Design, Simulation and Fabrication of Plasmonic Pyramid Substrates for Cell Transfection

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Nanoparticles attach to the cell membrane

Irradiating AuNPs near cells creates pores

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External molecules can enter the cell

External molecules can enter the cell

Goal: Plasmonic effect that creates pores without particle residue

External molecules can enter the cell

New approach: Use nanostructured gold surfaces instead of gold nanoparticles

Design aspects

1. Easy to Fabricate/Large-Scale-Fabrication
2. Adjustable
3. Strong Plasmonic Effect for Efficient and Localized Poration
4. Robust/Stable
Proposed structure

Gold Pyramids with Nano-Apertures
Experimental procedure

Cells growing on the Plasmonic Substrate

ufs-laser irradiation

Gene Expression
Outline

Fabrication

Simulation and Characterization
Fabrication

Chromium deposition

Si (100)
Fabrication

E-Beam Lithography
or Photolithography

Negative squares
of Cr thin films
Si (100) Inverted pyramids Fabrication

KOH Anisotropic etching

Inverted pyramids
Fabrication

Chromium etch

Template
Fabrication

Glass coverslip
UV-cured glue
Fabrication

Template-stripping
Fabrication

Tipless pyramids
Fabricated substrates
Large-scale fabrication with photolithography

Aperture: 300nm
Baseline: 2200nm
Separation: 1400nm
Total Area: \(\approx 2\text{cm}^2\)
Different aspect ratios
Design aspects

1. Easy to Fabricate/Large-Scale-Fabrication ✓

2. Adjustable ✓

3. Strong Plasmonic Effect for Efficient and Localized Poration

4. Robust/Stable
Fabrication

Simulation and Characterization
Ultra-short laser excitation of plasmonic structures

- Plasmon Oscillation
  - Enhanced Near-Field
    - Effect on Environment:
      - Plasma Generation
      - Chemical Damage
      - Bond Cutting
    - Thermalized Phonons
      - Effect on Structure:
        - Temperature Increase
        - Melting
        - Ablation
Simulations: Field Enhancement

Optimization for 800nm excitation

Geometrical Parameters to Explore:
- Baselength
- Aperture
- Separation

Figure of Merit:
Average Field Enhancement
5nm above the Aperture

\[
\frac{\int |E| ds}{\int ds |E_0|} = \frac{\bar{E}}{E_0}
\]
Optimization: Field Enhancement
Optimization: Field Enhancement

Geometrical Parameter Space for high Field Enhancement
Experiments vs Simulation
Experiments vs Simulation

[Image showing two graphs side by side: one labeled NSOM and the other FEM, both with color scales and labels for Photon Count and $E/E_0$]
Experiments vs Simulation
Simulations: Field Enhancement

Low-absorptance regime to avoid thermal damage of the structure
Ultra-short laser excitation of plasmonic structures

Plasmon Oscillation

Enhanced Near-Field

Effect on Environment:
- Plasma Generation
- Chemical Damage
- Bond Cutting

Thermalized Phonons

Effect on Structure:
- Temperature Increase
- Melting
- Ablation
Plasma-mediated bubble formation

Plasmonic enhancement

Plasma

Nanobubbles
Plasma-mediated bubble formation

Electron Density: 
\[ n_e > n_{\text{crit}} = 10^{21}\text{cm}^{-3} \]

Energy Density: 
\[ u_e > u_{\text{crit}} = 551\text{ Jcm}^{-3} \]

Critical Temperature for Bubble Formation: 
\[ T_w > 0.85 x T_{\text{crit}} = 550\text{ K} \]

Melting Temperature of Bulk Gold: 
\[ T_m = 1337\text{ K} \]

Plasma Formation

Wavelength: 800nm
Pulse length: 100fs
Fluence: 10mJ/cm²
Baselength: 1800nm
Aperture: 300nm
Gold Layer: 50nm
Plasma Formation

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Plasma Formation

![Graph showing electron density over time with a pulse and critical electron density markers.](image-url)
Plasma Formation

![Graph showing electron density as a function of fluence. The x-axis represents fluence in mJ/cm², ranging from 0 to 20. The y-axis represents electron density in 1/cm³, ranging from 10^17 to 10^22. There are data points indicating critical electron density.](image)
Plasma Formation

Threshold fluence: 3.5mJ/cm$^2$

Electron Density [1/cm$^3$] vs. Fluence [mJ/cm$^2$]

Critical Electron Density

Threshold fluence: 3.5mJ/cm$^2$
Plasma Formation

Critical Energy Density

Energy Density $[J/m^3]$

Fluence $[mJ/cm^2]$
Plasma Formation

Threshold fluence: 3.5 mJ/cm²

Energy Density [J/m³]

Fluence [mJ/cm²]

Critical Energy Density
Plasma Formation

![Graph showing the relationship between water temperature (K) and fluence (mJ/cm²) with a critical temperature line. The graph indicates an increase in water temperature with fluence.](graph.png)
Plasma Formation

Threshold fluence: 4.5 mJ/cm$^2$

Fluence [mJ/cm$^2$]

Critical Temperature

Water Temperature [K]

Threshold fluence: 4.5 mJ/cm$^2$
Plasma Formation

Fluence [mJ/cm$^2$] vs. Gold Temperature [K]

Melting Temperature of Bulk Gold
Fluence-Range for Bubble Formation without Melting the Structure
Design Aspects

1. Easy to Fabricate/Large-Scale-Fabrication ✓

2. Adjustable ✓

3. Strong Plasmonic Effect for Efficient and Localized Poration ✓

4. Robust/Stable (Theoretical) ✓
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