POROUS THIN FILMS CHARACTERIZED BY SPECTROSCOPIC ELLIPSOMETRY

Hui Zhang
Dept. of Electrical and Computer Engineering, Oregon
Graduate Institute of Science and Technology, Beaverton, OR 97006.
(now at Micron Technology)

J. Neal Cox
Intel Corp
Hillsboro, OR 97124
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 $>1000\ A$
- 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
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 \( \tan \psi \) and \( \cos \Delta \) where \( \tan \psi \) and \( \cos \Delta \) are given by:

\[
\tan \psi = \frac{|R_p|}{|R_s|}
\]

\[
\Delta = \delta_1 - \delta_2
\]

- \( R_p \) and \( R_s \) are ratios of outgoing wave amplitude to the incoming wave amplitude for parallel and perpendicular components.
- \( \delta_1 \) and \( \delta_2 \) denote the phase difference between the parallel component and perpendicular component of the incoming wave and outgoing wave.
WISE WORKSHOP 2000

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
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, \( \varepsilon_1 \) and \( \varepsilon_2 \) are the dielectric function of the two media under mixing.
Two EMA Models

- Sharp Interface
- Rough interface

- Interfacial layer
  - Thickness
  - Concentration
Sample #1

\((\lambda \gg R = \text{void radius, fine voids})\)

Models:

- **Point-by-Point (PP)**
  - NT extraction in the NIR range \((k=0)\)
  - NK extraction spectra in full wavelength \((250-750\text{nm})\)

- **EMA**
  - EMA using SiO\(_2\) + Air doesn’t give good fit

- **Cauchy law**
  - Produce same results as PP
Experimental data tan(\(\psi\)) & cos(\(\Delta\))

Optical constants obtained from NK extraction

05/09/00

H. Zhang and J.N. Cox
### Sample #2

*(𝜆 ~ R, Void density=D ~R, large voids)*

#### Models

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness and void concentration</td>
<td>T=685nm C=43.3%</td>
</tr>
<tr>
<td>Thickness of bulk film</td>
<td>T=488nm C=42.8%</td>
</tr>
<tr>
<td>Thickness of rough interface, concentration of film in rough layer</td>
<td>Tr=195nm Cr=97.0%</td>
</tr>
<tr>
<td>Thickness and refractive index assuming k=0 in NIR</td>
<td>T=686nm N=1.25</td>
</tr>
<tr>
<td>A, B, C and thickness assuming k=0 in NIR</td>
<td>T=685nm N=1.251</td>
</tr>
</tbody>
</table>

#### EMA in VIS/NIR
- One layer: SiO2 + voids
- Two layers: Rough Surface Layer
  - Bulk of film

#### Point-by-Point
- NT extraction in NIR

#### Cauchy in NIR region
EMA fit to the experimental data in VIS-NIR region

EMA fit to the experimental data in full region
Optical constants obtained from NK extraction
Sample #3: polyimide
(λ > R, D > R, medium voids)

**Results**

- **EMA**
  - One layer: dense film + voids
  - Parameters: Thickness and void concentration
  - Results: T=513nm, C=14.4%

- **EMA**
  - Two layers: Rough Interface
    - Bulks of film
  - Parameters: Thickness of bulk film, Concentration of void in bulk film
  - Results: T=503nm, C=14.2%

- **Point-by-Point**
  - NT extraction in NIR
  - Parameters: Thickness of rough interface, concentration of film in rough layer
  - Results: Tr=9.5nm, Cr=97.0%

- **Cauchy**
  - In NIR region
  - Parameters: A, B, C and thickness assuming k=0 in NIR
  - Results: T=471nm, N=1.51

**Models**

- **Cauchy**
  - In NIR region
  - Parameters: A, B, C and thickness assuming k=0 in NIR
  - Results: T=471nm, N=1.59

**Parameters**

- **Thickness and void concentration**
- **Thickness of bulk film**
- **Concentration of void in bulk film**
- **Thickness of rough interface, concentration of film in rough layer**
- **Thickness and refractive index assuming k=0 in NIR**
- **A, B, C and thickness assuming k=0 in NIR**
- **Results**
  - T=513nm, C=14.4%
  - T=503nm, C=14.2%
  - Tr=9.5nm, Cr=97.0%
  - T=471nm, N=1.51
  - T=471nm, N=1.59
Cauchy fit to extract the n&k profile

Optical constants obtained from Cauchy law
Conclusions

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Models</th>
<th>Material Type</th>
<th>Void Distribution</th>
<th>$\lambda / R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample #1</td>
<td>Yes/Yes</td>
<td>No</td>
<td>Single</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>PP/Cauchy</td>
<td>EMA</td>
<td></td>
<td>$&gt;&gt; 20$ (from process)</td>
</tr>
<tr>
<td>Sample #2</td>
<td>Yes/Yes</td>
<td>Yes</td>
<td>Mixed</td>
<td>Highly homogeneous</td>
</tr>
<tr>
<td>Sample #3</td>
<td>Yes/No</td>
<td>Yes</td>
<td>Mixed</td>
<td>Moderately homogeneous</td>
</tr>
</tbody>
</table>

SE DATA

PP/Cauchy

Yes

Homogeneous film

EMA

Yes

Mixture of film and voids

No

Single component film

No

Inhomogeneous film

EMA

Yes

Mixture of film and voids

No

Poor quality film
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.