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偏振敏感双机制增强近红外GeSn等离型光电探测器设计(特邀)

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摘　要：为了解决GeSn光电探测器反应能力不足和信号噪声比差等方面的不足,提出一种偏振敏感的双机制增强的GeSn光电探测器。该光电探测器同时具有法布里-珀罗模式和表面等离激元模式,其中,GeSn薄膜和二氧化硅薄膜提供了法布里-珀罗模式,而表面等离激元来源于附加在GeSn表面的Au光栅。模拟结果表明,该双机制增强的GeSn光电探测器将2 000 nm波长处的光学吸收率由20%提高到80%。此外,在2 000 nm时,TM光及TE光吸收率分别为80%和2.6%,消光比为31。高消光比表明该结构具有良好的偏振选择性。这些结果为新型GeSn光电探测器的开发提供了思路。

关键词：法布里-珀罗;表面等离激元;光栅;光电探测器;偏振
中图分类号：TN21;TN362　　**文献标识码**：A　　**doi**：10.3788/gzxb20215010.1004003

Design of Polarization-sensitive Infrared GeSn Plasmonic Photodetectors Enhanced by Dual Absorption Mechanism (Invited)

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Abstract: The GeSn photodetectors (PDs) have drawbacks such as the slow response speed and the poor signal-to-noise ratio. To overcome these disadvantages, we report one polarization-sensitive dual-mechanism-enhanced GeSn PD that contains both Fabry-Pérot (F-P) mode and Surface Plasmon Polaritons (SPP) mode. The F-P mode originates from the GeSn film assisted by an embedded SiO_2 film, while the SPP mode is associated to the added Au grating on the GeSn film. Simulation results show that these two types of modes can increase the optical absorption of GeSn from 20% to 80% at 2 000 nm. Moreover, under TM/TE polarization, absorption of the sample are 80% and 2.6%, respectively, and the extinction ratio is 31. Such a high extinction ratio indicates that the GeSn PD has great polarization selectivity. These results provide new ideas for the development of innovative GeSn PDs.

Key words: Fabry-Pérot; Surface plasmon polaritons; Grating; Photodetectors; Polarization
OCIS Codes: 040.5160; 230.5160; 230.3990; 250.5403; 240.6680

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0 Introduction

Infrared PDs, one of the key core components in the field of optoelectronic technology, are highly desired for various demanding applications, such as aerospace, missile tracking, wireless communication, safety monitoring and solar cell detection[1-2]. Although III-V semiconductors are inherently suitable for the fiber-optic telecommunication windows (1 265～1 675 nm)[3-4], the incompatibility of these materials with Complementary Metal-Oxide-Semiconductor (CMOS) processing technology makes their broad application impossible. Silicon-based PDs can effectively overcome this disadvantage. They may be a promising candidate for large-scale, compact, low-cost Electronic-Photonic Integrated Circuits (EPICs) [5]. Unfortunately, the cutoff wavelengths of typical Si and Ge PDs are 1 100 nm and 1 600 nm respectively[6]. In this case, there is no response or very low response at 1 550 nm (the most widely used in infrared communication window), and the response is almost zero at longer wavelengths[7-9]. Recently, a new type of group-IV PD based on GeSn alloy has been developed to solve this problem[10-13]. GeSn alloy exhibits an extended cutoff wavelength compared with Ge originates from the adjustable bandgap width due to the different content of Sn, therefore the absorption around 1 550 nm can be enhanced obviously compared with that of bulk Ge. At the same time, GeSn alloy also has advantages in the higher carrier mobility compared with Si/Ge and low cost for large-scale integration. As a result, GeSn alloy is an ideal material for application in the near and mid-infrared PDs.

