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Surface plasmon enhancement on infrared photodetection

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Abstract

InAsSb based infrared photodetector is an alternative to the existing HgCdTe, PbSnTe, and InSb counterparts, but its room temperature performance is still relatively poor. One of the ways to improve its performance is through surface plasmon, which provides near field confinement that leads to enhancement in light matter interaction. In this work, the role of each parameter of two dimensional metallic hole arrays in plasmonic enhancement is studied in details, such as the periodicity of hole array, hole diameter and metal film thickness. The plasmonic resonances and their corresponding electric field distributions are comprehensively studied in finite difference time domain simulation, which also would serve as a guide for designing surface plasmon enhanced InAsSb infrared detector with high quantum efficiency and signal-to-noise ratio.

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Keywords: InAsSb; Mid-infrared photodetectors; Sub-wavelength hole array; Surface plasmon enhancement

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1. Introduction

Infrared photodetectors are important optoelectronic devices and have wide applications in different infrared wavelength ranges, depending on the materials used for the devices [1-10]. Recently, photodetectors with peak sensitivity wavelength in the 3-5 μm have attracted more interests due to the highest atmospheric transmission in this mid-wave infrared spectral window [1, 3]. Traditional photodetectors operating in this wavelength range are

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mainly based on HgCdTe, PbSnTe and InSb, which are either involved with difficulties in repeatable growth of uniform composition bulk crystals and epitaxial layers or having poor performance near room temperature. This has encouraged the development of InAsSb based infrared photodetectors as an alternative. But the performance of the InAsSb only device is still not good enough for uncooled applications. Thus a concept of surface plasmon (SP) enhancement has been proposed in recent years [5]. Strong light focusing at sub-wavelength regime is achieved by using plasmonic structure, which is placed near absorption region of the detector [11]. Tight spatial confinement and high local field intensity of surface plasmon enable it to be particularly attractive for enhancing light-matter interaction and for improving the performance of light detection. The most widely used technique to excite SP is via sub-wavelength, metallic two-dimensional hole array (2DHA). This type of two-dimensional hole array is capable of sustaining the plasmonic modes and facilitating light coupling through Bragg scattering at the same time [12, 13]. Surface plasmon enhanced photodetectors opened a new research area for fundamental studies and practical applications in the fields of plasmonics and infrared photodetectors.

Absolute performance enhancement via surface plasmon was achieved first on an IR photodetector based on InAs quantum dots [12]. Since then, much research work has been done in this filed [14-16]. However, to the best of our knowledge, there is no report on the plasmon enhancement of InAsSb related photodetectors yet. Besides, the dependence of transmission and transmission efficiency through 2DHA on various variables is not fully understood. And the quantitative relation between extraordinary transmission through metallic 2DHA and performance enhancement of photodetector is not revealed yet. More importantly, the mechanism behind this performance enhancement of surface plasmon photodetector is still not clear.

We will demonstrate simulation results and detailed analysis of all possible variables which may affect the transmission through sub-wavelnegth hole array. Also, we will present our understanding of mechanism of surface plasmon enhancement on infrared photodetection.

Nomenclature

p	periodicity of hole array
d	hole diameter of hole array
t	thickness of metal film
T	absolute transmission through 2DHA
T_0	transmission through bare substrate without 2DHA
η	transmission efficiency

2. Designed photodetector structure

As shown in Figure 1, metallic two dimensional hole array is fabricated above dielectric substrate. Transmission through this sub-wavelength hole array is simulated using three-dimensional finite-difference time-domain (FDTD) methods. We have investigated all possible variables that may affect the transmission spectrum of the sub-wavelength hole array. They are periodicity of hole array, hole diameter, thickness of metal film and hole shape.

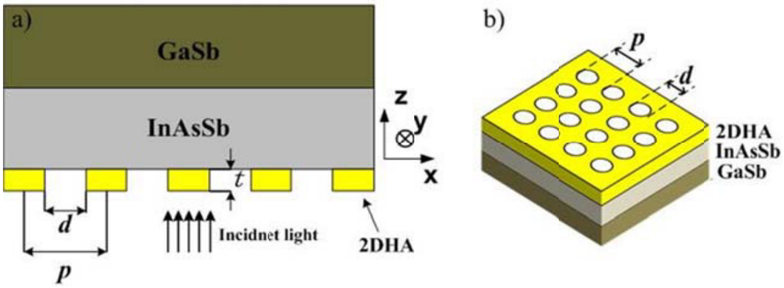

Fig. 1. (a) A cross-sectional view and (b) top view of 2DHA structure.

