Plasmonics using Metal Nanoparticles

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ECE 580 – Nano-Electro-Opto-Bio

April 1, 2007

Motivation

- Why study plasmonics?
  - Miniaturization of optics and photonics to subwavelength scales
  - Applications: fully integrated electro-opto circuits, high resolution microscopy, effective biosensors

- What is plasmonics?
  - Exploitation of the optical properties of surface plasmons (SP) in metals for local field enhancements and radiation confinement
  - Metal nanoparticles to create simple and novel structures (thin films, colloids, wires, shells, stars etc.)

Surface Plasmons (SP)

- Observed since the late 17th century (e.g. Lycurgus cup)
  - Addition of gold powder to glass to color it red
  - Scattering → looks green
  - Absorption → transmitted light looks red

- What is a SP?
  - EM wave propagates along surface of metal-dielectric interface coupled to collection of oscillating free conduction electrons

http://www.thebritishmuseum.ac.uk/science/lycurguscup/sr-lycurgus-p2b.html

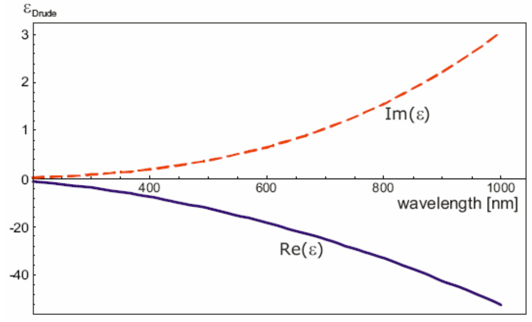
Optical Properties of Metals

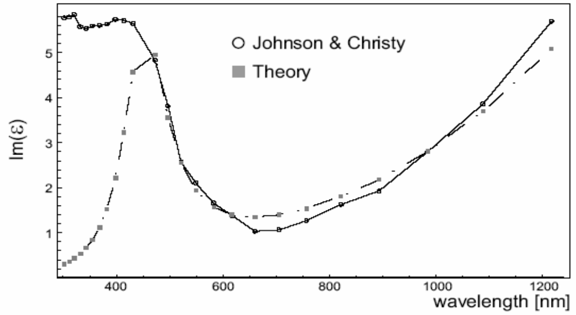
- To model the complex dielectric function of metals, need to consider:
  - (i) motion of free conduction electrons
  - (ii) interband transitions of bound electrons to conduction band given a excitation photon with sufficient energy

Calculated Dielectric Functions

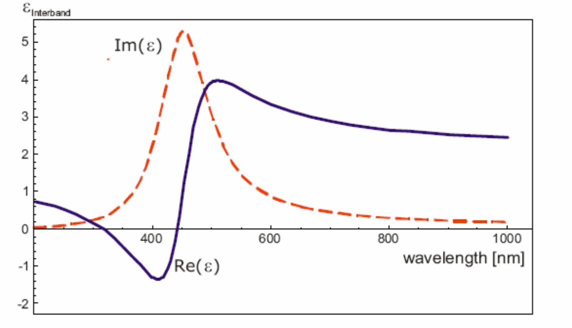
Theoretical vs. Experimental Results

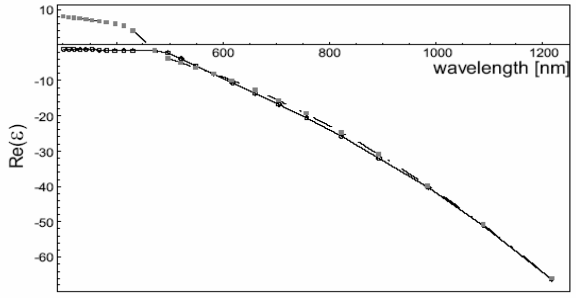
Drude-Sommerfeld Model



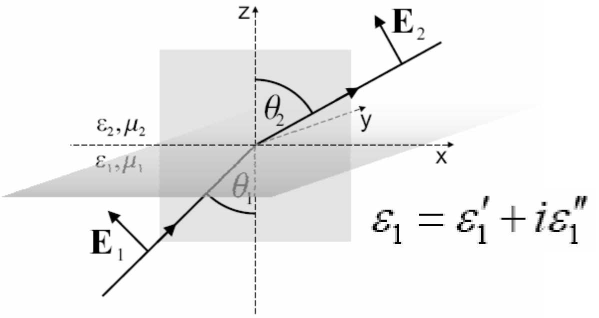


Interband Transitions





SP at Metal-Dielectric Interface



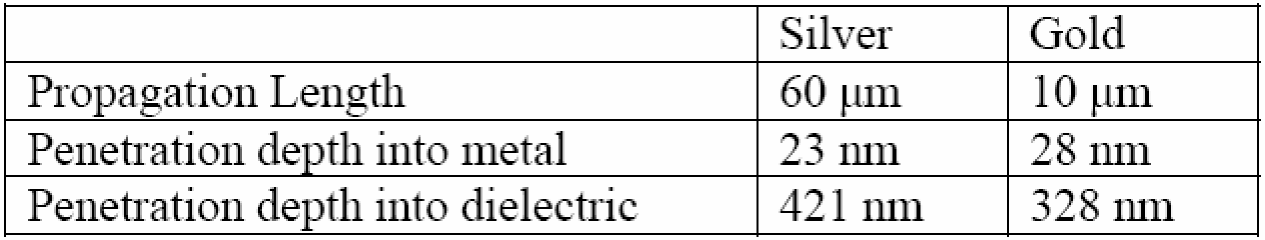
$$\varepsilon_1 = \varepsilon_1' + i\varepsilon_1''$$

