NCCAVS Thin Film User Group

Optical Metrology of Low-κ Dielectrics

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Outline

- Optical Thin Film Metrology
  - Hardware
  - Analysis Algorithms
- Correlation of Optical Properties With Thin Film Processing Conditions
- Correlation of Refractive Index With Dielectric Constant
- Examples of Low-κ Applications
  - Porous MSQ
  - SiLK
  - Inhomogenous Low-κ Films on Cu and W
  - Characterization of Plasma-Induced Damage of Treated Low-κ Films
- Conclusions

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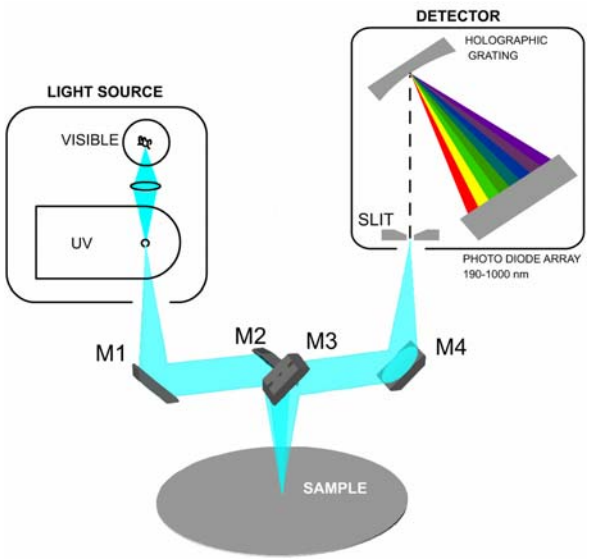
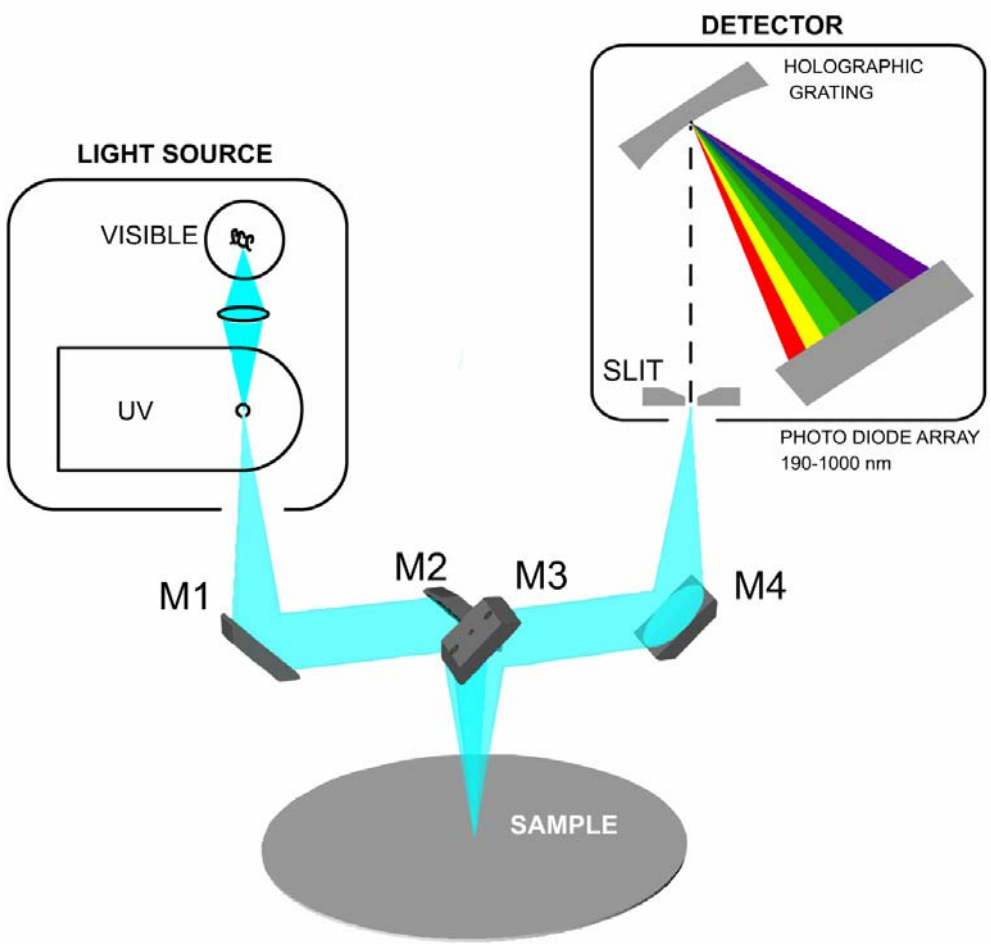
Optical System

- ***Method: Broadband Reflectometry***
- ***Spectral Range: 190 nm – 1000 nm***
- ***Optical Design: All-Reflective Optics***



n&k Analyzer 3300

Optical System



Analysis Model

Forouhi–Bloomer Dispersion Relations:

$$k(E) = \sum_{i=1}^{q} \frac{A_i (E - E_g)^2}{E^2 - B_i E + C_i}$$

$$n(E) = n(\infty) + \sum_{i}^{q} \frac{B_{0_i} E + C_{0_i}}{E^2 - B_i E + C_i}$$

The "n&k Method" is an accurate, reproducible thin film characterization technique, that incorporates the Forouhi-Bloomer dispersion relations for $n(\lambda)$ and $k(\lambda)$, along with a parameterized models for inhomogeneity and interface roughness, into Fresnel equations to generate theoretical Reflectance spectrum (R_{theor}) in terms of d, $n_f(\lambda)$, $k_f(\lambda)$, E_g, $n_s(\lambda)$, $k_s(\lambda)$, $\sigma_1(top)$ and $\sigma_2(bottom)$, whereby the wavelength and material dependence of $n(\lambda)$ and $k(\lambda)$ are obtained from the Forouhi-Bloomer formulation.

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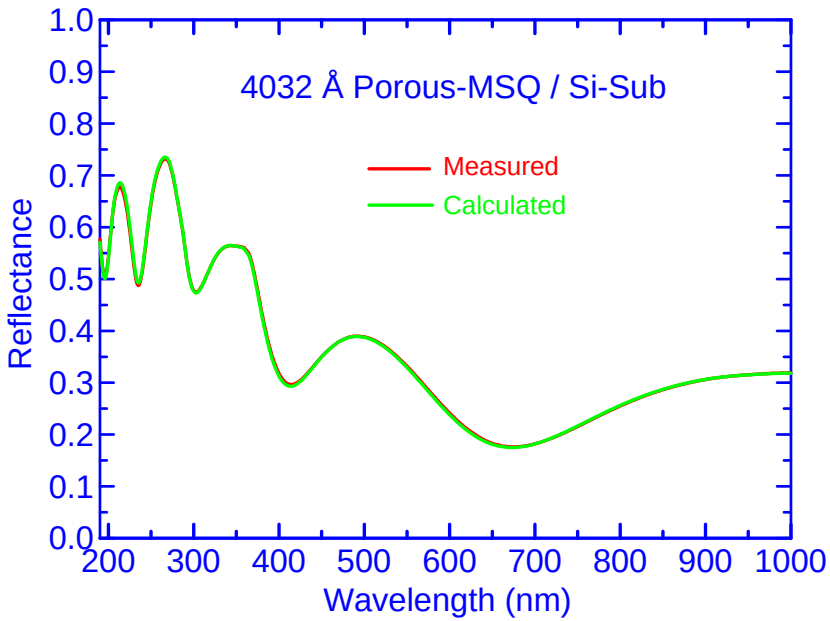
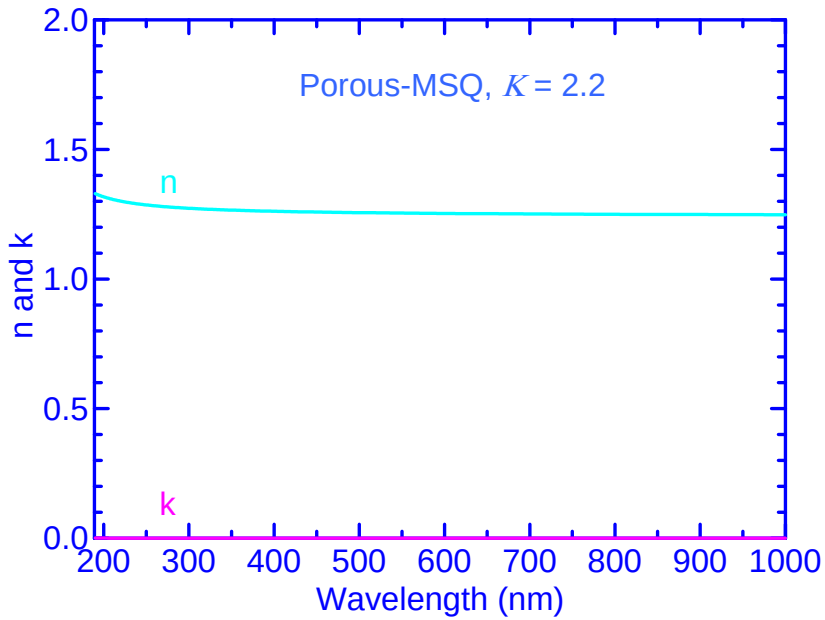
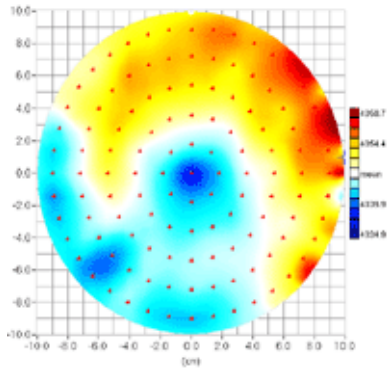
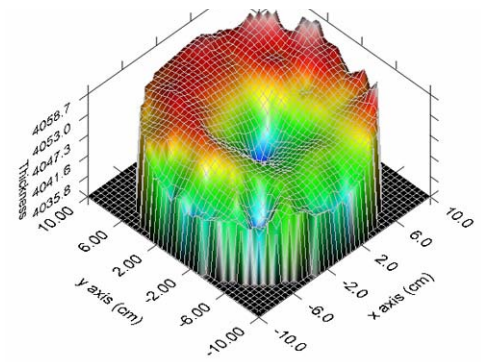
Porous-MSQ





