Best Student Paper Award

A normal-incident quantum well infrared photodetector enhanced by surface plasmon resonance

Wei Wu[a], Alireza Bonakdar, Ryan Gelfand, and Hooman Mohseni

Bio-inspired Sensors and Optoelectronics Lab
Department of Electrical Engineering and Computer Science, Northwestern University
2145 Sheridan Rd, Evanston, IL 60208, USA

ABSTRACT

Quantum well infrared photodetectors (QWIPs) have demonstrated applications in many different areas, such as medical and biological imaging, environmental and chemical monitoring, and infrared imaging for space and night vision. However, QWIPs still suffer from low quantum efficiency and detectivity compared with mercury cadmium telluride (MCT) based interband photodetectors, which dominate current infrared detector market. Besides, n-type QWIPs cannot detect the normal incident infrared radiations because of the polarization selection rules of intersubband transitions. Here, we used periodic holes array perforated in gold film to convert normal-incident infrared light to surface plasmon waves, which can excite the intersubband transitions and be absorbed by quantum wells (QWs). Our 3D FDTD simulation results show that electric field component in the QWs growth direction can be enhanced by more than 5 times compared with the total electric field intensity without any plasmonic arrays. The experimental results show that the photodetector has a peak detection wavelength at ~8 µm with a high detectivity of ~7.4×10^{10} Jones, and the photocurrent spectrum was very close to the simulation result of the electric field enhancement spectrum.

Keywords: photodetector, surface plasmon, and enhancement

1. Introduction

In the electromagnetic spectrum, mid-infrared light can be applied into many different areas[1], such as molecule and biological imaging, environmental and chemical monitoring, and infrared imaging for space and night vision. Currently, the most widely used infrared photodetector in the market is mercury cadmium telluride (MCT) based photodetectors, which have been studied and developed for a long time. It can easily detect different infrared wavelengths by changing the compositions of MCT. But one major issue for MCT photodetector is that MCT materials cannot grow into a large uniform area, which limits its applications into making large-pixel infrared imager[1]. Quantum well infrared photodetector (QWIP) which uses the intersubband transitions of carriers has also been developed for the mid- and long-infrared photon detection. It can be grown very uniformly into a large area by current epitaxial growth methods.[2] However, compared with MCT photodetector, QWIP has a weaker absorption, lower quantum efficiency and detectivity. Besides, n-type QWIP cannot detect the normal incident infrared light because of the polarization selection rules of intersubband transitions[3]. Therefore, it is quite necessary to improve the performances of QWIP.

Surface plasmons have attracted a lot of research interests since Ebbsen discovered the interesting extraordinary optical transmission of periodic holes array perforated in metal film[4]. Surface plasmons have been applied into different kinds of devices[5, 6], such as LED, lasers, solar cells. Here we are going to apply the surface plasmons to enhancing the optical absorption of quantum wells (QWs) and improving the performance of QWIPs[7]. In the mid-infrared region, the propagation length of surface plasmon waves can be large enough to effectively reach the whole quantum wells region,

a) Email: wwu@u.northwestern.edu, Group website: http://bisol.northwestern.edu

Detectors and Imaging Devices: Infrared, Focal Plane, Single Photon, edited by Eustace L. Dereniak, John P. Hartke, Paul D. LeVan, Randolph E. Longshore, Ashok K. Sood, Manijeh Razeghi, Rengarajan Sudharsanan, Proc. of SPIE Vol. 7780 · 77801A · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.871877

and the optical loss is relatively small. Besides, the surface plasmon waves are TM polarized, which has an electric field component in the z-direction, which can effectively induce the intersubband transitions of carriers and be absorbed by QWs. Periodic holes array perforated in the Au film were used to couple the normal incident infrared light to surface plasmon waves. Different parameters of the periodic hole arrays, such as the periodicity, the diameter of the holes, and the thickness of the metal films, were simulated and discussed in the paper. With the optimized conditions, the surface plasmonic enhanced QWIP was fabricated and characterized. The experimental characterizations of the photodetector demonstrate that under a normal incident infrared radiation it has a peak detection wavelength of ~8 μm with the responsivity as big as ~7 A/W and the detectivity of ~7.4 $\times10^{10}$ Jones. The detection spectrum is very close to the plasmonic enhanced spectrum. This technique opens an alternate way to fabricate high-performance infrared imager.

