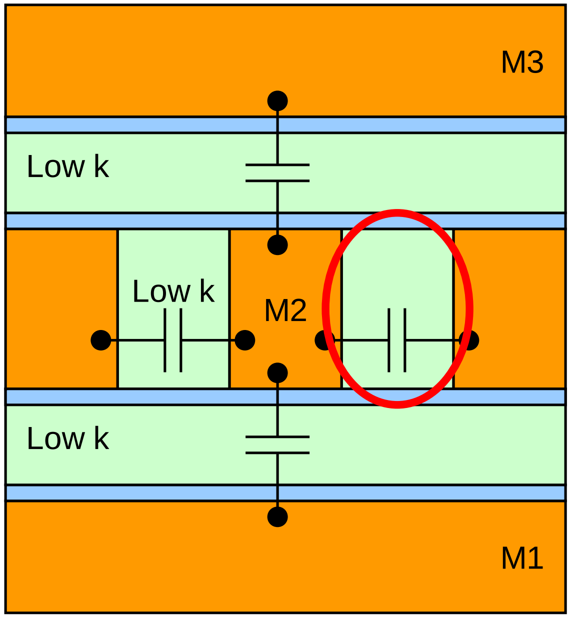
MISCAP

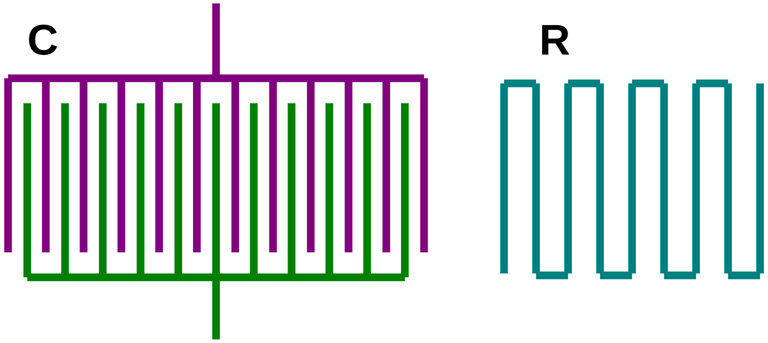
Good technique for measuring material properties -
considered more accurate than Hg probe

Requires electrode processing; can’t be used on product

Neither technique represents true low k processing

Modeled Effective Dielectric Constants





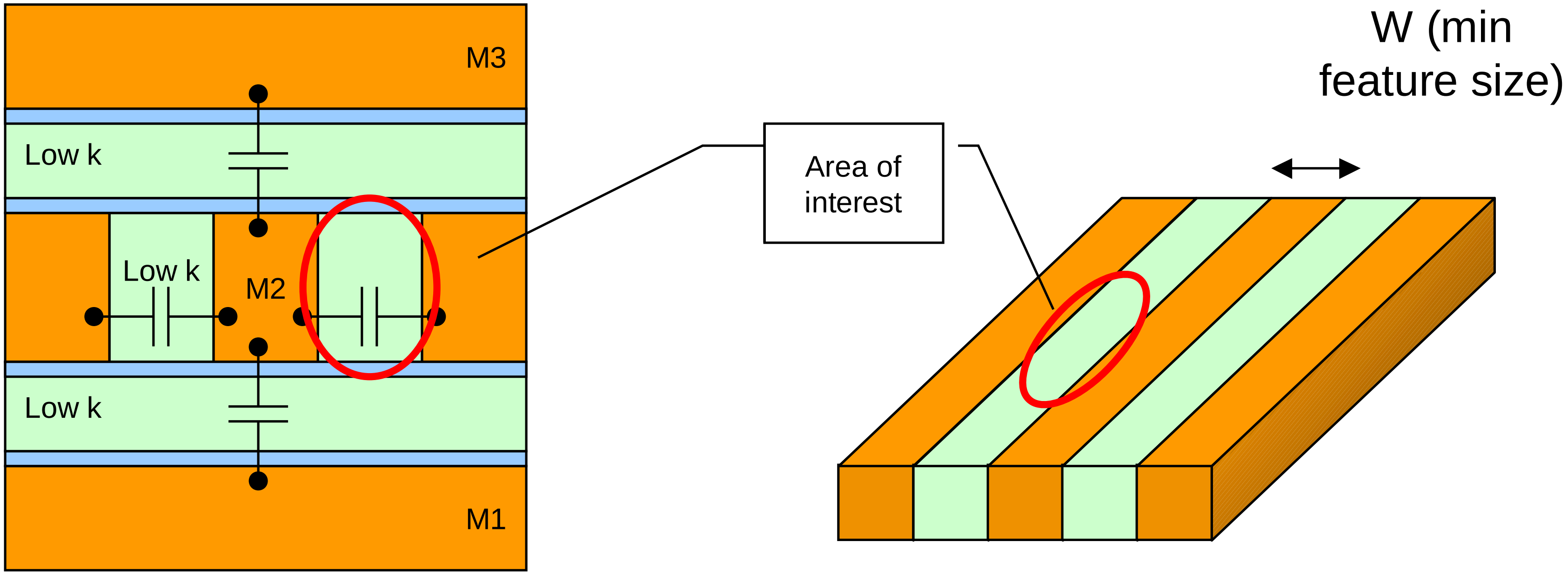
- **Comb/serp structure**
  - **Interdigitated comb structure for C**
  - **Long serpentine for R**

