Photonic Micro- and Nano-Structures for Enhancing Infrared Detection

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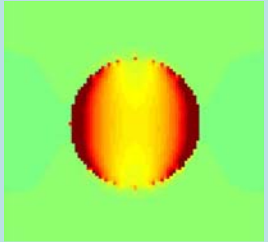

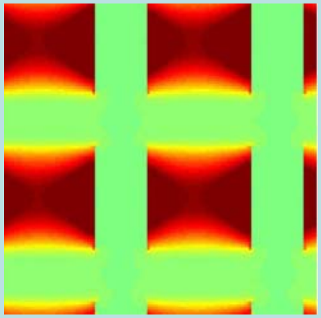

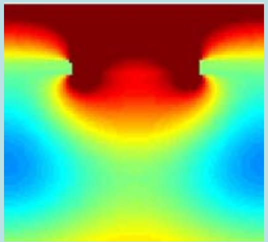

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Sanjay Krishna	QD Growth	UNM
Yagya D. Sharma	QD Growth	UNM

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Content

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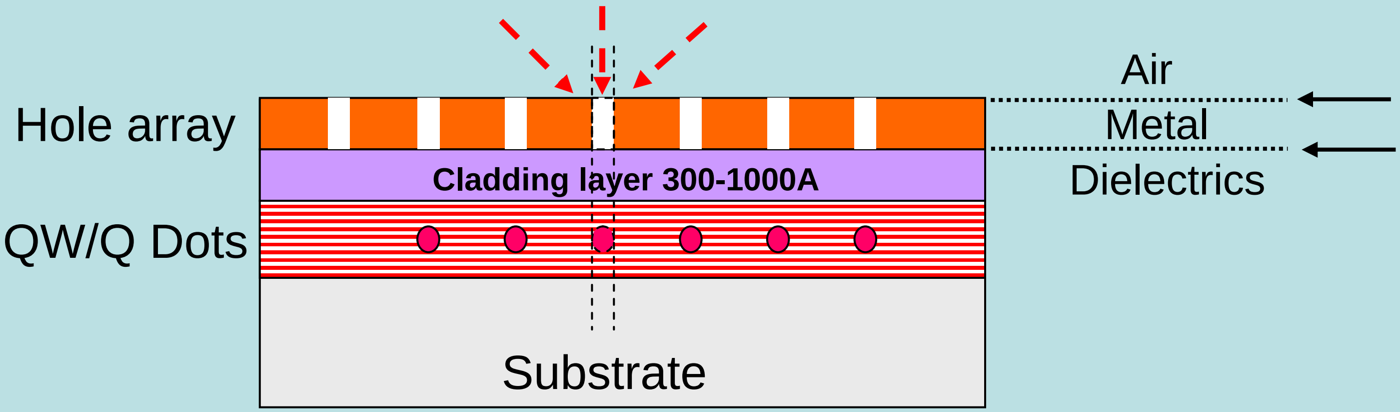
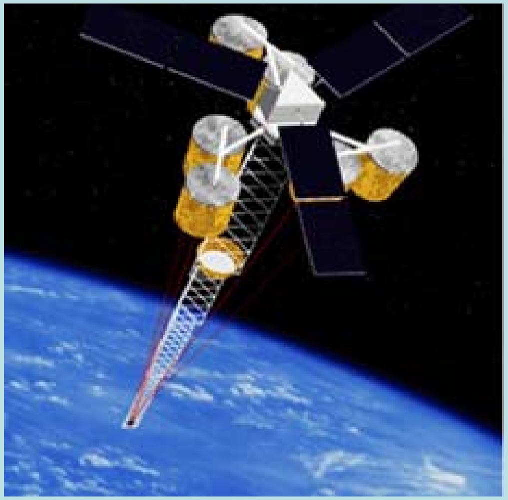
2. Fabrication and Testing
3. FDTD simulation
4. Integration with a QDIP Detector
5. Other promising designs

Our Objective is to Achieve Light Focusing at Sub-λ at the Near Field Without Using a Conventional Lens.

Light Focusing

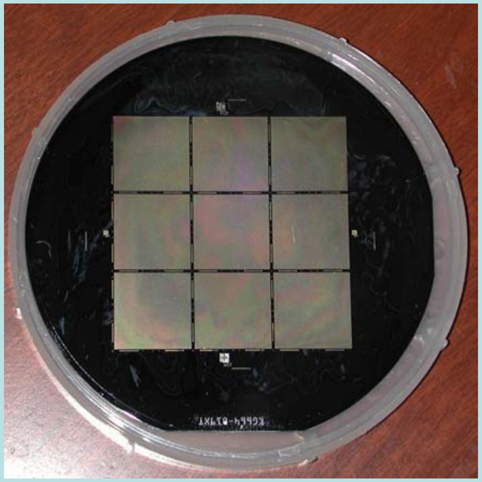




IR Sensing & Tracking

Objective
Field concentration at sub-λ
Compact / integrated design

Task
Maximize transmission (T)
Minimize area (A)
Maximize Flux: (**T/A**) >200%

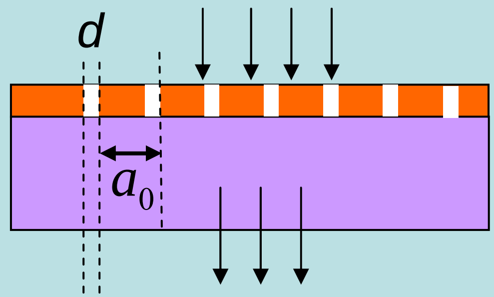


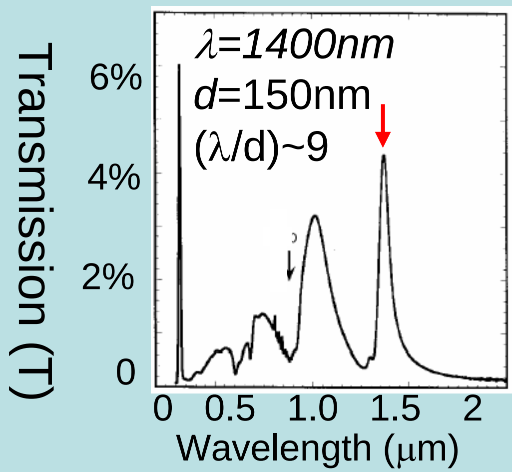
Chip Processing

Most of The Research of Light Focusing at Sub-λ, $(\lambda/d) >> 2$, is Focused On The Visible and Near-Infrared.

