University of Ioannina
Department of Materials Science & Engineering
Computational Materials Science

Plasmonics: Experiment, theory and applications

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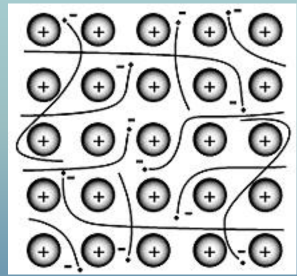
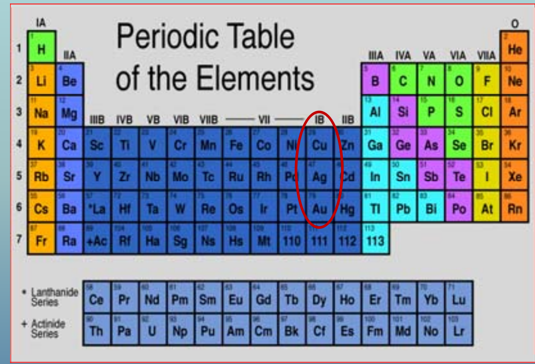
Plasmonics: photonics with free charges

- A "sea" of free electrons in a background of rigid positive ions





- Best conductors: noble metals Cu, Ag and Au
  - large electron charge density (about 1 free electron per atom)

$$N = \frac{\rho N_A}{A} \approx 10^{23} \text{ el/cm}^3$$

Drude theory of metals: DC

- Under the action of a constant external electric field
  - electrons get accelerated

$$\mathbf{F} = -e\mathbf{E}$$

  - if the average time between collisions is τ, then

$$<\mathbf{p}> = \mathbf{F}\tau \quad \Rightarrow \; <\mathbf{\upsilon}> = \frac{<\mathbf{p}>}{m} = -\frac{e\mathbf{E}}{m}\tau$$

  - this corresponds to a net current density

$$\mathbf{J} = -Ne<\mathbf{\upsilon}> = \left(\frac{Ne^2\tau}{m}\right)\mathbf{E}$$

  - and thus to a DC conductivity

$$\mathbf{J} = \sigma_0\mathbf{E} \quad \Rightarrow \boxed{\sigma_0 = \frac{Ne^2\tau}{m}}$$

Drude theory of metals: AC

- Under the action of an oscillating external electric field
  - within a time interval *dt* electrons get accelerated by the field, but also loose speed due to collisions

$$\frac{d<\mathbf{\upsilon}>}{dt} = -\frac{<\mathbf{\upsilon}>}{\tau} - \frac{e\mathbf{E}}{m}$$

  - assume a harmonic time dependence for both **E** and <*υ*> $\sim e^{-i\omega t}$

$$-i\omega<\mathbf{\upsilon}> = -\frac{<\mathbf{\upsilon}>}{\tau} - \frac{e\mathbf{E}}{m}$$

$$<\mathbf{\upsilon}> = -\frac{e\tau}{m}\frac{1}{(1-i\omega\tau)}\mathbf{E}$$

  - resulting into the AC conductivity

$$\mathbf{J} = -Ne<\mathbf{\upsilon}> = \sigma\mathbf{E} \quad \Rightarrow \boxed{\sigma(\omega) = \frac{\sigma_0}{1-i\omega\tau}}, \qquad \sigma_0 = \frac{Ne^2\tau}{m}$$

Metal dielectric function

- Maxwell's equation for non-magnetic conductive media

$$\nabla\times\mathbf{E} = -\frac{1}{c}\frac{\partial\mathbf{H}}{\partial t} \qquad \nabla\times\mathbf{H} = \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial\mathbf{E}}{\partial t}$$

- Combine the two $\nabla\times\left(\nabla\times\mathbf{E}\right) = \nabla\times\left(-\frac{1}{c}\frac{\partial\mathbf{H}}{\partial t}\right)$

$$\nabla\times\left(\nabla\times\mathbf{E}\right) = -\frac{1}{c}\frac{\partial(\nabla\times\mathbf{H})}{\partial t}$$

$$\nabla\times\left(\nabla\times\mathbf{E}\right) = -\frac{1}{c}\frac{\partial}{\partial t}\left(\frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial\mathbf{E}}{\partial t}\right)$$

$$\nabla\times\left(\nabla\times\mathbf{E}\right) = -\frac{4\pi}{c^2}\frac{\partial\mathbf{J}}{\partial t} - \frac{1}{c^2}\frac{\partial^2\mathbf{E}}{\partial t^2}$$

Metal dielectric function

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$$\nabla\times\left(\nabla\times\mathbf{E}\right) = -\frac{4\pi}{c^2}\frac{\partial\mathbf{J}}{\partial t} - \frac{1}{c^2}\frac{\partial^2\mathbf{E}}{\partial t^2}$$

- Use the vector identiy

$$\nabla\times\left(\nabla\times\mathbf{E}\right) = \nabla\cdot(\nabla\cdot\mathbf{E}) - \nabla^2\mathbf{E}$$

and due to Maxwell's first equation $\nabla\cdot\mathbf{E} = 0$

- so the wave equation $\nabla^2\mathbf{E} = \frac{4\pi}{c^2}\frac{\partial\mathbf{J}}{\partial t} + \frac{1}{c^2}\frac{\partial^2\mathbf{E}}{\partial t^2}$

- use the fact $\mathbf{E},\mathbf{J} \sim \mathrm{e}^{-i\omega t}$ and $\mathbf{J} = \sigma\mathbf{E}$

$$\frac{\partial\mathbf{J}}{\partial t} = -i\omega\mathbf{J} = -i\omega\sigma\mathbf{E} \qquad \frac{\partial^2\mathbf{E}}{\partial t^2} = -\omega^2\mathbf{E}$$

$$\nabla^2\mathbf{E} = -i\omega\frac{4\pi\sigma}{c^2}\mathbf{E} - \frac{\omega^2}{c^2}\mathbf{E} \qquad \Rightarrow \nabla^2\mathbf{E} + \frac{\omega^2}{c^2}\left(1 + i\frac{4\pi\sigma}{\omega}\right)\mathbf{E} = 0$$