- $\varepsilon_1(\omega)$– complex dielectric funtion (e.g. metal), ε_2 – real dielectric funtion (e.g. air)
- p-polarized wave satisfies wave equation: $$\nabla \times \nabla \times \bar{E}_i(\omega) - \frac{\omega^2}{c^2}\varepsilon_i(\omega)\bar{E}_i(\omega) = 0$$
- Solving wave equation with boundary conditions, get: $$E_{1,x} - E_{2,x} = 0$$ $$\varepsilon_1 E_{1,z} + \varepsilon_2 E_{2,z} = 0$$
- Assuming no sources: $$k_x E_{i,x} + k_{i,z} E_{i,z} = 0$$
- Solving these equation yields:
  - Normal component: $$k_{i,z}^2 = \frac{\varepsilon_i^2}{\varepsilon_1 + \varepsilon_2} k^2 \longrightarrow \boxed{\begin{array}{c}\varepsilon_1 + \varepsilon_2 < 0 \\ \varepsilon_1 \cdot \varepsilon_2 < 0\end{array}}$$
  - Dispersion relation: $$k_x^2 = \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2} k^2 = \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2} \frac{\omega^2}{c^2}$$

METALS!!!!!

Properties of SPP

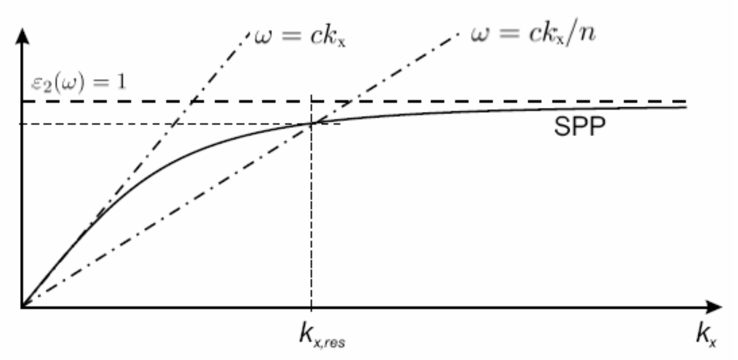
- SPP Wavevector: $k_x' \approx \sqrt{\frac{\varepsilon_1'\varepsilon_2}{\varepsilon_1'+\varepsilon_2}}\frac{\omega}{c}$ $k_x'' \approx \sqrt{\frac{\varepsilon_1'\varepsilon_2}{\varepsilon_1'+\varepsilon_2}}\frac{\varepsilon_1''\varepsilon_2}{2\varepsilon_1'(\varepsilon_1'+\varepsilon_2)}\frac{\omega}{c}$
- Wavelength of SP: $\lambda_{SPP} = \frac{2\pi}{k_x'} \approx \sqrt{\frac{\varepsilon_1'\varepsilon_2}{\varepsilon_1'+\varepsilon_2}}\lambda$
- Propagation Length: $1/k_x''$
- Sample numbers for $\lambda=630$ nm, $\varepsilon_2=1$



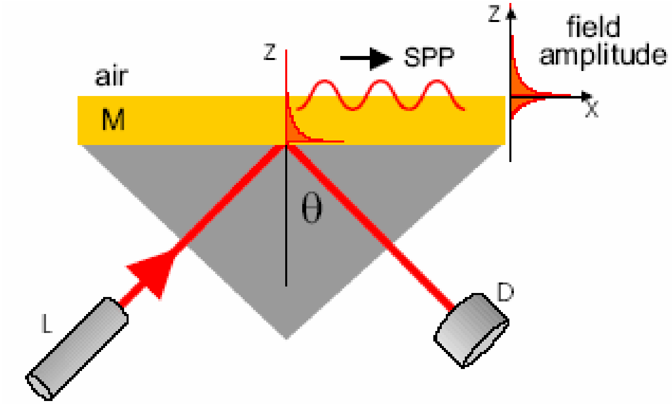
	Silver	Gold
Propagation Length	60 μm	10 μm
Penetration depth into metal	23 nm	28 nm
Penetration depth into dielectric	421 nm	328 nm

SP Excitation

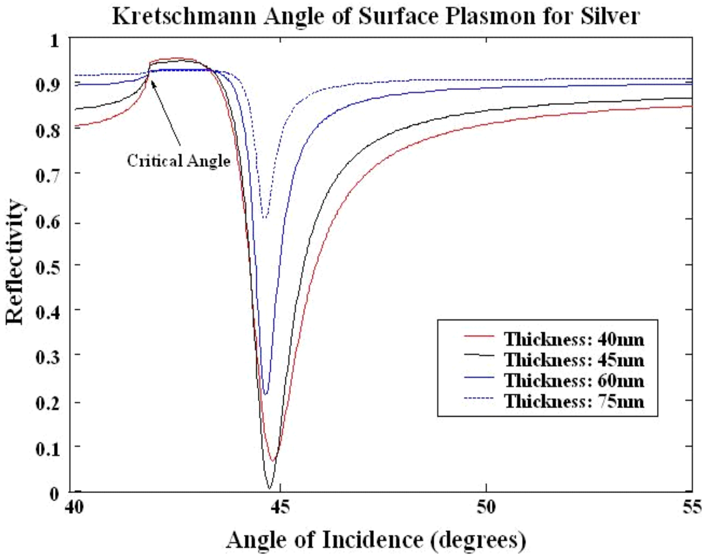
- Dispersion relation for SP
  - Momentum of SP larger than free space photon
  - Need dielectric material with n<1 to tilt light line