Extraordinary transmission through a 2D array
(Ebbesen et al, ***Nature* 391**, p.668, 1998)

Basic Structure:





λ=1400nm → ***mid- and long- IR***

T: 2-5% → ***50-80%***

Flux: → ***200-400%***

Mechanism:
Surface plasma (ω_{sp} - k)
Coupled interaction (tunneling)

A Brief Summary of Some of the Representative Works on 2D Hole Array

Figure-of-Merit

	Metal	λ	d	a_o	t	$\Delta\lambda$		(λ/d)**	$\Delta\lambda/\lambda$	T
Nature* '98	Ag	1.4μm	150nm	0.9μm	200nm	100nm		**9**	**0.08**	**5%**
JOSA-B* '99	Cr	1.4μm	0.5μm	1μm	100nm	800nm		2.8	0.6	40%
APL* '00	Ag, Ni	900nm	400nm	750nm	300nm	200nm		2.2	0.25	43%
PRL* '01	Ag	800nm	280nm	750nm	320nm	150nm		2.8	0.2	14%
JAP '06 (aperiodic)	Au	700nm	350nm	1μm	120nm	80nm		2	0.1	40%
This work	Au	**7.5μm**	1.3μm	2.5μm	50nm	800nm		**6**	**0.1**	**>60%**

- Trade-off (λ/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

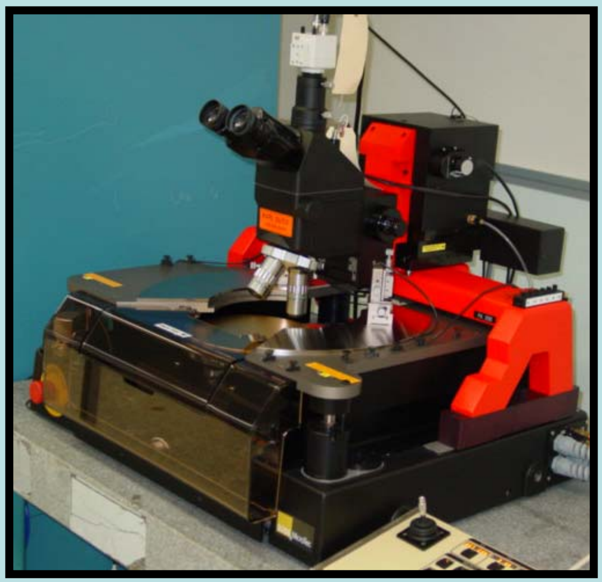
Key Facilities At Rensselaer Micro-Clean-Room (MCR)

