POROUS THIN FILMS CHARACTERIZED BY SPECTROSCOPIC ELLIPSOMETRY

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Porous “Low-K” Thin-Film Dielectrics for ULSI Chip Manufacture

- “Host” film may be silicate glass or organic polymer
- k is reduced further by introducing voids into the film
  - physical templating
  - steric effects from attached functional groups
  - mixing of dissimilar materials, followed by removal of one (usually by thermal degradation)
- void radius “R” can vary from < 10 A to > 1000A
- Void density can vary typically from 10 % to 60%
  - Higher densities typically observed in silicate films

Spectroscopic Ellipsometry

- **Spectroscopic Ellipsometry (SE)**
  - **SOPRA ES4G**
  - **Data Collection**
- **Modeling**
  - **Point-by-Point**
  - **Cauchy Law**
  - **Effective Medium Approximation(EMA)**
- **Thin films Characterized by SE**

  - Porous silicon dioxide (Sample #1; Sample #2)
  - **Point-by-point, Cauchy law and EMA**

  - Porous polyimide (Sample #3, Sample #4)
  - **Point-by-point, Cauchy law and EMA**
- **Conclusions**

Overview of Ellipsometry

- **What is Ellipsometry?**

  Measurement of the state of polarization of a polarized vector wave.
- **Advantages of Ellipsometry**
  - Non-contact, non-destructive method
  - Suitability for in-situ measurements
  - Sensitivity to minute interfacial effects
- **Applications**
  - Determine thickness
  - Determine refractive index and extinction coefficient
- **Limitations**
  - Quality and property of thin films
  - Modeling

SOPRA ES4G

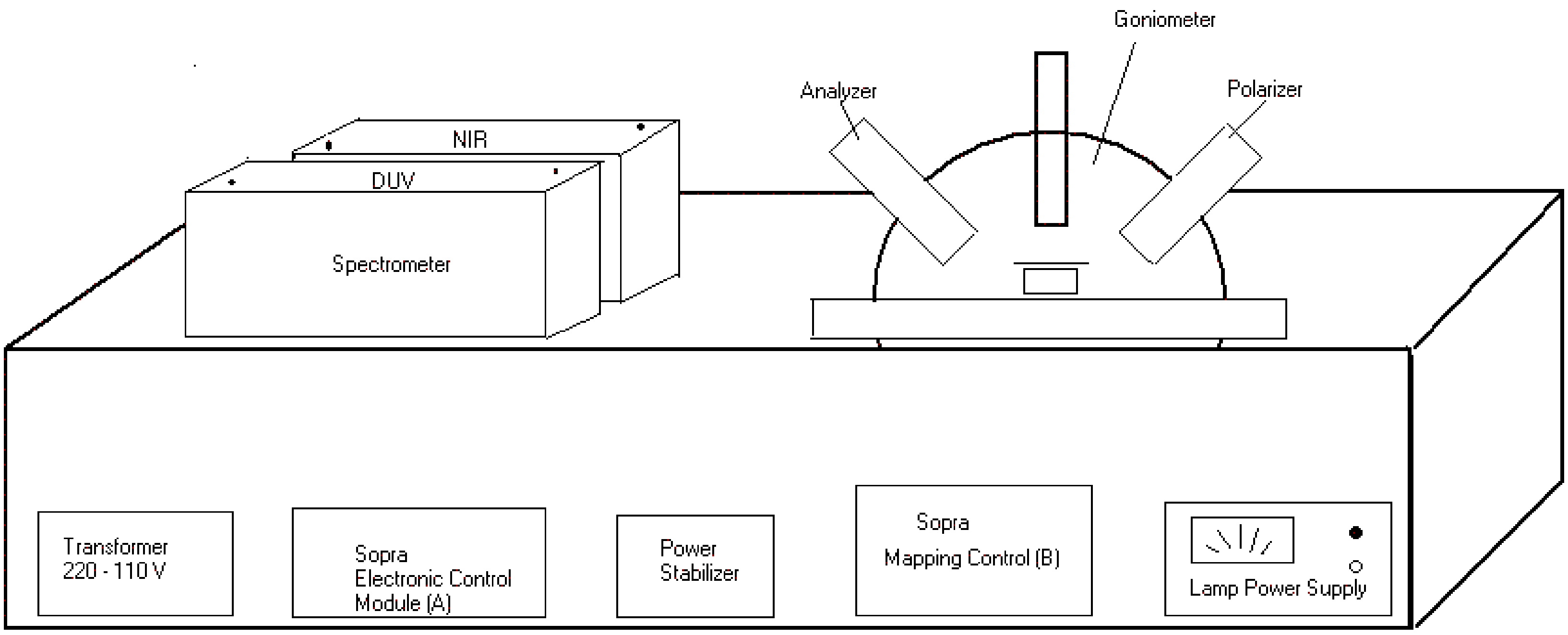


Figure 1. Sopra System Setup

Data Collection

- **Measurement of phase difference and amplitude change upon reflection:**
  - **Tan(Psi) and Cos(Delta) at each wavelength**
- **Working wavelength range: 190-1700nm**
- **Microspot: 50 x 80 μm**

