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Planar and Incident Angle-insensitive Hot-electron Photodetection with Tamm Plasmons

Xiaoyan Yang*

School of Politics and Public Administration, Guangxi Normal University, Guilin 541004, China

Abstract

Unlike nanostructured hot-electron photodetectors (HE PDs), planar counterpart is attracting increasing attention due to the advantages of the cost-effective fabrication and large-scale application. However, the working wavelengths of most HE PDs are closely related to the incident angles. Herein, it is demonstrated a planar HE PD based on Tamm plasmons whose excitation wavelength is insensitive to the incident angle under transverse-electric incidence. Detailed studies show that high refractive index of Ge is responsible for the relatively stable working wavelength when incident angle is variable.

Keywords

Hot Electron; Tamm Plasmons; Photodetection; Incident Angle; Resonance Wavelength.

1. Introduction

Extracting hot electrons generated in metals has shown to provide promising benefits in several photon technologies, such as photocatalysis [1], photovoltaics [2], and photodetection [3]. In particular, hot-electron photodetection has been attracting a great deal of interests due to the salient capabilities of room-temperature operation, gap-free detection, and ultra-fast response [4]. Utilizing internal photoemission mechanism, hot-electron photodetectors (HE PDs) convert incidence photon energies into measurable photocurrent. Over the past decades, many hot-electron photodetectors (HE PDs) with various device configurations have been demonstrated, exhibiting continuously improved responsivities. Among them, nanostructured HE PDs with manipulated spectral responses and enhanced photoelectric conversion efficiencies have been widely studied [5]. However, nanostructured HE PDs often require complicated/costly fabrication and confront difficulty in large-are application.

Instead of nanostructured HE PDs, planar HE PDs show advantages of cost-effective fabrication and large-scale application. In the past decade, a number of planar HE PDs based on excitations of micro-cavity and Tamm plasmons (TP) have been studied, paving a feasible route to practical photodetection [6]. However, to the best of our knowledge, most planar HE PDs suffer from the high dependences on incident angle. Consequently, the device working wavelengths should be adjusted with the incident angle to guarantee strong absorption efficiencies, degrading the flexibility of device operations. Therefore, the planar HE PDs with incident angle-insensitive spectral responses are highly desired.

In this work, we present a design of planar HE PDs composed of an Au layer supported by a distributed Bragg reflector (DBR) consisting of alternative Ge and SiO_2 layers. The designed device excites TP resonance around the Au-DBR interface and TP wavelength is insensitive to the incident angle under transversed electric (TE) incidence due to high refractive index of Ge layer. It is believed that our designed device can inspire further studies on planar hot-electron photodetection for practical applications.

2. Results and Discussion

The designed planar HE PD is composed of DBR and an Au layer, as shown in Fig. 1(a). The DBR consists of 10 pairs of periodically arranged Ge/SiO_2 layers. The contact between Au and adjacent Ge layer forms a Schottky junction with barrier height (Φ_b) of 0.59 eV [7]. Fig. 1(b) depicts the hot-electron dynamics within the Au-Ge junction. In specific, the energy depositions in Au layer induce the electronic transition from the levels below Fermi level (E_F) to the higher unoccupied levels, giving rise to the energetic electrons whose energy distributions significantly deviate from Fermi-Dirac distributions. The energy exceed E_F is denoted by E_e. The generated hot electrons diffuse to the Au-Ge interface, experiencing transport losses caused by electron-electron and electron-phonon scatterings. Upon arriving at the Au-Ge interface, the above-barrier ($E_e > \Phi_b$) hot electrons may inject into the Ge layer with interfacial loss, while below-barrier ($E_e < \Phi_b$) hot electrons would be blocked by the barrier. To assess the device performances, it is necessary to investigate the optical responses, as shown in Fig. 1(c). The wavelength-dependent reflection efficiencies of the designed device and bare DBR are studied in a finite-element platform. It is found that there is a reflection dip at 1199 nm in the forbidden band of bare DBR, indicating the excitation of Tamm plasmons (TPs) [8,9]. In general, TP excitations induce energy depositions in absorbable materials, i.e., Au and Ge. Therefore, the wavelength-dependent absorption was studied, as shown in Fig. 1(d). It is found that both absorptions in Ge and Au contribute to the high absorption efficiency at TP wavelength.