EVG Aligner and Bonder

GCA Stepper

Temescal EBeam

IPEC/Westech CMP



Suss Probe Station

CNF Cornell NanoScale Science and Technology Facility

Rensselaer’s Nano-Fabrication Facilities

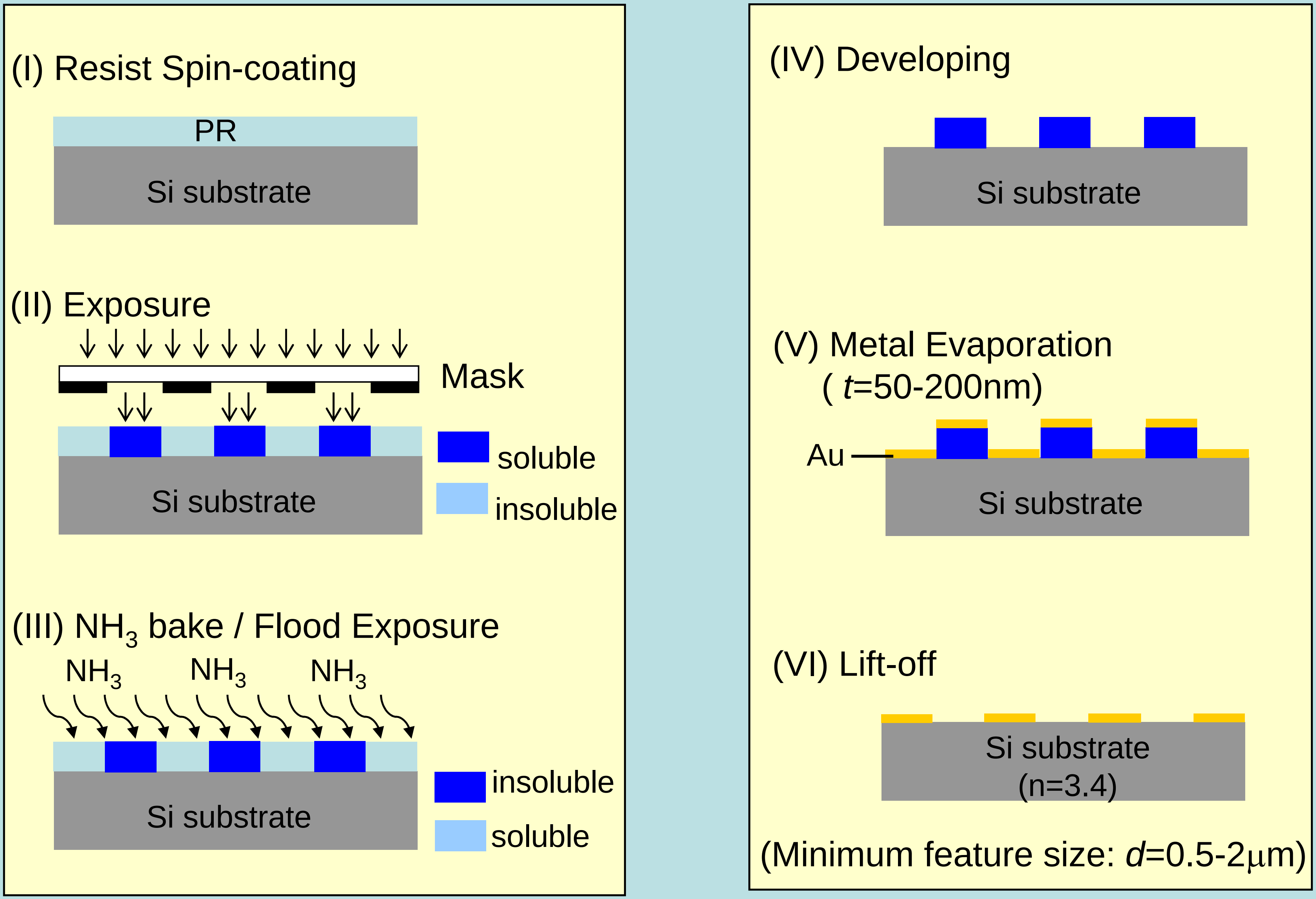
EVG
NanoImprint

Adixen DRIE

Applied PECVD

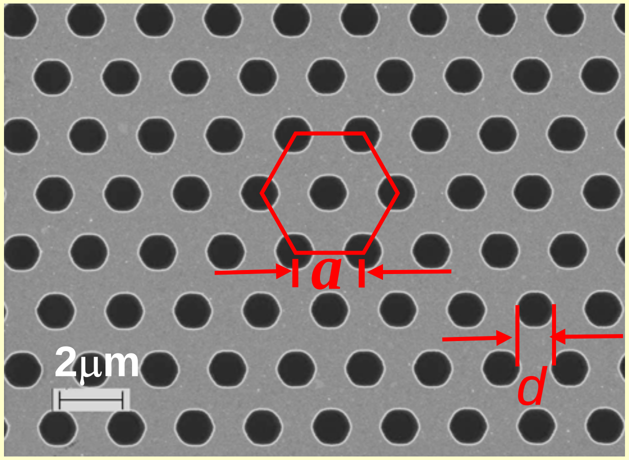
Zeiss SEM / EBeam

Process Flow For Fabricating 2D Hole Metallic Array.

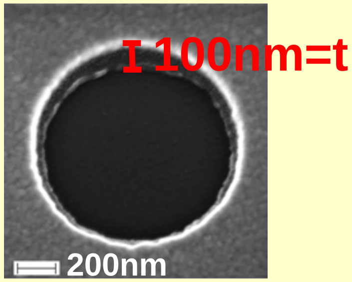


The SEM Image Shows Perfect Round Holes and Uniform Au Deposition.

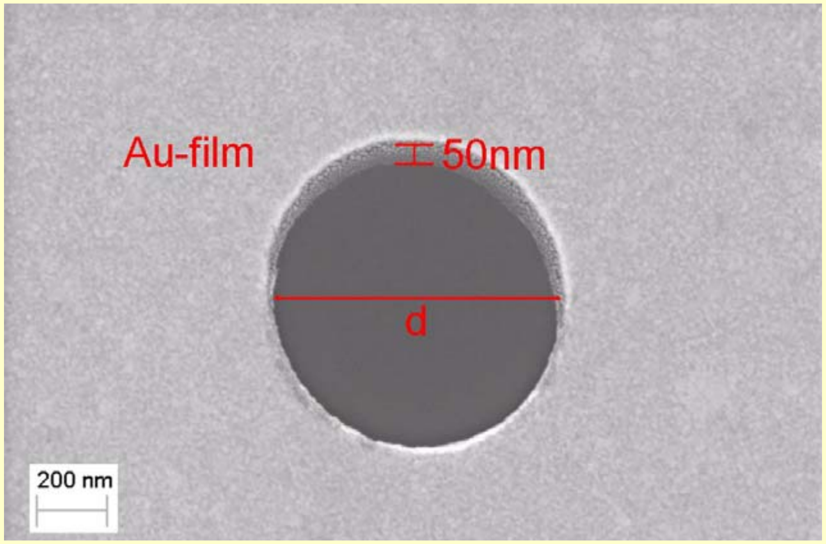
2D Au Hole-Array Sample



Au-film

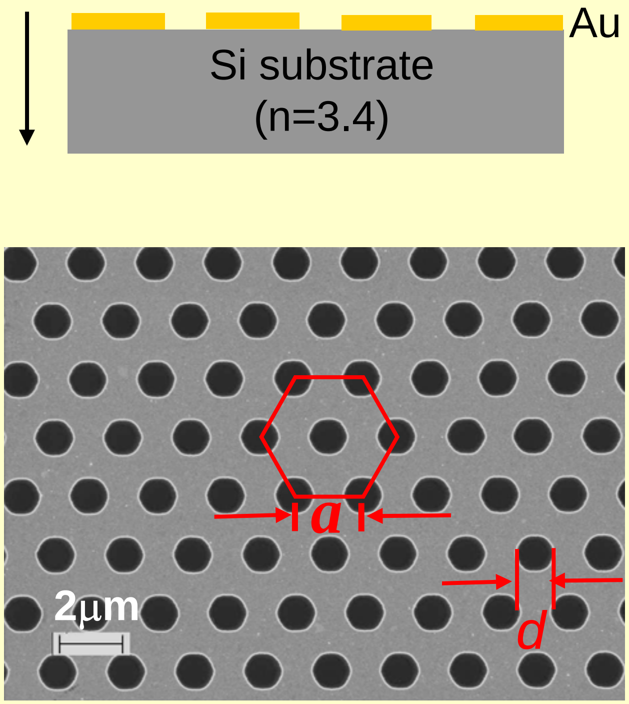


(Hole filling fraction ~25%)

