Overview of Optical Metrology of Advanced Semiconductor Materials

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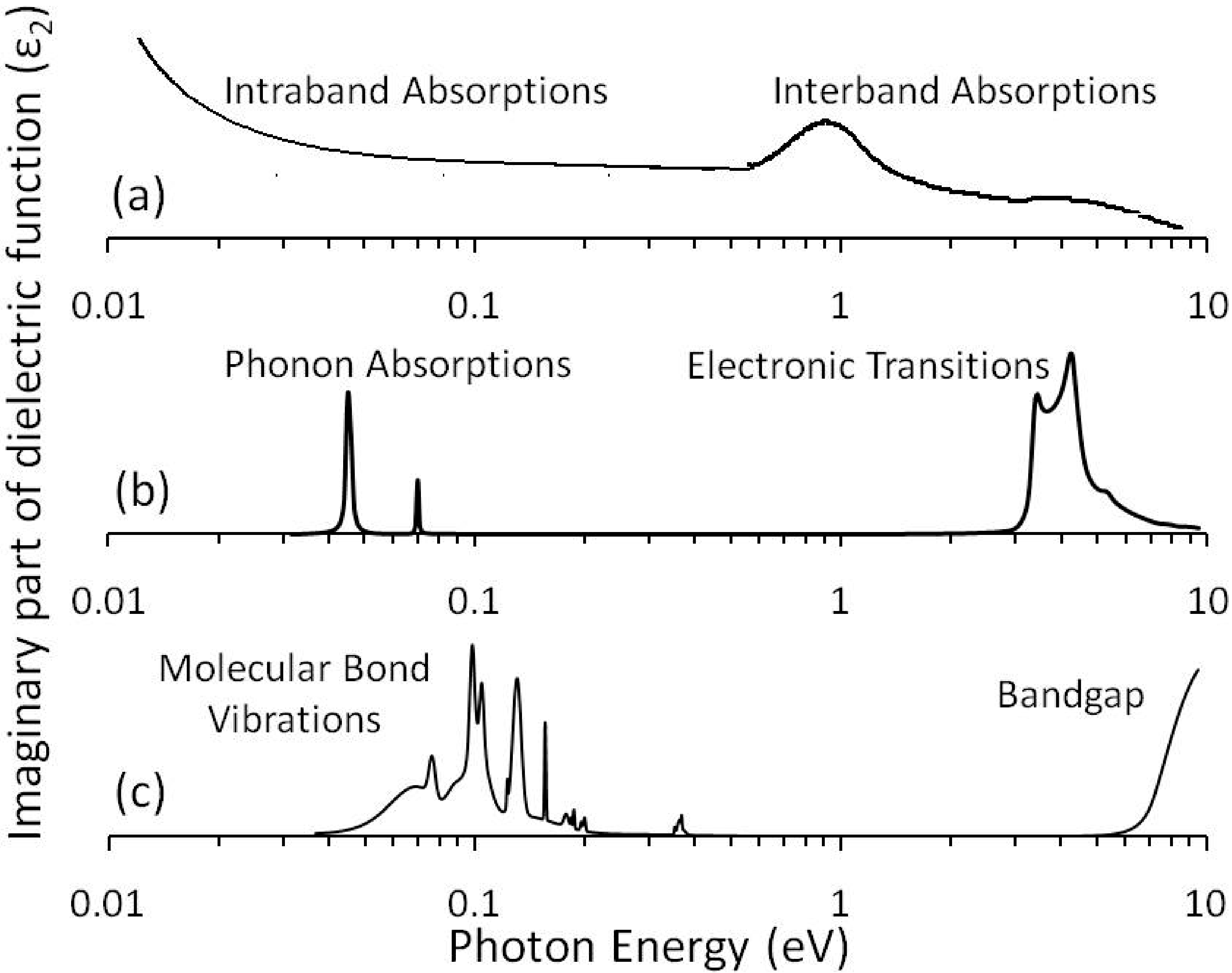
Outline

- Linear Optical Response of Materials
- Spectroscopic Ellipsometry
- Advanced Materials in the Semiconductor Industry
- Photoreflectance
- Photoluminescence
- Conclusions
- Acknowledgements

Linear Optical Response of Materials



Metals

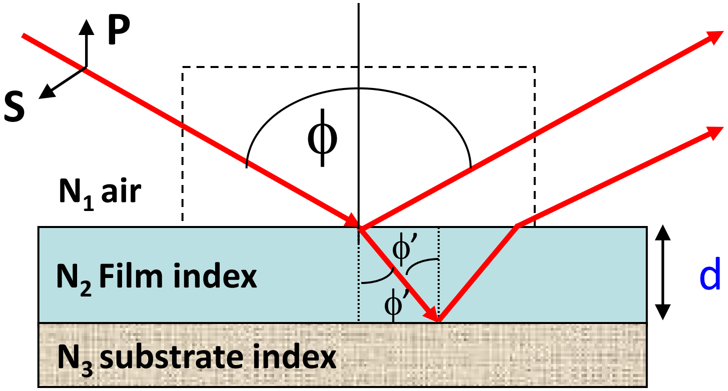
Semiconductors

Dielectrics

Spectroscopic Ellipsometry

Spectroscopic Ellipsometry: Light polarized in plane of reflection reflects differently than light polarized perpendicular to plane of reflection.

Reflection of Polarized Light



$$\beta = 2\pi(d/\lambda)N_2\cos\phi'$$

Fresnel Reflection Coefficients different for S and P polarizations

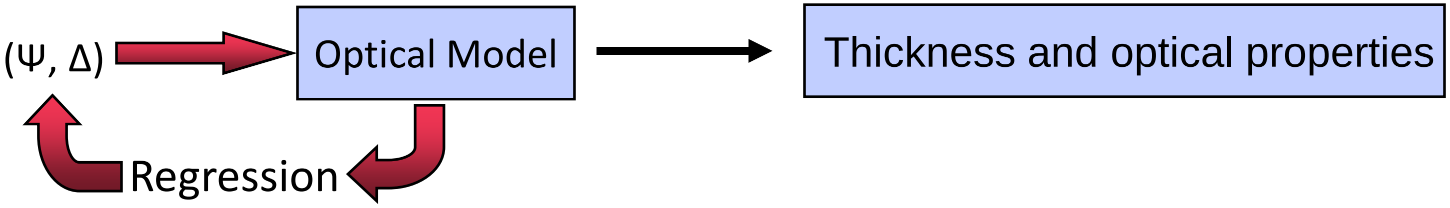
$$r_{12}^{P} = \frac{N_2\cos\phi - N_1\cos\phi'}{N_2\cos\phi + N_1\cos\phi'} \qquad r_{12}^{S} = \frac{N_1\cos\phi - N_2\cos\phi'}{N_2\cos\phi + N_1\cos\phi'}$$

$$R^{P} = \frac{r_{12}^{P} + r_{23}^{P}e^{-i2\beta}}{1 + r_{12}^{P}r_{23}^{P}e^{-i2\beta}} \qquad R^{S} = \frac{r_{12}^{S} + r_{23}^{S}e^{-i2\beta}}{1 + r_{12}^{S}r_{23}^{S}e^{-i2\beta}}$$

$$\boxed{\tan\Psi e^{i\Delta} = \frac{R^{P}}{R^{S}}} \qquad \boxed{\Psi = \tan^{-1}\left(\frac{|R^{P}|}{|R^{S}|}\right), \Delta = \delta_i - \delta_r}$$

P designation used for light polarized in plane of reflection (parallel)
S designation for light perpendicular to plane of reflection (senkrecht)

Spectroscopic Ellipsometry



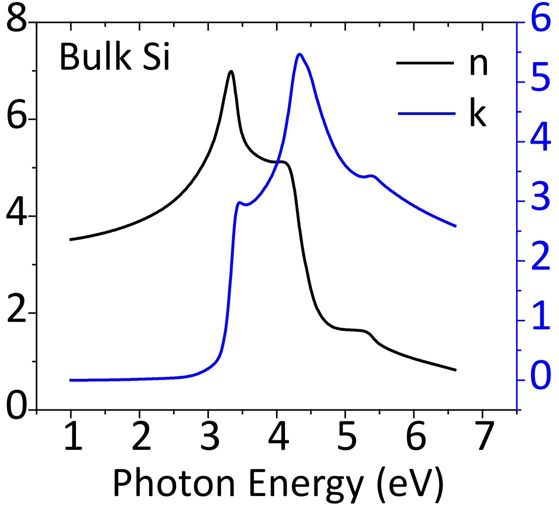
(Ψ, Δ) → **Optical Model** → **Thickness and optical properties**

Regression

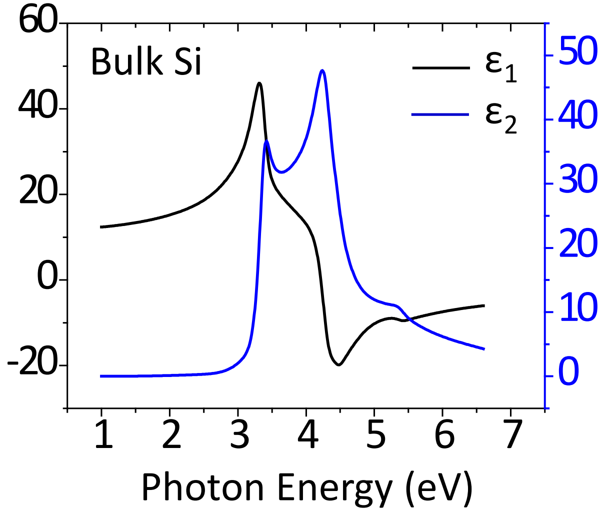
$$\boxed{\tilde{\varepsilon} = \varepsilon_1 + i\varepsilon_2 = (\tilde{N})^2 = (n+ik)^2 = (n^2 - k^2) + 2ink}$$

$$\boxed{\alpha = \frac{4\pi k}{\lambda}}$$

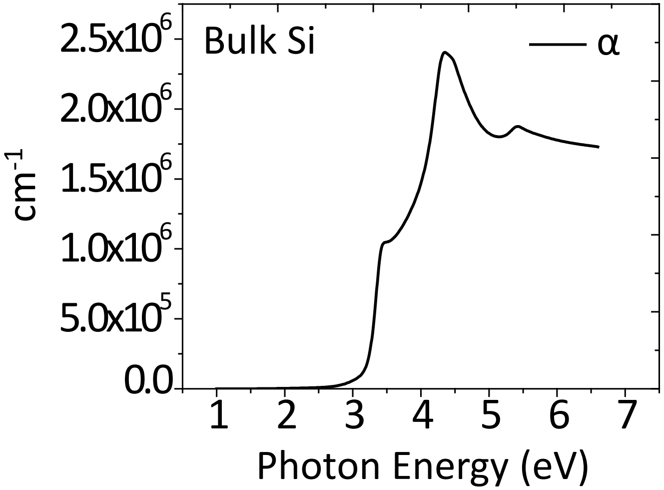
Refractive Index



Dielectric Function

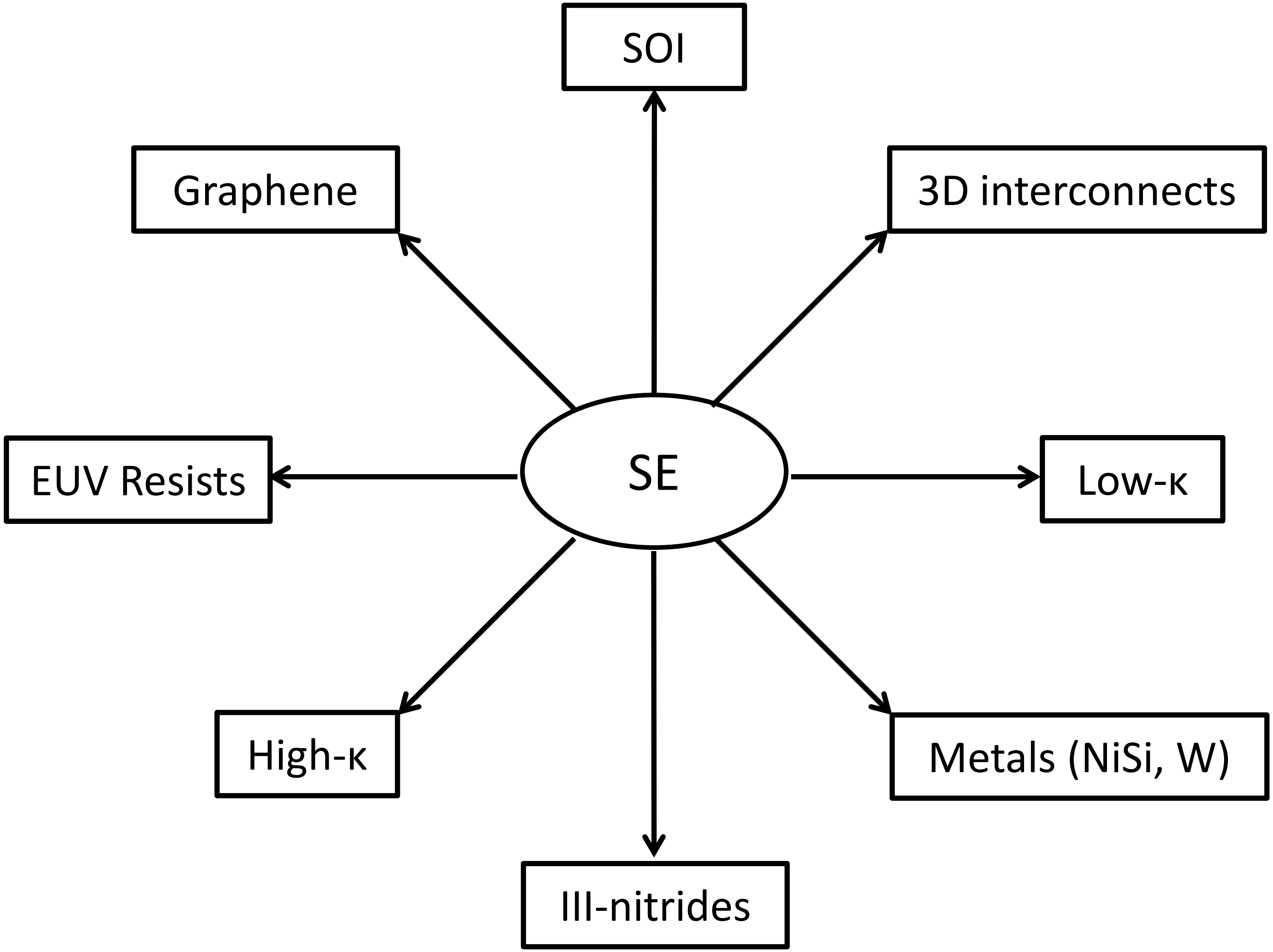


Absorption Coefficient

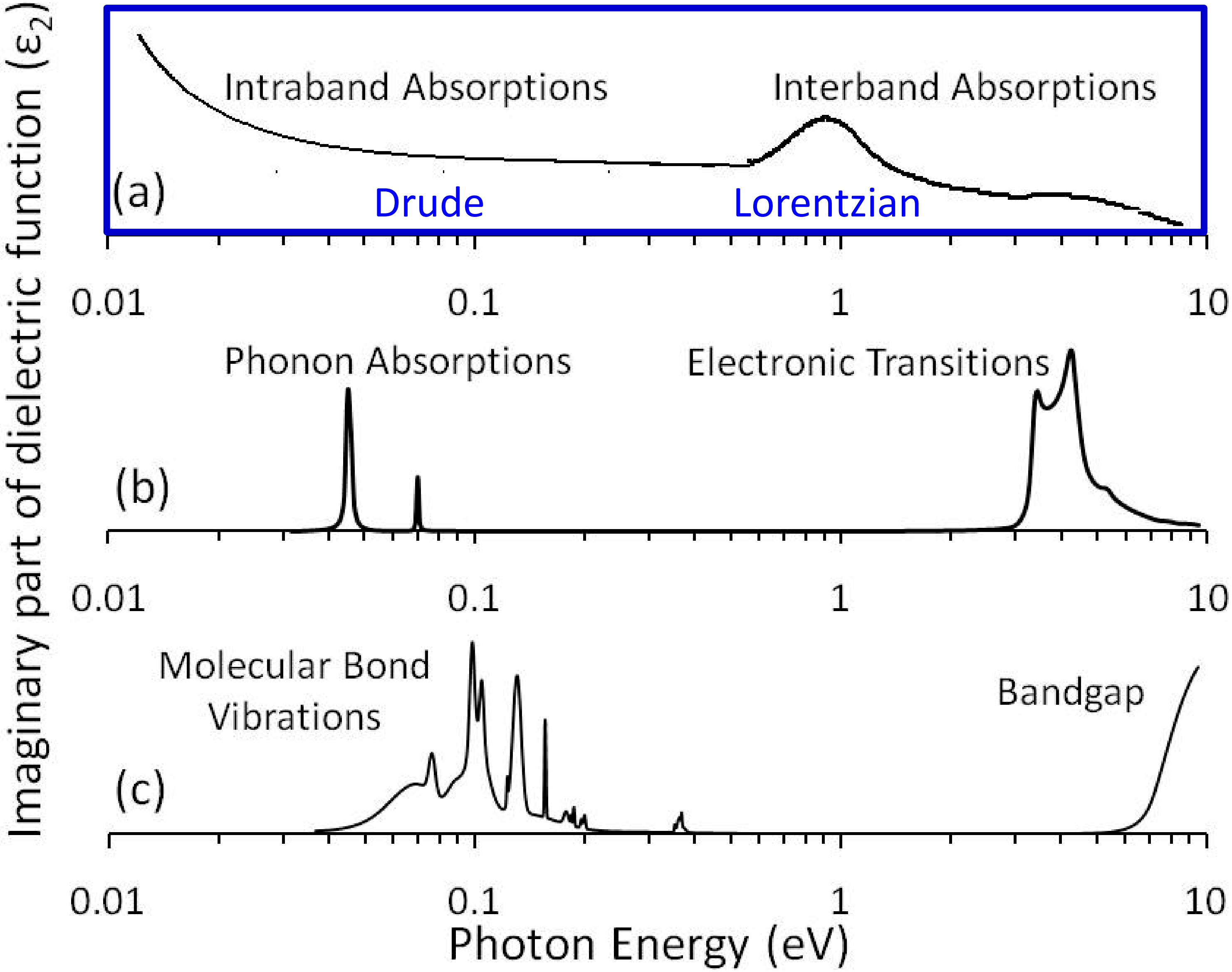


Ψ - amplitude ratio, Δ – phase difference, R– Fresnel reflection coefficient , n - real part of the refractive index, k – extinction coefficient, ε_1 – real part of the dielectric function, ε_2 – imaginary part of the dielectric function, α – absorption coefficient, λ – wavelength of light.

Advanced Materials in the Semiconductor Industry



Linear Optical Response of Materials



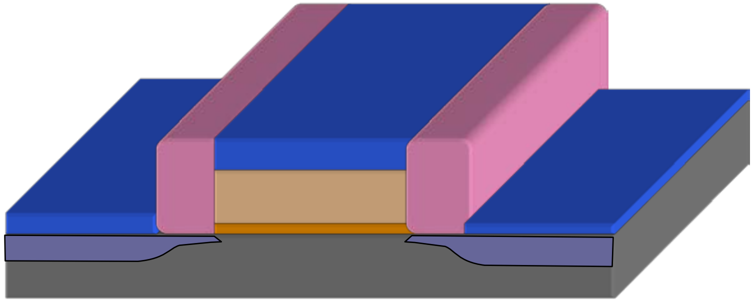
Metals

Semiconductors

Dielectrics

Thin Metal Films

Optical Metrology of thin metal films (Ni, NiSi, TiN and W)



- Poly-Si Gate Electrode
- Thermal SiO_2
- Nitride Spacer
- Nickel Silicide
- N^+ Doped Silicon Source Drain
- P well

V.K. Kamineni, M. Raymond, E.J. Bersch, B.B. Doris, and A.C. Diebold, Journal of Applied Physics, 107 (2010) 093525.

SE Methods & Limitations

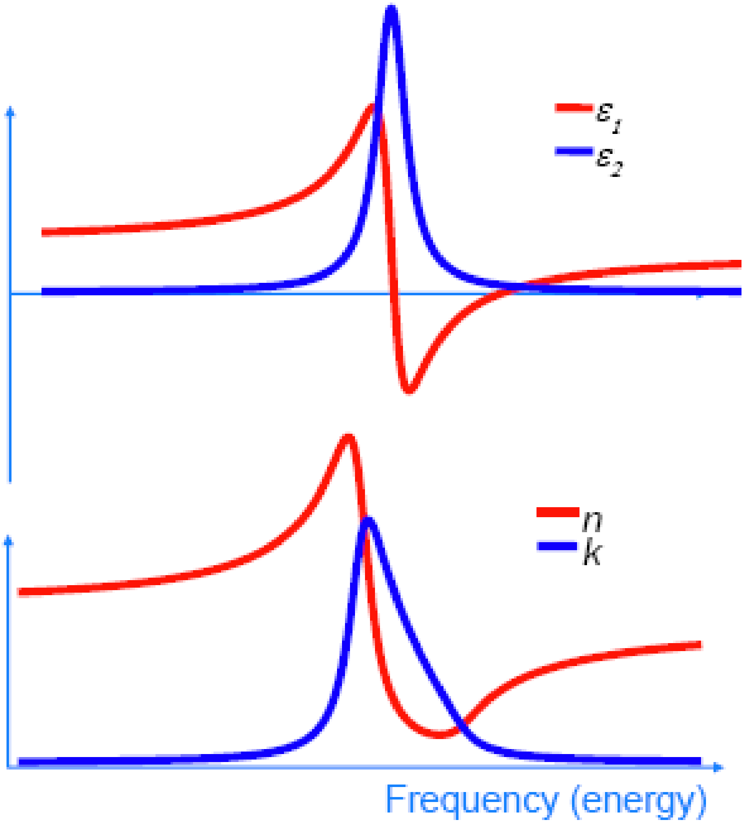
VUV VASE ⇒ $\frac{r_p}{r_s} = (\tan \psi) e^{i\Delta}$ ⇒ Ψ & Δ ⇒ *n, k & t*

✓ Transparent

✓ Semi-absorbing film

x Absorbing

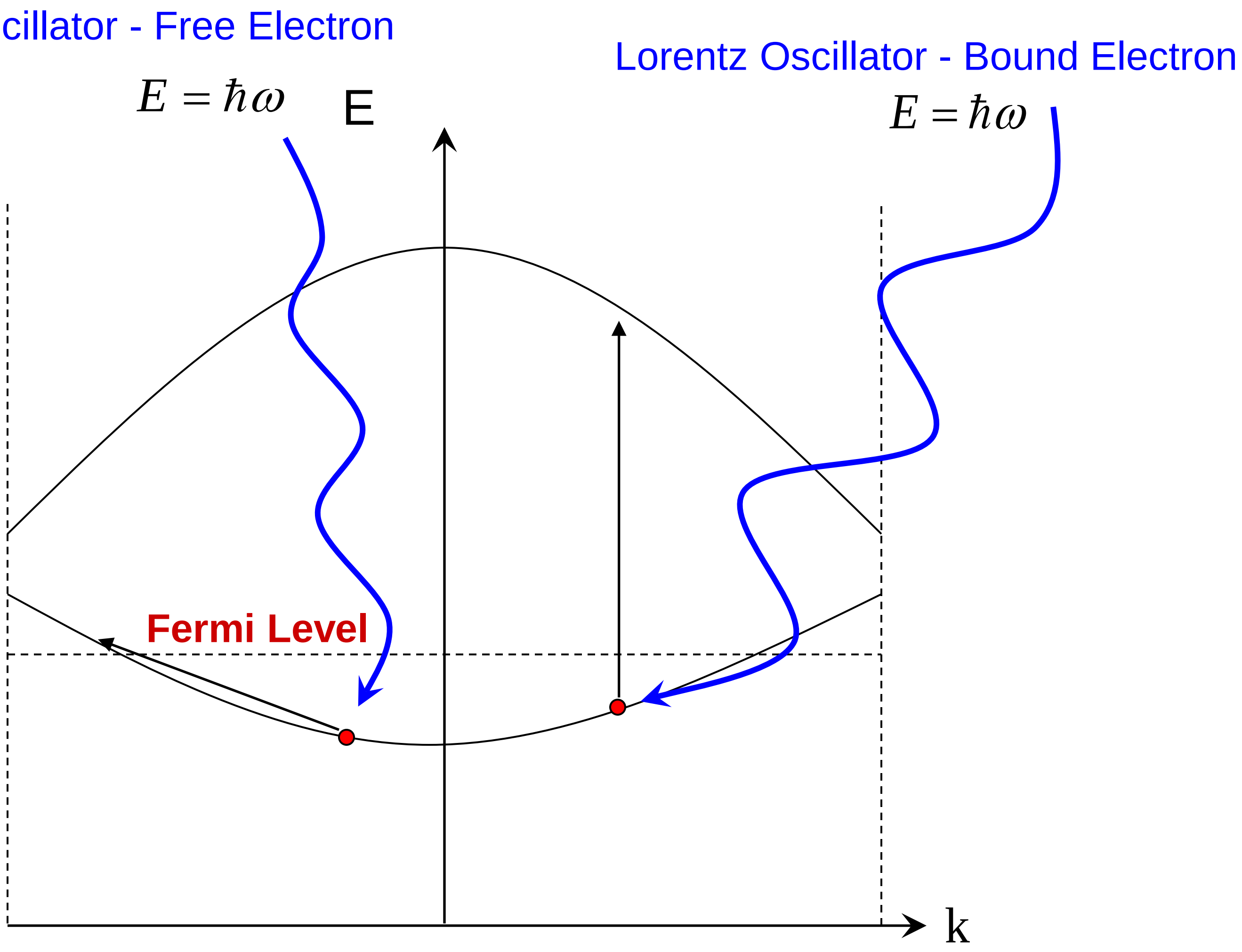
- Interference enhancements measurements (angle)
- Transmission intensity
- *In situ* measurements
- Optical constant parameterization