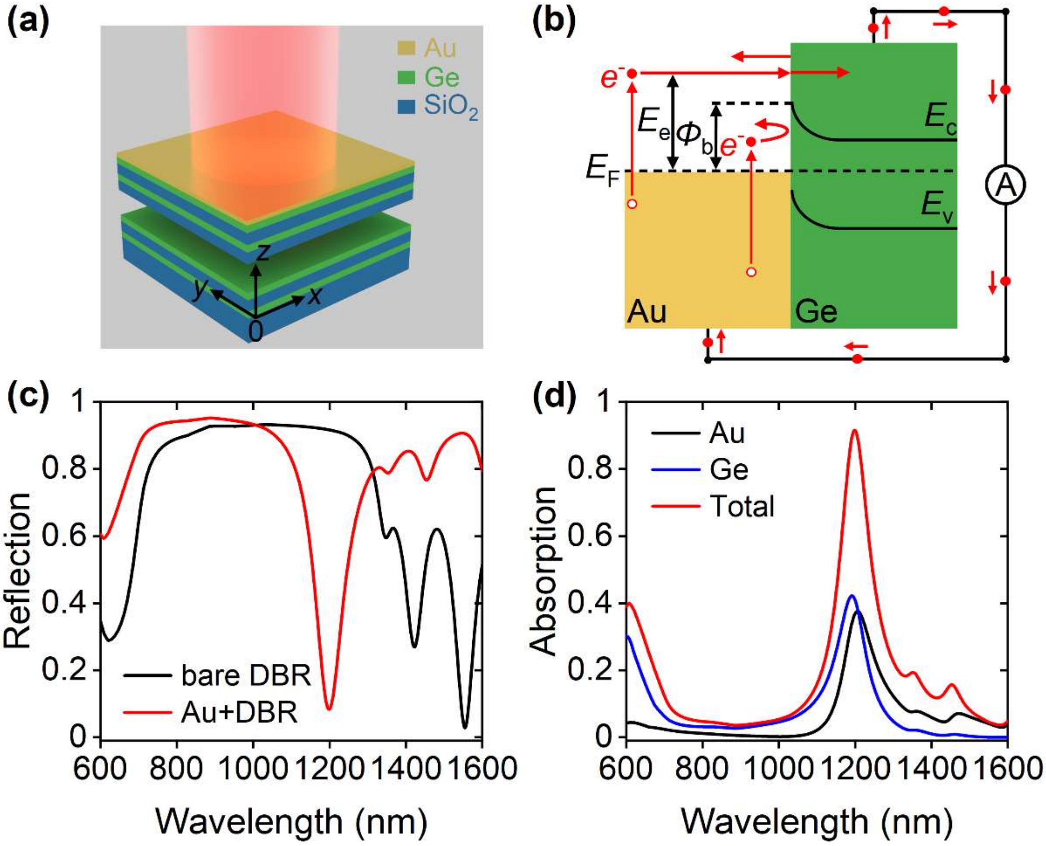

Fig. 1 (a) Schematic of the designed HE PD. (b) The energy diagram of the Au-Ge junction for hot-electron extraction. E_c and E_v are the conduction and valance bands of Ge, respectively. (c) The reflection spectra of the designed device and bare DBR obtained by removing Au layer. (d) Contributions of different layers to total absorption efficiency.

To gain more insight into the observed spectral response, the spatial distributions of electric ($|E|$) and magnetic ($|H|$) fields at TP wavelengths were studied. Note that $|E|$ and $|H|$ have been normalized by the electric ($|E_0|$) and magnetic ($|H_0|$) fields of incident light, as shown in Figs. 2(a) and 2(b)

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respectively. It is found that TP excitation produces field enhancements around the Au-Ge interface. To further assess the spectral tunability of the designed device, the relation between the reflection efficiencies and specified structural parameters, such as Au layer thickness (d_{Au}) and the thickness (d_{Ge}) of adjacent Ge layer, as depicted in Fig. 2(c) and 2(d) respectively. It is found that, with the increases of d_{Au}, TP wavelength experiences a blue-shift. However, TP wavelength shifts toward longer wavelengths when d_{Ge} increases from 30 nm to 70 nm. Anyway, the low reflection efficiencies maintain and one can conventionally adjust TP wavelength by adjusting d_{Au} and d_{Ge}.