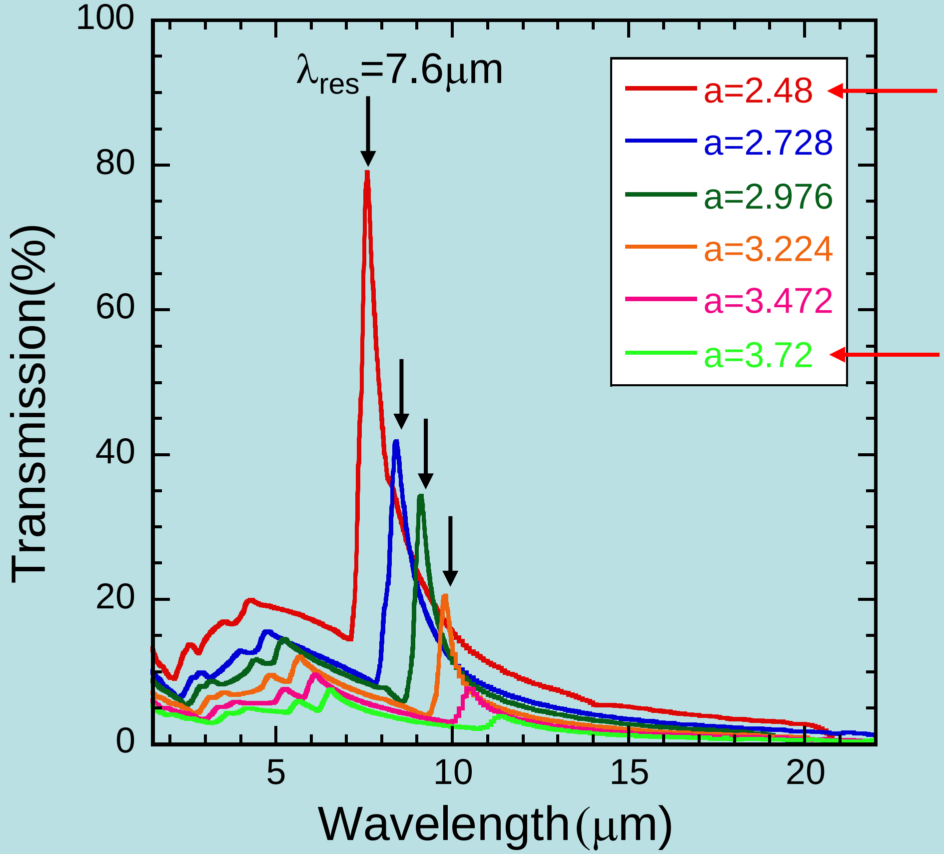


d=1.3μm
t = 50nm

A Clear, Sharp Transmission Peak Is Observed In The Infrared Wavelength.



(Hole filling fraction ~25%)

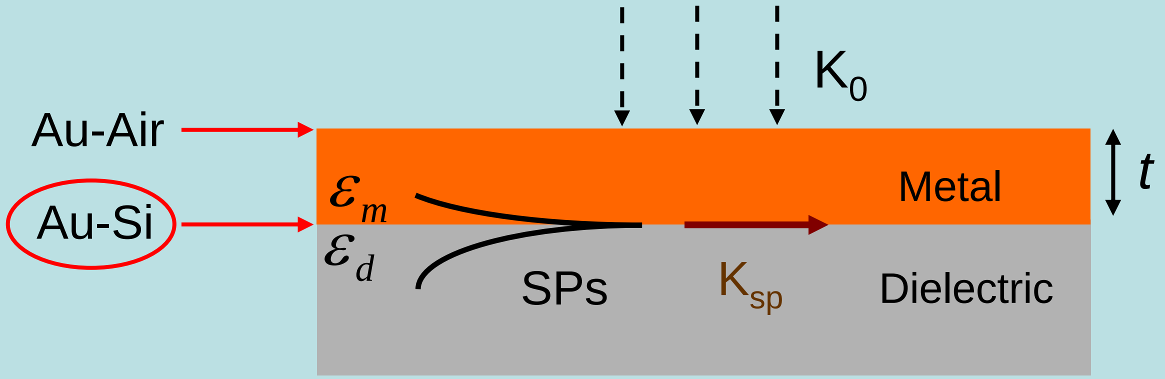


Sample Parameters:
a=2.48-3.72 μm, *d*=1.3μm, *t*=50nm

- 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.



- Tunneling
- Amp. vs *t*
- Position vs *t*

In-Plane Momentum Matching

$$\vec{K}_{sp} = \vec{K}_{//} + (i\vec{G}_x + j\vec{G}_y)$$

$$\lambda_{sp}(i,j) = \frac{a}{\sqrt{i^2 + j^2}}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}}$$

$$\lambda_{sp}(i,j) = \frac{a}{\sqrt{\frac{4}{3}(i^2 + ij + j^2)}}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}}$$

λ_{sp} at the Au/Si Interface

a **(μm)**	**Calculated λ_{sp} (μm)**	**FDTD λ_{sp} (μm)**	**Measured λ_{sp} (μm)**
2.48	7.35	7.56	7.58
2.73	8.1	8.3	8.4
2.98	8.8	9	9.1
3.22	9.5	9.7	9.8
3.47	10.3	10.4	10.5
3.72	11	11.1	11.4

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, λmax is the wavelength of maximal transmission, T is transmission.

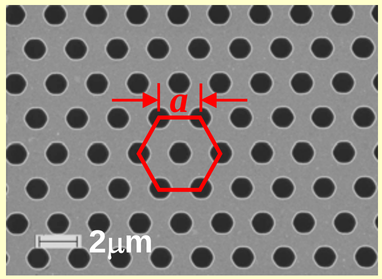
Sample	a (μm)	d (μm)	t (nm)	F.F.(%)	λmax (μm)	T (%)	T/F.F.
1	2.480	1.3	50	24.90	7.58	79	3.17
2	2.728	1.3	50	20.58	8.40	42	2.04
3	2.976	1.3	50	17.29	9.12	34	1.97
4	3.224	1.3	50	14.73	9.82	20	1.36
5	3.472	1.3	50	12.70	10.46	7.7	0.61
6	3.720	1.3	50	11.06	11.37	3.9	0.35

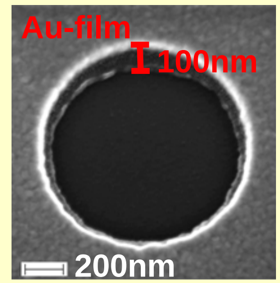
Finite Difference Time Domain (FDTD) Simulation

- 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.