Ellipsometry Equations

The SOPRA Ellipsometer measures tan ψ and cos Δ where tan ψ and cos Δ are given by:

$$\tan\ \psi = \frac{|R_p|}{|R_s|}$$

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

- **Rp and Rs are ratios of outgoing wave amplitude to the incoming wave amplitude for parallel and perpendicular components**
- **δ_1 and δ_2 denote the phase difference between the parallel component and perpendicular component of the incoming wave and outgoing wave**

Modeling available via Winelli

- **Dispersion Models**
  - Standard Dielectric Function
    - Cauchy Law
  - Forouhi Bloomer
- **Point by Point Extraction(PP)**
  - NK Extraction
    - n and k calculation at each wavelength with known thickness
  - NT Extraction
    - n and thickness calculation at each wavelength with k=0 (usually in the NIR for dielectrics)
- **Mixed Material Models**
  - based on n&k library files of media under mixing

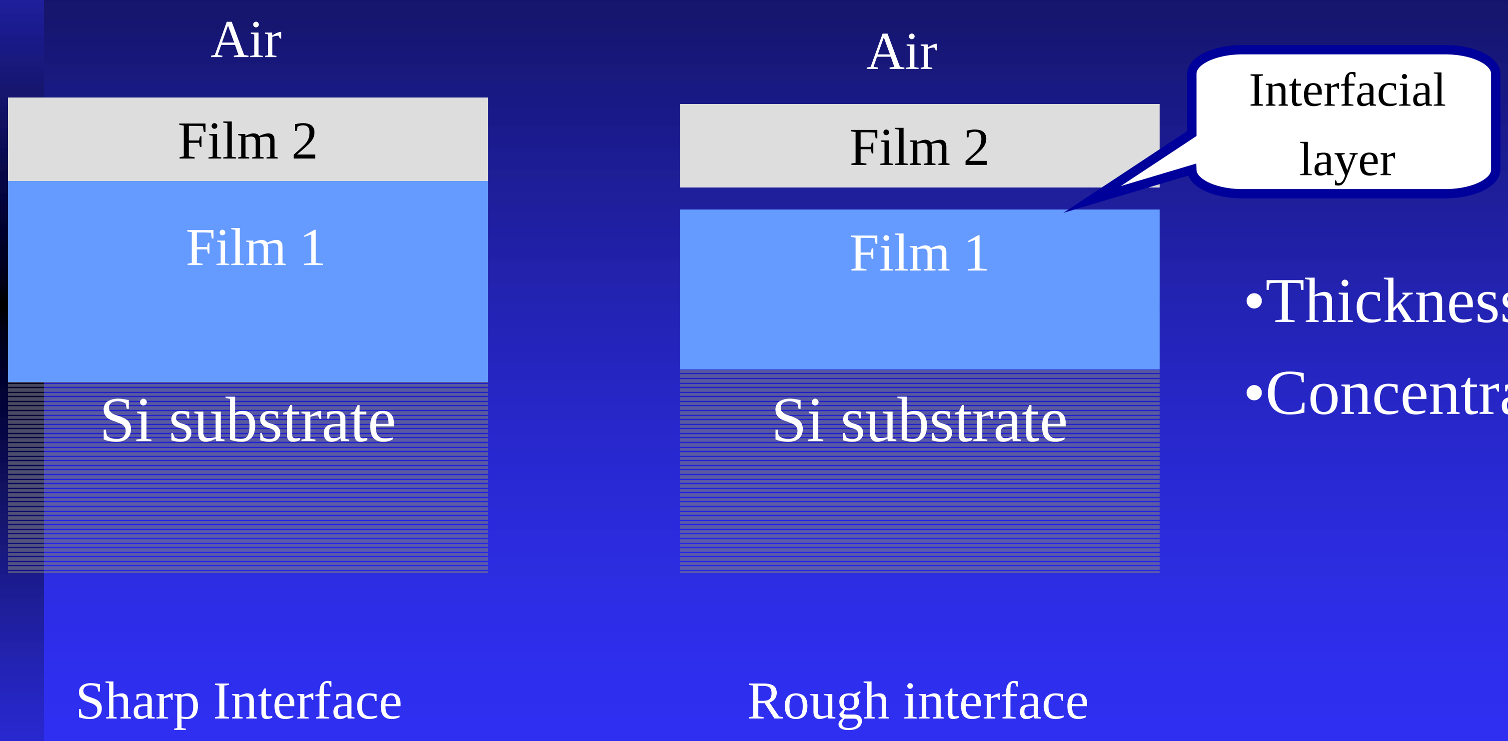
Mixed Materials Models

- **Effective Medium Approximation (EMA)**
  - **Bruggeman approximation**

$$0 = f\,\frac{\varepsilon_1 - \langle\varepsilon\rangle}{\varepsilon_1 + 2\langle\varepsilon\rangle} + (1 - f)\,\frac{\varepsilon_2 - \langle\varepsilon\rangle}{\varepsilon_2 + 2\langle\varepsilon\rangle}$$