Metal dielectric function

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- Thus the metal dielectric function is

$$\Rightarrow \nabla^2\mathbf{E} + \frac{\omega^2}{c^2}\underbrace{\left(1 + i\frac{4\pi\sigma}{\omega}\right)}\mathbf{E} = 0$$

$$\varepsilon(\omega) = 1 + i\frac{4\pi\sigma(\omega)}{\omega}$$

- so the wave equation $\nabla^2\mathbf{E} + \frac{\omega^2\varepsilon(\omega)}{c^2}\mathbf{E} = 0$

plasma frequency

$$\omega_p = \sqrt{\frac{4\pi Ne^2}{m}}$$

- if we substitute for $\sigma(\omega) = \frac{Ne^2\tau}{m}\frac{1}{1 - i\omega\tau}$

$$\varepsilon(\omega) = 1 + i\frac{4\pi}{\omega}\frac{Ne^2\tau}{m}\frac{1}{1 - i\omega\tau} = 1 - \frac{4\pi Ne^2}{m}\frac{1}{\omega^2 + i\omega/\tau}$$

Metal dielectric function

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- Back to the wave equation

$$\nabla^2\mathbf{E} + \frac{\omega^2\varepsilon(\omega)}{c^2}\mathbf{E} = 0$$

$$\nabla^2\mathbf{E} + k^2\mathbf{E} = 0$$

- wave solution $\mathbf{E} \sim e^{i\mathbf{k}\cdot\mathbf{r}}e^{-i\omega t} = e^{i(\mathbf{k}\cdot\mathbf{r} - \omega t)}$ $\qquad \nabla^2 e^{i\mathbf{k}\cdot\mathbf{r}} = -\left|\mathbf{k}\right|^2 e^{i\mathbf{k}\cdot\mathbf{r}} = -k^2 e^{i\mathbf{k}\cdot\mathbf{r}}$

- wavevector and index of refraction

$$k = \sqrt{\frac{\varepsilon\omega^2}{c^2}} = \frac{n\omega}{c} \qquad n(\omega) = \sqrt{\varepsilon(\omega)}$$

Διηλεκτρική συνάρτηση: $\varepsilon(\omega) = \varepsilon_r + i\varepsilon_i$
Πολωσιμότητα του υλικού και απορρόφηση
Προκύπτει απο την ηλεκτρονική διαμόρφωση

Δείκτης διάθλασης: $n = n_r + in_i$
Διασκεδασμός και απορρόφηση
Καθορίζει τις ιδιότητες διάδοσης

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- Wave propagation $\mathbf{E} = \mathbf{E}_0 e^{i(\mathbf{kr}-\omega t)} = \mathbf{E}_0 e^{i((\mathbf{k}_r+i\mathbf{k}_i)\mathbf{r}-\omega t)} = \mathbf{E}_0 e^{i(\mathbf{k}_r\mathbf{r}-\omega t)} e^{-\mathbf{k}_i\mathbf{r}}$
- along x direction $\mathbf{E} = \mathbf{E}_0 e^{i(kx-\omega t)} = \mathbf{E}_0 e^{i((k_r+ik_i)x-\omega t)} = \mathbf{E}_0 e^{i(k_r x-\omega t)} e^{-k_i x}$
- Δύο όροι:
  - αρμονική κυματική διάδοση με k_r
  - Εκθετική απόσβεση με k_i
- Η ροή ενέργειας δίνεται απο το διάνυσμα Poynting $\mathbf{S} = \mathrm{Re}\left\{\frac{c}{8\pi}(\mathbf{E}\times\mathbf{H}^*)\right\} = \frac{cn}{8\pi}|\mathbf{E}|^2$

$$|\mathbf{E}|^2 = |\mathbf{E}_0|^2 e^{-2k_i x} = |\mathbf{E}_0|^2 e^{-2n_i\omega x/c} = |\mathbf{E}_0|^2 e^{-\alpha x}$$

συντελεστής απόσβεσης $\alpha = \frac{2n_i\omega}{c} = 2n_i\frac{2\pi}{\lambda_0} = \frac{4\pi n_i}{\lambda_0}$

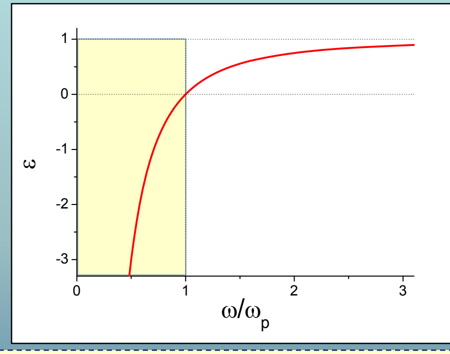
Metal dielectric function

- Drude dielectric function

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\omega/\tau}$$

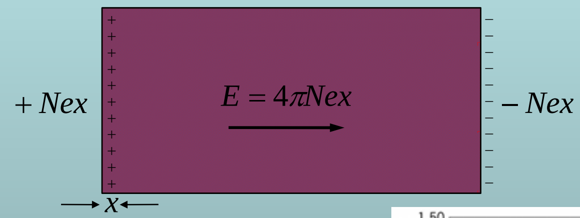
- For simplicity set $\tau = \infty$

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$



- for $\omega < \omega_p$: reflection — $\varepsilon < 0$, $n = \mathrm{imag} = in_i$, $R = \left|\frac{in_i - 1}{in_i + 1}\right|^2 = 1$
- for $\omega > \omega_p$: transmission — $\varepsilon > 0$, $n = \mathrm{real} = n_1$, $R = \left|\frac{n_r - 1}{n_r + 1}\right|^2 < 1$
- for $\omega = \omega_p$: bulk plasmons — $\varepsilon = 0$, $n = 0$, longitudinal waves: $\varepsilon\nabla\mathbf{E} = 0 \Rightarrow \nabla\mathbf{E} \neq 0$

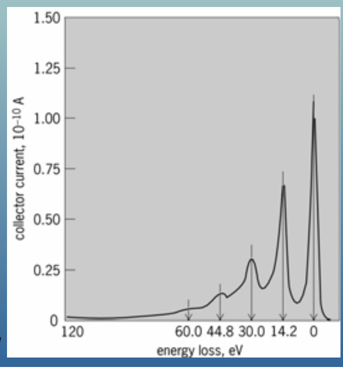
Bulk plasmon



$m\ddot{x} = -eE \Rightarrow$
$\ddot{x} + \frac{4\pi Ne^2}{m}x = 0$

self-sustained longitudinal charge oscillations with frequency ω_p

absorption peaks at $E = n\hbar\omega_p$



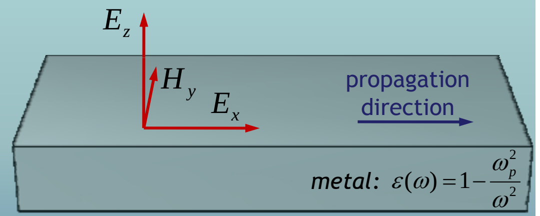
Number of detected electrons in a beam versus their energy loss during transit through a thin aluminum foil