SEM Images

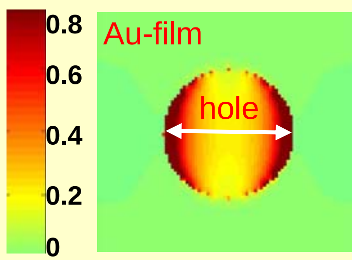


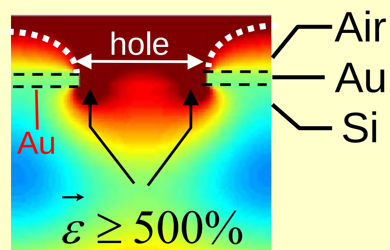


Top View

Side View

EM Field Profile



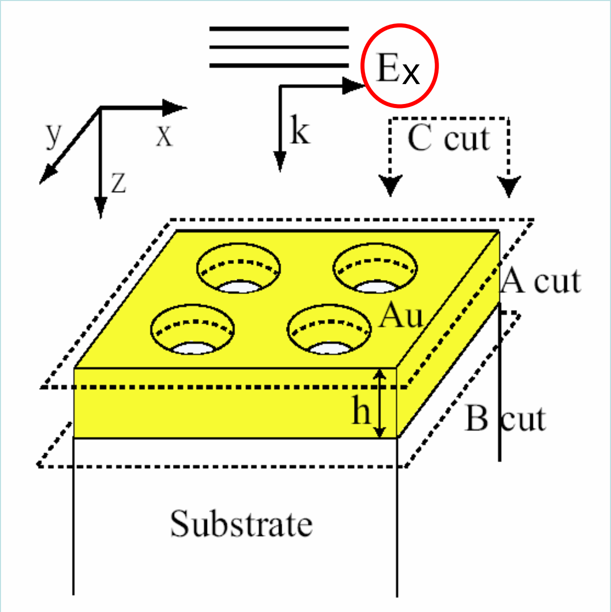


Field Concentration at the Au-Air interface.

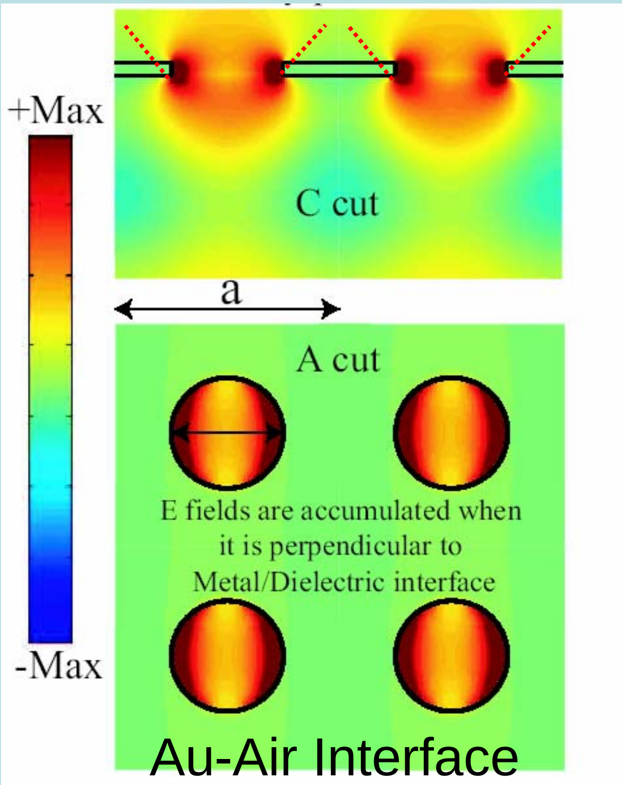
The EM field is funneled around the metal corner.

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

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



(E_x Profile)



FDTD Summary

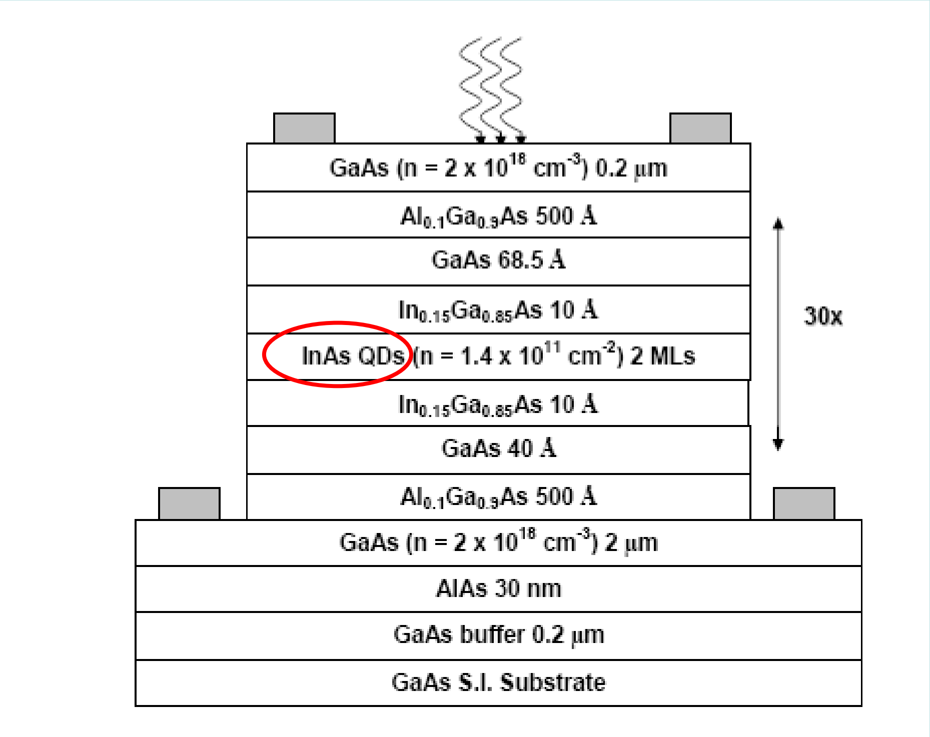
- Field concentration is induced at the metal corners.
- The resonance occurs at the Au-Si interface
- The 2D mode propagates along x with a wavevector, k_{sp}=G.

