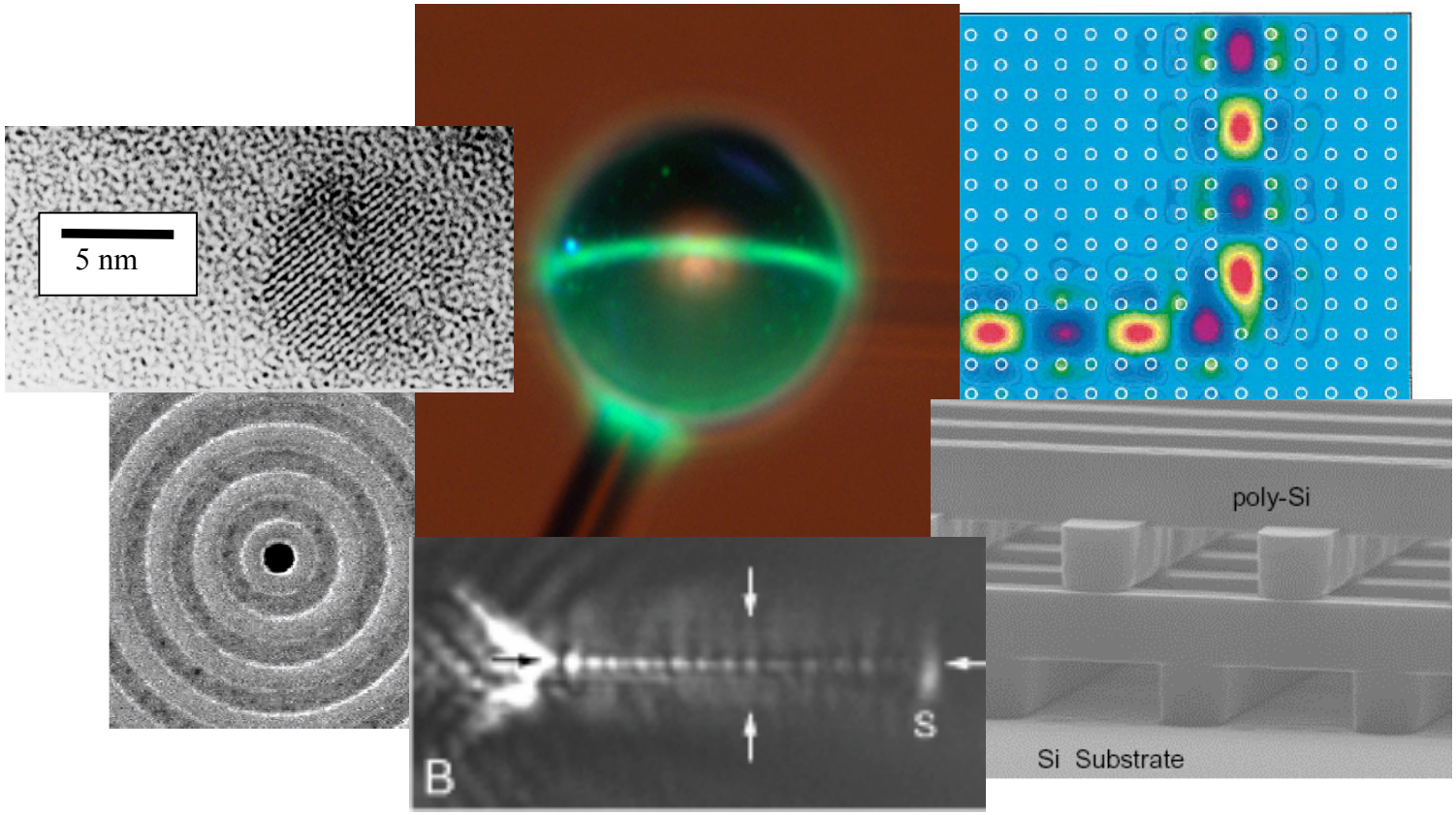
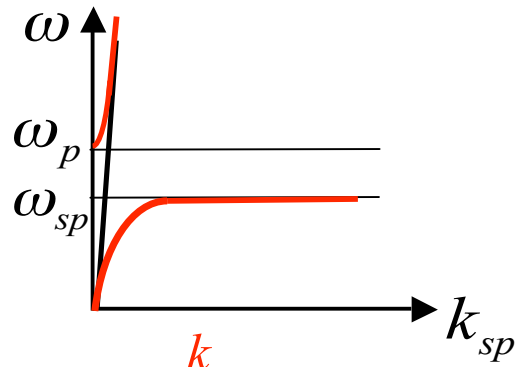
Lecture 10: Surface Plasmon Excitation



Summary

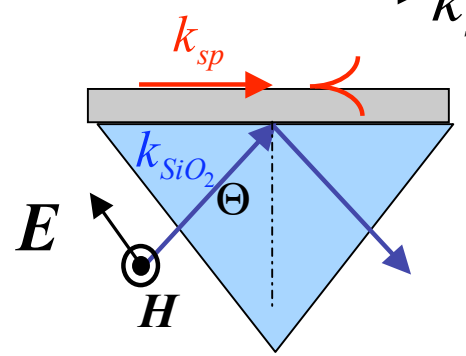
The dispersion relation for surface plasmons



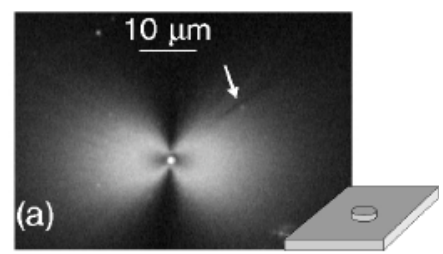
- Useful for describing plasmon excitation & propagation

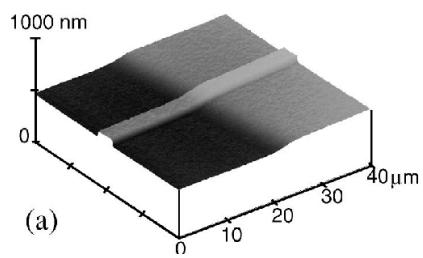
This lecture:

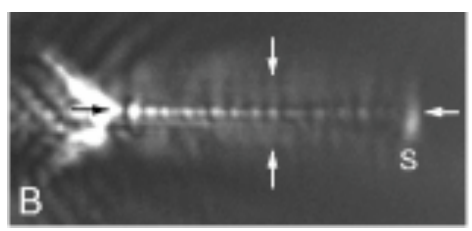
Coupling light to surface plasmon-polaritons

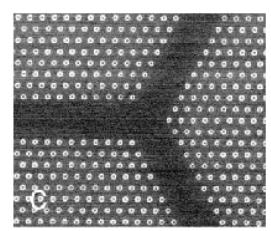


- Using high energy electrons (EELS)
- Kretschmann geometry $k_{//,SiO_2} = \sqrt{\varepsilon_d}\,\frac{\omega}{c}\sin\theta = k_{sp}$
- Grating coupling
- Coupling using subwavelength features
- A diversity of guiding geometries







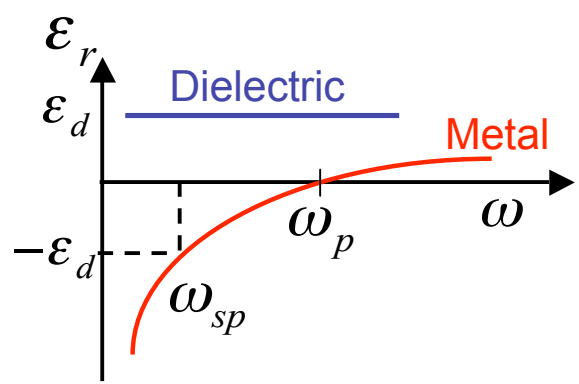


Dispersion Relation Surface-Plasmon Polaritons

Plot of the dispersion relation

- Last page: $k_x = \frac{\omega}{c}\left(\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{1/2}$

- Plot of the dielectric constants:

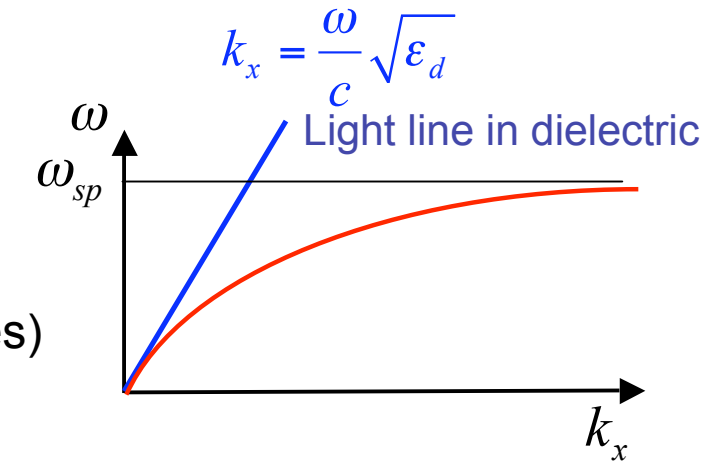


- Note: $k_x \to \infty$ when $\varepsilon_m = -\varepsilon_d$

  ➡ Define: $\boxed{\omega = \omega_{sp} \text{ when } \varepsilon_m = -\varepsilon_d}$

