

FINAL PROGRESS REPORT

To: gernot.pomrenke@afosr.af.mil
Subject: Annual Progress Statement to Dr. Gernot Pomrenke

Contract/Grant Title: Electromagnetic Field Concentration for an Enhanced Infrared Detection
Contract/Grant #: FA9550-06-1-0431
Reporting period: 1 June 2006 to 31 May 2009
Name/Institute of the PI: Dr. Shawn-Yu Lin/ Rensselaer Polytechnic Institute

Program accomplishments (200 words max):

Under this nano-initiative program, we have achieved a >300% field concentration at infrared wavelength using a 2D hole-array plasmonic structure. This is, to the best of our knowledge, the highest enhancement ever been reported in the infrared. Furthermore, we identify two key mechanisms, the electromagnetic tunneling and a hole-array mediated plasmonic resonance, which are responsible for the extraordinary field enhancement.

We have also been successful in the process development and sample growth for the realization of an integrated 2D hole-array/quantum-dot-infrared-detector device. Under the influence of a strong plasmonic resonance, we successfully demonstrated a more than 100% enhancement of infrared photo-response and detectivity, the best ever been achieved using this type of plasmonic device. Furthermore, we identify three criteria for achieving an optimum plasmonic-QD interaction: (1) spectral matching of the plasmonic resonance to QD spectral response; (2) design optimization to improve light transmittance through the 2D holes; and (3) spatial matching of plasmonic field to the QD region. By doing so, we show that it is possible to achieve a ten times enhancement of photo-response and detectivity.

Archival publications during reporting period:

1. A.S.P. Chang, Y. S. Kim, M. Chen, Z.P. Yang, J. A. Bur, S. Y. Lin, and K. M. Ho "Visible Three-Dimensional Metallic Photonic Crystal with non-localized propagation modes beyond the waveguide cutoff", *Opt. Exp.* **15**, 8428 June 2007.

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14. ABSTRACT An aspect that is important to space-based infrared (IR) detection systems is enhanced infrared detection using quantum-dot infrared detector arrays. For this purpose, strong infrared focusing at sub-wavelength is needed. Strong infrared focusing is also needed to further reduce the overall size of an infrared detector array while keeping its high resolution.					
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2. S.Y. Lin, "Toward 3D visible photonic crystal", ***SPIE Photonic West***, San Jose, (Invited talk, Jan. 23, 2007).
3. M. Chen, S.Y. Lin, A.S.P. Chang and H.C. Chang, "Physical origin of a resonant mode deep inside the stop band of a 3D metallodielectric photonic crystal", ***Phys. Rev. B* 78**, 085110 (2008).
4. Xinhua Hu, Ming Li, Zhuo Ye, Kai-Ming Ho, W.Y. Leung and S.Y. Lin, "Design of midinfrared photodetectors enhanced by resonant cavities with gold gratings", ***Appl. Physics Letters* 93**, 241108 (2008).
5. S.Y. Lin, "Nano Photonic Structures for Enhancing Infrared Detection", ***SPIE OPTO conference***, San Diego, (Invited talk, Aug. 27, 2007).
6. S.Y. Lin, "Electromagnetic Field Concentration for an Enhanced Infrared Detection", ***SPIE OPTO conference***, San Diego, (Invited talk, Aug. 12, 2008).
7. Dan Huang, G. Gumbs and S.Y. Lin, "Self-consistent theory for near-field distribution and spectrum with quantum wires and a conductive grating in terahertz regime", ***J. Appl. Phys.* 105**, 093715 (2009).
8. John Chun-Chieh Chang, Zu-Po Yang, Danhong Huang, and D. A. Cardimona, Shawn-Yu Lin' "Strong Light Focusing at the Sub-wavelength Scale by a Metallic Hole-Array Structure" ***Optics Letters* 34**, 106 (2009).
9. John Chun-Chieh Chang, Y. Sharma, Y.S. Kim, S. Krishna, Danhong Huang, Shawn-Yu Lin' "A Surface Plasmon Enhanced Infrared Photo-Detector Based on InGaAs Quantum Dots" Submitted to ***Nature Photonics*** August 2009.

Change in research objectives, if any: None

Change in AFOSR program manager, if any: None

Extensions granted or milestones slipped, if any: None

I. Introduction and Overall Objectives

A significantly enhanced infrared (IR) signature recognition and tracking could be

Under this program, our goal is to

explore plasmonic interaction taking place at sub-wavelength (sub- λ) scale and to achieve a >200-400% IR field enhancement. The specific accomplishments for the past twelve month are described below.

