Materials in Plasmonics
Workshop on Energy, Plasmonics, and Optimization
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Outline

- Linear models of metals and dielectrics
- The role of dielectric / metal properties in canonical plasmonic problems
- More materials: Metals, Semiconductors, Films, and Graphene
Plasmonic effects don’t scale

Plasmonic effects caused by behavior of metals in certain regimes.

- $\text{Re}\{\epsilon\} < 0$

In general, only possible where materials exhibit these features.
Linear Models of Metals

Lossless conduction
Electrons move freely due to $E$

$$\epsilon = 1 - \frac{\omega^2}{\omega^2}$$
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\[ \epsilon = 1 - \frac{\omega_p^2}{\omega^2} \]

**Drude Model**
Damping included

\[ \epsilon = 1 - \frac{\omega_p^2}{\omega^2 + i\Gamma\omega} \]
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**Lorentz (Bound Osc.) Model**

Damping + restoring force

$$\epsilon = 1 + \frac{\omega_p^2}{(\omega_0^2 - \omega^2 - i\Gamma\omega)}$$
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$$\epsilon = 1 + \frac{\omega_p^2}{(\omega_0^2 - \omega^2) - i\Gamma\omega}$$

**Lorentz-Drude (LD) Model**

$$\epsilon = 1 - \frac{f_0\omega_p^2}{\omega^2 + i\omega\Gamma_0} + \sum_{j=1}^{k} \frac{f_j\omega_p^2}{(\omega_j^2 - \omega^2) - i\omega\Gamma_j} (+\epsilon_\infty - 1)$$
Discrepancies in Models

\[
\begin{align*}
\sigma(c) & = \text{Drude - R1998} \\
\epsilon & = \text{LD - R1998} \\
\lambda & = \text{Drude - P2006} \\
\text{LD} & = \text{NH2012} \\
\text{Fit} & = \text{JC1972}
\end{align*}
\]
Impact: Planar SPP

Search for a solution to Maxwell’s Equations at a metal-dielectric interface which:

- is bound to the interface ($\text{Re } k_z = 0$)
- propagates along the interface ($\text{Re } k_x \neq 0$)

Propose solutions of the form of one wave in each medium.

Yields Brewster and Surface Plasmon Polariton (SPP) modes.

Existence, behavior and interpretation of these modes depends on material models.
Impact: Planar SPP w/ Lossless Conduction Model of Ag
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Surface Plasmon Polariton

E = 2.4856 eV

$y/\lambda_0$

$x/\lambda_0$

$E_{\text{eV}}$

$\text{Re}(k_x) \times 10^7$
Impact: Planar SPP w/ LD Model of Ag
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Implications of Model Selection

- Simple material models tend to agree for IR and below
- Losses in plasma conduction and interband oscillations
  - become relevant in the optical regime
  - “hybridize” SPP / Brewster mode behavior
  - limit maximum localization ($\lambda_0/\lambda_{spp} \leq 3$)
  - give rise to attenuation (propagation length, $\delta/\lambda_{spp}$)

Effects manifest in more complex problems in similar ways.
Quasi-static Spherical Plasmon Resonance Dependence on Model

\[ \sigma_s (\pi \kappa^4 a^6) \]

Graph showing the dependence of \( \sigma_s (\pi \kappa^4 a^6) \) on \( \lambda_0 \) for Lossless, Drude, and LD models.

Key:
- Blue: Lossless
- Red: Drude
- Orange: LD

Units:
- \( \sigma_s \): \( \text{eps} \)
- \( \lambda_0 \): \( \text{m} \)
- \( \kappa \): \( \text{m}^{-1} \)
- \( a \): \( \text{m} \)

Data Range:
- \( \lambda_0 \): 2 to 9 \( \cdot 10^{-7} \)
- \( \sigma_s (\pi \kappa^4 a^6) \): 10^0 to 10^6
More Materials: Noble Metals

![Graphs showing dielectric properties of noble metals](image)
More Materials: Noble Metals

\[ E = \hbar c k_0 \]

Graph showing the relationship between energy (E) in eV and wave vector (k_x) in m^{-1} for various materials including Au, Ag, Cu, Al, Be, and Cr. The graph includes a shaded region indicating a certain energy range.
More Materials: Noble Metals

The diagram shows the normalized cross-section $\sigma_s/(k^4 a^6)$ as a function of wavelength $\lambda_0$ in meters. The materials represented are:
- Au (gold)
- Ag (silver)
- Cu (copper)
- Al (aluminum)
- Be (beryllium)
- Cr (chromium)
- PEC (perfect electric conductor)

The y-axis represents the normalized cross-section, while the x-axis represents the wavelength in meters. The data points are plotted for different materials, with gold showing a sharp peak at a certain wavelength.
Designing Plasmonic Responses

To elicit certain responses:

- change geometry (size, shape, layering)
- change materials

From Mock 2002.
More Materials: Non-metals

Compounds accepting of dopants allow for modulation of SPP properties, but are limited to low energy regimes.
Nitrides present other metal alternatives, but require careful tuning to minimize losses (from Naik 2013).
More Materials: Nitrides

![Image of nitride materials: TiN, ZrN, HfN, TaN]
More Materials: Graphene

In the SPP regime within noble metals, confinement typically limited to

\[ k_x < \frac{3\omega}{c_0} \]

2D graphene is complex, but in the low energy \((k_x \ll k_F)\) regime,

\[ k_x = A\omega^2 \]

Opportunity for extreme confinement.

- assumes low-energy regime (THz)
- breaks down when \(\lambda_p \sim 1 - 10\) nm due to non-local effects

![Graphene on SiO₂, x20](https://example.com/graphene.png)

![Au-SiO₂](https://example.com/au-sio2.png)

\[ E = \hbar c k_0 \]
More Materials: Graphene

Graphene can be tuned through carrier density (from Naik 2013).
Non-local Effects

Strange things happen when field confinement approaches dimension of electron screening lengths.

Approach modelling via:
- size dependent effective medium
- layered media approach

From Luo, 2013
Conclusions

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- accurate modeling of material response is critical
- sub-optical models agree, many differ in the optical band and above
- exotic materials may offer high field confinement and tunability
Novotny and Hecht, “Principles of Nano-optics,” 2012  