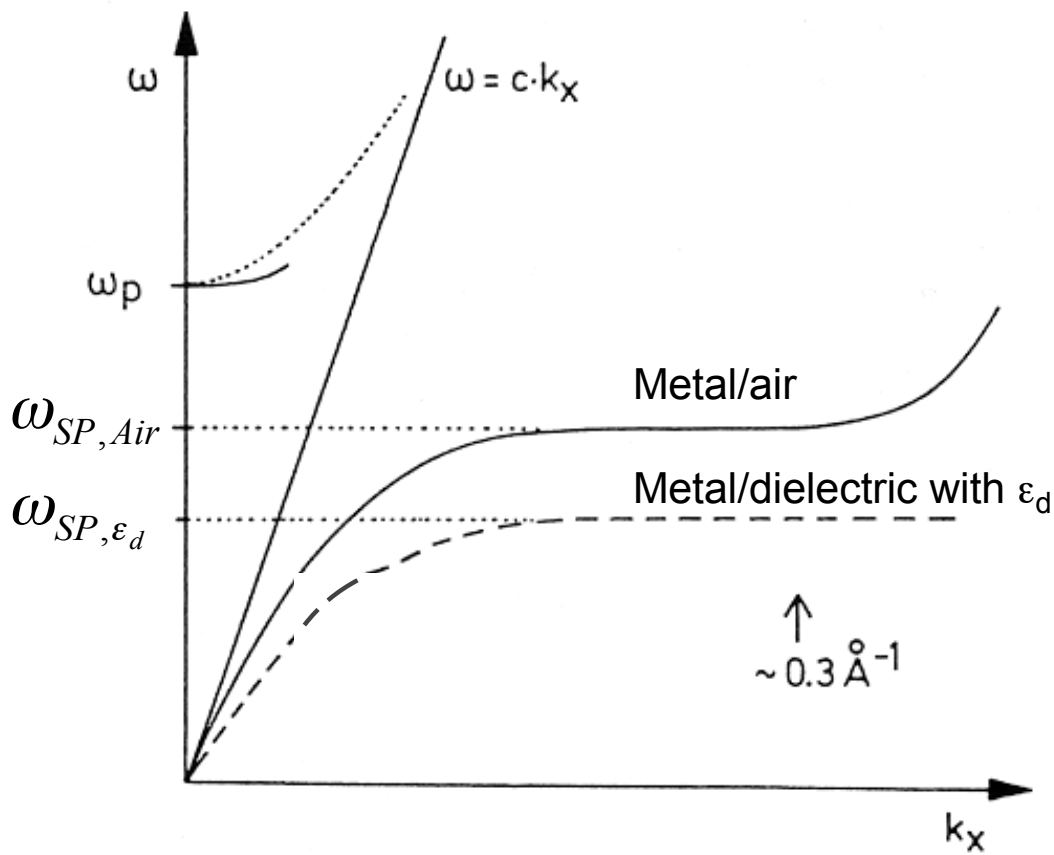
- Low ω: $k_x = \frac{\omega}{c}\lim_{\varepsilon_m \to -\infty}\left(\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{1/2} \approx \frac{\omega}{c}\sqrt{\varepsilon_d}$

- Solutions lie below the light line! (guided modes)



Dispersion Relation Surface-Plasmon Polaritons

Dispersion relation bulk and surface plasmons



- Note: Higher index medium on metal results in lower ω_{sp}

$\omega = \omega_{sp}$ when: $\varepsilon_m = 1 - \frac{\omega_p^2}{\omega^2} = -\varepsilon_d \Rightarrow \omega^2 - \omega_p^2 = -\varepsilon_d \omega^2 \Rightarrow \omega^2 = \frac{\omega_p^2}{1+\varepsilon_d} \Rightarrow \omega = \frac{\omega_p}{\sqrt{1+\varepsilon_d}}$

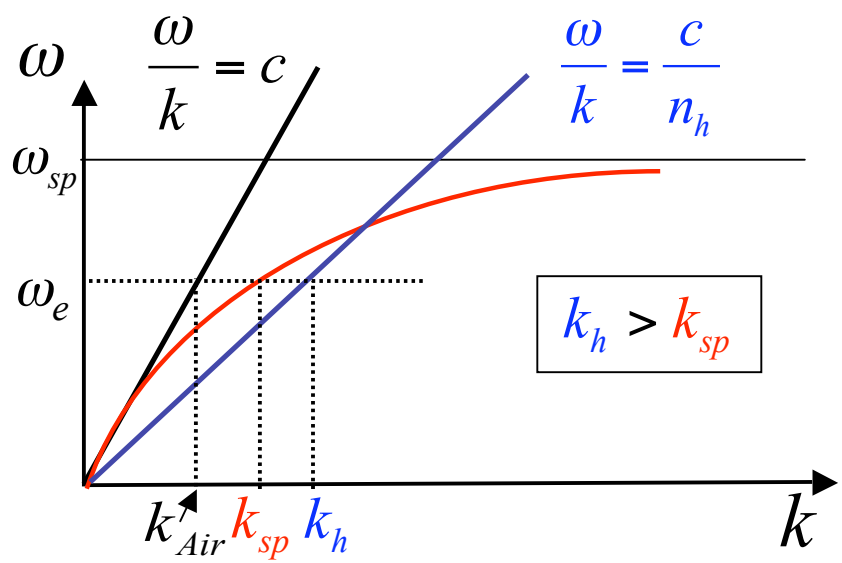
Excitation Surface-Plasmon Polaritons (SPPs) with Light

Problem SPP modes lie below the light line

- No coupling of SPP modes to far field and vice versa (reciprocity theorem)
- Need a “trick” to excite modes below the light line

Trick 1: Excitation from a high index medium

- Excitation SPP at a metal/air interface from a high index medium $n = n_h$



- SPP at metal/air interface can be excited from a high index medium!
- How does this work in practice ?

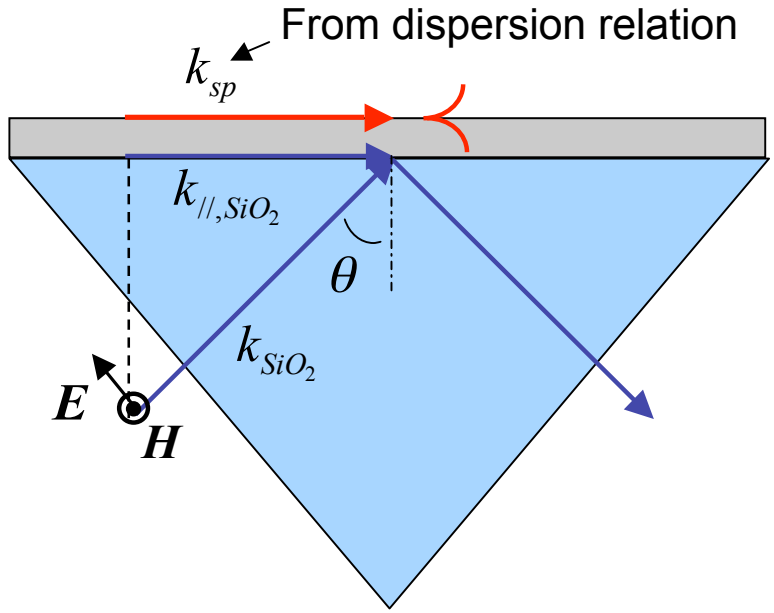
Excitation Surface-Plasmon Polaritons with Light

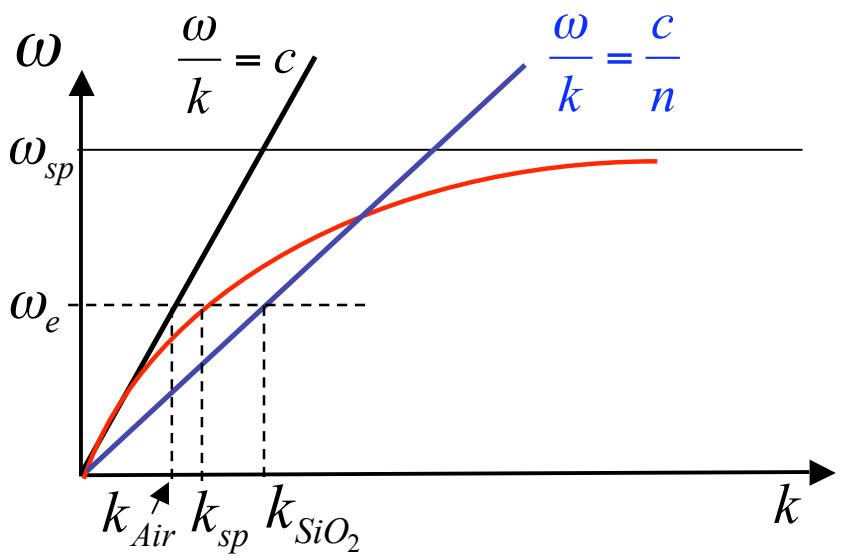
Kretschmann geometry (Trick 1)

- Makes use of SiO_2 prism
- Create evanescent wave by TIR
- Strong coupling when $k_{//,SiO2}$ to k_{sp}