2. Modeling of Surface Plasmonic Arrays

The modeling structure includes a periodic hole array on top of InGaAs/InP QWs, shown in figure 1. The diameter of the hole is *d*, and the period is *p.* The source used for the simulation is a plane wave propagating in the z-direction with electric field polarization in the y-direction. Because E_z in the QW active region can be used to induce intersubband transitions, we simulated and calculated the averaged E_z in the active region (from 140 nm below the Au-semiconductor interface to 584.8 nm below). Our QWIP was designed to work with the peak detection wavelength of ~8 um, so we optimized the parameters of Au holes array to get the optimized enhancement at ~8 um. We used 3D FDTD methods to simulate the electric field intensity in the structure. Figure 2(a) shows the averaged E_z in the active region using different periods of the hole arrays, while the radius of the holes were kept a constant ratio of the periods. It can be seen that using 2.9 um period the enhanced peak is at ~8 um. All the enhancement peaks were connected to show the relationship between periods, peak positions, and enhanced intensities. To optimize the diameter of the holes, we also simulated the averaged E_z enhancement using different diameters of the hole arrays with the same period of 2.9 um. In figure 2(b) we can see that changing the hole size does not change the position of the enhance peaks a lot, while it changes the peak intensity significantly. The maximum peak intensity appears when the radius is ~0.2**p*. We used the radius between 0.2**p* and 0.25**p* to maximize the peak intensity at ~ 8 μm. The effect of Au thickness was also modeled, and we found that the thickness does not change the spectrum a lot as long as the metal thickness is beyond certain values.

Using the period of 2.9 μm and diameter of 1.4 μm, we modeled E_z intensity distributed in the QW active region. Figure 3(a) shows E_z intensity distributed in the middle of the QWs active region at the wavelength of 8 μm (the circles representing the holes' positions). The strong optical modes have been formed on the edges of the periodic holes in the QW plane. Because the light source is polarized in the y-direction, the optical modes are on the edge of the holes in the y-direction. Figure 3(b) shows the E_z intensity distribution in the cross-section plane of the device at the y-point which has the strongest E_z intensity. The enhanced E_z intensity almost covers the whole lattice period of the holes array, and it can reach more than 800 nm below the Au/semiconductor interface, which can effectively cover the entire QW active region and enhance the optical absorption. Our calculation results show that the enhanced average E_z intensity in the QWs region with the plasmonic arrays can be more than 5 times larger than the average E_z without any plasmonic arrays.

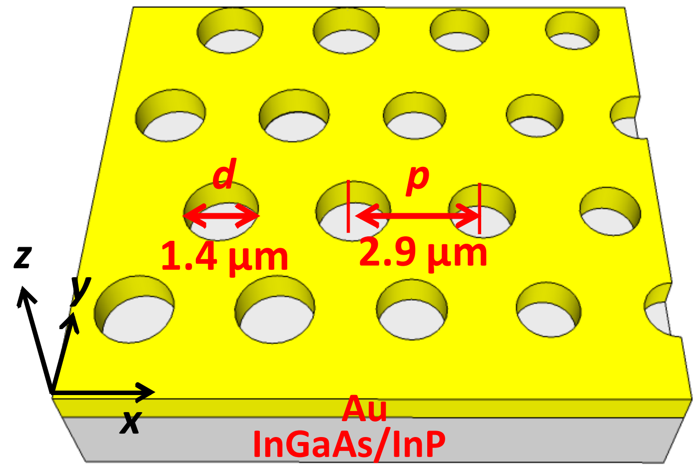

Figure 1 The modeling structure of plasmonic arrays on top of InGaAs/InP semiconductor layers.