Surface plasmon polaritons

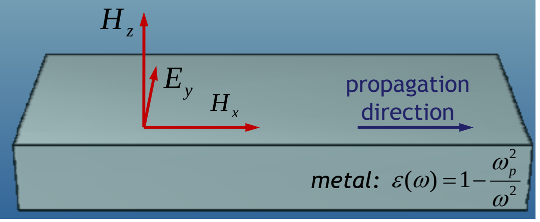
- A propagating wave bound on a metal-dielectric interface
  - e.g. metal-air interface
- Exponential decay away from the surface
- General form of all fields (i.e. $F \equiv E_x, E_y, E_z, H_x, H_y, H_z$)
  - above the interface (diel.) $F \propto e^{i(kx-\omega t)} e^{-\kappa z}$
  - below the interface (metal) $F' \propto e^{i(kx-\omega t)} e^{+\kappa' z}$

Two independent polarizations:

Transverse magnetic (TM) polarization



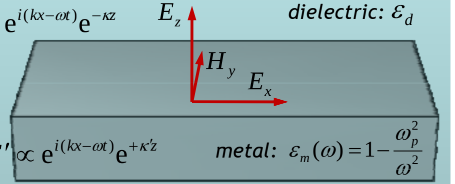
Transverse electric (TE) polarization



Surface plasmon polaritons

- Only the TM has plasmon solution
- SPP solution is obtained from combining:
  - boundary conditions
  - Maxwell's equation
  - wave equation

$F \propto e^{i(kx-\omega t)} e^{-\kappa z}$



$F' \propto e^{i(kx-\omega t)} e^{+\kappa' z}$

boundary conditions at z=0
- continuity of the parallel E

$$E_x = E'_x$$

- continuity of the parallel H

$$H_y = H'_y$$

- continuity of the perpendicular D

$$\varepsilon_d E_z = \varepsilon_m E'_z$$

Maxwell's equation

$$\nabla \times \mathbf{H} = \frac{\varepsilon}{c}\frac{\partial \mathbf{E}}{\partial t} \Rightarrow \begin{cases} \frac{\partial H_y}{\partial z} = -\frac{\varepsilon}{c}\frac{\partial E_x}{\partial t} & \begin{cases} c\kappa H_y = -i\varepsilon_d \omega E_x \\ c\kappa' H'_y = i\varepsilon_m \omega E'_x \end{cases} \\ \frac{\partial H_y}{\partial x} = \frac{\varepsilon}{c}\frac{\partial E_z}{\partial t} & \begin{cases} ckH_y = -i\varepsilon_d \omega E_x \\ ckH'_y = -i\varepsilon_m \omega E'_x \end{cases} \end{cases}$$

$$\Rightarrow \kappa = -\kappa' \varepsilon_d / \varepsilon_m$$

wave equation

$$\nabla^2 \mathbf{E} + \frac{\omega^2 \varepsilon(\omega)}{c^2}\mathbf{E} = 0 \Rightarrow \begin{cases} -k^2 + \kappa^2 + \omega^2 \varepsilon_d / c^2 = 0 \\ -k^2 + \kappa'^2 + \omega^2 \varepsilon_m / c^2 = 0 \end{cases}$$

SPP dispersion

$$k = \frac{\omega}{c}\sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}}$$

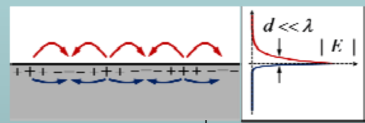
Surface plasmon polaritons

- Surface plasmon polariton (SPP)

$$\left.\begin{aligned} \kappa &= -\kappa' \varepsilon_d / \varepsilon_m \\ k &= \frac{\omega}{c}\sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}} \end{aligned}\right\}$$

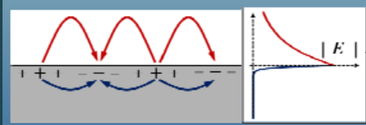
SPP condition
$\varepsilon_m(\omega) < -\varepsilon_d$

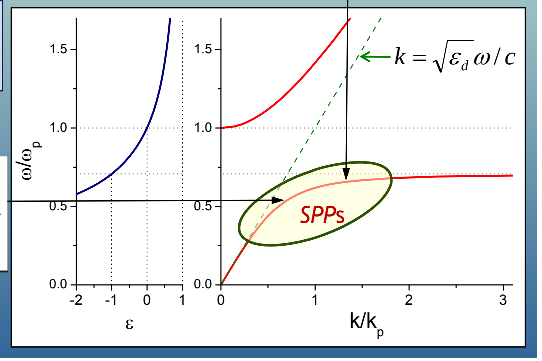
$$\varepsilon_m(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$



- Surface plasmon

$$\varepsilon_m(\omega) = -\varepsilon_d \Rightarrow \omega_{SP} = \frac{\omega_p}{\sqrt{1+\varepsilon_d}}$$





Guided light

- Free waves in 3D

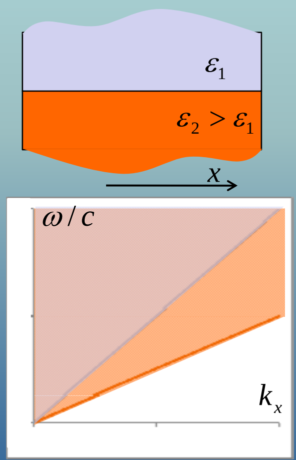
$$\left.\begin{aligned} \mathbf{E} &= \hat{\mathbf{e}} E_0 e^{i(k_x \cdot x + k_y \cdot y + k_z \cdot z - \omega t)} \\ \nabla^2 \mathbf{E} &+ \varepsilon \frac{\omega^2}{c^2}\mathbf{E} = 0 \end{aligned}\right\} \quad k_x^2 + k_y^2 + k_z^2 = \varepsilon \frac{\omega^2}{c^2}$$

- Assume an interface between two materials
  - x direction is uniform, and so k_x is conserved
  - in material 1

$$k_x^2 = \varepsilon_1 \frac{\omega^2}{c^2} - k_y^2 - k_z^2 \quad \Rightarrow k_x \le \sqrt{\varepsilon_1}\frac{\omega}{c}$$

  - in material 2

$$k_x^2 = \varepsilon_2 \frac{\omega^2}{c^2} - k_y^2 - k_z^2 \quad \Rightarrow k_x \le \sqrt{\varepsilon_2}\frac{\omega}{c}$$