II. An Extraordinary IR Focusing by Plasmonic Resonance at a Super Thin Metal Film

II (a): Experimental observation of a >300% transmission enhancement

Most of the current 2D hole-array plasmonic works are performed at either near infrared or optical wavelengths. All prior experimental data seems to suggest an intrinsic limit on the degree of achievable field concentration through the 2D holes. Particularly, there exists a fundamental trade-off between reducing the hole-area (i.e. the hole filling fraction) and enhancing the transmission amplitude (T).

Under this nano-initiative program, we have (1) successfully extended the operating wavelength of our plasmonic structure to infrared $\lambda=5-10\mu\text{m}$; (2) overcome the aforementioned fundamental limitation and achieved a >300% IR field concentration; (3) successfully developed a process receipt for integrating a 2D plasmonic hole array to a QDIP (quantum dot infrared detector). Experimental infrared photodetector setup has also been set up, which is under system calibration and will be ready for a full testing in three months.

Plasmonic field focusing

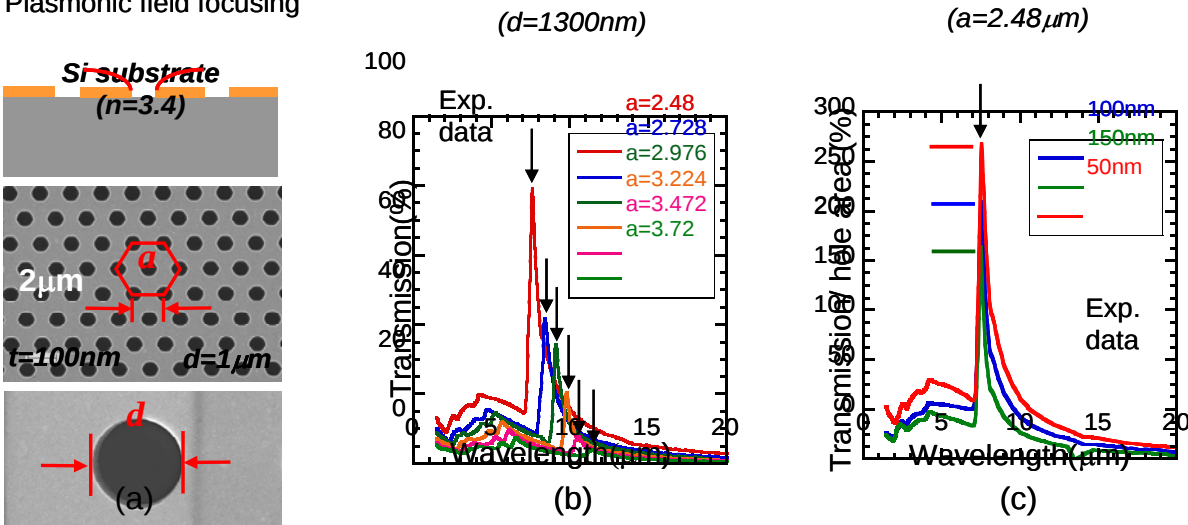


Figure 1 (a) A diagram showing a plasmonic field focusing at the metal corners, along with two SEM (scanning electron micrograph) images of a fabricated 2D Au hole-array structure at RPI; (b) our experimental data taken from a series of hole-array samples with lattice constant $a=2.48$ to $3.72\mu\text{m}$. The hole-diameter is kept fixed at $d=1300\text{nm}$. The transmission of 80% is exceedingly high. The shift of transmission peak (indicated by the black arrows) indicates that the resonance is mediated by the periodicity of the hole-array; (c) our experimental data taken from a series of samples with different Au thickness, $t=50-150\text{nm}$. The transmission flux (transmission/hole area) is >300% as compared to that of the incident light, the highest ever been reported.

The experimental data of **Figure 1** shows that we have achieved our objective of a sub- λ focusing ($\lambda/d \sim 7$) and, at the same time, an ultra high transmission of 80%. This feat is accomplished by two unique approaches: (1) the increase of resonance λ (for a given hole-size) by exciting plasmonic resonance at the Au-silicon interface and not the Au-air interface; and (2) the use of a super thin metal (i.e. $t=50\text{nm}$) to enhance tunneling probability of light through the metallic holes. The interplay of these two mechanisms enables us to achieve the highest IR transmission enhancement ever been reported.