- **Comb/serp structure**
  - RC product commonly used for comparison - standard in-line parametric test
  - More representative of real processing

    but
  - Calculating k from R, C requires extensive cross sections/Raphael modeling
  - Data collection is not real time

Better techniques are desired

New techniques needed



- **Desired metrology**
  - Can be used on product wafers (non destructive, non-contaminating
  - Measure k between metal lines (needs to measure thickness and C)
    - May be ok to measure a larger area (& not fight the probe size vs. min. feature size battle)
  - Real time / rapid data collection and analysis

Several different new ideas are being evaluated
Too early to say which show promise

Outline

- Background
  - Low k material & integration challenges
- Metrology challenges
  - Research, Development or Production need?
- Mechanical properties
- Porosimetry
- Dielectric Constant
- Defect Metrology
- Summary

Summary

- Porous low k materials present unique integration (and therefore metrology) challenges
- Research, Development, or Production
  - The needs are different (niche vs. large volume markets)
- Mechanical Properties
  - The old standby (nanoindentation) widely used
  - Scientific community would prefer more “accurate” measurement
- Porosimetry
  - Promising techniques emerging for pore size distribution
- Killer Pores
  - No known solutions for detecting “needle in the haystack”
- Dielectric Constant
  - Opportunity for new ideas

Poster Papers of Particular Interest

WE-02 - Low-k Dielectric Characterization by Infrared Spectroscopic Ellipsometry P. Boher et. al. SOPRA, Bois Colombes, France

WE-03 - Advances in X-Ray Reflectivity (XRR) and X-Ray Fluorescence (XRF) Measurements Provide Unique Advantages for Semiconductor Applications J. Spear, Technos International, Tempe, Arizona

WE-05 - Pore Size Distribution Measurement of Porous Low-k Dielectrics Using TR-SAXS S. Terada, T. Kinashi, and J. Spear, TECHNOS Co., Ltd., Osaka, Japan

WE-08 - Materials Characterization and the Formation of Nanoporous PMSSQ Low-k Dielectric P. Lazzeri, L. Vanzetti, E. Iacob, M. Bersani, and M. Anderle, ITC-irst, Povo, Italy; J. J. Park, Z. Lin, R. M. Briber, and G. W. Rubloff, University of Maryland, College Park, Maryland; and R. D. Miller, IBM Almaden Research Center, San Jose, California

WE-16 - Determination of Pore-Size Distributions in Low-k Dielectric Films by Transmission Electron Microscopy B. Foran and B. Kastenmeier, International SEMATECH, Austin, Texas; and D. S. Bright, NIST, Gaithersburg, Maryland

WE-19 - Porosity Characterization of Porous SiLK Low-k Dielectric Films C. E. Mohler, B. G. Landes, G. F. Meyers, B. J. Kern, and K. B. Ouellette, The Dow Chemical Company, Midland, Michigan

WE-28 - Small Angle Neutron Scattering Characterization of Nanoporous Low k Dielectric Constant Thin Films B. J. Bauer, H. Lee, R. C. Hedden, C. L. Soles, D. Liu, and W. Wu, NIST, Gaithersburg, Maryland

WE-30 - Characterization of Porous, Low-k Dielectric Thin-Films Using X-ray Reflectivity M. Wormington, Bede Scientific Incorporated, Englewood, Colorado

WE-36 - Measurement of the Structural Evolution of Pore Formation in SiLKTM Low-k Dielectric Thin Films M. S. Silverstein, Israel Institute of Technology, Haifa, Israel; B. J. Bauer, H.-J. Lee, and R. C. Hedden, NIST, Gaithersburg, Maryland; and B. Landes, J. Lyons, B. Kern, J. Niu, and T. Kalantar, Dow Chemical Company, Midland, Michigan

WE-37 - X-ray Porosimetry as a Metrology to Characterize the Pore Structure in Low-k Dielectric Films C. L. Soles, H.-J. Lee, D.-W. Liu, R. C. Hedden, B. J. Bauer, W.-l. Wu, and E. K. Lin, NIST, Gaithersburg, Maryland