Plasmonics: main concepts and equations

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Outline

1. Surface plasmons.

Surface plasmons, surface plasmon conditions, surface plasmon dispersion. Excitation of surface plasmons: ATR coupler (Kretschmanns and Otto configurations), grating coupler. Propagation length of surface plasmon . Surface plasmon on thin film.

2. Localized surface plasmons.

Localized surface plasmon modes in metallic particles: electrostatic solution. Localized surface plasmon in metalic sphere, void in metal, metallic shell. Electromagnetic solution. Radiative damping. Surface plasmons and surface localized plasmons: differences and similarities

3. Plasmons in nanoporous metal structures

Surface plasmon resonance on a flat surface. Localized surface plasmon resonance in voids. Rayleigh anomalies.

4. Total light absorption by plasmonic nanostructures

Effective surface impedance model. Multi-channel model: the Breit-Wigner approximation

Summary

Dielectric response of the metal: the Drude model

$$m\ddot{\mathbf{x}} + b\dot{\mathbf{x}} = e\mathbf{E} \qquad \mathbf{x} = -\frac{(e/m)\mathbf{E}}{w(w+in_e)} \qquad n_e = b/m \qquad w_p^{\ 2} = \frac{Ne^2}{m}$$

$$\mathbf{p} = e\mathbf{x}$$

$$\mathbf{P} = N\mathbf{p} = Ne\mathbf{x} = -\frac{w_p^2}{w(w+in_e)}\mathbf{E}$$

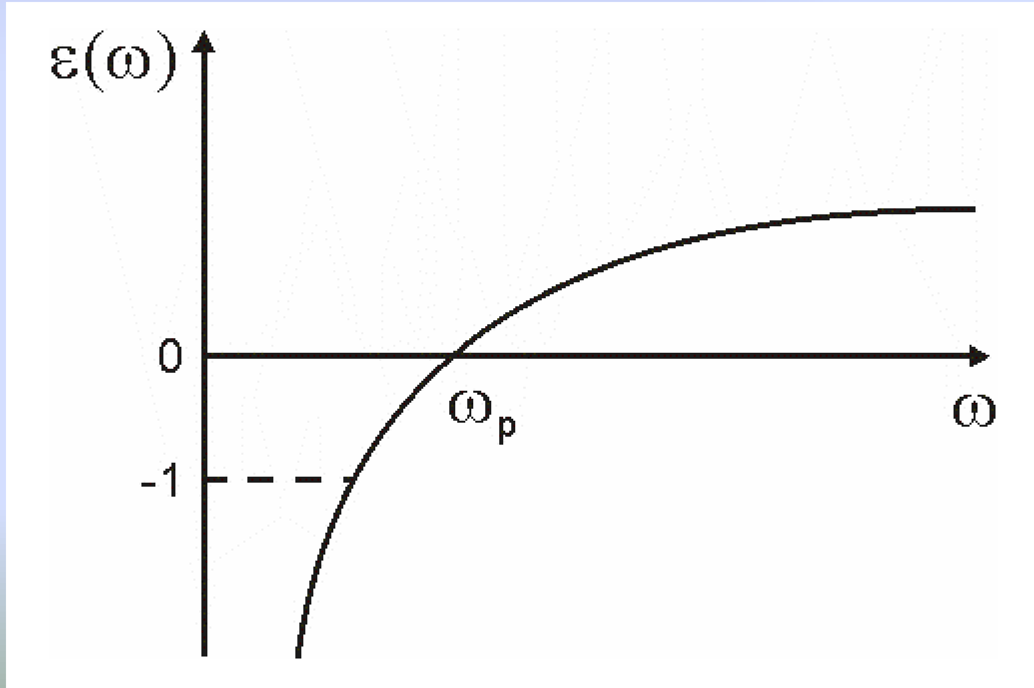
$$\mathbf{P} = c\mathbf{E} = (e-1)\mathbf{E}$$

$$\Rightarrow \quad e(w) = 1 - \frac{w_p^{\ 2}}{w(w+in_e)}$$

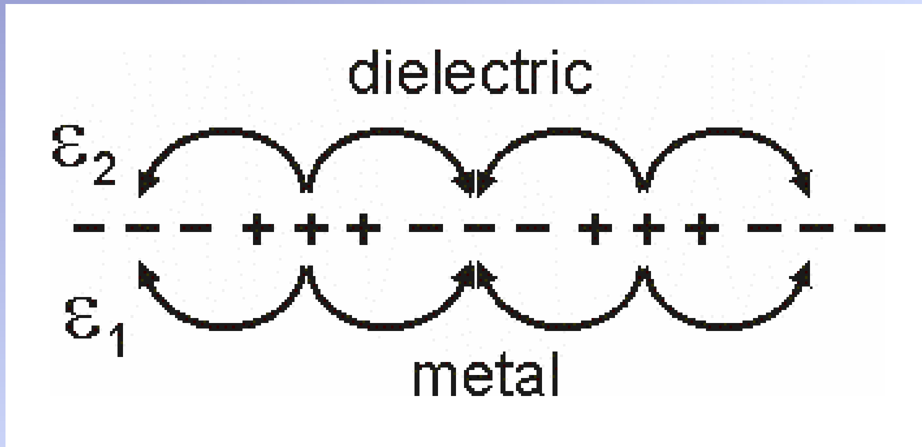
$$\Downarrow$$

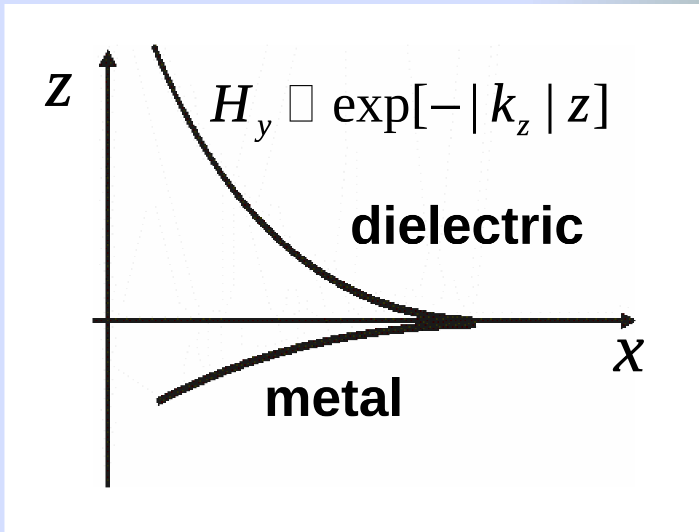
$$e(w) \cong 1 - \frac{w_p^2}{w^2}$$

$$w >> n_e$$



Surface plasmons



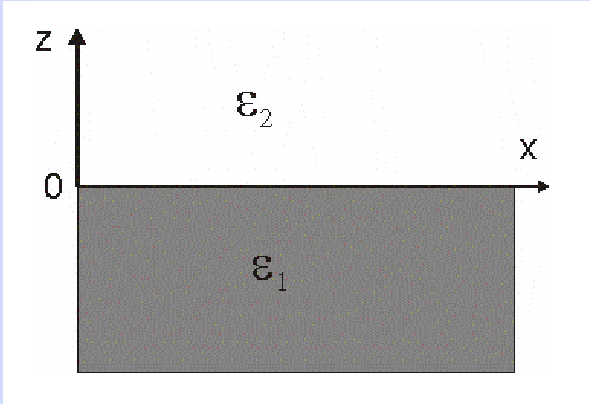


R.H.Ritchie, Phys. Rev. **106**, 874 (1957)

C.J.Powell, J.B.Swan, Phys. Rev. **118**, 640 (1960)

Surface plasmon condition 1

Maxwell's equations:



$$\nabla \times \mathbf{H} = e \frac{1}{c}\frac{\partial}{\partial t}\mathbf{E}$$

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

$$\nabla \cdot (e\mathbf{E}) = 0$$

$$\nabla \cdot \mathbf{H} = 0$$

$$i = 1,2$$

***p*-polarization**

$$\mathbf{E}_i = (E_{i_x}, 0, E_{i_z})\exp[-k_i\,|z|]\exp[iqx - iwt]$$

$$\mathbf{H}_i = (0, H_{i_y}, 0)\exp[-k_i\,|z|]\exp[iqx - iwt]$$

$$ik_1 H_{1_y} = \frac{w}{c} e_1 E_{1_x}$$

$$k_i = \sqrt{q^2 - e_i\left(\frac{w}{c}\right)^2} \quad (1)$$

$$ik_2 H_{2_y} = -\frac{w}{c} e_2 E_{2_x}$$

Surface plasmon condition 2

Boundary conditions:

$$\begin{cases} E_{1_x} = E_{2_x} \\ H_{1_y} = H_{2_y} \end{cases} \Rightarrow \begin{cases} \frac{k_1}{e_1} H_{1_y} + \frac{k_2}{e_2} H_{2_y} = 0 \\ H_{1_y} - H_{2_y} = 0 \end{cases} \Rightarrow \frac{e_1}{k_1} + \frac{e_2}{k_2} = 0 \quad (2)$$

$$k_i = \sqrt{q^2 - e_i \left(\frac{w}{c} \right)^2} \quad (1)$$

$$q(w) = \frac{w}{c} \sqrt{\frac{e_1 e_2}{e_1 + e_2}} \Rightarrow e_1 + e_2 = 0$$

nonretarded surface plasmon

$$k_1 = k_2 = q$$

Surface plasmon dispersion

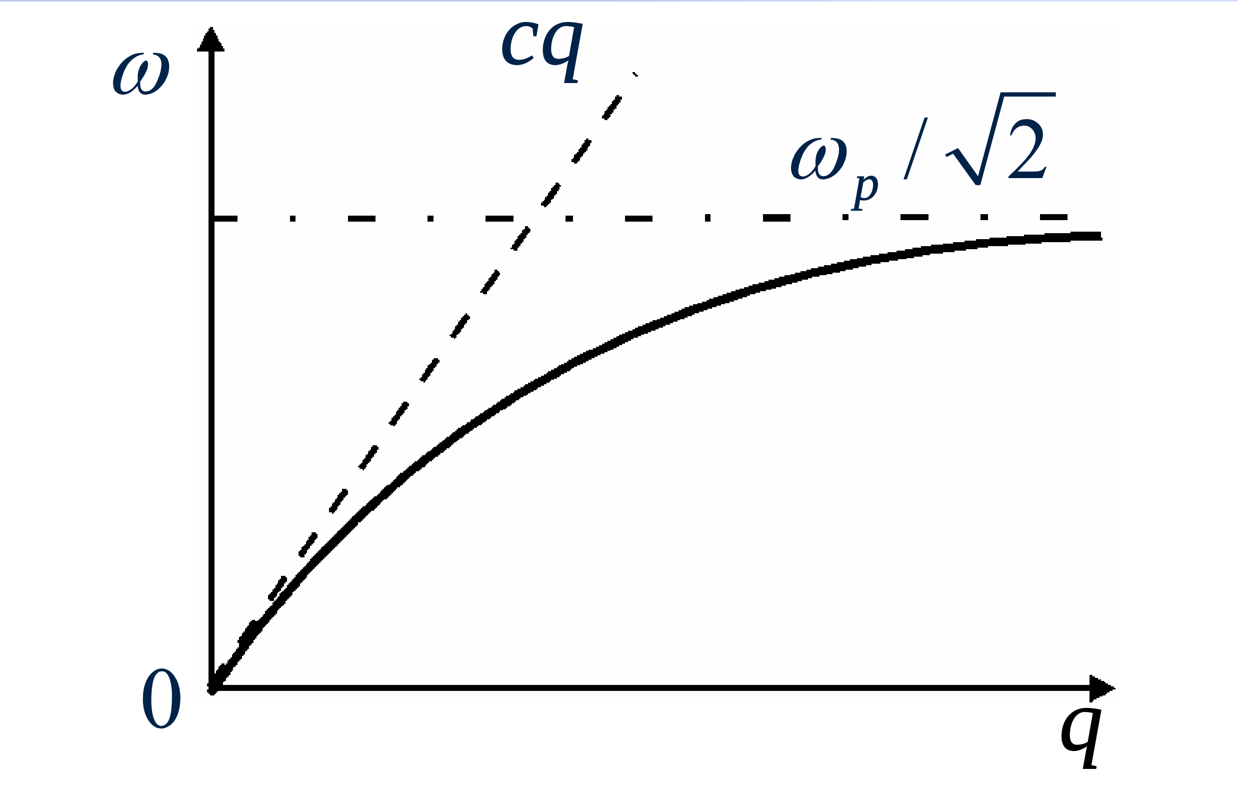
$$e_1 = 1 - \frac{w_p^2}{w^2}$$

$$e_2 = 1$$

$$q(w) = \frac{w}{c}\sqrt{\frac{w^2 - w_p^2}{2w^2 - w_p^2}}$$

$$w = w_p / \sqrt{2}$$

for large *q*



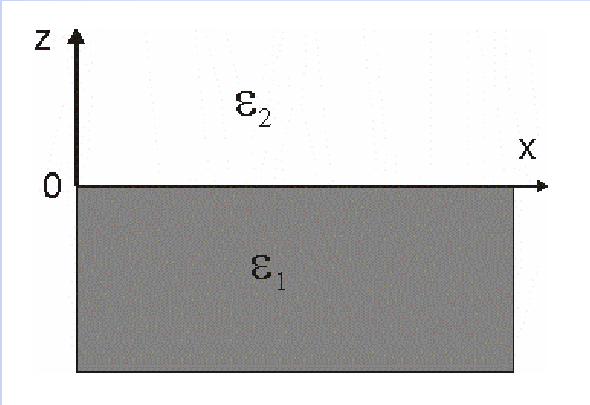
$$w = w_p / \sqrt{e_2 + 1}$$

for large *q*

$$e_2 \neq 1$$

S-polarization

Maxwell's equations:



$$\nabla \times \mathbf{H} = e \frac{1}{c} \frac{\partial}{\partial t} \mathbf{E}$$

