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A metal cascaded resonant cavity structure to enhance responsivity of photodetctor

Mingdi Du [a,b], Junqiang Sun [a,*]

[a] Wuhan National Laboratory for Optoelectronics, School of Optoelectronic Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, PR China

[b] Electric and Information Engineering Department, Hunan Institute of Technology, Hengyan, 421002, China

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ABSTRACT

A cascaded resonant F-P cavity structure is proposed to improve the responsivity of high-speed photodetector, which consists of subwavelength metal grating and metal film. Responsivity enhancement can be achieved by high light transmittance and high quantum efficiency, simultaneously. High transmission arises from slit cavity mode resonance of subwavelength metal grating, and high quantum efficiency is due to adopting resonant cavity enhanced structure. In our proposed photodetctor structure, subwavelength metal grating plays a very important role in performance enhancement. The results show that responsivity can be increased about 31 times compared to the conventional photodetector by optimizing the structure parameters.

1. Introduction

The increasing bit rate of optical communication systems is a driving force for research in photodetectors with high speed and high responsivity. Metal-semiconductor-metal (MSM) electrode, as a high-speed structure, has been demonstrated to decrease capacitance and increase bandwidth, compared with the PIN structure for the same active area [1]. Therefore, the MSM electrode structure has been widely used in photomixer to generate THz wave [2]. However, a portion of light is limited to reach active layer by metal fingers, as a result of decreasing responsivity. Fortunately, Ebbesen et al. have demonstrated extraordinary optical transmission through subwavelength apertures [3]. This has inspired the development of photodetector with subwavelength metal grating (SMG) [4–6], since the structure can provide high transmittance and high response speed. The present common understanding of SMG high transmission is the excitation of horizontal surface plasmon (HSP) [7]. However, F. Romanato et al. have presented that transmission properties of SMG which are governed by HSP resonance and vertical slit cavity mode resonance [8,9]. They have also proved that HSP resonance is responsible for extinction transmission and slit cavity mode resonance is associated with extraordinary transmission.

Thin absorption layer is another method to increase response speed due to its low carrier transmittance time. However, only a small portion of the light injected into the photodetector can be absorbed by thin semiconductor material, resulting in low quantum efficiency. The resonant cavity enhanced (RCE) structure has more than one absorbing path inside the intrinsic region. So it can get high quantum efficiency in a thin absorption layer. Conventional schemes usually employ the RCE structure formed by semiconductor using distributed Bragg reflectors (DBRs). However, reflectance and bandwidth of the reflectors are limited by small contrast of dielectric constant in different semiconductors.

Photodetector with both MSM electrode and thin absorption layer can further increase response speed. How can its responsivity be enhanced?

In this paper, we propose a metal cascaded-cavity photodetector which can obtain high light transmittance and quantum efficiency simultaneously. The cascaded structure consists of top slit cavity and bottom RCE structure. In addition, the RCE structure would replace thick DBRs with SMG and metal film. By optimizing the SMG structure, the photodetector can lead to 31 times responsivity enhancement compared to the conventional structure.

2. Structure design

A cross-sectional view of the photodetector is shown in Fig. 1. The top cavity is formed by air, SMG and semiconductor absorbing material, and the cavity is carefully designed to achieve high

* Corresponding author.
E-mail address: jqsun@mail.hust.edu.cn (J. Sun).

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transmittance. The bottom cavity contains SMG, absorption layer, buffer layer and metal film, and the cavity is primarily responsible for high quantum efficiency. The reflectance of metal film is high enough to act as bottom reflection mirror. Absorption layer is made of ErAs:$In_{0.53}Ga_{0.47}As$ which is sensitive to 1550 nm wavelength. ErAs:$In_{0.53}Ga_{0.47}As$ has 0.2 ps carrier lifetime [10] and 10,000 /cm absorption coefficient. The grating period, slit width, and slit height are denoted by p, w, and h, respectively. Dielectrics 1 and 2 are air, and dielectric 3 is absorption layer, as shown in the top right corner of Fig. 1. The photodetector should be illuminated by TM polarized plane wave (the central wavelength is 1550 nm).

3. Simulation and discussion

We first focus on the optimized design of SMG to achieve high transmittance. For metal material, gold is a good choice due to its low dissipation compared to other metals. Neglecting all evanescent modes and assuming only fundamental propagating eigenmode inside the slits, an analytical expression for far-field transmittance can be derived as follows [11]:

$$T = \frac{|t_{12}|^2 |t_{23}|^2 e^{-2\left|k''\right|h}}{\sqrt{\varepsilon}\left|1 - r_{21} r_{23} e^{2ik'h}\right|^2} \qquad (1)$$

where t and r are the transmission and reflection coefficients at different interfaces of grating, respectively; ε is the dielectric constant of absorption layer, φ_{tot} is the total phase accumulated by the single propagating mode traveling forward and back inside the slit, $\varphi_{tot} = \varphi_{21} + \varphi_{23} + 2k_0 n_{eff} h$, $n_{eff} = k/k_0$ ($n_{eff}$is the effective refraction index of slit), where $k = k' + ik''$ is the complex wave vector of the slit plasmon mode, k'' is the loss of metal. When slit width w is reduced below diffraction limit, the effective refraction index of slit can be modulated by slit width [12].