Recognizing that the skin depth of Au-film is $\delta \sim 10\text{nm}$ in this wavelength regime, we should be able to decrease the Au-film thickness further to about $t=30\text{nm}$ and observe an even higher resonant transmission. In this case, we expect to observe a resonant transmission of $>95\%$ and a corresponding transmission flux enhancement of 380%. This experimental work is currently underway. This is an important task that we anticipate to achieve under this program as our next six month's milestone.

II (b): The two key mechanisms- plasmonic resonance and electromagnetic wave tunneling

We have also investigated the underlying mechanisms responsible for the experimentally observed strong transmission. A result of finite difference time domain modeling offers several important clues for the field enhancement: (1) the incoming EM field is strongly funneled right at the metal corners; (2) the plasmonic resonance occurs at the corner of the metal/silicon interface (indicated in **Figure 2(a)** by the black arrows); and (3) the field amplitude builds up in time when it is on resonance (see **Figure 2(c)**). This study not only confirms our experimental finding, but also identifies the essential design criteria for achieving enhanced sub- λ transmission at any wavelengths.

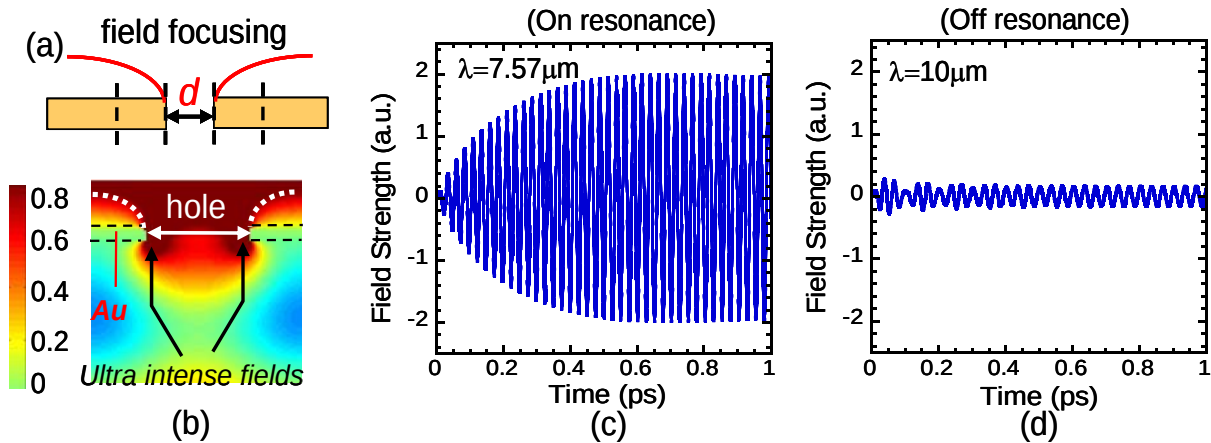


Figure 2 (a) A diagram showing focusing of EM field by metallic corners. It is in this sense that a 2D hole-array could function as a “planar lens”; (b) a cross section plot of field profile around a metallic hole. There is an ultra intense field at the bottom metal corner near the metal/ substrate interface (indicated by the black arrows); (c) at the resonance $\lambda=7.57\mu\text{m}$, the field strength at the bottom interface increases quickly, leading to an enhanced light transmission; (d) when the incident light is off resonance, the field does not build-up and the corresponding transmission is low.

II (c): The material growth of QDIP, succesful process development and a test system build up

By working with scientists at AFRL, we have come to an important conclusion that the field enhancement is large enough and the next step is to integrate a 2D hole-array to a QDIP (quantum-dot-infrared-photodetector). The challenges of this integration are three-folds: (1) the advancement of device processing to integrate the delicate 2D hole-array fabrication to the QDIP device processing; (2) the growth of a well-controlled QDIP semiconductor structure; (3) the set-up and calibration of an IR photodetector testing system.

For the QDIP growth, we have contacted Prof. S. Krishna of University of New Mexico and obtained high quality samples. At RPI, we have focused our effort on semiconductor process development. We have also purchased a brand new infrared detection system that includes a broadband IR light source and an IR monochromator. We have also setup a low temperature ($T=4.2-77K$) optical dewar for sample mounting and for cold-shielding. This setup along with our process development will allow us to evaluate device response and show improvement of system performance as a result of our plasmonic structure.