- Kretschmann configuration
  - Glass prism
  - Optimal angle of incidence, θ_K

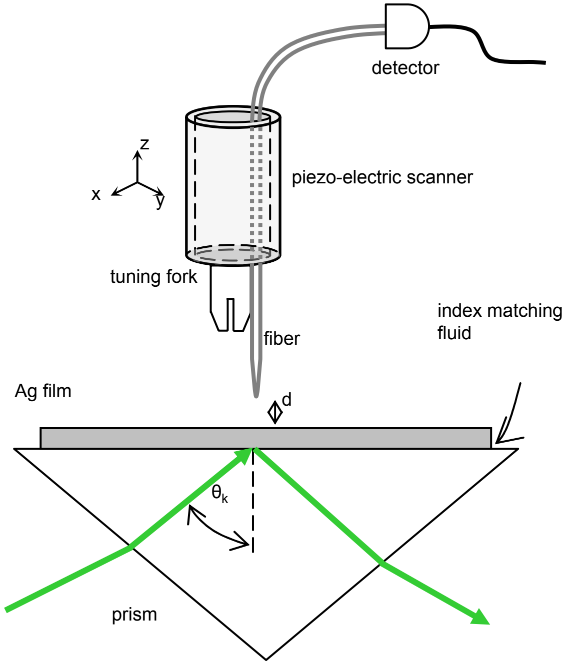


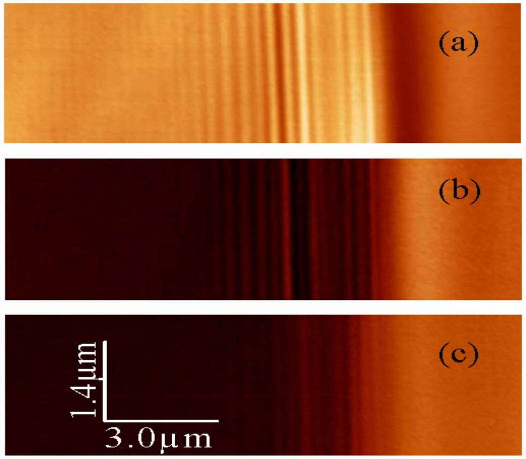
Reflectivity (θ, film thickness)



Near-Field Microscopy

- Photon Scanning Tunneling Microscopy (PSTM)
  - Kretschmann configuration
  - Evanescent field couples into propagating mode of fiber
  - Topography & field intensity measurements





- Typical results

  (a) SPP standing wave
  (b) tuned away from θ_K,
  (c) s-polarized light

Sensors

- Surface Plasmon Resonance (SPR) sensor for gas detection and biosensors

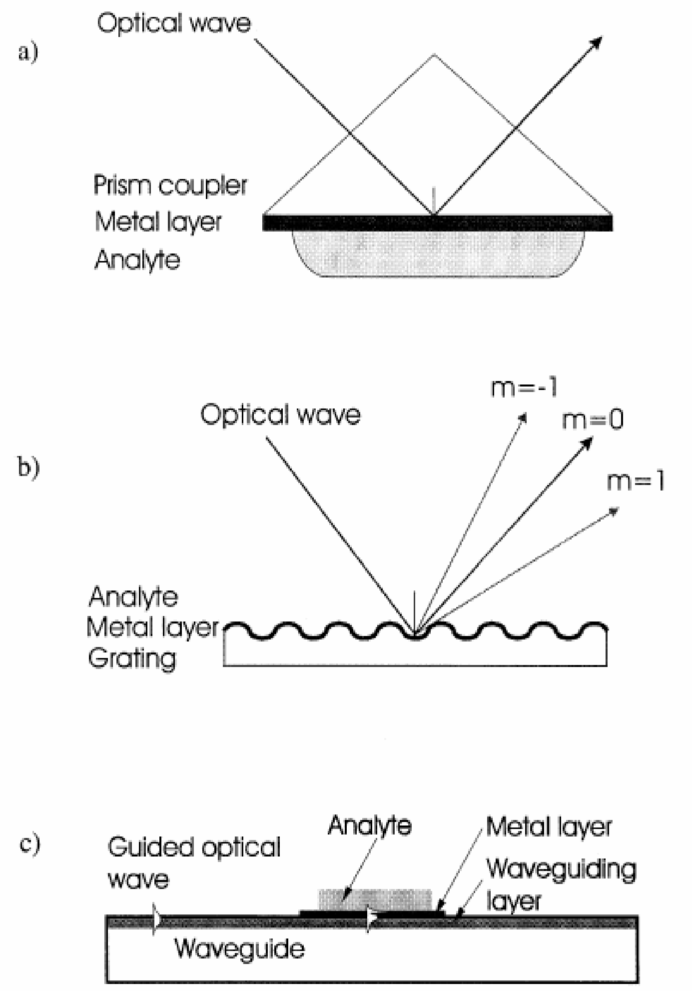
- Components:
  - optical system (light excitation, metal structure)
  - transducing material (whose properties being sensed)
  - detection system

- Sensor performance:
  - sensitivity, resolution, and operation range

Types of Sensors

- Types of sensors:
  - prism-based
  - grating-based
  - Waveguide-based

- Materials & Fabrication:
  - prism-based: glass or plastic
  - grating-based: holograhic technique in plastic
  - waveguide-based: CVD for semiconductor, ion exchange for glasses