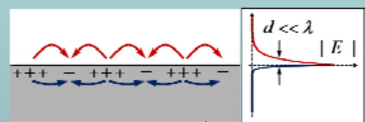
Surface plasmon polaritons

- Surface plasmon polariton (SPP)

$$\left.\begin{aligned} \kappa &= -\kappa' \varepsilon_d / \varepsilon_m \\ k &= \frac{\omega}{c}\sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}} \end{aligned}\right\}$$

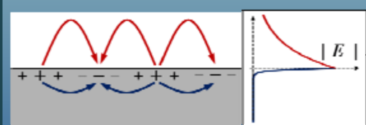
SPP condition
$\varepsilon_m(\omega) < -\varepsilon_d$

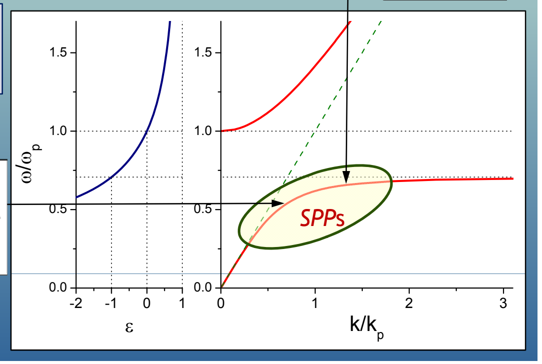
$$\varepsilon_m(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$



- Surface plasmon

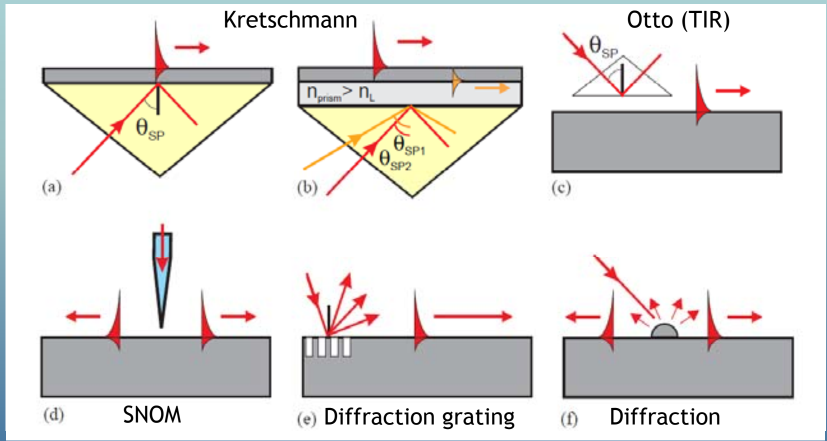
$$\varepsilon_m(\omega) = -\varepsilon_d \Rightarrow \omega_{SP} = \frac{\omega_p}{\sqrt{1+\varepsilon_d}}$$





Excitation of SPPs

- Surface plasmon polaritons exist below the light-cone
  - special care is needed to excite them



Zayats, Smolyaninov and Maradudin, Phys. Rep. 408, 131 (2005)

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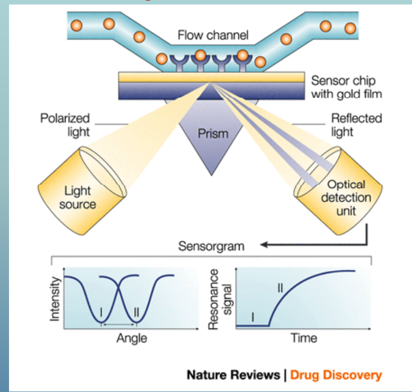
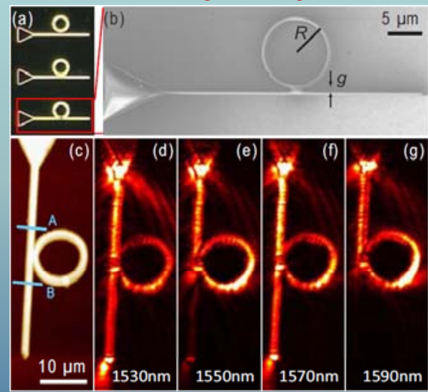
SPP applications

biological sensors



M.A. Cooper, NRDD 1, 515 (2002)

subwavelength waveguides



T. Holmgaard et al., APL 94, 051111 (2009)

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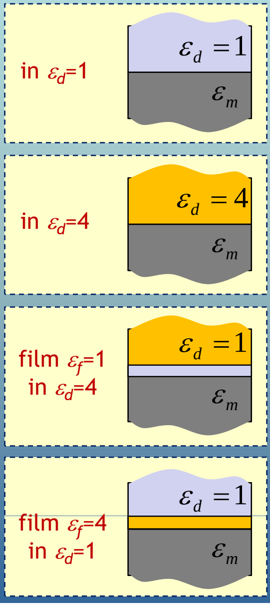
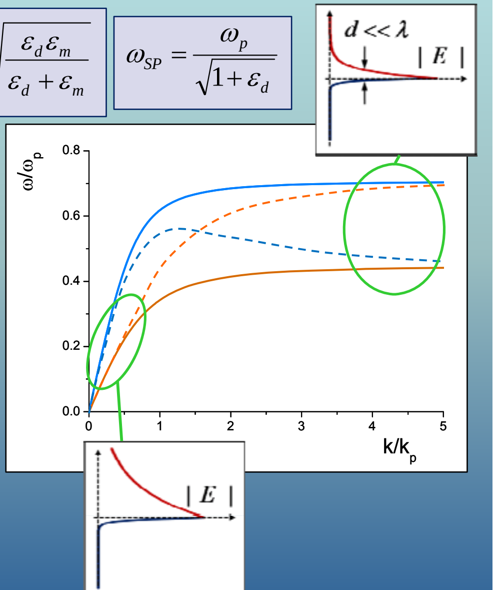
More complex SPPs



$$k = \frac{\omega}{c}\sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}}$$

$$\omega_{SP} = \frac{\omega_p}{\sqrt{1+\varepsilon_d}}$$



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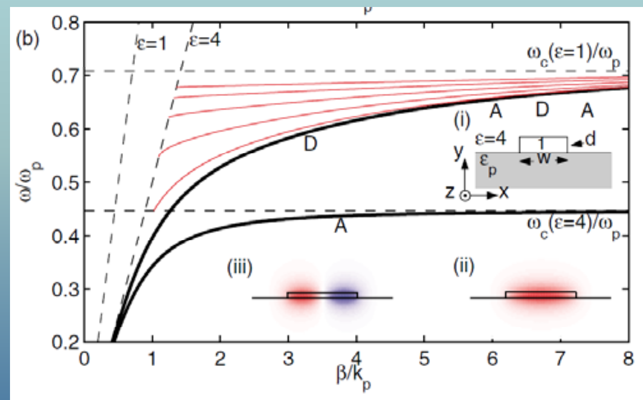
SPP waveguides

