ECE 496 – Individual Study Course

- **Title:** Ellipsometric Characterization of Plasmonic Materials
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- **Credit Hours:** 2
Ellipsometric Characterization of Plasmonic Materials

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Motivation

• Nanoscale size of circuits
  - *Improve performance as size decreases*

• Circuit component losses
  - *Reduce power dissipation in device*
Possible Solutions

• Typical photonic elements
  - Optical fibers

• Plasmonic materials:
  - Metals
    • Examples include Gold, Silver, Copper, etc.
  - Alternative materials
    • Examples include Oxides and Nitrides
Optical Fibers

• Channel light with very little losses

• However, it cannot go lower than the micrometer scale
  – Because of diffraction limitations

Boltasseva, ECE 414 PPT Slides (2012)
Plasmonic Materials: *Metals*

- Abundance of free carriers
- But
  - *High losses in some wavelength ranges*
  - *Incompatibility with semiconductor nanofabrication processes due to deep level traps*
Plasmonic Materials: *Oxides and Nitrides*

- **Semiconductor-based Oxides in the Near infrared range**
  - further doping semiconductor (increasing carrier levels)
  - Examples include *Al:ZnO, Ga:ZnO, ITO*

- **Transition-metal Nitrides in the visible range**
  - analogous to diluting a metal (decreasing carrier levels)
  - Examples include *TiN and ZrN*
The dielectric function describes the optical properties of a gas of free electrons

\[ \varepsilon = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \]

- \( \varepsilon_\infty \) is due to interband transition (effect of positive ion core)
  - \( \varepsilon_\infty = 1 \) for an ideal metal
- \( \gamma \) is the collision frequency
- \( \omega_p \) is the plasma frequency of the free electron gas

\[ \omega_p^2 = \frac{ne^2}{\varepsilon_0 m} \]
Theory

\( \varepsilon \) can be written as

\[ \varepsilon = \varepsilon' + i\varepsilon'' \]

\[ \varepsilon' = \left( 1 - \frac{\omega_p^2 \tau^2}{1 + \omega^2 \tau^2} \right) \]

\(-\) corresponds to the strength of electric polarization

\[ \varepsilon'' = \left[ \frac{\omega_p^2 \tau}{\omega (1 + \omega^2 \tau^2)} \right] \]

\(-\) represents the absorption
Measurements: **Ellipsometry**

The reflectance ratio is:

$$\rho = \tan(\psi)e^{i\Delta}$$

- $\tan(\psi)$ is the reflectance ratio
- $\Delta$ is the phase shift

http://en.wikipedia.org/wiki/Ellipsometry
Models Used

(WVASE Sofware, J. A. Woollam Co., Inc.)

Lorentz oscillator model (Semiconductors)

\[ \varepsilon = offset + \frac{A_nE_n}{E_n^2 - E^2 - iB\tau_nE} \]

Drude model (Metals)

\[ \varepsilon = offset - \frac{A_n}{E^2 + iB\tau_nE} \]
Results:

ZnO (70nm) layer on Glass

Fig. 1: The arctan(reflectivity ratio) vs wavelength

Fig. 2: The real and imaginary permittivity vs wavelength for 70nm of ZnO deposited on glass layer
Results:  

Ag (30nm) layer on Glass

Fig. 3: The arctan(reflectivity ratio) vs wavelength

Fig. 4: The real and imaginary permittivity vs wavelength for 30nm of Ag deposited on glass layer
Results:

**Al:ZnO (250nm) layer on Silicon**

- **Fig. 5:** The arctan(reflectivity ratio) vs wavelength
- **Fig. 6:** The real and imaginary permittivity vs wavelength for Al:ZnO deposited on silicon layer
Results:

TiN (30nm) layer on Sapphire

Fig. 7: The arctan(reflectivity ratio) vs wavelength

Fig. 8: The real and imaginary permittivity vs wavelength for TiN deposited on sapphire layer
Observations

• In Ag, losses increase when approaching infrared region
• In Al:ZnO, losses are small even until ~1500nm
• In TiN, losses are relatively high when approaching infrared region
Conclusion

• Al:ZnO is a good replacement for metals in the infrared region because of its low losses. However, it is difficult to achieve a negative real permittivity in the near-infrared region.

• TiN is a good replacement for metals in the visible range. However, it has higher losses compared to metals.

• There is a need to come up with a good benchmark that takes the real and imaginary parts of the permittivity into account.
I also carried out an ellipsometric scan of CuPc and BCP organic filament but I am yet to obtain their dielectric parameters.
Thank you
Extra: Procedure to speed up fitting

• Obtain known material properties
  – Thickness of substrate/superstrate, Long energy index, concentration, bandgap.
• Add material layers to the layer window
• Set \( \varepsilon \) to a little less than the \((\text{long energy index})^2\)
• Set \( E_n \) close to the bandgap
• Set \( A_n \) such that \( \frac{A_n}{E_n} + \varepsilon_1 \) is approximately the long energy index
• If carrier concentration is greater than \(10^{18}/\text{cm}^3\), include another oscillator with \( E_n = 0 \)
• Set model to back side corrected if there is reflection on back surface
Procedure to speed up fitting (continued)

- Run Normal Fitting and aim for small MSE ($\leq 7$)
- Also, look at the values of $\varepsilon_1$ and $\varepsilon_2$ to see if they are reasonable
- If MSE is larger than 7, attempt a point by point fit
- Again, check to see if the values of $\varepsilon_1$ and $\varepsilon_2$ to see if they are reasonable
- Limits may also be set on the parameters
- Furthermore, wavelength range can be split to fit each segment separately
References

• G.V. Naik, J. Kim and A. Boltasseva, "Oxides and nitrides as alternative plasmonic materials in the optical range," *Optical Material Express*, vol. 1, no. 6, pp. 1090-1099, 2011.