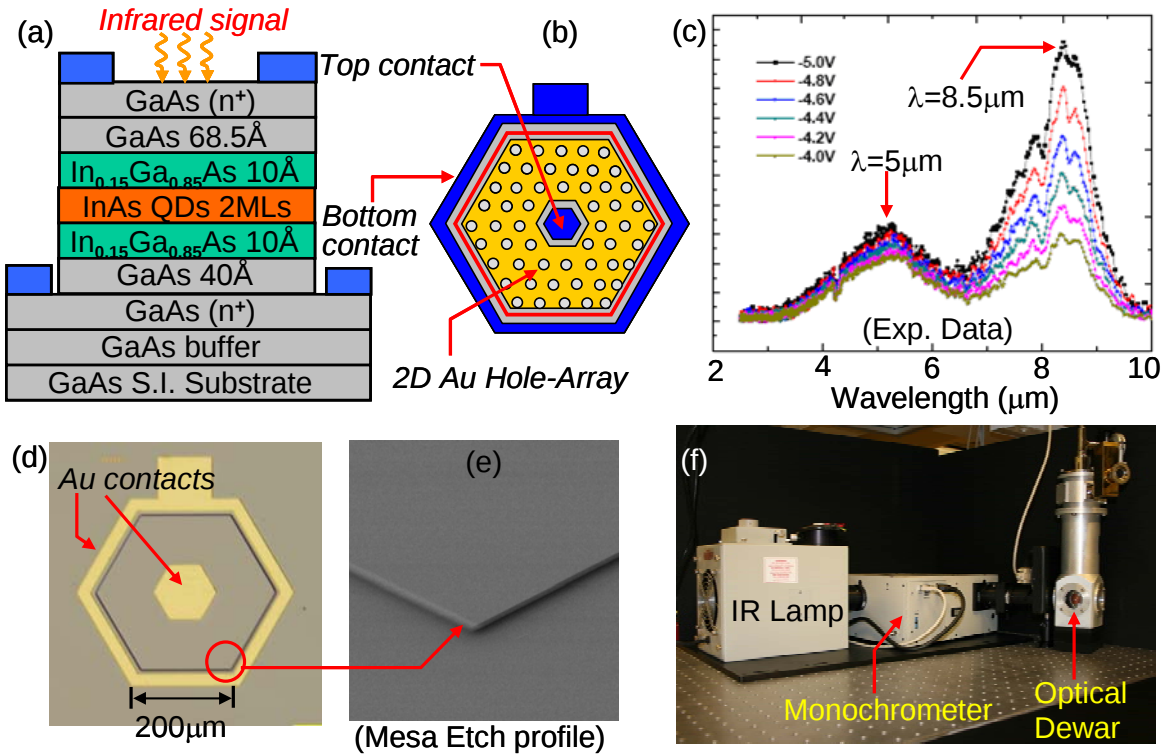


Figure 3 (a) a diagram of our QDIP growth structure; (b) a hexagon design of an integrated 2D hole-array/ QDIP device; (c) the photo-response of our QDIP at both the mid-IR and long-IR regime; (d) a top view photo of a test sample, showing a well-controlled mesa etch to define the hexagon region and the Au-deposition; (e) a SEM image of a clean and well-defined mesa etch profile; and (f) a photo of our new infrared photo-detector measurement system at RPI.

II (d). Extraordinary plasmonic-quantum dots interaction for a >100% enhancement in detectivity

In **Figure 4(a), (b) and (c)**, we show photo-response curves (the blue squares) taken from three 2DHA-QD samples with $a = 2.8, 3.0$ and $3.2 \mu\text{m}$, respectively. The data taken from QD-samples without 2DHA (the black dots) are also shown as a reference. For the 2DHA-QD sample with $a = 2.8 \mu\text{m}$ (**figure 4a**), its photo-response is similar to the reference one. However, there is one exception between them, i.e. the appearance of a small, but clear kink at $\lambda = 7.8 \mu\text{m}$ for the 2DHA-QDIP sample. For the sample with a larger $a=3.0 \mu\text{m}$ (**figure 4b**), it shows a similar response curve. But, this time, the strength of the kink becomes stronger. As we continue to increase $a = 3.2 \mu\text{m}$ (**figure 4c**), we achieve a nearly perfect matching of the kink- λ to one of the QDIP response maxima at $\lambda=8.8 \mu\text{m}$. In this case, our data exhibits a large 65% enhancement (or 165% signal strength as compared to the reference) of photo-response at $\lambda=8.8 \mu\text{m}$. In **Figure 4(d), (e) and (f)**, we show photo-response curves (the blue squares) taken from three 2DHA-QD samples with $a = 3.2 \mu\text{m}$ and $d=1.1, 1.2$ and $1.6 \mu\text{m}$, respectively. The largest enhancement is observed to be 130% for the $d=1.6 \mu\text{m}$ sample.