The transmission properties of SMG depends on grating period p, slit width w and grating height h. Let us check how transmittance varies with the grating period. For calculations, we make use of two sets parameters of metal grating. One is with fixed height $h = 300$ nm and three different slit widths $w = 160$ nm, 220 nm, 280 nm, and the other is with fixed width $w = 280$ nm and three different slit heights $h = 280$ nm, 300 nm and 320 nm. The variations of transmittance against the grating period are shown in Fig. 2(a) and (b), respectively. It can be found that the characteristic of these curves in two figures are different. However, there is a noteworthy feature that the maximum transmittance is at the same position $p = 820$ nm. It can be deduced that HSP (near field) is nearly zero and the magnetic field is only within the slit for 820 nm period. The pure cavity mode generated by slit leads to a far-field transmission maximum [8]. So 820 nm is the best choice for the SMG structure.

After determining the period, we analyze the influences of slit width and grating height on transmittance. According to Eq. (1), transmittance is maximized when the denominator is minimized, which occurs on total phase $\varphi_{tot} = 2m\pi$ (m is an integer and the order of resonance). For slit width $w = 160$ nm, 220 nm, 280 nm and 340 nm, respectively, transmittance dependence on grating height is displayed in Fig. 3. It shows that the curves agree with the Fabry–Perot cavity excellently [13,14], whose peaks are associated with a cavity mode resonance. In addition, it can be seen that the transmittance at the first-order resonance is higher than the second-order for the same slit width. This is because loss in

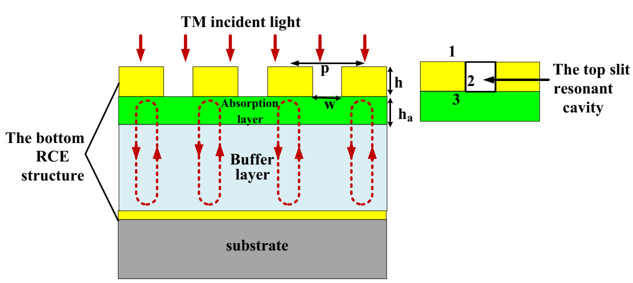

Fig. 1. Schematic diagram of metal cascaded resonant cavity photodetector, the yellow part is subwavelength metal grating and metal film. Absorption layer thickness h_a is 100 nm, and the buffer layer is 750 nm. The yellow grating is also positive and negative electrode. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

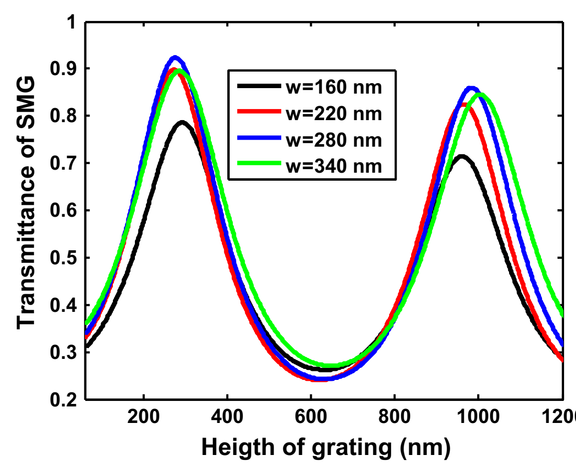

Fig. 3. Plot of the transmittance as a function of grating height for the fixed period $p = 820$ nm and four different widths $w = 160$ nm, 220 nm, 280 nm and 340 nm, respectively.

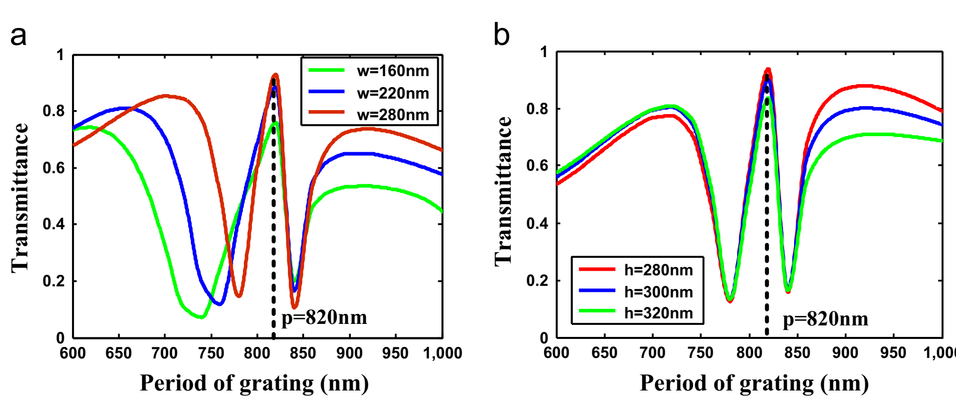

Fig. 2. (a) Transmittance of the grating versus period for the fixed height and three different slit widths. (b) Transmittance versus period for the fixed slit width and three different grating heights.