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

$$\nabla \cdot (e \mathbf{E}) = 0$$

$$\nabla \cdot \mathbf{H} = 0$$

$$\mathbf{E}_i = (0, E_{i_y}, 0) \exp[-k_i |z|] \exp[iqx - iwt]$$

$$\mathbf{H}_i = (H_{i_x}, 0, H_{i_z}) \exp[-k_i |z|] \exp[iqx - iwt]$$

$$i = 1, 2$$

$$k_i = \sqrt{q^2 - e_i \left(\frac{w}{c}\right)^2} \quad (1)$$

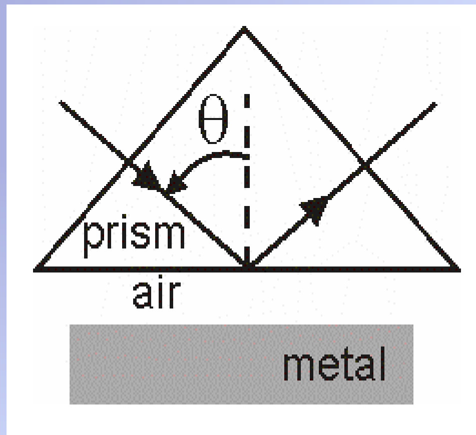
$$k_1 = -k_2 \quad (2)$$

contradiction

Excitation of surface plasmons: ATR coupler

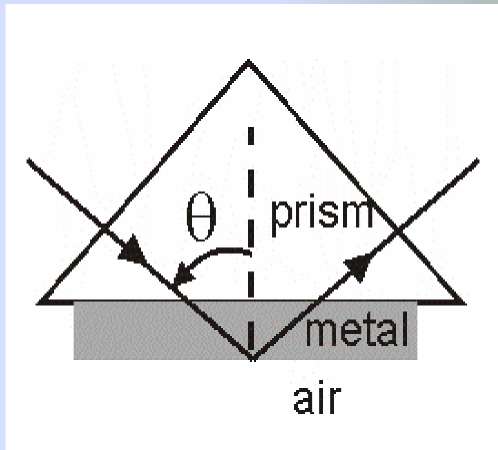
Kretschmann's configuration

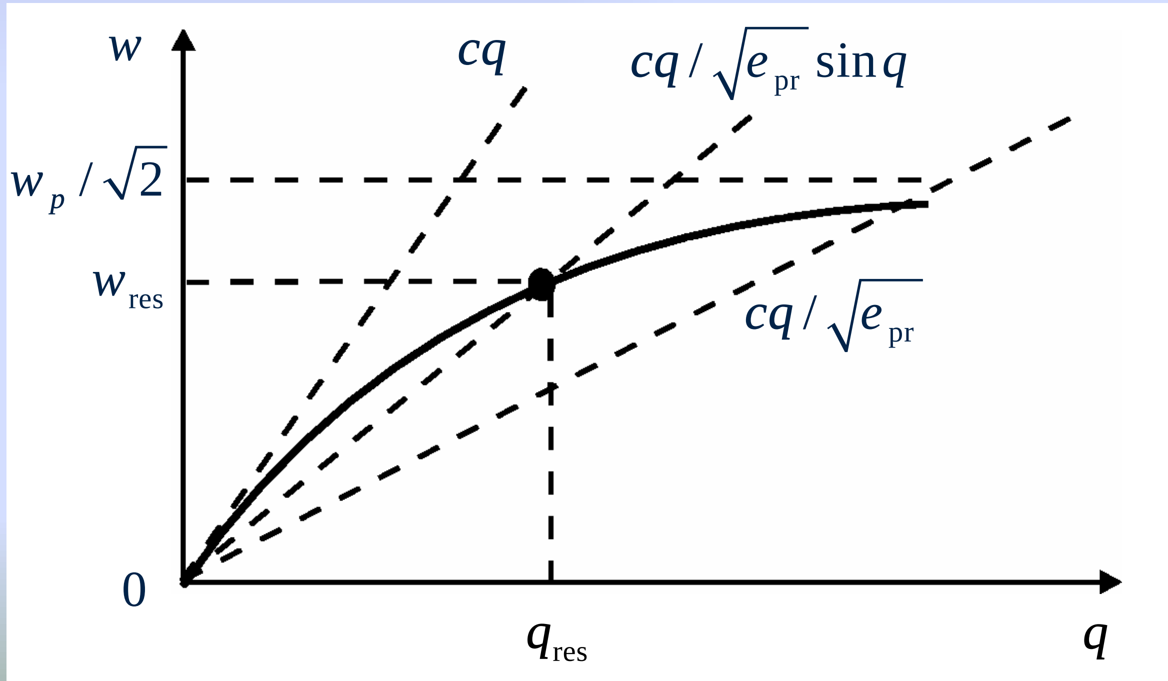
⇒



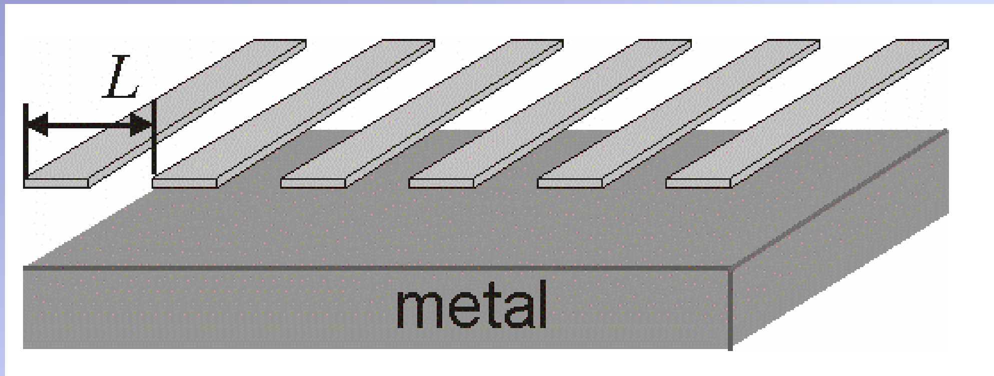
Otto's configuration

⇒





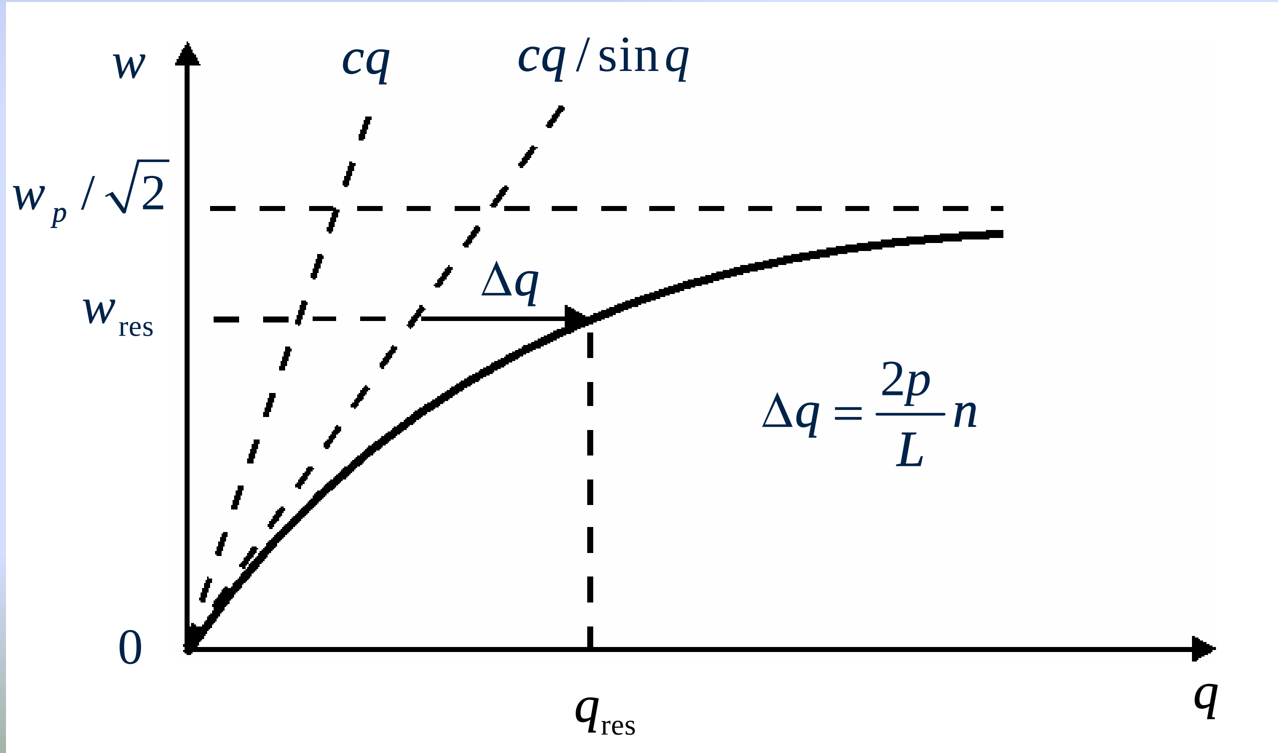
Excitation of surface plasmons: Grating coupler



$$q = q_{\|} \pm \frac{2p}{L} n = \frac{w}{c} \sin q \pm \frac{2p}{L} n,$$

$$n = 0, 1, 2, \ldots$$

$$\frac{w}{c} \sin q + \Delta q = q_{sp}$$



Propagation length of surface plasmons

$$\mathbf{E} \sim e^{iqx} = e^{-q''x} e^{iq'x}$$

$$q = q' + iq''$$

$$I \sim e^{-2q''x} \qquad 1/e$$

$$l = \frac{1}{2q''}$$

$$q = \frac{w}{c}\sqrt{\frac{e_1 e_2}{e_1 + e_2}} \qquad q' = \frac{w}{c}\left(\frac{e'_1 e_2}{e'_1 + e_2}\right)^{1/2} \qquad q'' = \frac{w}{c}\left(\frac{e'_1 e_2}{e'_1 + e_2}\right)^{3/2} \frac{e''_1}{2(e'_1)^2}$$

$$e_1 = e'_1 + ie''_1 \qquad e''_1 << e'_1$$

Ag: 22mm l=515 nm

500mm l=1060 nm

Surface plasmons on thin film

Maxwell's equations:

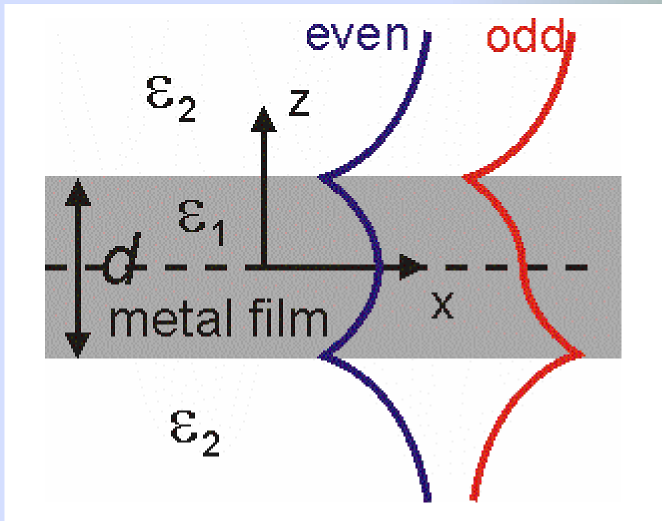
$$i = 1, 2$$

$$\nabla \times \mathbf{H} = e \frac{1}{c} \frac{\partial}{\partial t} \mathbf{E}$$

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

$$\nabla \cdot (e\mathbf{E}) = 0$$

$$\nabla \cdot \mathbf{H} = 0$$



***p*-polarization**

$$\mathbf{E}_i = (E_{i_x}, 0, E_{i_z})$$

$$\mathbf{H}_i = (0, H_{i_y}, 0)$$

even mode

$$H_{1_y} = H_1[\mathrm{e}^{k_1 z} + \mathrm{e}^{ik_1 z}]\mathrm{e}^{iqx - iwt}$$

$$H_{2_y} = H_2\, \mathrm{e}^{-k_2|z|}\, \mathrm{e}^{iqx - iwt}$$

$$H_{1_y}(z = \frac{d}{2}) = H_{1_y}(z = -\frac{d}{2}) = 2H_1 \cosh[k_1 d / 2]$$

odd mode

$$H_{1_y} = H_1[\mathrm{e}^{k_1 z} - \mathrm{e}^{-k_1 z}]\mathrm{e}^{iqx - iwt}$$

$$H_{2_y} = H_2\, \mathrm{e}^{-k_2|z|}\, \mathrm{e}^{iqx - iwt}$$

$$H_{1_y}(z = \frac{d}{2}) = -H_{1_y}(z = -\frac{d}{2}) = 2H_1 \sinh[k_1 d / 2]$$

Surface plasmons on thin film

$$\frac{e_1}{k_1 \tanh(k_1 d/2)} + \frac{e_2}{k_2} = 0 \quad \textbf{even plasmon}$$

$$\frac{e_1}{k_1 \coth(k_1 d/2)} + \frac{e_2}{k_2} = 0 \quad \textbf{odd plasmon}$$

$$\Downarrow$$

$$\frac{e_2 + e_1}{e_2 - e_1} = \mathbf{m} \exp(-qd), \qquad k_1 = k_2 = q$$

$$\Downarrow \; e_2 = 1$$

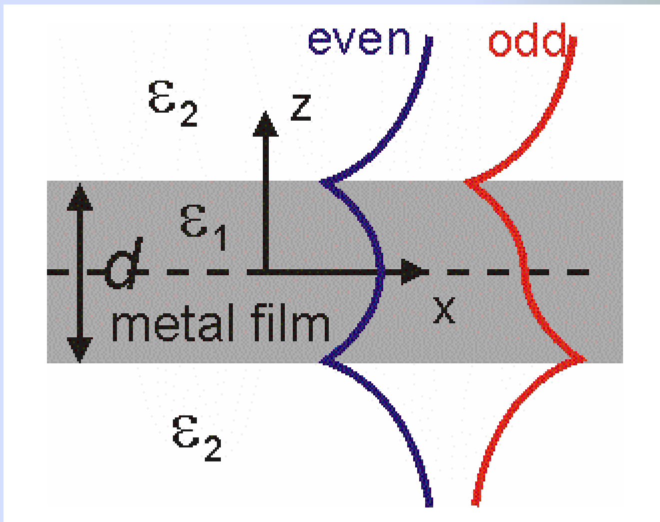
even plasmon

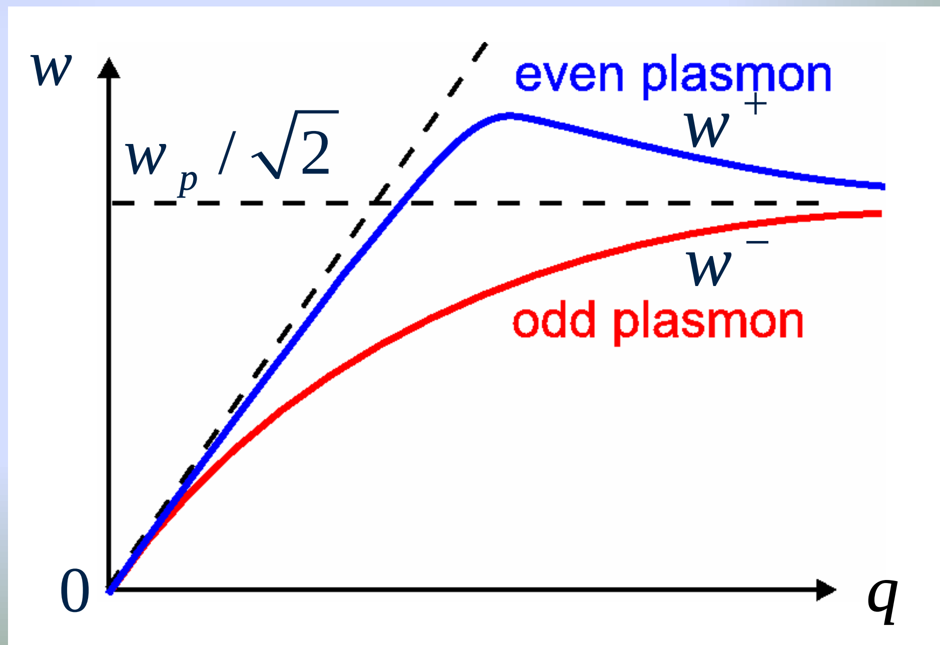
$$w^+ = \frac{w_p}{\sqrt{2}} [1 + \exp(-qd)]^{1/2}$$

