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The enhanced infrared absorption of quantum well infrared photodetector based on a hybrid structure of periodic gold stripes overlaid with a gold film

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ABSTRACT

The hybrid structure of periodic gold stripes overlaid with a gold film is proposed to enhance the infrared absorption of quantum well infrared photodetector. The reflection spectra and the field distributions are numerically calculated by a finite difference time-domain method. The results show that the electric field component perpendicular to the quantum well is strongly enhanced when the plasmonic resonance of the hybrid structure occurs at the operation wavelength of the quantum well infrared photodetector. The effect of the structural parameters on the plasmonic resonant wavelength is discussed, which indicates that the localized surface plasmon as well as surface plasmon polariton plays a role in the light coupling with the hybrid structure. A high coupling efficiency can be obtained with the optimized structural parameters. In addition, the performance of the hybrid structure at the tilted incidence is investigated.

1. Introduction

Quantum well infrared photodetectors (QWIPs) have experienced rapid developments [1–10] in the last three decades. According to the polarization selection rule of intersubband transition (ISBT) [11], for the n-type QWIPs, the infrared absorption is possible only when the electric field of the radiation has a component perpendicular to the quantum well layers. In order to couple the incident light to the quantum well, some optical coupling schemes like the Brewster angle geometry [12] and 45° polished facet [13] have been proposed.

The majority of applications for infrared detectors are related to imaging by using small-pixel and large-area focal plane arrays (FPAs) [14]. For FPAs, planar device geometry and large area normal illumination are essential. So some other ways need to be used to control the light absorption in QW layers. Several different grating structures including linear grating [15], two-dimensional periodic grating [16], bi-periodic grating [17], random grating [18] and corrugated structure [19] have demonstrated efficient light coupling to QWIPs. These gratings deflect the incoming light away from the direction normal to the surface, enabling intersubband absorption.

Since Ebbesen found the extraordinary optical transmission [20] of periodic metal hole arrays, the properties of surface plasmon have been applied to improve the performances of optoelectronic devices such as solar cells [21], photodetectors [22], light-emitting diodes [23] and so on. Recently, an approach to enhance the infrared absorption and improve the performances of QWIPs by periodic metallic structures has been experimentally studied. One-dimensional metallic gratings [24,25], metal films perforated with two-dimensional hole arrays(2DHA) [26,27] or periodic metallic particles [28,29] were integrated on the top of the quantum well (QW). The surface plasmon supports TM mode and requires the electric field normal to the surface because of the generation of surface charge [30]. And the near-field effect [31] of surface plasmon results in an evanescent wave which induces a nonzero electric field component along the growth direction in the quantum well region, which can fulfill the intersubband transition.

But in the structures reported in [24–29], the mediums on the two sides of the structured metal are not identical. One is the material of the top contact of the QWIP and the other is air. The plasmonic resonant frequencies of the two surfaces are different, which decreases the transmission. For example, the transmission of the gold film perforated with hole arrays studied in Ref. [27] is only 53% at the resonant wavelength. The frontside illuminated light cannot be sufficiently coupled with the QW layers. In this paper, a hybrid structure consisting of periodic gold stripes and an overlaying gold film is designed on the top of a GaAs-based QWIP.

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The periodic gold stripes can excite the surface plasmon wave at a certain wavelength and generate a z-component of electric field that can be absorbed in the quantum well. The overlaying gold film can prevent the incident light from transmitting through the metallic structure and another Au/GaAs surface identical with the metallic grating surface can be formed to enhance the light coupling. And the hybrid structure is suitable to be applied in a standard FPA device which requires backside illumination of light. What is more, it is easy to fabricate such a device. The overlaying metal film can be used an Ohmic contact as well as a reflector. As a summary, the advantages of the hybrid structure investigated in this paper are the following three factors: higher coupling efficiency, suitability to be used in FPAs and easiness in fabrication.

Although similar hybrid structures have already been studied [32,33], only the influence of grating period on the performance of the QWIP was investigated. In our work, it is found that changing the width and depth of the metal grating can also shift the resonant wavelength. To obtain a strongly enhanced field component along the growth direction of the QW layers, the plasmonic resonance is expected to occur at the operating wavelength of the QWIP. Thus, the structural parameters of the hybrid structure need to be carefully optimized to make the resonant wavelength satisfy the desired operation wavelength of the QWIP. Numerical simulations made by the finite difference time-domain method [34] have indicated that the strong z component of electric field is induced in growth direction of the quantum well. A high coupling efficiency can be obtained. It can be deduced that the infrared absorption of the QWIP can be greatly improved.

2. Theoretical model and method

The QWIP in our study is desired to operate at 4.3 μm. Each layer of the device without the metallic hybrid structure is listed in Table 1. The device is grown on a semi-insulating GaAs substrate which is 625 μm thick. The 0.8 μm-thick top and 1 μm-thick bottom contact are GaAs layers with 10^{18} cm^{-3} Si donors. The active region is 1128 nm thick, containing a 500 Å $Al_{0.33}Ga_{0.67}As$ barrier layer and a 20-period MQW with a 10 Å undoped GaAs well, 24 Å $In_{0.36}Ga_{0.64}As$ well doped with 4×10^{18} cm^{-3} Si donors, a 10 Å undoped GaAs well and a 500 Å $Al_{0.33}Ga_{0.67}As$ barrier layer in each period.