where f is the volume ratio of material 2, $\langle\varepsilon\rangle$ is the effective dielectric function, ε_1 and ε_2 are the dielectric function of the two media under mixing

Two EMA Models

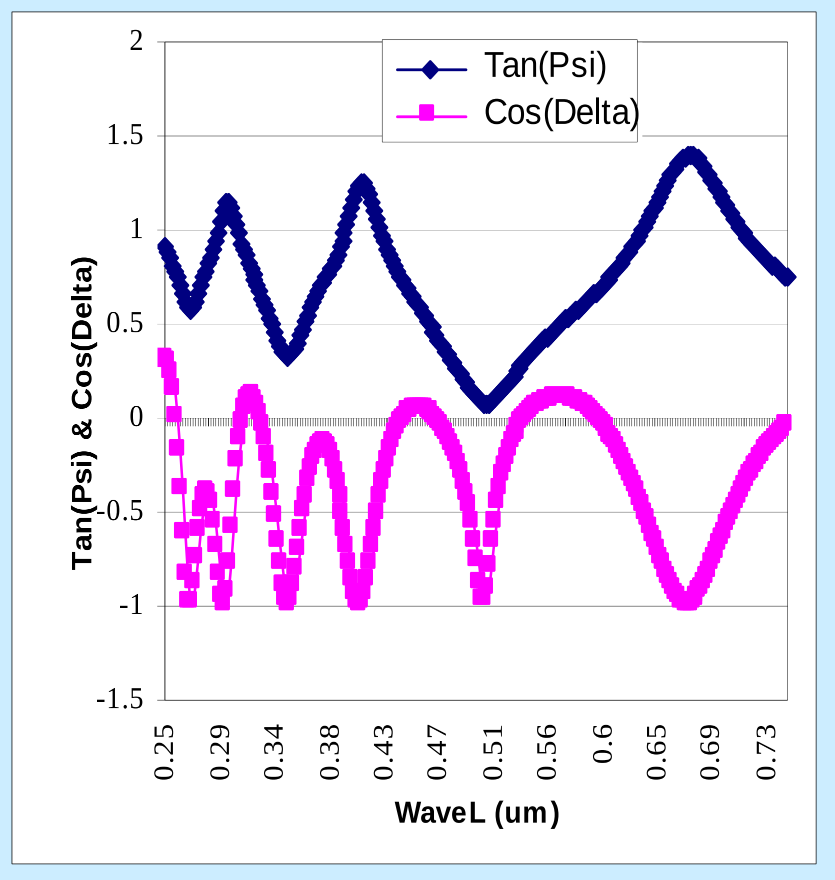


- Thickness
- Concentration

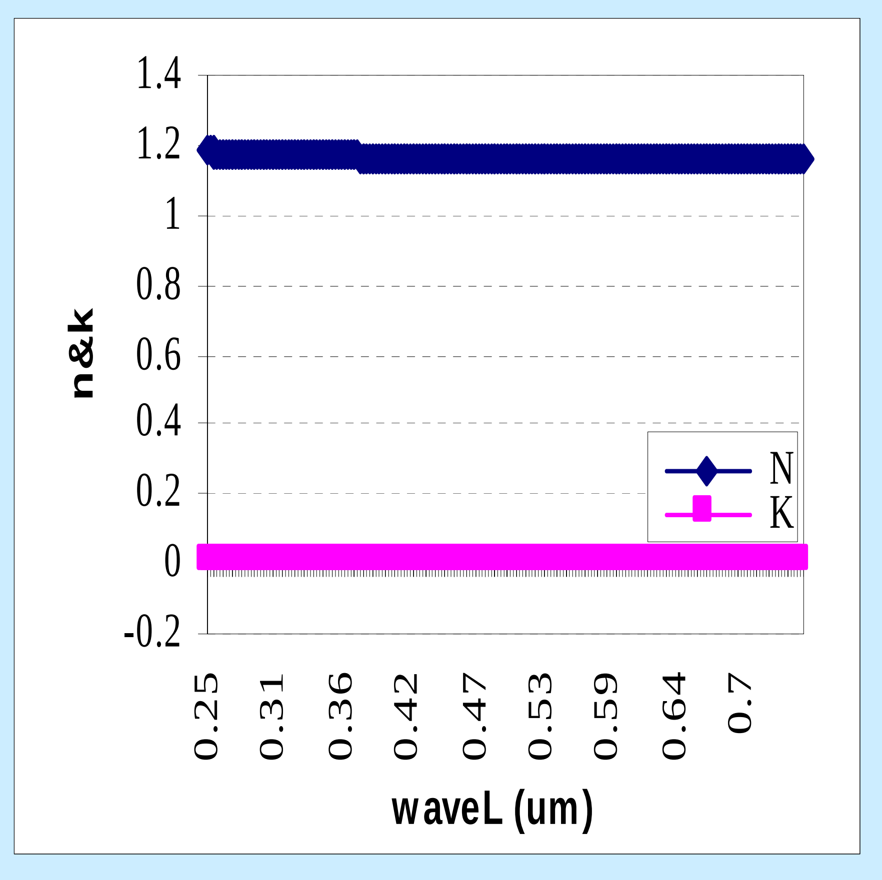
Sample #1
(λ >> R=void radius, fine voids)