Integration with a QDIP Detector

- Quantum Dot Sample Growth (UNM)
- Sample Processing (RPI)
- Testing

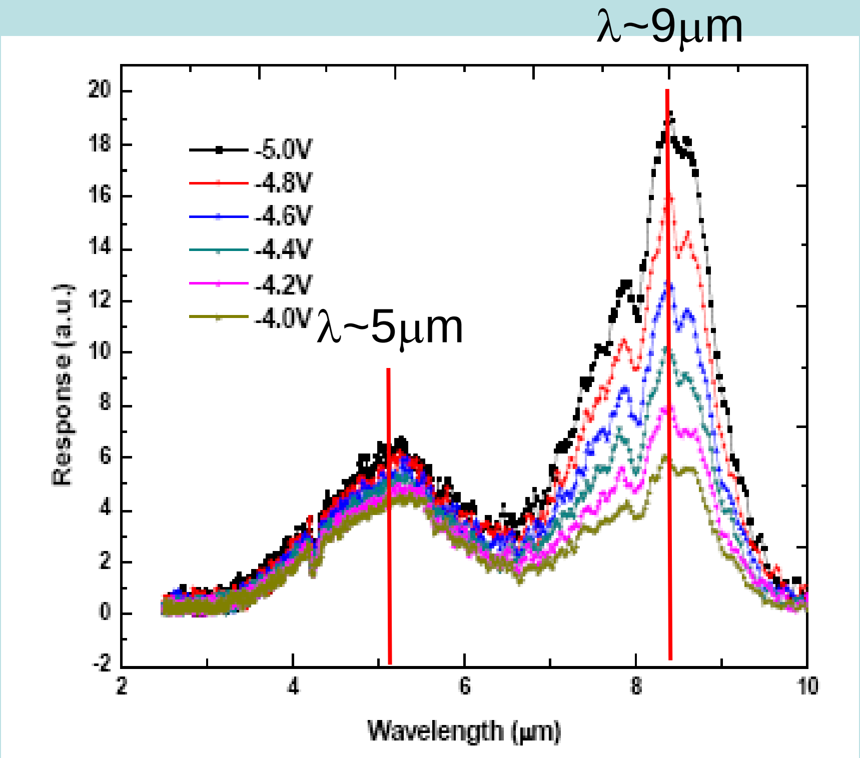
A High Quality QD Infrared Photodetector Sample With a Dual Band Response Was Grown at U New Mexico.

Sample Structure



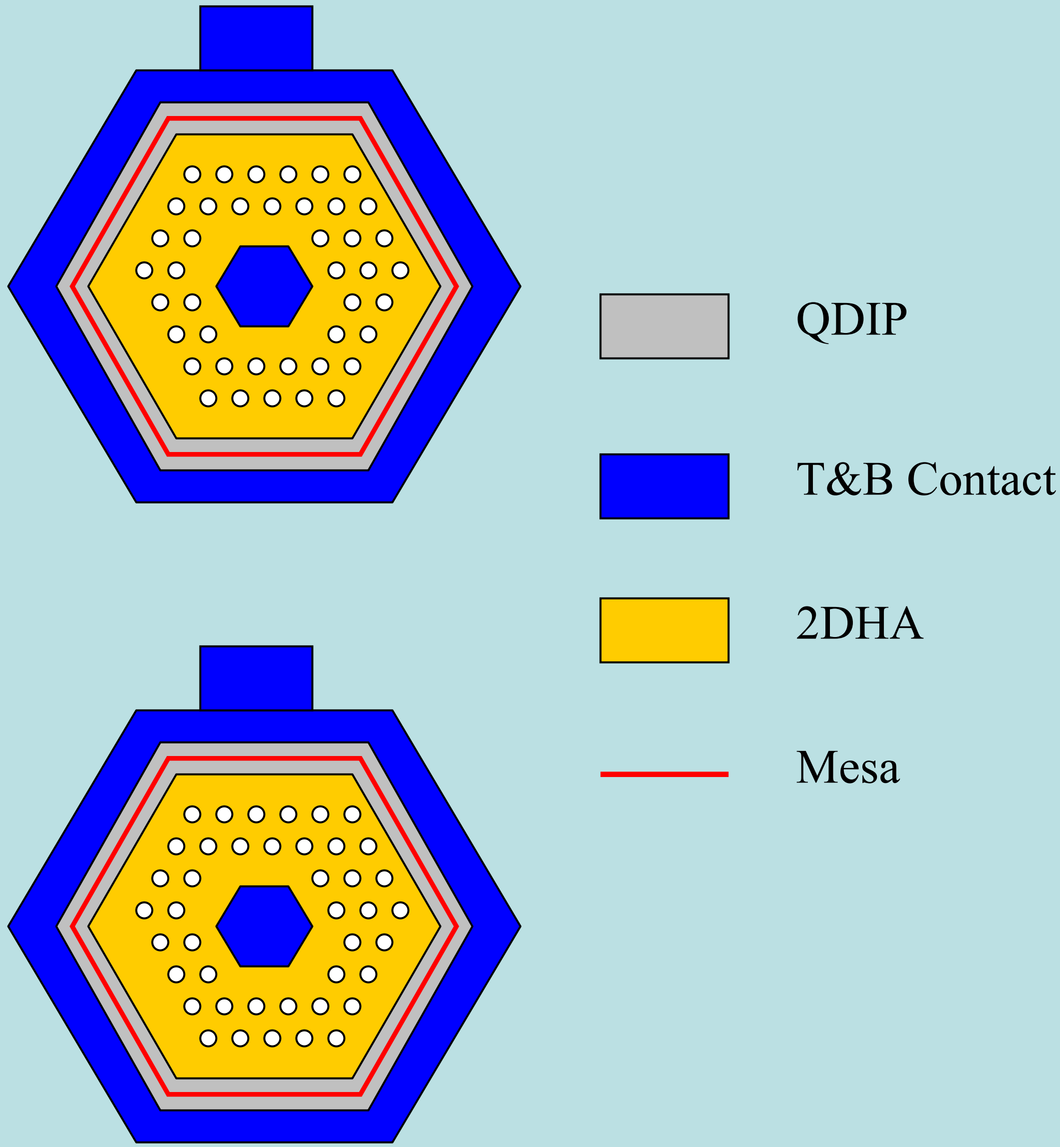
30 Periods Quantum Dot (QD)