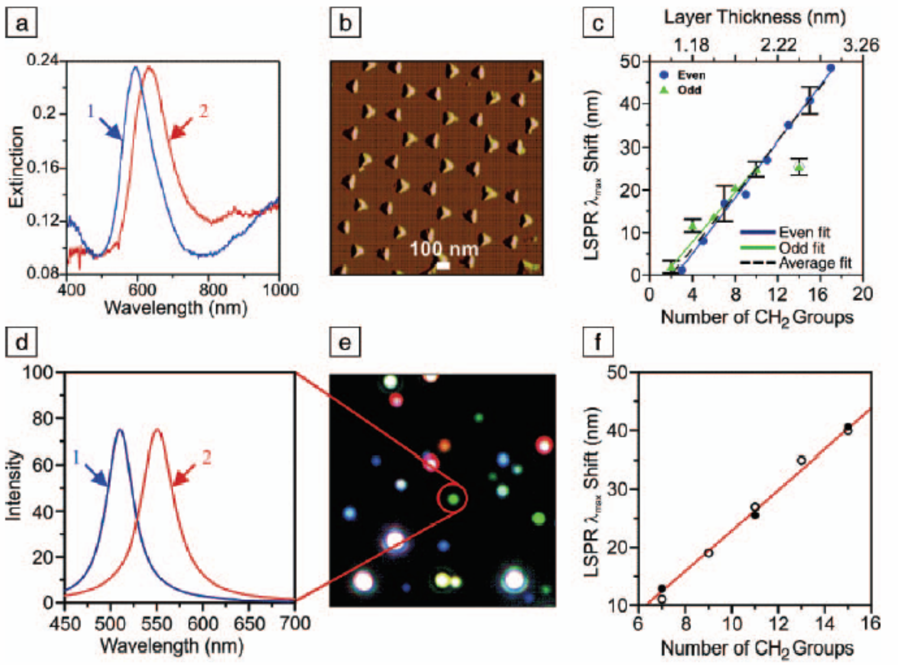


Sensor Examples

- To measure chemisorption of 1 monolayer of hexadecanethiol using Ag nanoparticles

- Methods
  - Top Row: Nanosphere lithography
  - Bottom row: single Ag particles

- Results:
  - Both: ~40 nm shift in SPR from 1 monolayer

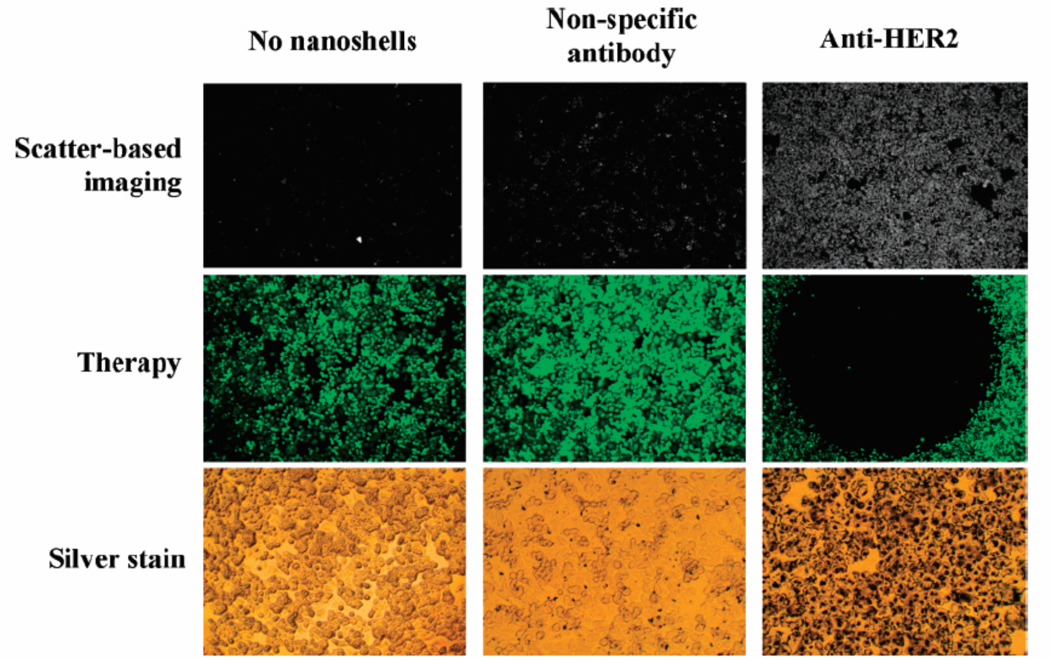


Biophotonics

- Nanoshell with dielectric cores for imaging and therapy
  - silica cores with colloidal gold nanoparticles formed as shells
  - tuned to NIR for biological tissue to either scatter light for imaging or absorb light for therapy

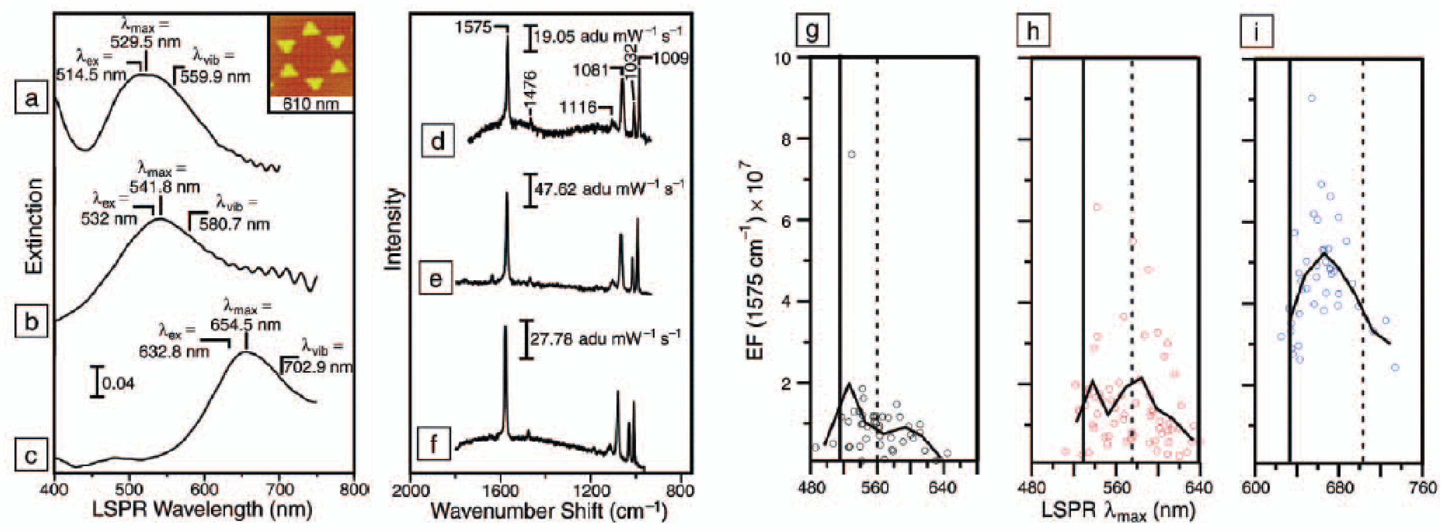
- Results from Halas group: nanoshell particles tuned to both scatter and treat cancer cells by photothermally