2D Thickness Uniformity Map





3D Thickness Uniformity Map

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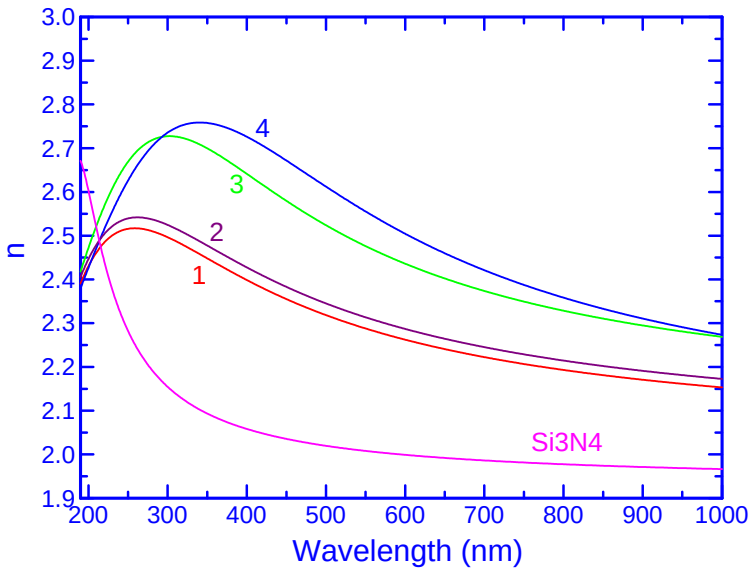
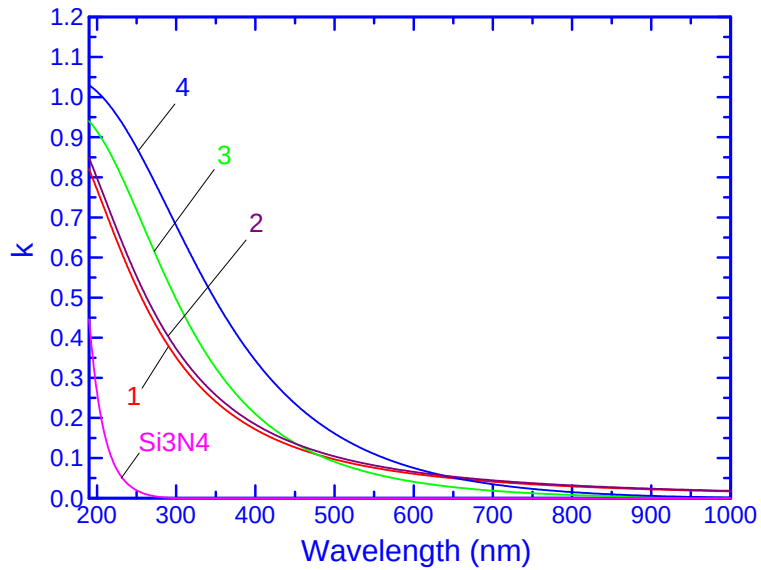
Materials Characterization

Si-to-N Ratio in SiN_X Films

Correlation: The higher the values of *k* in the DUV, the higher the Si-to-N ratio of the SiN_x films

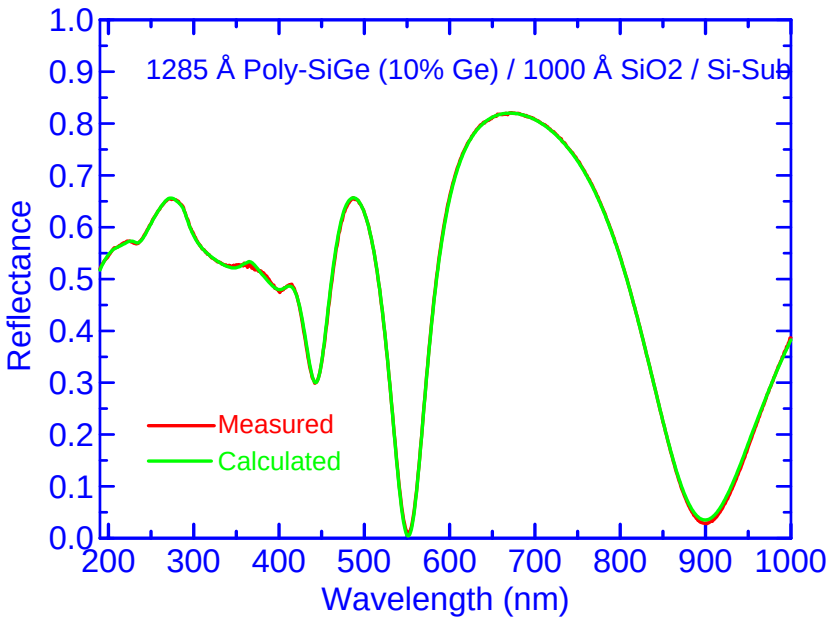
***n* and *k* Spectra of Si_3N_4 and various SiN_x films**

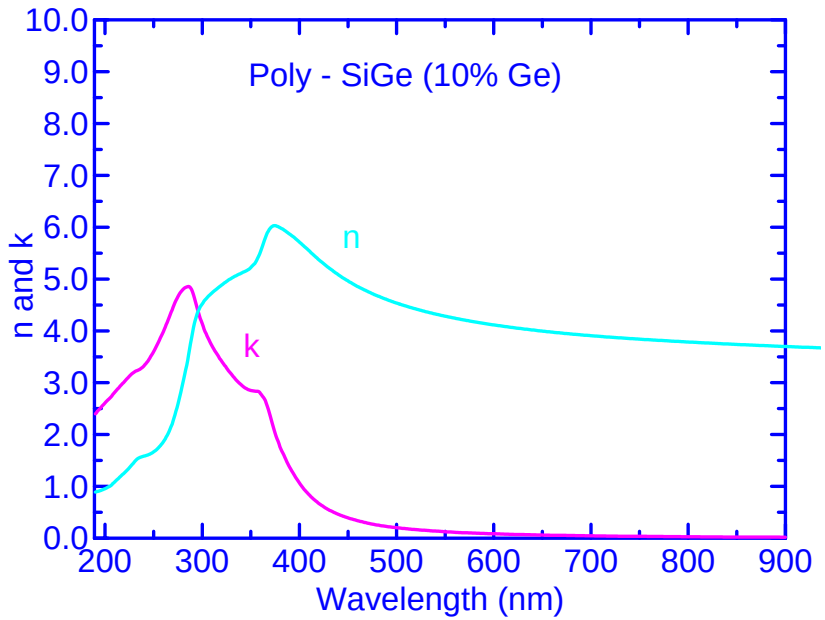




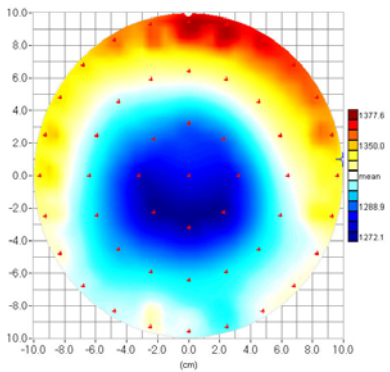
Materials Characterization

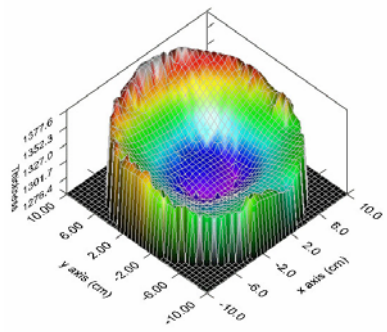
Polycrystalline Si_XGe_{1-X} (10% Ge)





2D Thickness Uniformity Map





3D Thickness Uniformity Map

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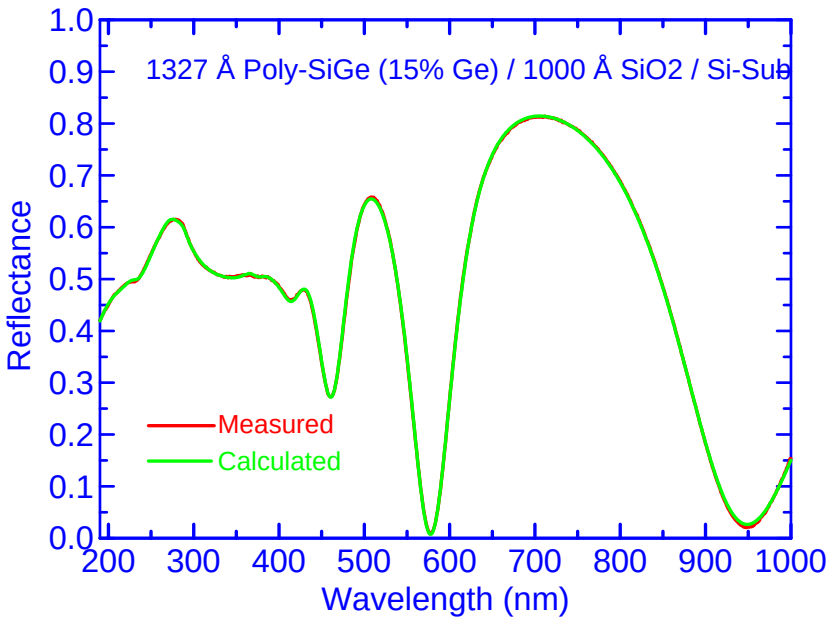
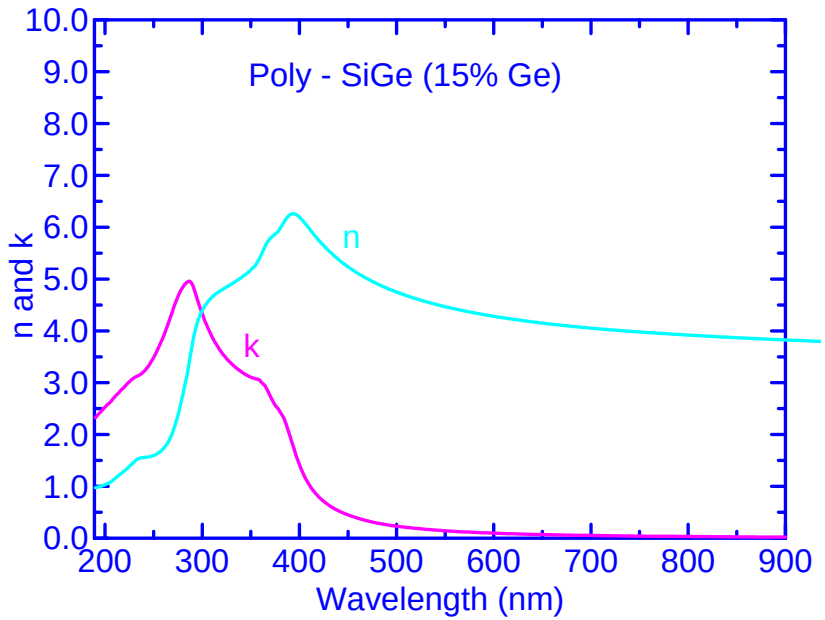
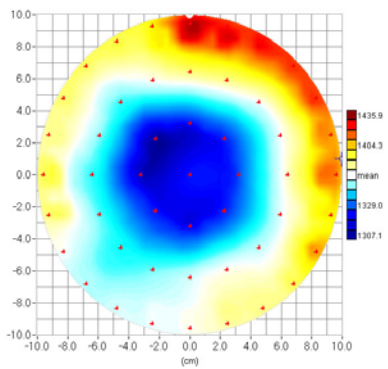
Materials Characterization

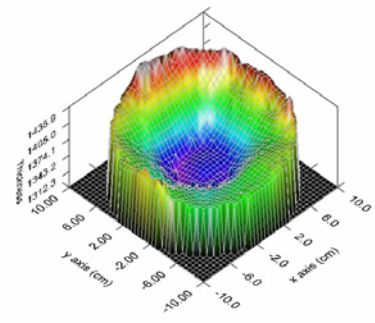
Polycrystalline Si_XGe_{1-X} (15% Ge)