odd plasmon

$$w^- = \frac{w_p}{\sqrt{2}} [1 - \exp(-qd)]^{1/2}$$

$$k_1 = \sqrt{q^2 - e_1 \left(w^{\pm}/c\right)^2}$$

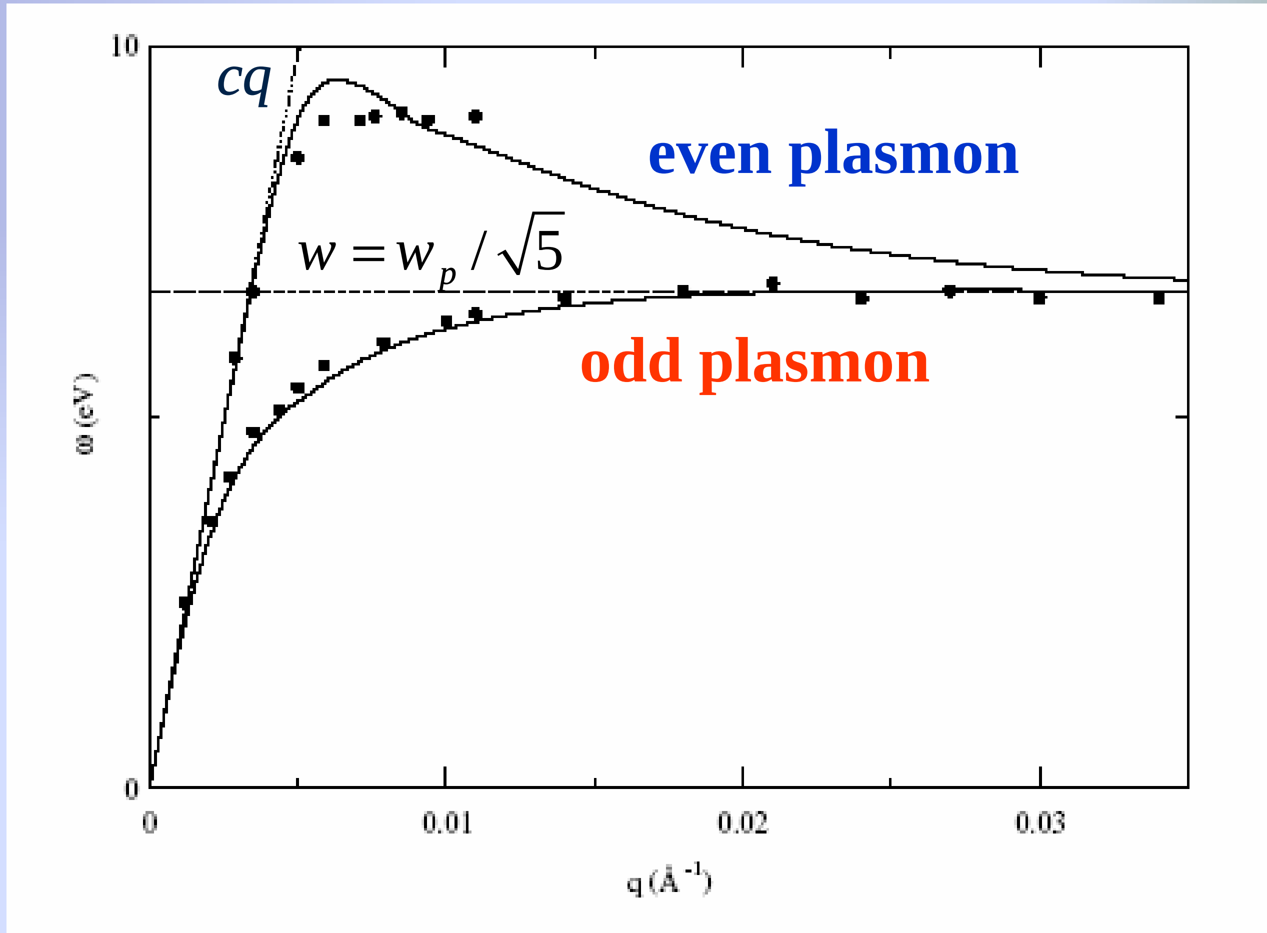




Surface plasmons of on Al film

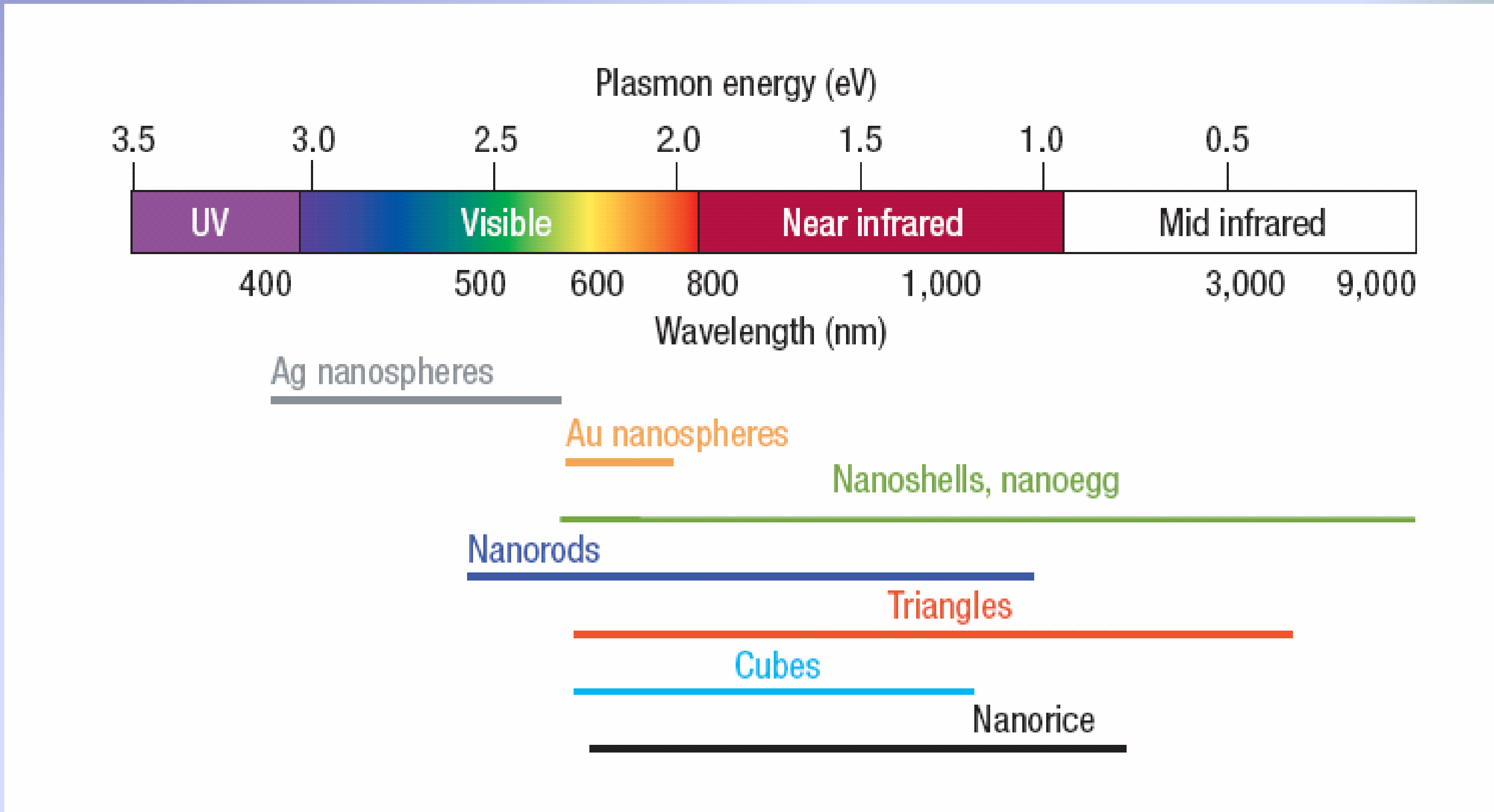
$a = 120Å$
$t = 40Å$ $\varepsilon_0 = 4.$

Al: $\omega_p = 15$ eV
$n_e = 0.75$ eV



R.B.Pettit, J.Silcox, R.Vincent, Phys. Rev. B 11 3116 (1975)
H. Raether, *Surface Plasmons*, 1988;
J M Pitarke et al., Rep. Prog. Phys. 70 1(2007).

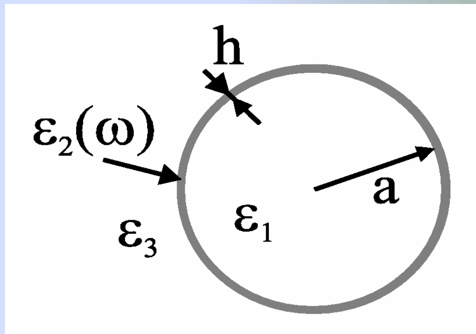
Localized surface plasmons



Surbhi Lal, Stephan Link, Naomi J. Halas
Nature Photonics, **1** 641 (2007)

A single plasmonic nanoshell: quasi-electrostatic limit

Laplace equation $\nabla^2\Phi = 0$

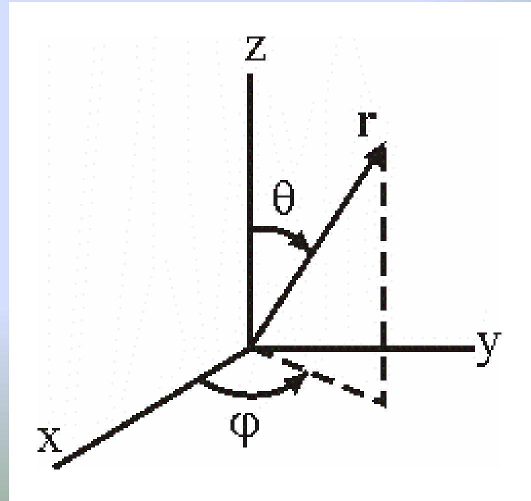


$$\frac{1}{r}\frac{\partial^2}{\partial r^2}(r\Phi) + \frac{1}{r^2 \sin q}\frac{\partial}{\partial q}\left(\sin q \frac{\partial \Phi}{\partial q}\right) + \frac{1}{r^2 \sin^2 q}\frac{\partial^2 \Phi}{\partial j^2} = 0$$

$$\Phi = \frac{U(r)}{r} P(q) Q(j)$$

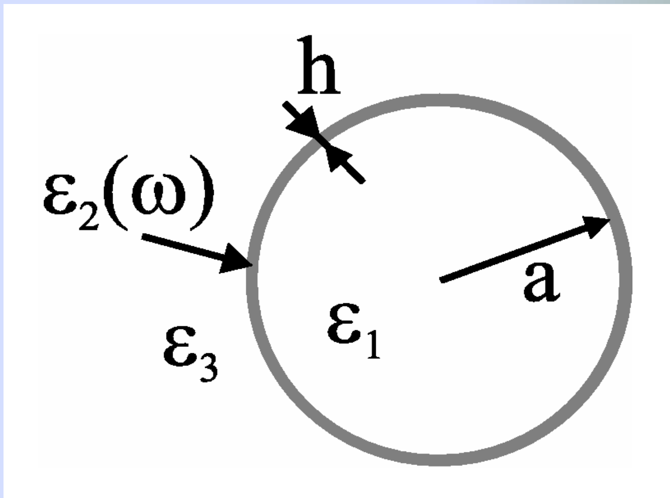
General solution for a problem possessing azimuthal symmetry

$$\Phi = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} [A_{lm} r^l + B_{lm} r^{-(l+1)}] Y_{lm}(q, j)$$



A single plasmonic nanoshell: boundary conditions

$$\begin{cases} \Phi_1 = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} A_l r^l Y_{lm}(q, j) \\ \Phi_2 = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} [B_l r^l + C_l r^{-(l+1)}] Y_{lm}(q, j) \\ \Phi_3 = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} D_l r^{-(l+1)} Y_{lm}(q, j) \end{cases}$$



$$\begin{cases} \Phi_1 = \Phi_2, \quad e_1 \frac{\partial \Phi_1}{\partial r} = e_2 \frac{\partial \Phi_2}{\partial r}, \quad r = a \\ \Phi_2 = \Phi_3, \quad e_2 \frac{\partial \Phi_2}{\partial r} = e_3 \frac{\partial \Phi_3}{\partial r}, \quad r = a + h \end{cases}$$

$$f = a^{2l+1} / (a+h)^{2l+1}$$

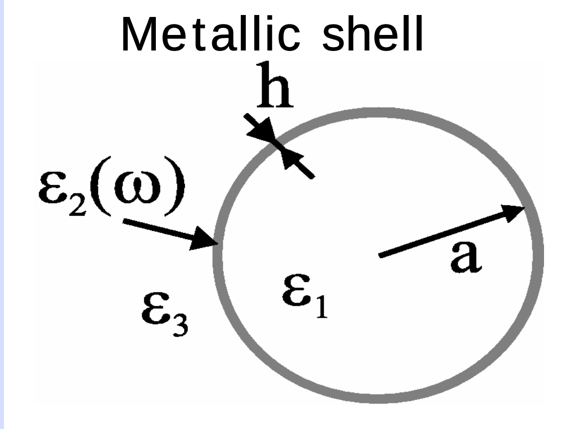
$$\frac{l e_1 + l e_2(w) + e_2(w)}{e_1 - e_2(w)} = f l(l+1) \frac{e_3 - e_2(w)}{l e_2(w) + l e_3 + e_3}$$