Nanoshells were antibody conjugated to target HER2 which are overexpressed by the type of cancer cells used



SERS

- SERS
  - enhancement of Raman signals which are typically very small
  - Attachment of molecule to nanoparticles results in high scattering cross sections



Surface Plasmon Subwavelength Optics

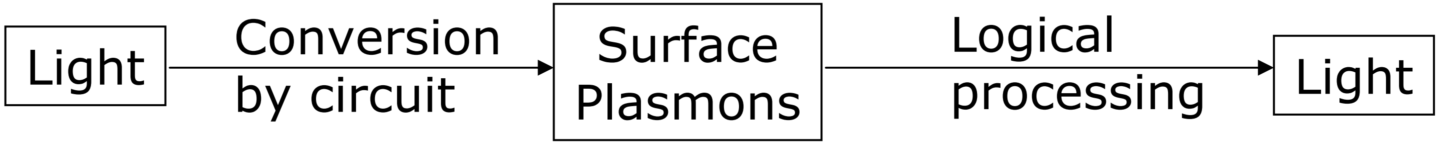
Issues:

- Scaling of interconnects
- Component dimensions – How to beat the diffraction limit ?

Solution → Surface Plasmons

- Recap: SPs are light waves that propagate along metal/dielectric interfaces on interaction with surface electrons
- Key aspect: different relative permittivities

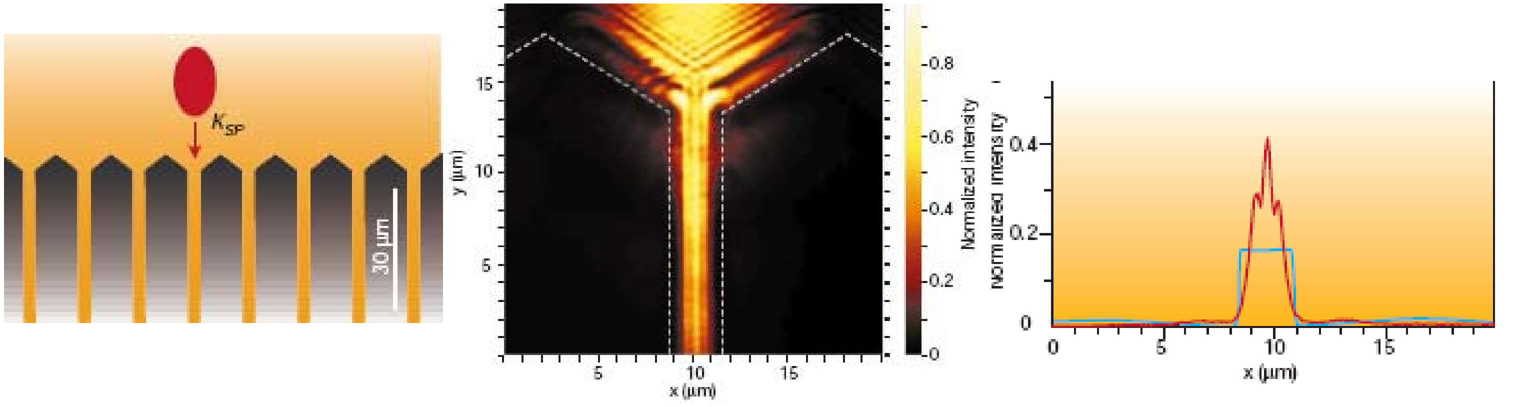
$$k_{SP} = k_0 \sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}}$$


