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Performance enhancement of photodetector using defect subwavelength metallic Grating

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ABSTRACT

A defect subwavelength metallic grating is proposed to improve light transmittance and quantum efficiency, leading to better responsivity of photodetector at 1550 nm wavelength. We mainly focus on the refractive index of rectangle defect influence on performance. With optimizing the parameter, responsivity can be increased 4.5 times, compared to the photodetector with uniform subwavelength metallic grating. In addition, response bandwidth of the structure can reach 76 GHz.

1. Introduction

High-speed data communications require photodetectors to have high responsivity and high speed. However, conventional design is subject to the trade-off between response speed and responsivity. Recently, photodetector with subwavelength metallic grating (SMG) has been proposed to overcome the trade-off [1,2]. In the structure, the SMG acting as interdigitated electrodes has a lower capacitance than p-i-n structure, thus it can gain higher cut-off frequency. In addition, the subwavelength structure can provide extraordinary light transmission, which has been proved during the past years [3–7]. The present common understanding of the mechanism responsible for the extraordinary enhanced transmission is the excitation of horizontal surface plasmons (HSP) at the surface of the SMG. The HSP significantly increases the near-field density of SMG, so responsivity enhancement is limited in a thin absorption layer. Recently, Cao et al. have proved that horizontal SPP resonance is responsible for transmission extinction and cavity mode resonance is associated to the extraordinary transmission [8]. Of course, cavity mode tends to increase the transmitted far-field. Thus, the uniform SMG needs to be improved the structure only presence cavity mode.

For the identical transmitted optical field, resonant cavity-enhanced (RCE) structure has stronger absorption than single absorption layer [9]. In RCE structure, the conventional scheme to form the top-bottom reflector is distributed by Bragg reflectors (DBRs), which consists of alternate quarter-wave semiconductor layer with low and high refractive. Fortunately, one-dimensional uniform SMG has been proposed to act as top reflecting mirror of resonant cavity [10]. Therefore, the SMG can have three functions, such as providing low capacitance electrode, obtaining transmittance enhancement, and acting as top reflectivity mirror of RCE. However, its reflectance is more than 90%, resulting in relatively low quantum efficiency. If the quantum efficiency of the RCE structure requires to further increase, the SMG structure should be improved to reduce the top reflectance.

In this letter, based on photodetector structure in Ref. [10], we replace the one-dimensional uniform SMG with the one-dimensional rectangle defect SMG. The defect part can increase cavity field in the slit and reduce the top reflectance of RCE structure, simultaneously. Here, we comparatively study the defect SMG with the uniform structure, and get 4.5 times responsivity enhancement.

2. Structure design

A schematic of the proposed F–P resonant cavity is presented in Fig. 1a. The structure contains defect SMG, absorption layer, buffer layer, and bottom reflection layer. For the SMG, the red part is metallic material and the gray rectangle defect is semiconductor material with refractive index n_c. The metallic part is made of gold due to its low dissipation and well-defined plasmonic property compared to other metals. The SMG has structure parameters: the grating period $p = 1000$ nm, slit width $w = 100$ nm, and slit height

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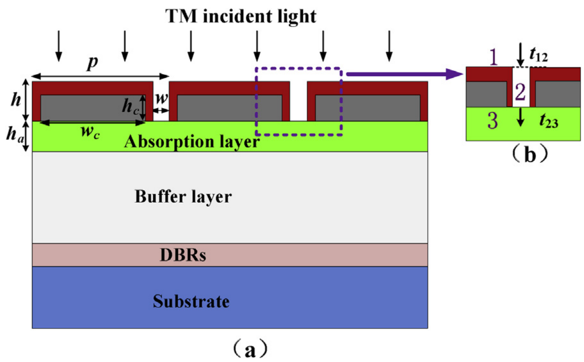

Fig. 1. (a) Schematic diagram resonant cavity photodetector with defect SMG. (b) A simple structure model of light transmission through a slit. The relevant scattering coefficients and the domain used for the model have been marked. Dielectric 1 and 2 are air, and dielectric 3 is the semiconductor absorption layer.

h = 260 nm, respectively. In addition, the rectangle defect is width $w_c = 800$ nm and height h_c = 150 nm, respectively. The absorption layer made of ErAs:$In_{0.53}Ga_{0.47}As$, which is sensitive to 1550 nm wavelength and has short carrier lifetime, and its height h_a = 200 nm. The bottom reflector is DBRs, The photodetector is illuminated by plane wave of 1550 nm wavelength TM polarization from the top.