2D Thickness Uniformity Map

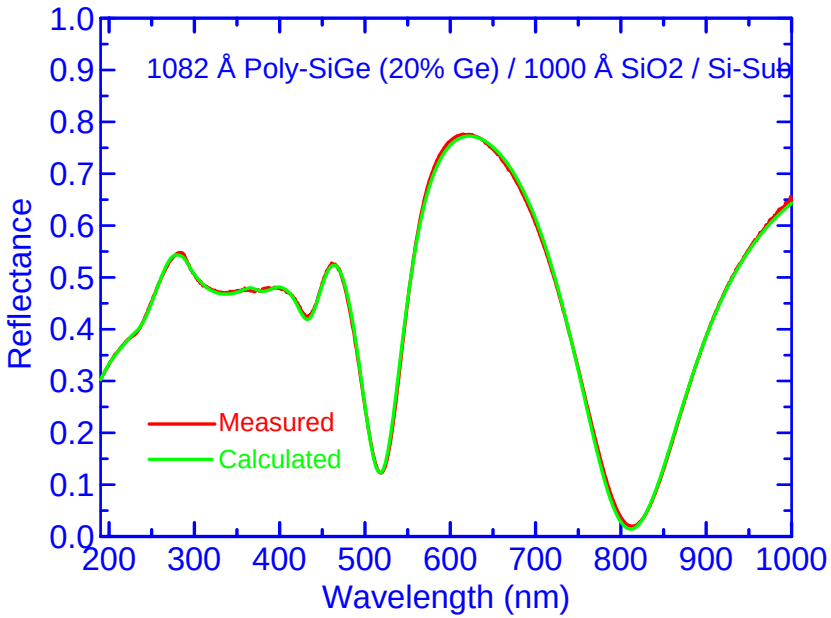


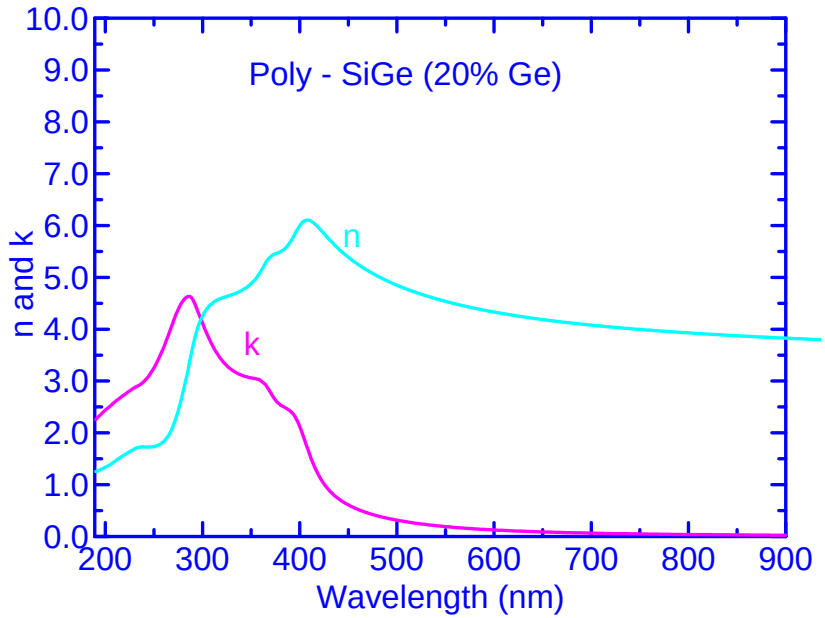


3D Thickness Uniformity Map

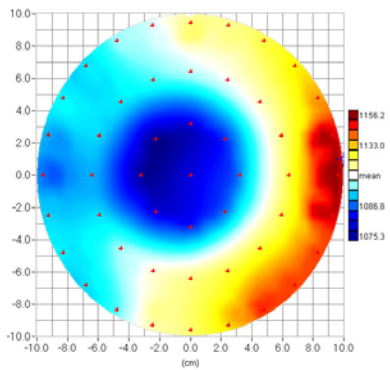
Materials Characterization

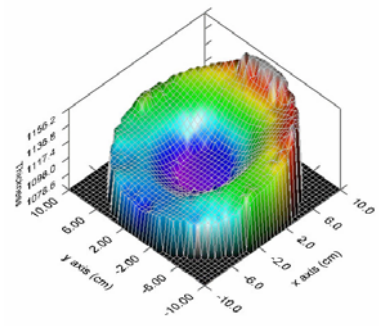
Polycrystalline Si_XGe_{1-X} (20% Ge)





2D Thickness Uniformity Map

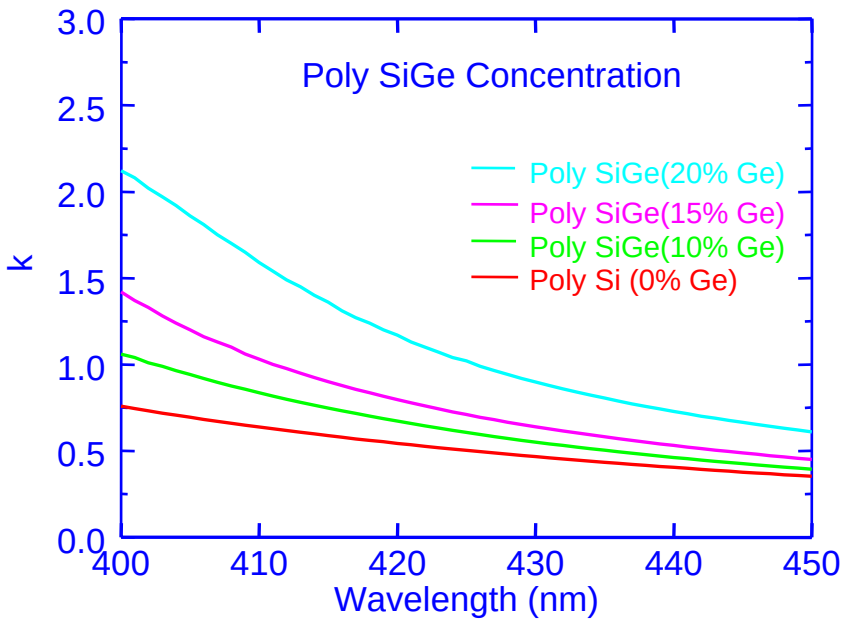


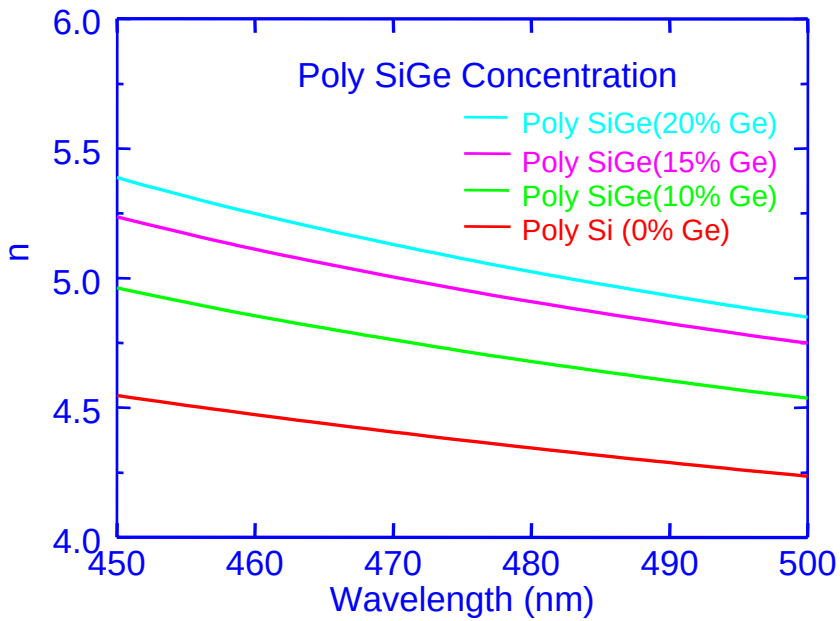


3D Thickness Uniformity Map

Materials Characterization

Polycrystalline Si_XGe_{1-X}





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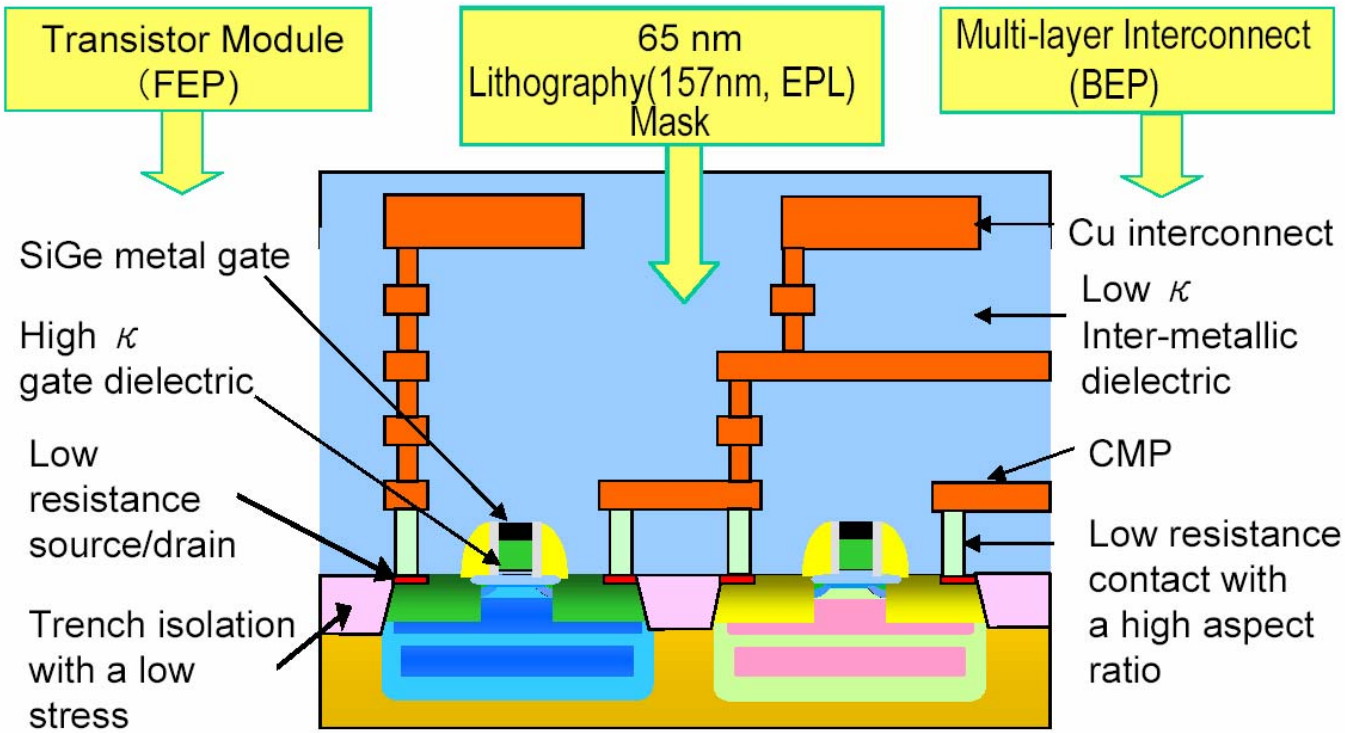
SELETE 65nm Node Program

Source: http://www.selete.co.jp

Selete

Process Modules to be developed by Asuka



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Relationship Between Dielectric Constant, κ, and Refractive Index, n

- Complex Index of Refraction: $N(E) = n(E) - ik(E)$
- Complex Dielectric Function: $\varepsilon(\nu) = \varepsilon_1(\nu) - i\varepsilon_2(\nu)$

$\varepsilon = N^2$

Therefore:

$\varepsilon_1 = n^2 - k^2$

$\varepsilon_2 = 2nk$

- Dielectric Constants: $\kappa = \lim_{\nu \to 0} \varepsilon_1(\nu)$

Thus: $\kappa \sim n^2$

ν (frequency), *E* (Energy), and λ (wavelength) are used interchangeably in this presentation.

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Classification of Low-κ Dielectric

(Slide adapted from a presentation by Dr. Osamu Aoki, JSR Microelectronics, Inc., USA.)