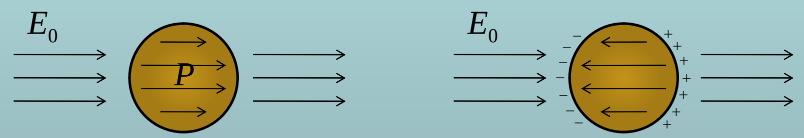
- Surface-plasmon-assisted guiding of *broadband* *slow* and *subwavelength* light in *air*



Karalis, Lidorikis, Ibanescu, Joannopoulos and Soljacic, PRL 95, 063901 (2005)

Metallic nanoparticles

- A metallic nanoparticle inside a electromagnetic field
  - $a << \lambda \Rightarrow$ electrostatic limit



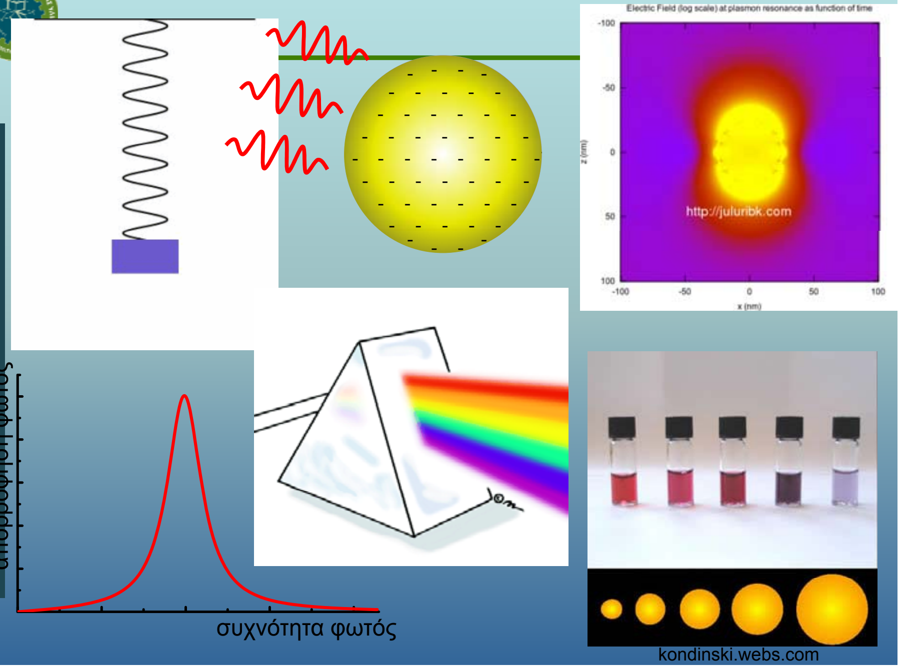
$$\Phi_{in} = -\left(\frac{3}{\varepsilon_m + 2\varepsilon_d}\right) E_0 r \cos\theta$$
$\underbrace{}$ uniform

$$\Phi_{out} = \underbrace{-E_0 r \cos\theta}_{\text{uniform}} + \underbrace{\left(\frac{\varepsilon_m - \varepsilon_d}{\varepsilon_m + 2\varepsilon_d}\right) E_0 \frac{a^3}{r^2}\cos\theta}_{\text{dipole}}$$

Inside an electric field a nanoparticle gets polarized

$$p(t) \cong 4\pi a^3 \left(\frac{\varepsilon_m - \varepsilon_d}{\varepsilon_m + 2\varepsilon_d}\right) E(t)$$

- strong scattering
- strong local fields



Localized surface plasmon resonance

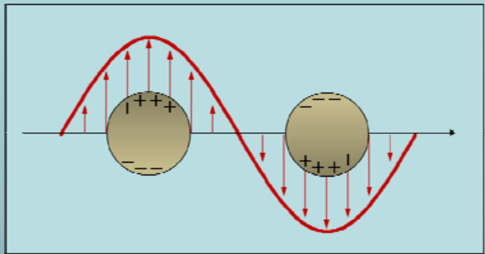
- Inside an electromagnetic field the nanoparticle gets polarized

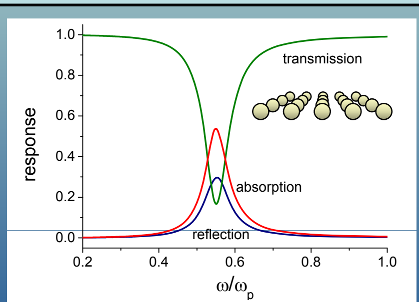
$$p(t) \cong 4\pi a^3 \left(\frac{\varepsilon_m - \varepsilon_d}{\varepsilon_m + 2\varepsilon_d}\right) E(t)$$

- Surface Plasmon Resonance

$$\varepsilon_m(\omega) = -2\varepsilon_d \Rightarrow$$
$$\omega_{LSPR} = \frac{\omega_p}{\sqrt{1+2\varepsilon_d}}$$

- At resonance we get extreme optical behavior
  - local fields get maximized
  - scattering gets maximized
  - absorption gets maximized





Localized surface plasmon resonance

- Assume the metal dielectric

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\omega/\tau}$$

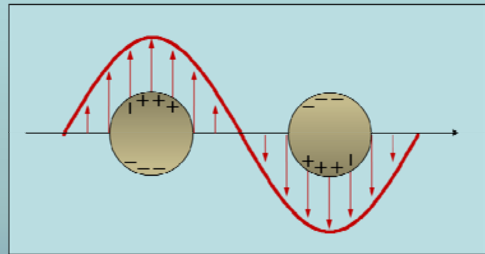
- We calculate the effective medium produced by the NPs
  - Maxwell-Garnett formula

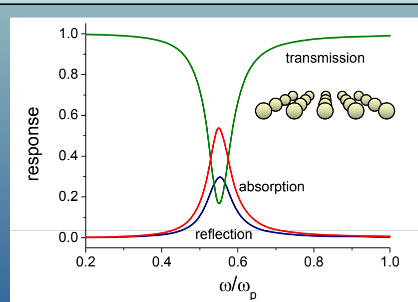
$$\frac{\tilde{\varepsilon} - \varepsilon_d}{\tilde{\varepsilon} + 2\varepsilon_d} = f \frac{\varepsilon_m - \varepsilon_d}{\varepsilon_m + 2\varepsilon_d}$$

for $\varepsilon_d = 1$:

