Photonic Micro- and Nano-Structures for Enhancing Infrared Detection

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## Acknowledgement

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
<th>Institution</th>
</tr>
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<tbody>
<tr>
<td>John Chang</td>
<td>Fabrication</td>
<td>RPI</td>
</tr>
<tr>
<td>Allan Chang</td>
<td>Fabrication</td>
<td>RPI</td>
</tr>
<tr>
<td>Min-Feng Chen</td>
<td>Calculation</td>
<td>RPI &amp; NTU</td>
</tr>
<tr>
<td>Zu-Po Yang</td>
<td>Testing</td>
<td>RPI</td>
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<tr>
<td>James Bur</td>
<td>Testing</td>
<td>RPI</td>
</tr>
<tr>
<td>Dan Huang</td>
<td>Theory &amp; Design</td>
<td>AFRL-Kirtland</td>
</tr>
<tr>
<td>Dave Cardimona</td>
<td>Design &amp; Appl.</td>
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</tr>
<tr>
<td>Sanjay Krishna</td>
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</tr>
<tr>
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<td>QD Growth</td>
<td>UNM</td>
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(This work is supported by AFOSR/ Dr. Gernot Pomrenke.)
Content

1. Introduction
2. Fabrication and Testing
3. FDTD simulation
4. Integration with a QDIP Detector
5. Other promising designs
Our Objective is to Achieve Light Focusing at Sub-$\lambda$ at the Near Field Without Using a Conventional Lens.

**Objective**
- Field concentration at sub-$\lambda$
- Compact / integrated design

**Task**
- Maximize transmission ($T$)
- Minimize area ($A$)
- Maximize Flux: $(T/A) > 200\%$
Most of the research of light focusing at sub-\(\lambda\), \((\lambda/d)>>2\), is focused on the visible and near-infrared.


**Mechanism:**
- Surface plasma \((\omega_{sp} - k)\)
- Coupled interaction (tunneling)

**Basic Structure:**

**Transmission (T):**
- \(\lambda=1400\text{nm}\) → mid- and long- IR
- \(T: 2-5\%\) → 50-80%
- Flux: → 200-400%

**Graph:**
- Wavelength (\(\mu\text{m}\))
- Transmission (%) vs Wavelength
  - \(\lambda=1400\text{nm}\)
  - \(d=150\text{nm}\)
  - \((\lambda/d)\sim9\)
A Brief Summary of Some of the Representative Works on 2D Hole Array

<table>
<thead>
<tr>
<th>Metal</th>
<th>$\lambda$</th>
<th>d</th>
<th>$a_0$</th>
<th>t</th>
<th>$\Delta\lambda$</th>
<th>$(\lambda/d)^{**}$</th>
<th>$\Delta\lambda/\lambda$</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nature* ‘98</td>
<td>Ag</td>
<td>1.4µm</td>
<td>150nm</td>
<td>0.9µm</td>
<td>200nm</td>
<td>100nm</td>
<td>9</td>
<td>0.08</td>
</tr>
<tr>
<td>JOSA-B* ‘99</td>
<td>Cr</td>
<td>1.4µm</td>
<td>0.5µm</td>
<td>1µm</td>
<td>100nm</td>
<td>800nm</td>
<td>2.8</td>
<td>0.6</td>
</tr>
<tr>
<td>APL* ‘00</td>
<td>Ag, Ni</td>
<td>900nm</td>
<td>400nm</td>
<td>750nm</td>
<td>300nm</td>
<td>200nm</td>
<td>2.2</td>
<td>0.25</td>
</tr>
<tr>
<td>PRL* ‘01</td>
<td>Ag</td>
<td>800nm</td>
<td>280nm</td>
<td>750nm</td>
<td>320nm</td>
<td>150nm</td>
<td>2.8</td>
<td>0.2</td>
</tr>
<tr>
<td>JAP ’06 (aperiodic)</td>
<td>Au</td>
<td>700nm</td>
<td>350nm</td>
<td>1µm</td>
<td>120nm</td>
<td>80nm</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>This work</td>
<td>Au</td>
<td>7.5µm</td>
<td>1.3µm</td>
<td>2.5µm</td>
<td>50nm</td>
<td>800nm</td>
<td>6</td>
<td>0.1</td>
</tr>
</tbody>
</table>