ñ = n - ik ⇒ *Kramers-Kronig Consistency*

$$\varepsilon_1 + i\varepsilon_2 = (n - ik)^2$$

Background



$$\varepsilon_1 = \varepsilon_1^f + \varepsilon_1^b$$

$$\varepsilon_2 = \varepsilon_2^f + \varepsilon_2^b$$

Thickness Dependent Optical Properties

Optical model for metals

$$\boxed{\varepsilon_1 = \varepsilon_\infty + \omega_{pb}^2 \frac{\tau_b{}^2(\omega_o^2 - \omega^2)}{\tau_b{}^2(\omega_o^2 - \omega^2)^2 + \omega^2} - \omega_{pf}^2 \frac{\tau_f{}^2}{\tau_f{}^2\omega^2 + 1}}$$

$$\boxed{\varepsilon_2 = \varepsilon_\infty + \omega_{pb}^2 \frac{\tau_b\omega}{\tau_b{}^2(\omega_o^2 - \omega^2)^2 + \omega^2} + \omega_{pf}^2 \frac{\tau_f}{\omega(\tau_f{}^2\omega^2 + 1)}}$$

From Ellipsometry you can extract τ_f

Mayadas and Shatzkes -

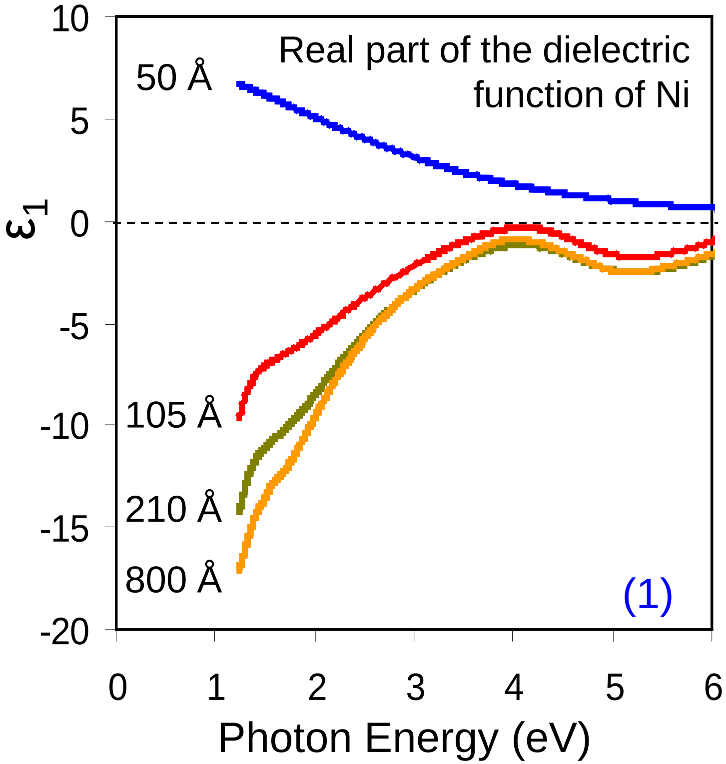
$$\frac{1}{\tau_f} = \frac{1}{\boxed{\tau_{bulk}}} + \frac{\boxed{v_F}}{\lambda} \Longrightarrow \lambda = \left[\frac{2(1-\Re)}{3\Re}\right] R_g$$

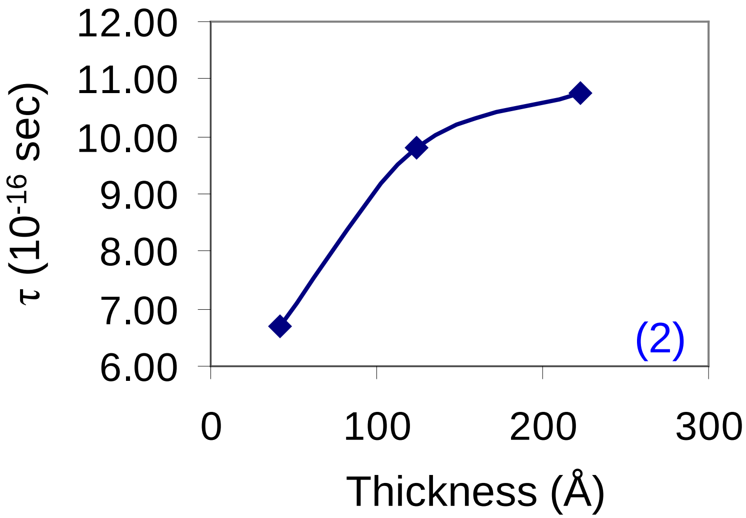
S. Marsillac, N. Barreau, H. Khatri, J. Li, D. Sainju, A. Parikh, N.J. Podraza, and R.W. Collins, *physica status solidi (c)* 5, 1244-1248 (2008).

Results and Discussion

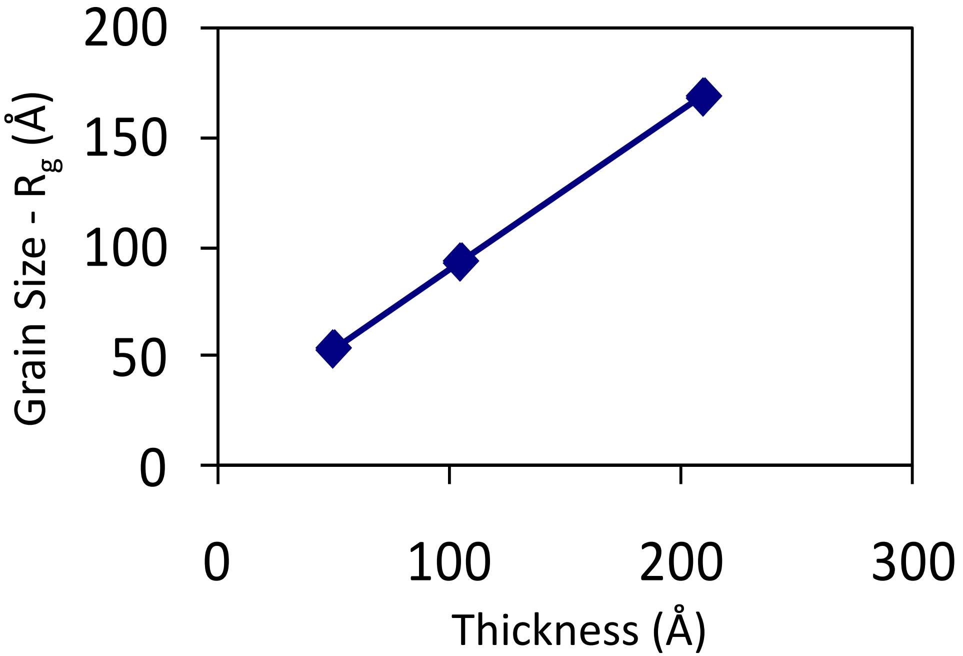
Mayadas and Shatzkes

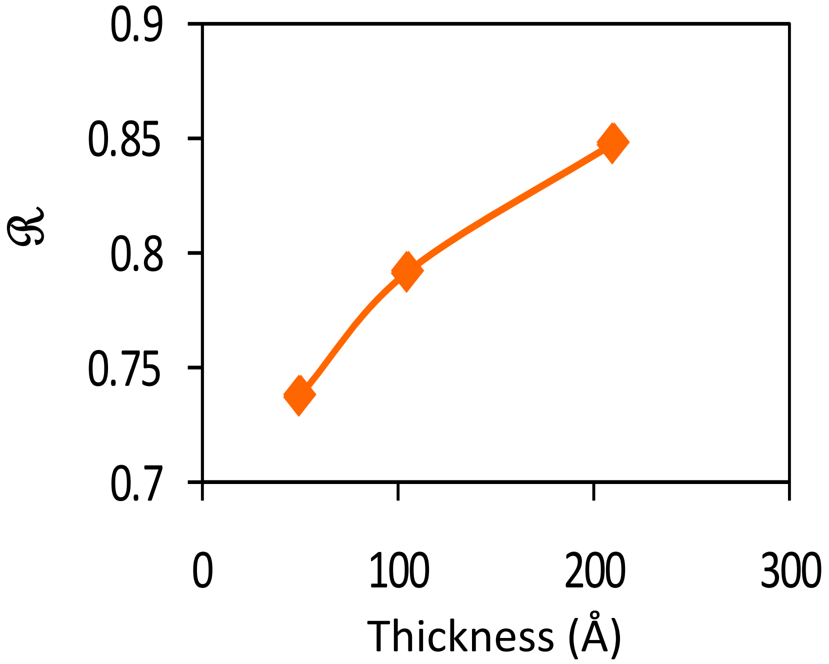
$$\frac{1}{\tau_f} = \frac{1}{\tau_{bulk}} + \frac{v_F}{\lambda} \qquad \lambda = \left[\frac{2(1-\Re)}{3\Re}\right] R_g$$





Results and Discussion

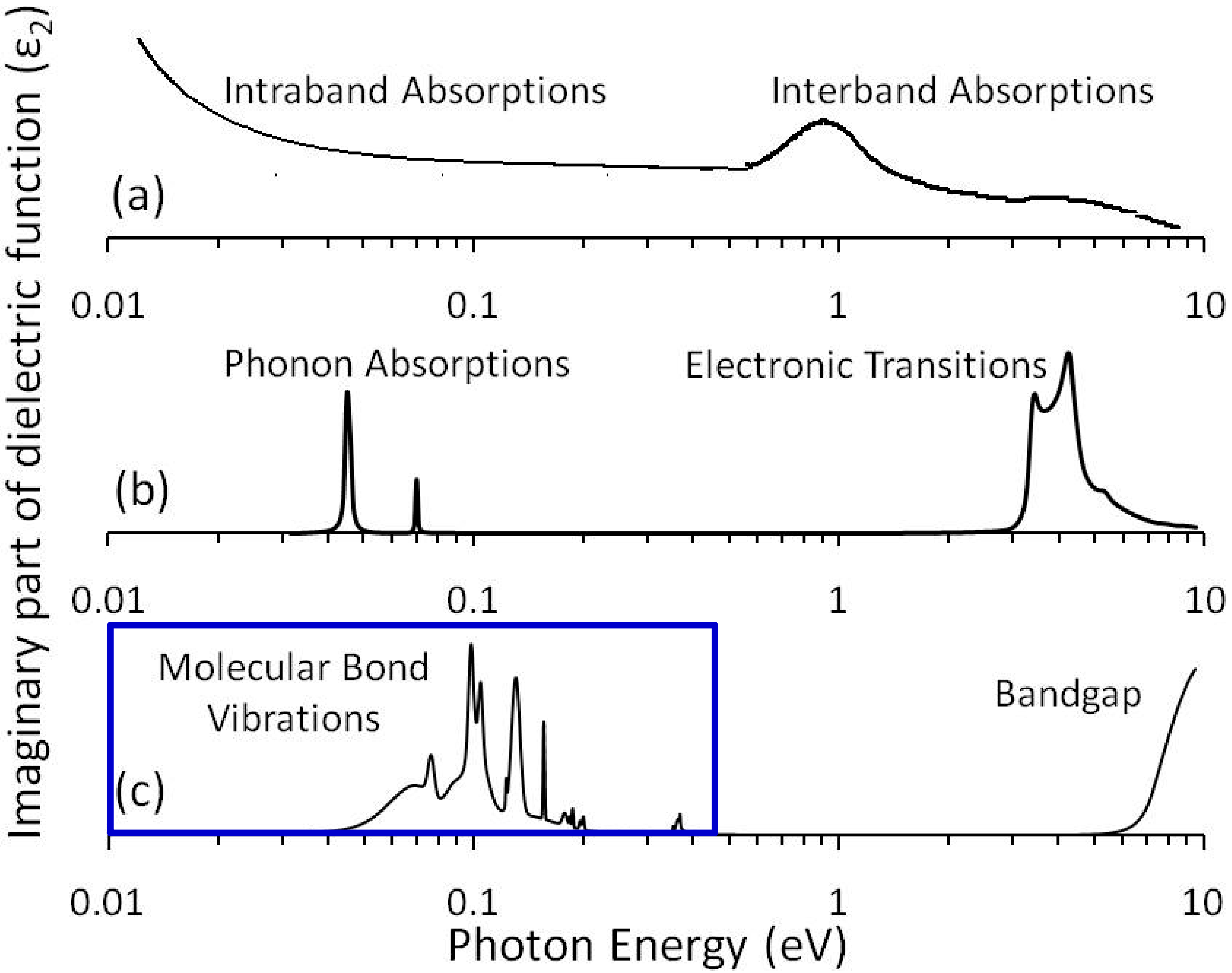




Conclusions

1. An Optical model was developed to determine the thickness of thin metal films.
2. Model was built to show that the thickness-dependent optical properties of thin metal films are correlated to the change in Drude free electron relaxation time.
3. The change in free electron relaxation time was traced to the change in grain boundary reflection coefficient and grain size.

Linear Optical Response of Materials



Metals

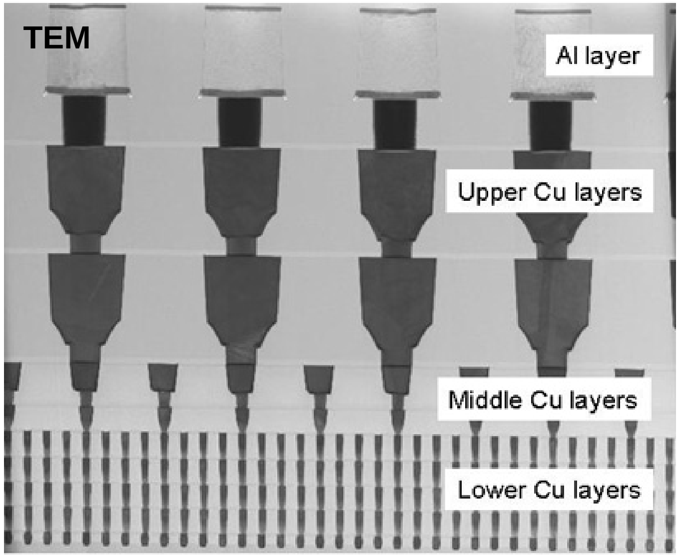
Semiconductors

Dielectrics

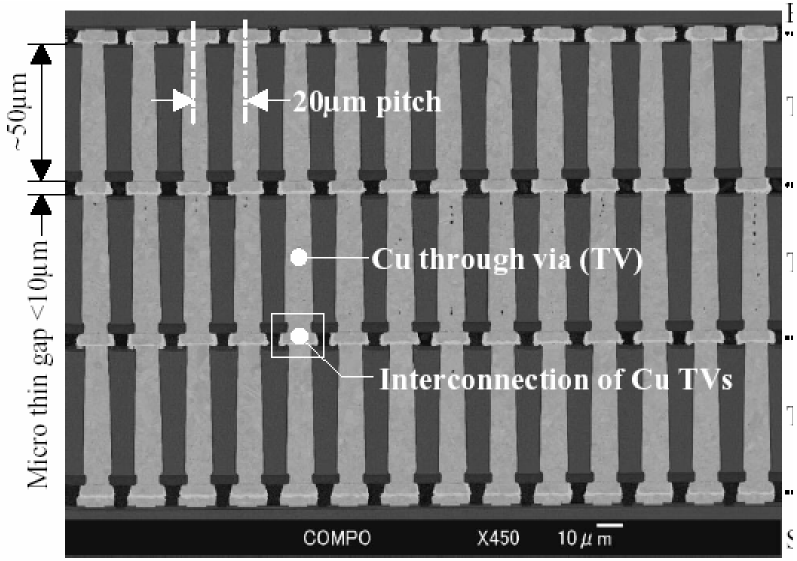
3D Interconnects (Benzocyclobutene)

Investigation of Optical Properties of BCB Wafer Bonding Layer used for 3D Interconnects via Infrared Spectroscopic Ellipsometry

2D Interconnects – 45 nm node



3D Interconnects – TSV



V.K. Kamineni, P. Singh, L.-W. Kong, J. Hudnall, J. Qureshi, C. Taylor, A. Rudack, S. Arkalgud, and A.C. Diebold, Thin Solid Films, 519 (2011) 2924.

P. Singh, J. Hudnall, J. Qureshi, V.K. Kamineni, C. Taylor, A. Rudack, A. Diebold and S. Arkalgud, Mater. Res. Soc. Symp. Proc., 1249 (2010) 309.

[1] Fujitsu Sci. Tech. J., Vol. 46, No.1

[4] ASM International

Why 3D Interconnects?

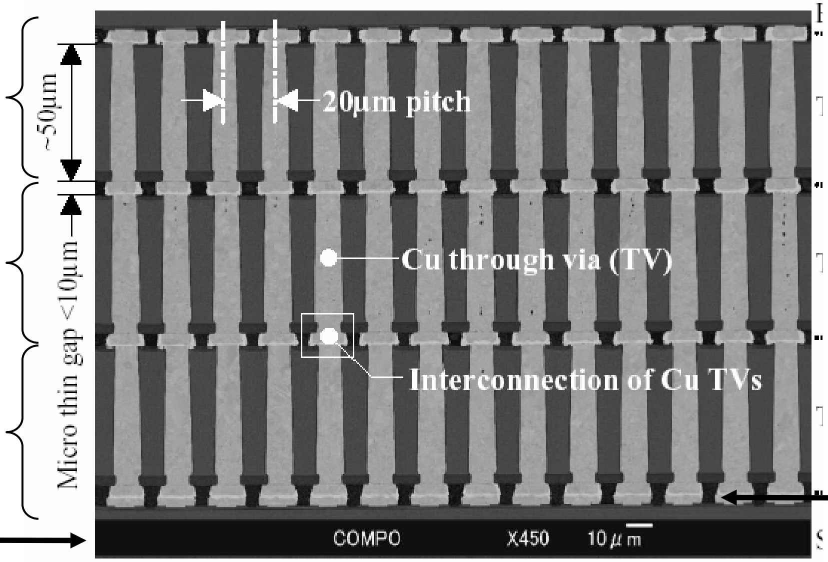
- Replacing long horizontal lines with short vertical interconnects
  - Addresses RC delay, crosstalk and power consumption
- Enables integration of heterogeneous devices & technologies (memory, logic, RF, analog, sensors)
  - Enables new functionalities
  - Cost reduction compared to SoC

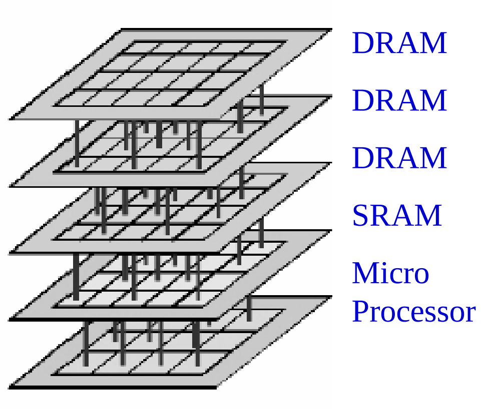
3rd Level (thinned substrate)

2nd Level (thinned substrate)

1st Level after backgrinding

Device layer / IMD





BCB (Benzocyclobutene)

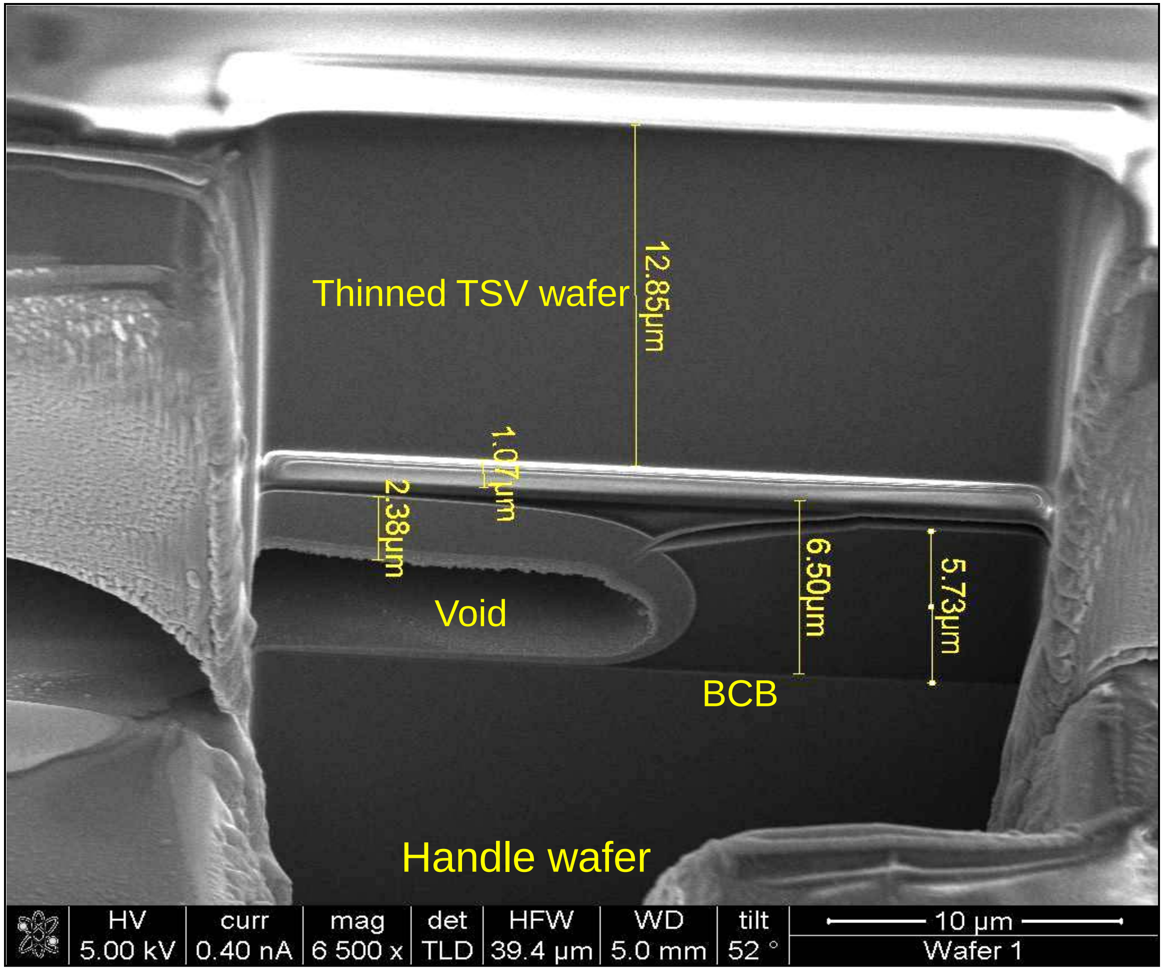
Bonding Layer

Substrate

[4]ASM International

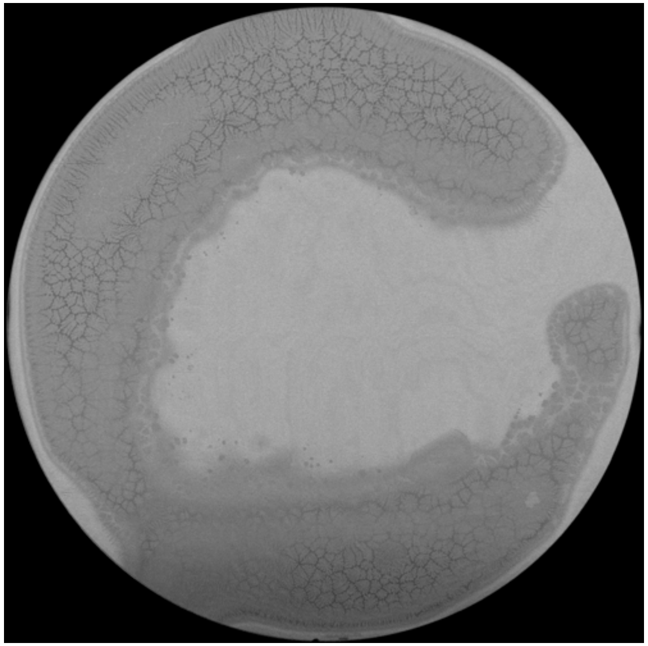
Integration Issues

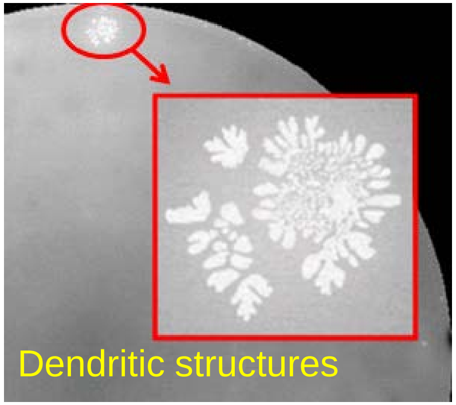
Top wafer peeling due to air pockets in the BCB film