Material	κ = 4.1	κ = 3.5	κ = 2.6 – 3.2	κ = 2.0 – 2.5	Process	Vendor
Inorganic	SiO2	SiO2:F	FOx	XLX	CVD CVD Spin-on	- - Dow Corning
Hybrid			Dense-MSQ BlackDiamond CORAL	Porous-MSQ BlackDiamond POLA	Spin-on CVD CVD	JSR Applied Novellus
Organic			SiLK FLARE	Nautilus FLARE	Spin-on Spin-on	Dow Chemical Honeywell

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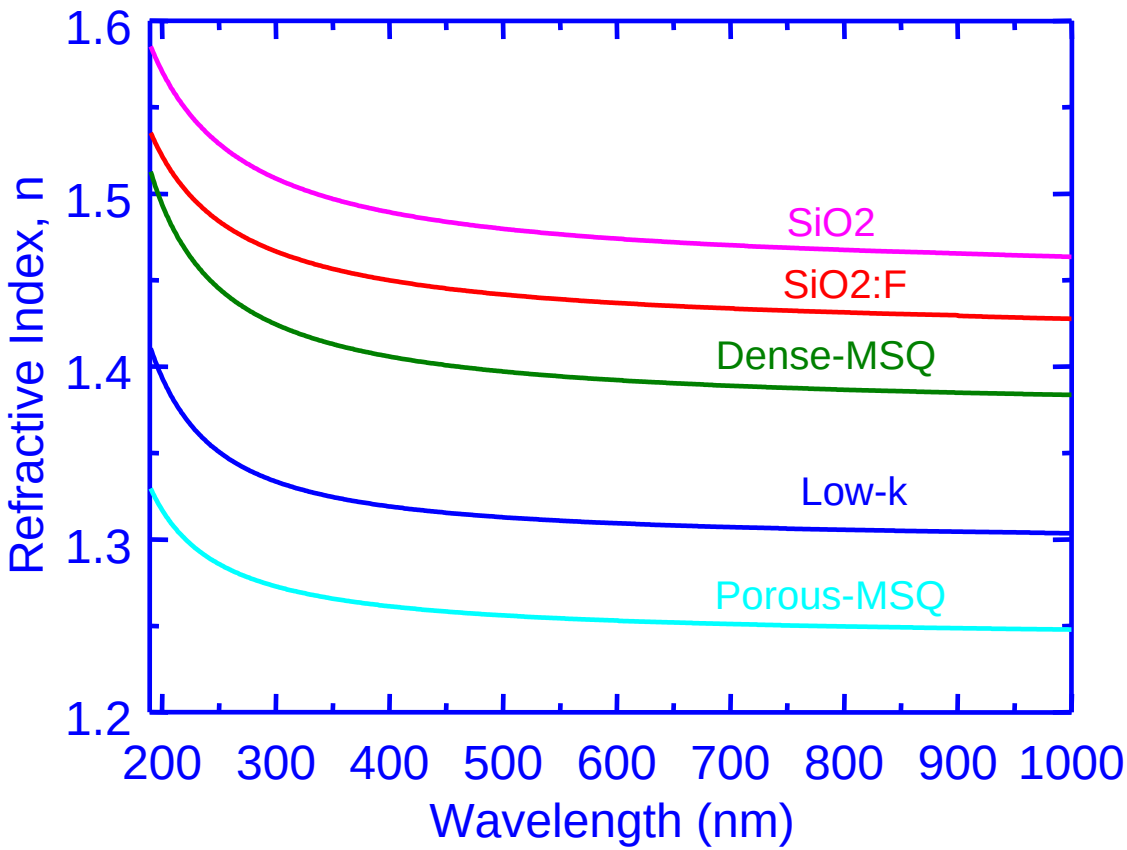
Comparison of *n* Spectra for Various Low-κ Materials



Porous-MSQ < Low-*k* < Dense-MSQ

2.2 < Dielectric Constant < 3

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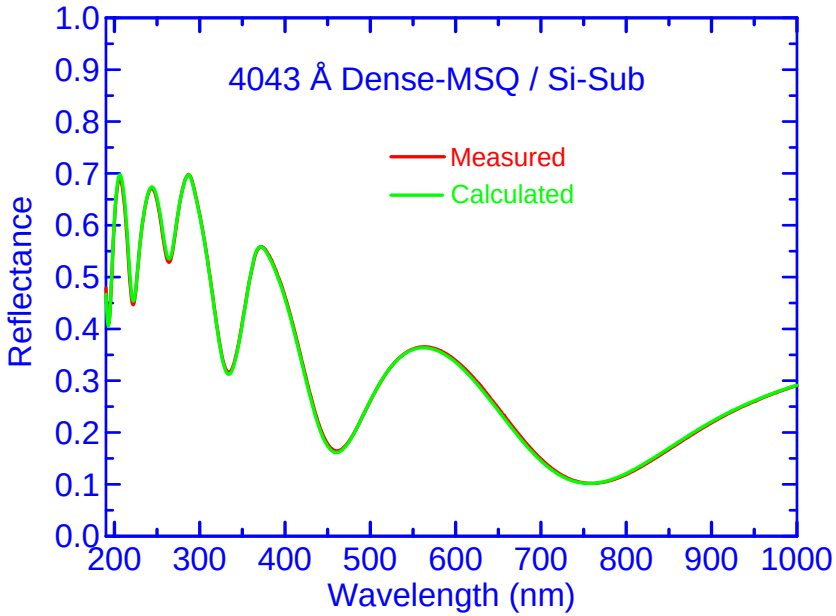
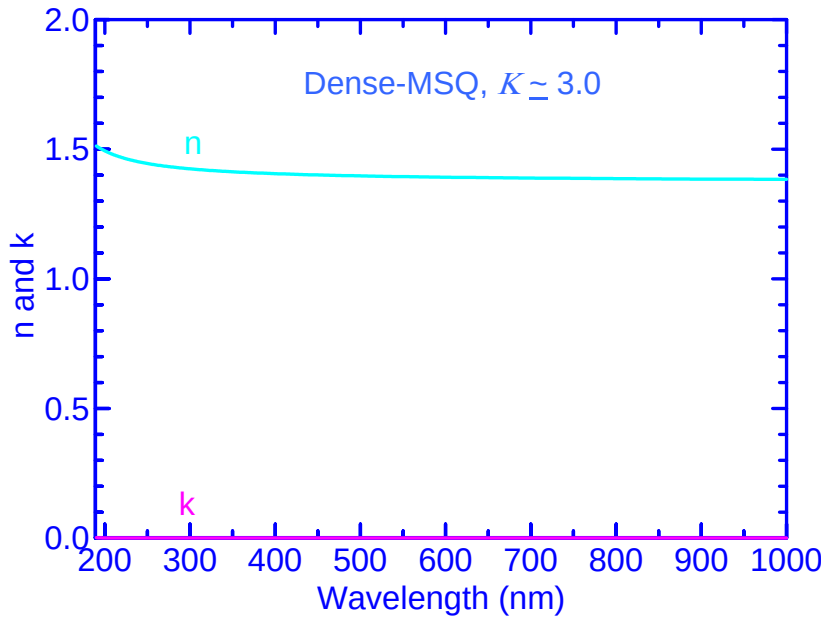
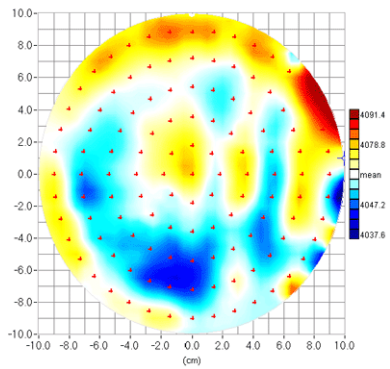
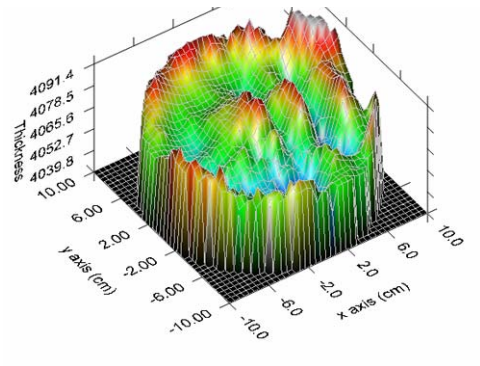
Dense-MSQ





2D Thickness Uniformity Map





2D Thickness Uniformity Map

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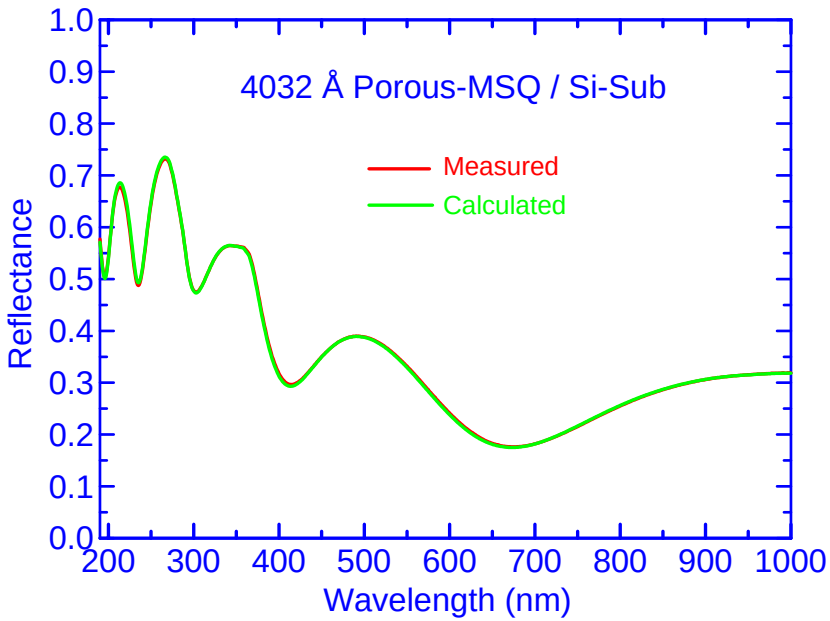
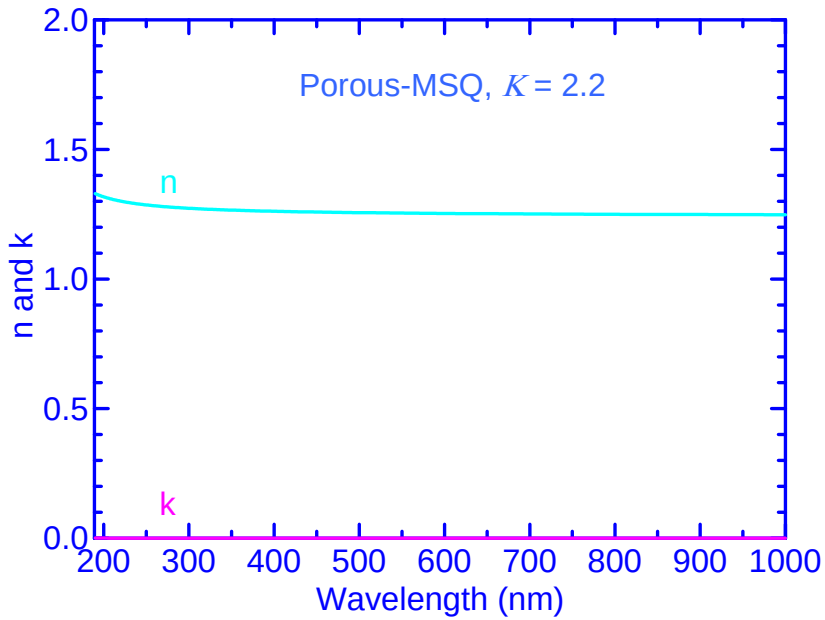
Porous-MSQ