- **Models:**
  - **Point-by-Point(PP)**
    - **NT extraction in the NIR range (k=0)**
    - **NK extraction spectra in full wavelength (250-750nm)**
  - **EMA**
    - **EMA using SiO_2 + Air doesn't give good fit**
  - **Cauchy law**
    - **Produce same results as PP**

Sample #1 (cont'd)

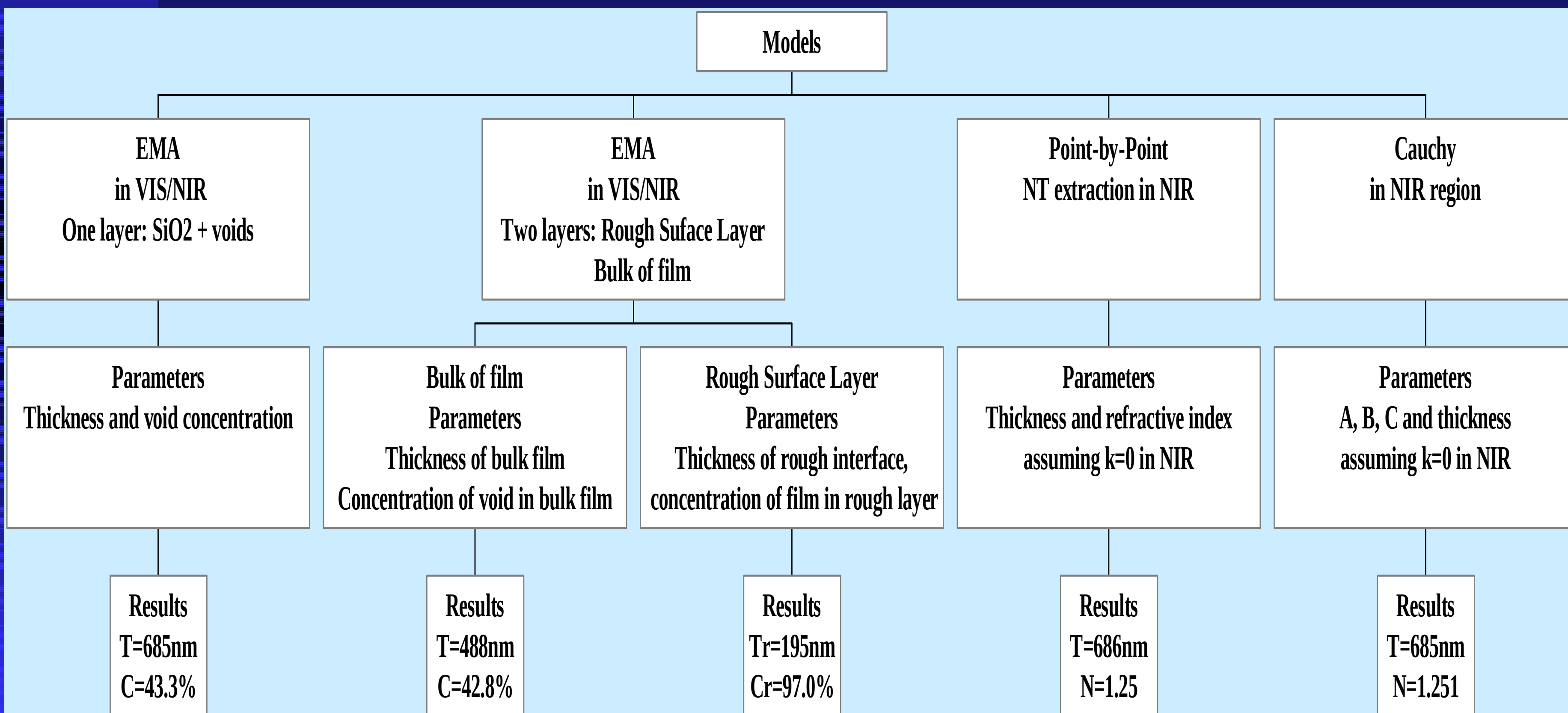


Experimental data tan(psi) & cos(delta)