However, in spite of the benefits of GeSn alloy, the GeSn PDs still have drawbacks such as insufficient responsivity and poor signal-to-noise ratio[14]. In order to solve these problems, many new types of solutions have been proposed, including Avalanche Photo Diode (APD)[15-16], heterojunction phototransistor[17-18], Metal-Semiconductor-Metal (MSM) PDs[19-20], and so on. In addition, it is also an effective method to improve the performance of PDs by introducing dielectric resonators and metal nanostructures. The cavity modes and SPP can be supported in the resonators and nanostructures respectively, which can greatly increase the light absorption of the device due to the enhancement of the light-matter interaction. In this case, a significant increase of the External Quantum Efficiency (EQE) and responsivity of the device can be achieved. Therefore, the performance of PDs can be significantly improved by introducing specially designed dielectric resonators and metal nanostructures, which will have great potential for application in innovative optoelectronic devices, particularly for high response GeSn infrared PDs.

In this paper, we demonstrate the polarization-sensitive infrared MSM GeSn PDs containing both F-P modes and SPP modes. The F-P mode originates from the GeSn film assisted by a SiO_2 film, while the SPP mode is associated to the added Au grating. The absorption enhancement of this sample are obtained. The contributions of F-P mode and SPP mode are discussed by the absorption spectra and the field distributions. Reference GeSn PDs containing F-P mode or SPP mode or neither these modes are also proposed. By adjusting the geometrical parameters of GeSn film and Au grating, optical absorption at 2 000 nm of the sample is 80%, which is 4 times larger than the result of the referenced PD without F-P mode and SPP mode. At the same time, the polarization properties of the sample containing the dual types of modes are also discussed. A large extinction ratio around 31 are obtained. Our results reveal some unique features of GeSn PD enhanced by the F-P mode and SPP mode, which make GeSn PDs become promising candidates for innovative Si-based PDs.

1 Device design

The four types of MSM PDs based on GeSn alloy are schematically shown in Fig.1. The first type of GeSn PD exhibited in Fig. 1(a) consists of the Ge substrate, a 3.5-μm-thickGeSn film grown on the substrate and the double top Au electrodes. When the incident light is absorbed by the GeSn film, the electron hole pairs will be generated, and then collected by the Au electrodes based on photoconductive effect. In this case, the performance of the PD mainly depends on the absorption efficiency of GeSn. The structure of the GeSnPD containing F-P mode are exhibited in Fig. 1(b), which has an additional 3.5-μm-thick SiO_2 layer based on the structure of first type of PD. In this case, the F-P mode can be supported in the GeSn layer because of the large refractive index difference between GeSn and SiO_2 film, the GeSn film acts as a dielectric resonator, which results in an increase of the light-matter interaction. Therefore, the optical absorption efficiency of GeSn is significantly enhanced. The schematic of the third type of GeSn PD shown in Fig. 1(c) includes an additional top Au grating compared with the GeSn PD exhibited in Fig. 1(a). Once the SPP derived from the grating is excited, the localized electromagnetic filed can be generated around the grating in a space quiet smaller than the wavelength of the incident light. Thus, the interaction between incident light and GeSn layer can be enhanced, which result in the improving optical response of the PDs. Fig. 1(d) shows the last type of the PDs containing both the SiO_2film and the Au grating. In this case, the light-matter interaction in this device can be simultaneously enhanced by F-P modes and SPP mode, that is the double-mechanism enhanced GeSn PD.