Spectral Response

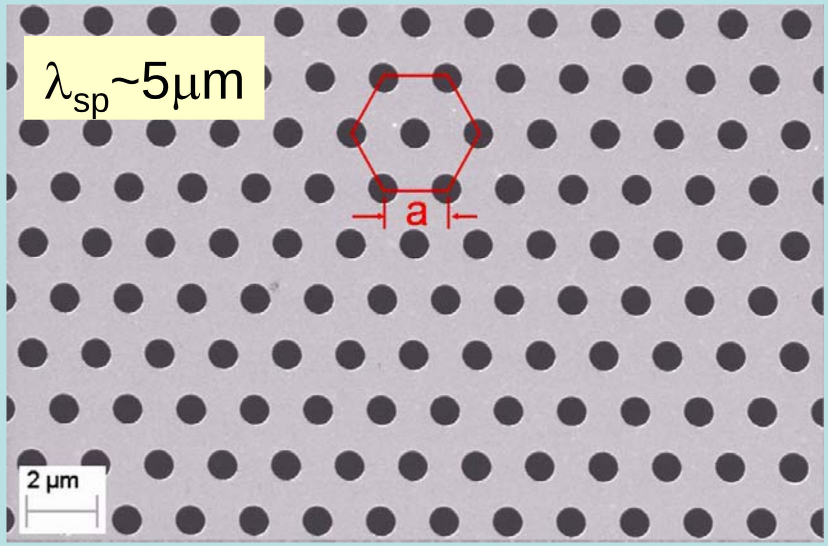


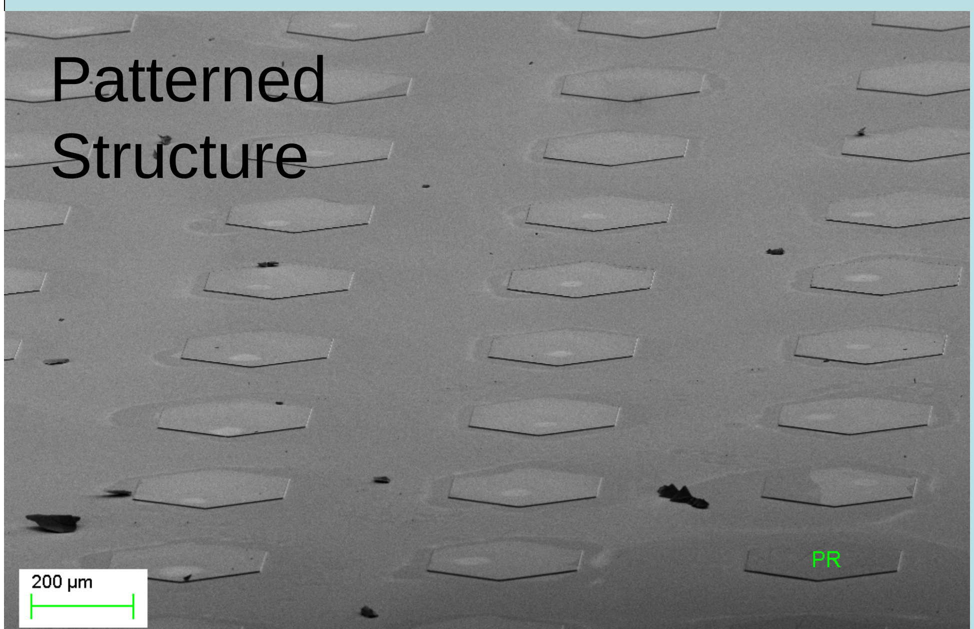
Spectral response for the QD infrared photodetector at 77K.

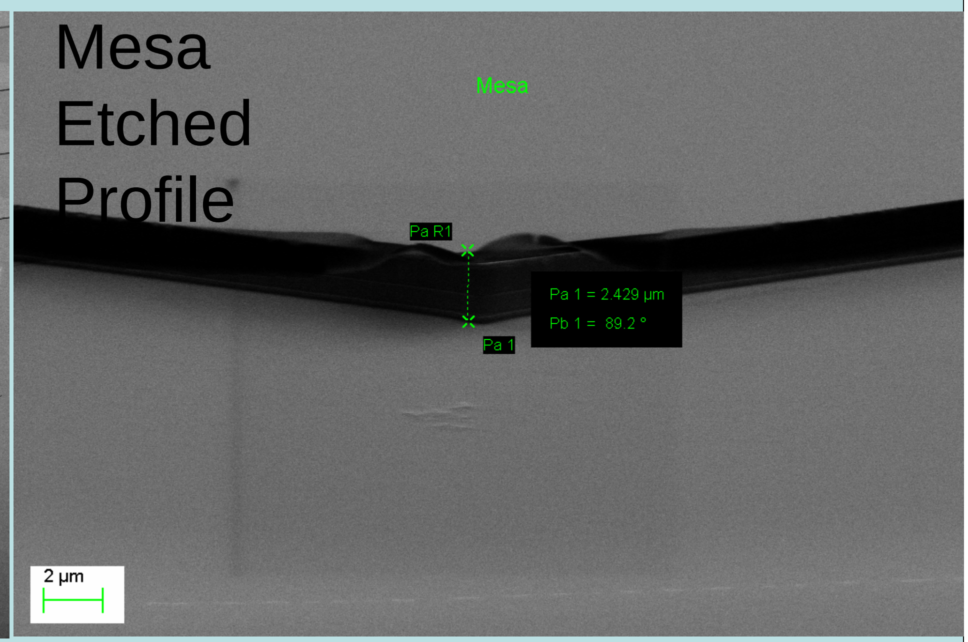
Mask Layout For Enhancing Infrared Response at λ=5μm and 8.5μm Wavelengths.



Our Process Development Is Almost Complete For 2DHA and QDIP Integration .







