Plasmons in Metallic Nanostructures: Excitation, Propagation and Detection

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- Introduction

- **Localized** plasmon modes in gold nanoparticles imaged by
  - local ablation of a substrate
  - local melting of the structures
  - two-photon photopolymerization

- **Propagating** plasmon modes in thin mesoscopic gold stripes on Silicon membranes, imaged by
  - plasmon-phonon conversion
  - plasmon-photon conversion

- Conclusions
Optical Antenna

triangle edge length 128nm, thickness 32nm

Fig. 1. Atomic force microscope images (a and b) and dark field scattering spectra (c) of a single gold bowtie optical nanoantenna with feedgap of 35 nm (black line) and 5 nm (red line).

Electronic Transport Through Atomic-Size Contacts

Influence of laser light

$G_0 = \frac{2e^2}{h} \approx \frac{1}{12k\Omega}$

Light-induced Conductance Change

Illumination at 488nm

Interpretation: at 648nm plasmons are excited in the leads, which propagate into the contact area.
Outline

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light
metal particle
Near-field Distribution of Au Triangles

fs pulse

film thickness 40nm, substrate: glass or Si
Optical Near-fields of Metal Nanostructures

Au on Si: “near-field photography“ (with 150fs laser pulse, 800nm)

Comparison with FDTD Simulations

(Finite Difference in the Time Domain)

500nm Au structures on Si, irradiated with 800nm fs laser pulse

⇒ good agreement in the near field distribution between simulations and experiment

(if one takes into account details of the structure and the substrate, like the curvature of the „triangles“ and the SiO₂ surface layer)
Optical Nearfield Enhancement: Quantitative Determination by Local Ablation

245 mJ/cm² ← increasing fluence → 215 mJ/cm²

500nm polarization ↔
Optical Nearfield Enhancement: Quantitative Determination by Local Ablation

Depth of ablated hole

- by ablation using the near field enhancement at the triangle tip

- by ablation using a focused laser beam in the far field (focus 30µm)

Enhancement factor ~ 11 (quadrupole mode)
Effect of ps Pulses?

Au triangles on Si after irradiation with ps laser pulse

Optical Nearfield Enhancement: Quantitative Determination

Simulation for locally dissipated energy (amplification compared to a smooth gold film)
Optical Nearfield Enhancement: Quantitative Determination by Local Melting

85 mJ/cm² increasing fluence → 185 mJ/cm²
polarization ↔ 1 µm
Optical Near Field Enhancement determined by local melting

Melting threshold for triangle tips: 60 mJ/cm²
Melting threshold of the unstructured gold film: 550 mJ/cm²
⇒ amplification factor ~ 9
Near Field Imaging by Two-Photon Polymerization using the nonlinear intensity dependence of SU8 polymerization for 800nm light

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Propagating Surface Plasmon Polariton
Excitation of Surface Plasmons with Photons

Problem: matching the wave vectors of plasmon and photon
(excitation on a smooth metal surface is not possible)

coupling via prism
(Kretschmann configuration)

coupling via grating
Gold Structure on Thin Si Membrane

Si: 340nm thick
Au: 40nm
Design: MCBJ
Grating for Plasmon Excitation

generated with Focussed Ion Beam
Optical Set-up

Pump-probe technique:
Laser diode: pump
LED: probe
(presently: 100ns resolution)
Spectral Transmissivity of Si Membranes

340nm thick
Temperature Dependence of the Optical Transmissivity

Graph showing the temperature dependence of optical transmissivity. The graph plots relative transmission against temperature difference in Kelvin (K). The graph includes lines for Messung 488nm, Berechnung 488nm, Exp-Fit 488nm, Messung 550nm, Berechnung 550nm, and Poynom-Fit 550nm. The graph has a vertical line at 300K.
Temperature Map

of a membrane which is heated in the centre by a focussed laser beam
Plasmon propagation along strip? Influence of the constriction?

Insert: Simulation by Golaleh Ghafoori
Heating the Grating
with a focussed laser beam

polarization horizontal

polarization vertical

calculated absorption: 19%
calculated absorption 11%

⇒ coupling is strongly enhanced by the grating
Propagation of Plasmons?
Propagation of Plasmons

Scattered light in optical microscope
Propagation of Plasmons
Indium Particles on a Si Membrane, heated by a 1000µs laser pulse

(example for a time-resolved measurement)

Sequence taken at time intervals of 200µs
Time-resolved Measurements

Light polarization horizontal (i.e. parallel to grating bars)

temperature map at t=1.5µs

time evolution at different positions

laser pulse
Time-resolved Measurements

Light polarization horizontal (i.e. parallel to grating bars)

temperature map at t=1.5µs

time evolution at different positions

diffusive heat transport in Si membrane
enhanced transport due to plasmons
Comparison with Simulation

Crosses: experiment (laser pulse width 2µs)
Lines: simulation using COMSOL Multiphysics (heat source defined by a simulation using Lumerical FDTD)
Conclusions

- Plasmon resonances in metallic nanostructures can lead to strong (local) enhancement of the electromagnetic field

- The optical near field distribution can be imaged by various techniques, e.g.
  - local ablation of proper substrates (e.g. smooth Si wafers)
  - local melting
  - 2-photon polymerization
  - ...

- The enhancement can be localized to $d << \lambda_{\text{light}}$

- Good agreement with FDTD calculations has been obtained
  - for the spatial distributions
  - enhancement factors? (under investigation)

- Plasmonic effects on conductivity, nanostructuring, nanomelting, spin-plasmonic devices ...

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- Si membranes are efficient thermometers: high temporal and spatial resolution
Thanks to …

Department of Physics, University of Konstanz:
Johannes Boneberg
Anton Plech
Christof Bartels
Hans-Joachim Münzer
Juliane König-Birk
Mario Mosbacher
Tobias Geldhauser
Andreas Kolloch
Daniel Benner
Paul Kühler
Philipp Leiprecht
Julia Gleixner
Simon Dickreuter
Andreas Ganser

Instituto de Optica, CSIC, Madrid
Carmen Afonso
Jan Siegel
Javier Solis
Theory: Javier Garcia de Abajo

RIES, Hokkaido University, Sapporo
Hiroaki Misawa
Tobias Geldhauser
Kosei Ueno
Saulius Joudkazis
(now Swinburne Univ., Melbourne)

Groups of Prof. Dekorsy, Leitenstorfer and Scheer

… and thank you!