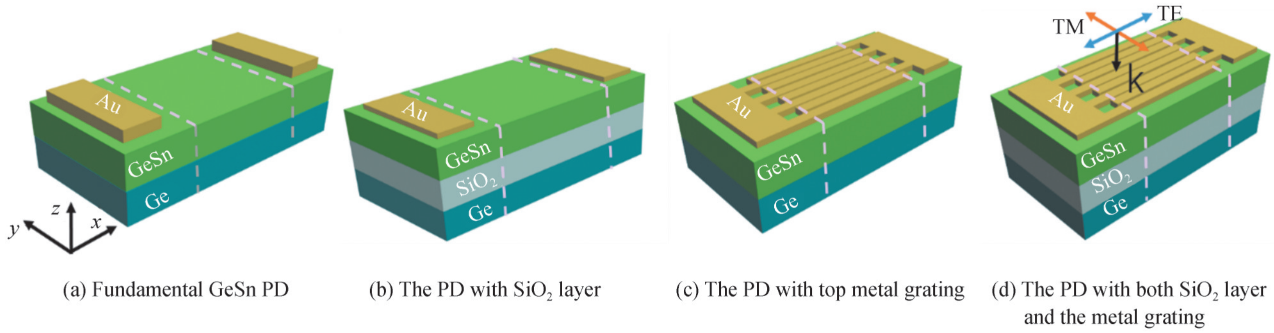


Fig. 1 The schematic structures of GeSn PD and the pink dotted line donates the boundary of the structure used in FDTD simulations

2 Numerical simulations and discussion

2.1 Optical absorption results of the four types of samples

FDTD method is used to analyze and optimize the four types of devices discussed above. The Gaussian light source is used in the simulation. The light source propagates along the Z-axis in the negative direction, and the polarization direction is perpendicular to the metal grating (along the X-axis). The numerical aperture is 15 μm and Perfectly Matched Layer (PML) boundary conditions are imposed. The optical absorption spectra of these four types of samples are shown in Fig.2. The optical absorption of GeSn PD (Fig. 1(a)) decreases with the increase of wavelength. And there are no obvious resonance peaks from 1 400 nm to 2 500 nm. For the PD with the added SiO_2 film (Fig. 1(b)), the optical absorption still shows a downward trend with the increasing of wavelength. However, the spectrum also has several obvious absorption peaks located at 1 456 nm, 1 601 nm, 1 779 nm, 1 995 nm and 2 254 nm, respectively, which represents the F-P modes supported in the GeSn film. The detail will be discussed below. It can be seen that light absorption GeSn PD without and with SiO_2 layer at 2 000 nm are 35% and 20%, respectively, which indicates that the F-P mode can obviously enhance the optical absorption of the GeSn film.

The absorption spectrum of the GeSn PD with the top Au grating is also shown in Fig. 2, which exhibits an first increase and then decrease. An absorption peak due to SPP mode in Au grating is obtained around 2 000 nm. It can be seen that the spectra of GeSn PD with and without Au grating are quite different, which indicates that

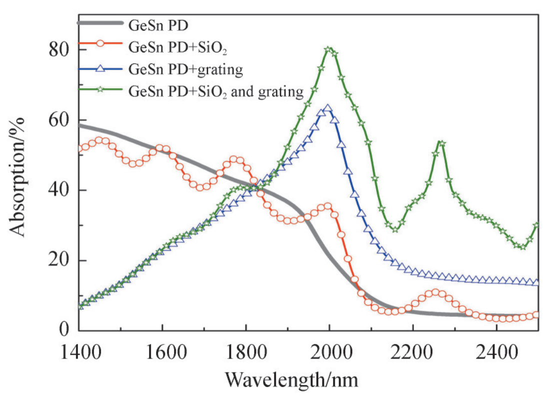


Fig. 2 Optical absorption spectra of the GeSn PD with the four structures

the absorption properties of GeSn can be obviously modified by an Au grating. The absorption of the PD with Au grating is 63% around 2 000 nm, which is larger than the result of PD containing F-P mode. This is an advantage of Au grating. When the F-P mode and SPP mode are supported in the GeSn PD simultaneously as shown in Fig. 1(d), the absorption spectrum can be significantly adjusted (Fig. 2).It can be seen from the Fig.2 that the overall trend of the spectrum is basically consistent with that of the PD only containing the Au grating. On this basis, a series of relatively small absorption peaks appear, and the corresponding wavelengths consist with the resonant wavelength of F-P mode supported in the GeSn PD containing SiO_2 layer. Therefore, the F-P mode and SPP mode are supported simultaneously in the GeSn PD by adding the SiO_2 layer and the top Au grating. At the wavelength of 2 000 nm, the optical absorption corresponding to this sample is 80%. Considering the optical absorption (20%) of GeSn PD without F-P mode or SPP mode, the enhancement of absorption caused by the F-P mode, SPP mode and the dual modes can be calculated, they are 15%, 43% and 60%, respectively. It is interesting that the absorption enhancement (60%) due to the dual modes are close to the superposition of the effects of F-P mode and SPP mode(58%), which indicate that the interference between this two modes can be ignored. The related mechanism will be discussed below.