⇩

- Reflected wave reduced in intensity

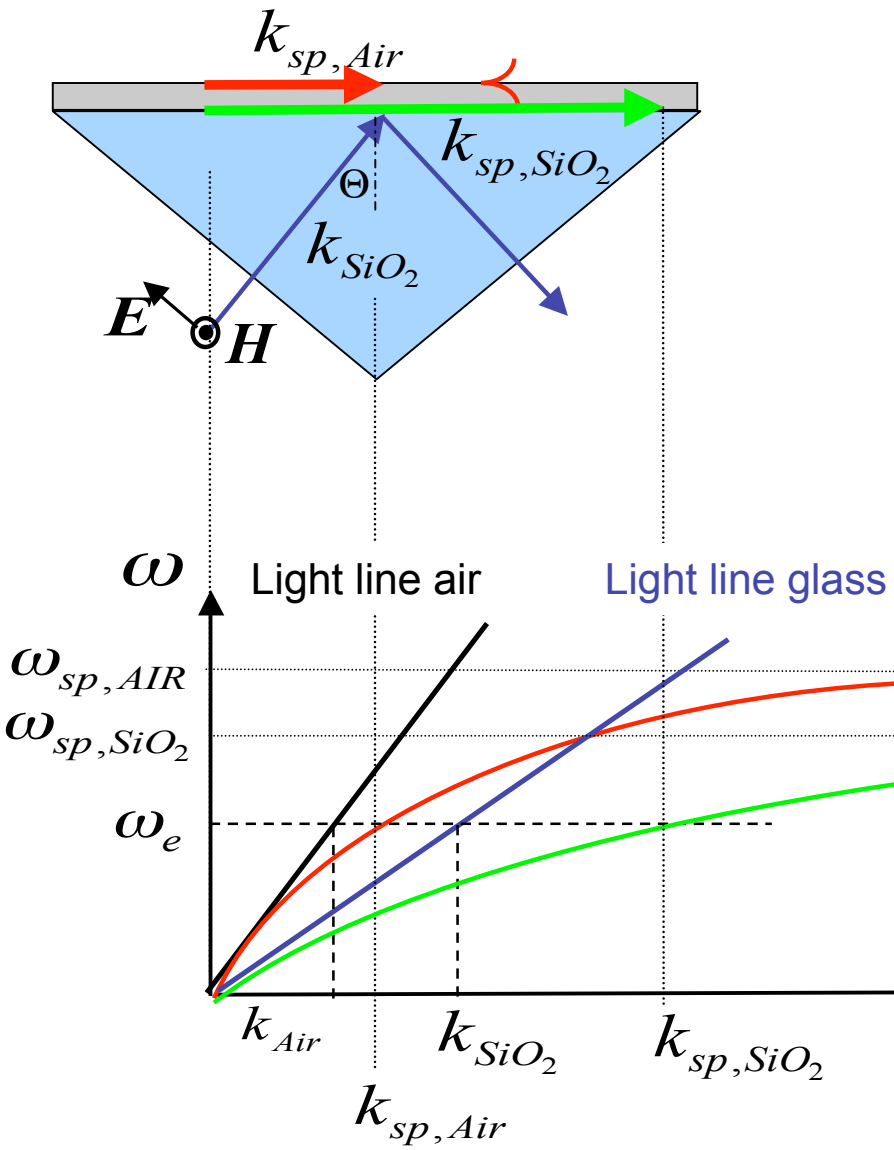




Note: we are matching energy and momentum

Surface-Plasmon is Excited at the Metal/Air Interface

Kretschmann geometry



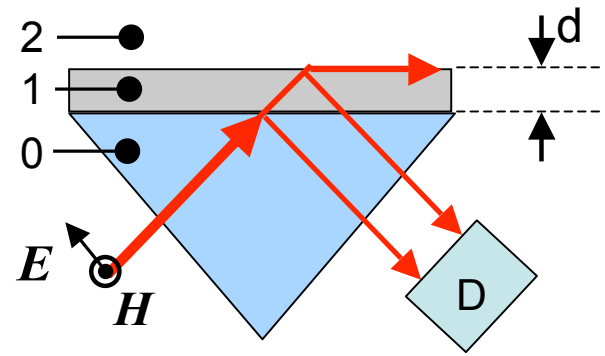
- Makes use of SiO_2 prism
- Enables excitation surface plasmons at the Air/Metal interface
- Surface plasmons at the metal/glass interface can <u>not</u> be excited!

$$k_{//,SiO_2} = \sqrt{\varepsilon_d}\,\frac{\omega}{c}\sin\theta = k_{sp}$$

Quantitative Description of the Coupling to SPP's

Calculation of reflection coefficient

- Solve Maxwell's equations for
- Assume plane polarized light
- Find case of no reflection



- Solution (e.g. transfer matrix theory! ☺)

$$R = \left| \frac{E_r^p}{E_0^p} \right|^2 = \left| \frac{r_{01}^p + r_{12}^p \exp\left(2ik_{z1}d\right)}{1 + r_{01}^p r_{12}^p \exp\left(2ik_{z1}d\right)} \right|^2$$

Plane polarized light

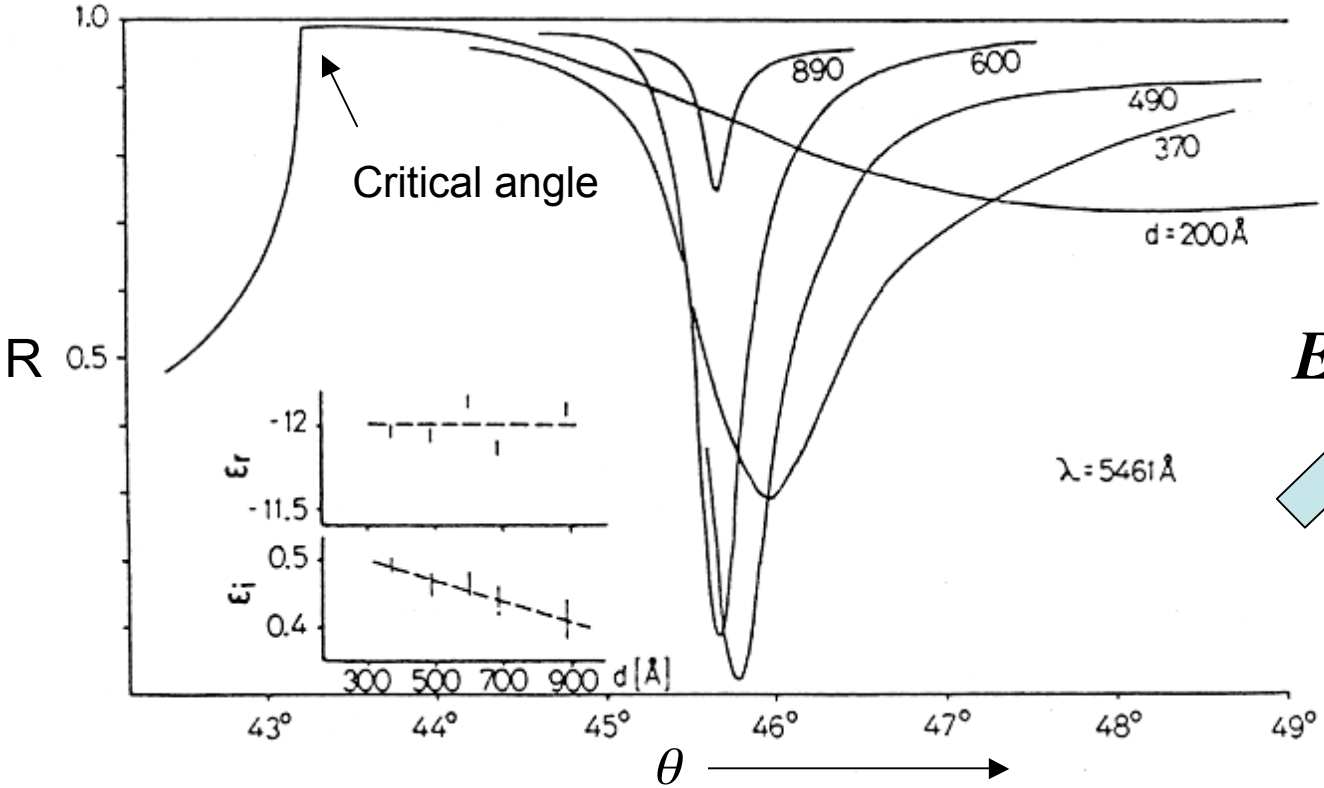
where r_{ik}^p are the amplitude reflection coefficients

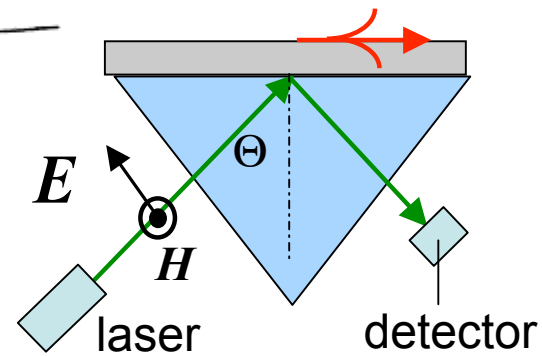
$$r_{ik}^p = \left(\frac{k_{zi}}{\varepsilon_i} - \frac{k_{zk}}{\varepsilon_k} \right) \Big/ \left(\frac{k_{zi}}{\varepsilon_i} + \frac{k_{zk}}{\varepsilon_k} \right)$$

Also known as Fresnel coefficients (p 95 optics, by Hecht)

Notes: Light intensity reflected from the back surface depends on the film thickness
There exists a film thickness for perfect coupling (destructive interference between two refl. beams)
When light coupled in perfectly, all the EM energy dissipated in the film)

Dependence on Film Thickness





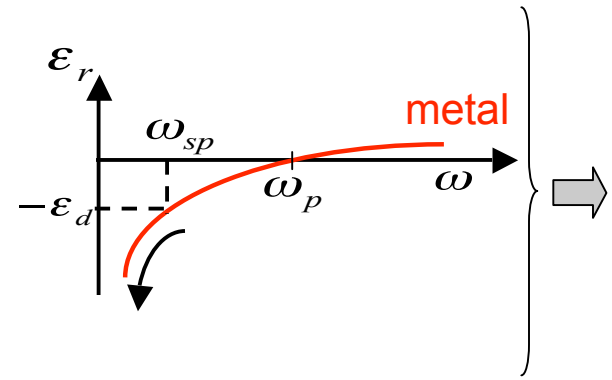
Raether, "Surface plasmons"

- Width resonance related to damping of the SPP
- Light escapes prism below critical angle for total internal reflection
- Technique can be used to determine the thickness of metallic thin films

Quantitative Description of the Coupling to SPP's

Intuitive picture: A resonating system

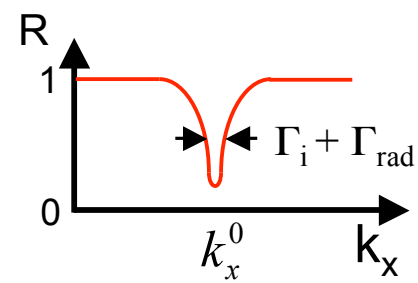
- When $\left|\varepsilon_m^{'}\right| >> 1$ …well below ω_{sp}:



- and $\left|\varepsilon_m^{''}\right| << \left|\varepsilon_m^{'}\right|$ …low loss…