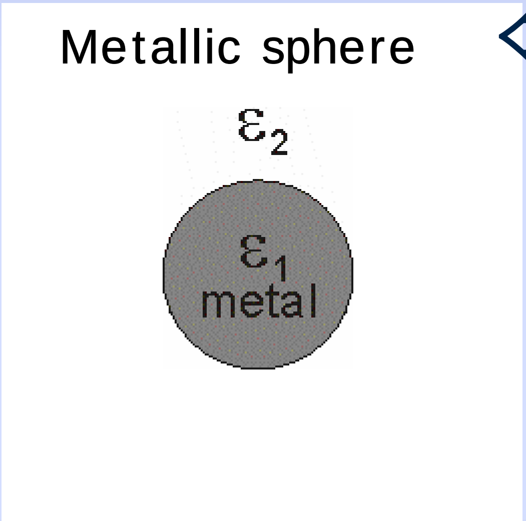
Localized surface plasmons

$$e(w) = 1 - w_p^{\,2}/w^2 \qquad e_1 = e_3 = 1$$

$$[w^{\pm}]^2 = w_p^2 \frac{1}{2l+1}\left[l + \frac{1}{2} \pm \sqrt{\frac{1}{4} + fl(l+1)} \right] \Rightarrow$$

$$f = a^{2l+1}/(a+h)^{2l+1}$$

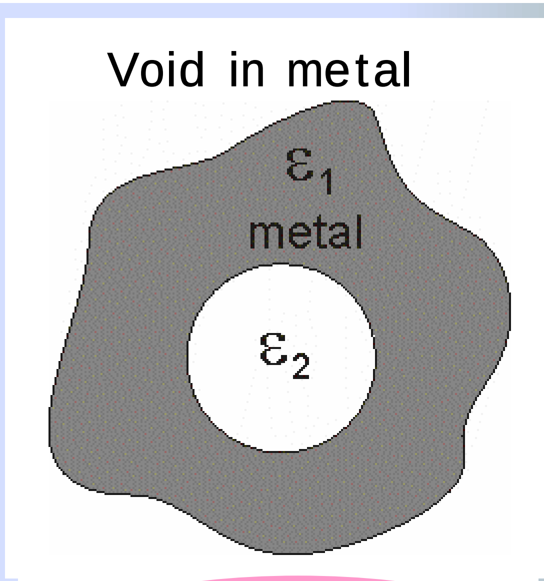




$\Leftarrow$

$$w_s = w_p \sqrt{\frac{l}{2l+1}}$$

$$w_v = w_p \sqrt{\frac{l+1}{2l+1}} \Rightarrow$$



$$w = w_p/\sqrt{2} \quad l \to \infty$$

surface plasmon

$$w = w_p \quad l = 0$$

bulk plasmon

D.W.Brandl, C.Oubre, P.Nordlander, J.Chem.Phys. **123**, 024701 2005

Localized surface plasmons: Fröhlich modes

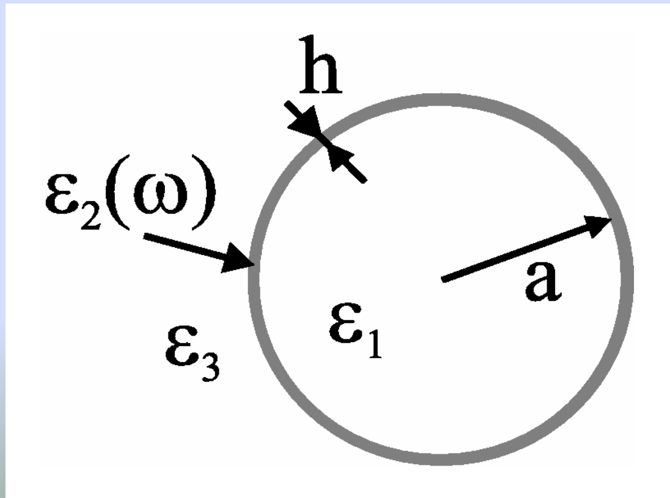
metallic sphere $w_s = w_p / \sqrt{3}$

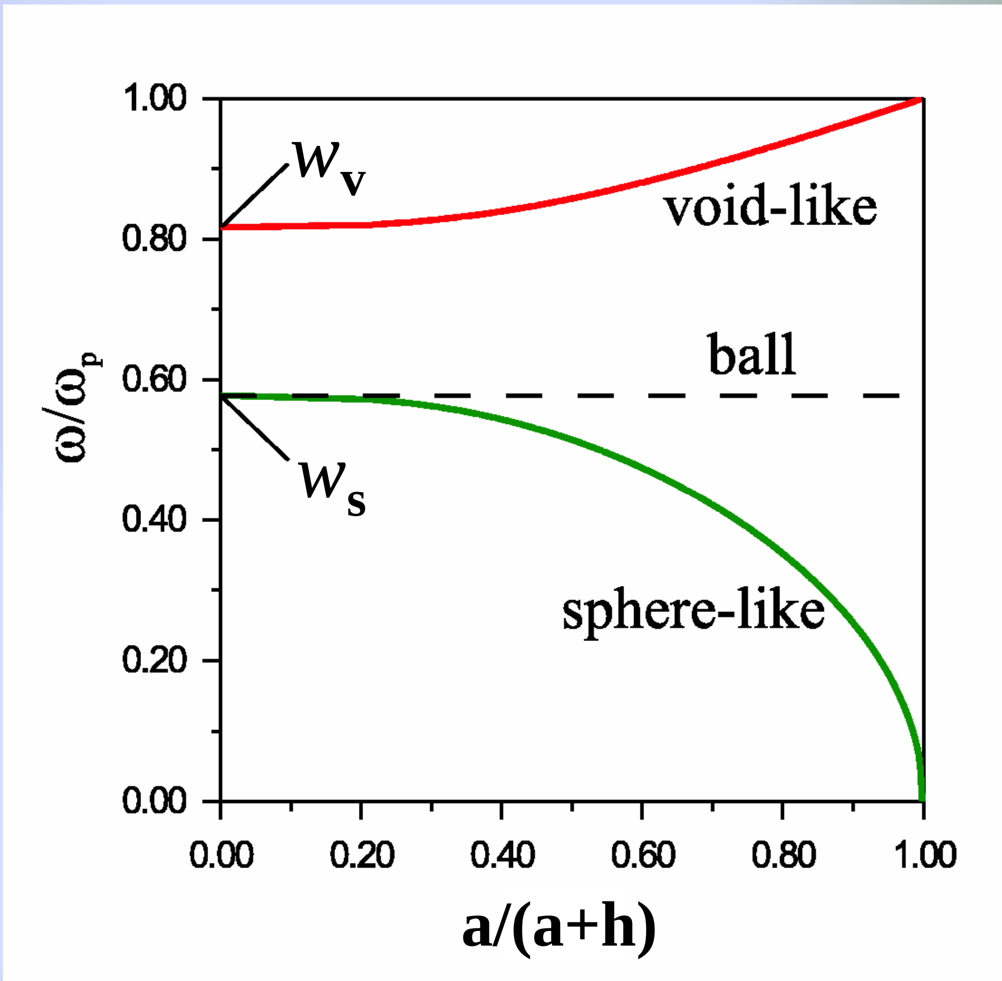
void in metal $w_v = w_p \sqrt{2/3}$

metallic shell

$$w_{\pm}^2 = \frac{4w_p^2(1-f)}{4(1-f)+(5+4f \mp 3\sqrt{1+8f})}$$

$$f = a^3/(a+h)^3$$





A single plasmonic nanoshell: electrodynamic approach

$$\mathbf{E} = \mathbf{L}y^{M} - \frac{i}{k}\nabla\times\mathbf{L}y^{E}$$

$$\mathbf{H} = \frac{i}{km_i}\nabla\times\mathbf{L}y^{M} - e_j\mathbf{L}y^{E}$$

$$(\nabla^2 + k_j^2)y = 0 \qquad y = \begin{bmatrix} y^{M} \\ y^{E} \end{bmatrix}$$

$$\mathbf{L} = -i\mathbf{r}\times\nabla$$

$$k_j = k\sqrt{e_j m_j}$$

$$k = w/c$$

$$h_l^{(1,2)}(x) = j_l(x) \pm i n_l(x)$$

$$y = \sum_{l,m}[A_{lm}h_l^{(1)}(k_i r) + B_{lm}h_l^{(2)}(k_i r)]Y_{lm}(q, j)$$

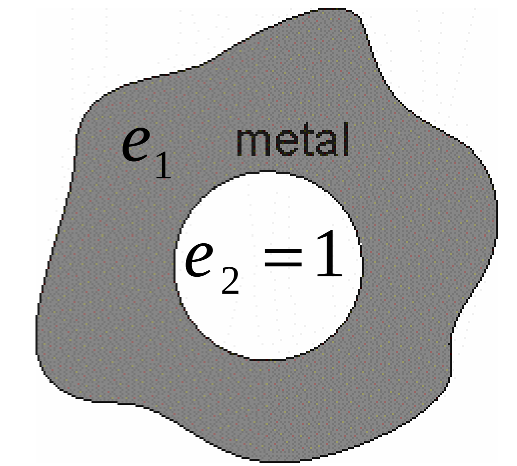
Void in metal

$$h_l^{(1)}(r_1)[r_2 j_l(r_2)]' = e_1 j_l(r_2)[r_1 h_l^{(1)}(r_2)]'$$

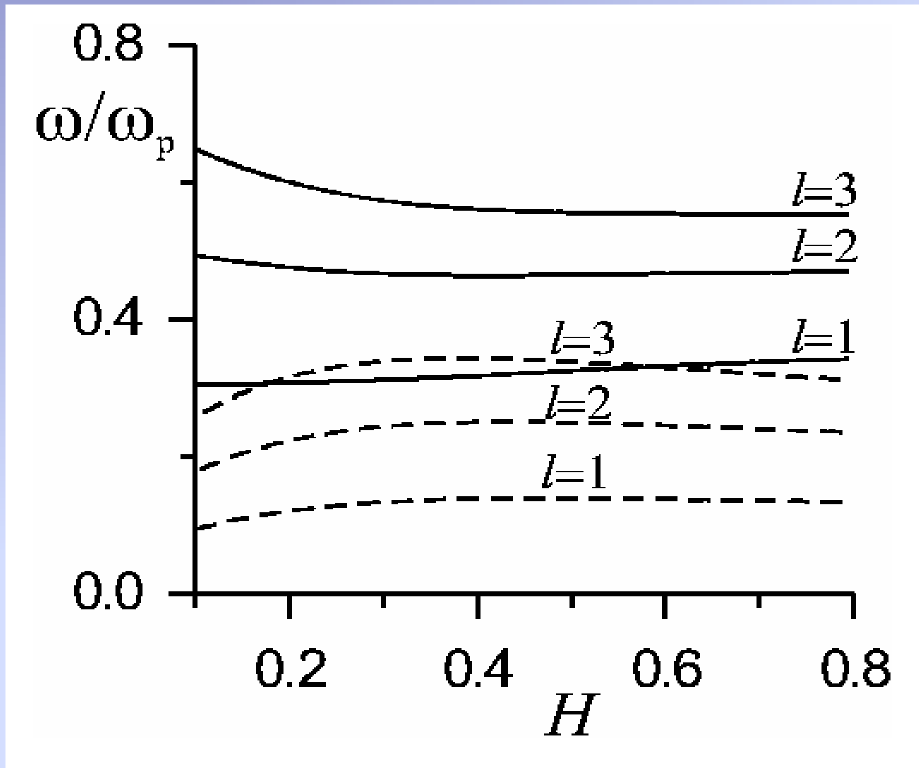
$$r_1 = kd\sqrt{e_1(w)}/2 \qquad r_2 = kd/2$$

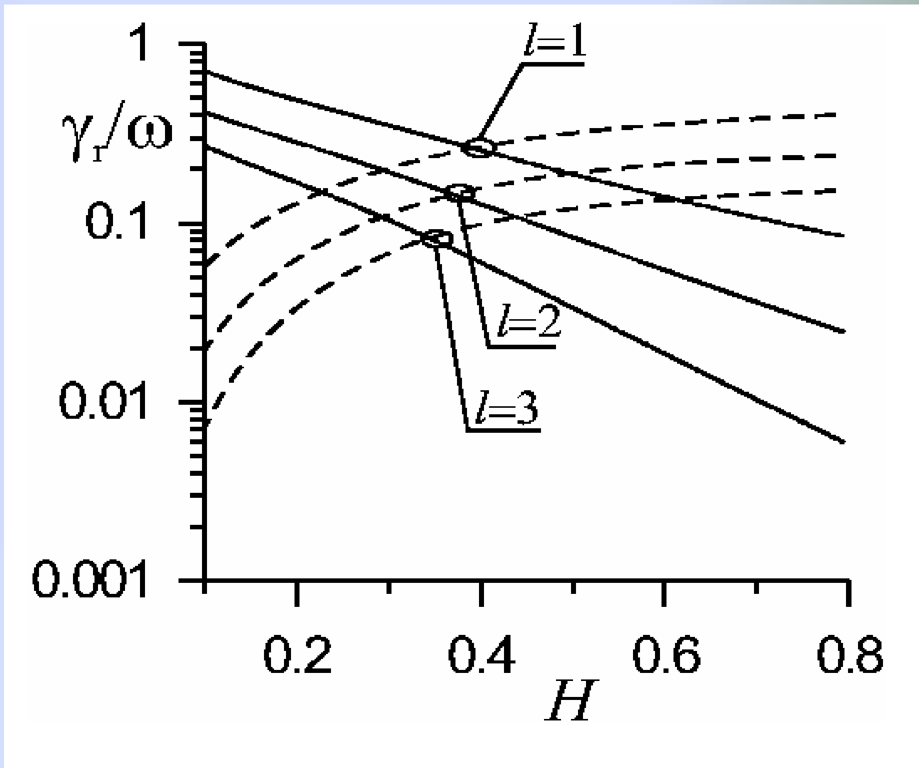
J.D.Jackson, *Classical electrodynamics*, 1975