2.2 The influence of the F-P mode supported in GeSn film

The well-known F-P mode origins from that light propagates along the z direction and reflected at the opposite surface of the GeSn film, as shown in Fig. 1(b). In this case, embedding a SiO_2 film into the interface between the GeSn and Ge substrate is necessary to increase the reflectance of incident light on the interface. These F-P mode only allows a standing wave whose half wavelength is an integral multiple of the thickness of the film, the resonant wavelength (λ) can be given by

$$m\left(\frac{\lambda}{2n}\right)=T \qquad m=1,2,3,\cdots,N \tag{2}$$

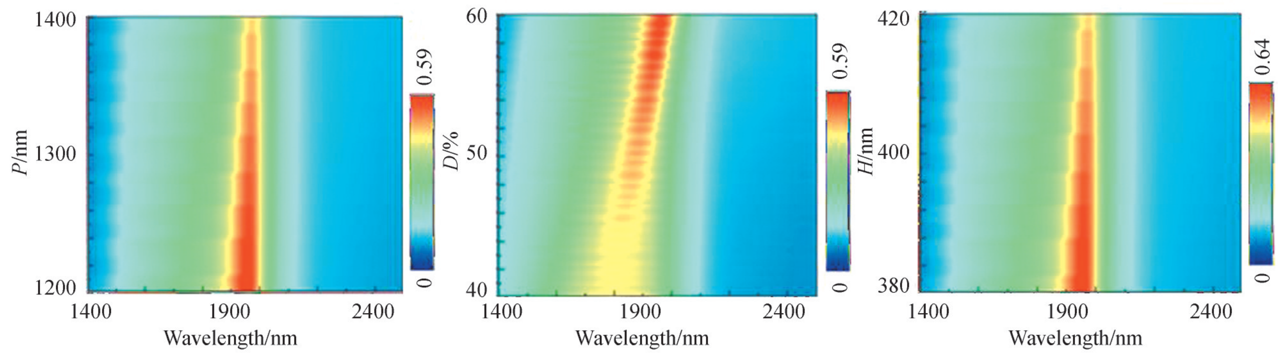
where T and n are the thickness and the refractive index of the GeSn film, m is the order of the F-P mode. From Eq.(2), the resonant wavelengths of the F-P mode are proportional to the thickness (T) of the GeSn film. While top GeSn layer is 1.864 μm, the wavelengths of the F-P mode supported in GeSn film (n=4.31) can be calculated to be 1.461 μm (m=11), 1.607 μm (m=10), 1.785 μm (m=9), 2.009 μm (m=8) and 2.295 μm (m=7), respectively. At the same time, the absorption peaks shown in the simulated absorption spectrum are located at 1.456 μm, 1.601 μm, 1.779 μm, 1.995 μm and 2.254 μm. These calculated wavelengths of F-P mode based on Eq. (2) consist with the locations of the absorption peaks shown in Fig.2. As a result, the peaks in the absorption spectrum of GeSn film containing SiO_2 are attributed to the F-P mode, the wavelengths of these peaks can be adjusted by the thickness of GeSn film obviously.