➡ Reflection coefficient has Lorentzian line shape (characteristic of resonators)

$$R = 1 - \frac{4\Gamma_i \Gamma_{rad}}{\left[\left(k_x - k_x^0\right)^2 + \left(\Gamma_i + \Gamma_{rad}\right)^2\right]}$$



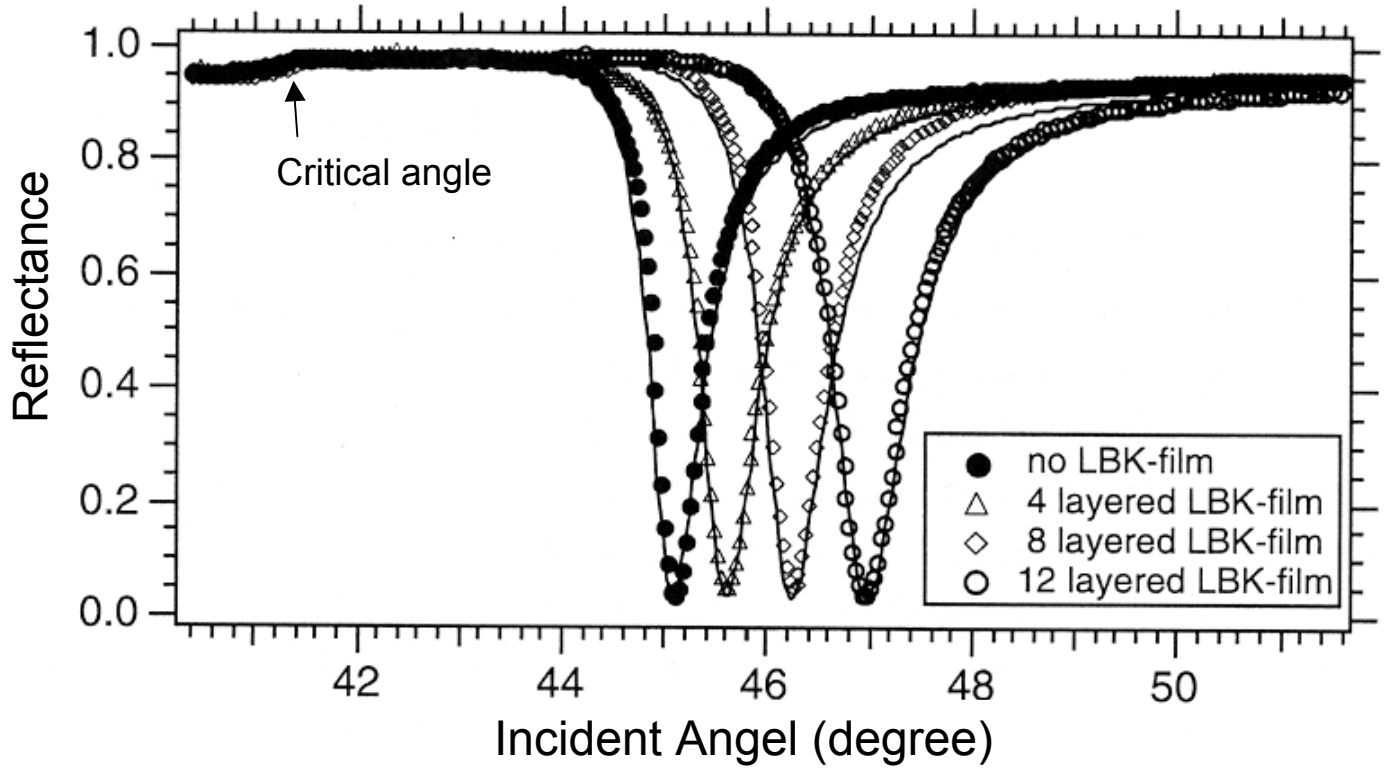
Where Γ_i : Damping due to resistive heating
Γ_{rad}: Damping due to re-radiation into the prism
k_x^0 : The resonance wave vector (maximum coupling)

Note: R goes to zero when $\Gamma_i = \Gamma_{rad}$

Current Use of the Surface Plasmon Resonance Technique

Determination film thickness of deposited films

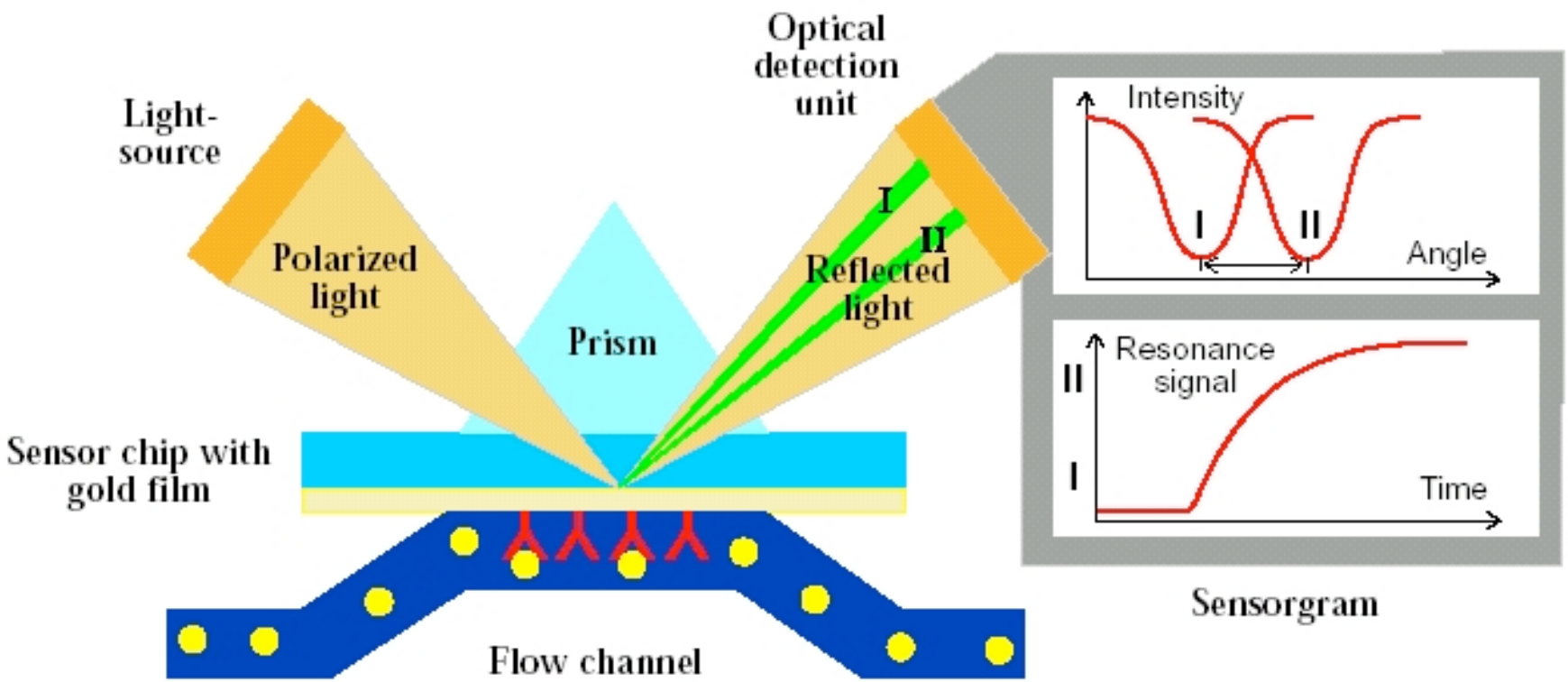
- Example: Investigation Langmuir-Blodgett-Kuhn (LBK) films



- Coupling angle strongly dependent on the film thickness of the LBK film
- Detection of just a few LBK layers is feasible

Hiroshi Kano, "Near-field optics and Surface Plasmon Polaritons", Springer Verlag