3. Simulation results and detailed analysis

3.1. Periodicity and hole diameter

First, we consider transmission through metallic 2DHA with different periodicities. The diameter d of circular hole is fixed at 0.46 μm, and the metal film is made of gold, with thickness of t = 20 nm. The periodicity is varied between 0.72-1.12 μm, with other parameters remain unchanged. The wave source we use here is normally incident along positive z direction, polarized in x direction, with wavelength range from 1.5 μm to 6.5 μm. Simulated absolute transmission spectrum is shown in Figure 2.

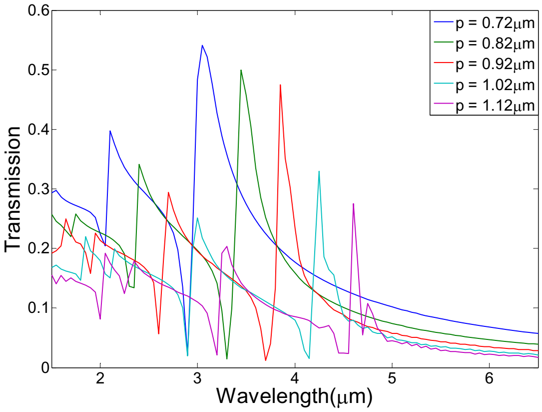

Fig. 2. Transmission spectra of gold 2DHAs with different periodicities (d = 0.46 μm, t = 20 nm).

If we compare these transmission curves with each other, we may find that position of spectra peaks shift to longer wavelength with increasing periodicity of hole array. In fact, the simulated transmission spectra shows that the peak wavelength is linearly dependent on periodicity of hole array, which can be verified by theoretical calculation [10].

Next, we discuss 2DHA with different hole diameters. The circular hole diameter d changes from 0.3 to 0.6 μm, and the periodicity of hole array is set as 0.92 μm. The simulation result is shown in Figure 3. It is very clear that when periodicity is fixed, the positions of peak wavelengths are almost the same for different hole diameters. And the absolute transmission of main resonance increase for larger hole diameters.

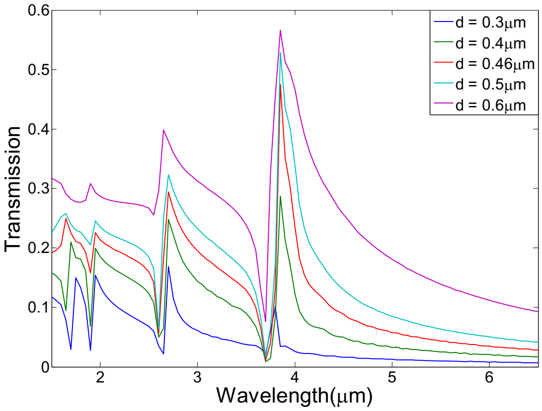

Fig. 3. Transmission spectra of gold 2DHA with different hole diameters (p = 0.92 μm, t = 20 nm).

To evaluate the transmission performance of sub-wavelength hole array, transmission efficiency is defined here, using below equation

$$\eta = \frac{T}{T_0 * F} \tag{1}$$

where T denotes absolute transmission, F is filling fraction of hole area in metal film.

Using equation (1), we calculated transmission efficiency of main peak when either hole diameter is fixed at d = 0.46 μm or periodicity is fixed at p = 0.92 μm. The results are shown in the following Figure 4.

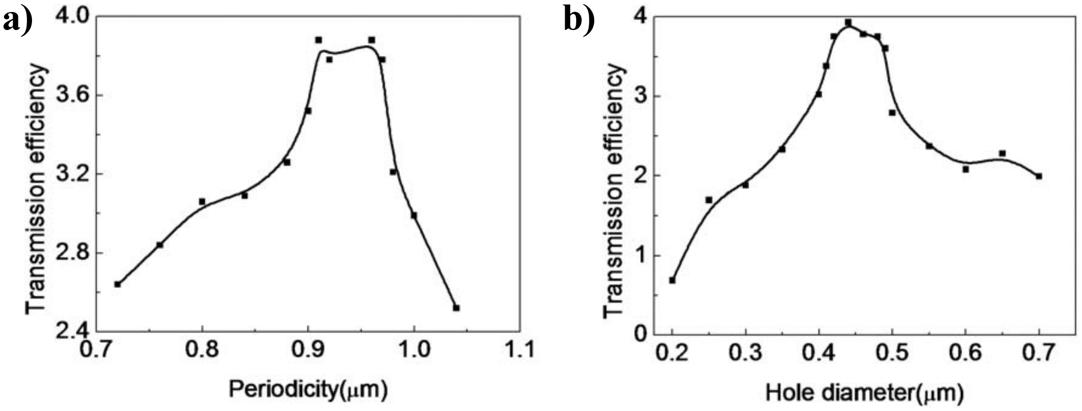

Fig. 4. A plot of transmission efficiency as a function of (a) the periodicity p (d = 0.46 μm) and (b) hole diameter d (p = 0.92 μm).