2.3 The effects of SPP mode originates from the Au grating

The SPP mode supported in Au grating can significantly modify the electromagnetic field around the grating, which results in a absorption peak in the absorption spectrum as exhibited in Fig.2[21].Meanwhile, the wavelength of the SPP mode and the intensity of electromagnetic field can be modified by adjusting the geometric parameters of the grating, such as the period (P), duty cycle (D) and height (H). Because the resonant wavelength (λ) of SPPis given by

$$\frac{2\pi}{\lambda}\sin\theta-n\frac{2\pi}{p}=-\frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon_{\mathrm{m}}(\omega)\varepsilon}{\varepsilon_{\mathrm{m}}(\omega)+\varepsilon}}=k_{\mathrm{spp}} \qquad n=0,\pm 1,\dots,\pm N \tag{1}$$

where, θ is the incident angle of incident light, ε is the dielectric constant of the substrate material on the lower surface of the grating, ε_m is the dielectric constant of the metal grating, and n represents the orders of SPP mode. Fig. 3(a) exhibits the optical absorption spectra of GeSn PD containing Au grating with different P. The position of SPP mode induced by the metal grating is red-shifted and become narrower with increase the P from 1 200 nm to 1 400 nm. It can be concluded that the resonant wavelength is very sensitive to the change of grating period P. With the increase of the D, the resonant wavelength of the Au grating structure is red shifted and the absorption peak is gradually narrowed. The redshift of absorption peak is due to the increase of effective dielectric constant caused by rising the D[22]. Fig. 3 (c) shows the dependency of optical absorption spectrum on the grating H. When the H of the grating changes in the range of 380~420 nm, the peak position of the optical absorption spectra hardly changes with the H. However, the intensity of the peak is greatly affected by H, which is consistent with the SPP mode excitation condition of grating structure.