Surface Plasmon Sensors

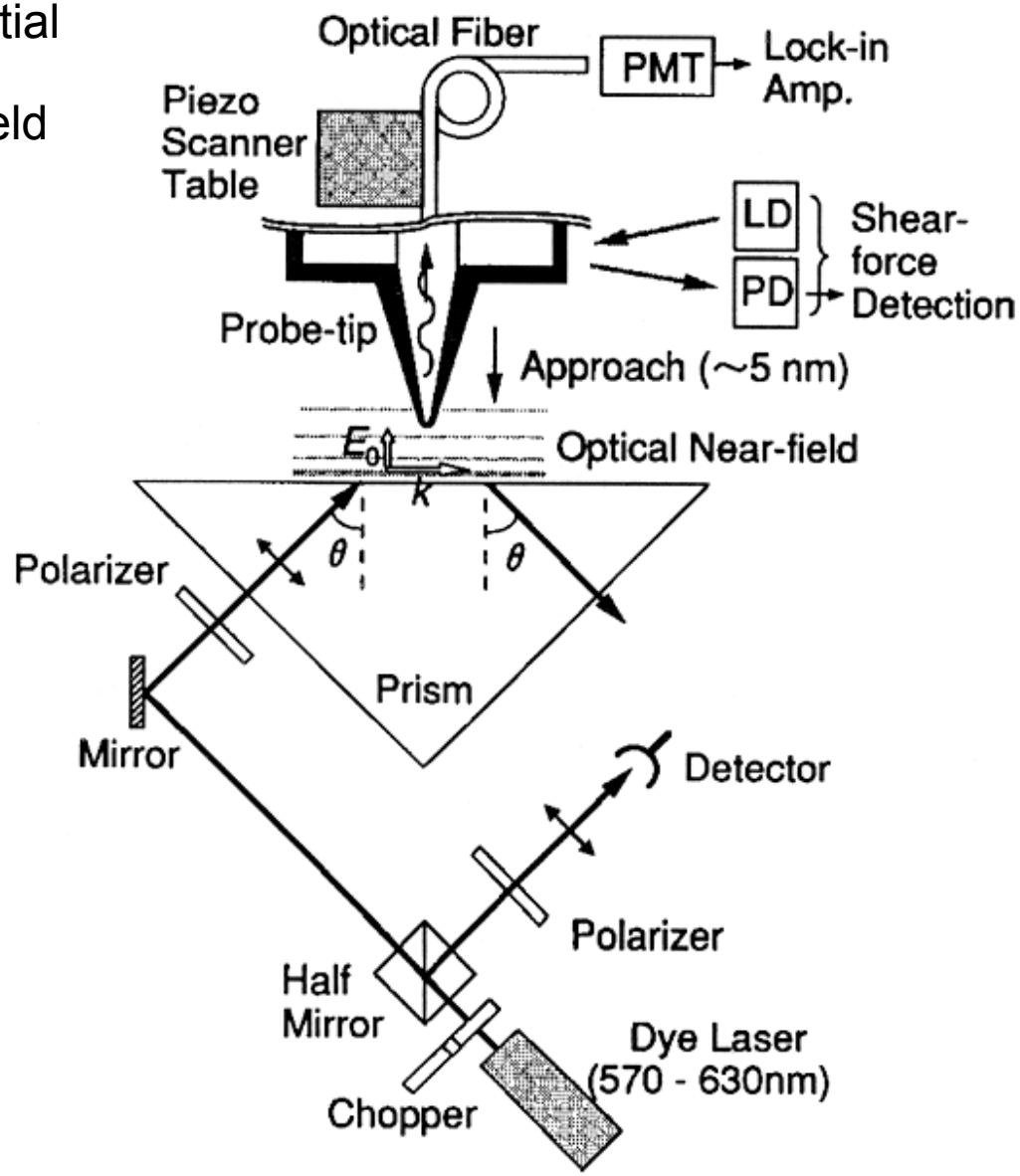


Advantages
- Evanescent field interacts with adsorbed molecules only
- Coupling angle strongly depends on ε_d
- Use of well-established surface chemistry for Au (thiol chemistry)

http://chem.ch.huji.ac.il/~eugeniik/spr.htm#reviews

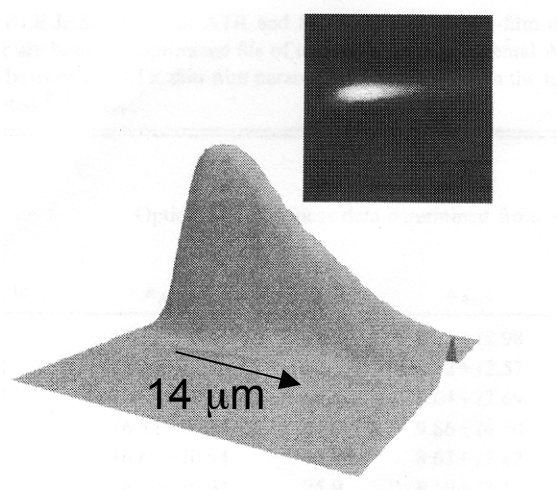
Imaging SPP waves

- Near-field optics is essential
- Tip “taps” into the near-field



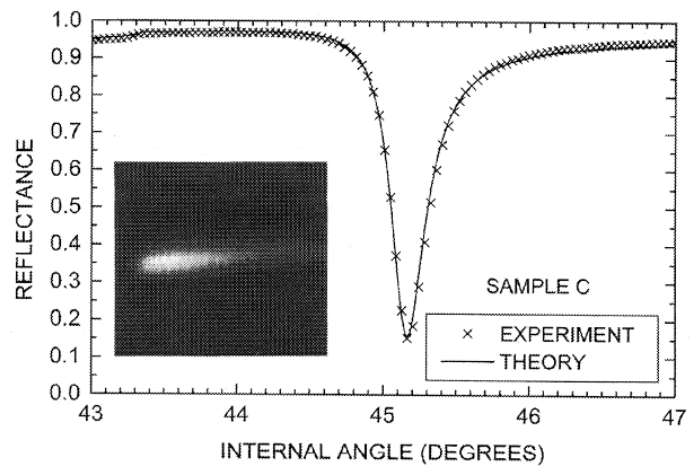
Direct Measurement of the Attenuation of SPP's

- Local excitation using Kretchmann geometry



- Imaging of the (decay length of the) SPP

- Width resonance peak gives same result



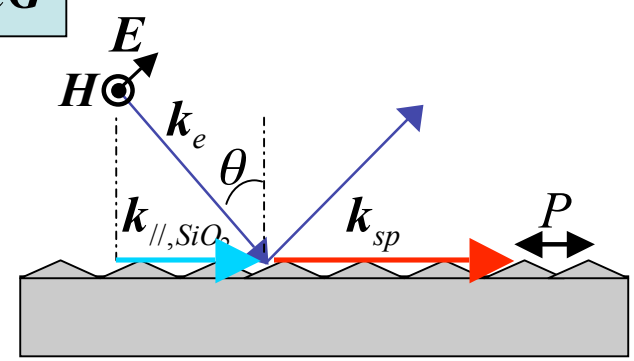
P. Dawson et al. Phys. Rev. B **63**, 205410 (2001)

Excitation Surface-Plasmon Polaritons with Gratings (trick 2)

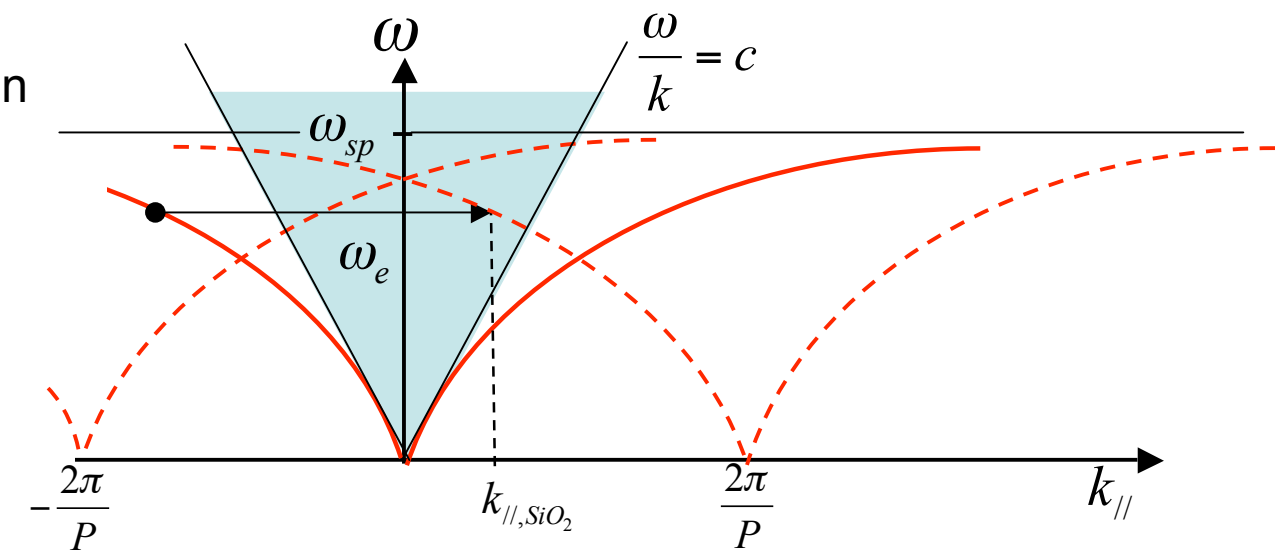
Grating coupling geometry (trick 2)

- Bloch: Periodic dielectric constant couples waves for which the k-vectors differ by a reciprocal lattice vector $\boldsymbol{G}$
- Strong coupling occurs when $\boxed{\boldsymbol{k}_{//,SiO_2} = \boldsymbol{k}_{sp} \pm m\boldsymbol{G}}$

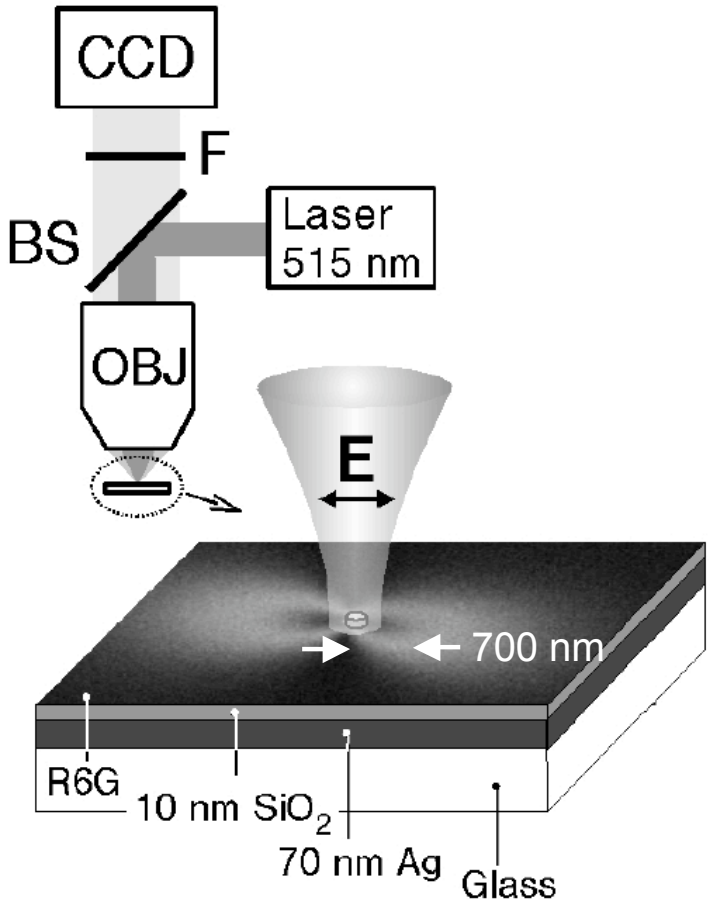
where:
$$\begin{cases} k_{//,SiO_2} = |\boldsymbol{k}_e| = \sqrt{\varepsilon_d}\,\dfrac{\omega}{c}\sin\theta \\ k_{sp} = \dfrac{\omega}{c}\left(\dfrac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{1/2} \\ |\boldsymbol{G}| = 2\pi/P \end{cases}$$