3. Simulation and discussion

For the first step in design, we carefully discuss how to achieve high transmittance of the defect SMG. To develop a simple structure for light transmission through a slit, we first make the construction of an intuitive model, showing in Fig. 1b. The plane wave couples into plasmon mode supported by the slit with transmission coefficient t_{12}, the downward propagating plasmon mode is coupled out to slit with transmission coefficient t_{23}. For the defect SMG, we develop the diffracted evanescent wave model [11] to predict the transmittance properties and quantify the associated performance enhancement. The transmittance function can be written as:

$$T = |t_{12}|^2 |t_{23}|^2 \left| t_h \right|^2, \quad (1)$$

where t_h is relation to the cavity mode in the slits, the two transmission coefficients can be expressed as:

$$\begin{aligned} t_{12} &\propto 1 + 2\sum_{1}^{N} \frac{1}{jp} \cos\left(\frac{2\pi}{\lambda} n_0 jp + \frac{\pi}{2}\right) \\ t_{23} &\propto 1 + 2\sum_{1}^{N} \frac{1}{jp} \cos\left(\frac{2\pi}{\lambda} n_1 jp + \frac{\pi}{2} + \Delta\varphi\right) \end{aligned}, \quad (2)$$

where λ is the incident wavelength; n_0, n_1 is the effective refractive index on the top and bottom surface of the defect SMG; $\Delta\varphi$ is the phase difference of grating bottom surface resulting from the semiconductor rectangle defect. After the structure parameters of defect SMG have been determined, the phase difference is a key factor of influence on transmittance according to Eqs. (1) and (2). In addition, the formula of the phase difference is $\Delta\varphi = 2kn_c h_c = \frac{4\pi}{\lambda} n_c h_c$. Therefore, the transmittance of SMG only depends on the refractive index of defect part n_c.

The transmittance spectra of the uniform SMG and the defect SMG with three different refractive indexes n_c = 1.5, 2.0, and 2.5 are presented in Fig. 2, respectively. It can be observed that spectral width of the uniform SMG is the narrowest. At incident wavelength λ = 1550 nm, its transmittance being 0.35 has been marked in black dot A. For the defect SMG, it is found that the transmittance peaks increase and redshift with the refractive index n_c decreasing.

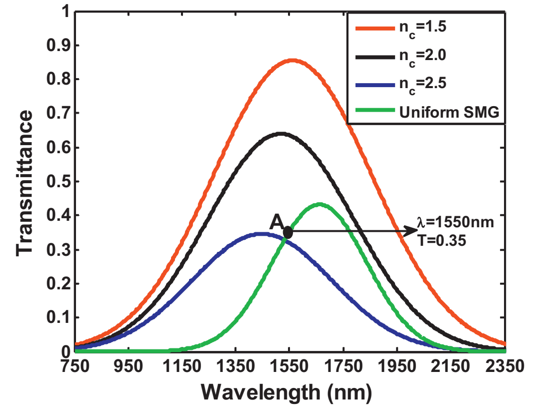

Fig. 2. The transmittance of the uniform SMG and the defect SMG with three different refractive indexes n_c = 1.5, 2.0, and 2.5, respectively. The black dot A is the transmittance of the uniform SMG at 1550 nm wavelength.

Hence, when the incident wavelength is 1550 nm, the refractive index n_c needs to be optimized in detail to obtain the maximum transmittance.

The influence of the refractive index n_c on transmittance is shown in Fig. 3 in blue scale at incident wavelength λ = 1550 nm. The transmittance value ranges from about 0.1 to 0.9, that is, the curve exhibits large change in the whole range. When the refractive index n_c is less than 2.4, the transmittance is higher than that of the uniform SMG. Therefore, the refractive index n_c is a very important factor to control transmittance. Additionally, the maximum transmittance value is 0.89 where the refractive index n_c = 1.4, as marked in the figure in black dot A.

To prove the high transmittance arising from cavity mode, we simulate the magnetic field distribution of uniform SMG and defect SMG. A commercial software COMSOL Multiphysics is exploited to simulate field distribution. The incident light of two structures is supposed to be the same and the refractive index n_c of the defect structure is chosen as 1.4. The normalized magnetic field of two structures is shown in Fig. 4a and b, respectively. It is obvious that strong near-field intensity is in the vicinity of the uniform SMG bottom surface, which is undesirable for our design optoelectronic photodetector. In addition, there is weak cavity mode inside the slit. However, for the defect SMG, it can be clearly seen that HSP mode is almost disappearing, and quite strong cavity mode exists in the slit.

Then the optimized design of the RCE structure is taken into account to obtain high quantum efficiency of absorption region.

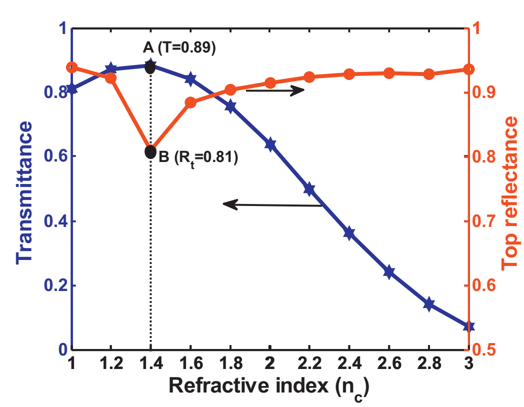

Fig. 3. The transmittance of the defect SMG (the left blue scale) and the top reflectance of RCE (the right red scale) are dependence on refractive index (n_c) at λ = 1550 nm. The black dot A and B correspond to the maximum transmittance of defect SMG and the minimum top reflectance in the whole range, respectively.