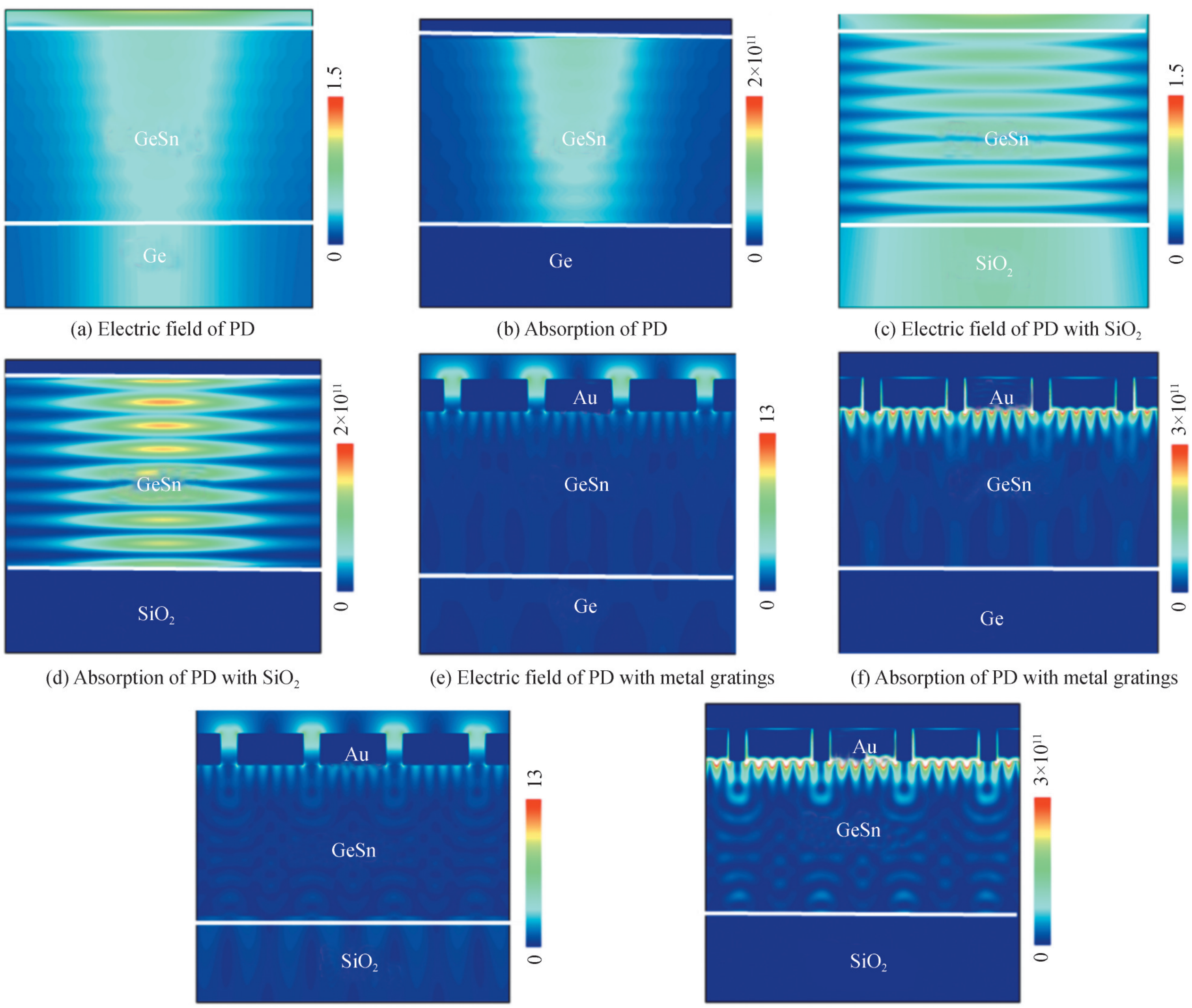


(a) The change of period (b) The change of duty cycle (c) The change of height

Fig. 3 The optical absorption spectra in the range of 1 400~2 500 nm of the GeSn PD containing an Au grating with different grating changes

2.4 The field distributions and the corresponding absorption distributions of these four types of samples

Figs. 4(a) and 4(b) exhibit the electric field and absorption distributions at 2 000 nm of GeSn PDs without the SiO_2 layer or the Au grating. The field distributions in the GeSn and Ge layer are similar, however, the



(a) Electric field of PD (b) Absorption of PD (c) Electric field of PD with SiO_2

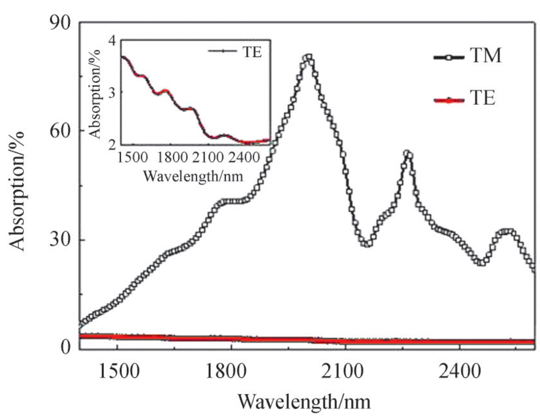
(d) Absorption of PD with SiO_2 (e) Electric field of PD with metal gratings (f) Absorption of PD with metal gratings

(g) Electric field of PD with dual-structure (h) Absorption of PD with dual-structure

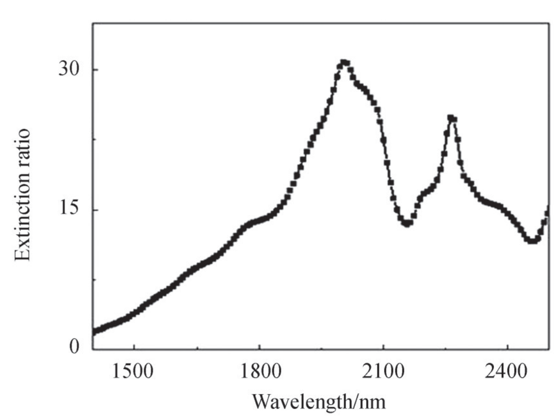
Fig.4 Simulated electric field distribution at 2 000 nm and the corresponding absorption distributions of these four types of samples