Optical constants obtained from NK extraction

Sample #2
(λ ~ R, Void density=D ~R, large voids)



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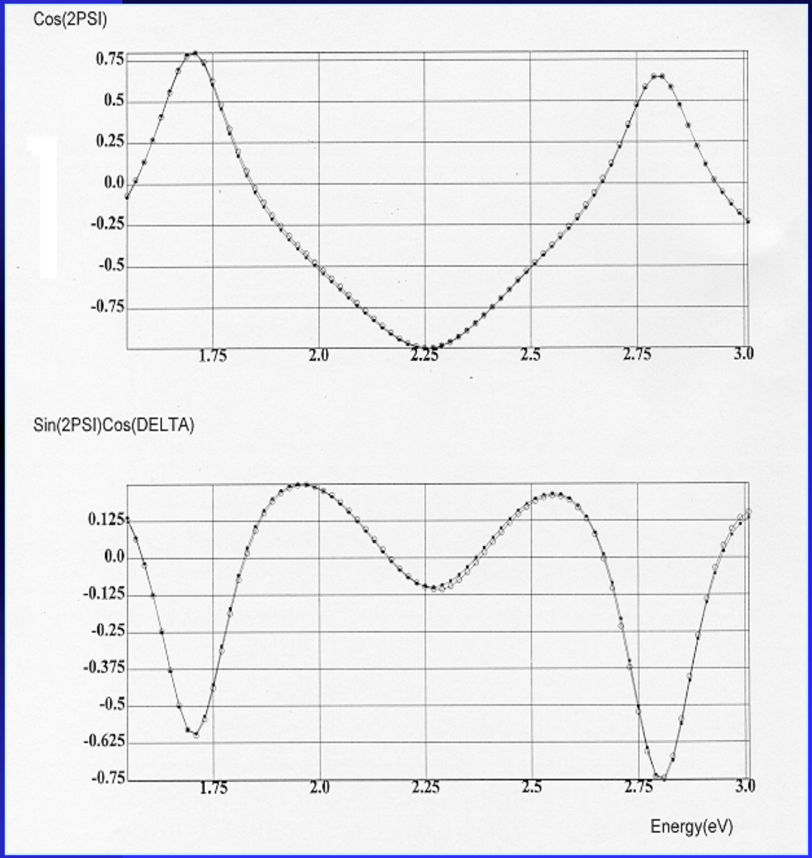
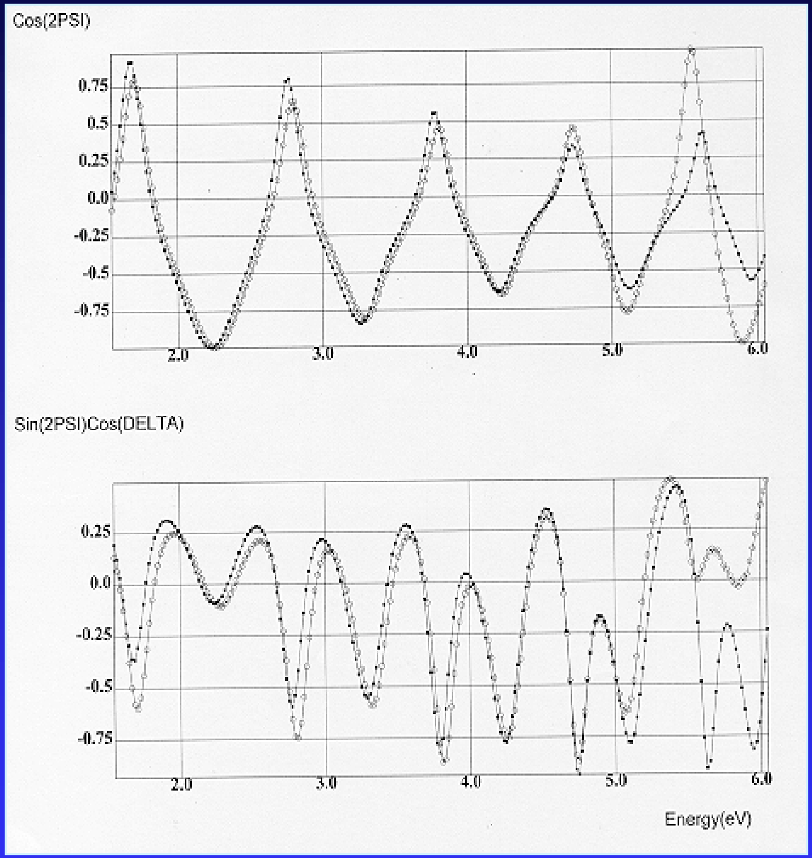
Sample #2 (cont'd)