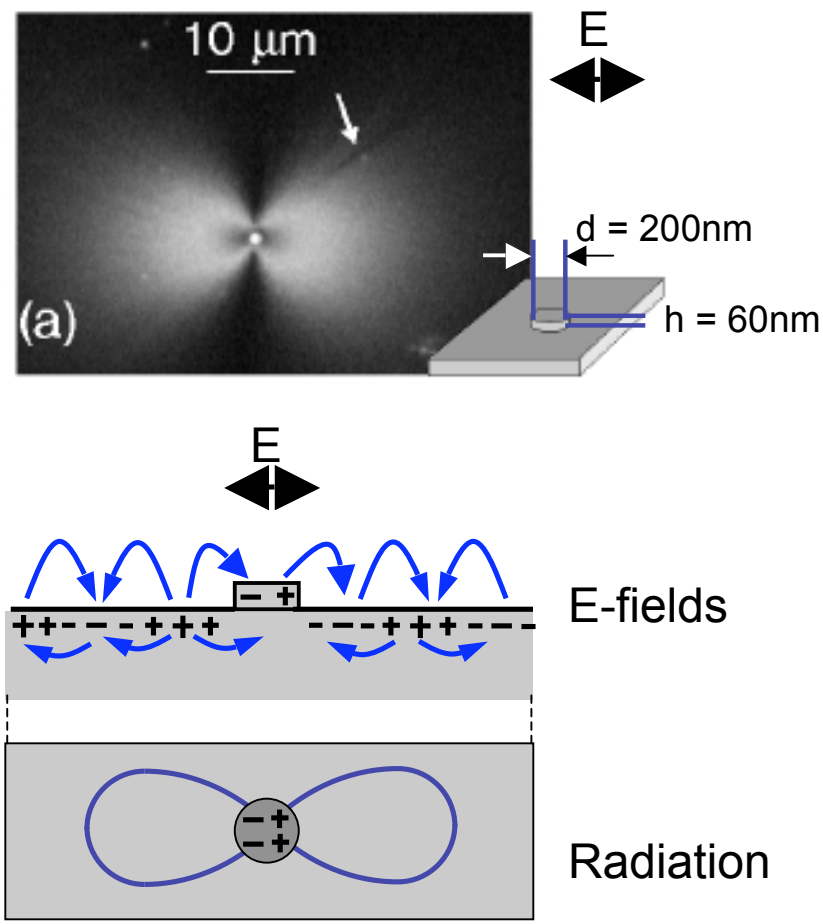
- Graphic representation



Excitation Surface-Plasmon Polaritons with Dots (Trick 3)



Dipolar radiation pattern



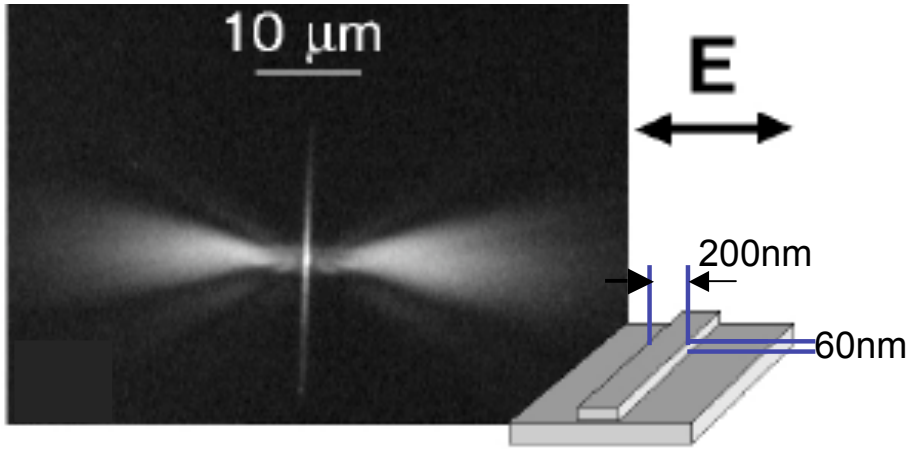
- Strong coupling: $\boldsymbol{k}_{//,SiO_2} = \boldsymbol{k}_{sp} \pm \Delta k_{dot}$

Spatial Fourier transform of the dot contains significant contributions of Δk_{dot} values up to $2\pi/d$

H. Ditlbacher, Appl. Phys. Lett. ***80****, 404 (2002)*

- Dipole radiation in direction of charge oscillation!
- Reason: Plasmon wave is longitudinal

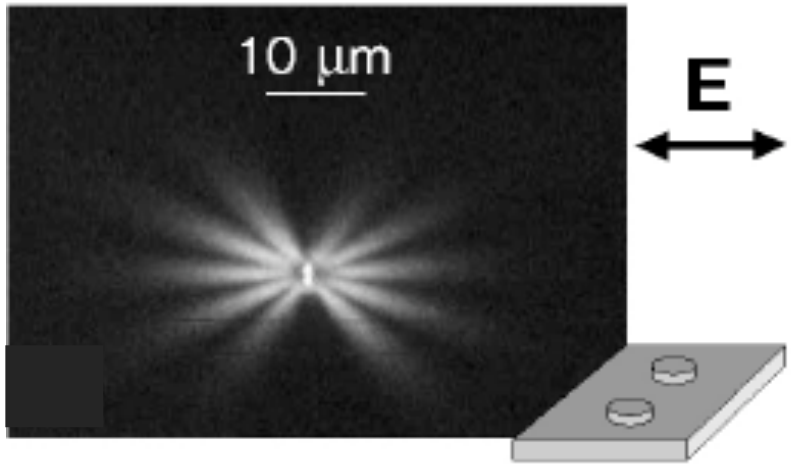
Other Excitation Geometries



- Radiation pattern more directional
- Divergence angle determined by spot size

700nm

- Illumination whole line ➡ radiation ⊥ to line

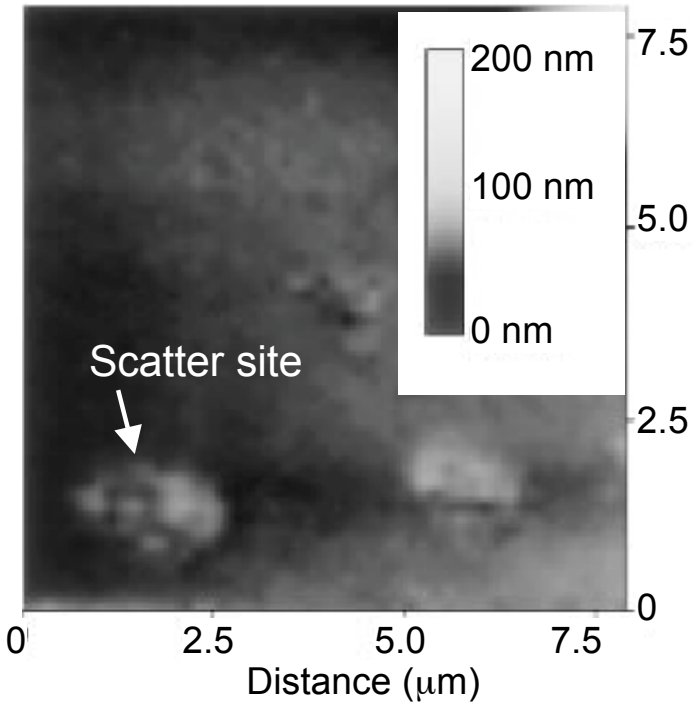


- Pattern results from interference 2 dipoles

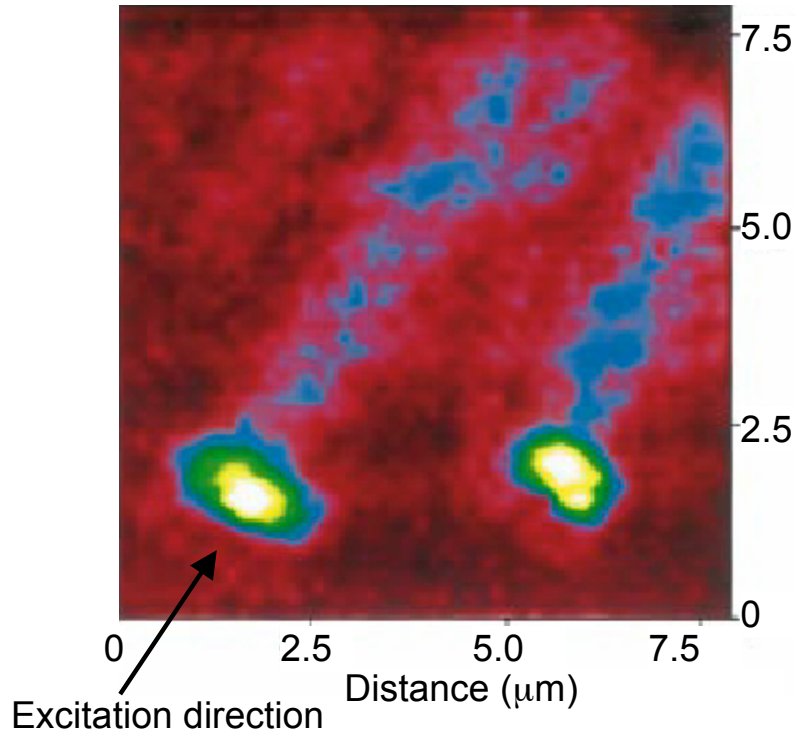
H. Ditlbacher, Appl. Phys. Lett. ***80****, 404 (2002)*

Excitation Surface-Plasmon Polaritons from a Scattering Particle

Atomic Force Microscopy Image

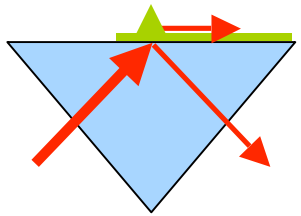


Near-field Optical Microscopy Image



- Scattering site created by local metal ablation with a 248 nm excimer laser (P=200 GW/m^2)

