Excitation Electronique de Plasmons de Surface

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Electronic excitation of surface plasmons

General Outlook

Surface plasmons of gold nanoparticles and nanostructures are of great interest for a number of applications.

For some applications, light excitation of surface plasmons is essential, e.g. photocatalysis, surface enhanced Raman spectroscopy, light harvesting.

However, for many applications, light excitation of surface plasmons is a problem and should be replaced by electron excitation, e.g. chemical and biological sensors, plasmonic circuitry, optical nanosources (SPASERs).

Electronic excitation is essential for all applications that require miniaturization of plasmonic devices down to the nanometer-scale and/or integration into nanoelectronics.
How can we excite surface plasmons?

Photons (bosons) can be converted into Surface Plasmons (bosons) with an ultimate high efficiency (up to 100 %)

However Photon excitation of Surface Plasmons suffers from fundamental limitations:
- K matching
- Size matching
- Photon sources (lasers, OLEDs, QWs) are all created by electron excitation

Electron excitation of surface plasmons is expected to solve the K matching and size matching problems and to directly transfer energy to surface plasmons without going through the excitation of photons.
K matching problem for conversion of photons into surface plasmons

Coupling condition:
\[ K_{spp} = K \sin \Theta \]

i.e. \( K > K_{spp} \)

Photon dispersion in glass (\( n = \text{index of refraction} \))

Surface Plasmon Polariton dispersion relation (air-metal interface)

\[ k_x = n\omega/c \]

Energy

Wavevector

Kretschmann geometry for excitation...

...or for detection

Laser

Metal film

Glass prism

Energy vs. Wavevector

\[ \omega \]

\[ k_x \]
Laser (785 nm) excitation of surface plasmons in a silver nanowire (L=18.6 μm, φ=120 nm)

Laser spot has a size of a few μms, i.e. much larger than the diameter of the nanowire (120 nm)
- Electrical excitation of surface plasmons is expected to solve these K matching and size matching problems

- Fundamental interest of comparing electron excitation of photons and electron excitation of surface plasmons

- Electrical excitation + Electrical detection of surface plasmons
  ➔ electrical plasmonic devices fully integrated at the nano-scale, (plasmonic circuitry, SPASERs, chemical- and bio-sensing, etc)
Electrical excitation of surface plasmons versus Electrical excitation of photons

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A new method for the generation of light, inelastic electron tunneling excitation of plasmons
Inelastic electron tunneling

\[ \delta E : \text{plasmon excitation} \]
Surface plasmons excitation using the scanning tunneling microscope (STM)

J.K. Gimzewski et al. (IBM)  

Only localized gap plasmons can be detected

T. Wang et al. Nanotechnology 22, 175201 (2011)

Both localized gap plasmons and propagating Plasmons can be detected
Electrical nanosource of surface plasmons using inelastic electron tunneling with the STM

- Very local excitation (10 nm) + variable position + imaging
- Equivalent to an oscillating vertical dipole with a broadband spectrum
- Low energy electrical excitation (< 3V)
- Excite both localized (LSP) and propagating (SPP) surface plasmons
- STM works in vacuum, air or liquid

T. Wang et al. Nanotechnology 22, 175201 (2011)

$V = 2.8 \, \text{V}$, $I = 2 \, \text{nA}$
Quantitative measurements of the intensity of localized and propagating plasmons

$V_s = +2.5 \ \text{V} \quad I = 6\text{nA}$

$e = 35 \ \text{nm}$

Localized plasmons

Propagating plasmons

Localized nanocavity

T. Wang et al. Nanotechnology 22, 175201 (2011)
An electrically excited nanoscale light source with active angular control of the emitted light

Surface plasmon excitation in gold using high energy (10 keV) electrons

History: Crookes tube in 1879, discovery of X-rays by W. Röntgen in 1895, discovery of fluorescence tube by T. Edison in 1895, discovery of the electron by J.J. Thomson in 1897


Plasmon excitation on a 50 nm thick Ag film using 20 keV electrons

3.6 eV EELS (Electron Energy Loss Spectroscopy)

3.7 eV photon emission
Surface plasmon excitation in gold using high energy (10 keV) electrons

Surface plasmon excitation can be probed by EELS (Electron Energy Loss Spectroscopy) and by detecting emitted radiation (Cathodoluminescence)

F.J. Garcia de Abajo, Rev. Mod. Phys. 82, 209 (2010)
Surface plasmon excitation in gold using high energy (30 keV) electrons

The spatial resolution of cathodoluminescence, \( \approx 10 \text{ nm} \), is determined by the radial drop of the electro-magnetic field.

Electrical nanosource of surface plasmons using high energy (10 keV) electrons (cathodoluminescence).

- Very local excitation (10 nm) + variable position + imaging + EELS spectroscopy
- Equivalent to an oscillating vertical dipole with a broadband spectrum
- High energy electrical excitation (10 keV)
- Excite localized (LSP) (TEM and SEM) and propagating (SPP) surface plasmons (SEM)
- Works only in vacuum

Directional emission from a plasmonic Yagi-Uda antenna of gold particles

200 nm 5 gold particles on Si (Φ = 98 nm, h = 70 nm)

30 keV electrons (Secondary Electron Microscope)

Cathodoluminescence Intensity (λ = 500 nm)

Cathodoluminescence directionality (λ = 500 nm)

T. Coenen et al. Nano Lett. 11, 3779 (2011)
Towards on-chip applications of electron-to-plasmon energy conversion using gold nanoparticles

Towards on-chip applications of electron-to-plasmon energy conversion using gold nanoparticles

Electrical excitation of hybrid plasmon-exciton nanostructures

...... towards spasers or nano-lasers
SPASER (Surface Plasmon Amplification by Stimulated Emission of Radiation)

Similar to a laser but at the nanoscale

**0D hybrid plasmon-exciton nanostructure**
(demonstrated by laser excitation)

**1D hybrid plasmon-exciton nanostructure**
(in preparation, J.L. Duvail et al.)

Electrical excitation of hybrid plasmon-exciton nanostructures has never been performed so far
Demonstration of a spaser-based nanolaser (laser excitation)

\[ \lambda = 488 \text{ nm (5 ns)} \]

\textbf{Au core} \( d = 14 \text{ nm} \)

\textbf{Silica shell} \( e = 15 \text{ nm} \)
(doped with \( 2.7 \times 10^3 \) dye molecules)

\textbf{Energy transfer}

\textbf{Exciton} (dye molecules)

\textbf{Plasmon} (gold core)

The plasmon resonance is equivalent to the light and the resonant cavity of a laser

Gain from the excitonic material overcomes the losses of localized surface plasmons

Spasing generates coherent surface plasmons in individual nanoparticles

\textit{M.A. Noginov et al. Nature 460, 1110 (2009)}
Electrical detection of surface plasmons

Superconducting detector in the near-field

785 nm diode laser

Gold film (125 nm thick)

NbN wire (100 µm long, 100 nm wide, 5 nm thin)

TC = 9K

I < Ic = 12 µA

Basse température (< 9 K)

Single plasmon detection

100 MHz detection

2.7 x 10^{-3} efficiency

Conclusions

Electrical nanometer-scale (10 nm) sources of surface plasmons in gold nanoparticles or nanostructures can be achieved using low energy tunnel electrons from an STM or high energy electrons from a TEM or SEM.

Both the electrical excitation and electrical detection can be miniaturized at the nanometer scale and integrated in nanoelectronic devices.

However, fully electrically integrated (excitation + detection) gold plasmonic devices are still far from being achieved.

Main problems: Low efficiency of the electrical excitation and detection.