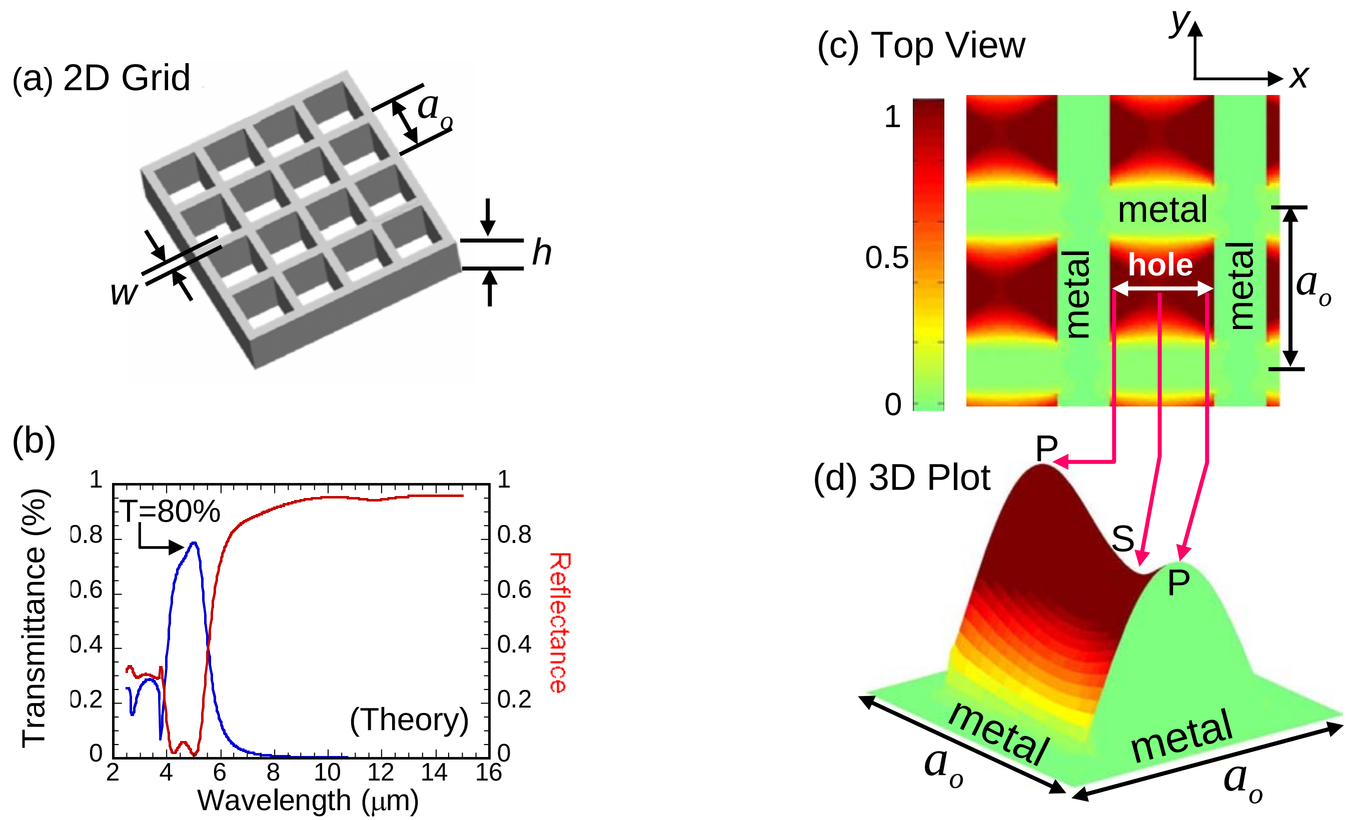
Conclusion

- Extended 2DHA focusing to the infrared (λ=3-10μm).
- Demonstrated a flux enhancement (>300%) at sub-λ.
- Discovered the role of metal corner for light focusing.
- Integrate 2DHA with a QD infrared photodetector.

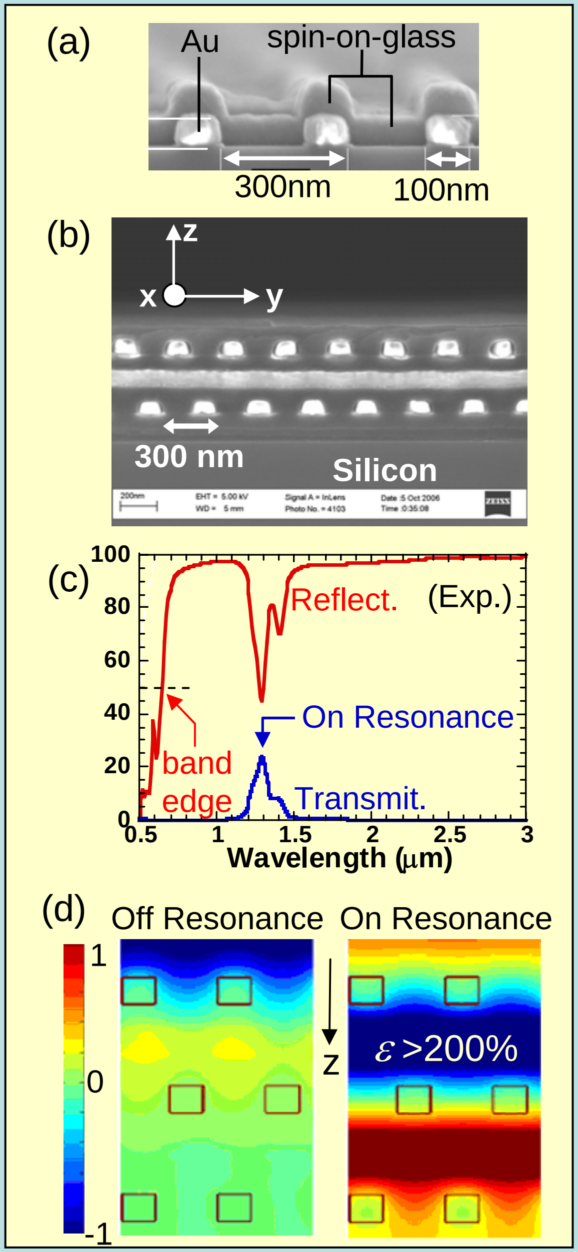
Appendix: Other Designs for Field Enhancement

1. 2D metallic mesh design
2. 3D metallic photonic crystal

1. 2D Metallic Mesh Design



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 λ~650nm.

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

(Optics Express **15,** 8428 (2007).