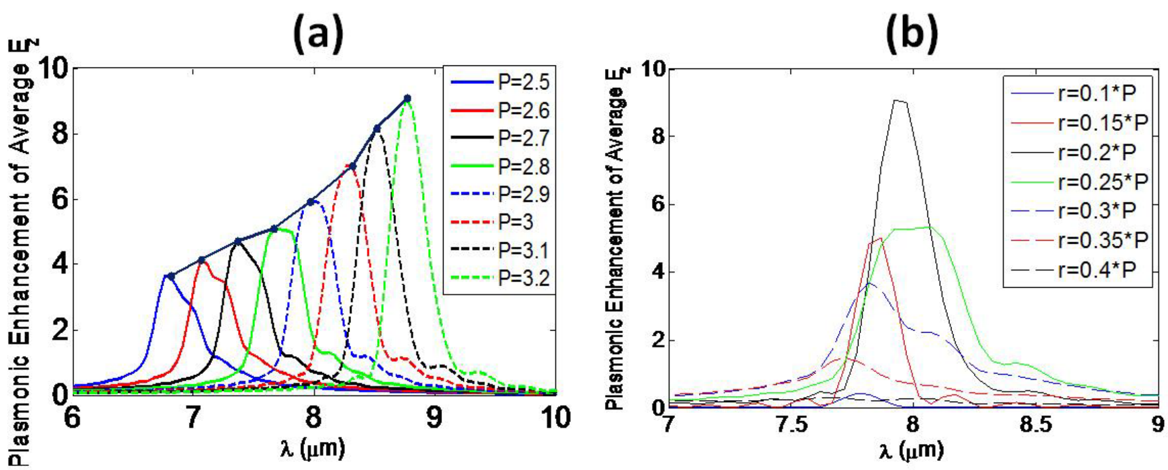

Figure 2 (a) Plasmonic enhancement of average E_z intensity for different periods of the plasmonic arrays; (b) different E_z enhancement by changing the radius of the holes.

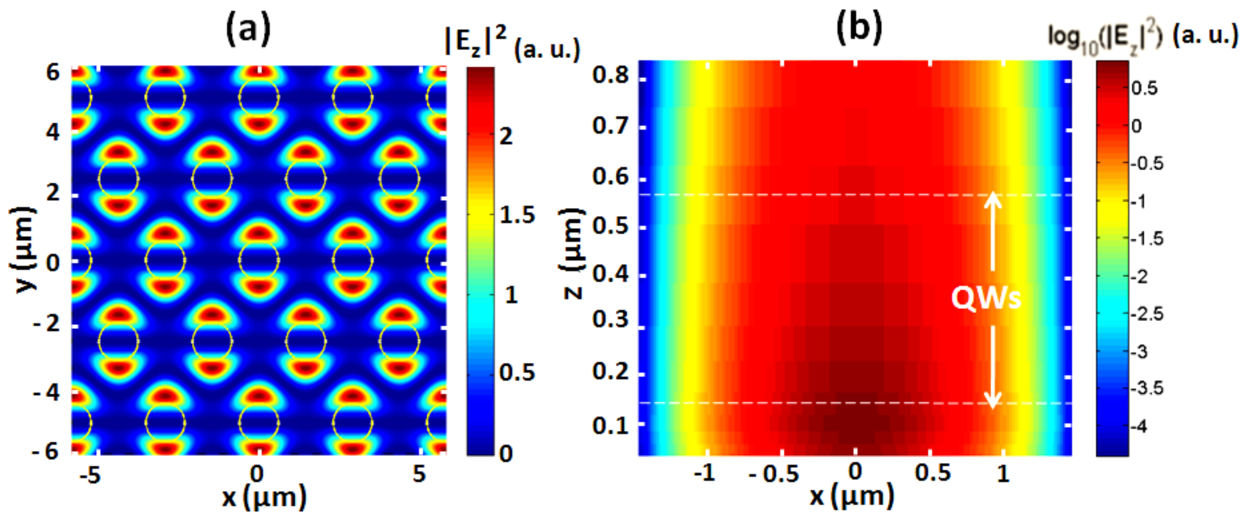

Figure 3 (a) E_z intensity distributed in the middle of the QWs active region (with circles representing the holes' positions); (b) E_z intensity distribution in the cross-section plane of the device.

3. Device Fabrication

The semiconductor wafer is grown by Metal-Organic Chemical Vapor Deposition (MOCVD) on a semi-insulating InP substrate, which includes 8 periods of 5.6 nm thick $In_{0.53}Ga_{0.47}As$ QWs (n=2.5x10^{17} cm^{-3}) and 50 nm thick undoped InP quantum barriers. Two highly doped InGaAs (n=1x10^{18} cm^{-3}) layers with the thicknesses of 40 nm and 500 nm separately are on the top and bottom of the QWs for forming ohmic contacts. The quantum well region is designed to be close to the top surface to be strongly coupled with the surface plasmon waves. The semiconductor layers are illustrated in table 4(c). The wafer was defined into different mesas by standard photolithography and chemical etching. A passivation SiN layer was deposited on the sample by PECVD. The SiN layer was opened by photolithograpy and RIE. A thick Ti/Au layer was patterned to form ohmic contacts to the top of the mesa and the bottom doped InGaAs layer. 40 nm thick Au layer was deposited on top of the mesa by electron beam evaporation and patterned with periodic holes using focal ion beam (FIB) milling. A final device structure is shown in figure 4(a). The top contact was connected to the top of the mesa by a small opening in the SiN layer. Figure 4(b) is the tilted SEM view of the holes perforated in Au film on top of the mesa. The measured diameter *d* of the hole is ~1.4 µm, and the period *p* of the array is ~2.9 µm. Other lithography techniques such as the Super Lens Lithography[8, 9] can also be applied to pattern these periodic hole arrays with a high throughput.