As shown in Figure 4, at the resonance wavelengths, the highest transmission efficiency is around 3.85, which indicates much more light than that is directly impinging into the hole area is transmitted. Besides, from these two figures, we can find that transmission efficiency reaches a maximum value when hole diameter is approximately half of periodicity.

The geometry condition for achieving highest transmission efficiency is very important. Because absolute transmission itself is not what determines the potential applications of the extraordinary transmission induced by SPP. Higher transmission can be achieved via increasing hole diameter, but a large fraction of electric field would be transmitted directly through the holes, rather than being excited as SPP. Thus, optimal geometry parameters for highest transmission efficiency have significant influence on practical applications.

Now, let's look at poynting vector in the vicinity of hole array. Figure 5 shows x component of poynting vector in the x-z plane. It is shown that x component always propagates along metal-dielectric interfaces in opposite direction in two sides of the hole. Besides, x component inside and outside hole area both propagates to the hole rim, which makes light concentration around hole rim possible. In conclusion, metallic hole array excites the incident wave source as SPP, and then channel this surface wave to the rim of hole.

From these results, we can imagine that the power flow along the metal surfaces and inside the holes, as plotted in Figure 6. The electromagnetic wave is concentrated at the surface, and it propagates along the metal surface and oscillates around the metal-dielectric interface. This oscillation process will enhance the interaction of light and matter in active region of photodetector. This will then increase quantum efficiency of photodetector, thus the performance of it. We believe this is why SPP can be used for enhancing performance of photodetector.

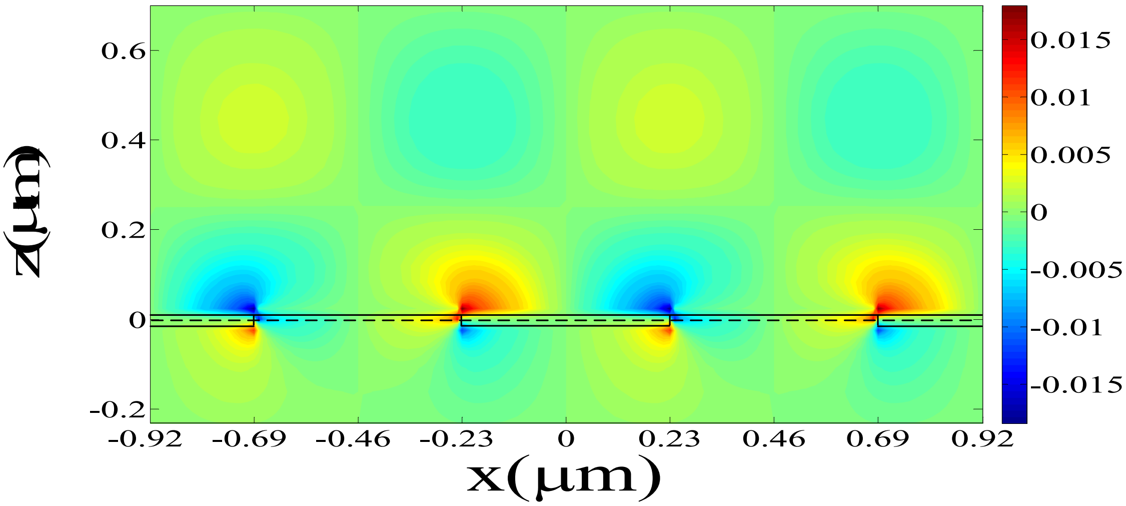

Fig. 5. Simulated *x* component of poynting vector in the vicinity of hole array. Dashed line denotes *z* = 0 plane, i.e., center plane of metal film.