SEM cross-section image

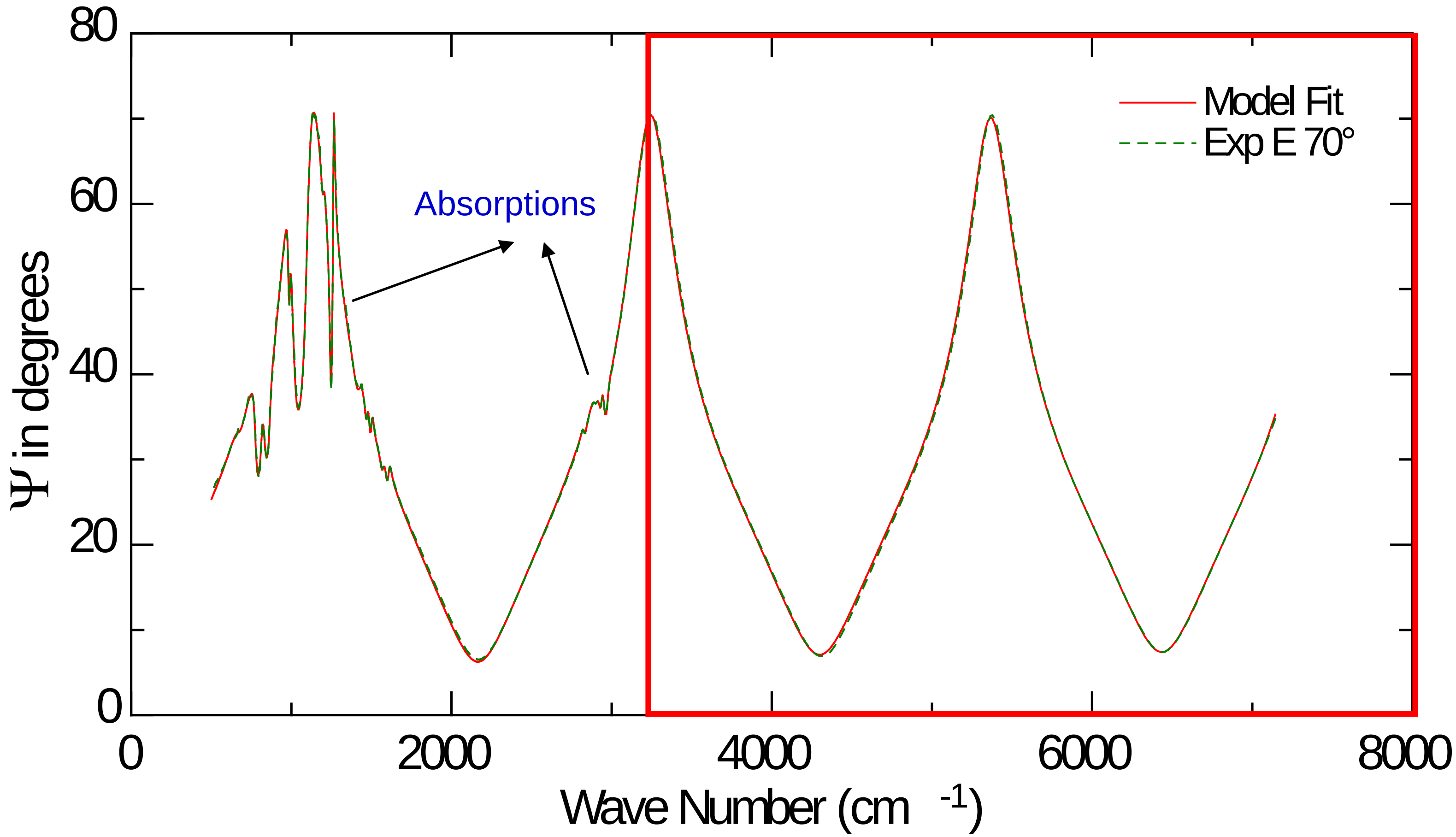
37% cross-linked BCB bond





SAM image

IR Semi-absorbing Film on a Transparent Substrate

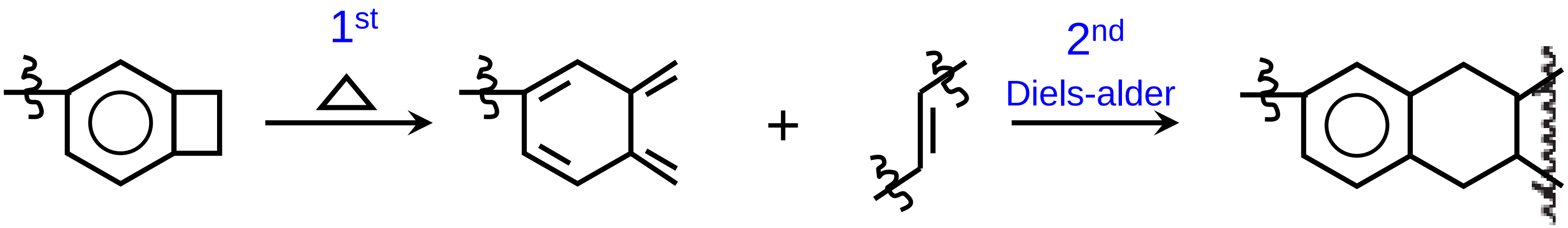


$(\Psi,\Delta)\rightarrow(n,t)$ when $k = 0 \Rightarrow$ in a transparent region and determining thickness

Transparent Region ☐

$t \Rightarrow (\Psi,\Delta)\rightarrow(n,k)$ in the entire spectrum

IRSE Absorption Spectra of BCB



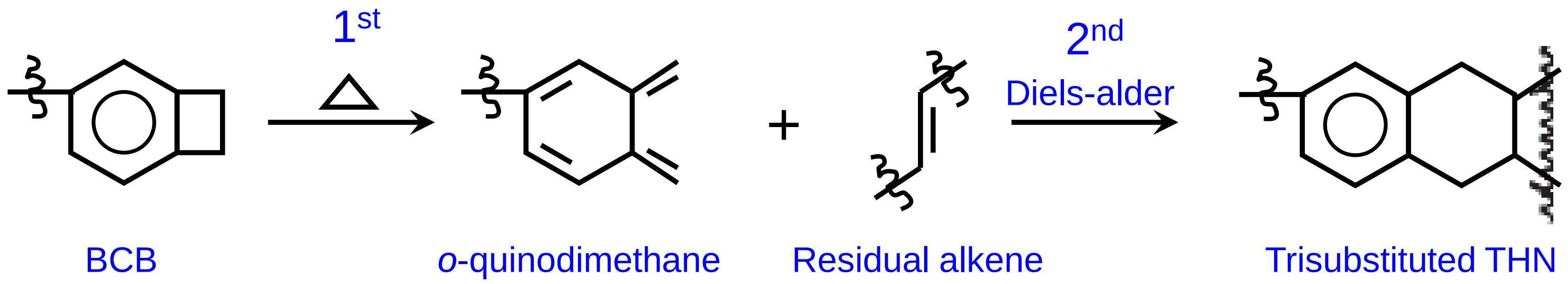
The thermal curing of BCB polymers is a two step process:

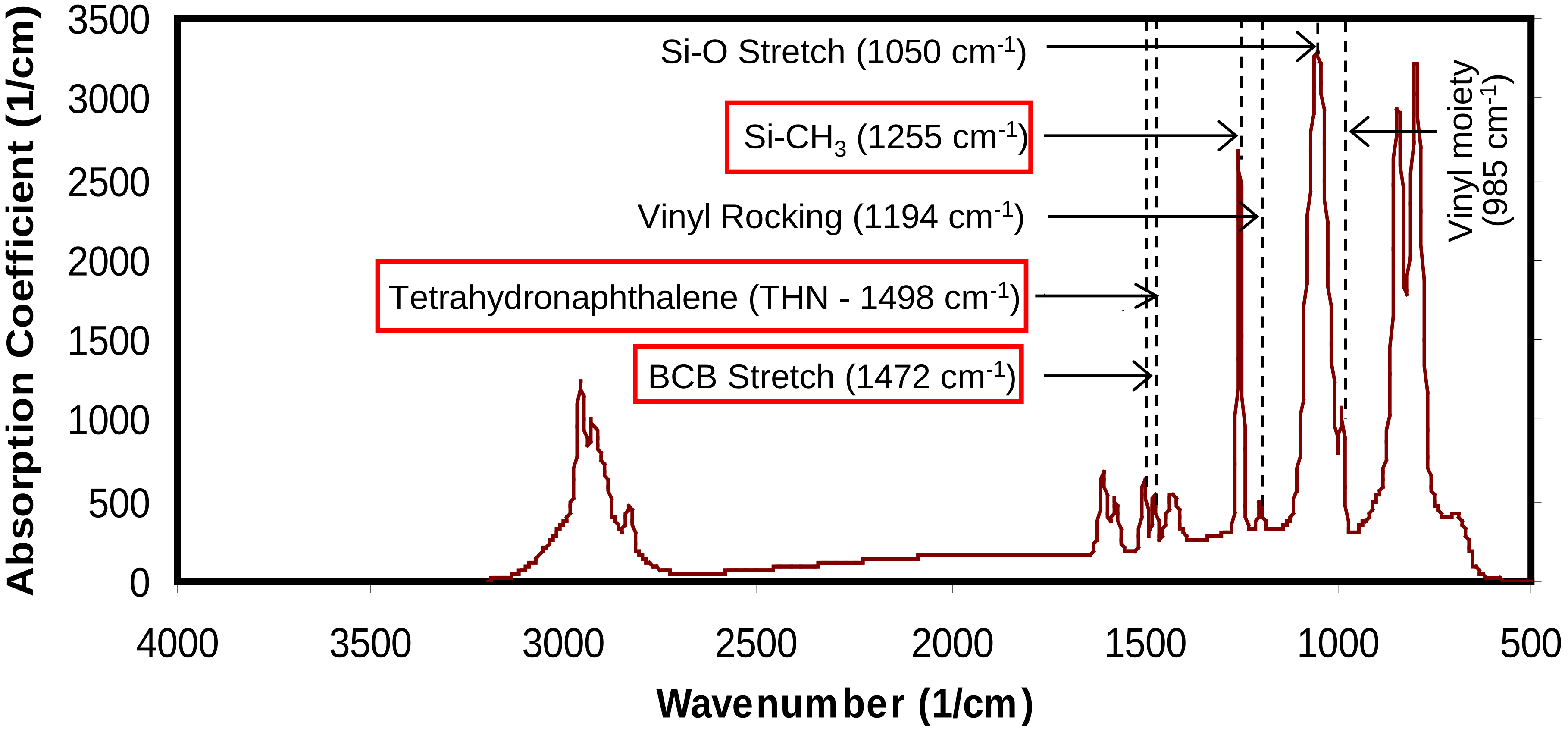
1. Thermally activated opening of the BCB ring to form an o-quinodimethane intermediate.

2. The o-quinodimethane reacts with residual alkene groups in the via a Diels-Alder reaction, forming a tri-substituted tetrahydronaphthalene (THN).

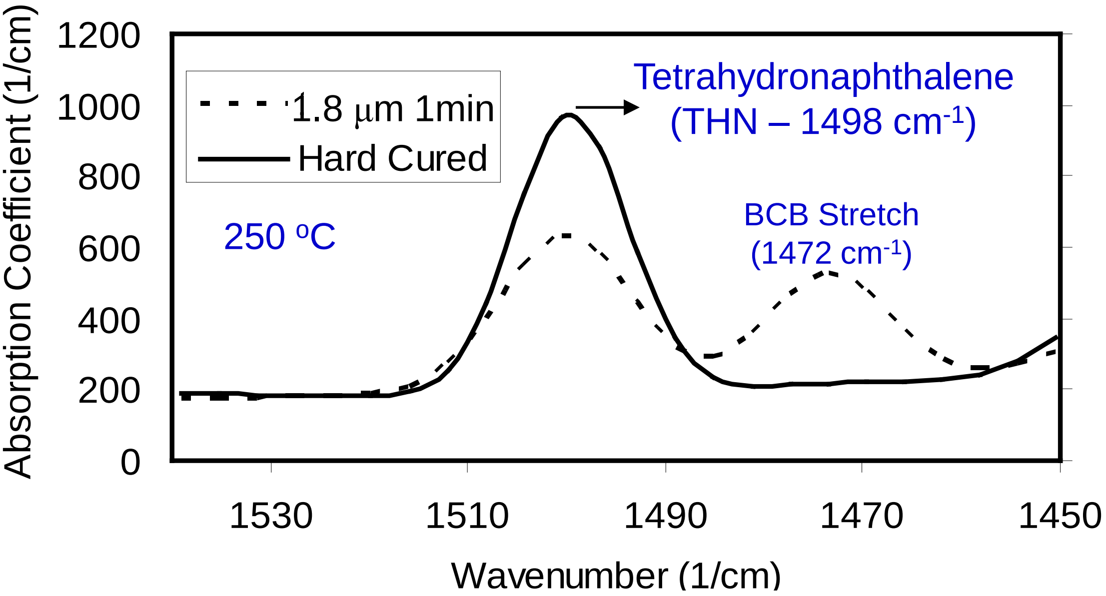
Dow Chemicals: Cyclotene

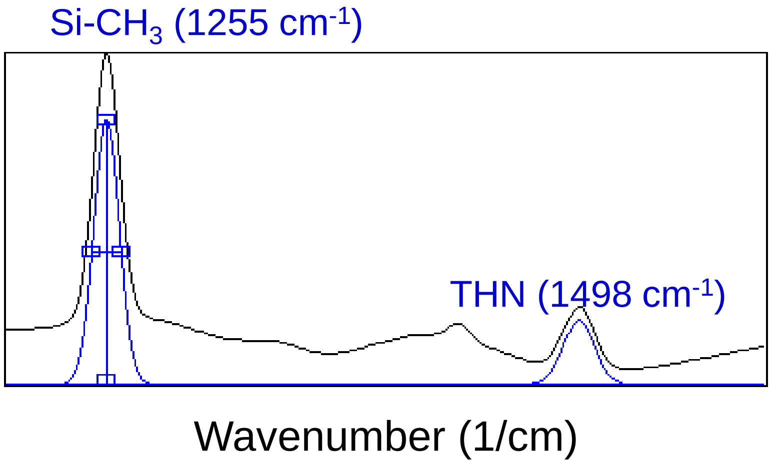
IRSE Absorption Spectra of BCB





IRSE Percentage Cure



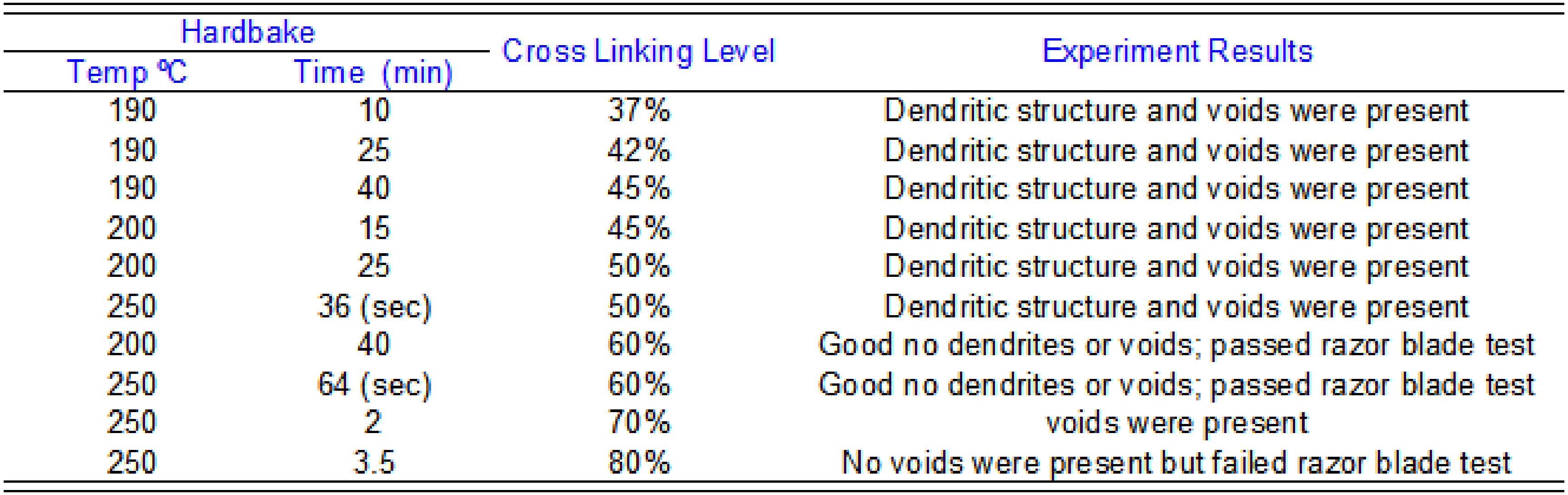


Film of interest

$$\% \text{ curing} = 95\,\frac{\left(A_{1498}/A_{1255}\right)}{\left(A_{1498}/A_{1255}\right)_{\text{Hardcured}}}$$

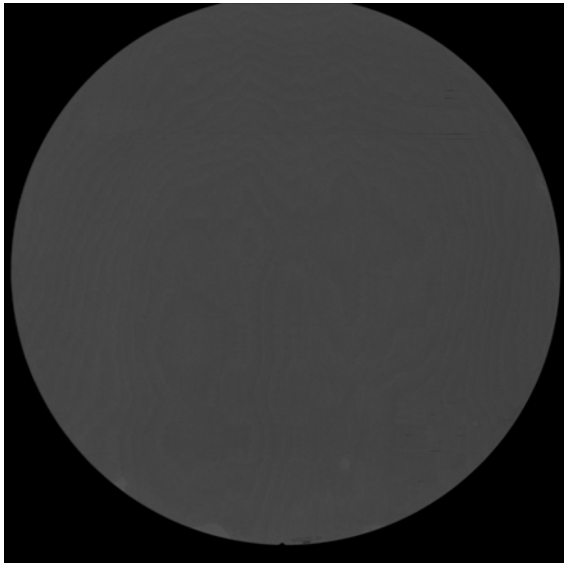
$$\text{Area} = \text{Peak} \times \frac{\text{F.W.H.M}}{\sqrt[2]{2\ln(2)}} \times \sqrt{2\pi}$$

Ideal Bonded Wafer: 60% Cross-linked BCB Bond



Hardbake		Cross Linking Level	Experiment Results
Temp °C	Time (min)		
190	10	37%	Dendritic structure and voids were present
190	25	42%	Dendritic structure and voids were present
190	40	45%	Dendritic structure and voids were present
200	15	45%	Dendritic structure and voids were present
200	25	50%	Dendritic structure and voids were present
250	36 (sec)	50%	Dendritic structure and voids were present
200	40	60%	Good no dendrites or voids; passed razor blade test
250	64 (sec)	60%	Good no dendrites or voids; passed razor blade test
250	2	70%	voids were present
250	3.5	80%	No voids were present but failed razor blade test

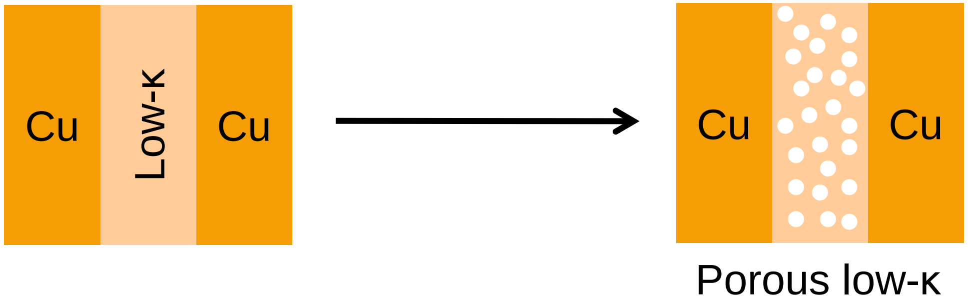
SAM image



Future Directions:

- Bonding using adhesive materials is relatively new in the semiconductor industry.
  - IRSE can aid in screening newly investigated materials.
  - IRSE will aid in process tuning and development.

Spectroscopic Ellipsometry of Porous Low-κ Dielectric Thin Films



V.K. Kamineni, C.M. Settens, A. Grill, G.A. Antonelli, R.J. Matyi, and A.C. Diebold, Frontiers of Characterization and Metrology for Nanoelectronics, AIP Conference Proceedings, 1173 (2009) 168.

C.M. Settens, V.K. Kamineni, G.A. Antonelli, A. Grill, A.C. Diebold, and R.J. Matyi, Frontiers of Characterization and Metrology for Nanoelectronics, AIP Conference Proceedings, 1173 (2009) 163.

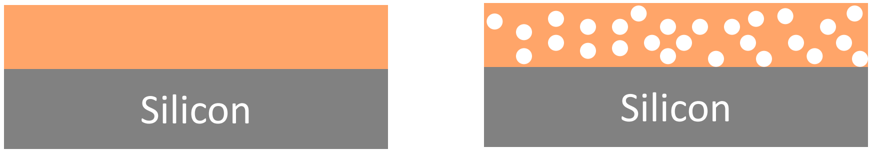
Introduction to Low-κ dielectrics

- Pores reduce the effective dielectric constant of the material
- Decrease signal propagation delays (faster switching speed)
- Reduction in crosstalk and power consumption
- Lower heat dissipation
- Pore volume fraction and pore size will effect the thermo-mechanical properties

IBM (Porous SiCOH)

PECVD of dual-phase materials (matrix and organic precursors)

UV cured to desorb porogens (organic precursor)



Sample	κ	Thickness (nm)
SiCOH1	3.0	1000
SiCOH2	2.2-2.4	333
SiCOH3	2.2-2.4	363

Novellus (ULK)

PECVD of porous low-κ with different dielectric constant

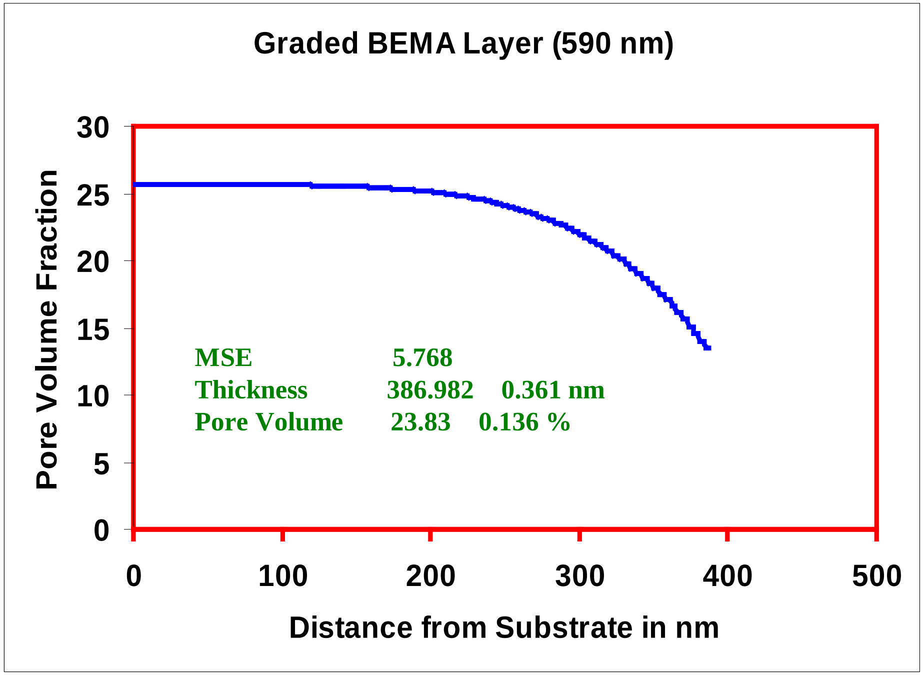
Sample	κ	Thickness (nm)
ULK1	2.75	150
ULK2	2.65	150
ULK3	2.55	150

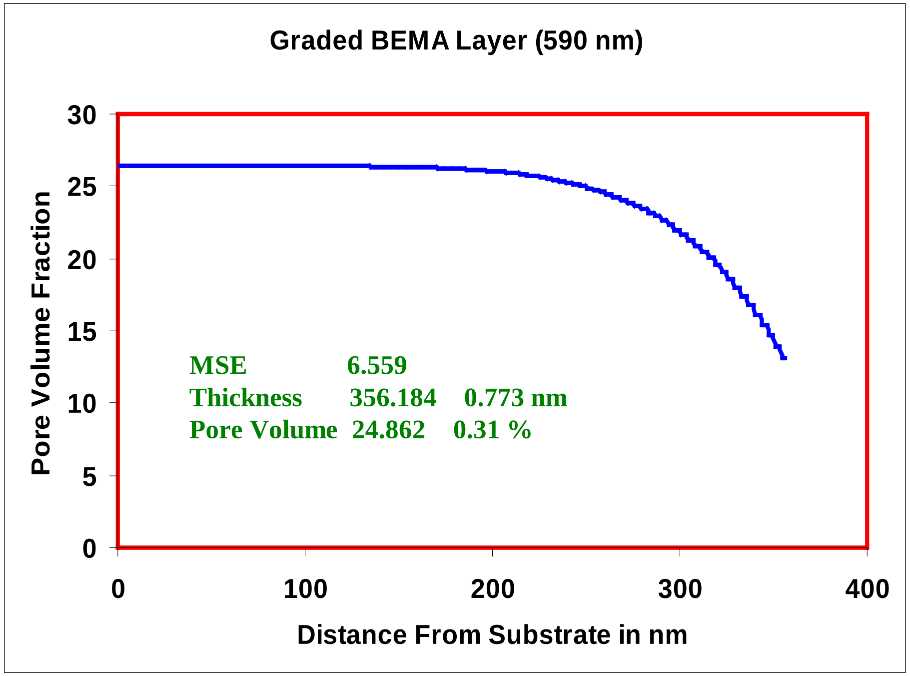
VUV-VASE Results (IBM)