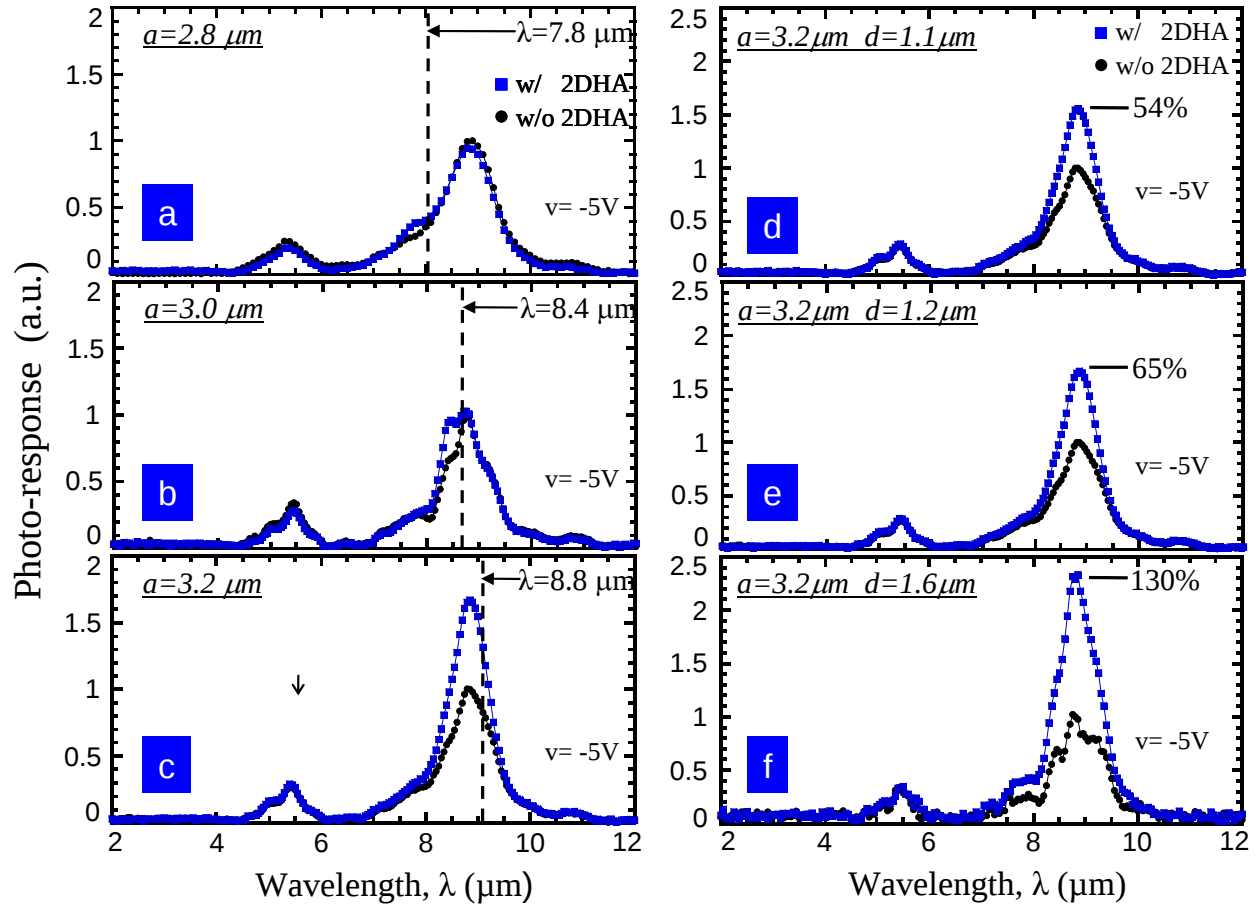


Figure 4 (a), (b), (c), Photoresponse curves taken from 2DHA-QD samples with three different hole-to-hole spacing $a=2.8, 3$ and $3.2 \mu\text{m}$, respectively.

Figure 4 (d), (e), (f), Photoresponse curves taken from 2DHA-QD samples with the same $a=3.2 \mu\text{m}$, but three different hole-diameter $d=1.1, 1.2$ and $1.6 \mu\text{m}$, respectively.