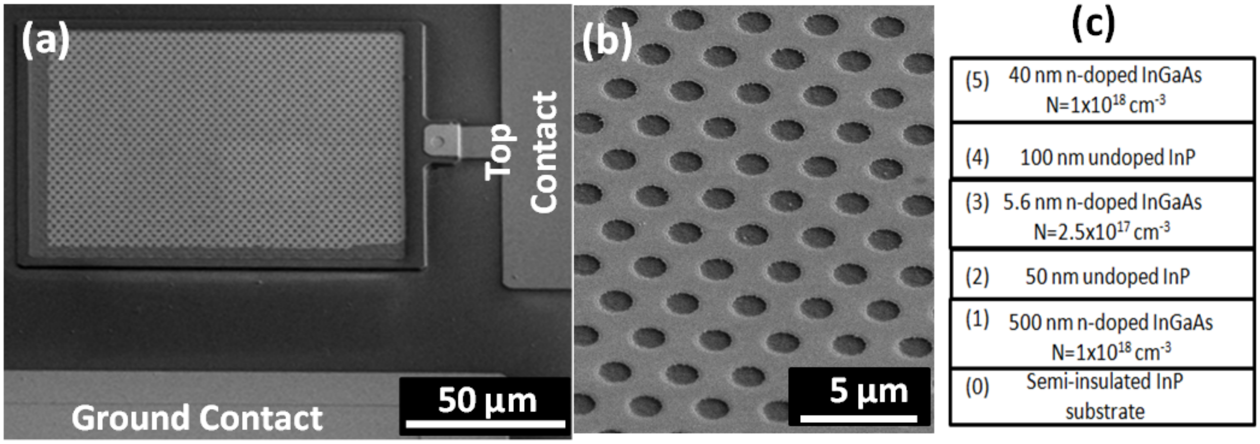

Figure 4 (a) Fabricated plasmonic enhanced QWIP device with top and ground contacts; (b) the enlarged view of the holes perforated in Au film; (c) the structure of QW semiconductor layers.

4. Characterizations &Discussions

We characterized our device in a cryostat cooled down to 78 K using liquid N_2. The dark current density-voltage curve of the device was measured and shown in figure 5(a). It can be seen that the dark current at a positive bias is smaller than that at a negative bias, which might be attributed to the asymmetrical quantum well/barrier heterointerface. The photo-response of the device was characterized using a Fourier transform infrared (FT-IR) spectrometer equipped with calibrated HgCdTe (MCT) photodetector with peak detection wavelength of ~8.8 µm. The IR light source is normally incident on the front side of the device patterned with Au holes arrays. Figure 5(b) shows the responsivity and detectivity spectrum of the device at a bias of 0.7 V (black line), and the simulated E_z enhancement spectrum (red line). The two curves are very close to each other, which confirms that the device is modulated by the surface plasmon coupling. The peak responsivity of the sample is as high as ~7 A/W at ~8.06 µm (the left axis of figure 5(b)). The detectivity of the device was also calculated using the measured dark currents and responsivity, and the peak value is ~7.4×10^{10} Jones (the right axis). The detectivity is a few times higher than other InP/InGaAs QWIP devices[10, 11] working at a similar wavelength and temperature, because of the surface plasmonic enhancement. The reason for the high detectivity of our photodetector can also be attributed to the reduced field-of-view angles of the background radiations by the surface plasmonic arrays. Further experiments can be helpful to understand this better.