Bruggeman expression for effective medium approximation on porous SiCOH samples

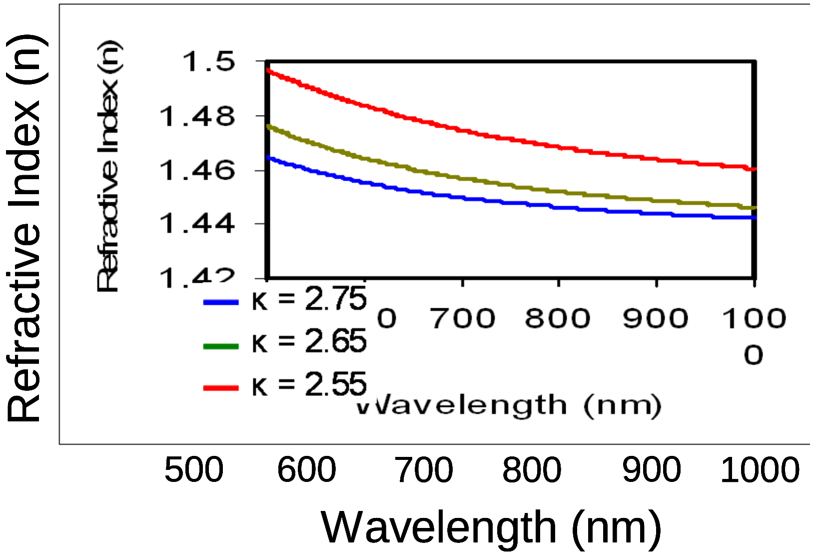
$$f_a \frac{\varepsilon_a - \varepsilon}{\varepsilon_a + 2\varepsilon} + f_b \frac{\varepsilon_b - \varepsilon}{\varepsilon_b + 2\varepsilon} = 0$$

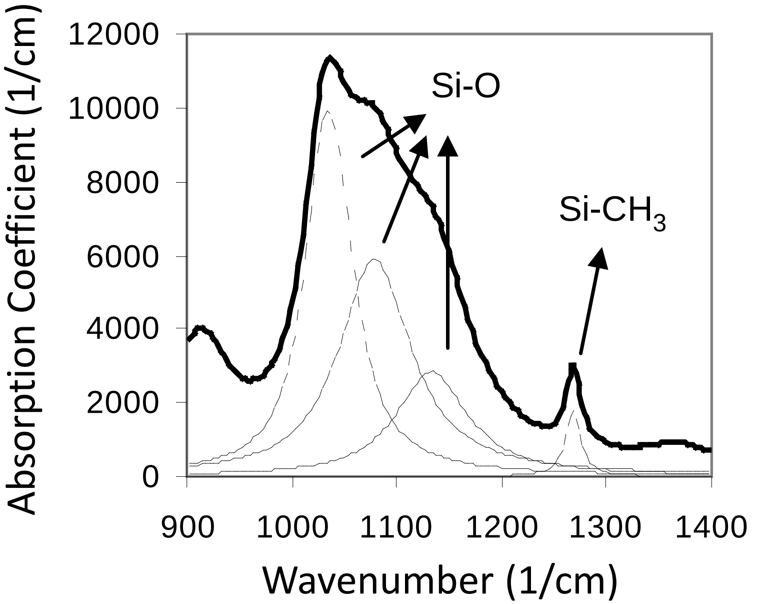
	Pore Volume Fraction	Thickness (nm)
Control	0%	1055.0 0.2
333 nm	24.8 0.3 %	352.6 1.0
363 nm	23.8 0.1 %	379.5 0.4

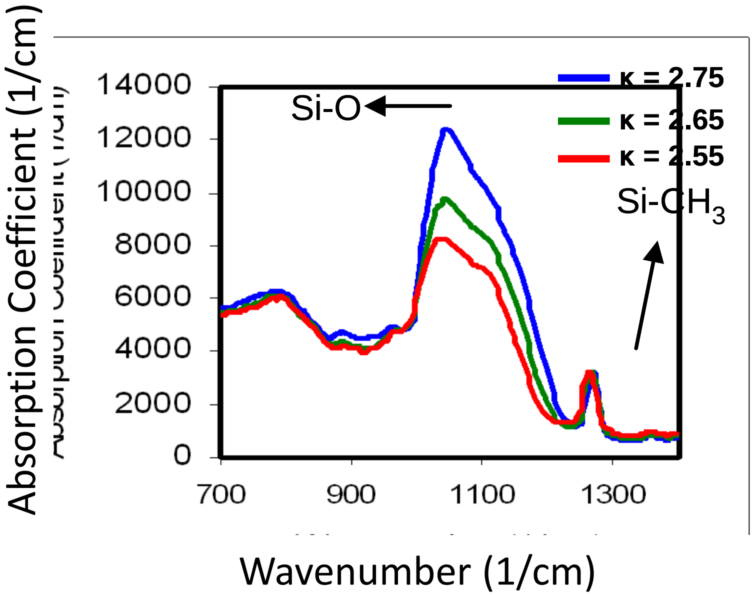




Molecular Bond Vibrations (Novellus)







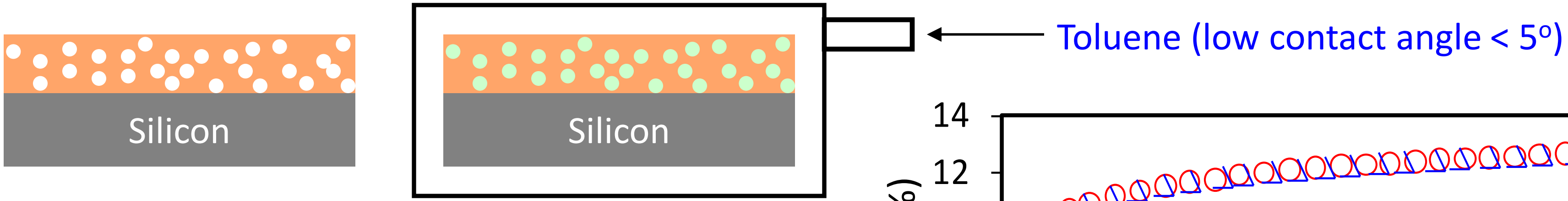
$$\text{Relative Carbon Concentration (\%)} = \frac{A_C}{A_O + A_C}$$

$$\text{Area} = \text{Peak} \times \frac{\text{F.W.H.M}}{\sqrt{2\ln(2)}} \times \sqrt{2}$$

κ	n	Carbon (%)
2.55	1.48	4
2.65	1.461	2.4
2.75	1.453	1.5

A_C - area under the Si-CH$_3$ peak
A_O - area under the Si-O peak

Ellipsometry Porosimetry (ULK)

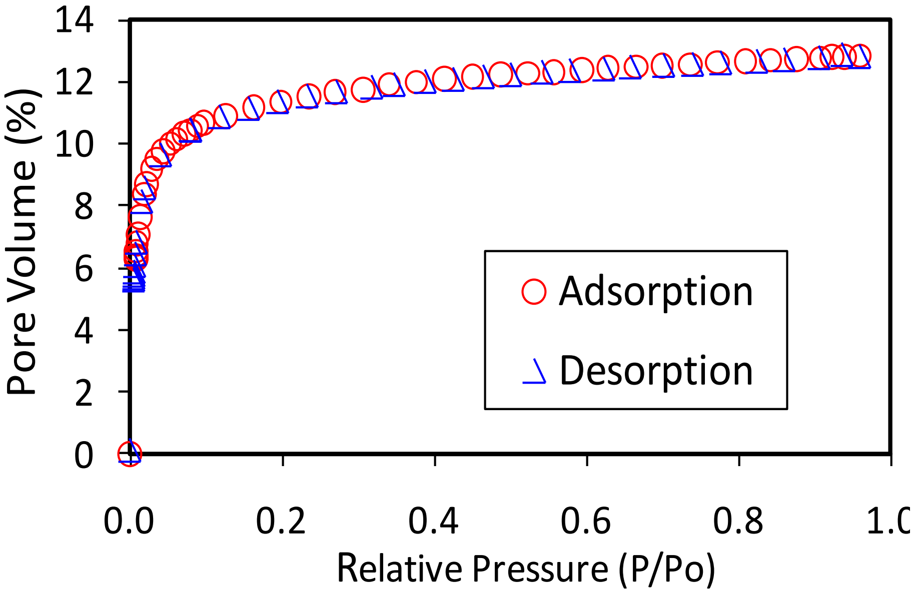


Lorentz-Lorenz

$$B_{eff} = \frac{3}{4\pi}\cdot\frac{(n_{eff}^2-1)}{(n_{eff}^2+2)} = \sum N_i\alpha_i$$

$$P = \frac{B_{sat}-B_0}{B_{tol}}$$

$$\boxed{P = \frac{\dfrac{n_{sat}^2-1}{n_{sat}^2+2}-\dfrac{n_0^2-1}{n_0^2+2}}{\dfrac{n_{tol}^2-1}{n_{tol}^2+2}}}$$



Sample	Refractive Index *(n)*	Porosity (%)
κ = 2.55	1.48	13.19
κ = 2.65	1.461	11.76
κ = 2.75	1.453	7.92

B_{eff} – effective polarizability

n_{eff} – effective refractive index (RI)

N_i - number of molecules

α_i – molecular polarizability

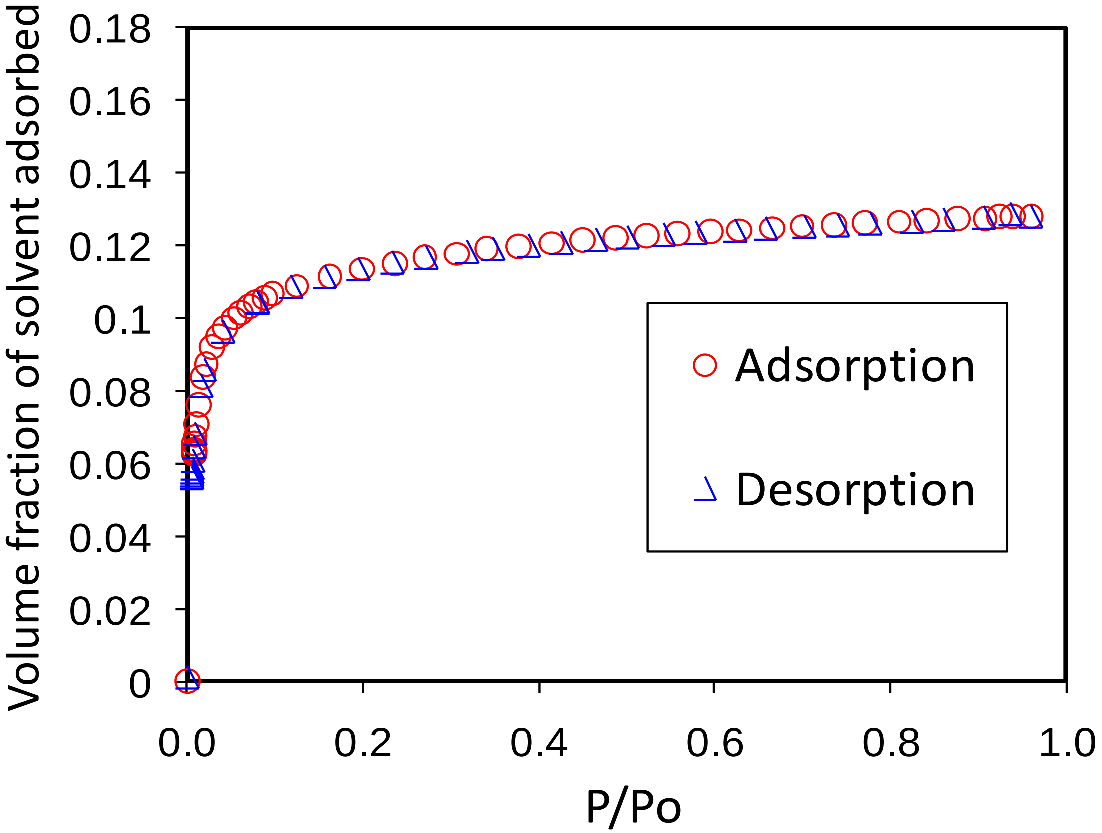
n_{sat} – RI of film filled with toluene

n_{tol} – RI of toluene

n_o – RI of film without toluene

P - porosity

Micropore Size (ULK)



Dubinin and Radushkevitch (DR)

$$V = V_0 \exp\left[-\frac{1}{(\beta E_0)^2}\left(RT\ln\frac{P}{P_0}\right)^2\right]$$

$$\boxed{\ln V = \ln V_O - BA^2}$$

$$A = RT\ln\left(\frac{P_0}{P}\right) \qquad B = \frac{1}{(\beta E_0)^2}$$

$$\boxed{r = \frac{K}{2E_0}}$$

Sample	Refractive Index *(n)*	Pore radius (nm)
κ = 2.55	1.48	0.82
κ = 2.65	1.461	0.79
κ = 2.75	1.453	0.84

A – adsorption potential

R – universal gas constant

V – adsorbate volume

V_0 – total micro pore volume

β – function of toluene only

E_0 - solid characteristic energy towards a reference adsorbate

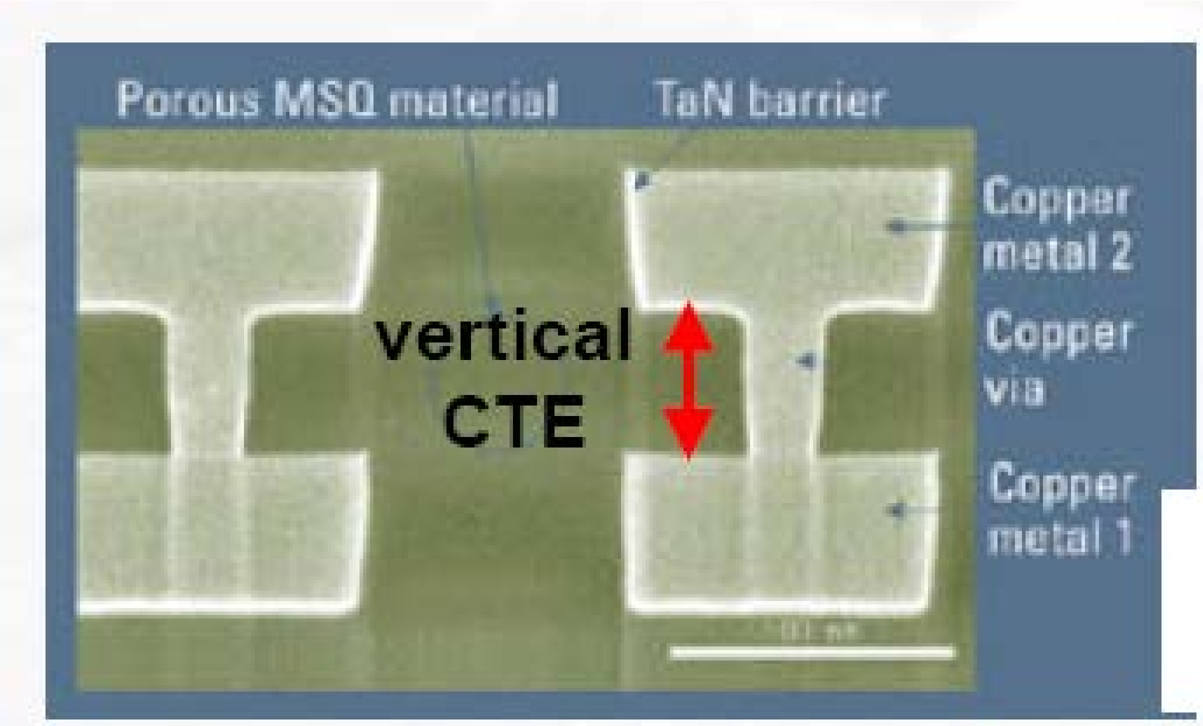
K – empirical constant ≈ 12

Mechanical Properties (ULK)

SE can measure critical mechanical parameters (Young’s modulus, CTE)

- Young's modulus is a measure of the stiffness of the porous low-κ dielectric material

- A low CTE will prevent a connection failure between via/M1 and/or via/M2

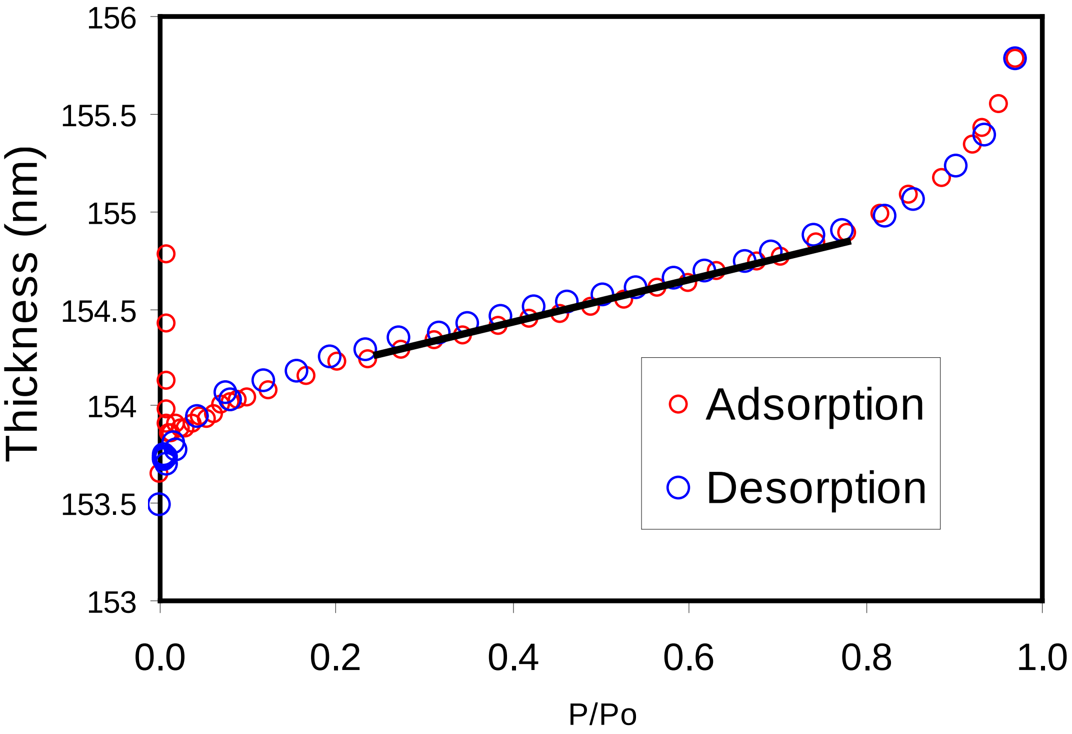


Copper CTE ~ 20×10^{-6}/ C

SEMATECH (Alain Diebold)

CTE – Coefficient of thermal expansion

Young's Modulus (ULK)



K. P. Mogilnikov and M. R. Baklanovz

$$d = d_0 - k \ln \frac{P}{P_0}$$

$$\boxed{E = \frac{d_0 RT}{kV_L}}$$

Sample	Porosity (%)	Pore radius (nm)	EP Young's Modulus (GPa)
κ = 2.55	13.19	0.82	2.74
κ = 2.65	11.76	0.79	3.96
κ = 2.75	7.92	0.84	7.08

V_L – molecular volume

E – Young's modulus

High Temperature Thickness Measurements (ULK)

Free standing film (thermal expansion rate)

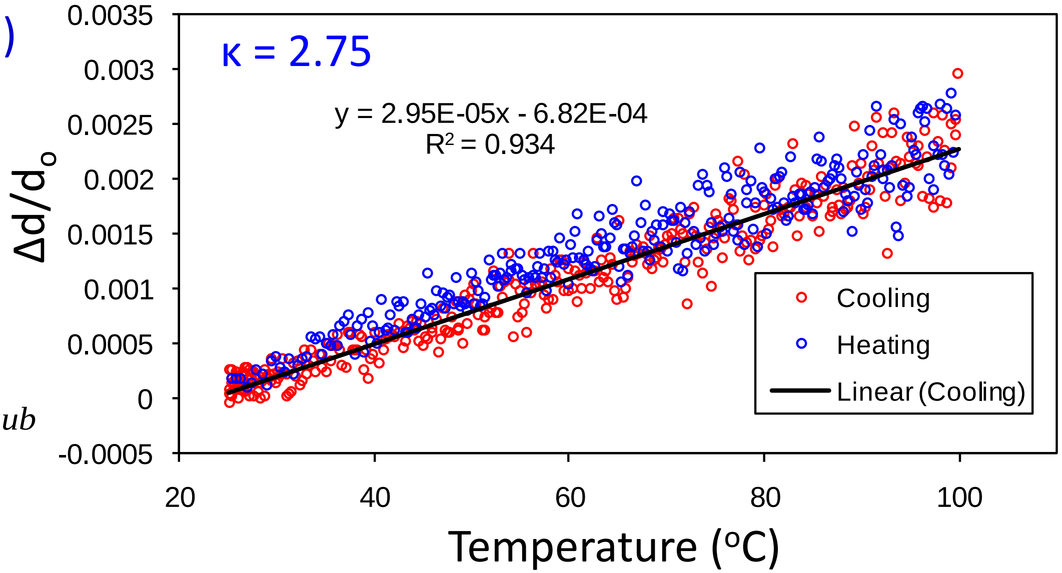
$$\frac{1}{L_o}\frac{dL}{dT}=\alpha$$

Film on substrate (CTE)

$$\frac{1}{L_o}\frac{dL}{dT}=\left(\frac{1+\nu_{film}}{1-\nu_{film}}\right)\alpha_{film}-\left(\frac{2\nu_{film}}{1-\nu_{film}}\right)\alpha_{sub}$$

$$\nu_{film}=\text{Poisson's Ratio}=0.25$$

$$\alpha_{substrate}=2.6\times10^{-6}\,/\,^{o}C$$



$$\frac{1}{L_o}\frac{dL}{dT}=\alpha=29.5\times10^{-6}/^{o}C$$

Sample	Refractive Index *(n)* 632.8 nm	TER ($10^{-6}/^oC$)	CTE ($10^{-6}/^oC$)
κ = 2.55	1.48	70.2	44.72
κ = 2.65	1.461	54.9	35.54
κ = 2.75	1.453	29.5	20.30

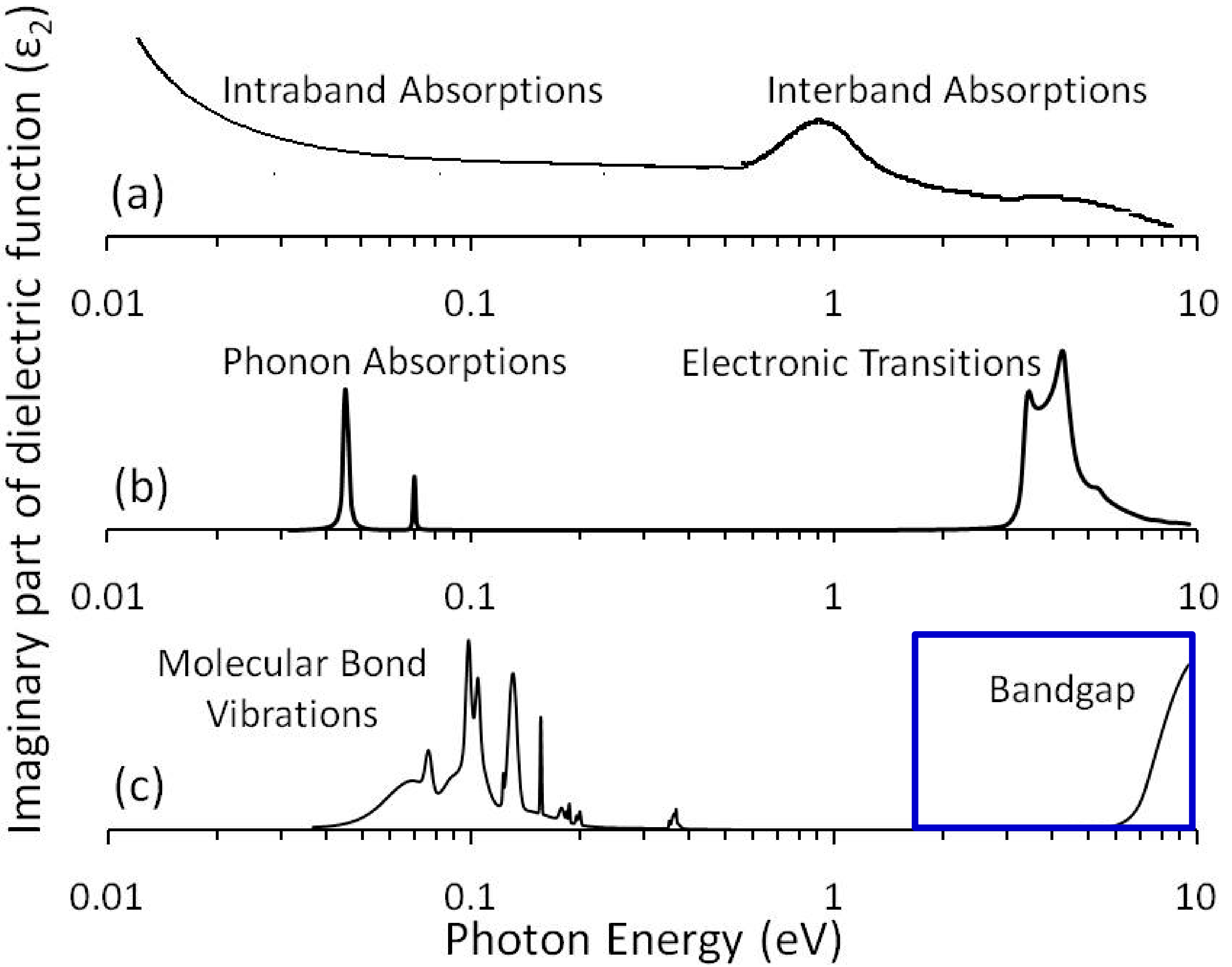
Note: Fitting for the substrate expansion using the silicon temperature library (J.A.Woollam)

Summary on Low-κ

- The following parameters were determined using SE.
    - SICOH (IBM)
        - Porosity (BEMA)
        - Grading in porosity
    - ULK (Novellus)
        - Carbon content
        - Porosity (EP)
        - Pore size
        - Young's modulus
        - Coefficient of thermal expansion
- Complementary techniques such as specular XRR, off-specular XRR and SAXS were also performed on these films. Both, the optical and x-ray metrology agreed reasonably well.