* Trade-off ($\lambda/d$) and $T$

*reprint by all or part of the list: Ebbesen, Lezec, Ghaemi, Thio, Wolf, Pendry, etc

**(λ/d)>2-3: beyond the waveguide cutoff transmission.
Sample Fabrication and Optical Testing
Key Facilities At Rensselaer Micro-Clean-Room (MCR)

- EVG Aligner and Bonder
- IPEC/Westech CMP
- GCA Stepper
- Temescal EBeam
- Suss Probe Station
Rensselaer’s Nano-Fabrication Facilities

- EVG NanoImprint
- Adixen DRIE
- Applied PECVD
- Zeiss SEM / EBeam
Process Flow For Fabricating 2D Hole Metallic Array.

(I) Resist Spin-coating

(II) Exposure

(III) NH₃ bake / Flood Exposure

(IV) Developing

(V) Metal Evaporation (t=50-200nm)

(VI) Lift-off

(Minimum feature size: \( d = 0.5-2 \mu m \))
The SEM Image Shows Perfect Round Holes and Uniform Au Deposition.

2D Au Hole-Array Sample

(Hole filling fraction ~25%)

Au-film

d=1.3µm
t = 50nm
A Clear, Sharp Transmission Peak Is Observed In The Infrared Wavelength.

Sample Parameters:
\[ a = 2.48 - 3.72 \, \mu m, \quad d = 1.3 \, \mu m, \quad t = 50nm \]

- Infrared (sharp resonance)
- High T (T/A>300%)
- Sharp Resonance (vs “a” linearly)
- Lineshape asymmetry (Fano)

(*Work to be submitted for journal publication.*)
The Sharp Transmission Is Due to Plasmonic Resonance at the Au-Silicon Interface.

In-Plane Momentum Matching

\[ K_{sp} = K_{//} + (iG_x + jG_y) \]

\[ \lambda_{sp} = \frac{\alpha}{\sqrt{i^2 + j^2}} \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \]

\[ \lambda_{sp} = \frac{\alpha}{\sqrt{\frac{4}{3} (i^2 + ij + j^2)}} \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \]

\[ \lambda_{sp} \text{ at the Au/Si Interface} \]

<table>
<thead>
<tr>
<th>( a (\mu m) )</th>
<th>Calculated ( \lambda_{sp} (\mu m) )</th>
<th>FDTD ( \lambda_{sp} (\mu m) )</th>
<th>Measured ( \lambda_{sp} (\mu m) )</th>
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</thead>
<tbody>
<tr>
<td>2.48</td>
<td>7.35</td>
<td>7.56</td>
<td>7.58</td>
</tr>
<tr>
<td>2.73</td>
<td>8.1</td>
<td>8.3</td>
<td>8.4</td>
</tr>
<tr>
<td>2.98</td>
<td>8.8</td>
<td>9</td>
<td>9.1</td>
</tr>
<tr>
<td>3.22</td>
<td>9.5</td>
<td>9.7</td>
<td>9.8</td>
</tr>
<tr>
<td>3.47</td>
<td>10.3</td>
<td>10.4</td>
<td>10.5</td>
</tr>
<tr>
<td>3.72</td>
<td>11</td>
<td>11.1</td>
<td>11.4</td>
</tr>
</tbody>
</table>

- Tunneling
- Amp. vs \( t \)
- Position vs \( t \)
Our Structure Is Promising in Enhancing Transmission Flux (i.e. Transmission Amplitude / F.F.) to Much Greater Than 100%.