Light → Conversion by circuit → Surface Plasmons → Logical processing → Light

- Propagation distances: 10-100 μm

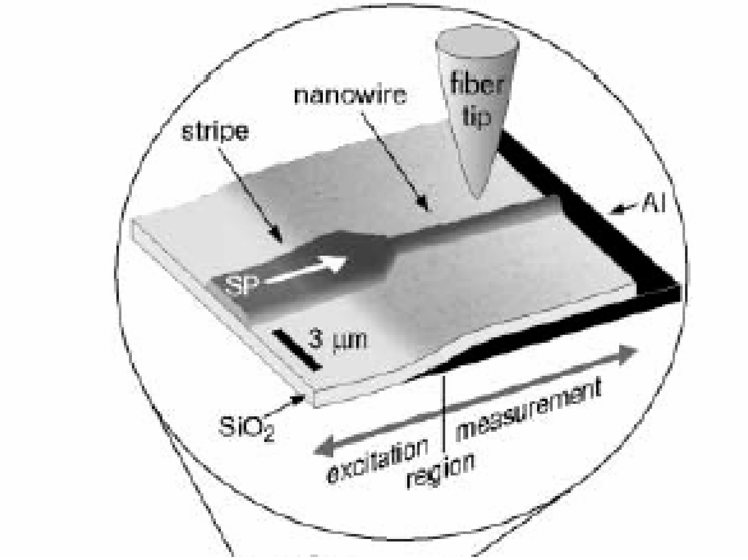
Surface Plasmon Waveguides

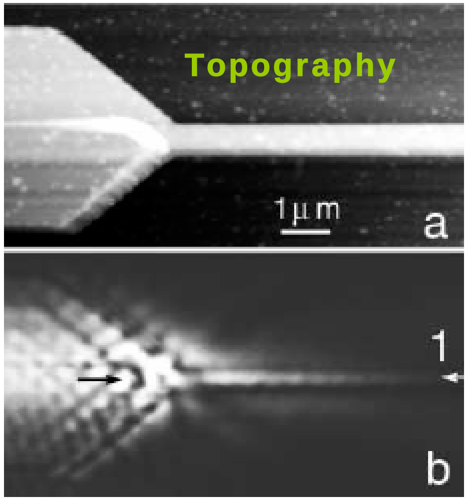
- Ordered arrays
- Stripe Waveguides



- Nanowires

(Barnes et al, Nature 2003)



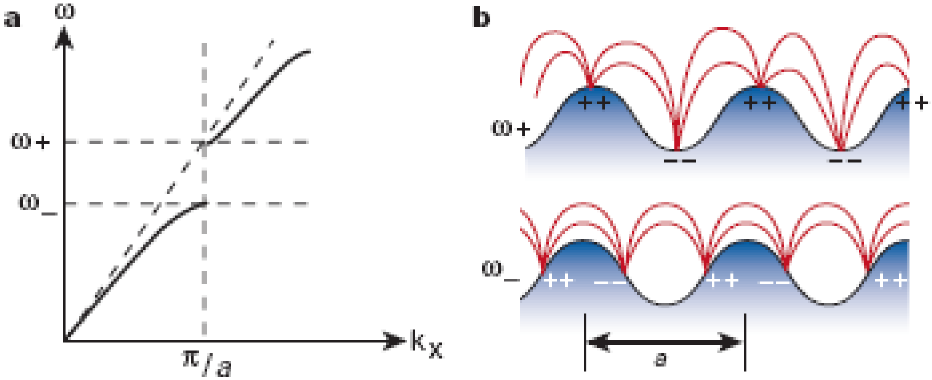


Optical near field intensity

(Krenn et al, Europhys. Letts. 2002)

Surface Plasmon Photonic Bandgaps (SPPBG)

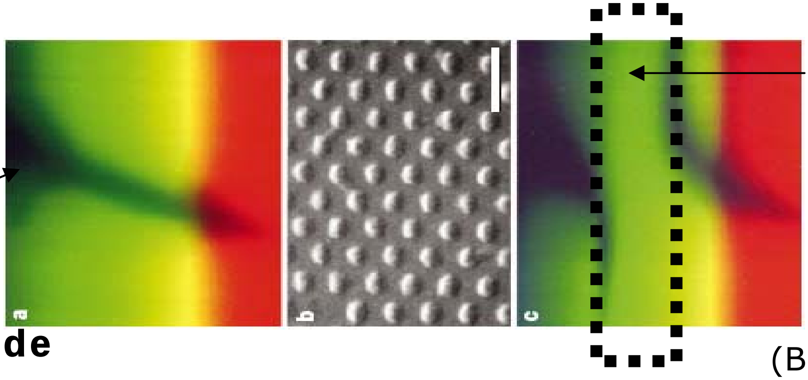
❖Regions of periodic index modulations that form a ‘stop’ band



(Barnes et al, Nature 2003)

Bandgap Period: $a = (1/2)\,\lambda_{SP}$

- High density of SP states at band edge
- Increase in field enhancement



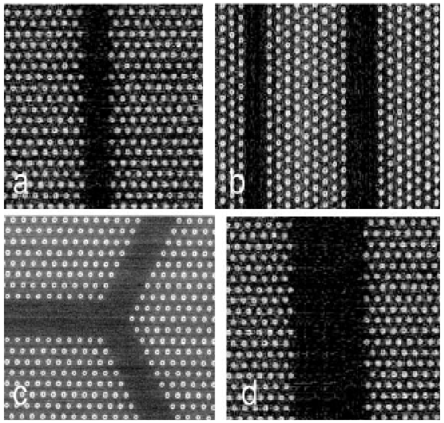
Photonic Bandgap

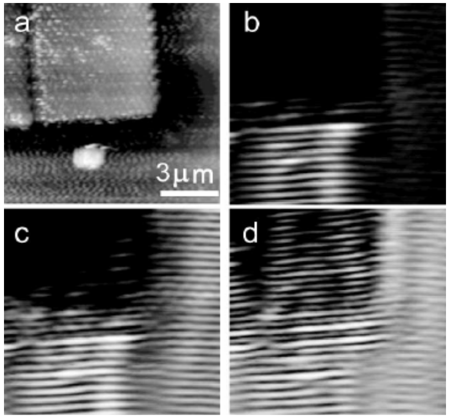
Incident light coupling to SP mode

(Barnes et al, Nature 2003)