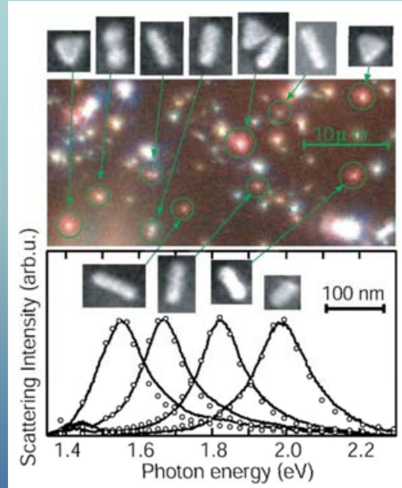
$$\tilde{\varepsilon} = 1 + \frac{f\omega_p^2}{(1-f)\omega_{LSPR}^2 - \omega^2 - i\omega/\tau}$$

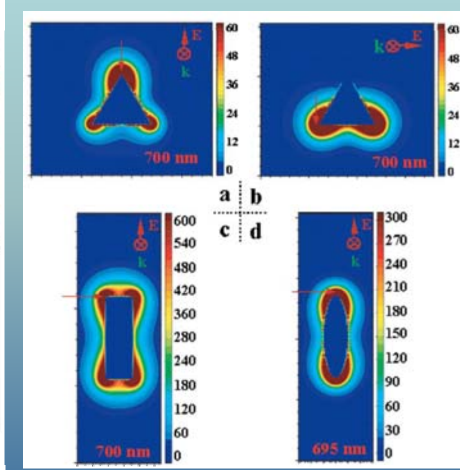
- This is a Lorentzian!
  - The free electrons oscillate as a driven oscillator
  - NPs are like polarizable atoms





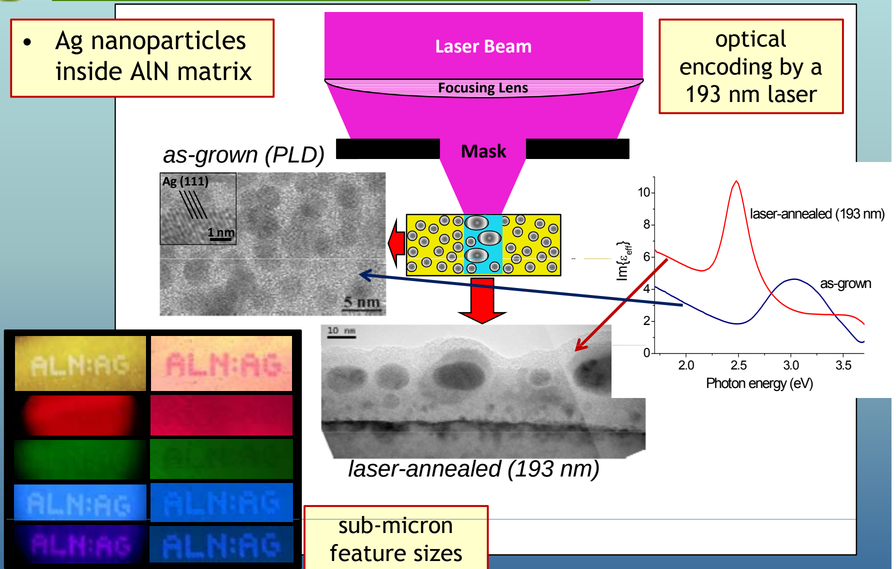
Au and Ag nanoprisms





Maier et al., JAP **98, 011101 (2005)**

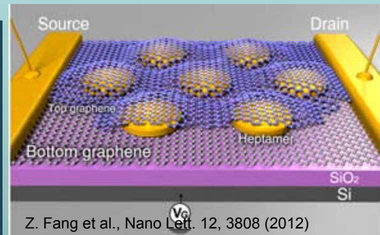
Optical encoding with LSPRs



Koutsogiorgis, Lidorikis, Patsalas et al., unpublished

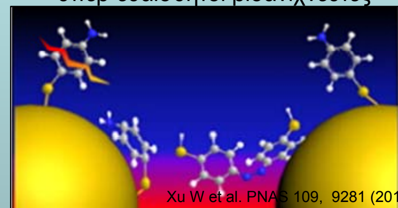
Εφαρμογές πλασμονικών νανοσωματιδίων

Ταχύτατες οπτοηλεκτρονικές διατάξεις



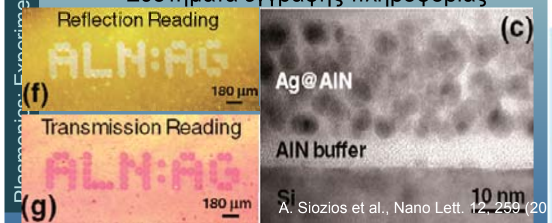
Z. Fang et al., Nano Lett. 12, 3808 (2012)

υπερ-ευαίσθητοι βιοανιχνευτές



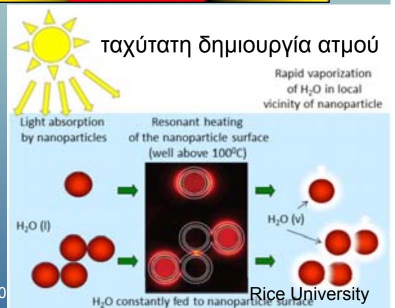
Xu W et al. PNAS 109, 9281 (2012)

Συστήματα εγγραφής πληροφορίας



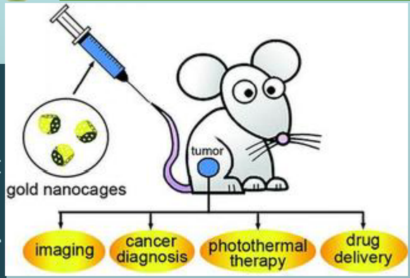
A. Siozios et al., Nano Lett. 12, 259 (2012)

ταχύτατη δημιουργία ατμού

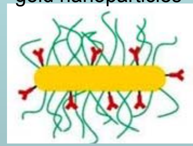


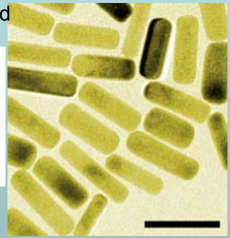
Rice University

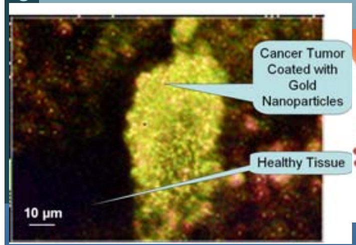
Εφαρμογές πλασμονικών νανοσωματιδίων στην ιατρική