Table 1. Summary of sample geometries and measured transmission results, where \( a \) is lattice constant, \( d \) is hole diameter, \( t \) is thickness, F.F. is filling fraction, \( \lambda_{\text{max}} \) is the wavelength of maximal transmission, \( T \) is transmission.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( a ) (( \mu \text{m} ))</th>
<th>( d ) (( \mu \text{m} ))</th>
<th>( t ) (( \text{nm} ))</th>
<th>F.F. (( % ))</th>
<th>( \lambda_{\text{max}} ) (( \mu \text{m} ))</th>
<th>( T ) (( % ))</th>
<th>T/F.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.480</td>
<td>1.3</td>
<td>50</td>
<td>24.90</td>
<td>7.58</td>
<td>79</td>
<td>3.17</td>
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<tr>
<td>2</td>
<td>2.728</td>
<td>1.3</td>
<td>50</td>
<td>20.58</td>
<td>8.40</td>
<td>42</td>
<td>2.04</td>
</tr>
<tr>
<td>3</td>
<td>2.976</td>
<td>1.3</td>
<td>50</td>
<td>17.29</td>
<td>9.12</td>
<td>34</td>
<td>1.97</td>
</tr>
<tr>
<td>4</td>
<td>3.224</td>
<td>1.3</td>
<td>50</td>
<td>14.73</td>
<td>9.82</td>
<td>20</td>
<td>1.36</td>
</tr>
<tr>
<td>5</td>
<td>3.472</td>
<td>1.3</td>
<td>50</td>
<td>12.70</td>
<td>10.46</td>
<td>7.7</td>
<td>0.61</td>
</tr>
<tr>
<td>6</td>
<td>3.720</td>
<td>1.3</td>
<td>50</td>
<td>11.06</td>
<td>11.37</td>
<td>3.9</td>
<td>0.35</td>
</tr>
</tbody>
</table>
Finite Difference Time Domain (FDTD) Simulation

- Mode @ Au-Silicon Interface
- Origin of Field Concentration
(1) Results of FDTD Shows That The Fields Are Strongly Concentrated Near the Au-Air and Au-Si Interface.

- Au-Silicon resonance
- Light bends at the “corner”
- Focusing w/o lens, QD/QW/PV

Field Concentration at the Au-Air interface. The EM field is funneled around the metal corner.

SEM Images

EM Field Profile
(2) Results of FDTD Shows That The Fields Are Strongly Concentrated Near the Au-Air and Au-Si Interface.
FDTD Summary

• Field concentration is induced at the metal corners.

• The resonance occurs at the Au-Si interface

• The 2D mode propagates along x with a wavevector, $k_{sp}=G$. 
Integration with a QDIP Detector

- Quantum Dot Sample Growth (UNM)
- Sample Processing (RPI)
- Testing
A High Quality QD Infrared Photodetector Sample With a Dual Band Response Was Grown at U New Mexico.

Sample Structure

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs (n = 2 x 10^{19} cm^{-3})</td>
<td>0.2 µm</td>
<td></td>
</tr>
<tr>
<td>Al_{0.1}Ga_{0.9}As 500 Å</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaAs 68.5 Å</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In_{0.15}Ga_{0.85}As 10 Å</td>
<td></td>
<td></td>
</tr>
<tr>
<td>InAs QDs (n = 1.4 x 10^{11} cm^{-2}) 2 MLs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In_{0.15}Ga_{0.85}As 10 Å</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaAs 40 Å</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al_{0.1}Ga_{0.9}As 500 Å</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaAs (n = 2 x 10^{18} cm^{-3}) 2 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AlAs 30 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaAs buffer 0.2 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaAs S.i. Substrate</td>
<td></td>
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30 Periods Quantum Dot (QD)

Spectral Response

- λ~9µm
- λ~5µm

Spectral response for the QD infrared photodetector at 77K.
Mask Layout For Enhancing Infrared Response at $\lambda=5\mu m$ and $8.5\mu m$ Wavelengths.
Our Process Development Is Almost Complete For 2DHA and QDIP Integration.

\[ \lambda_{sp} \approx 5 \mu m \]

Patterned Structure

Mesa Etched Profile
Conclusion

- Extended 2DHA focusing to the infrared (\(\lambda=3-10\mu m\)).
- Demonstrated a flux enhancement (>300\%) at sub-\(\lambda\).
- Discovered the role of metal corner for light focusing.
- Integrate 2DHA with a QD infrared photodetector.
Appendix: Other Designs for Field Enhancement

1. 2D metallic mesh design
2. 3D metallic photonic crystal
1. 2D Metallic Mesh Design

(a) 2D Grid

(b) Transmittance (%) vs. Wavelength (µm)

(c) Top View

(d) 3D Plot
2. 3D Metallic Photonic Crystal at Visible Wavelengths.

This 3D photonic-crystal has the shortest operating wavelength in the world. Its feature size is the smallest ever been produced in such a multi-layer nanostructure.

An experimental reflectance data taken at different incident angles. The band edge is at $\lambda \approx 650\text{nm}$.

The EM field is strongly enhanced, >200%, when excited at the resonant frequency

(Optics Express 15, 8428 (2007).)