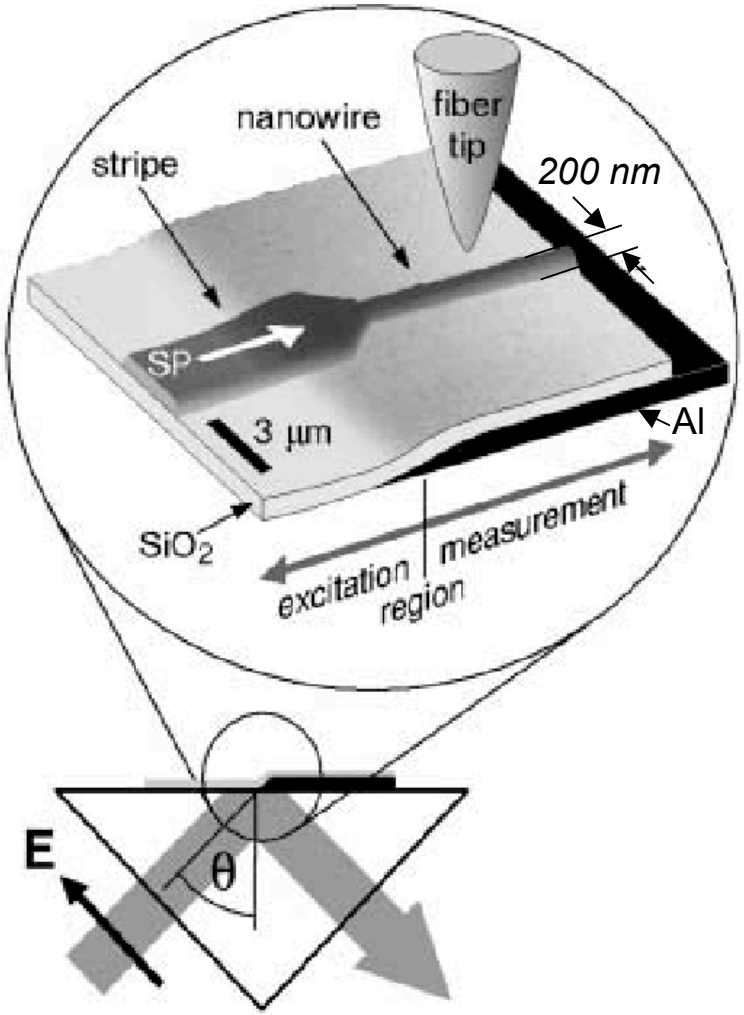
- Scattering site brakes translational symmetry
- Enables coupling to SPP at non-resonant angles



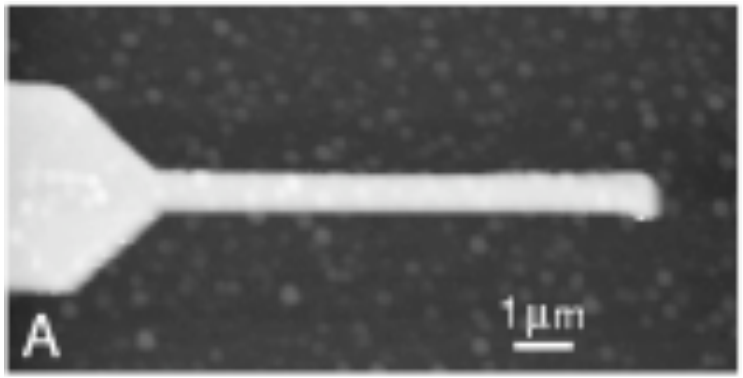
I.I. Smolyaninov, Phys. Rev. Lett. ***77,*** *3877 (1996)*

Excitation SPPs on stripes with d < λ

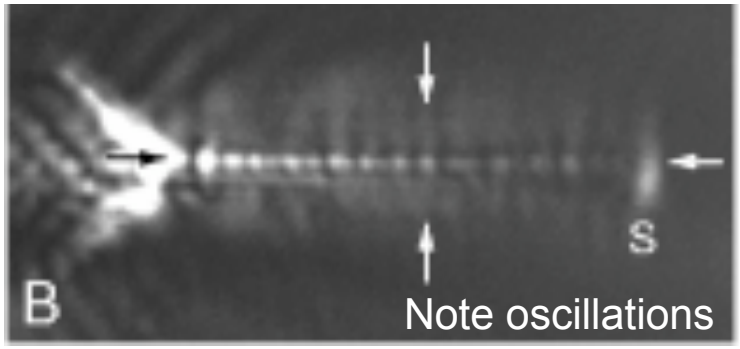
Excitation using a launch pad



Atomic Force Microscopy image



Near Field Optical Microscopy image

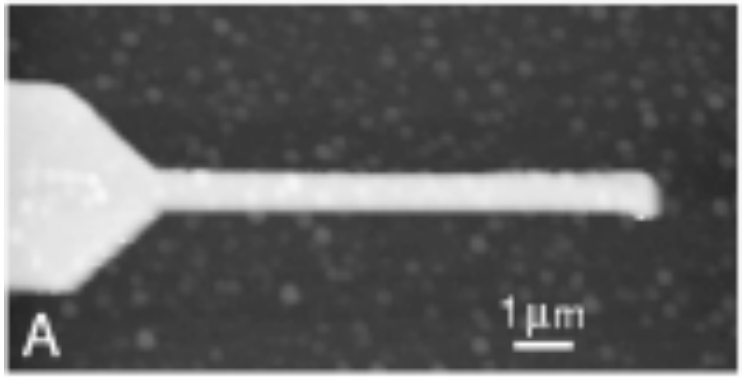


End stripe

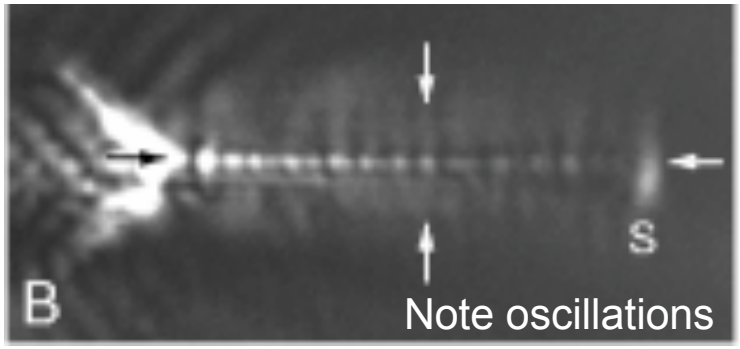
J.R. Krenn et al., Europhys. Lett. ***60,*** *663-669 (2002)*

Excitation SPPs on stripes with d < λ

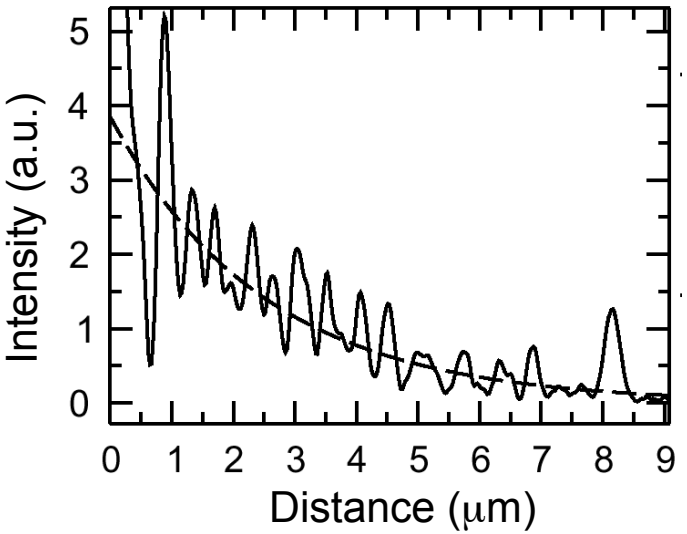
Atomic Force Microscopy image



Near Field Optical Microscopy image



End stripe

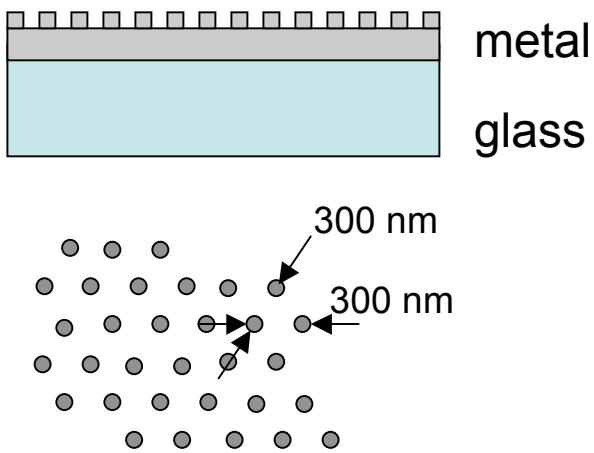


Note: Oscillations are due to backreflection

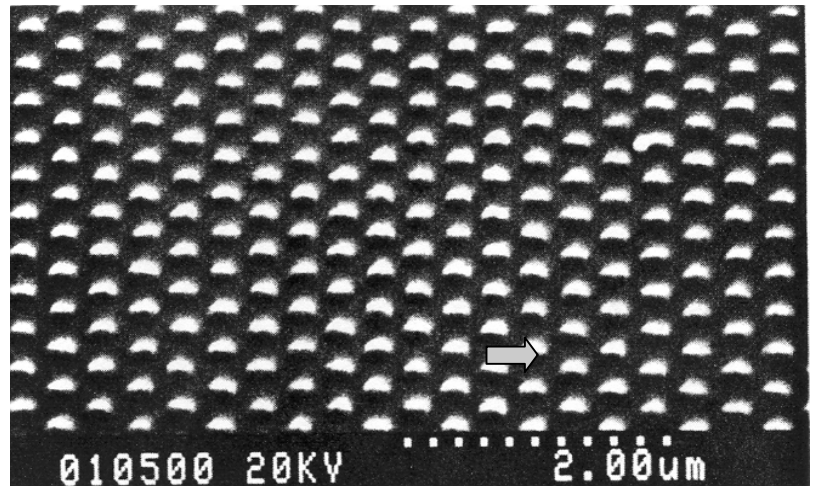
2D Metallo-dielectric Photonic Crystals

Full photonic bandgap for SPPs

- Hexagonal array of metallic dots



Scanning Electron Microscopy image (tilted)