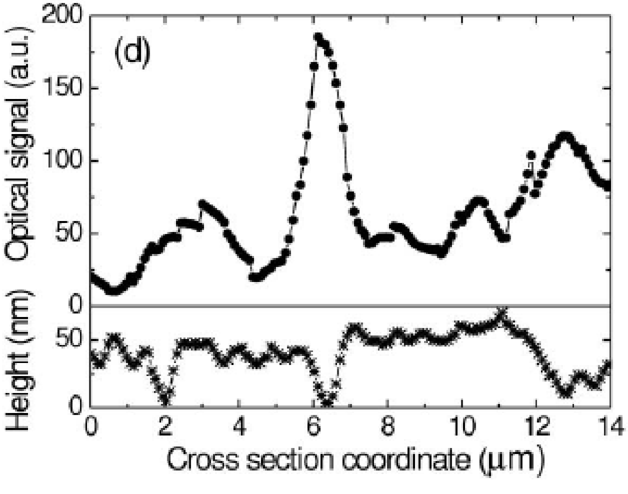
Waveguiding with SPPBG

- SPP guided along ΓK line defect
- Triangular lattice with 400 nm period on a 45nm gold film
- Decay length: $L_{SPP} = 35\ \mu m$

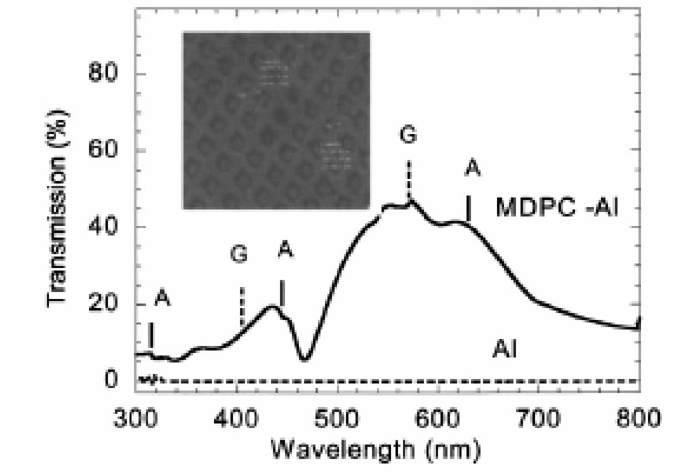




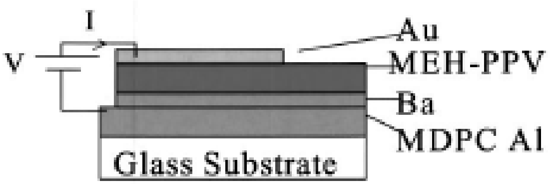
Reflectivity measurements conclusively prove the presence of an optical bandgap !