Sample	Thickness (nm)	*n* (632.8 nm)	Carbon %	Porosity (%)	Pore radius (nm)	EP Young's Modulus (GPa)	TER $(10^{-6}/^{o}C)$	CTE $(10^{-6}/^{o}C)$
κ = 2.55	155.6	1.48	4	13.19	0.82	2.74	70.2	44.72
κ = 2.65	154.7	1.461	2.4	11.76	0.79	3.96	54.9	35.54
κ = 2.75	147.1	1.453	1.5	7.92	0.84	7.08	29.5	20.30

Linear Optical Response of Materials

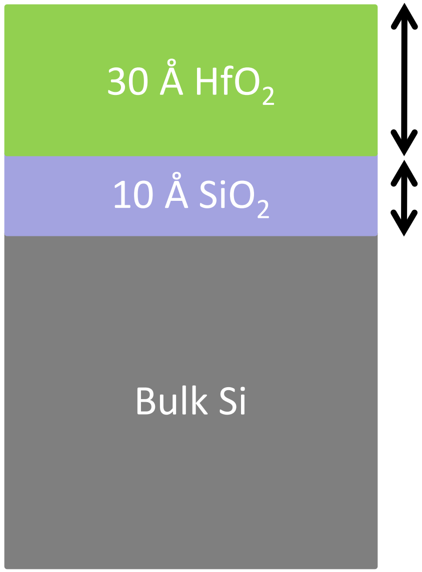


Metals

Semiconductors

Dielectrics

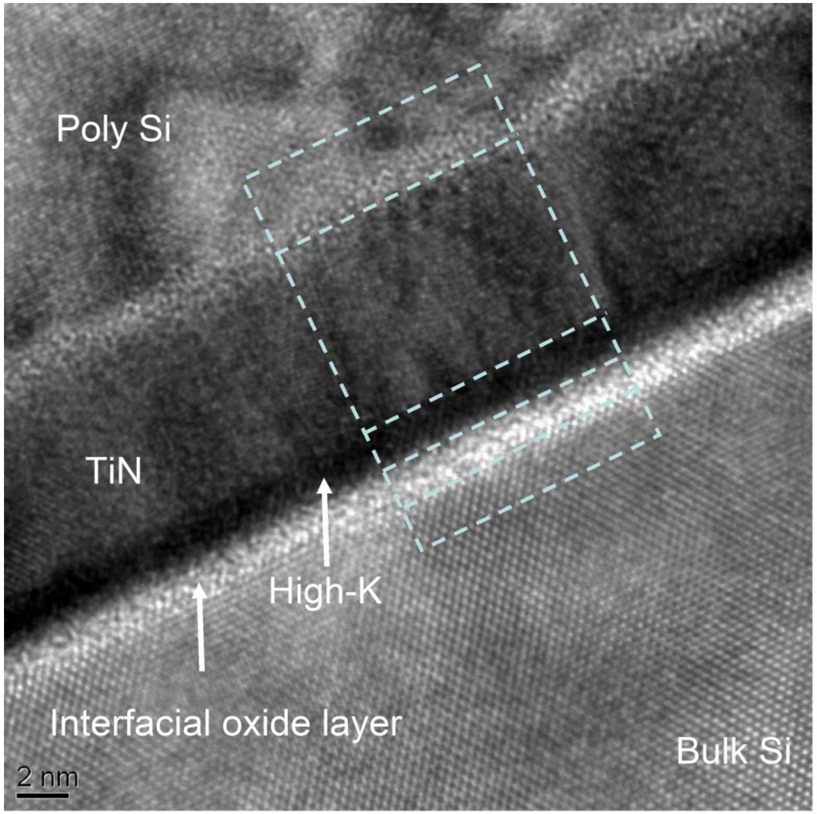
Extension of Far UV spectroscopic ellipsometry studies of High-κ dielectric films to 130 nm



30 Å HfO_2

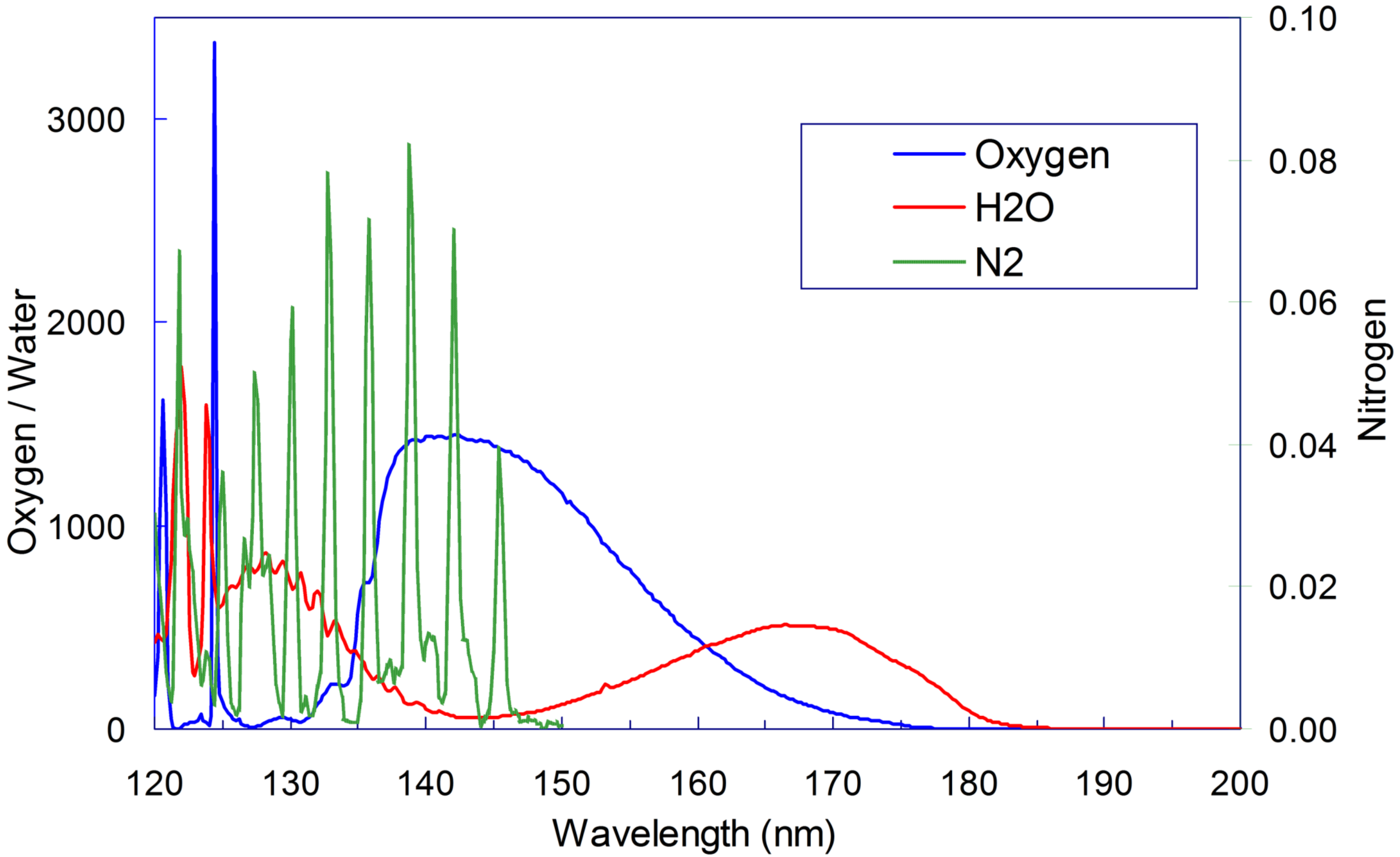
10 Å SiO_2

Bulk Si



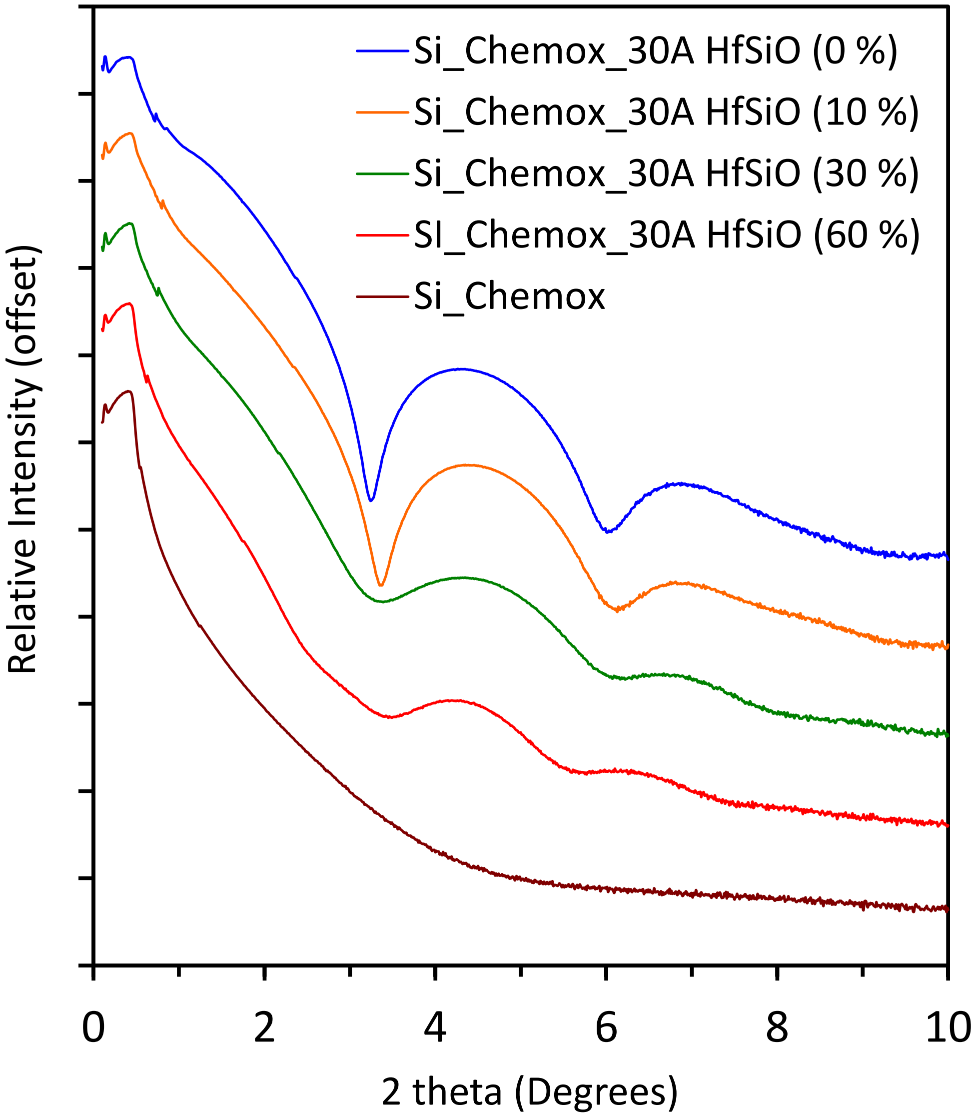
V. K. Kamineni, J. Hilfiker, J. Freeouf, S. Consiglio, R. Clark, G.J. Leusink, and A. C. Diebold, Thin Solid Films, 519 (2011) 2894.

Absorption Cross-section

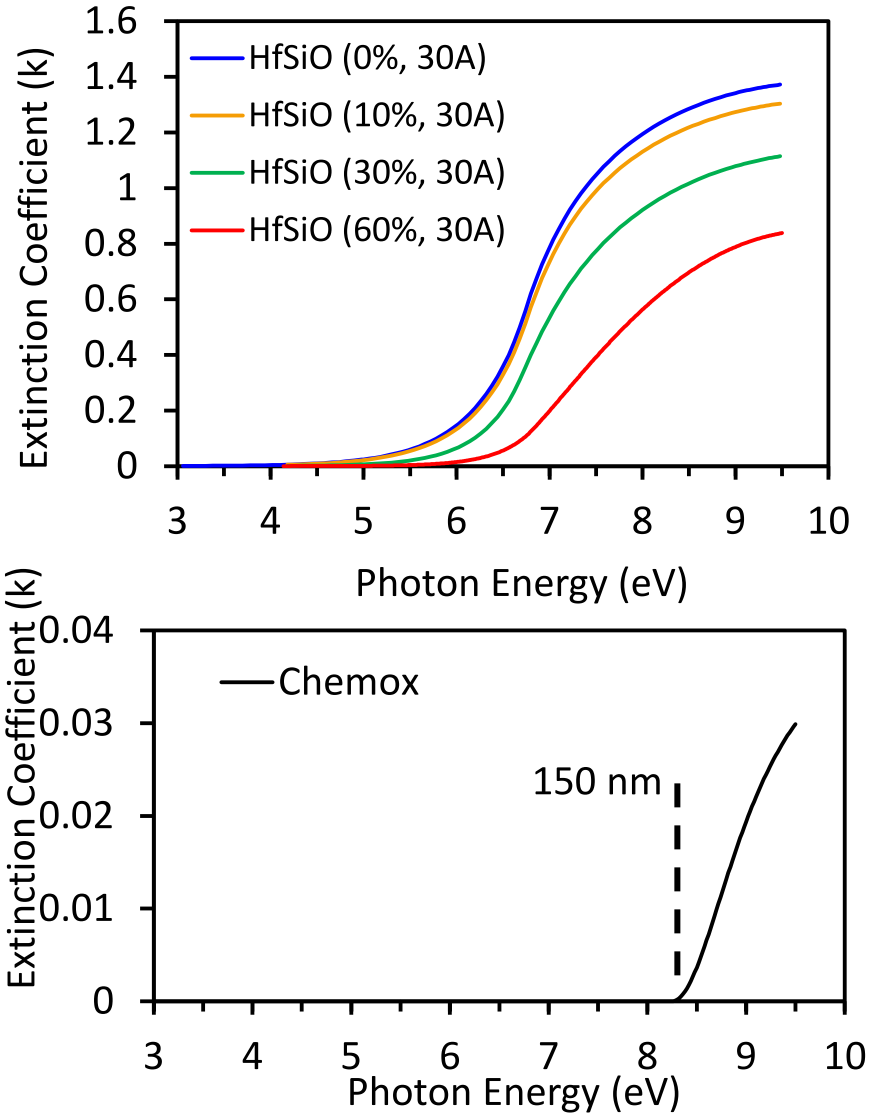


Thickness metrology

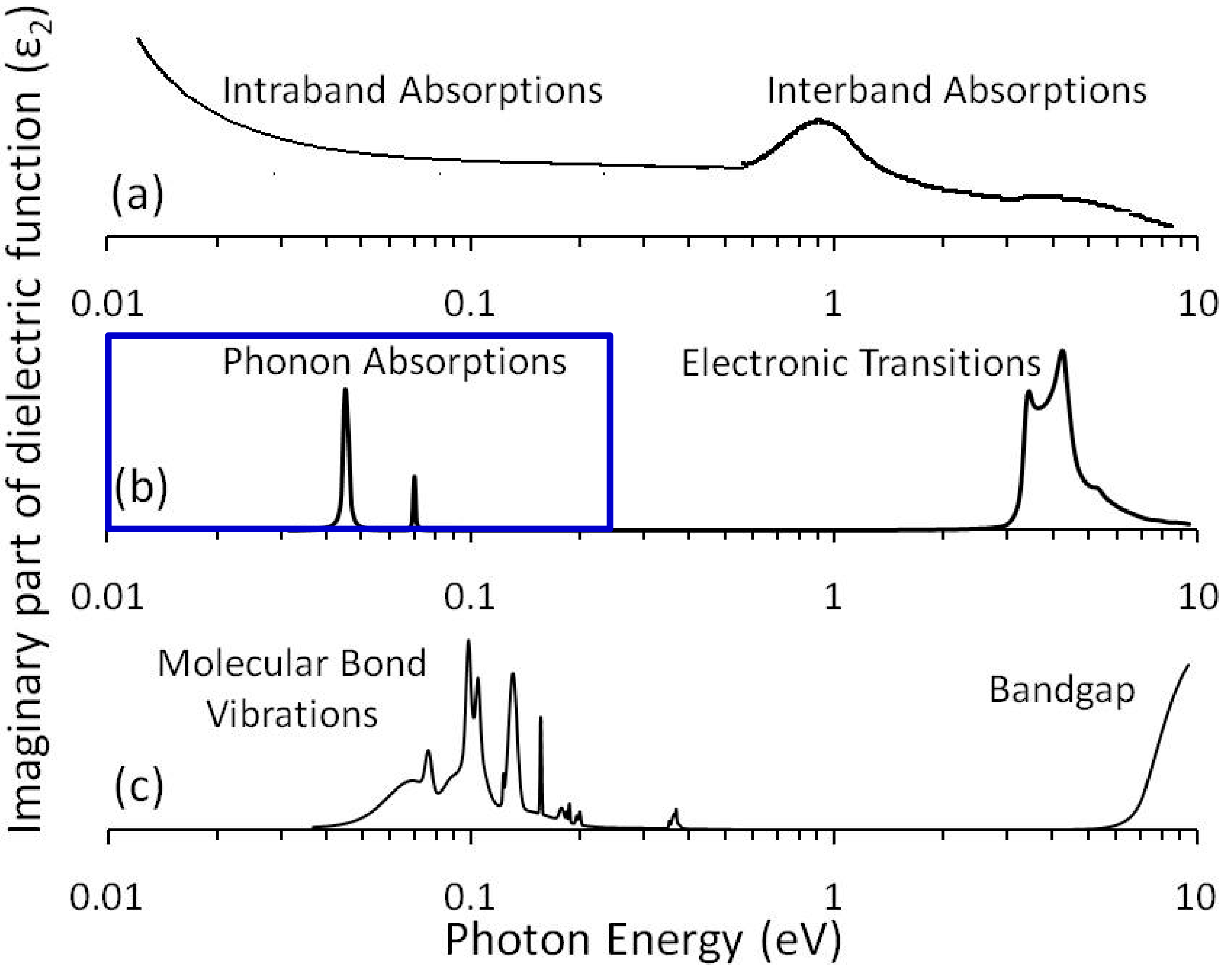
XRR



SE



Linear Optical Response of Materials

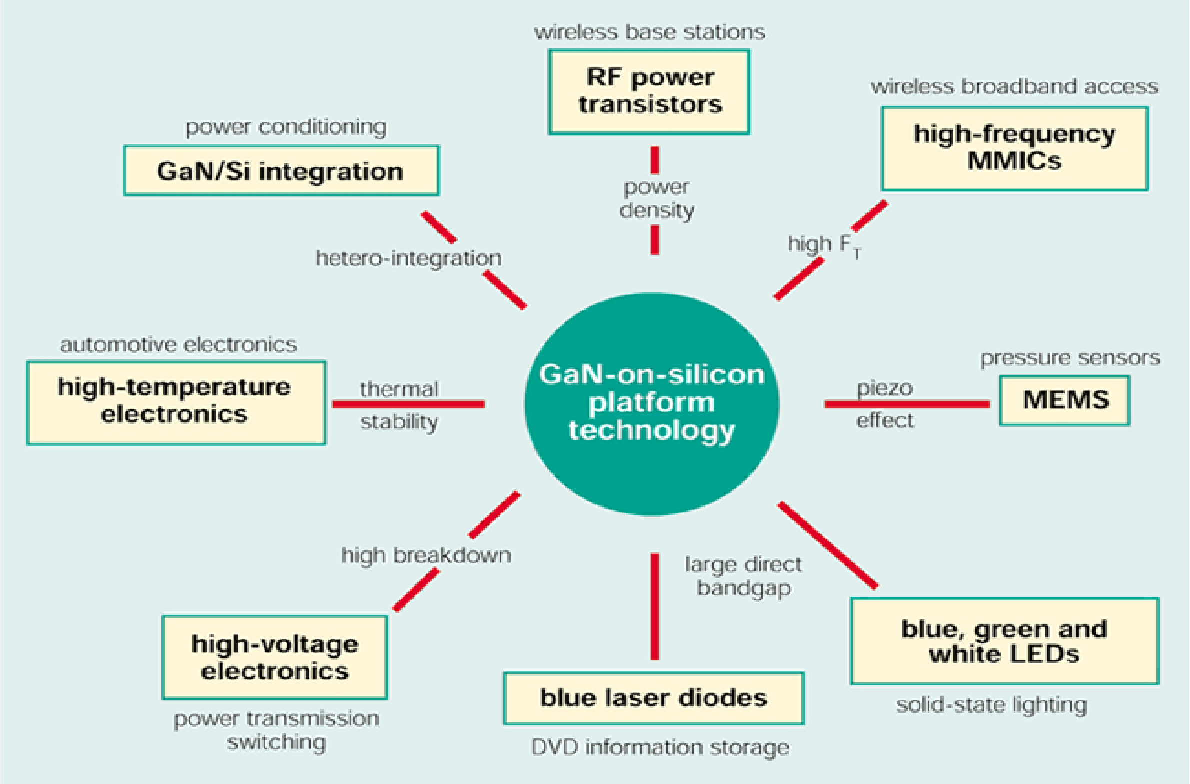


Metals

Semiconductors

Dielectrics

Metrology of Strain Engineered GaN/AlN/Si(111) Thin Films Grown by MOCVD



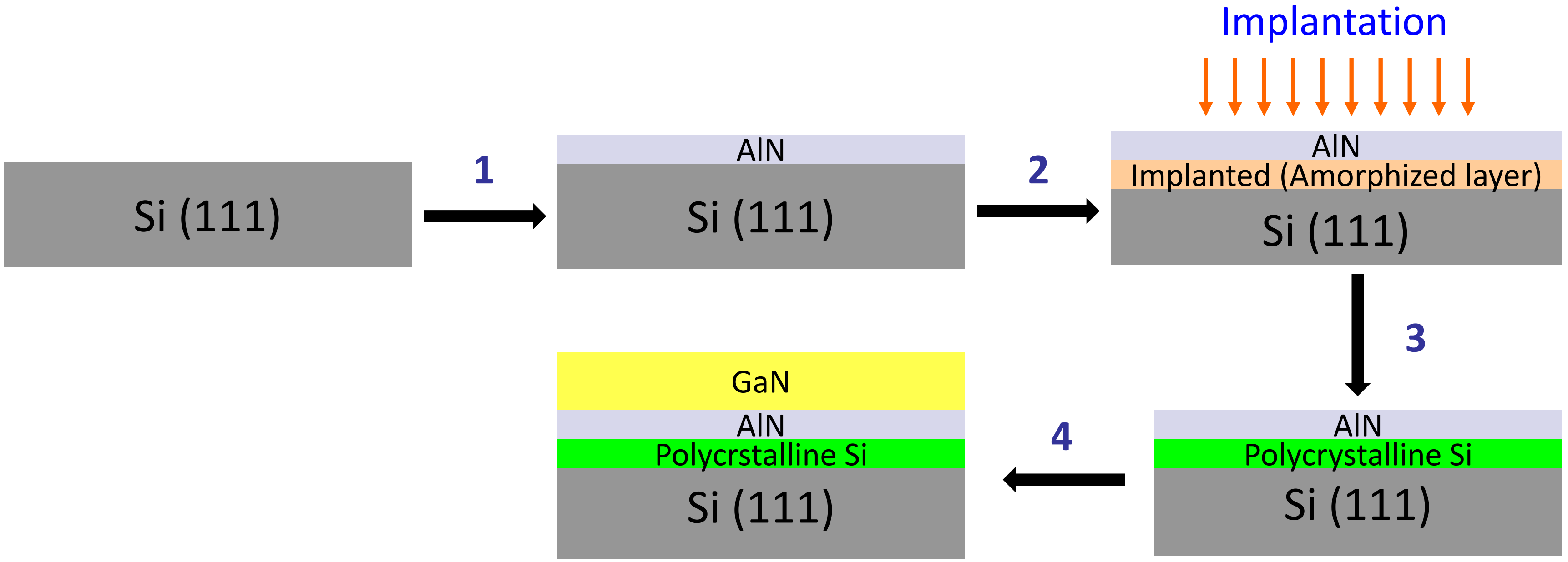
M. Tungare, V. K. Kamineni, F. Shahedipour-Sandvik and A. C. Diebold, Thin Solid Films, 519 (2011) 2929.

http://images.iop.org/objects/compsemi/features/thumb/7/11/5/csnit1_11-01.jpg

Substrate Engineering Technique

Wide Band Gap Optronix Lab

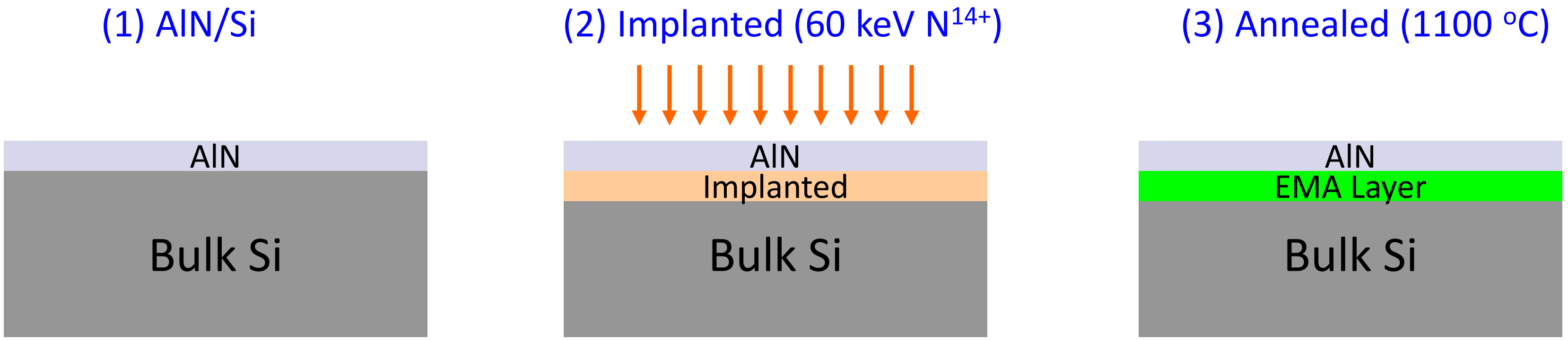
Prof. Shadi Shahedipour-Sandvik and Mihir Tungare