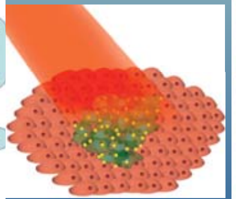


anti-EGFR conjugated gold nanoparticles









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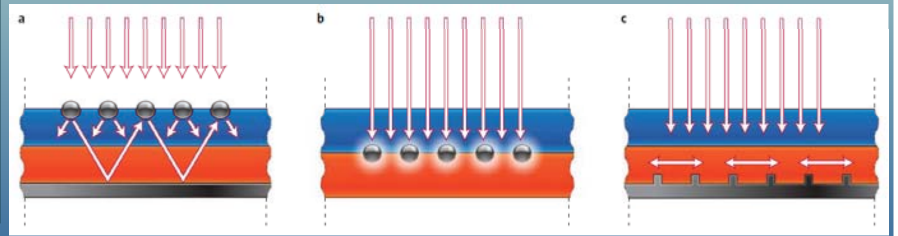
Enhanced solar absorption

- Metallic nanoparticles and/or nanostructures can be used:
  - on the surface
  - inside the semiconductor
  - on the back contact
- Enhancement due to:
  - Scattering from the nanoparticles: increased optical path
  - LSPR near-fields: increased fields driving the absorption

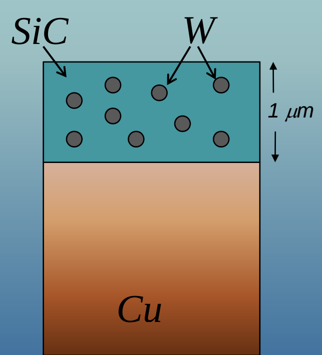
Particularly important for organic and thin film solar cells

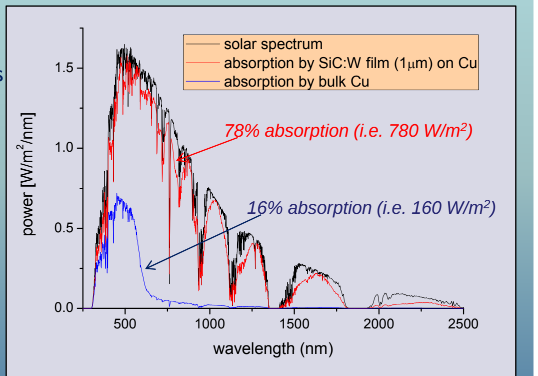


Atwater and Polman, Nature Mater. 9, 205 (2010)

Solar harvesting

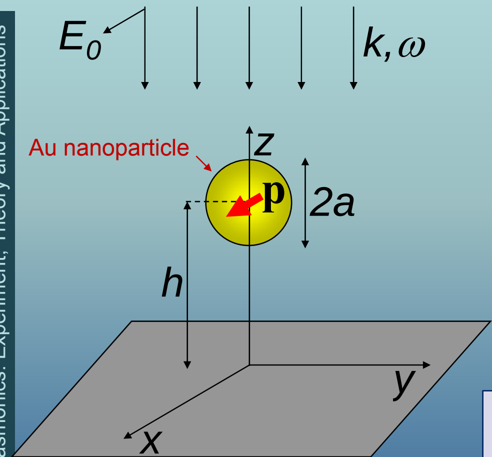
- A thin composite film of SiC with W nanoparticles
  - absorbs most of spectrum
  - inert and stable (protection)
  - withstands high temperatures (>1000 °C)

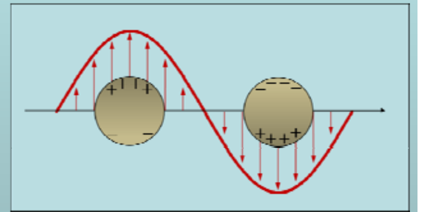




Bellas and Lidorikis, unpublished

Theory of SPR near-field enhancement





$$\mathbf{p}(\omega) = \varepsilon_0 \varepsilon_d \alpha_{np}(\omega) \mathbf{E}_0$$

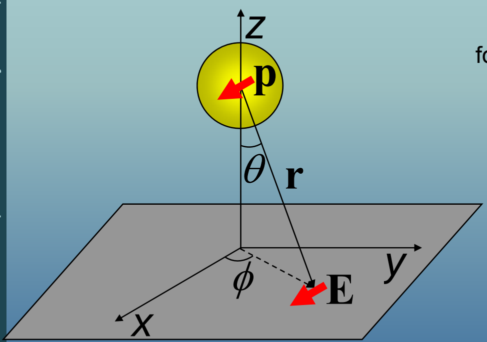
for a<<λ

$$\alpha_{np}(\omega) \equiv 4\pi a^3 Q \cong 4\pi a^3 \left(\frac{\varepsilon_m - \varepsilon_d}{\varepsilon_m + 2\varepsilon_d} \right)$$

Theory of SPR near-field enhancement

$$\mathbf{E}(\mathbf{r},\omega) \approx \mathbf{E}_0(\mathbf{r},\omega)\hat{\mathbf{x}} + \frac{e^{ikr}}{4\pi\varepsilon_d\varepsilon_0}\left[\frac{k^2}{r}\hat{\mathbf{r}}\times(\mathbf{p}\times\hat{\mathbf{r}}) + \left(\frac{1}{r^3} - \frac{ik}{r^2}\right)[3\hat{\mathbf{r}}(\hat{\mathbf{r}}\cdot\mathbf{p}) - \mathbf{p}]\right]$$

$\propto [\lambda^2 r]^{-1}$ $\propto r^{-3}$ $\propto [\lambda r^2]^{-1}$



for $r<<\lambda$ the dominant term is the r^{-3}

$$|\mathbf{E}_d(\mathbf{r},\omega)| \propto a_{np}(\omega) r^{-3}$$

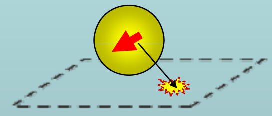
absorption enhancement

$$\propto |\mathbf{E}(\mathbf{r},\omega)|^2$$

Absorption enhancement

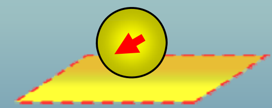
- at a point

$$F(\mathbf{r},\omega) \cong 1 + |Q|^2 \left(\frac{a}{r}\right)^6 (3x^2+1) +$$
$$+ 2|Q|\left(\frac{a}{r}\right)^3 (3x^2-1)\cos\Delta$$