Void in metal



Plasmon modes of a metallic nanoshell

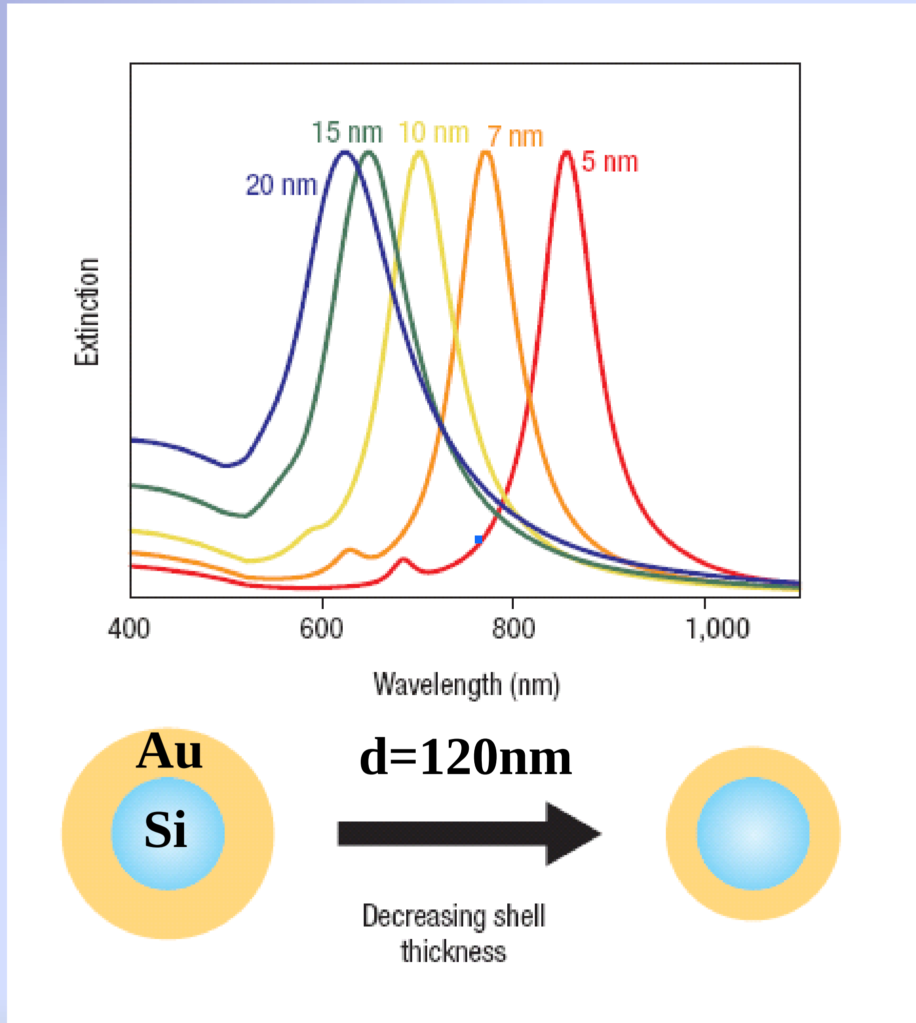




$e(w) \cong 1 - \frac{w_p^2}{w^2}$ $w >> n_e$ $H = \frac{h}{dl}$ d **is the skin depth**

T.V. Teperik, V.V. Popov, and F.J. García de Abajo, *Phys. Rev. B* 69, 155402 (2005).

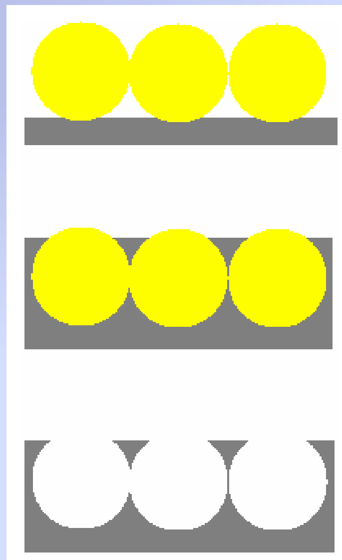
Tunability of nanoshells.

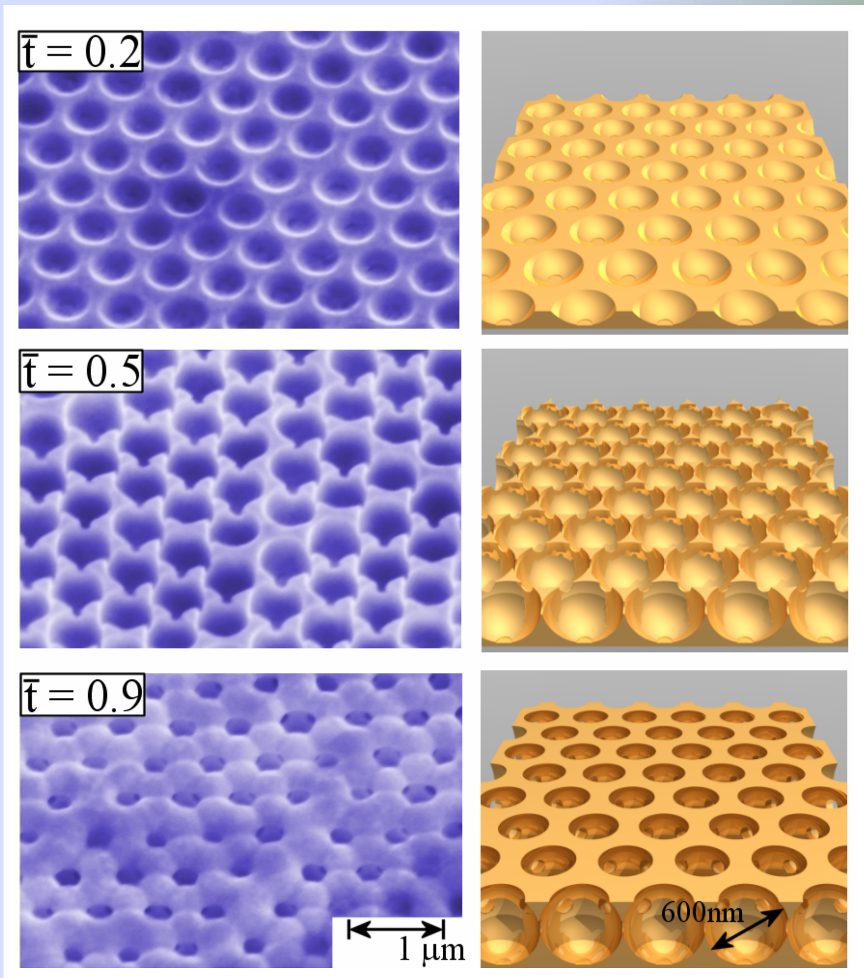


Surbhi Lal, Stephan Link, Naomi J. Halas, *Nature Photonics*, **1** 641 (2007)

Nanoporous metal structure: technology and experiment

<u>Technology and experiment:</u>
Department of Physics and Astronomy,
Department of Chemistry,
University of Southampton,
United Kingdom





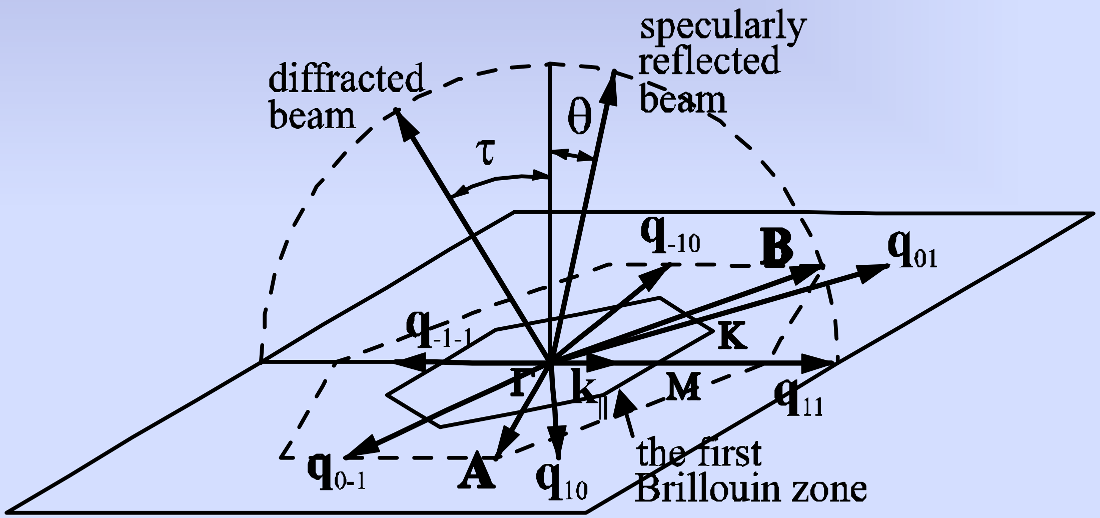
Pore diameter Ø ~ 500 nm (nanoscale casting technique with the electrochemical deposition of metal through a self-assembled latex template)

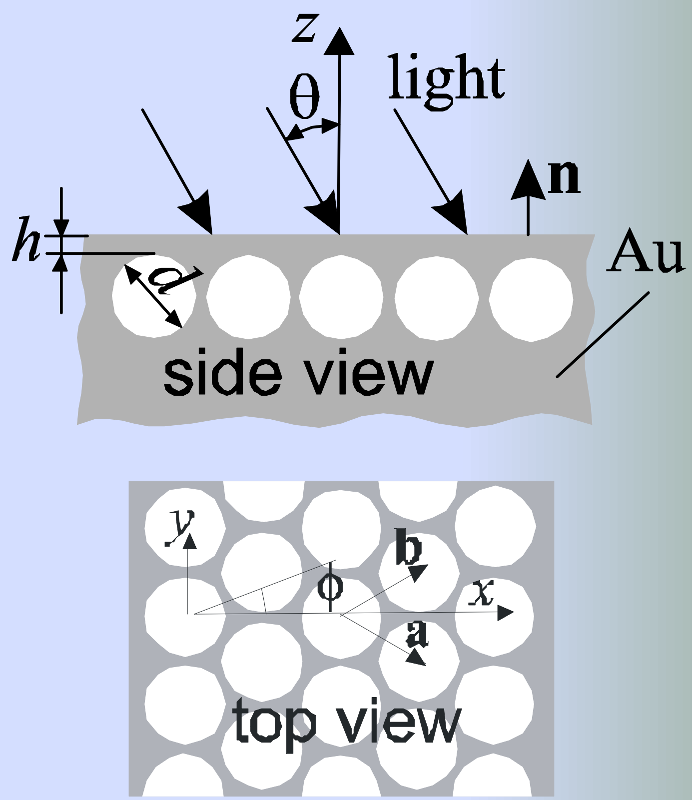
Jeremy J. Baumberg et al. Adv. Mat. **13** (2001), (2003); *PRL* **87** (2001); *APL* **83** (2003), *Faraday Discussion* (2003)

Nanoporous metal structure: theory

<u>Theory:</u>

- **Instituto de Optica, Madrid, Spain**
- **Donostia International Physics Center, San Sebastian, Spain**
- **Institute of Radio Engineering and Electronics, (Saratov Division), RAS**



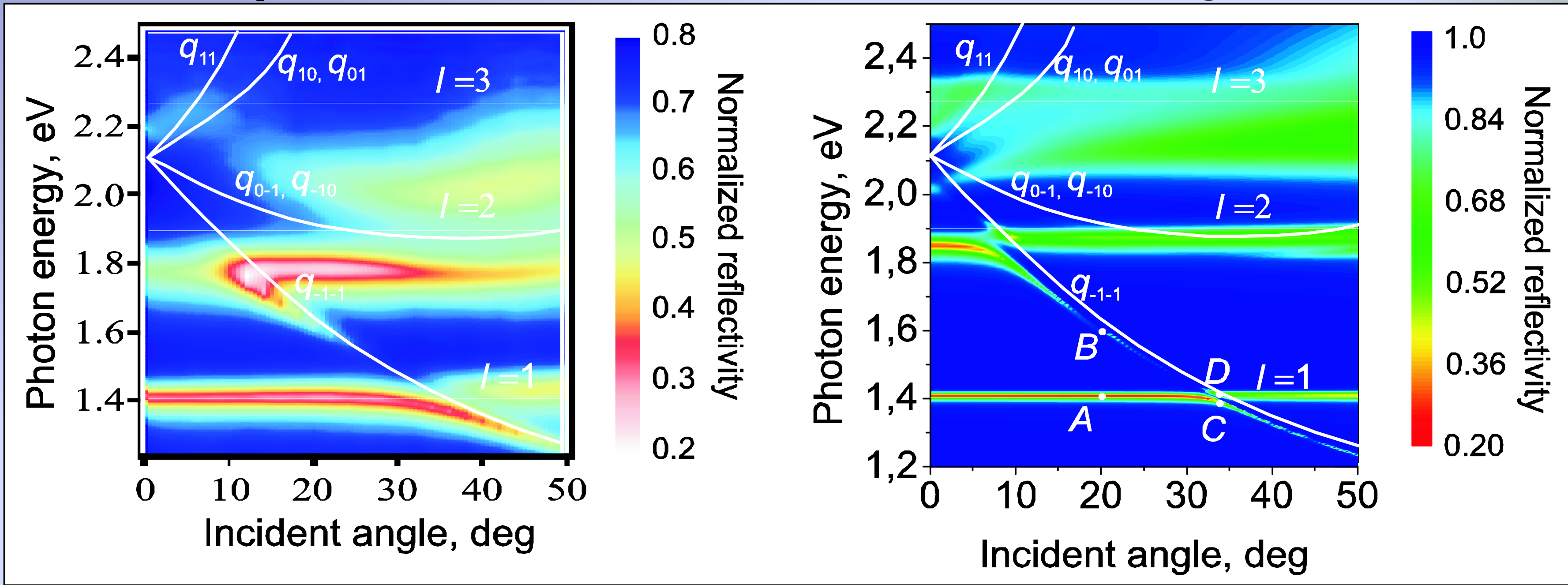


Rigorous self-consistent electromagnetic multiple-scattering layer-Korringa-Kohn-Rostoker approach

N. Stefanou, V. Yannopapas, and A. Modinos, Comput. Phys. Commun. 113 **49** (1998)

Reflection spectra of nanoporous metal surface. Localised and delocalised plasmons: anticrossing regime.