Substrate engineering consists of 4 major steps:

1) Growth of an epitaxial AlN buffer layer on Si
2) Implantation of AlN/Si with N^+ ions to create a defective layer in Si below AlN buffer
3) Annealing of AlN/Si to recover any loss of crystallinity due to implantation
4) Growth of thick (2 µm) GaN on AlN/Si

IRSE of Substrate Engineered AlN Layers



(1) AlN/Si

AlN

Bulk Si

(2) Implanted (60 keV N^{14+})

AlN

Implanted

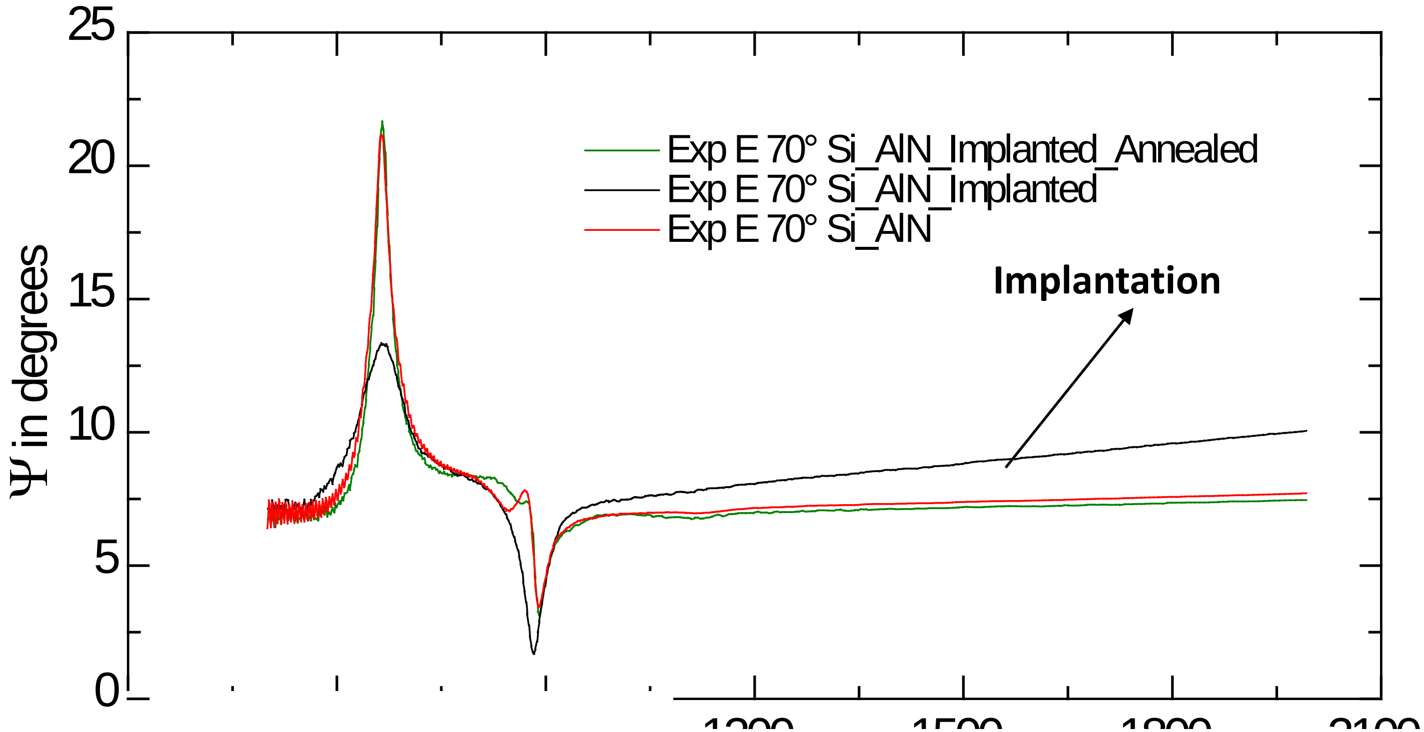
Bulk Si

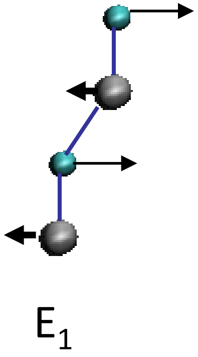
(3) Annealed (1100 °C)

AlN

EMA Layer

Bulk Si



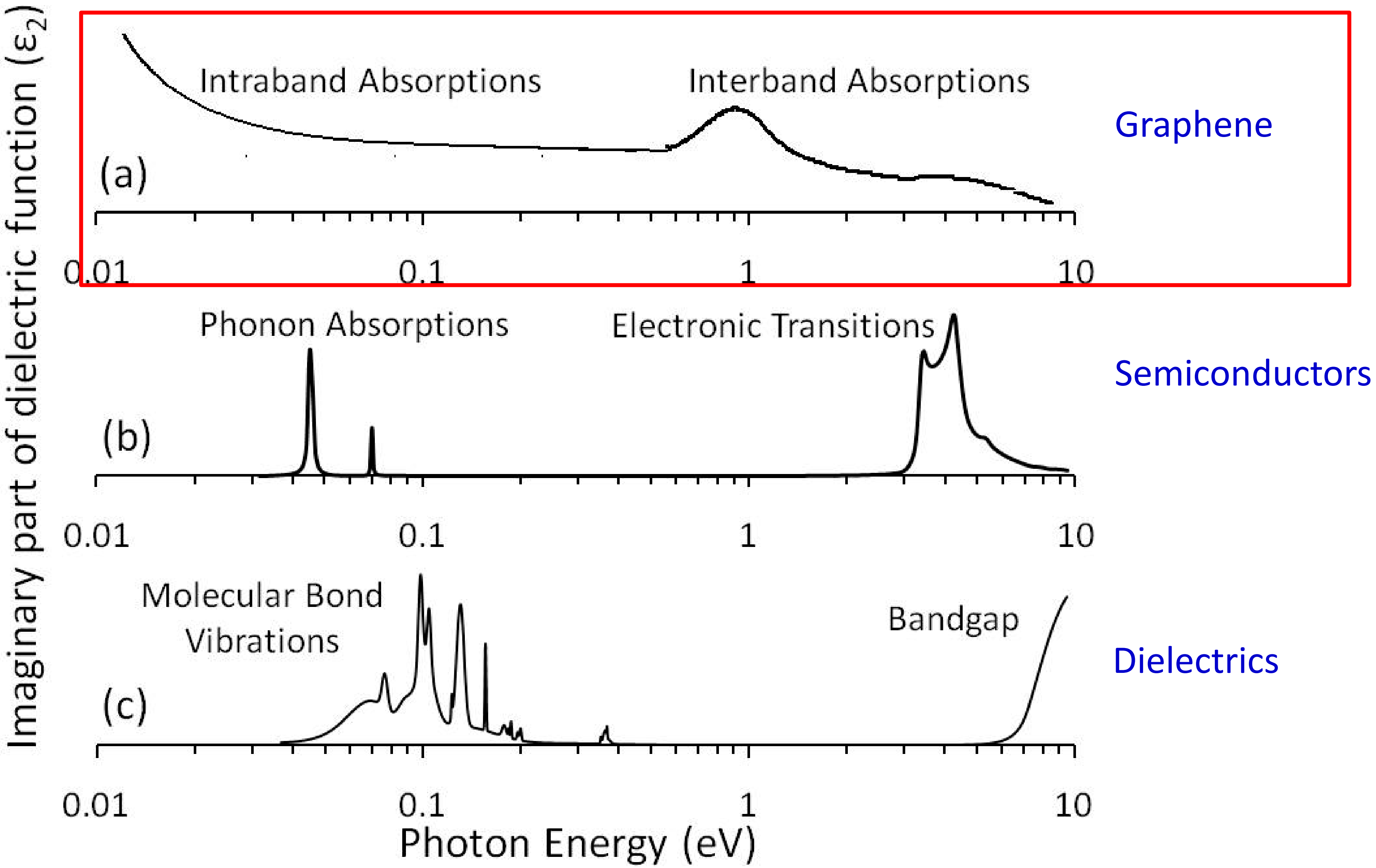


Stress Measurements

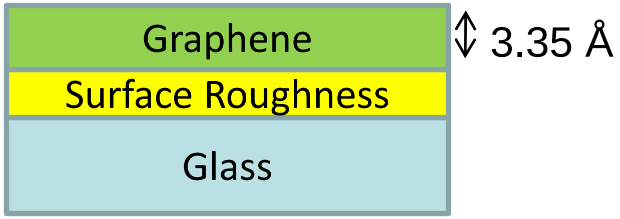
- Resolution = 2 cm^{-1}
- E_1 (TO) Bulk AlN = 666 cm^{-1}
- Isotropic model due to very thin AlN films (IR Probe)
- Tensile Biaxial Strain
- Broadening of the E_1 (TO) phonon mode in implanted AlN is clear sign of presence of defects
- Not sensitive to the A_1 (TO) due to c-plane orientation

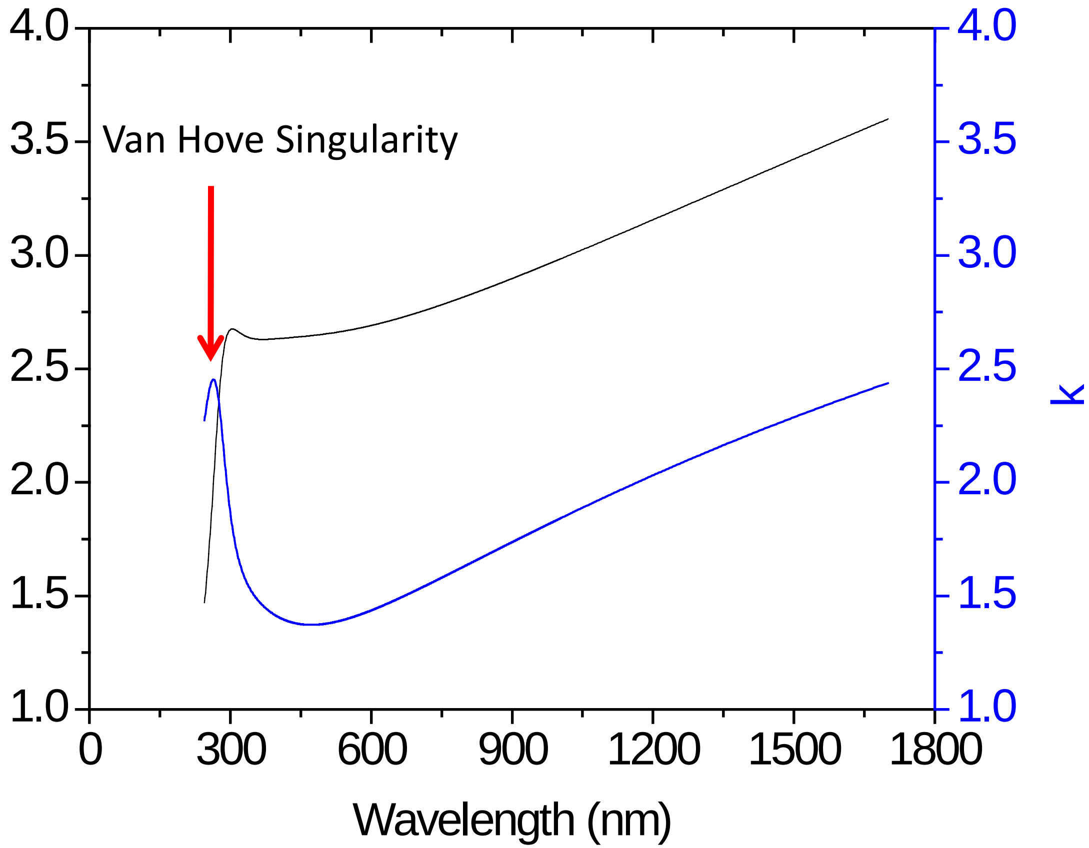
Sample List	**E1(TO) cm^{-1}**	**γ (cm^{-1})**	**$\Delta\omega$ (cm^{-1})**	**$d\omega_o/dP$**	**Stress (GPa)**
Si_AlN	662.2 0.08	19.5 0.2	3.8	4.5	0.84
Si_AlN_Implanted	664.5 0.24	56.0 0.4	1.5	4.5	0.33
Si_AlN_Annealed	663.8 0.16	21.2 0.2	2.1	4.5	0.48

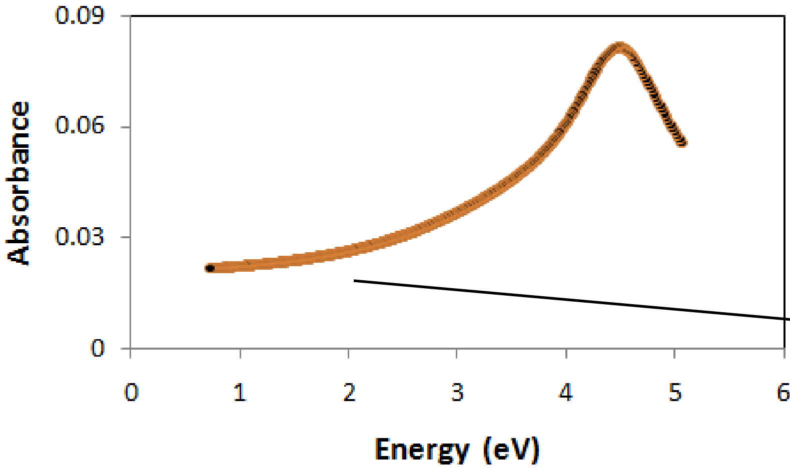
Linear Optical Response of Materials



Spectroscopic Ellipsometry of CVD Graphene



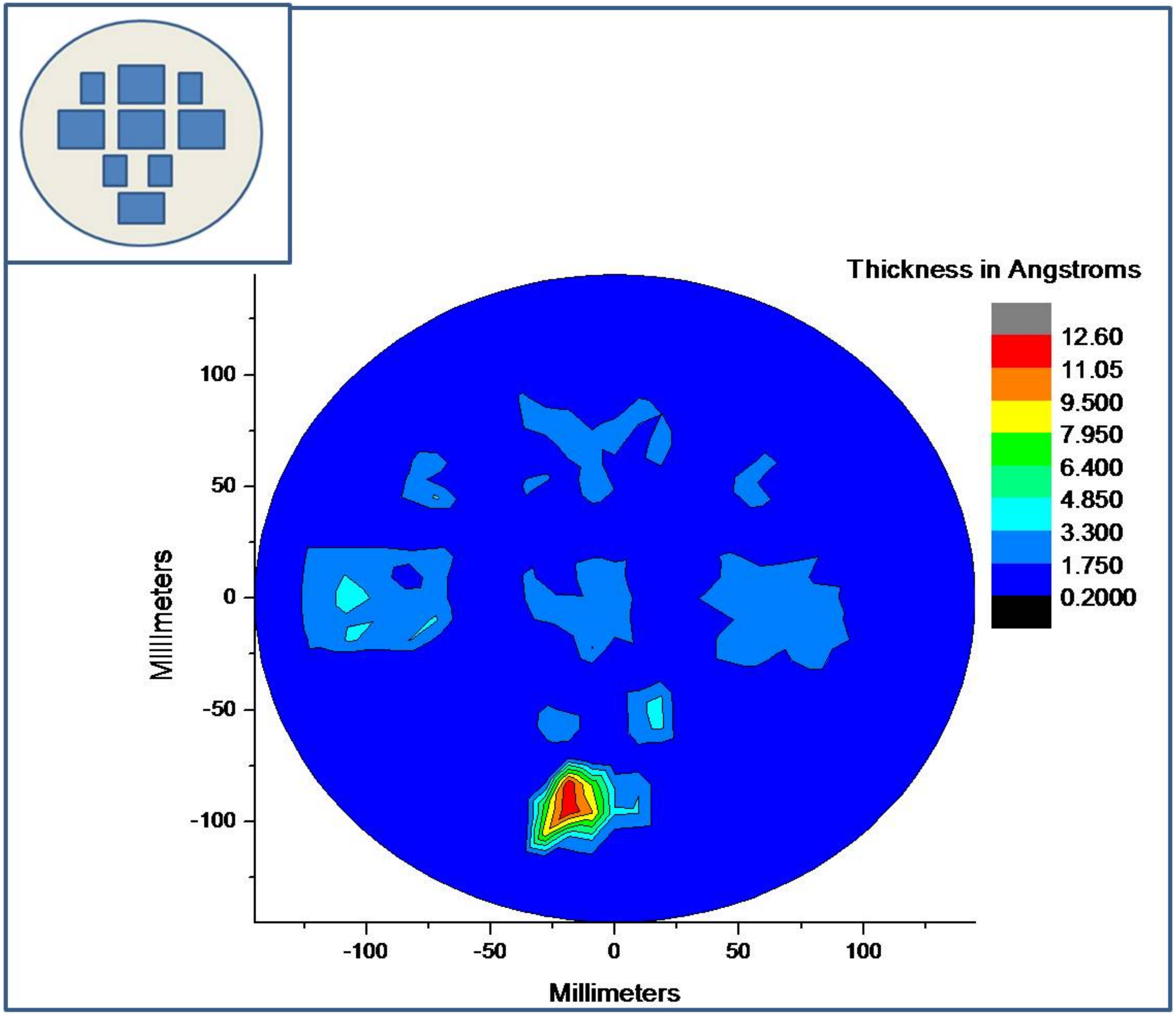




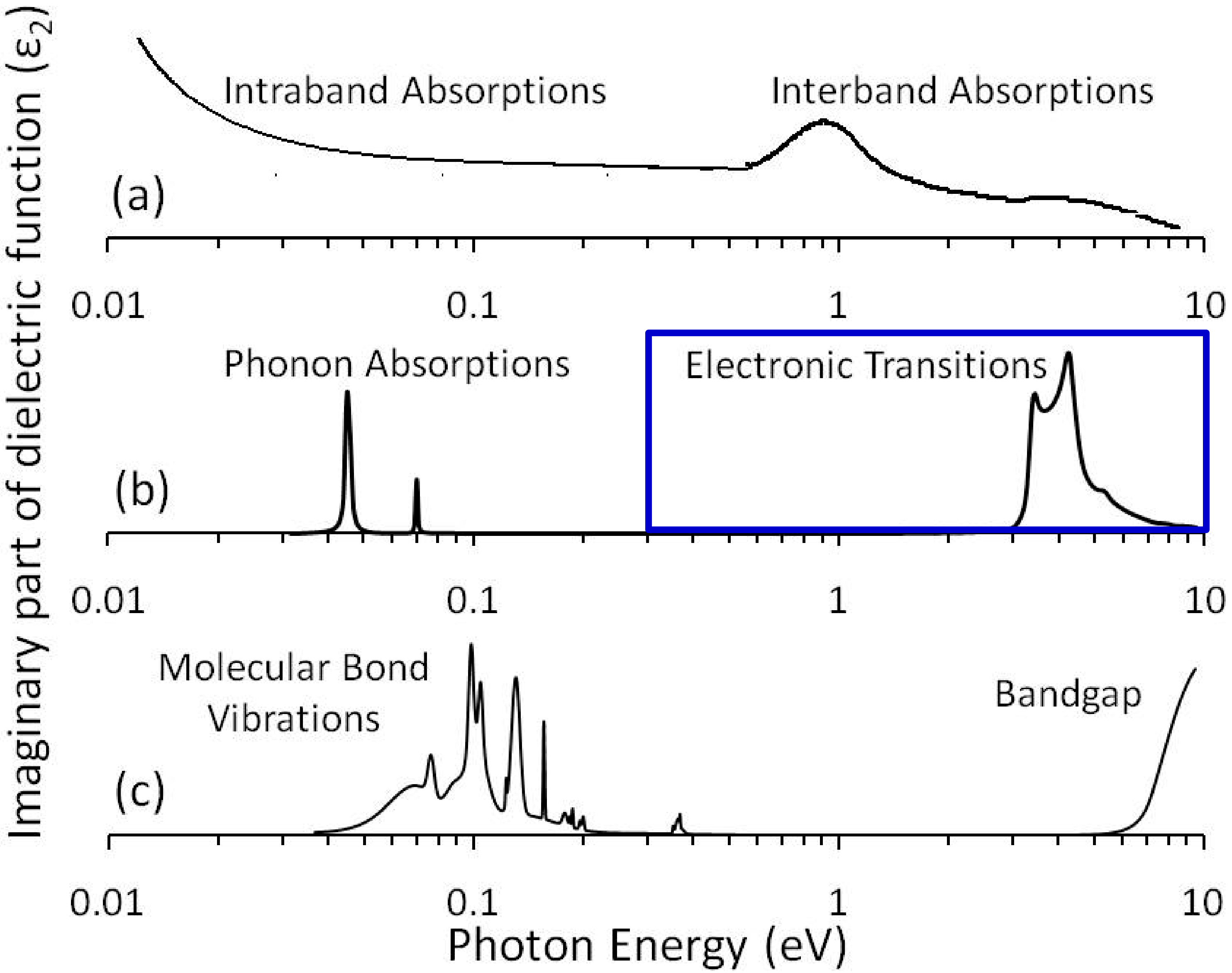
*Graphene's infrared-to-visible absorbance: ~2.3%

F. J. Nelson, V. K. Kamineni, T. Zhang, E. S. Comfort, J. U. Lee, and A. C. Diebold, Appl. Phys. Lett., 97 (2010) 253110.

Wafer Mapping- CVD Graphene on 300nm SiO_2/Si



Linear Optical Response of Materials



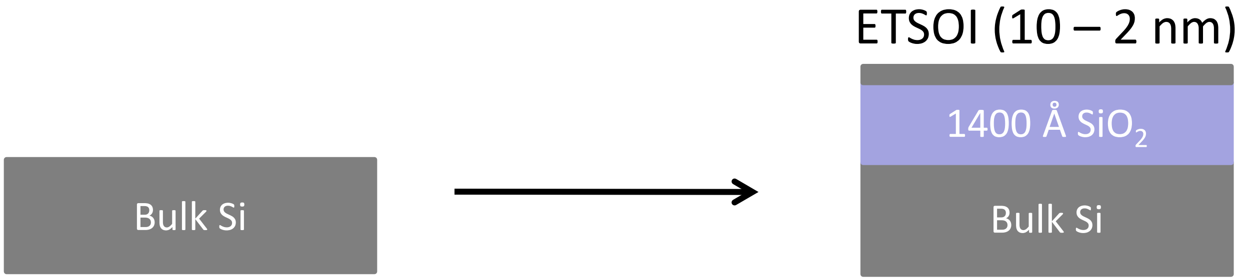
Metals

Semiconductors

Dielectrics

Silicon-on-insulator (SOI)

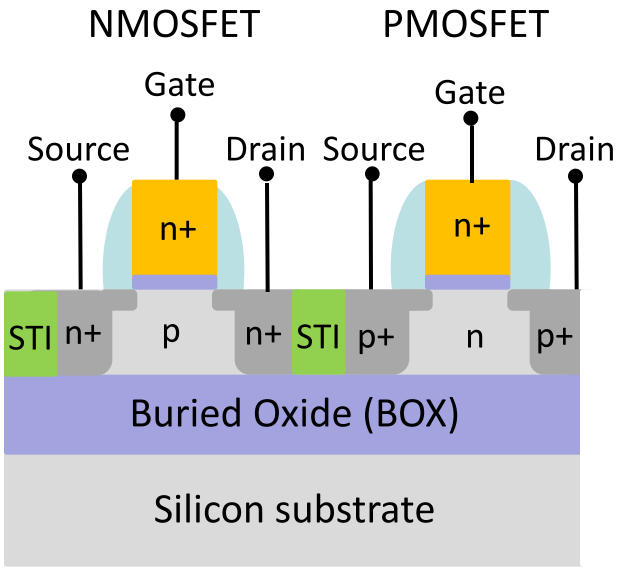
Temperature and thickness dependence of the dielectric function and interband critical points in ETSOI

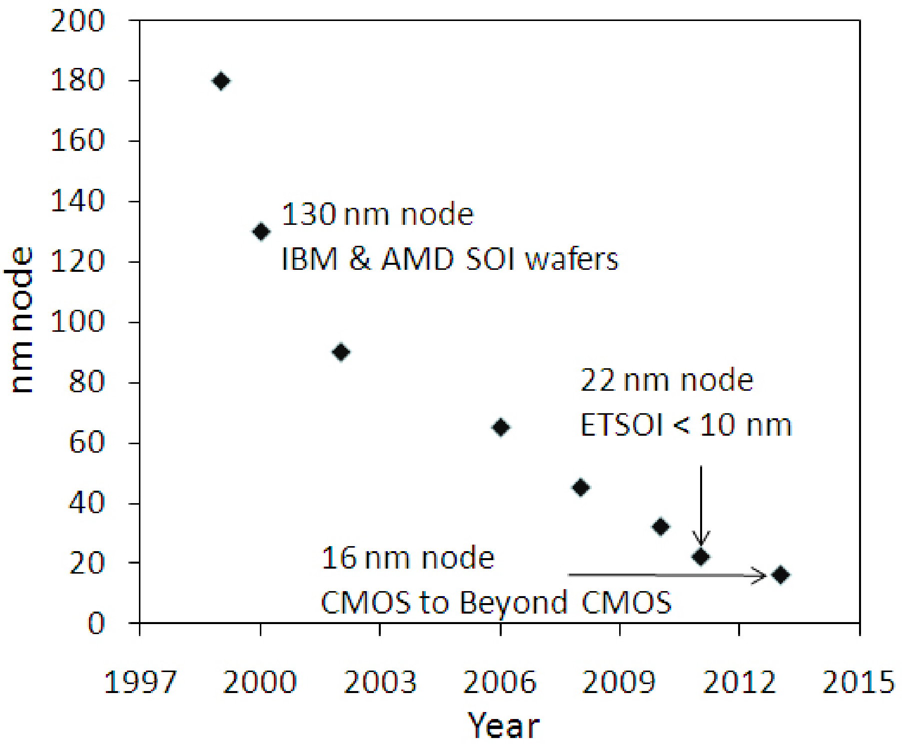


Dielectric response of bulk Si and nanoscale silicon films in different

V. K. Kamineni and A. C. Diebold, "Evidence of the phonon confinement on the linear optical response of nanoscale silicon films", arXiv:1103.4102v2.