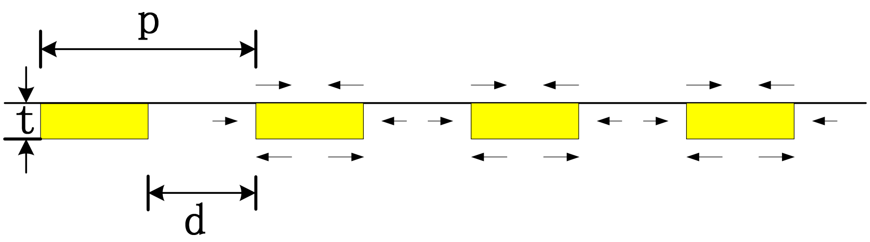

Fig. 6. Schematic of power flow of SPP excited by 2DHA.

3.2. Thickness of metal film

Here, we analyze the effect of metal film thickness on transmission. Before presenting simulation results, we first analyze this effect theoretically. Apparently, in the process of exciting the incident light as SPP, the metal film performs an important role. Since we hope the light is only transmitted in the form of SPP, the metal film should be as thick as possible. However, thicker metal film also means higher reflection, thus lower transmission. In other words, if the film is too thick, although almost all of the transmitted light is SPP, the absolute transmission is extremely small. This extremely small transmission is obviously useless in practical applications. Hence, there should be a trade-off for the metal film thickness.

Now, let us look at the simulated transmission spectrum shown in Figure 7. Here we consider circular hole array with $p = 0.92\ \mu$m and $d = .046\ \mu$m. The thickness of gold film is varied from 20 nm to 60 nm.

It is clearly shown in the figure that resonance wavelengths are almost same for different film thickness, which indicates that metal film thickness t has no observable effect on resonance wavelengths. Apart from this, as t decreases, absolute transmission increases. This means in order to achieve high transmission, thin metal film should be used.

In addition, we notice that there is a sharp increase of transmission at resonance wavelength when t decreases from 30 nm to 20 nm. We believe this is because t = 20 nm is approaching skin depth of SPP sustained at gold-dielectric interface. In fact, starting from dispersion relation equation, the expression for calculating skin depth of SPP can be derived. In the wavelength range we consider here, the skin depth of SPP is almost a constant of ~25 nm. This means in the 25 nm thick metal film, the intensity of electric filed decays to $1/e^2$ in the opposite side. When the thickness is even smaller, the SPP in metal would touch the other metal surface before decaying to desired very low intensity. In other words, the SPP would radiate through the other surface directly, instead of being trapped at the metal surface in this case. When the thickness of metal film is too small, this portion of un-trapped SPP cannot be neglected any more.

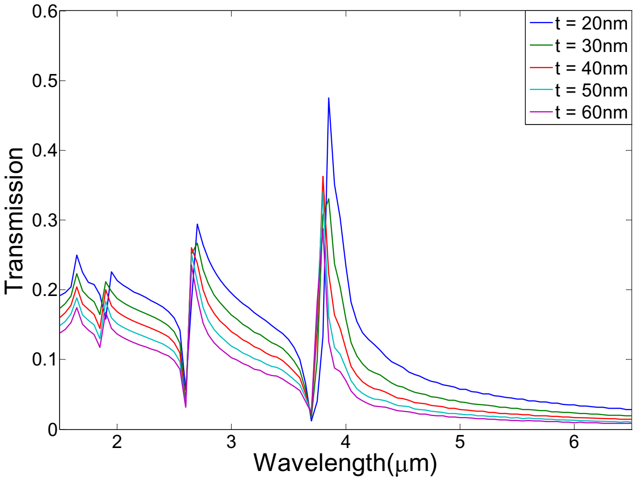

Fig. 7. Transmission spectra of gold 2DHA with different metal film thickness.

4. Conclusions

In this paper, we have presented a complete simulation and detailed analysis of transmission through sub-wavelength hole array. Various possible variables of structure that can determine the dependence of absolute transmission and transmission efficiency are discussed. The resonance wavelengths are linear dependent on periodicity of hole array, and they are not affected by hole diameter. And the transmission efficiency reaches maximum value when hole diameter is around half of periodicity. Also, to excite SPP efficiently and avoid high reflection at the same time, the optimal thickness of metal film should be approximately skin depth of SPP in metal.

Mechanism of extraordinary transmission and performance enhancement is also discussed. Being excited as SPP when the light is incident to the metal surface, it travels to the rim of holes, propagates along the side wall of hole and then transmits through the hole. Besides, we found the oscillation of SPP around the metal-dielectric interface. This oscillation process will enhance the interaction of light and matter in active region of photodetector, thus enhance the performance of photodetector.

Acknowledgements

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