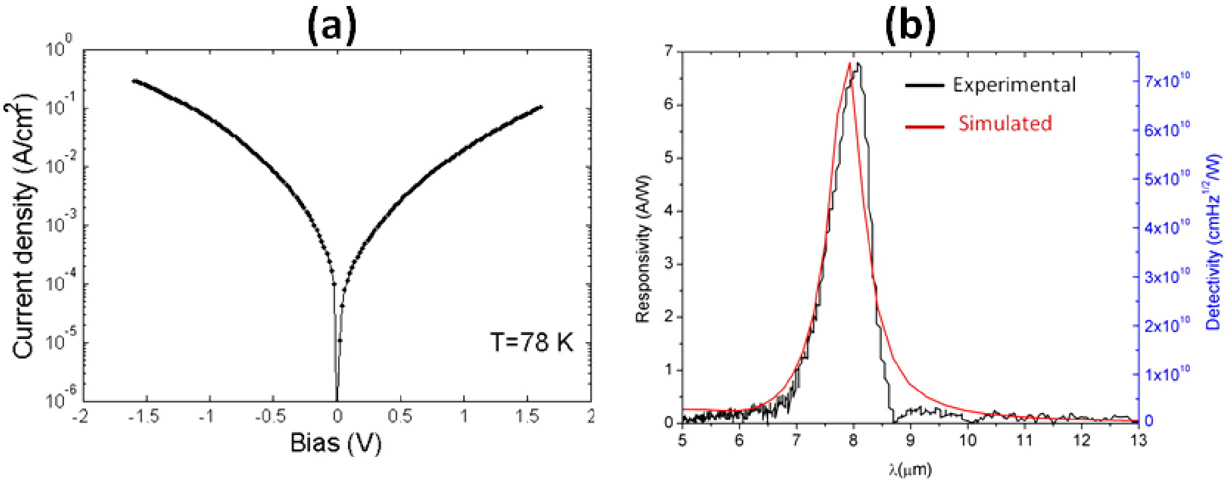

Figure 5 (a) The dark current density versus different biases; (b) photocurrent responsivity spectrum at the bias of 0.7V (left) and the detectivity spectrum (right) compared with simulated enhanced E_z.

5. Conclusions

We have demonstrated a high-detectivity normal-incident quantum well infrared photodetector enhanced by surface plasmon resonance of periodic hole arrays perforated in metal film. Our 3D FDTD models showed the z-component electric field intensity in the quantum wells region could be enhanced more than 5 times compared with the electric field intensity without any plasmonic enhancement. The normal-incidence infrared light can be converted to the parallel propagating surface plasmonic waves and effectively absorbed by the quantum wells at certain wavelength. The characterization results of the photodetector shows that the peak detectivity of the photodetector can be up to 7.4×10^{10} Jones at the detection wavelength of ~8 μm at 78 K. Such a photodetector is promising for fabricating high-performance infrared imagers.

References

[1] A. Rogalski, "Infrared detectors: status and trends," Progress in Quantum Electronics 27, 59–210 (2003)
[2] A. Rogalski, "Quantum well photoconductors in infrared detector technology, " J. Appl. Phys., 93, 8, 4355 (2003)
[3] B. F. Levine, "Quantum Well Infrared Photodetectors (QWIPs), " J. Appl. Phys, 74 (8), R1(1993)
[4] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, "Extraordinary optical transmission through sub-wavelength hole arrays", Nature 391, 667, (1998)
[5] S. Pillai, K. R. Catchpole, T. Trupke, and M. A. Green, "Surface plasmon enhanced silicon solar cells," J. Appl. Phys. 101, 093105 (2007)
[6] K. Okamoto, I. Niki, A. Shvartser, Y. Narukawa, T. Mukai, and A. Scherer, "Surface plasmon based on InGaN quantum wells," Nat. Mater. 3, 601 (2004)
[7] W. Wu, A. Bonakadar, and H. Mohseni, "Plasmonic enhanced QWIP with high detectivity, " Appl. Phys. Lett. 96, 161107 (2010)
[8] W. Wu, A. Katsnelson, O. G. Memis, and H. Mohseni, "A deep sub-wavelength process for the formation of highly uniform arrays of nanoholes and nanopillars," Nanotechnology 18, 485302 (2007)
[9] W. Wu, D. Dey, A. Katsnelson, O. G. Memis, and H. Mohseni, "Large areas of periodic nanoholes perforated in multistacked films produced by lift-off," J. Vac. Sci. Technol. B 26, 1745 (2008)
[10] O. O. Cellek, S. Ozer, and C. Besikci, "High responsivity InP-InGaAs quantum-well infrared photodetectors: Characteristics and focal plane array performance," IEEE J. Quantum. Electron. 41, 980 (2005)
[11] J. Y. Andersson, L. Lundqvist, Z. F. Paska, K. Streubel, and J. Wallin, "Long-wavelength quantum-well infrared detectors based on intersubband transitions in InGaAs/InP quantum wells," SPIE 1762, 216 (1992)