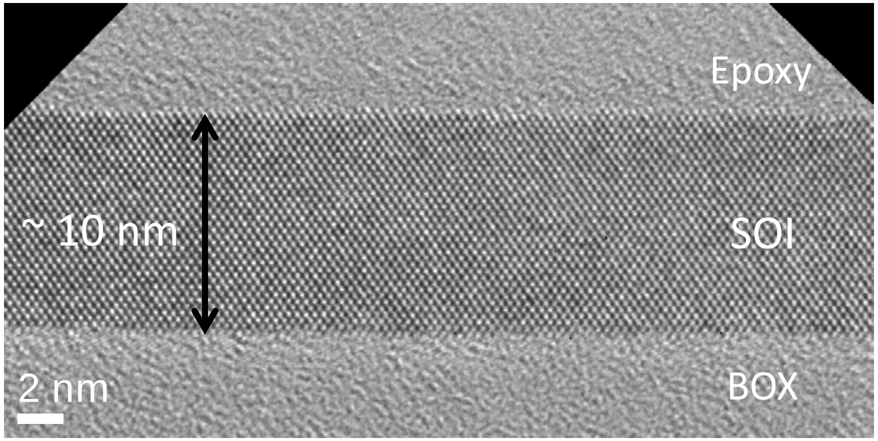
Introduction to Silicon-on-insulator (SOI)





Advantages of SOI technology:

- Excellent isolation of active devices
- Lowers the parasitic capacitance
- Lower leakage current
- Faster device operation
- Lower power consumption

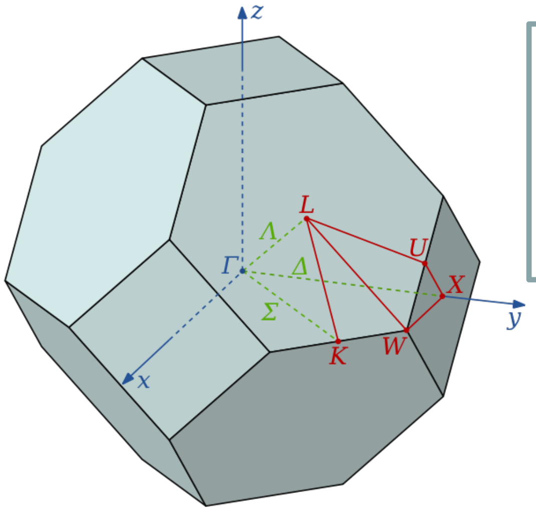


BOX – buried oxide layer

A. Diebold, TEM compliment of Mark Clark, ATDF

Electronic transitions

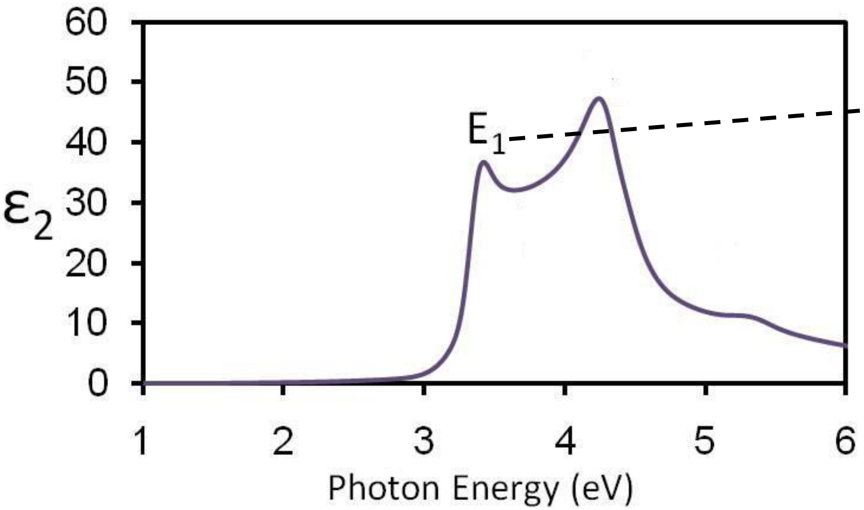
First Brillouin zone (truncated octahedron) of FCC Lattice[1]



[100] Direction: $\overline{\Gamma \quad \Delta \quad X}$

[111] Direction: $\overline{\Gamma \quad \Lambda \quad L}$

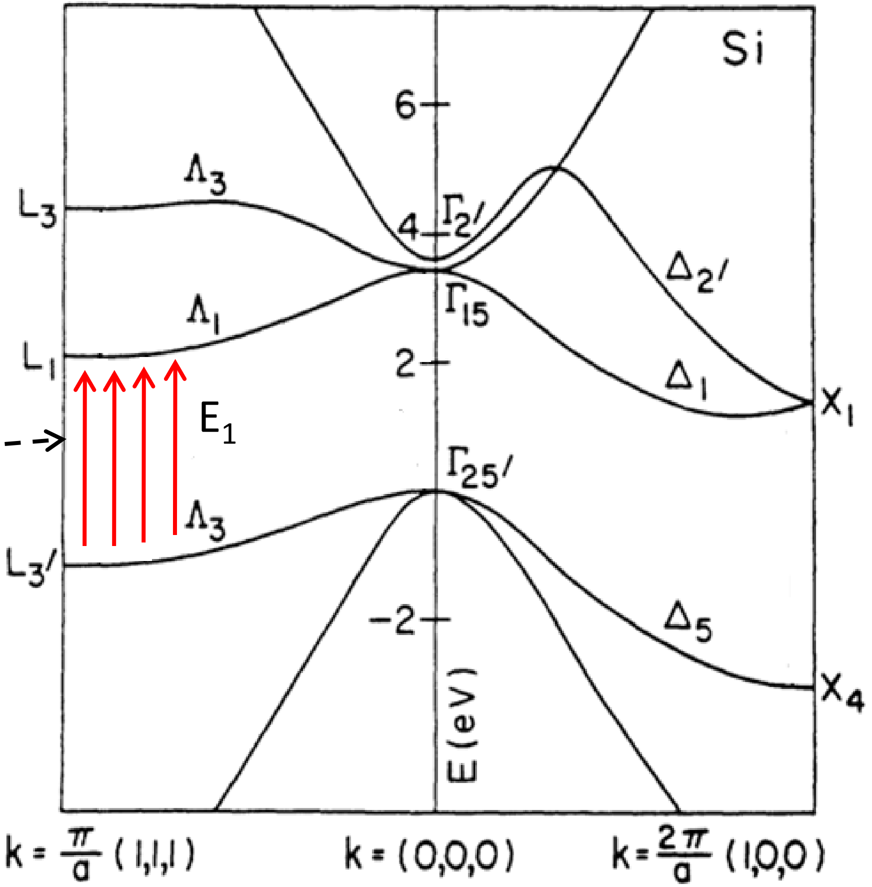
[110] Direction: $\overline{\Gamma \quad \Sigma \quad K}$



ε_2: Imaginary part of the dielectric function

Critical Point

- Constant energy difference between the valence and conduction band.
- In optical physics terms – a high joint density of states



Band structure of Si calculated from the **k·p** method[2]

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[1] C. Kittel, Introduction to Solid State Physics (Wiley, New York, 1996)

[2] M. Cardona and F. H. Pollak, Phys. Rev. B 142, 530 (1966).

Direct space analysis

Direct space analysis:

Lorentzian line shape

$$\varepsilon = Ce^{i\beta}\left(E - E_g + i\Gamma\right)^{-\mu}$$

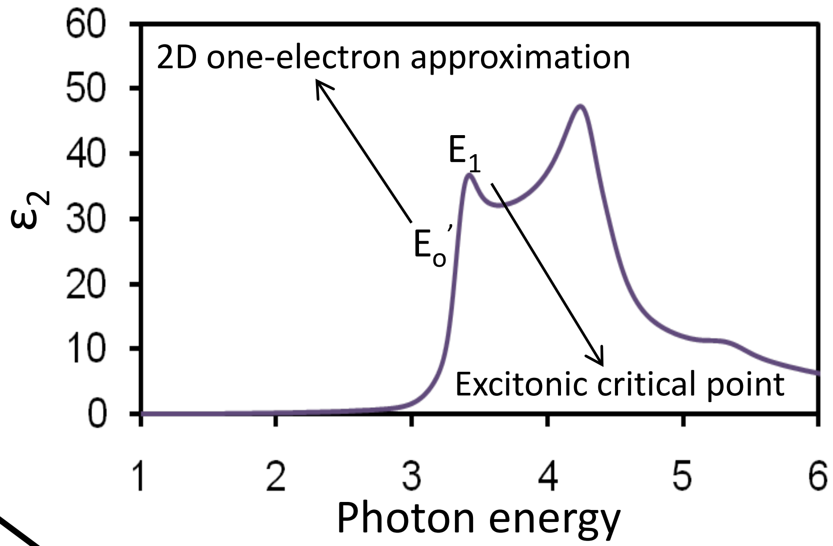
Double derivative of the Lorentzian line shape

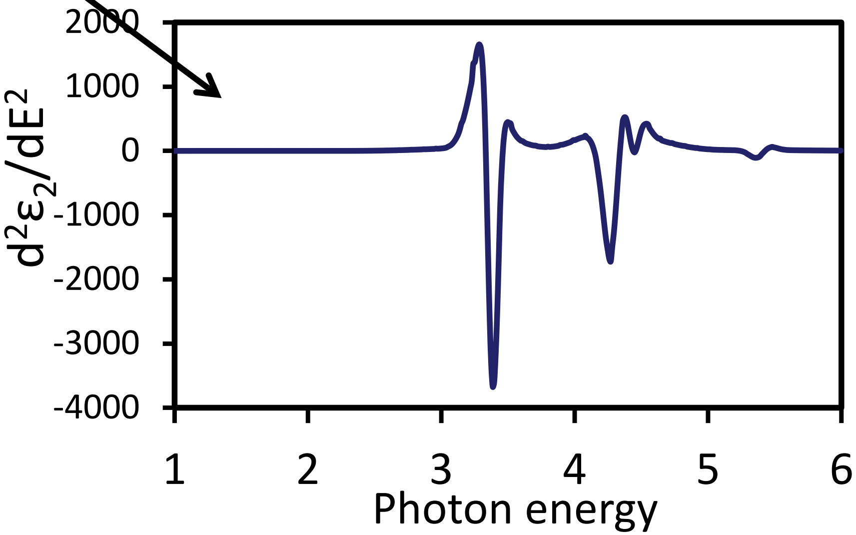
$$\frac{d^2\varepsilon}{dE^2} = \begin{cases} \mu(\mu+1)Ce^{i\beta}\left(E - E_g + i\Gamma\right)^{-\mu-2}, \mu \neq 0 \\ Ce^{i\beta}\left(E - E_g + i\Gamma\right)^{-2}, \mu = 0 \end{cases}$$

C – amplitude
β – phase factor
E_g – threshold energy (E_{CP})
Γ – lifetimebroadening
μ – order of singularity

μ = ½ (3D one-electron approximation)
μ = 0 (2D one-electron approximation)
μ = -½ (1D one-electron approximation)
μ = 1 (excitonic critical points)

Dielectric function of Si (experimental):





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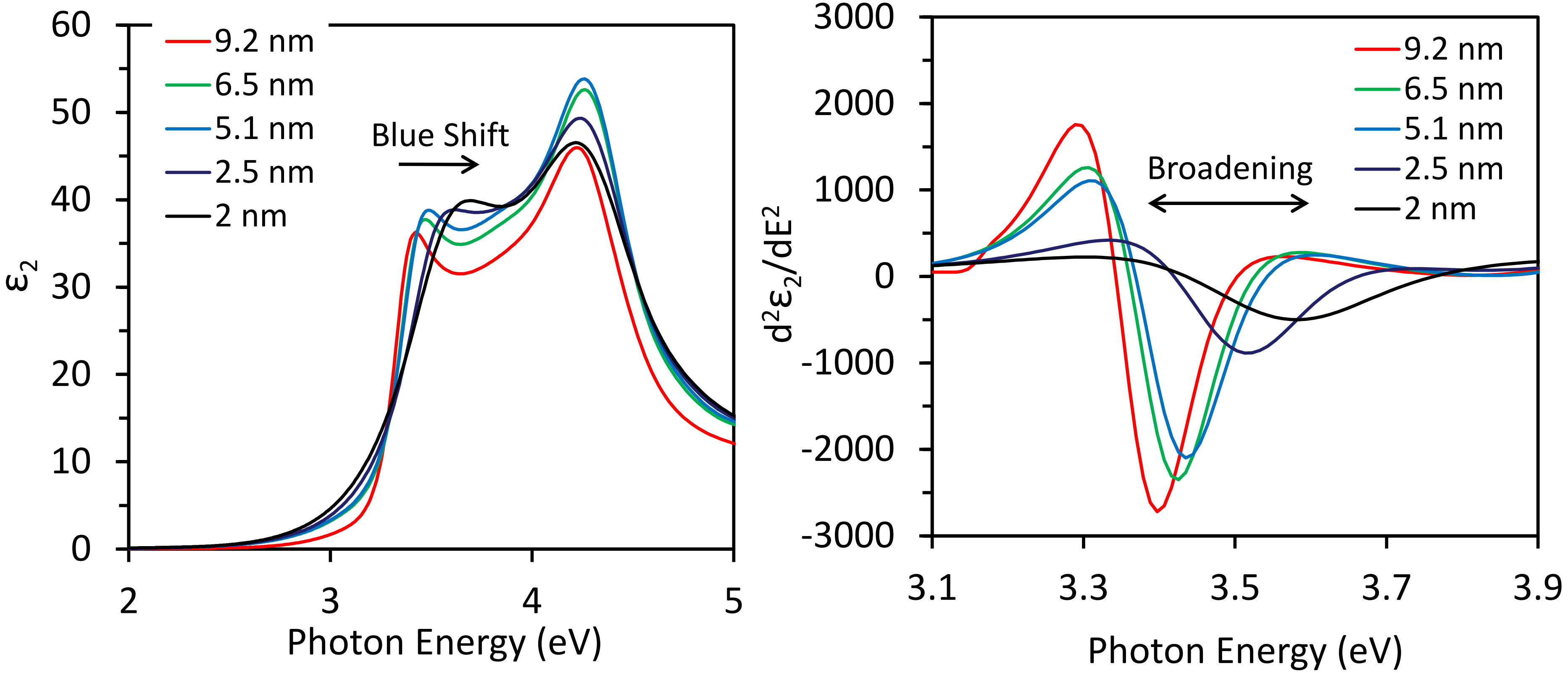
[1] P. Y. Yu and M. Cardona, Fundamentals of Semiconductors (Springer, Berlin, 2001).

Direct space analysis

Imaginary part of the dielectric function and its second derivative

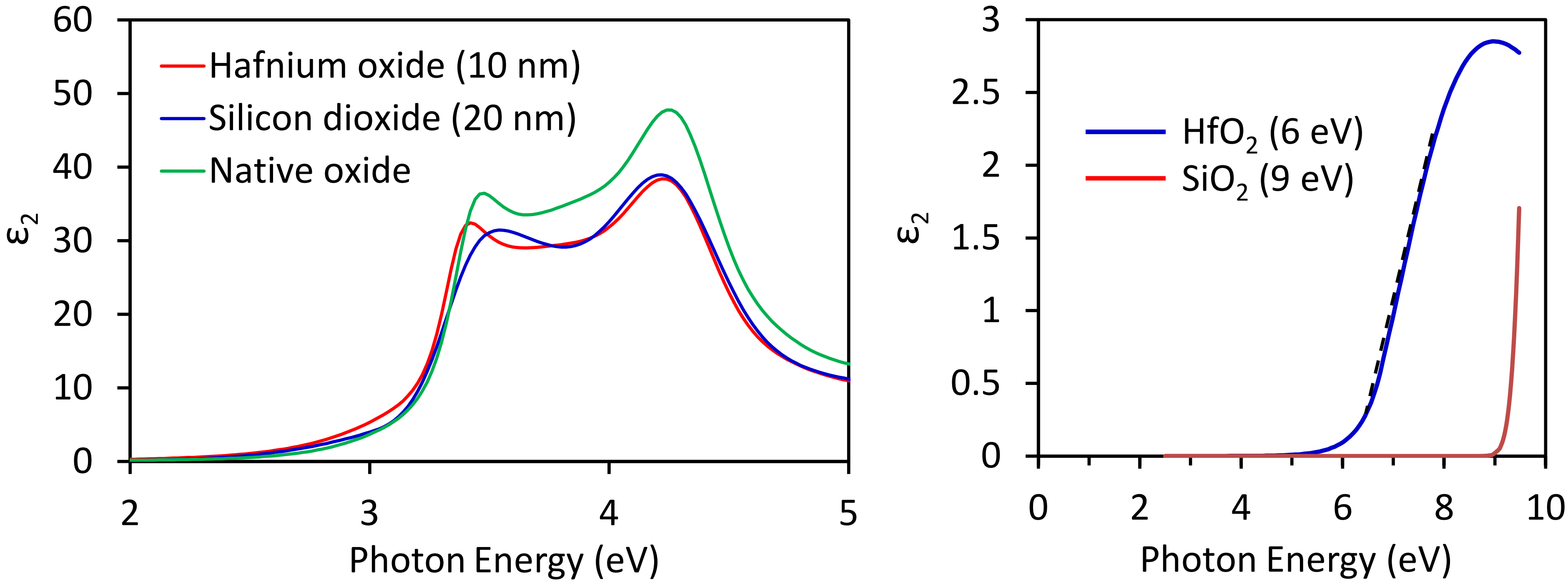


- Change in the dielectric function of c-Si nanoscale films at different thickness
- Blue shift in the critical point energy is observed

A. Diebold et al., phys. stat. sol. (a) 205, 896 (2008)

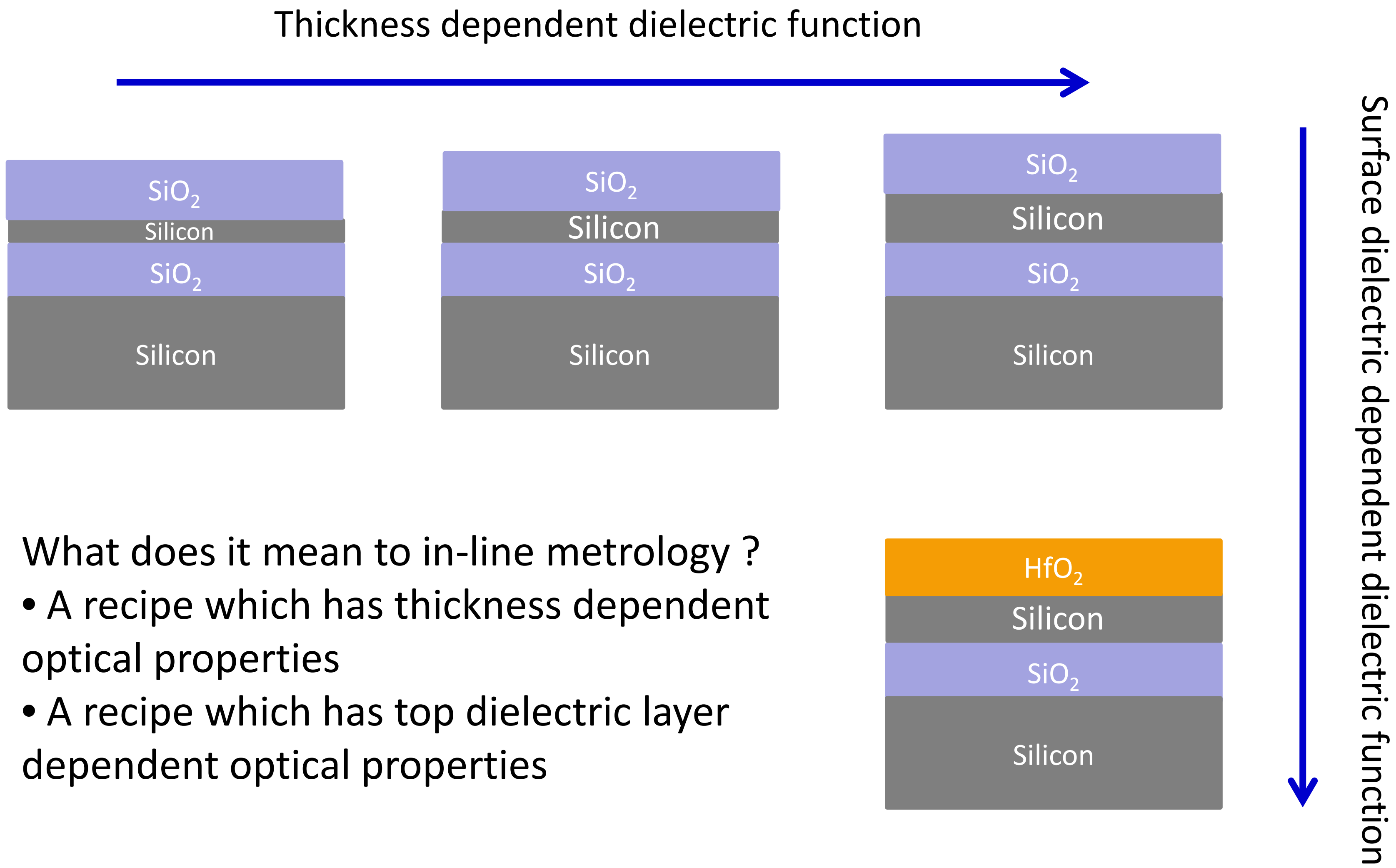
Surface dielectric layer

Imaginary part of the dielectric function of *c*-Si QWs (~ 5 nm)



Altering the optical response by changing the top dielectric layer: changes in quantum confinement and electron-phonon interaction

In-line optical metrology



What does it mean to in-line metrology ?