experiment **theory**



void plasmons

$$h_l^{(1)}(r_0)[r_1 j_l(r_1)]' = e(w)\, j_l(r_1)[r_0 h_l^{(1)}(r_0)]'$$

$$r_0 = wd\sqrt{e(w)}/2c \qquad r_1 = wd/2c$$

|**a**|=|**b**|=505 nm, *d* = 500 nm ϕ = 0^{O}, p-polarization

T.V.Teperik et al., Optics Express **14**,1965 (2006**).**

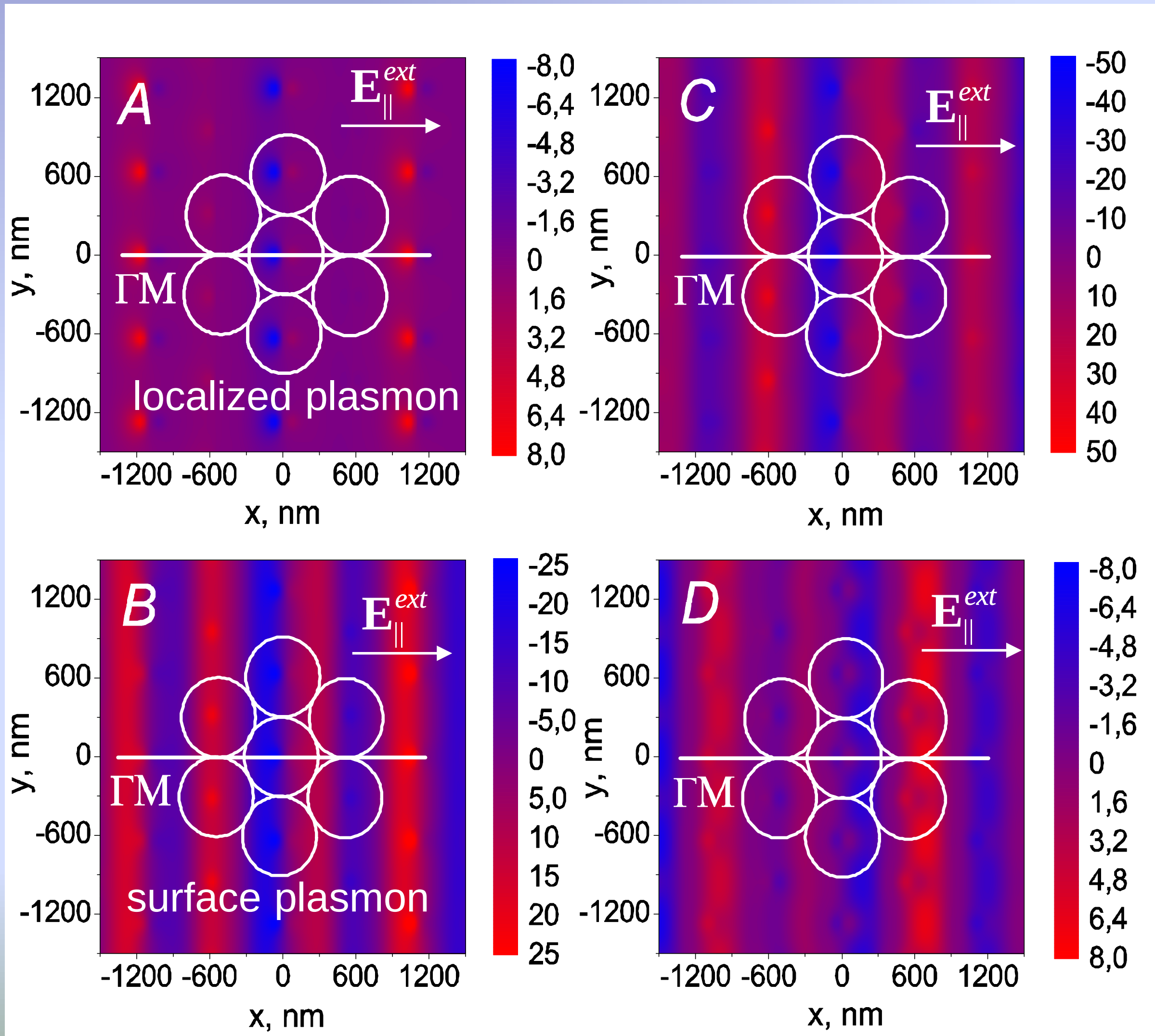
surface plasmons

$$q_{pq}^2 = \left(\frac{w}{c}\right)^2 \frac{e(w)}{1+e(w)}$$

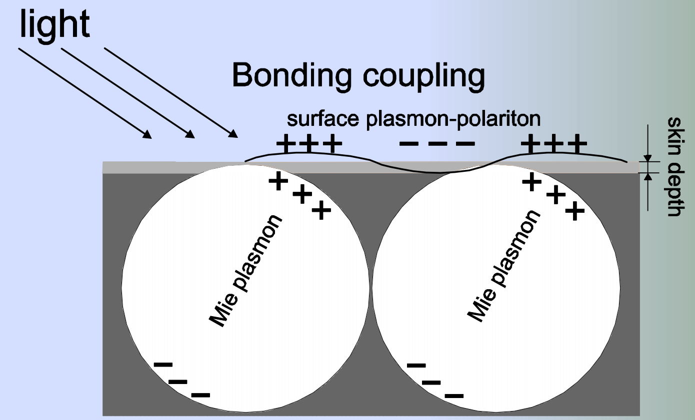
$$\mathbf{q}_{pq} = \mathbf{k}_{\|} + \mathbf{g}_{pq} \quad k_{\|} = w \sin q / c$$

$$\mathbf{g}_{pq} = p\mathbf{A} + q\mathbf{B}$$

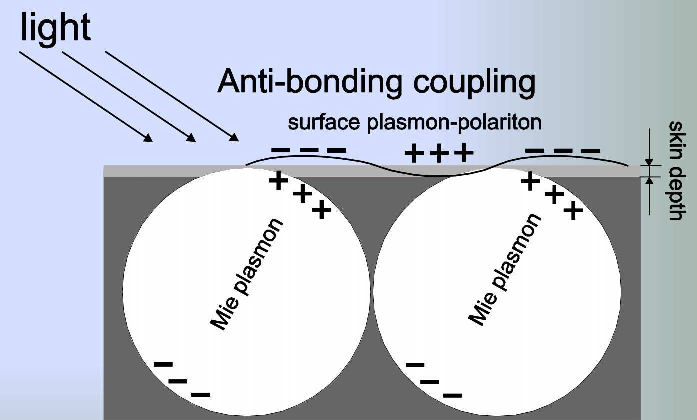
Field snapshots of plasmon modes excited on nanoporous metal surface



bonding state

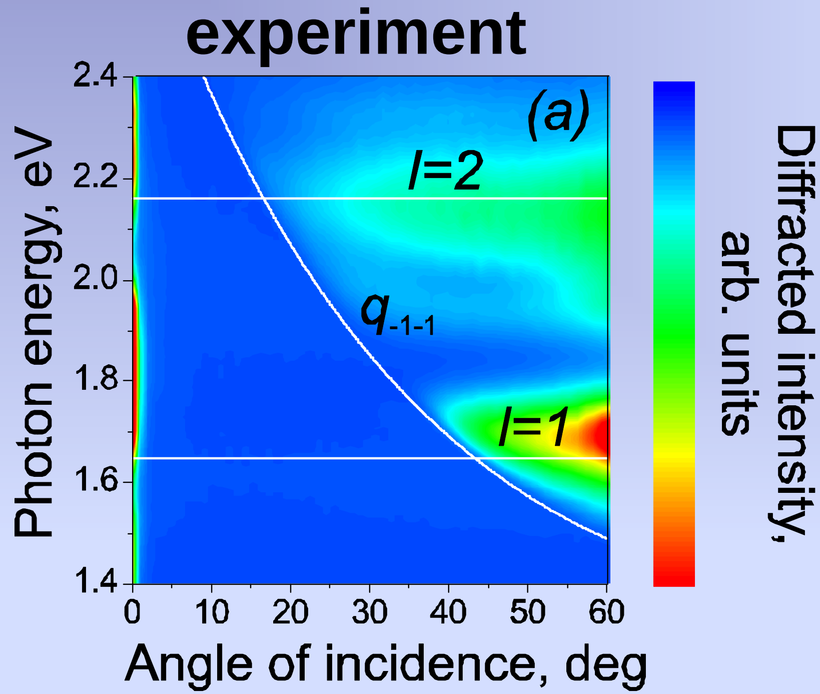


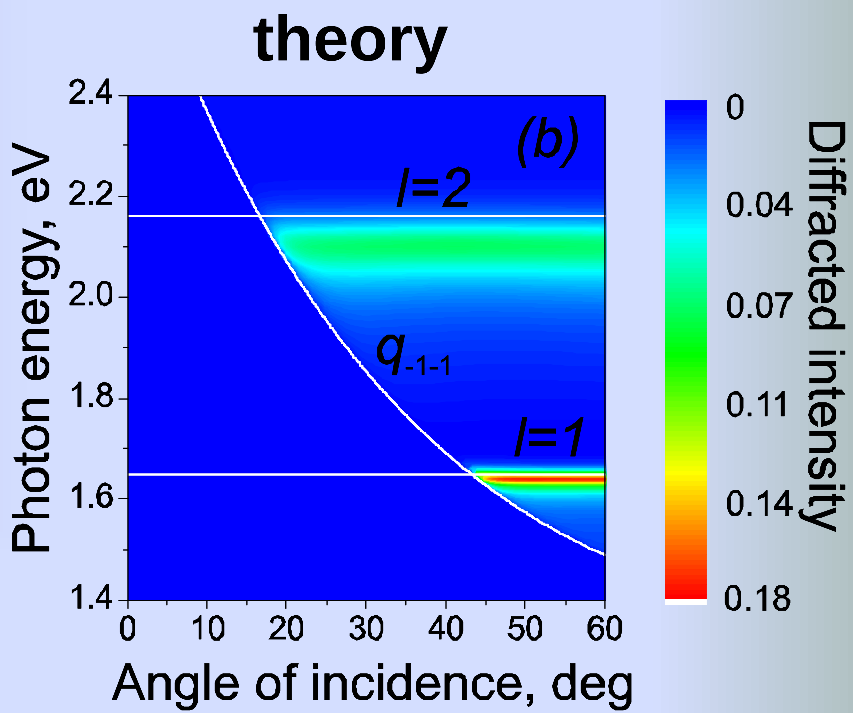
anti-bonding state



T.V.Teperik et al., Optics Express **14**,1965 (2006).

Resonant diffraction on the nanoprous metal surface: Rayleigh anomalies versus localized plasmons





$$h_l^{(1)}(r_0)[r_1 j_l(r_1)]' = e(w)\, j_l(r_1)[r_0 h_l^{(1)}(r_0)]'$$ ← *void plasmons*

$$q_{pq} = w/c$$ ← *grazing photons*

$$\mathbf{q}_{pq} = \mathbf{k}_{||} + \mathbf{g}_{pq}$$

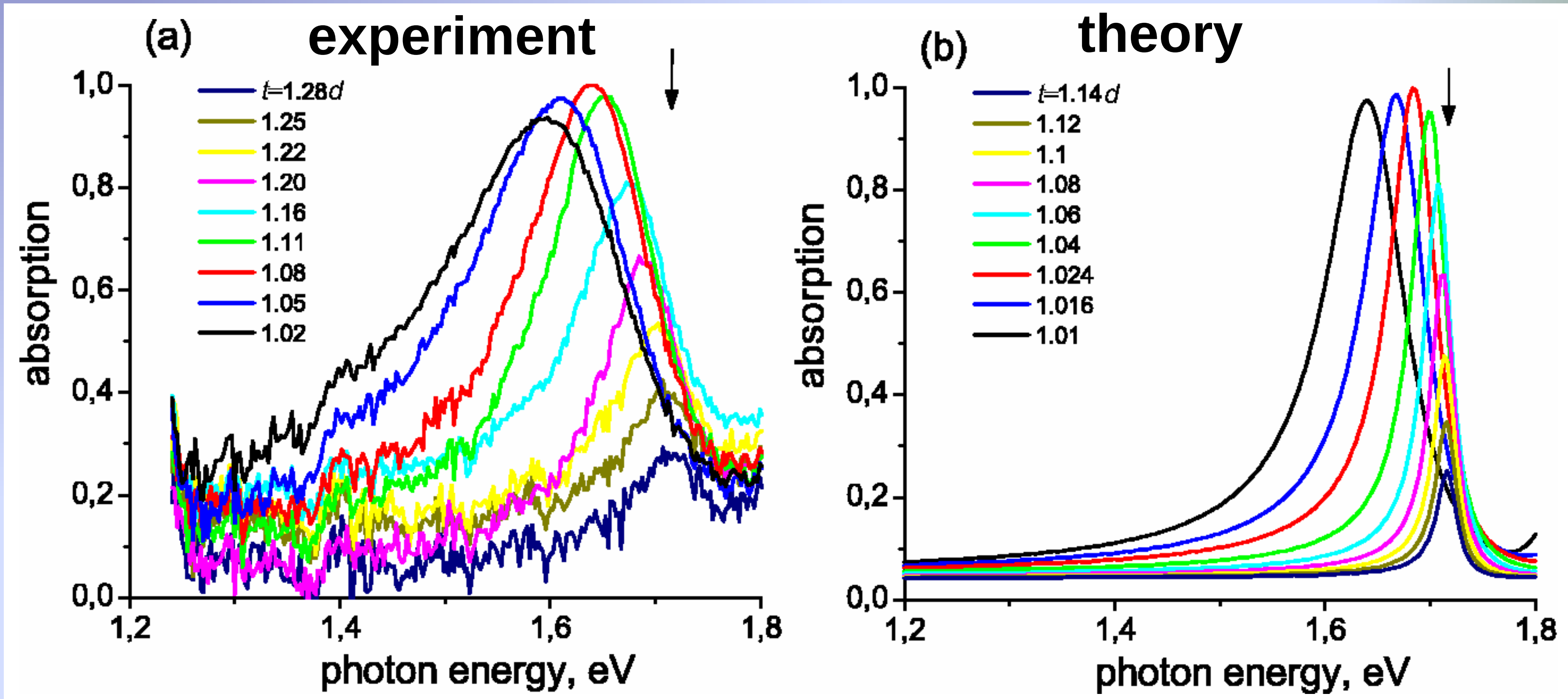
surface plasmons

$$q_{pq} = \frac{w}{c}\sqrt{\frac{w^2 - w_p^2}{2w^2 - w_p^2}} \cong \frac{w}{c} \quad w << w_p$$

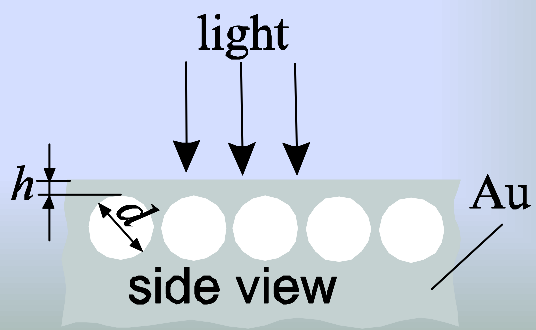
T.V. Teperik et al., Optics Express **14**, 11964 (2006)

|**a**|=|**b**|=515 nm, h=5 nm, *d* = 500 nm
ϕ = 0^{O} p-polarization

Total light absorption by nanoporous metal surface



|**a**|=|**b**|=505 nm d = 500 nm,
normal incidence
t=d+h is the nanoporous film thickness



Why flat metal surfaces absorb light poorly?