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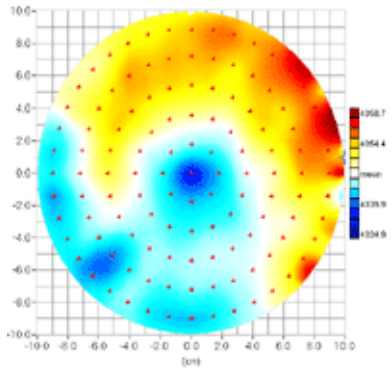

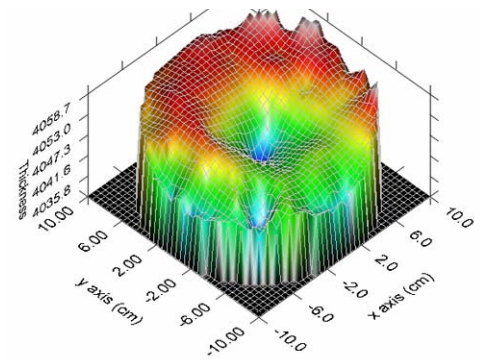

3D Thickness Uniformity Map

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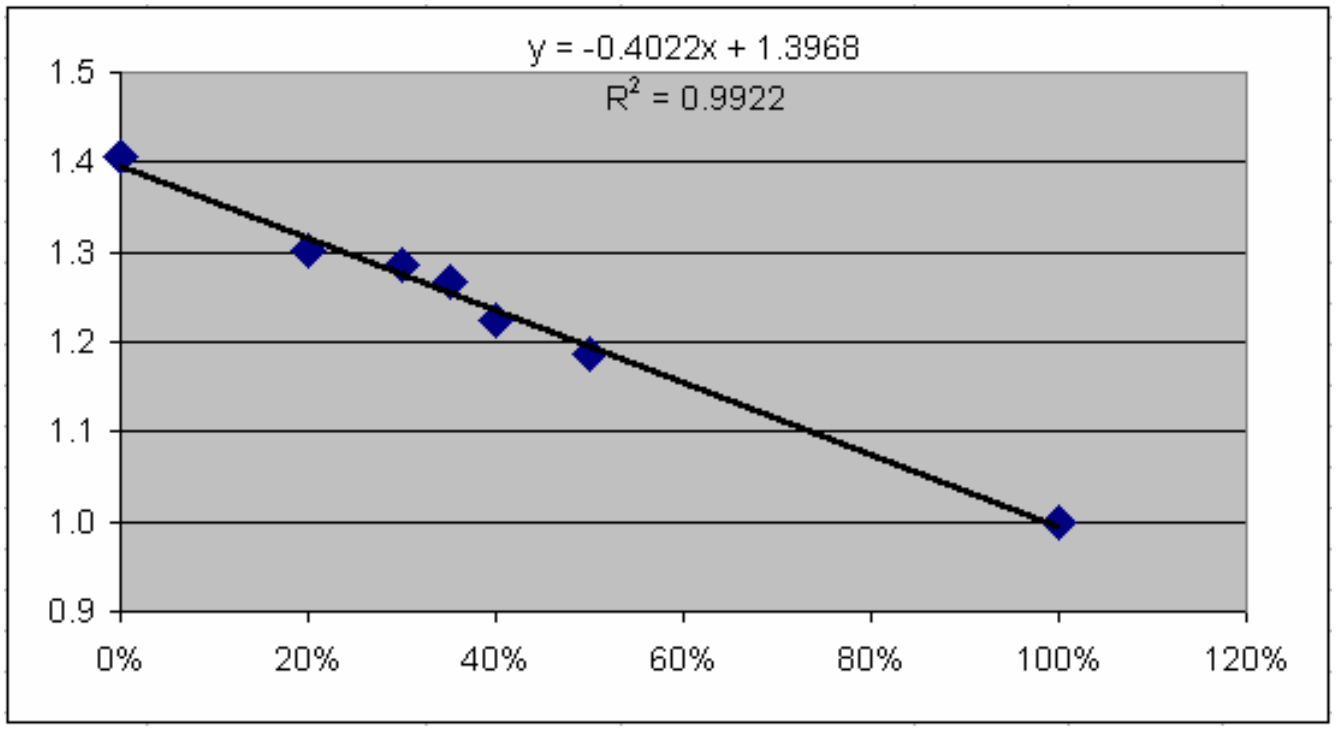
Correlation Between *n* and Porosity

n at 633nm versus Porosity



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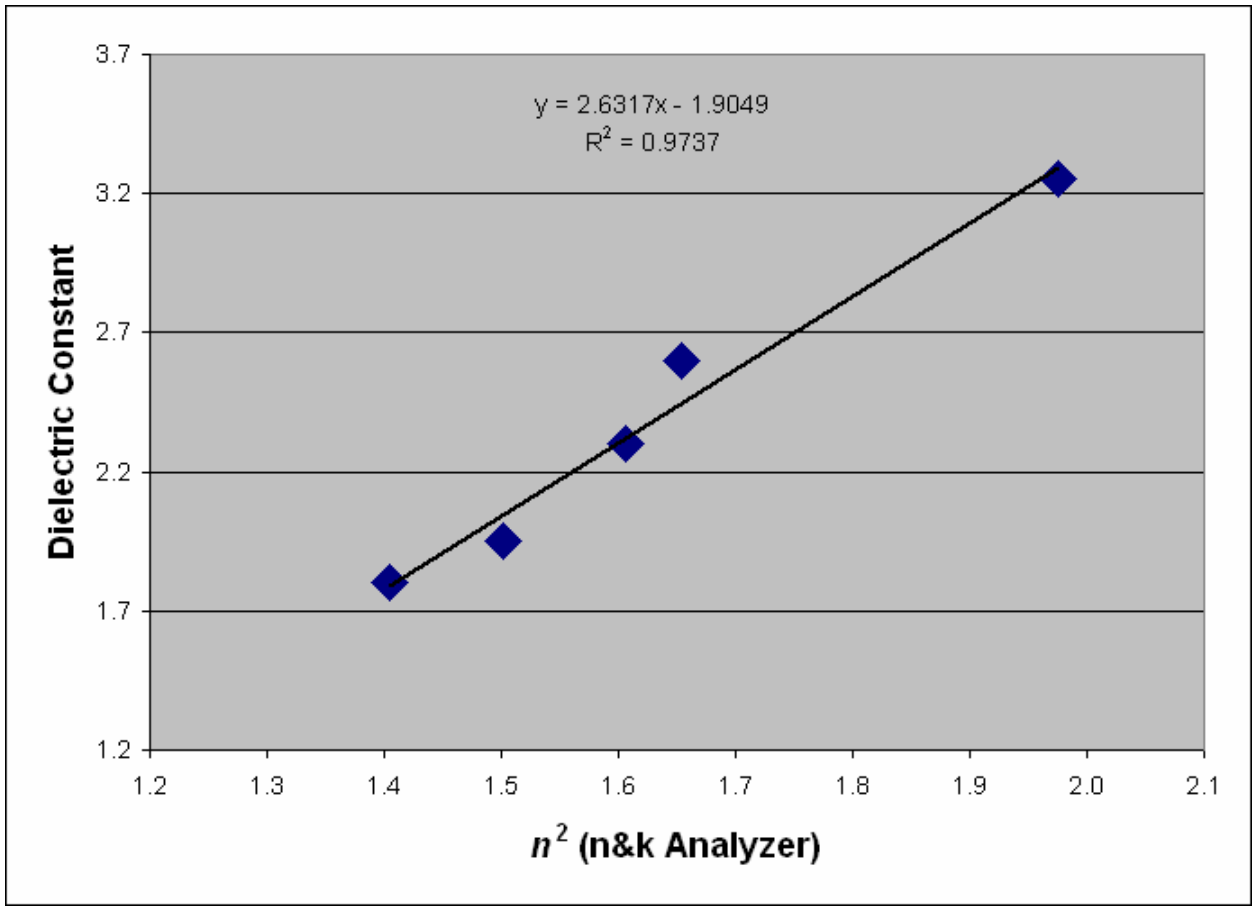
Correlation Between n^2 and κ



SiLK

The following set of *SiLK* samples were provided to n&k Technology for characterization.

Sample	Cure Temp / Time
1	320 ^{O}C / 90 s
2	420 ^{O}C / 120 s
3	440 ^{O}C / 120 s
4	440 ^{O}C / 120 s
5	440 ^{O}C / 120 s
6	470 ^{O}C / 120 s

SiLK on samples 3, 4, and 5 was processed identically.

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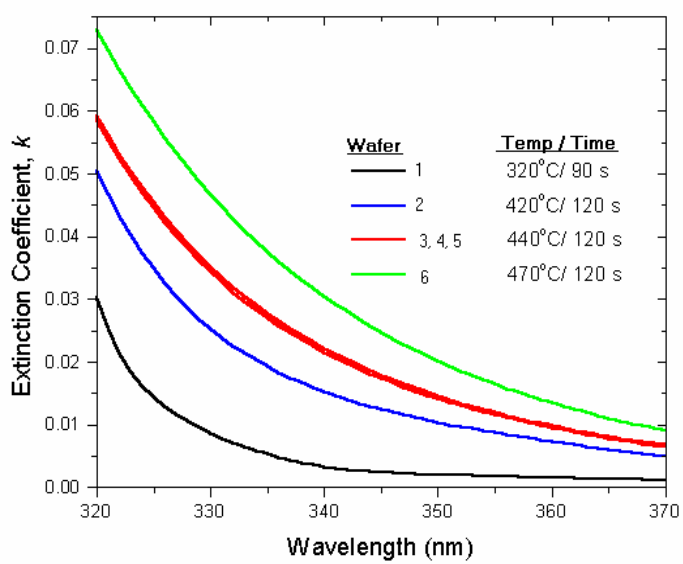
SiLK

Dependence of k on Curing Conditions

Sample	Cure Temp / Time	Thickness (Å)	Band Gap Eg (eV)	Extinction Coefficient *k* (at 330nm)	Index of Refraction *n* (at 314 nm)
1	320 ^{O}C / 90s	5133	3.86	0.009	1.969
2	420 ^{O}C / 90s	5188	3.77	0.025	1.925
3	440 ^{O}C / 90s	5192	3.70	0.034	1.910
4	440 ^{O}C / 90s	5191	3.69	0.034	1.909
5	440 ^{O}C / 90s	5200	3.70	0.033	1.912
6	470 ^{O}C / 90s	520.7	3.62	0.046	1.900



- Curing condition of *SiLK* films are conventionally monitored through determination of n at 314 nm
- Correlation is significantly improved when considering k-spectra from 320 - 380 nm range

Plots of the extinction coefficient *k* of six spin-on polymer films near the UV absorption edge demonstrate the uniform increase of *k* with cure cycle in this spectral region. The data taken at the wafer centers are illustrated by the solid curves. The range of within-wafer variations are shown by the crosses.

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Low-κ Films Deposited on Cu and W

For the demonstration of this capability two samples with the following nominal film structures were measured:

Case Study 1: Black Diamond™ (3000Å) / SiC (500Å) / Cu (3000Å) / Si Substrate
Case Study 2: Black Diamond™ (3300Å) / SiC (500Å) / W (3000Å) / Si Substrate

In order to analyze the samples described above we first had to characterize underlying SiC, Cu and W films. For this purpose, two background samples of the following nominal film structures were provided:

Background Sample 1: SiC (500Å) / Cu (3000Å) / Si Substrate
Background Sample 2: SiC (500Å) / W (3000Å) / Si Substrate

As the results of the analysis of these samples we were able to obtain *n* and *k* spectra for SiC film, Cu and W films.