- A recipe which has thickness dependent optical properties
- A recipe which has top dielectric layer dependent optical properties

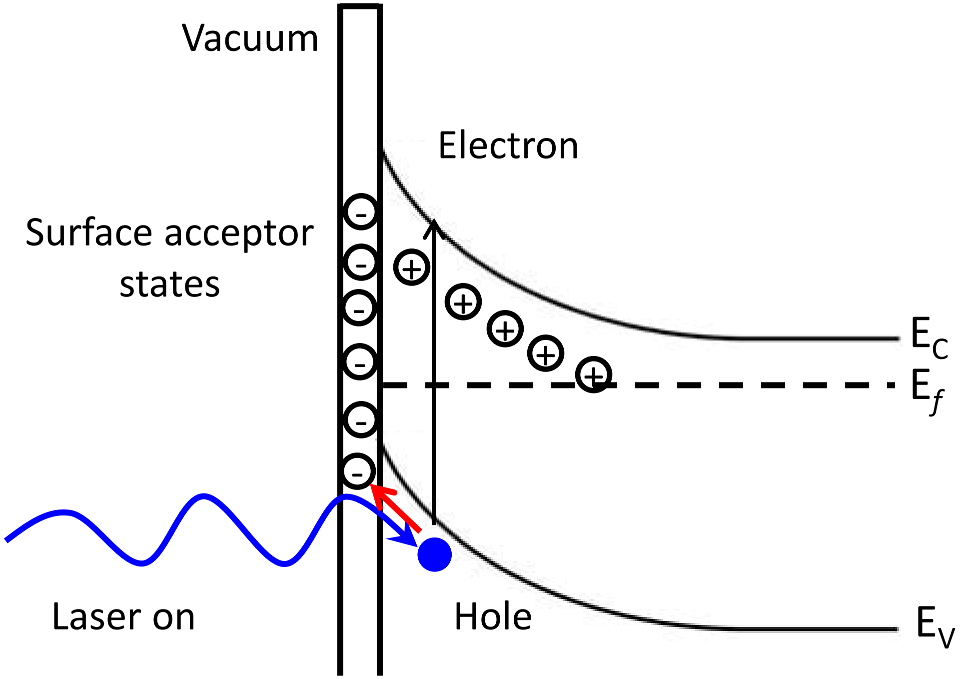
Outline

- Linear Optical Response of Materials
- Spectroscopic Ellipsometry
- Advanced Materials in the Semiconductor Industry
- Photoreflectance
- Photoluminescence
- Conclusions
- Acknowledgements

Photoreflectance

Modulation spectroscopy (non-linear optical spectroscopy)

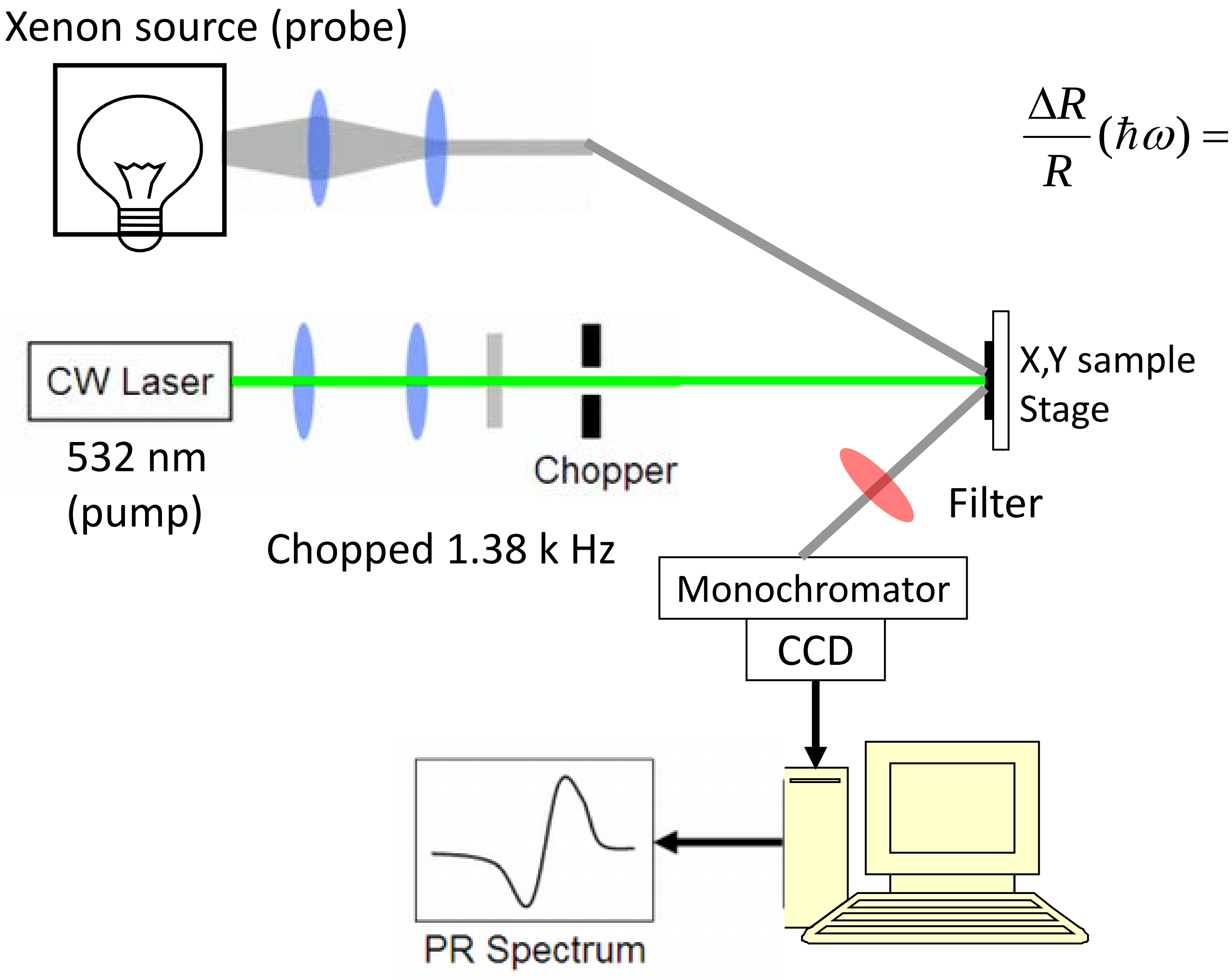
- Space charge layer at the surface due to Fermi level pinning
- Laser light produces carriers
- Carriers neutralize charge at the interface
- Modulation of light alters band bending
- Complex dielectric functions changes with band bending



n-type semiconductor

Complementary technique to measure the shift in the energy and lifetime broadening of the E_1 critical point

Photoreflectance



Xenon source (probe)

CW Laser

532 nm
(pump)

Chopper

Chopped 1.38 k Hz

X,Y sample
Stage

Filter

Monochromator

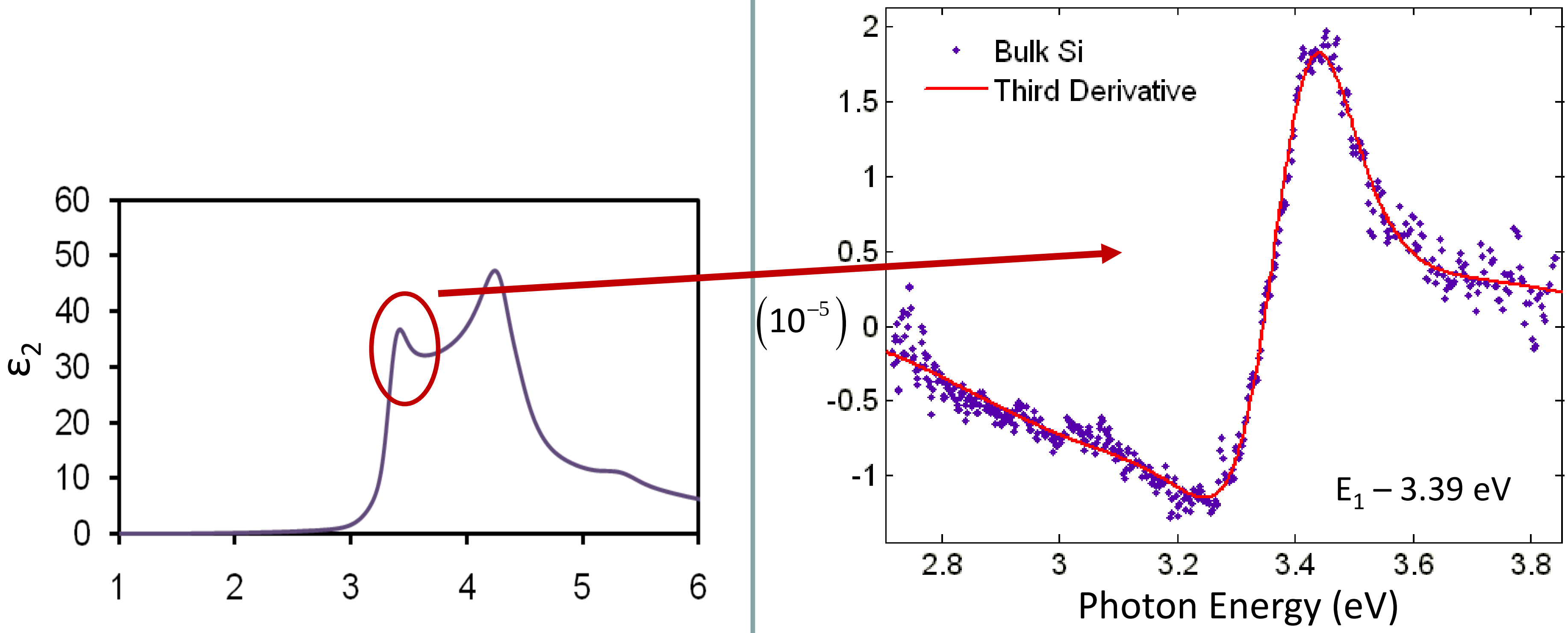
CCD

PR Spectrum

$$\frac{\Delta R}{R}(\hbar\omega) = \frac{R_{off}(\hbar\omega) - R_{on}(\hbar\omega)}{R_{off}(\hbar\omega)}$$

Photoreflectance

perimental



A: Amplitude

Θ: Phase

E_{CP}: Critical point

Γ: Lineshape Broadening

n: Determined by type of CP

Photoreflectance of Strained SOI

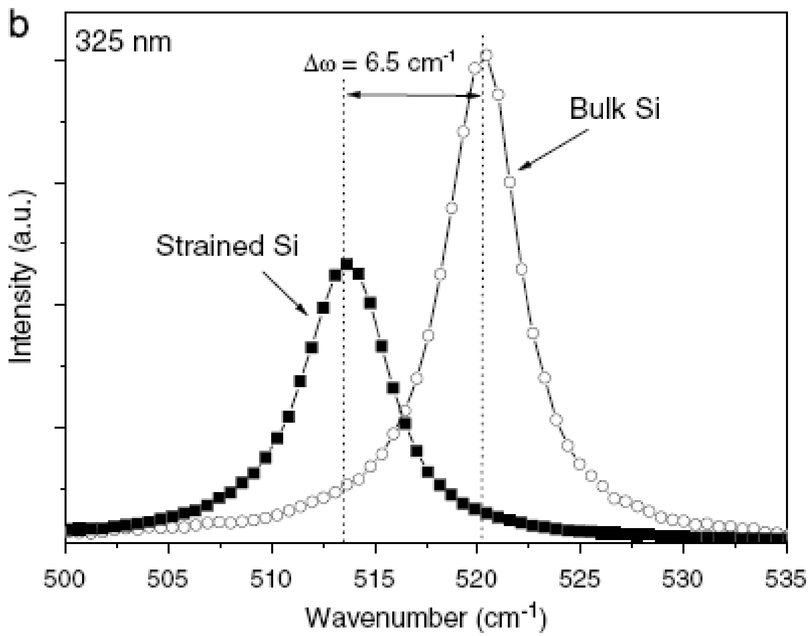


Fig. 1. Raman spectra corresponding to the sSOI sample using visible (514 nm) (a) and UV (325 nm) excitation (b).

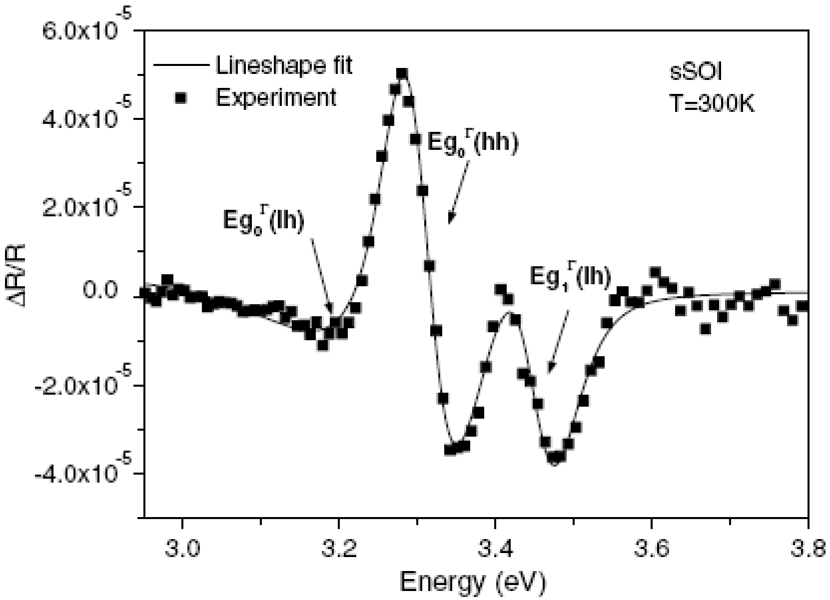


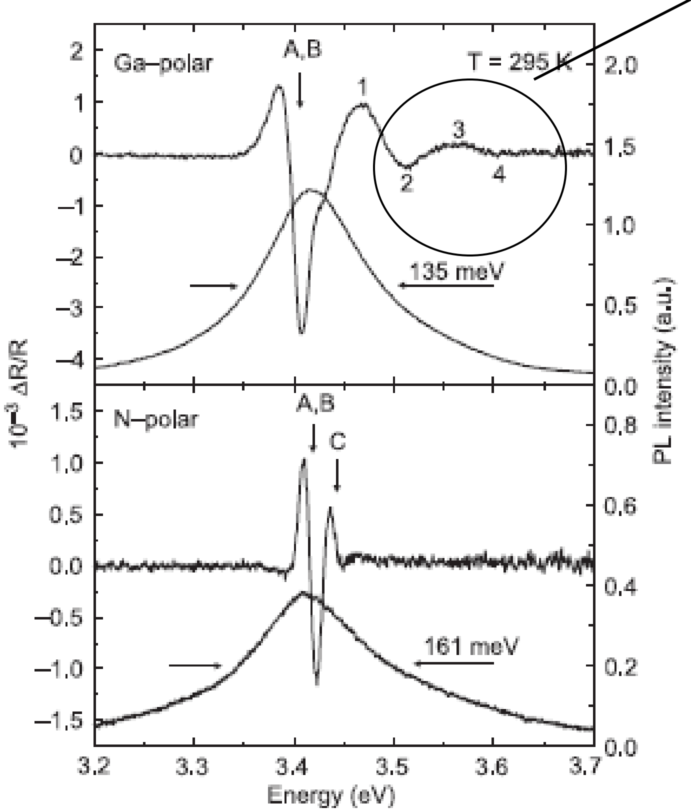
Fig. 4. PR spectrum of strained silicon layer at room temperature (dotted curve). The solid line is corresponds to the theoretical fit.

- Three transitions energies are (i) 3.19 eV, (ii) 3.30 eV and (iii) 3.45 eV.
- Calculations show tensile strain of 1% in the strained Si overlayer
- This value is again in good agreement with the nominal tensile strain and with the values obtained from RS and Low Temp PhotoLuninescence.

Nuclear Instruments and Methods in Physics Research B 253 (2006) 18–21

Franz Keldysh Oscillations

Franz Keldysh Oscillations
Due to internal electric field in polar GaN



g. 1. Photoluminescence and photoreflectance spectra of Ga-and N-polar thick GaN layers grown by HVPE.

$$\frac{\Delta R}{R} \propto \exp\left[\frac{-2\Gamma\sqrt{E-E_g}}{(\hbar\theta)^{3/2}}\right] \times\cos\left[\frac{4}{3}\left(\frac{E-E_g}{\hbar\theta}\right)^{3/2}+\phi\right]\frac{1}{E^2(E-E_g)},$$

$$F=\frac{(\hbar\theta)^{3/2}\sqrt{2\mu}}{e\hbar},$$

where $\hbar\theta$ is the electro-optic energy, Γ is the linewidth, ϕ is the phase factor, F is the electric field, and μ is the electron hole reduced mass ($\mu = 0.2\ m_e$). The field estimated from the period of FKOs is 215 kV/cm (see Fig. 3). Such a huge

OPTO-ELECTRONICS REVIEW **12**(4), 435.439

GaAsSb

Sample	A	B	C	D	E
%Sb	38.3	38	45.7	51	52.5
Thickness *d* (nm)	41	72	50	72	41
E_{GHH} (eV)	0.730	0.732	0.705	0.694	0.692
E_{GLH} (eV)	0.681	0.681	0.689	0.695	0.696
$\Delta E_{\mathrm{GHH\text{-}GLH}}$ (meV)	49	51	16	1	4
F (kV/cm)	92	52	80	54	96

Internal E Field

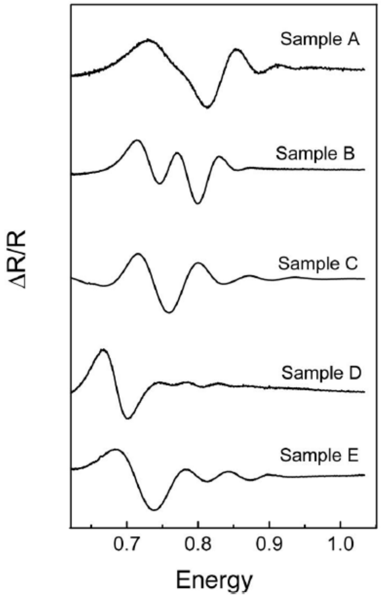
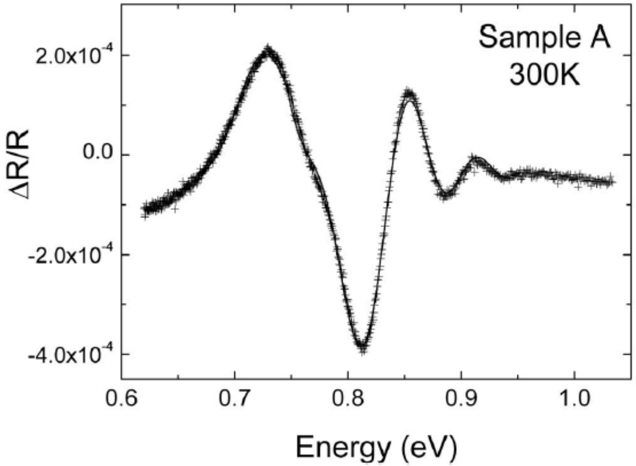


FIG. 1. Room temperature PR spectra for all samples.



Chouaib, APL 93, (2008) 041913

Outline

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- Advanced Materials in the Semiconductor Industry
- Photoreflectance
- Photoluminescence
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- Acknowledgements

Photoluminescence

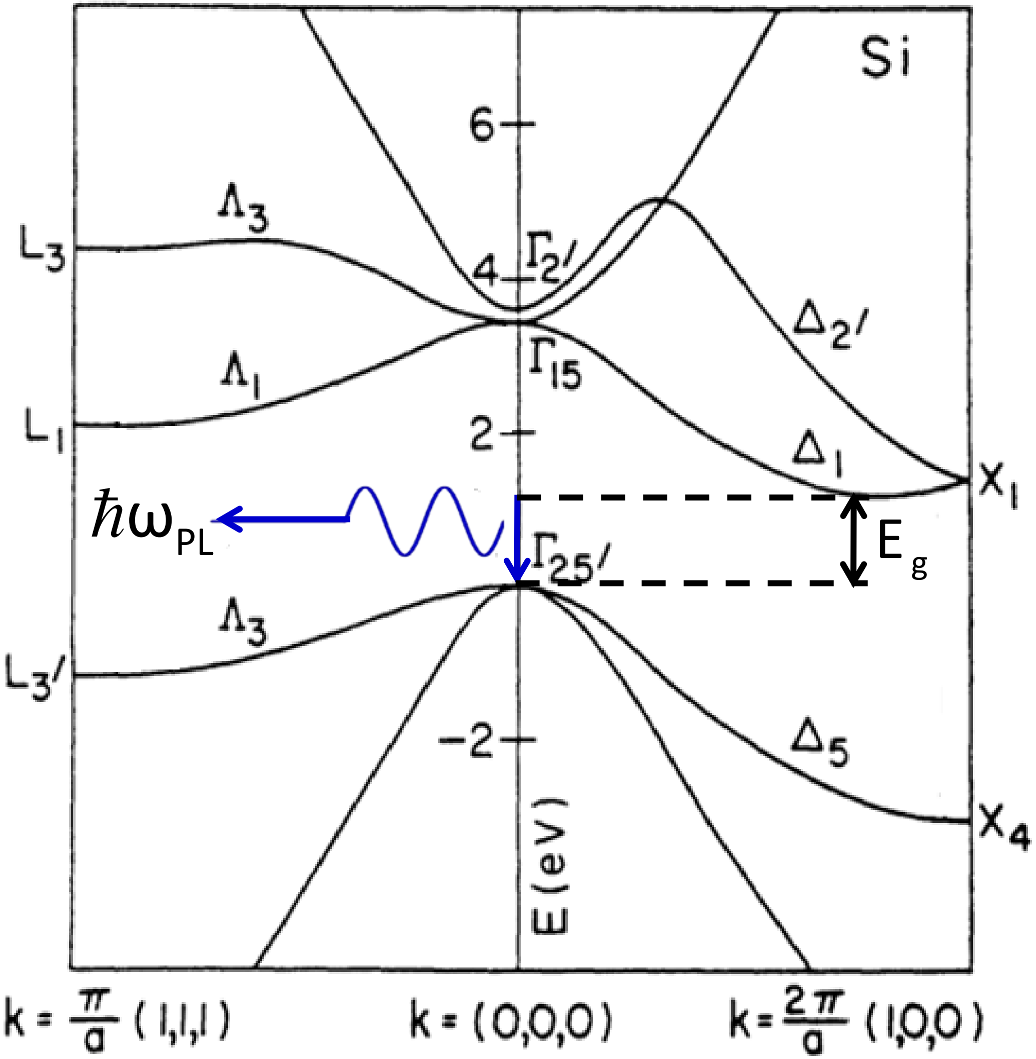
Photoluminescence is used to study the changes in the indirect transitions due to quantum confinement and change in dielectric medium

Photoluminescence peak energy (2D)

$$E = E_{gap} + E_{QC} - \frac{R_y}{\left(n - \frac{1}{2}\right)^2} + \frac{\hbar^2\left(k_x^2 + k_y^2\right)}{2M}$$

$$E_{QC} = \frac{\hbar^2\pi^2}{2ML^2}$$

$$R_y = \frac{m^*}{2}\left(\frac{e^2}{4\pi\varepsilon\hbar}\right)^2 \rightarrow \text{Rydberg}$$



Band structure of Si calculated from the **k·p** method[1]

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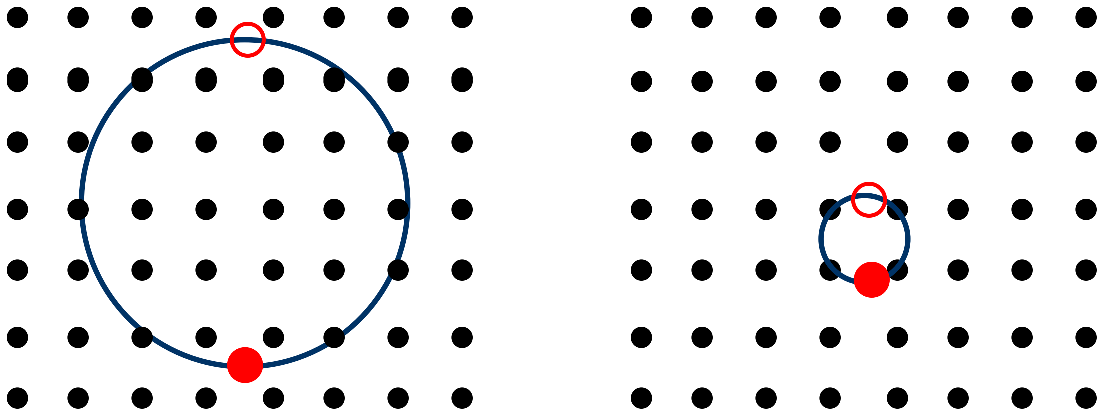
[1] M. Cardona and F. H. Pollak, Phys. Rev. B 142, 530 (1966).

Photoluminescence

BE ~ 0.01 eV



BE ~ 0.1 to 1 eV

a) Free Excitons

(Wannier-Mott Excitons)

(Delocalized states)

b) Bound Excitons

(Frenkel Excitons)

(Localized states)

$$n << \left(\frac{mk_B T}{2\pi\hbar^2}\right)^{\frac{3}{2}} Exp\left(\frac{-E_g}{2k_B T}\right)$$

As the power is increased, at high densities, and at low temperatures the free excitons condense to form a liquid phase.

This liquid phase manifests itself in the formation of EHD (Electron-hole droplets) – a broad feature in luminescence.

BE – Binding Energy

Photoluminescence of SOI Quality

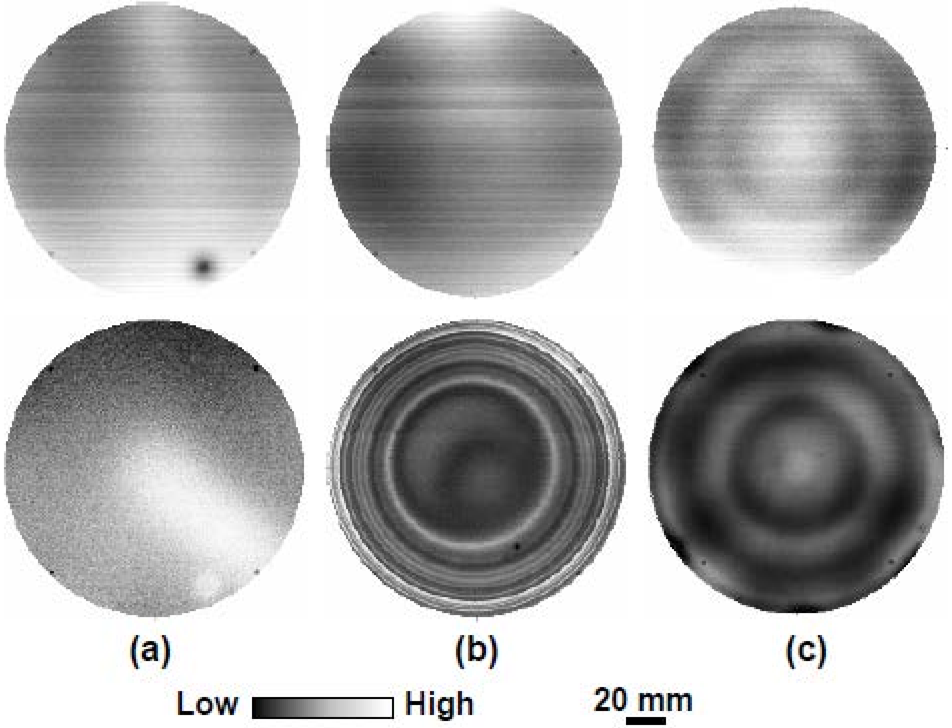


Fig. 2. PL mapping on (a) SIMOX, (b) Unibond®, and (c) ELTRAN® wafers with t_{SOI} = 170 - 200 nm at room temperature: Upper and lower figures are on top Si layers and substrates, respectively.

N. Pauc et al., Phys. Rev. B 72, 205325 (2005)

Outline

- Linear Optical Response of Materials
- Spectroscopic Ellipsometry
- Advanced Materials in the Semiconductor Industry
- Photoreflectance
- Photoluminescence
- Conclusions
- Acknowledgements

Conclusions

- A wide range of wavelengths makes Spectroscopic Ellipsometry a very powerful method capable of measuring more than just thickness and refractive index

- Non Linear Optical methods such as Photoreflectance and Photoluminescence provide information not available from spectroscopic ellipsometry

Any questions?