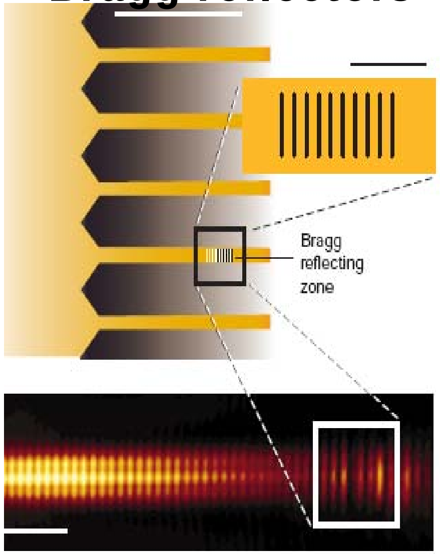
Surface Plasmon Photonic Devices



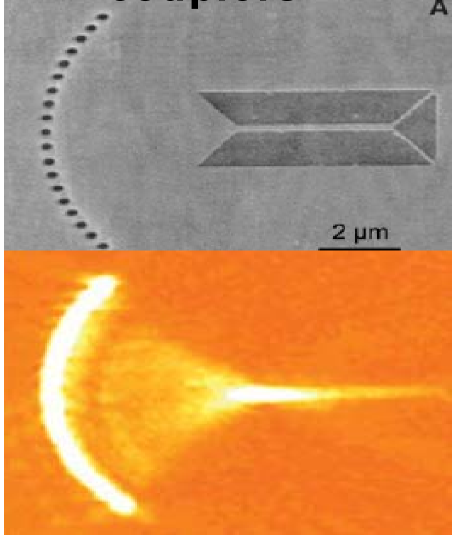
- **SP-based LEDs**



- **SP-based Bragg reflectors**

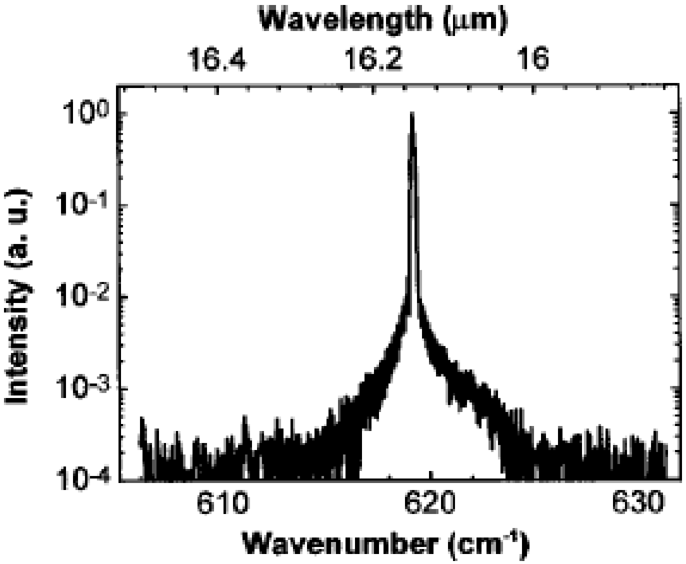


- **SP-based couplers**



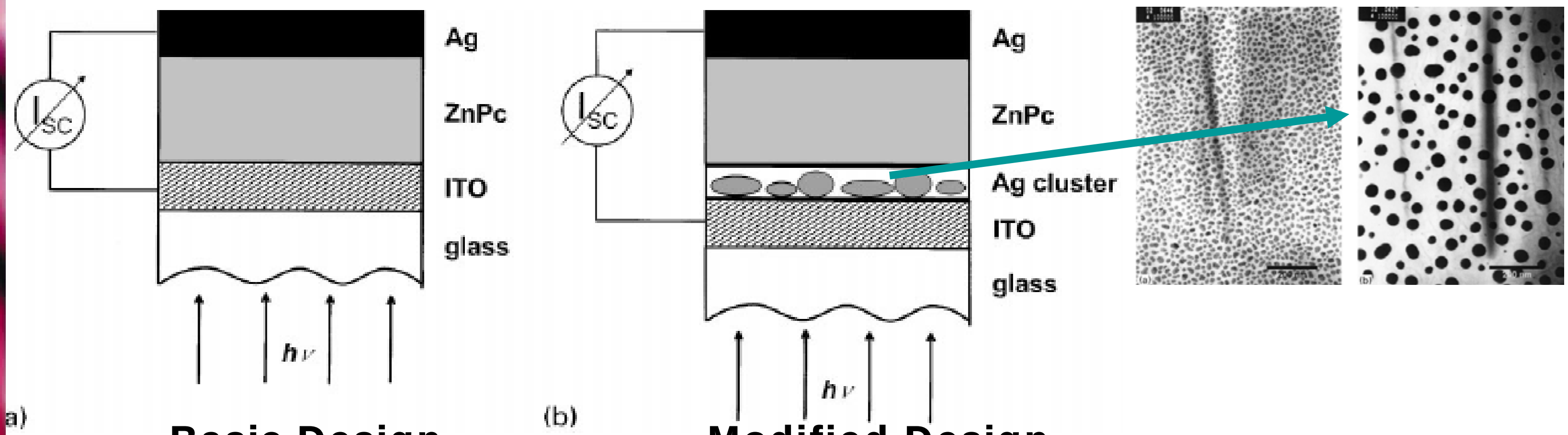
Other Applications - Lasers

- Operate in the far-IR (>15 μm)
- Low loss
- Low lasing threshold
- Consist of 300 nm gold film deposited on quantum cascade active materials
- Total epitaxial thickness: 4 μm
- Dimensions of device: 25 μm wide and 800 μm long



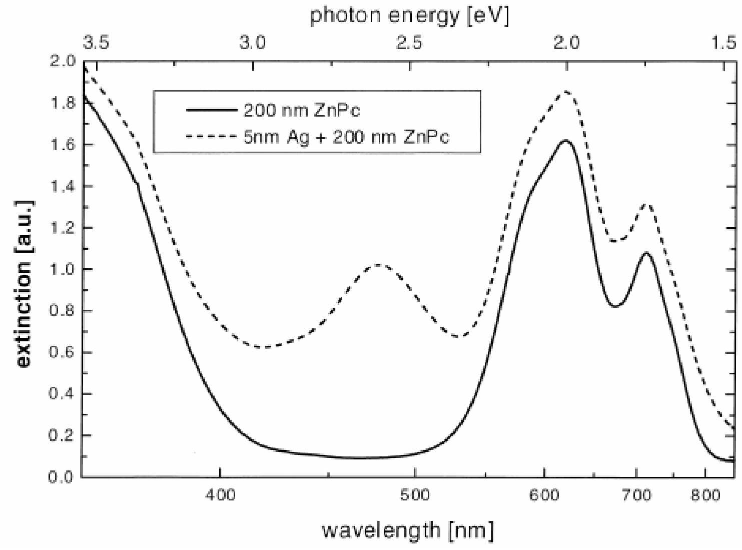
Spectrum of emission of 50 ns pulses at 84.2 kHz

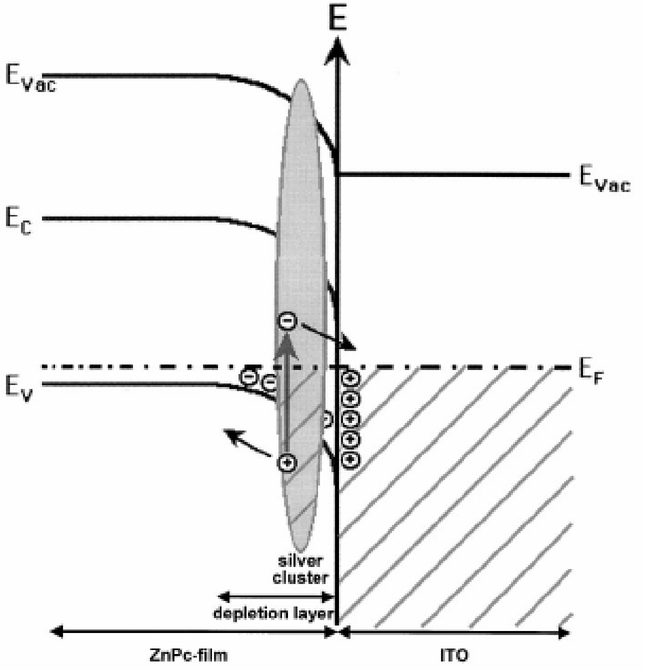
Other Applications – Solar cells



Basic Design **Modified Design**

- ➢Silver nanoclusters are deposited on ITO substrate
- ➢Generated e$^-$ - h$^+$ pair in cluster contributes to photocurrent





Future Directions

- Light generation: organic LEDs
- Components for photonic circuits
- SPR sensors
- Designing of SP-based devices
- Fabrication of SP-based devices