Plasmon Printing

Using metal nanoparticle arrays for near field optical lithography

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**Projection lithography and the diffraction limit**

**Projection lithography**

smallest feature size \( \sim \lambda \)

**Plasmon printing**

smallest feature size \( \sim 0.1 \lambda \)

*(Adapted from J. T. Weed and L. Karklin, Canon USA)*
The surface plasmon resonance

Absorption and scattering of light by small particles, Bohren & Huffman

low frequency

high frequency

resonance: electron phase lag 90° \( \Rightarrow \) field enhancement
Resonance in Ag nanoparticles

Ag (⌀ 41 nm) in solution

Resonance at $\varepsilon_{Ag} = -2 \varepsilon_{H2O}$

$\lambda_{res} = 410$ nm

$\tau_{relax} \approx 2$ fs

AZ photoresist (g-line)

Resonance wavelength: $N_e$, $n_{matrix}$, shape, size

Resonance strength: $\tau_e$ (“internal” + surface scattering)

Ag: Strong resonance within sensitivity of standard g-line photoresist

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Printing scheme

- **MASK**
- **PHOTORESIST**
- **SUBSTRATE**

**EXPOSE**
- 410 nm

**DEVELOP**

- high resolution mask ($$$)
- standard resist
- simple light source
- parallel, sub-wavelength

Mask fabricated with JPL, Pasadena, CA

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3D Finite Difference Time Domain calculations

- Enhanced energy density directly below particle
- Phase lag 90° ⇒ resonant excitation

Ag: Drude model

\[ \varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 - i\omega\gamma} \]

with \( \gamma = \tau_e^{-1} \)

- Wavelength: 439 nm
- Simulate: 20 cycles
- Time step: 750 / cycle
Time averaged energy density

- enhanced exposure in photoresist layer
- interference fringes due to scattering
- phase lag $\Rightarrow$ spot anisotropy
- inclined illumination improves spot shape

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- smallest features $\lambda/15$ (limited by simulation)
- trade-off: smaller width at the cost of lower depth
- maximum size determined by field enhancement
Particle-particle interactions

Closely spaced particles: collective modes and shifted resonances

Can be compensated by particle shape (e.g. 1:3 aspect ⇒ 70 nm shift)
**Initial experiments**

**Nanoparticles**
colloidal Ag (\(\phi 41\) nm) in aqueous solution
deposit on resist (nebulize)

**Resist**
AZ1813 resist, diluted to 1:4 with EBR
spin 5000 rpm 60s \(\Rightarrow\) 75 nm thick layer
developing tested OK

**Substrate**
glass slide, roughness 5Å RMS

1. Expose  
broad beam, Xe arc lamp at 410 nm
intensity ~1 mW/cm\(^2\) (TM)
exposure 15 / 30 / 45 / 60 s

2. Develop  
diluted 1:1 – dev. time ~20 s

3. Analyze  
Use AFM to image printed features
Illumination setup

- Xe lamp 1000 W
- monochromator
- Si diode
- polarizer
- cyl. lens
- sample stage
- coll. lens

Sample holder
Beam shape
**Contact mode AFM**

**sample:** Ag 40 nm    AZ resist 75 nm    exp. 15s (410 nm)    dev. 20s

see - remaining Ag particles (swept by AFM tip) and
- sub-wavelength size dips    width 30-60 nm, depth 10-15 nm
Conclusion and outlook

**Plasmon printing** may be used to print high resolution patterns using standard photoresist and broad-beam illumination with visible light

**Future work**
- investigate effects of particle shape and areal density
- replicate complex e-beam defined masks