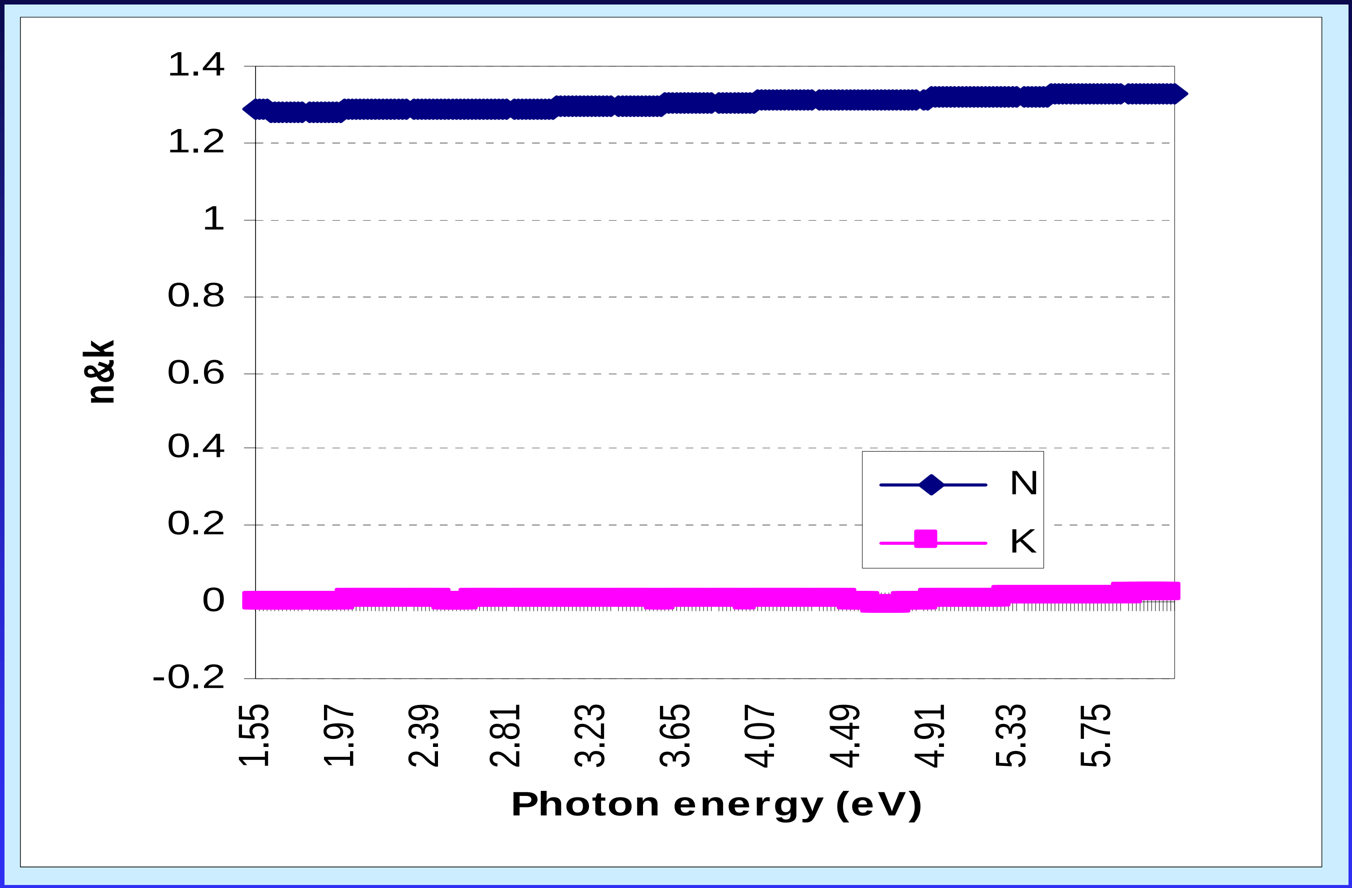


EMA fit to the experimental data in VIS-NIR region



EMA fit to the experimental data in full region

Sample #2 (cont'd)