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Low-κ Black Diamond™ Film
Detection of Inhomogeneity

For the characterization of the optical properties of the Black Diamond™ film, a single-layer Black Diamond™ on Silicon Substrate background sample was provided. Immediately upon inspection of the Reflectance spectrum it became evident that the film is inhomogeneous, i.e. optical properties of the film change with depth.

Calculation 1
Homogeneous Black Diamond™ Model
GOF = 94.76%

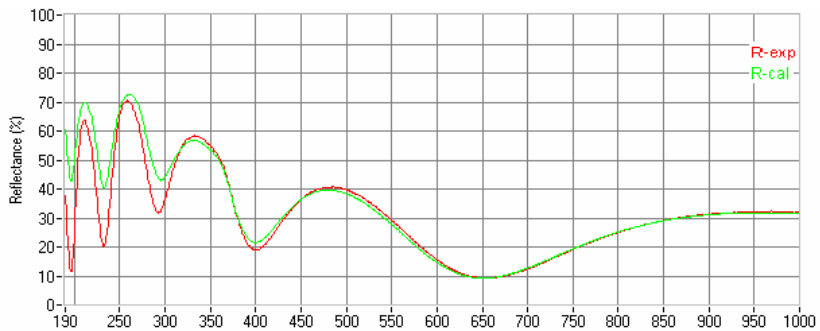

Figure 2A. Plots of measured (red) and calculated (green) Reflectance spectra versus Wavelength (nm).

Calculation 2
Inhomogeneous Black Diamond™ Model
GOF = 98.16%

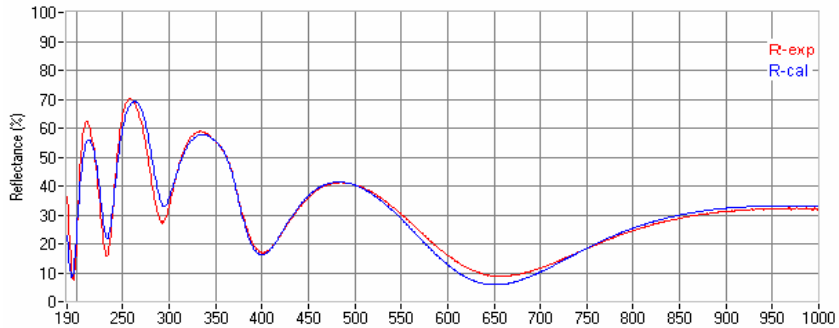

Figure 2B. Plots of measured (red) and calculated (green) Reflectance spectra versus Wavelength (nm).

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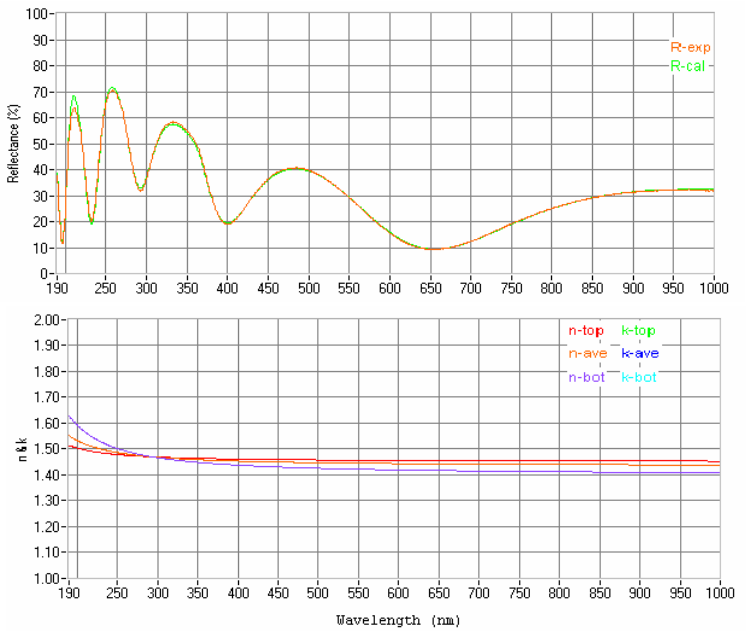
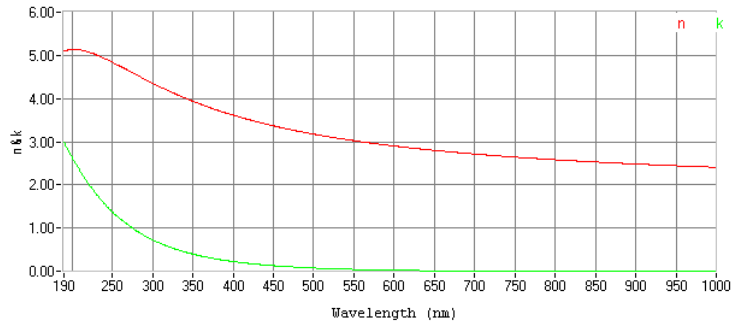
Low-κ Black Diamond™ Film
Detection of Ultra-Thin Terminating Layer

The most physically plausible explanation of the bad fit is a possible presence of an extra layer in the film stack. A new computational model for analysis was developed, where on top of the inhomogeneous Black Diamond™ layer an ultra-thin "terminating layer" was placed.

Inhomogeneous Black Diamond™ Model with the Ultra-Thin Terminating Layer.

Goodness of Fit: 99.35%





Low-κ Films Deposited on Cu and W

Case Study 1: (Terminating Layer / Inhomogeneous Black Diamond™ / SiC / Cu / Si Substrate)

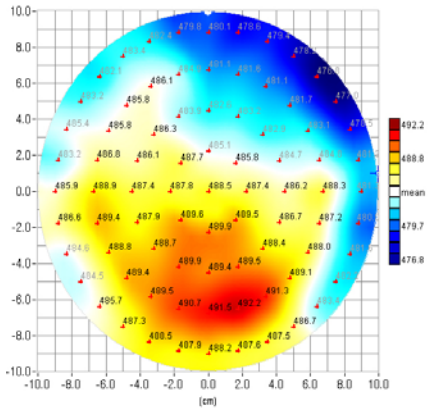


Figure 6A. Thickness uniformity map of the SiC layer.

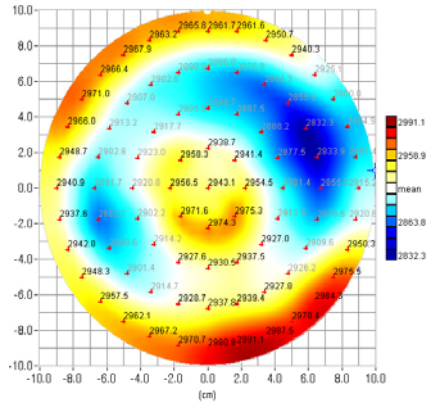


Figure 6B. Thickness uniformity map of the inhomogeneous Black Diamond™ layer.

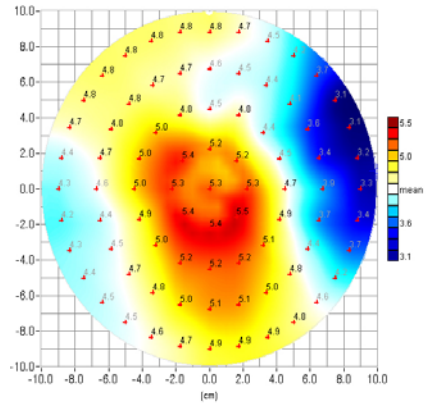


Figure 6C. Thickness uniformity map of the ultra-thin terminating layer.

Low-κ Films Deposited on Cu and W

Case Study 2: (Terminating Layer / Inhomogeneous Black Diamond™ / SiC / W / Si Substrate)

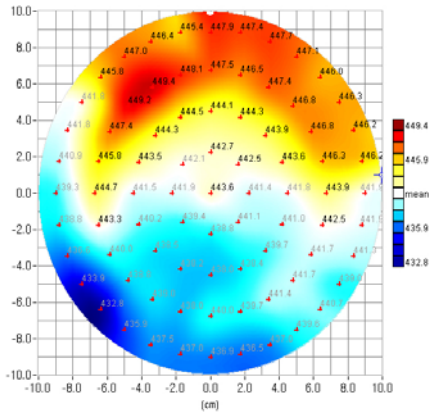


Figure 7A. Thickness uniformity map of the SiC layer.

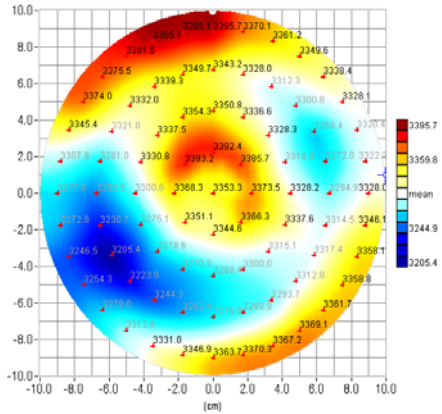


Figure 7B. Thickness uniformity map of the inhomogeneous Black Diamond™ layer.

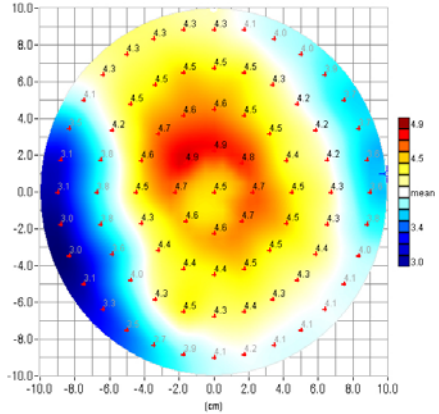


Figure 7C. Thickness uniformity map of the ultra-thin terminating layer.

Low-κ Films Deposited on Cu and W
Measurements on Patterned Wafers

The next challenge was to measure a similar film structure on a patterned wafer. For this purpose, a patterned sample of the following nominal film structure was provided:

Patterned Sample: Black Diamond™ (7700A) / SiC (500A) / Cu (3000A) / Si Substrate

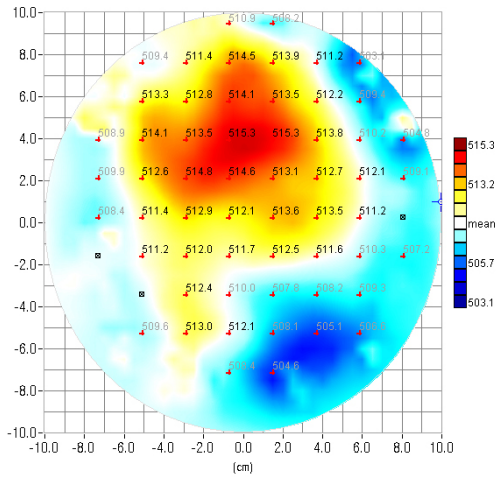


Figure 8A. Thickness uniformity map of the SiC layer.

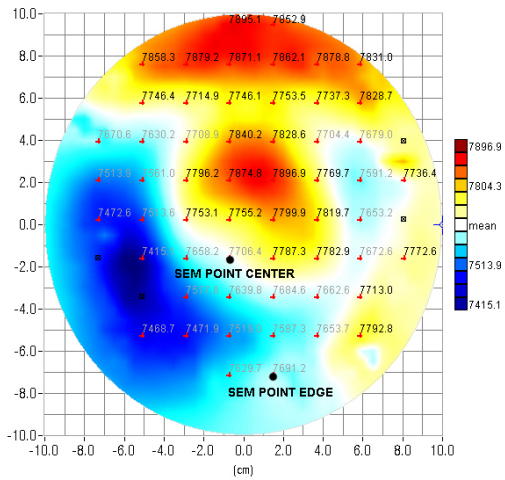


Figure 8B. Thickness uniformity map of the inhomogeneous Black Diamond™ layer.