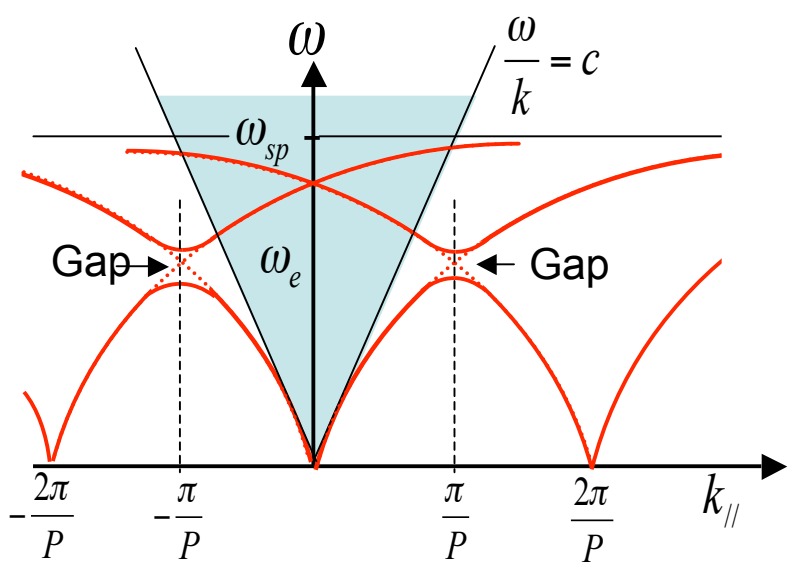


S.C. Kitson, Phys Rev Lett. ***77****, 2670 (1996)*

- Array causes coupling between waves
  for w

$k_{sp} = \pi/P$ or $\lambda_{sp}=2\pi/k_{sp}= 2P$

- Gap opens up at the zone boundary

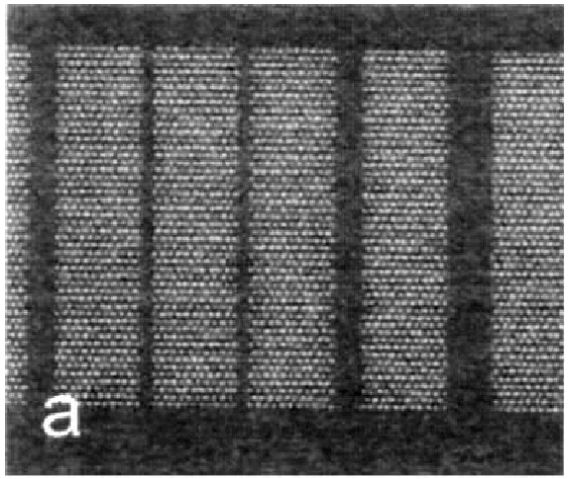


Guiding SPPs in 2D metallo-dielectric Photonic Crystals

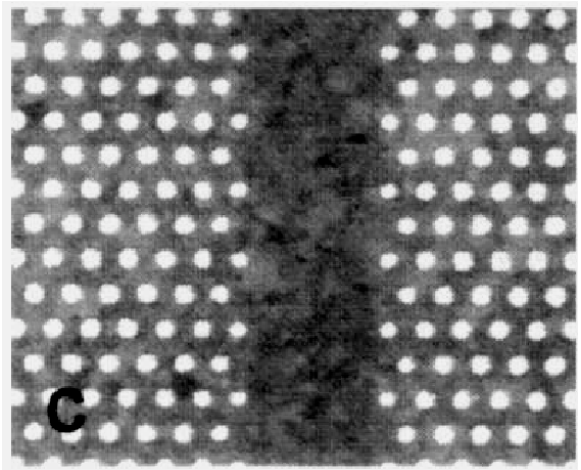
Guiding along line defects in hexagonal arrays of metallic dots (period 400 nm)

- Scanning electron microscopy images

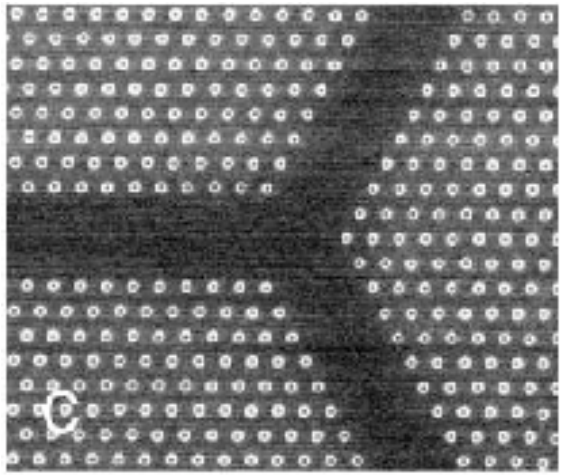
Linear guides



Close-up



Y-Splitter



- SPP is confined to the plane
- Full photonic bandgap confines SPP to the line defect created in the array

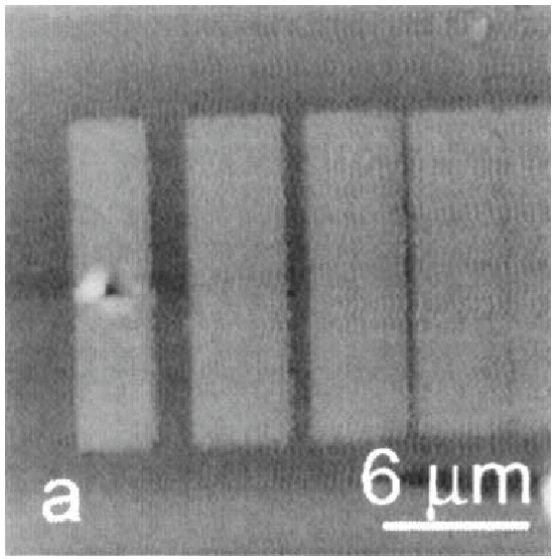
S.I. Bozhevolnyi, Phys Rev Lett. ***86****, 3008 (2001)*

Guiding SPPs in 2D metallo-dielectric Photonic Crystals

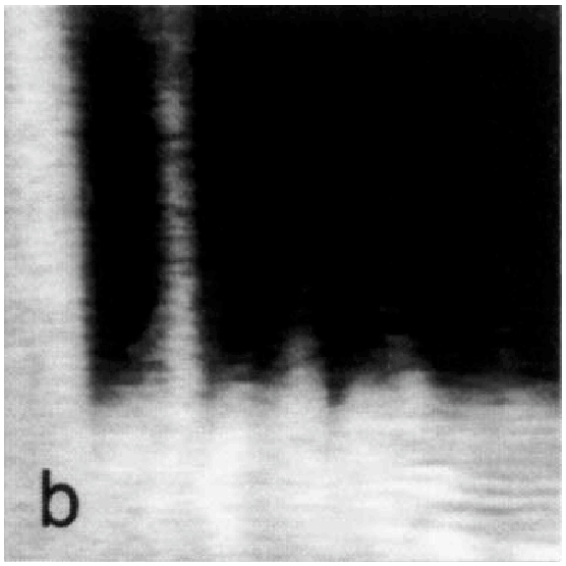
First results

- Scanning electron microscopy images

Atomic Force Microscopy image



Near-field Optical Microscopy image



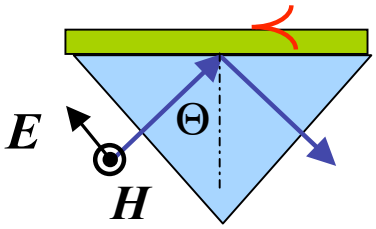
Dot spacing: d = 380 nm
Excitation: λ_e = 725 nm
SPP: λ_{sp} = 760 nm = 2d

S.I. Bozhevolnyi, Phys Rev Lett. ***86****, 3008 (2001)*

Summary

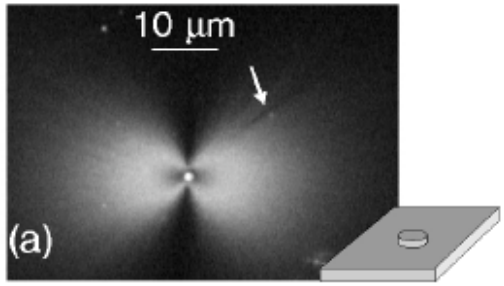
Coupling light to surface plasmon-polaritons

- Kretchman geometry $k_{//,SiO_2} = \sqrt{\varepsilon_d}\,\frac{\omega}{c}\sin\theta = k_{sp}$



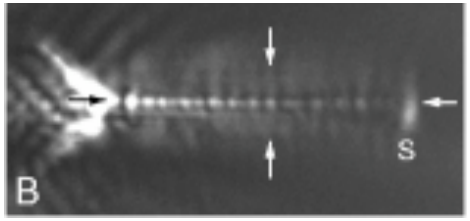
- Grating coupling $\boldsymbol{k}_{//,Air} = \boldsymbol{k}_{sp} \pm m\boldsymbol{G}$

- Coupling using a metal dot (sub-λ structure)

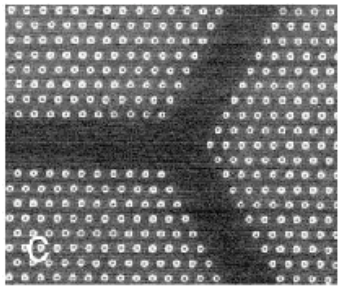


Guiding geometries

- Stripes and wires



- Line defects in hexagonal arrays (2d photonic crystals)



- Next lecture: nanoparticle arrays