Could nanostructured metallic surfaces absorb light completely?

1. **Effective surface impedance model**
2. **Multi-channel model: the Breit-Wigner approximation**

Planar surface of metal

⇒

Drude model: $s_e(w) = \frac{e^2 N_e}{m(n_e - iw)}$

$$Z_e = \frac{1}{s_e d} = R_e - iwL_e \neq Z_0$$

$$R_e = \frac{mn_e}{e^2 d N_e} \left[\frac{\text{Ohm}}{\square}\right]$$

$$L_e = \frac{m}{e^2 d N_e} \left[\frac{\text{H}}{\square}\right]$$

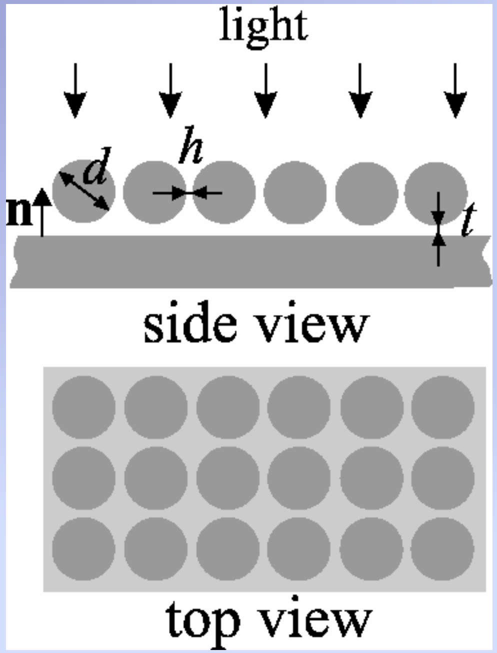
$$Z_0 = 120\pi \ [\text{Ohm}]$$

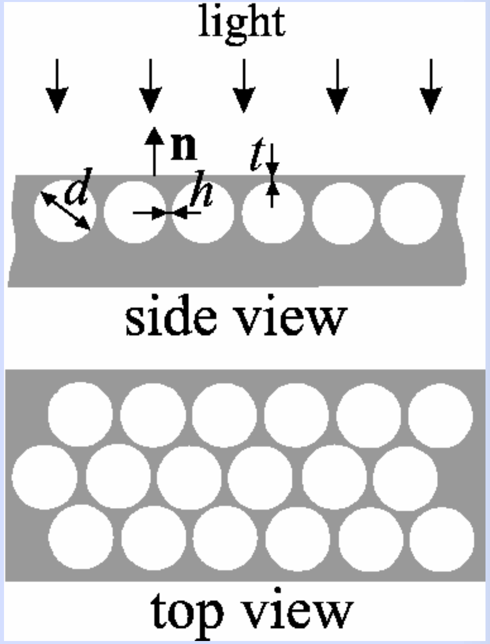
$$R_e << Z_0 \quad \omega L_e >> R_e$$

→ **Strong reflection**

$$Z_l = R_l - i\omega L_l + \frac{i}{\omega C_l} \Rightarrow Z_0$$

Inverted plasmonic nanostructures





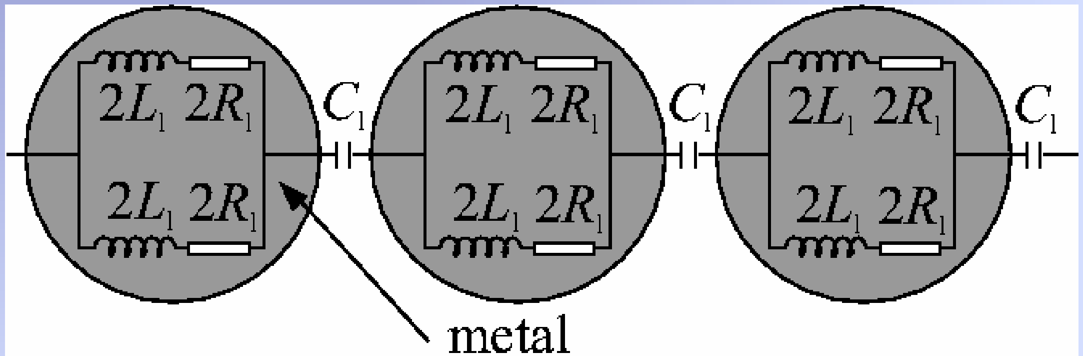
$$N_l \ll N_e \;\; (R_l \ll R_e)$$
$$wL_l = -1/wC_l$$

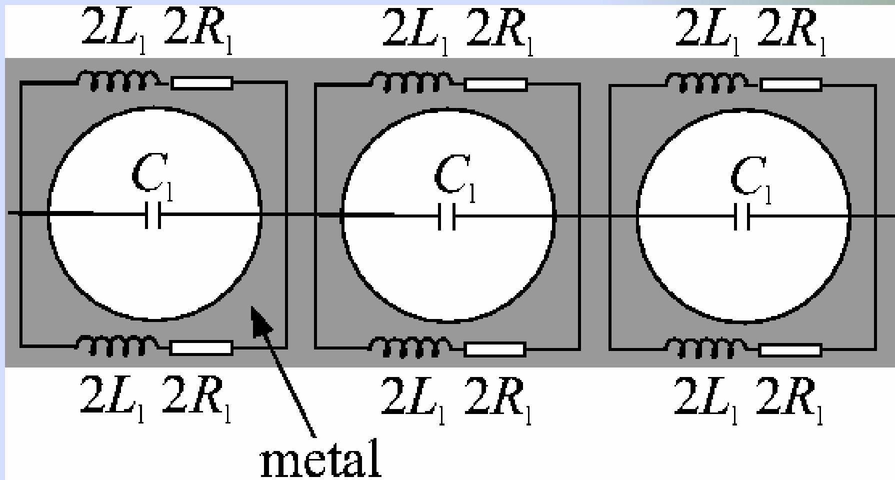
$$Z_l = R_l = Z_0$$

Total absorption

$$r = \frac{Z_{\text{eff}} - Z_0}{Z_{\text{eff}} + Z_0} \quad (Z_0 = 120\pi\,[\text{Ohm}]) \quad \text{R=rr*} \quad \text{A=1-R}$$

Equivalent RLC circuits of plasmonic nanostructures





$$Z_l^{(s)} = R_l^{(s)} - iwL_l^{(s)} + i/wC_l^{(s)}$$

$$Z_l^{(v)} = \frac{R_l^{(v)} - iwL_l^{(v)}}{1 - w^2 L_l^{(v)} C_l^{(v)} - iwR_l^{(v)} C_l^{(v)}}$$

$$C_l = |f_l|^2 b^{(s,v)} e_0 \quad \left[\frac{\text{F}}{\square}\right]$$

$$R_l = \frac{2m_l^{(s.v)}}{e^2 \Delta_l^{(s.v)} d N_e} = \left[\frac{\text{Ohm}}{\square}\right]$$

$$L_l = \frac{m}{e^2 \Delta_l^{(s,v)} d N_e} \quad \left[\frac{\text{H}}{\square}\right]$$

$$b^{(s)} = a - d, \quad b^{(v)} = d$$

Effective surface impedance

Lorentzian approximation $\Rightarrow$

$w \approx w_l, \quad n_l << w_l$

$$Z_{\text{eff}}^{(s)} = \frac{i}{\left|b_l^{(s)}\right|^2} \frac{2m}{e^2 \Delta_l^{(s)} d\, N_e} [w_l^{(s)} - w - i n_l^{(s)}]$$

lattice of spheres

$$Z_{\text{eff}}^{(v)} = -i \frac{m \left|b_l^{(v)}\right|^2}{2e^2 \Delta_l^{(v)} d\, N_e} \frac{[w_l^{(v)}]^2}{[w_l^{(v)} - w - i n_l^{(v)}]}$$

lattice of voids

series resonance
parallel resonance

$$\left\{ \begin{array}{l} Z_{eff}^{(s)} = 0 \\ Z_{eff}^{(v)} \to \infty \end{array} \right\} \text{ at } \quad n_l = 0 \quad w = w_l$$

$$w_l = \frac{1}{\sqrt{L_l^{(s,v)} C_l^{(s,v)}}}$$

frequency of the *l*-th plasmon mode

$n_l^{(s,v)}$ dissipative damping of the *l*-th plasmon mode

$| b_l^{(s,v)} |^2 < 1$ coupling coefficient

Light absorption by a resonant surface

$$r = \frac{Z_{\text{eff}} - Z_0}{Z_{\text{eff}} + Z_0} \qquad Z_0 = 120p \text{ [Ohm]}$$

Reflectance

$$R = rr^* \approx \frac{(g_l^{(s,v)} - n_l^{(s,v)})^2 + (w_l^{(s,v)} - w)^2}{(g_l^{(s,v)} + n_l^{(s,v)})^2 + (w_l^{(s,v)} - w)^2}$$

Absorbance

$$A = 1 - R \approx \frac{4 g_l^{(s,v)} n_l^{(s,v)}}{(g_l^{(s,v)} + n_l^{(s,v)})^2 + (w_l^{(s,v)} - w)^2}$$

$$\left.\begin{aligned} R &= 0 \\ A &= 1 \end{aligned}\right\} \quad \text{at} \quad g_l = n_l \quad w = w_l$$

$$g_l^{(s)} = \frac{Z_0 \,|\, b_l^{(s)} \,|^2\, e^2 \Delta_l^{(s)} d\, N_e}{2m}$$

radiative damping of the *l*-th plasmon mode of a metallic sphere

$$g_l^{(v)} = \frac{|\, b_l^{(v)} \,|^2\, m[w_l^{(v)}]^2}{2 Z_0 e^2 \Delta_l^{(v)} d\, N_e}$$

radiative damping of the *l*-th plasmon mode of a void in metal

$$\gamma_l = \nu_l$$

$$Z_{eff} = Z_0$$

T. Teperik, V. Popov, and F. Garcıa de Abajo, J. Opt. A: Pure Appl. Opt. 9, S458 (2007)

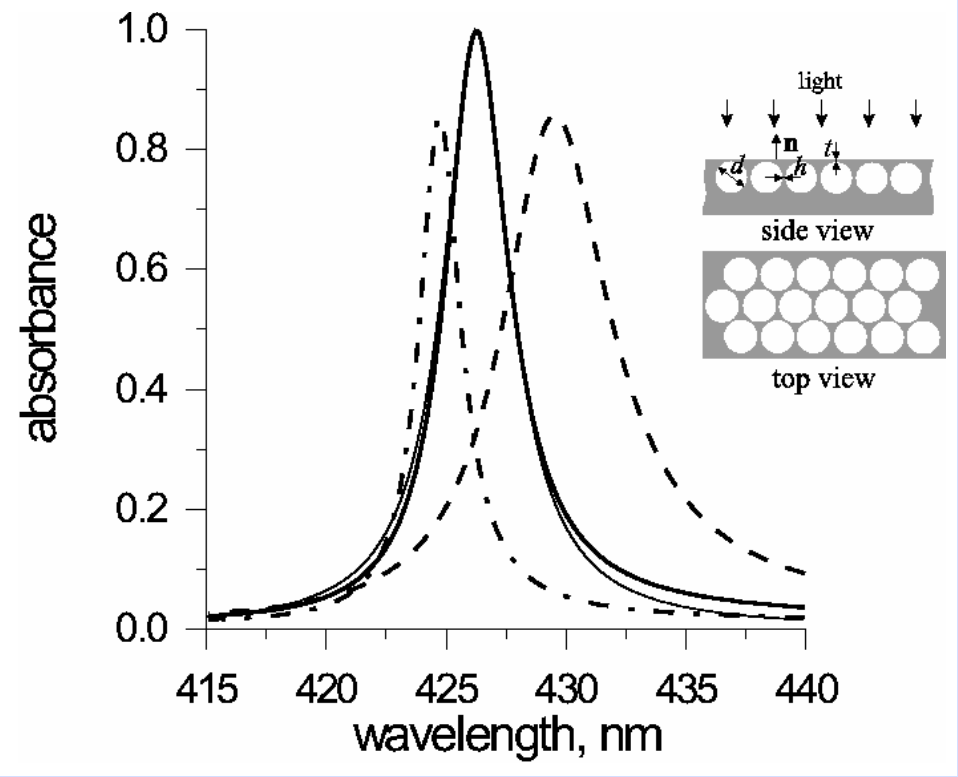
Total light absorption by a lattice of voids in silver

$g_l^{(v)} << n_l^{(v)}$

weak coupling

$\Downarrow$

weak absorption



$g_l^{(v)} >> n_l^{(v)}$

strong coupling

$\Downarrow$

re-radiation

$\Downarrow$

weak absorption

t=25 nm (dash-dotted curve)
15 nm (solid curve)
8 nm (dashed curve)

$g_l^{(s)} = n_l^{(s)}$

$Z_{eff} = Z_0$

total light absorption

T. V. Teperik, V. V. Popov, and F. J. García de Abajo, Phys. Rev. B 71, 085408 (2005)

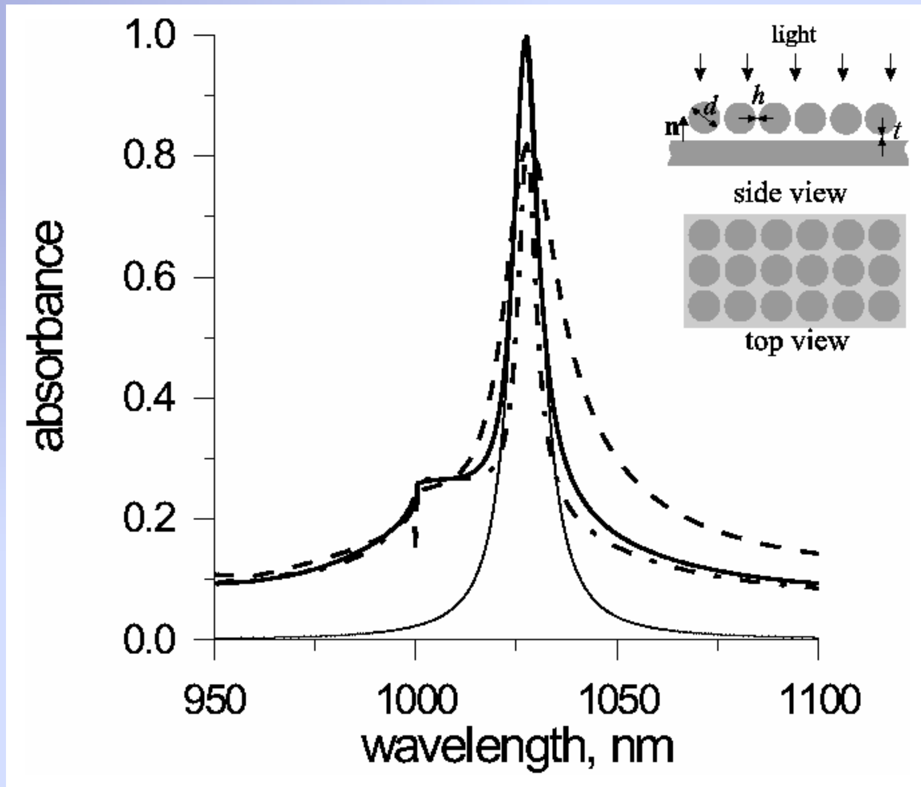
Total light absorption by a lattice of gold spheres

$$g_l^{(s)} << n_l^{(s)}$$

weak coupling

$\Downarrow$

weak absorption



$$g_l^{(s)} >> n_l^{(s)}$$

strong coupling

$\Downarrow$

re-radiation

$\Downarrow$

weak absorption

t=210 nm (dash-dotted curve)
170 nm (solid curve)
70 nm (dashed curve)

$$g_l^{(s)} = n_l^{(s)}$$
$$Z_{eff} = Z_0$$

total light absorption

T. Teperik, V. Popov, and F. Garcıa de Abajo, J. Opt. A: Pure Appl. Opt. 9 S458 (2007)

Effective surface impedance model

Excitation of a plasmon resonance at the nanostructured metallic surface ensures matching between the surface impedance and the free-space impedance and, hence, enables obtaining the total absorption of light on a high-conductivity metal surface