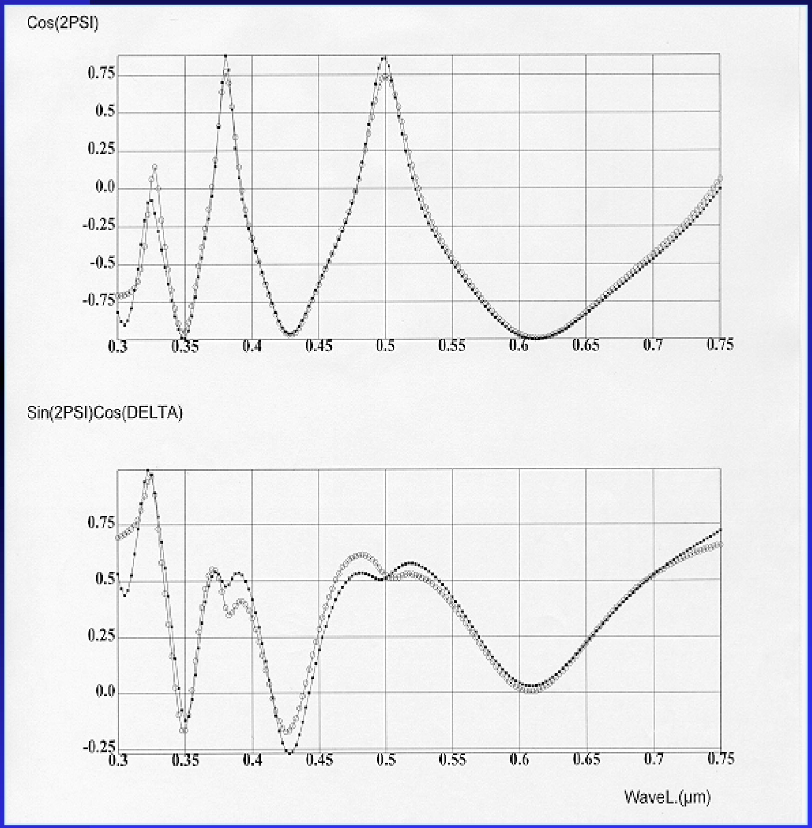
Optical constants obtained from NK extraction

Sample #3: polyimide
(λ > R, D > R, medium voids)

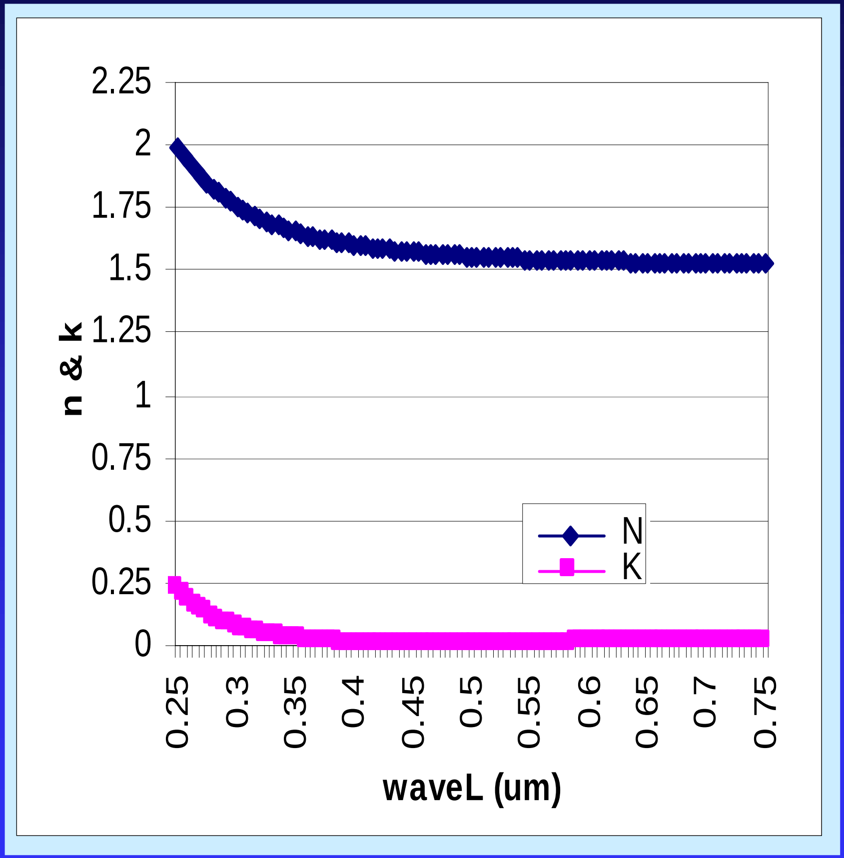
Models

- **EMA** — One layer: dense film + voids
  - Parameters: Thickness and void concentration
    - Results: T=513nm, C=14.4%
- **EMA** — Two layers: Rough Interface, Bulk of film
  - Parameters: Thickness of bulk film, Concentration of void in bulk film
    - Results: T=503nm, C=14.2%
  - Parameters: Thickness of rough interface, concentration of film in rough layer
    - Results: Tr=9.5nm, Cr=97.0%
- **Point-by-Point** — NT extraction in NIR
  - Parameters: Thickness and refractive index assuming k=0 in NIR
    - Results: T=512nm, N=1.51
- **Cauchy** — In NIR region
  - Parameters: A, B, C and thickness assuming k=0 in NIR
    - Results: T=471nm, N=1.59