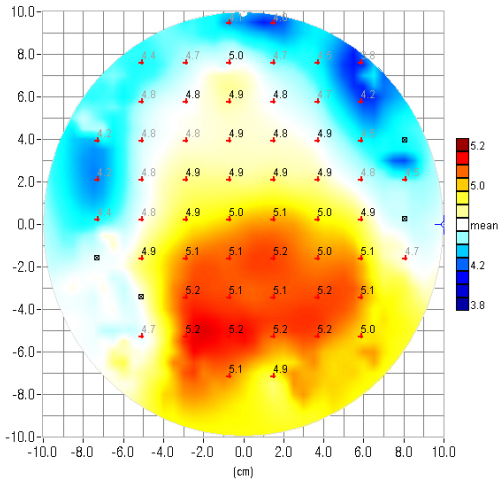


Figure 8C. Thickness uniformity map of the ultra-thin terminating layer.

Low-κ Films Deposited on Cu and W

SEM Comparison

Two SEM cross section scans were performed on the same wafer: one at a location near the center of the wafer, and another one at the location near the edge

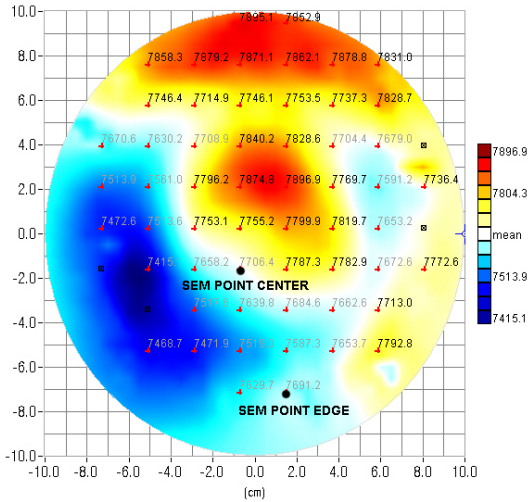


Figure 9A. Thickness uniformity map of the inhomogeneous Black Diamond™ layer.

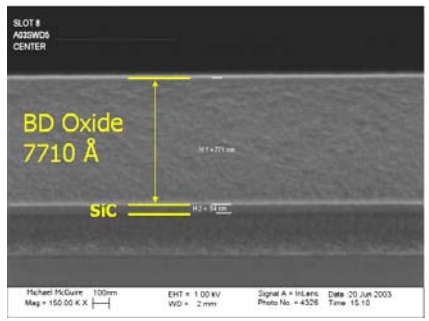


Figure 9B. SEM cross section image at a location close to the center of the wafer.

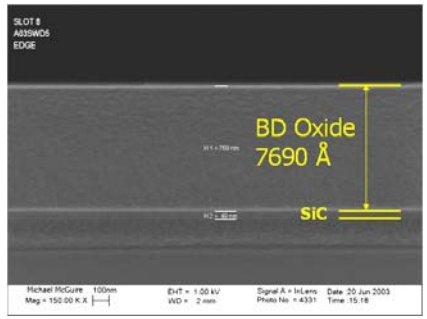


Figure 9C. SEM cross section image at a location close to the edge of the wafer.

Both cross sections closely correspond to the results obtained using n&k Analyzer (7706.4A at the center and 7691.2A at the edge, using n&k Analyzer; 7710A at the center and 7690A at the edge, using SEM).

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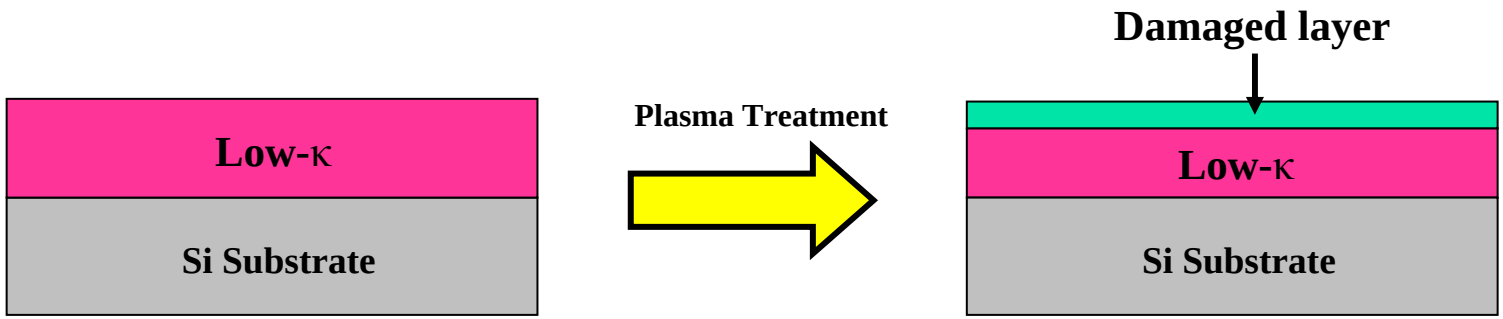
Low-κ Damage Due To Ashing

- Plasma damage during ashing, etching, etc. densifies top layer of the low-κ film.
- This results in two layers, consisting of a thin damaged layer on top of the original low-κ film.
- Generally, densification causes an increase in *n* for the damaged layer.



Low-κ Damage Due To Ashing

Sample Split

	Ashing Chemical	Remark
1	No Treatment	Ref.
2	He/H2 Ashing	Low Damage Ashing (Selete)
3	NH3 Ashing	Low Damage Ashing
4	O2 Ashing	Conventional Ashing

Ref: Katsumi Yoneda (SELETE), presented at Semicon Japan, December, 2004.

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Low-κ Damage Due To Ashing

n&k Analyzer Measurements

Single Layer-Analysis on Plasma-treated Low-k

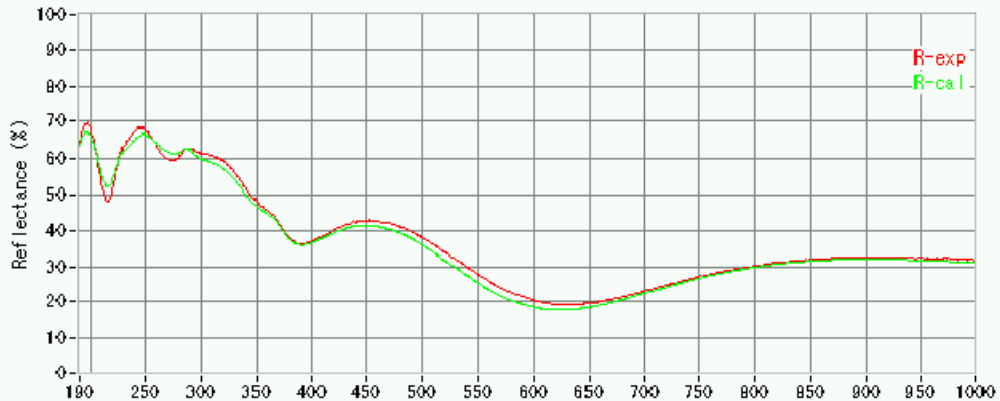
Goodness of Fit = 0.9835 Eg(V) = 6.49eV

WL(nm):	193	248	365	633
n :	1.304	1.283	1.269	1.262
k :	0.001	0.000	0.000	0.000
Rexp %:	68.2	68.3	44.3	19.3
Rcal %:	66.4	66.9	43.7	17.8

Film Structure

	Thickness (Å)
Low-k	3693
Si Substrate	1.000 mm (F)

Unknown Material: previous result
Recipe Details: +/- 1000 A, 0.0 nm, Film, Energy



Ref: Katsumi Yoneda (SELETE), presented at Semicon Japan, December, 2004.

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Low-κ Damage Due To Ashing

n&k Analyzer Measurements

2 Layer-Analysis on Plasma-treated Low-k

Goodness of Fit = 0.9953 Eg(V) = 6.49eV

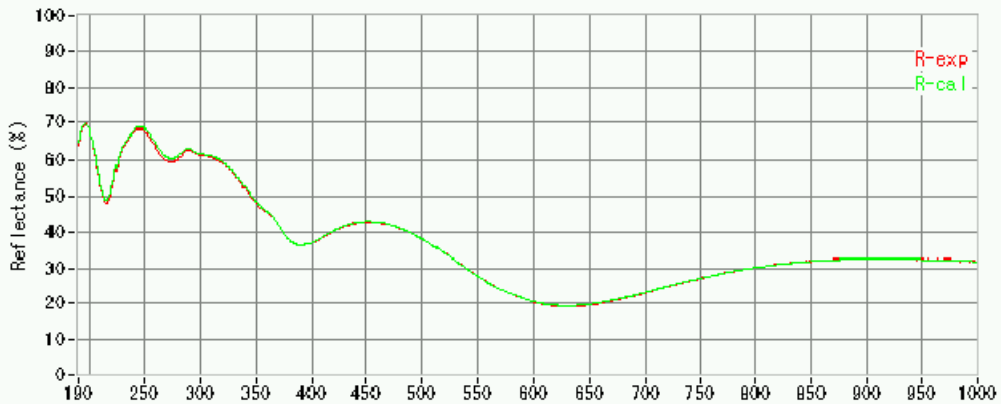
WL(nm):	193	248	365	633
n :	1.375	1.355	1.341	1.335
k :	0.000	0.000	0.000	0.000
Rexp %:	68.2	68.3	44.3	19.3
Rcal %:	68.5	68.9	44.6	19.4

Film Structure

	Thickness (Å)
Damaged Layer	243
Low-k	3507
Si Substrate	1.000 mm (F)

Unknown Material: previous result
Recipe Details: +/- 1000 A, 0.0 nm, Film, Energy

$N_{damaged}$ (1.335) > n_{bulk} (1.213)



Ref: Katsumi Yoneda (SELETE), presented at Semicon Japan, December, 2004.