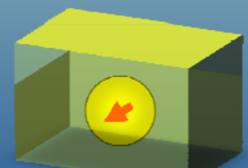
- if we integrate on a plane

$$F(z,\omega) \cong 1 - \sigma(1-\delta^2) +$$
$$+ \frac{1}{4}\sigma|Q|^2\left(\frac{a}{z}\right)^4 (5\delta^4 - 2\delta^6) +$$
$$+ 2\sigma|Q|\left(\frac{a}{|z|}\right)\delta(1-\delta^2-k^2z^2)\cos\Delta'$$



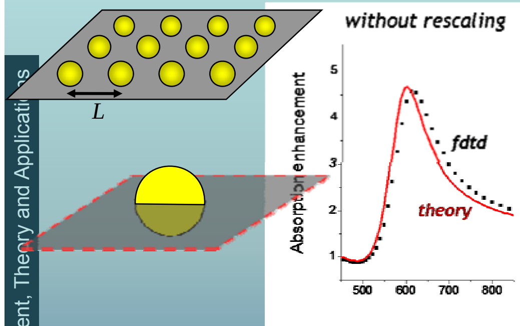
- if we integrate within a volume

$$F(\omega) \cong 1 - f + 2f|Q|^2 + 2f\,\mathrm{Re}\{Q\}$$



$\delta = \min(1,|z|/a)$ $\Delta = kr - kz + \zeta$ $\Delta' = k|z|/\delta - kz + \zeta$ $Q = |Q|e^{i\zeta}$

Planar absorption enhancement

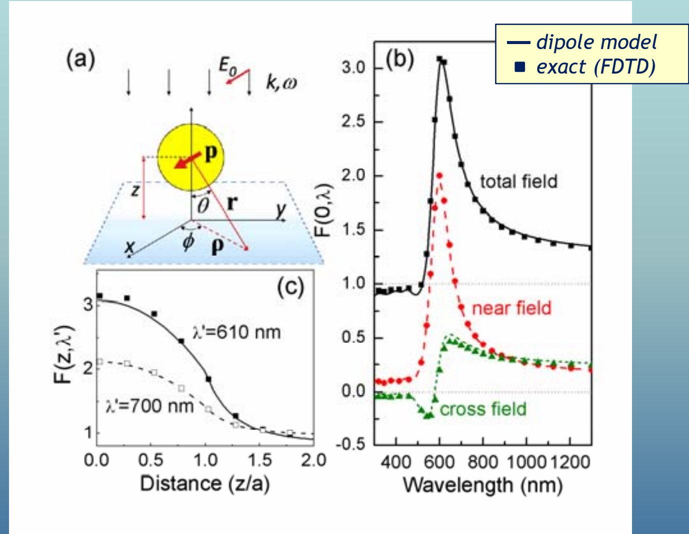


- Multiple scattering → Claussius-Mossotti $\alpha_{np} \to \dfrac{a_{np}}{1-\dfrac{N}{3}\alpha_{np}} \Rightarrow Q \to \dfrac{Q}{1-f\cdot Q}$

- Absorption in the nanoparticle → reduced field strength

$$|E_0|^2 \to |E_0|^2(1-C_{abs}/L^2) = \gamma|E_0|^2$$
$$C_{abs} = k\,\mathrm{Im}\{\alpha_{np}\} = 4\pi a^3 k\,\mathrm{Im}\{Q\}$$

Planar absorption enhancement

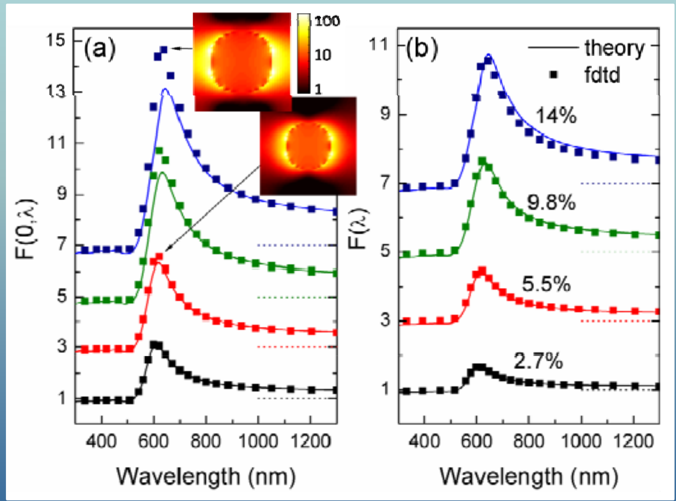


Simple dipole model has excellent agreement with exact numerical simulations (FDTD)

Planar and volume absorption enhancement

enhancement on a plane through the nanoparticle center

enhancement in all volume around the nanoparticle



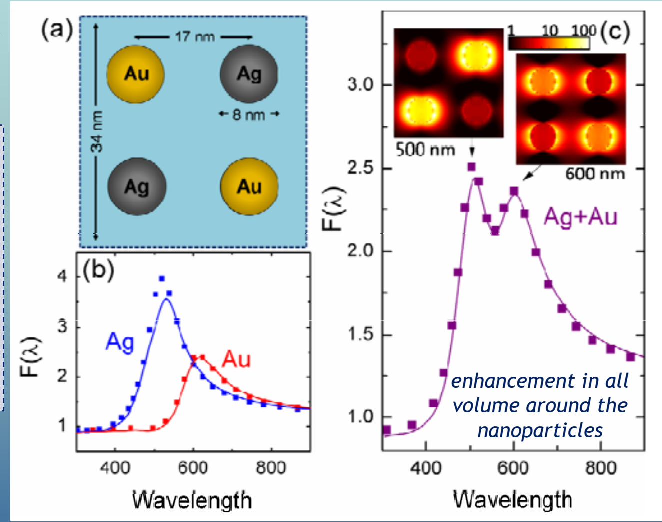
Volume enhancement of composites

if more than one type of nanoaprticles is present, the rescallings become:

$$Q_i \rightarrow \frac{Q_i}{1-\sum f_i Q_i}$$

$$\gamma = 1 - \frac{\sum f_i C_i}{L^2 f}$$

$$\sum f_i = f$$



combining different nanoparticles we can tailor the absorption spectrum of the semiconductor

Lagos, Sigalas and Lidorikis, submitted

Conclusions

- Exciting time for plasmonics
  - sensors
  - optical waveguides and components
  - encoding
  - biomedical
  - solar harvesting
  - enhanced light-matter interactions
  - and many more to come…

Thank you for your attention!