Sample #3 (cont'd)



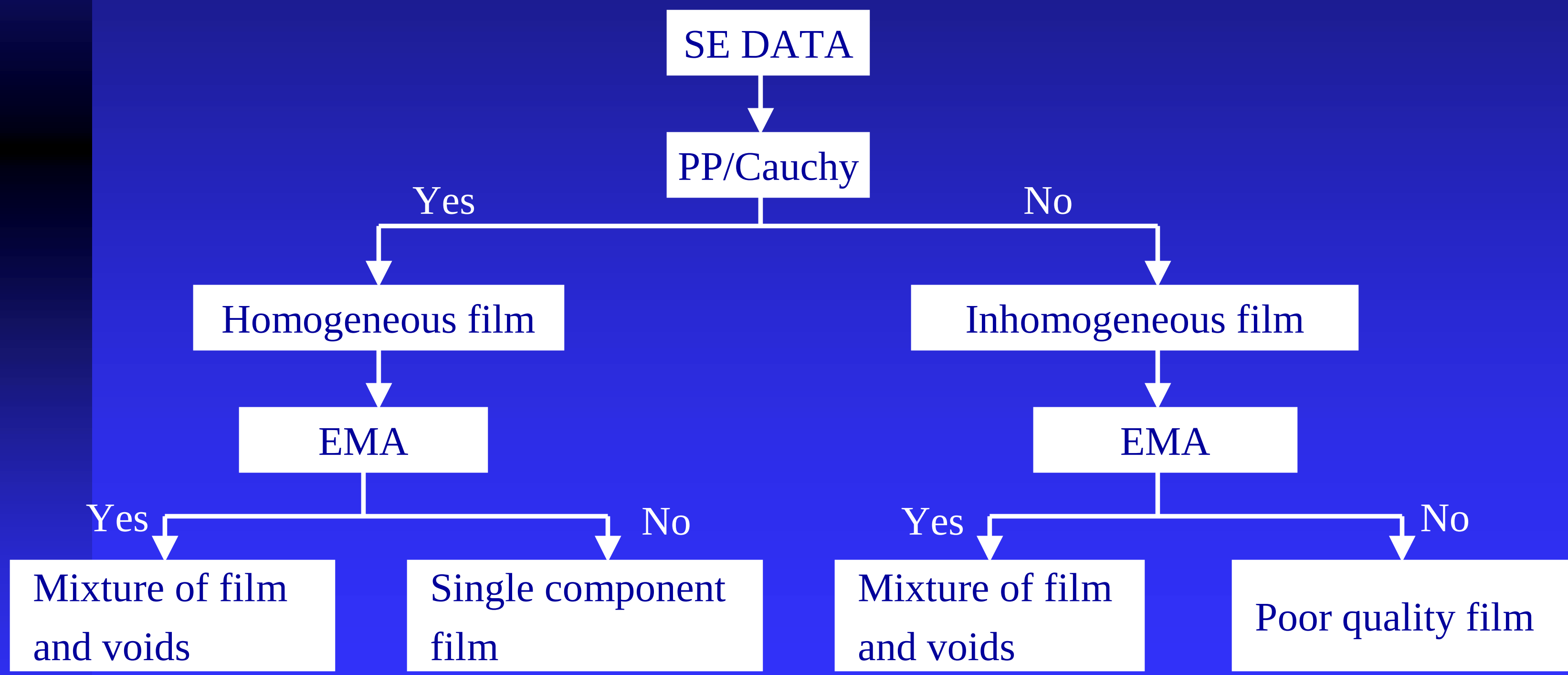
Cauchy fit to extract the n&k profile



Optical constants obtained from Cauchy law

Conclusions

Sample ID	Models		Material Type		λ / R
	PP/Cauchy	EMA	Single/Mixed	Void Distribution	
Sample #1	Yes/Yes	No	Single	NA	>> 20 (from process)
Sample #2	Yes/Yes	Yes	Mixed	Highly homogeneous	> 1 (from data)
Sample #3	Yes/No	Yes	Mixed	Moderately homogeneous	> 20 (from data)



Conclusions

- Current "most popular" candidates for "low-k" dielectric applications have void radii that are too small to be studied by SE out to 193 nm.
  - SE used during development of these materials
- SE may be useful for examining future material since further reductions in k may be attempted by introducing a low density of larger voids into the current generation of films
- EMA is limited in its ability to analyze voidy films.
  - New models needed that explicitly include void radii and void spacing.