GeSn film dominates the optical absorption. This phenomenon originates from the longer cutoff wavelength of GeSn compared with that of Ge. At the same time, the incident light is transmitted rather than reflected at the GeSn/Ge interface because of the small difference of the refractive index between GeSn and Ge, thus the similar field distributions are obtained in the GeSn and Ge layer. In the case of the GeSn PD with SiO_2 layer, the antinodes and node of the electric field alternating appear in the GeSn layer as shown in Fig. 3(c), which is a typical feature of the F-P mode. Based on the field distribution, the order of the P-F mode can be determined to be 8, which is consistent with the calculated result according to Eq. (2). Meanwhile, the absorption intensity in the GeSn layer is obviously enhanced as shown in Fig. 4(d). This feature donates the benefits of F-P mode on the absorption enhancement. In a GeSn PD with an Au grating, the intensity of electric field near the surface of the grating are significantly higher than those in other regions as shown in Fig. 4(e), which is attributed to the SPP mode supported in the grating. And the enhanced optical absorption (Fig. 4(f)) is mainly appeared at the place close to the interface of grating and GeSn film. When the GeSn PD containing the dual structure (the added SiO_2 layer and the Au grating), the electric field localized near the grating surface and in the GeSn film are obtained simultaneously as exhibited in Fig. 4(g). The former origins from the SPP mode, the latter is attributed to the F-P mode based on the results shown in Figs. 4(c) and 4(e), respectively. The corresponding optical absorption distributions are exhibited in Fig. 4(h), which shows similar characters compared with the field distributions. At the same time, the electric field and optical absorption distributions attributed to SPP mode are unchanged compared with those shown in the GeSn PD only containing an Au grating, while the F-P part is obviously modified compared with the results in GeSn PD with a SiO_2 layer. This phenomenon indicates that the absorption enhancement caused by SPP mode are larger than the effect due to F-P mode. Moreover, the overlap of the electric field between F-P mode and SPP mode are quiet small, thus the interference between these two parts can be ignored. These features are verified by the simulated absorption spectra as shown in Fig.2.

In order to study the influence of polarization, the absorption spectra of GeSn PD containing the dual structure under TM and TE polarization are simulated respectively (Fig. 5(a)), where TE/TM indicates whether the electric field component of the incident light is parallel or perpendicular to the direction of Au nanorods as shown in Fig. 1. The optical absorptivity of the sample is around 80% at 2 000 nm under the TM polarization, while that is only 2.6% under the TE polarization (the inset of Fig. 5(a)). A large extinction ratio around 31 is obtained at 2 000 nm as shown in Fig. 5(b). Under TE polarization, the size of the grating in the polarization direction of the light source is much larger than the skin depth of the Au, which can no longer meet the condition of SPP (Eq. (1)). In this case, most of the incident light is reflected rather than transmitted/absorbed around the grating surface. Thus, the absorption of the GeSn PD containing the dual-structure under the TE polarization is very low, which results in a large extinction ratio around 31 at 2 000 nm. At the same time, because the F-P mode supported in the GeSn film are independent of the polarization, the polarization sensitivity of the sample is associated to the SPP mode. As a result, the optical absorption spectrum can be



(a) Optical absorption spectra under the TM and TE polarization



(b) Extinction ratio as a function of wavelength

Fig.5 Optical absorption spectra and extinction ratio of the GeSn PD with the dual-structure modified obviously by changing the polarization of the incident light. This advantages make the GeSn PD with the dual-structure promising for applications in polarization-dependent devices.

3 Conclusion

In conclusion, an innovative GeSn PD enhanced by the F-P mode and the SPP mode are proposed. The F-P mode originates from the GeSn film assisted by an embedded SiO_2 film, while the SPP mode is associated to the added Au grating. Because of the enhanced light-matter interaction by the dual-mode, the absorption at 2 000 nm of the PD is increased to 80%, which is four times larger than that of the GeSn PD without the dual structure. At the same time, based on the results of field distribution, these two types of modes can be considered independent due to the small electric field overlap between them. Thus, the absorption enhancement comes from the superposition of the effects of these dual-mode. Meanwhile, because the SPP mode in the grating is sensitive to the polarization, a large extinction ratio around 31 is obtained at 2 000 nm. Considing the considerable large absorption and the polarization sensitivity, GeSn PD containing the dual-structure promises to be a unique candidate for the Si-based innovative optoelectronic devices.

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