Table 1
The structure of the device without the metallic hybrid structure.

Top contact: 0.8 μm silicon-doped GaAs ($N=10^{18}$ cm^{-3})	
500 Å $Al_{0.33}Ga_{0.67}As$ barrier	
10 Å GaAs well	×20
24 Å silicon-doped $In_{0.36}Ga_{0.64}As$ well ($N=4\times10^{18}$ cm^{-3})	
5 Å GaAs well	
500 Å $Al_{0.33}Ga_{0.67}As$ barrier	
Bottom contact: 1 μm silicon-doped GaAs ($N=10^{18}$ cm^{-3})	
625 μm semi-insulating GaAs (100) substrate	

The unit cell of the simulated structure can be schematically modeled as that in Fig. 1. Periodic gold stripes overlaid with a gold film are integrated on the top of the quantum well. The overlaying gold film is thick enough to prevent light from transmitting through the metallic hybrid structure. The period, depth and width of the gold stripes are p, d and a, respectively. The thickness of the top contact is reduced to the depth (d) of the gold stripe so that the active region of the QWIP is placed right below the gold stripe surface. In this way, the induced z-component of the electric field can be sufficiently absorbed by the intrinsic layers of the QWIP. The total thickness of the top and bottom contact, the active region and the substrate, is much longer than the wavelength of the incident light. The difference among the refractive index of each layer in Table 1 is small enough to be neglected. So the whole semi-conductor part can be simplified as a half-infinite dielectric whose refractive index is 3.3 [35]. The absorption coefficient of the simplified dielectric is zero.

The hybrid structure is illuminated normally along z-axis from the substrate backside by a linearly-polarized plane wave with electric field vector parallel to x-axis. The permittivity of gold is based on the Lorentz–Drude model [36]

$$\varepsilon(\omega) = 1 - \frac{f_0\omega_p^2}{\omega(\omega - i\Gamma_0)} + \sum_{j=1}^{k} \frac{f_j\omega_p^2}{\omega_j^2 - \omega^2 + i\omega\Gamma_j} \tag{1}$$

where ω is the frequency of incident wave, $\omega_p = 2.18 \times 10^{15}$ Hz is the plasma frequency, $k=5$ is the number of oscillators with frequency ω_j, strength f_j and lifetime $1/\Gamma_j$, while $\Omega_p = \sqrt{f_0}\omega_p$ is the plasma frequency associated with intraband transitions with oscillator strength f_0 and damping constant Γ_0. The dispersion parameters of gold in Eq. (1) are listed in Table 2.

The finite difference time-domain(FDTD) method is employed to investigate the reflection spectra and field distributions of the hybrid structure. In the calculation, the spatial mesh cell is set to $\Delta s = \Delta x = \Delta y = \Delta z = 20$ nm and the time step is taken as $\Delta t = \Delta s/2c = 3.3353 \times 10^{-17}$ s. The perfect matched layer (PML) conditions are imposed at the boundaries along z-axis and the periodic boundary conditions are adopted in x and y directions.

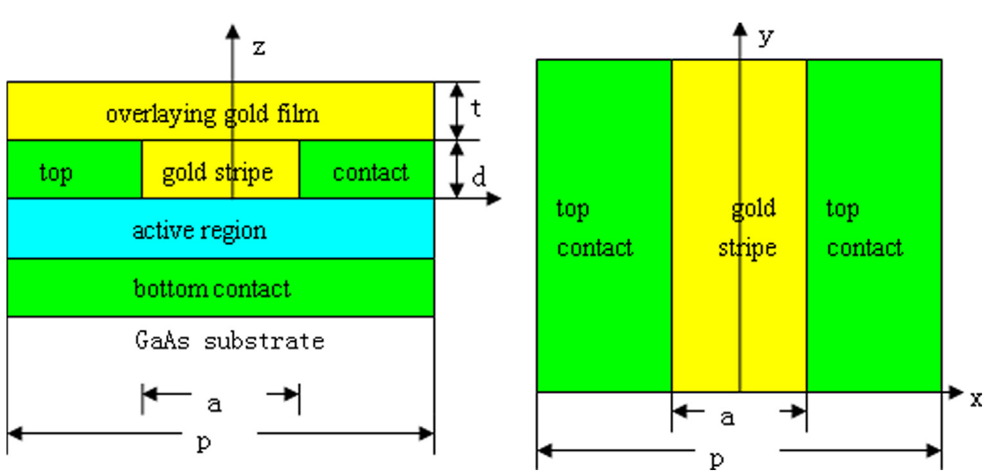

Fig. 1. The schematic view of a periodic unit for the simulated structure.