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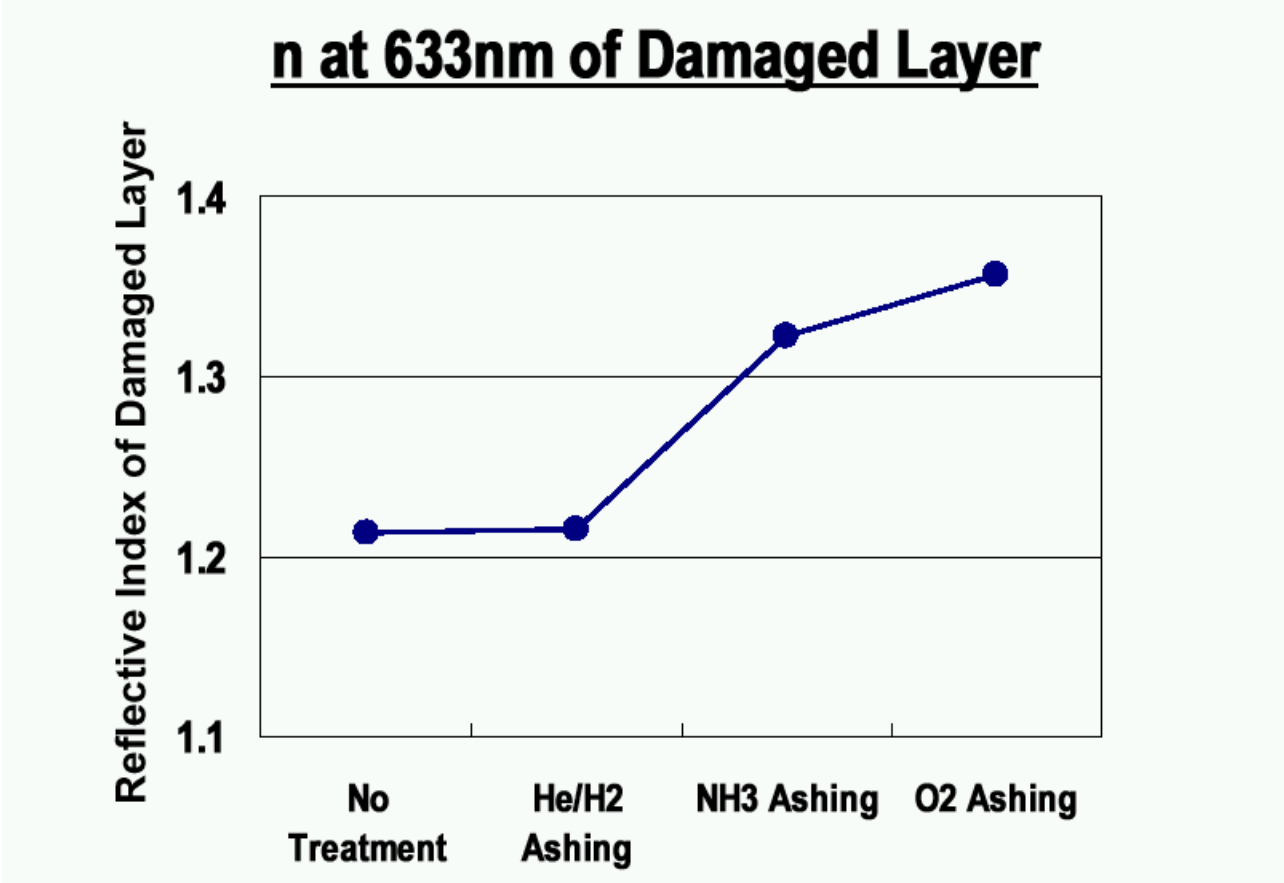
Low-κ Damage Due To Ashing

n&k Analyzer Measurements



Ref: Katsumi Yoneda (SELETE), presented at Semicon Japan, December, 2004.

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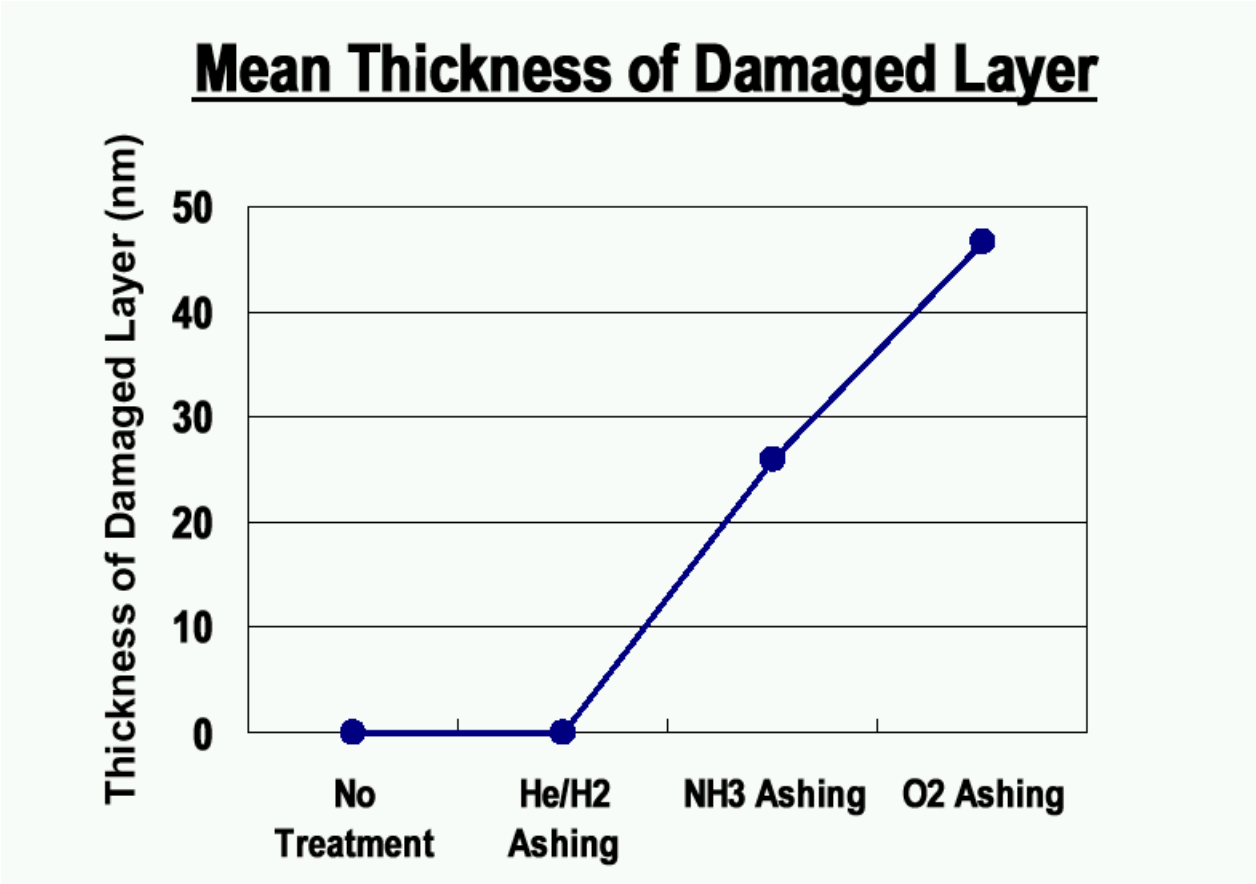
Low-κ Damage Due To Ashing

n&k Analyzer Measurements



Ref: Katsumi Yoneda (SELETE), presented at Semicon Japan, December, 2004.

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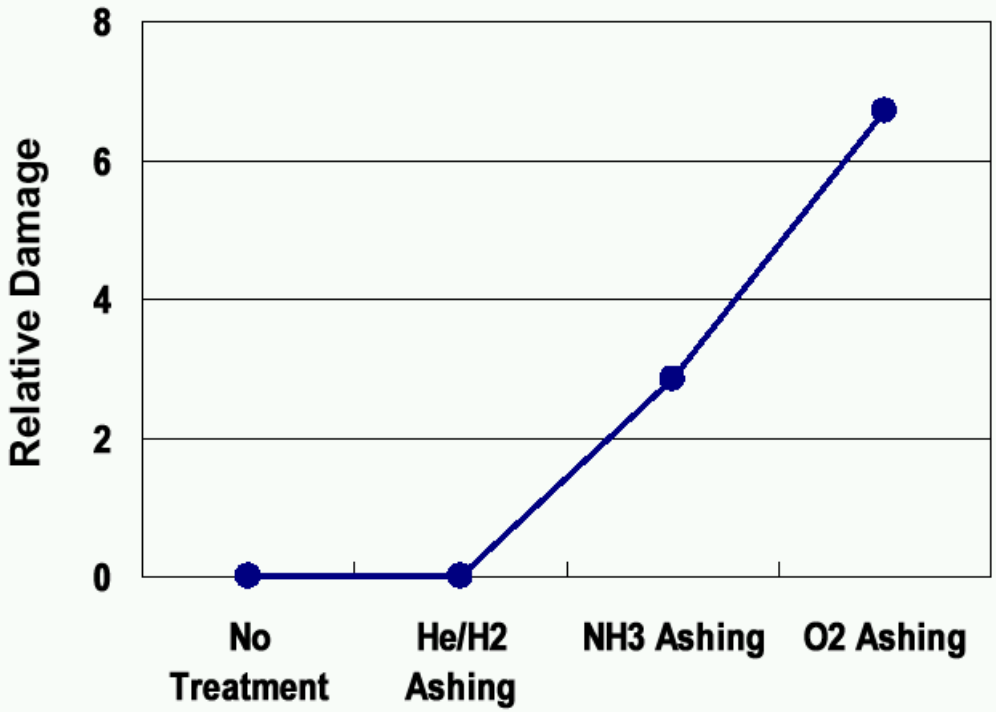
Low-κ Damage Due To Ashing

n&k Analyzer Measurements

Relative Damage : $(n_{damaged} - n_{ref.}) \times Thickness_{damaged}$



Ref: Katsumi Yoneda (SELETE), presented at Semicon Japan, December, 2004.

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Low-κ Films Deposited on Cu and W
Measurements on Patterned Wafers

Note that the terminating layer in the previous Black Diamond example is consistent with the He/H2 ashing condition:

Patterned Sample: Black Diamond™ (7700A) / SiC (500A) / Cu (3000A) / Si Substrate

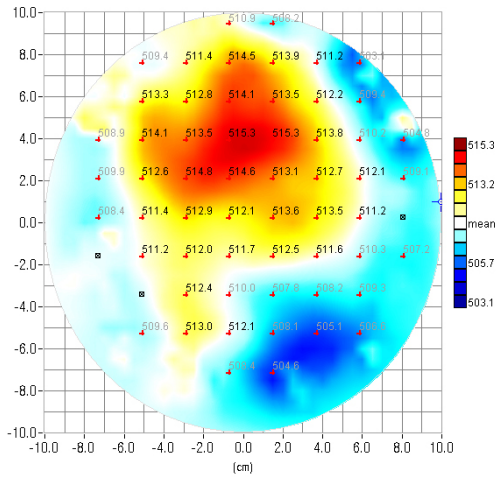

Figure 8A. Thickness uniformity map of the SiC layer.

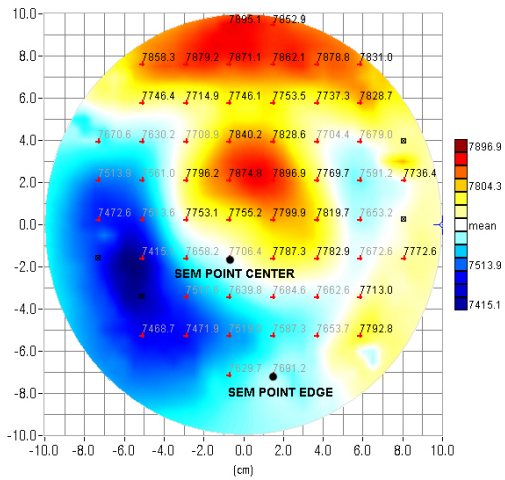

Figure 8B. Thickness uniformity map of the inhomogeneous Black Diamond™ layer.

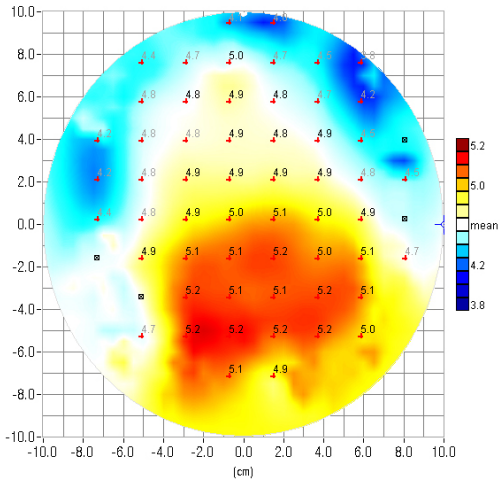

Figure 8C. Thickness uniformity map of the ultra-thin terminating layer.

Conclusions

- Can use optical metrology to:
  - Rapidly, nondestructively, and simultaneously determine film thickness, *n*, and *k*
  - Correlate *n* and *k* to film processing conditions
- Optical metrology of low-κ films:
  - Correlation of *n* to dielectric constant
  - Porous films
  - Inhomogeneous films
  - Films on metallic substrates
  - Characterization of plasma-induced damage

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