Total light absorption in plasmonic nanostructures

partially disordered silver films

- O. Hunderi and H. P. Myers, J. Phys. F: Metal Phys. 3, 683 (1973)

metal diffraction grating and double-period metal gratings

- M. C. Hutley and D. Maystre, Optics Communications 19, 431 (1976)
- D. Maystre and R. Petit, Optics Communications 17, 196 (1976)
- W.-C. Tan, J. R. Sambles, and T. W. Preist, Phys. Rev. B 61, 13177 (1999)
- E.Popov and L.Tsonev, Surface Science Letters 271, L378 (1992)

doped silicon lamellar grating

- F. Marquier, M. Laroche, R. Carminati, J.-J. Greffet, Journal of Heat Transfer 129, 11 (2007)
- J.-J. Greffet, R. Carminati, K. Joulain, J.-P. Mulet, S. Mainguy, Y. Chen, Nature 416, 61 (2002)

semiconductor and metal-semiconductor-metal nanostructures

- S. Collin, F. Pardo, R. Teissier, and J.-L. Pelouard, Appl. Phys. Lett. 85, 194 (2004)
- T.V. Teperik, F.J. García de Abajo, V.V. Popov, and M.S. Shur, Appl. Phys. Lett. 90 251910 (2007).

multiplayer of metallic nanoparticles and nanopores in metal

- T. V. Teperik, V. V. Popov, and F. J. García de Abajo, Phys. Rev. B 71, 085408 (2005)
- T. Teperik, V. Popov, and F. Garcıa de Abajo, J. Opt. A: Pure Appl. Opt. 0, 0 (2007)
- S.Kachan, O. Stenzel, and A. Ponyavina, Appl. Phys. B 84, 281 (2006)

overdense plasma slab (in the microwave frequency range)

- Y. P. Bliokh, J. Felsteiner, and Y. Z. Slutsker, Phys. Rev. Lett. 95, 165003 (2005).

Total light absorption in plasmonic nanostructures

1. ***The light transmission through the entire structure is forbidden***

2. ***The total light absorption effect relies on the excitation of intrinsic resonance in the structure***

3. ***The total light absorption effect requires specific conditions of effective coupling of light with resonant excitations in the system***

Multi-channel model: the Breit-Wigner approximation

$$\mathbf{B}_1 = \mathbf{e}\frac{1}{\sqrt{k_\perp}}\left[\exp(-ik_\perp z) + S_{11}\exp(ik_\perp z)\right] \qquad w = c\sqrt{k_\perp^2 + k_\parallel^2}$$

$$S_{11} = \exp(2id_{11}) - \frac{iM_{11}\Gamma}{w - w_0 + i\Gamma/2}\exp(2id_{11})$$

$$\left|S_{11}\right|^2 + j = 1 \qquad \left|\frac{M_{11}\Gamma}{w - w_0 + i\Gamma/2}\right|^2 = j$$

$$\Downarrow$$

$$\left|M_{11}\right|^2\Gamma = \mathrm{Re}\left\{iM_{11}(w - w_0) + M_{11}\Gamma/2\right\} \quad \Longrightarrow \quad M_{11} = \frac{1}{2}$$

$$R = \left|S_{11}\right|^2 = \frac{(w - w_0)^2}{(w - w_0)^2 + \Gamma^2/4} \quad \Longrightarrow \quad R = 0 \quad \text{at } w = w_0$$

L. Landau and E. Lifshitz (Butterworth-Heinemann, Oxford, 1996).
A. G. Borisov, F. J. Garcıa de Abajo, S. V. Shabanov, Phys. Rev. B 71, 075408 (2005).
N. A. Gippius, S. G. Tikhodeev, T. Ishihara, Phys. Rev. B 72, 045138 (2005).

Total light absorption conditions

If the trapped electromagnetic mode (resonance) is such that

(i) there is only specular reflection from the nanostructured metal surface with no diffracted beams;

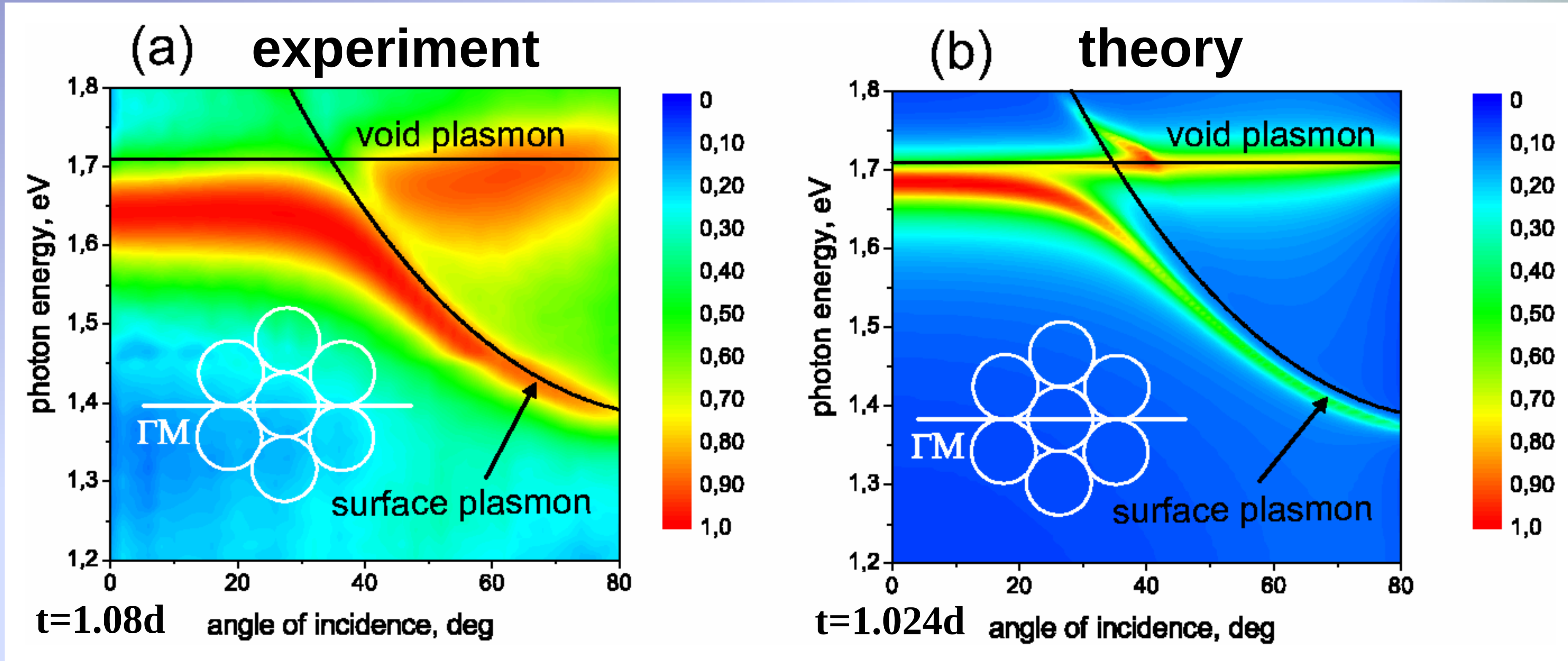
(ii) there is no polarization conversion, and

(iii) the radiative decay of the resonance is equal to its dissipative decay, then the whole energy from the incident light will be transformed into the losses in metal

$$R = \left|S_{11}\right|^2 = \frac{(w - w_0)^2}{(w - w_0)^2 + \Gamma^2/4} \text{ at } w = w_0 \begin{bmatrix} R = 0 \\ A = 1 - R = 1 \end{bmatrix}$$

T.V.Teperik, F.J.Garcıa de Abajo, A.G.Borisov, M.Abdelsalam, P.N.Bartlett, Y.Sugawara, J.J.Baumberg, Nature Photonics, 2008

Absorption spectra of nanoporous metal surface.



void plasmons

$$h_l^{(1)}(r_0)[r_1 j_1(r_1)]' = e(w)\, j_1(r_1)[r_0 h_l^{(1)}(r_0)]'$$

$$r_0 = wd\sqrt{e(w)}/2c \qquad r_1 = wd/2c$$

|**a**|=|**b**|=505 nm, *d* = 500 nm, ϕ = 0^{O}, p-polarization

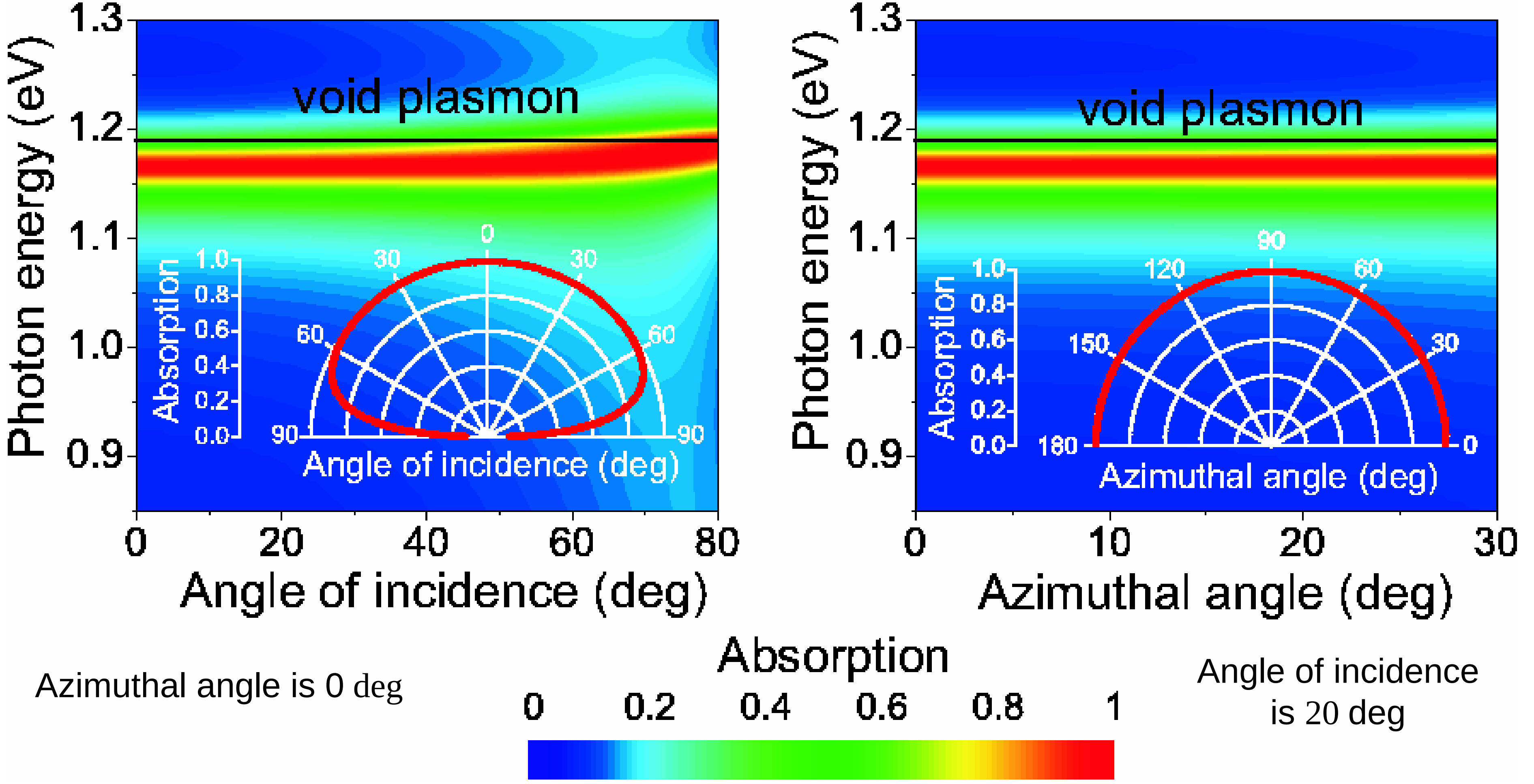
surface plasmons

$$q_{pq}^2 = \left(\frac{w}{c}\right)^2 \frac{e(w)}{1+e(w)}$$

$$\mathbf{q}_{pq} = \mathbf{k}_{||} + \mathbf{g}_{pq} \quad k_{||} = w \sin q / c$$

T.V.Teperik et al., Optics Express **14**,1965 (2006**).**

Omnidirectional total light absorption



Azimuthal angle is 0 deg

Angle of incidence is 20 deg

T.V.Teperik, F.J.Garcıa de Abajo, A.G.Borisov, M.Abdelsalam, P.N.Bartlett, Y.Sugawara, J.J.Baumberg, Nature Photonics, 2008

***Plasmonics** is the rapidly emerging field that is concerned primarily with the manipulation of light at the nanoscale, based on the exploiting the both localized and propagating surface plasmons. Owing to considerable advances made in nanotechnology a large variety of structures can be synthesized with controllable size and narrow size distribution. Modern elaborated theory allows us to describe their unique plasmonic properties. It is believed that plasmonic components can be successfully used for technologically important applications such as sensing and plasmonic guiding.*

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Thank you for attention!