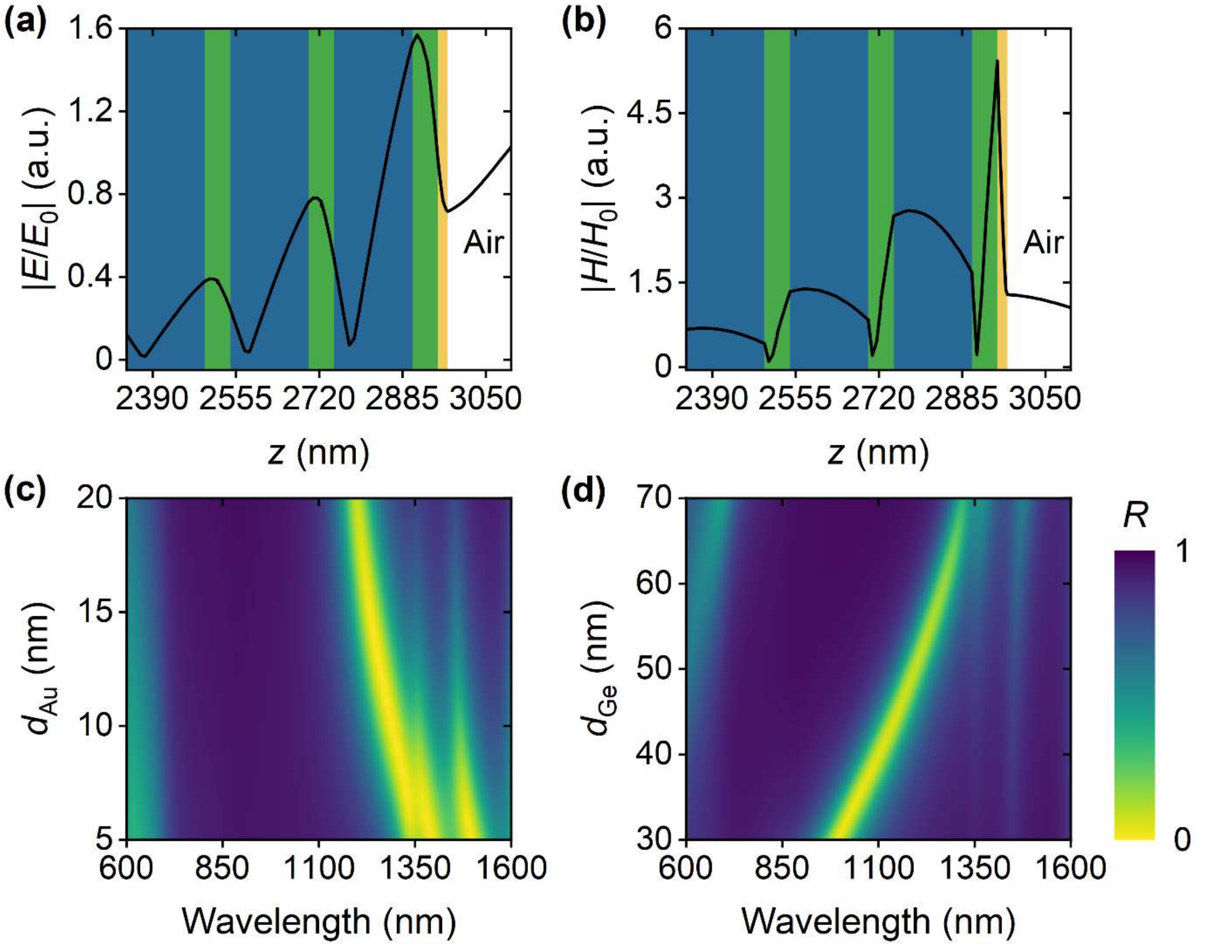

Fig. 2 (a) Profiles of (a) normalized electric ($|E/E_0|$) and (b) magnetic ($|H/H_0|$) fields at TP wavelength of 1199 nm. Wavelength-dependent reflection as a function of (c) d_{Au} and (d) d_{Ge}.

In order to realize incident angle-insensitive photoelectric conversion, it is absolutely necessary to explore the dependences of absorption efficiencies (A) in the Au layer on the incident angle. As shown in Figs. 3(a) and 3(b), the designed device exhibits relatively stable TP wavelengths when incident angle varies from 0° to 60° under transverse-electric (TE) transverse-magnetic (TM) incidences, respectively. In specific, TE-polarized incidence is more favorable for achieving incident angle-insensitive hot-electron extractions. It is because that the shift of resonance wavelength is reversely proportional to the refractive index of dielectric used [10]. For the designed device, Ge refractive index is up to 4.46. After necessary optical investigations on TP excitations, attentions were turned to electrical assessments of the designed device. The well-known Fowler equation was employed to obtain responsivity spectra, as shown in Figs. 3(c) and 3(d). It is found that the responsivity at 1196 nm at reach to 7.7 mA/W when incident angle is 0°. With incident angle goes up to 50°, the designed device has a 6.9 mA/W (9.8 mA/W) at 1167 nm (1108 nm) under TE (TM) incidence.

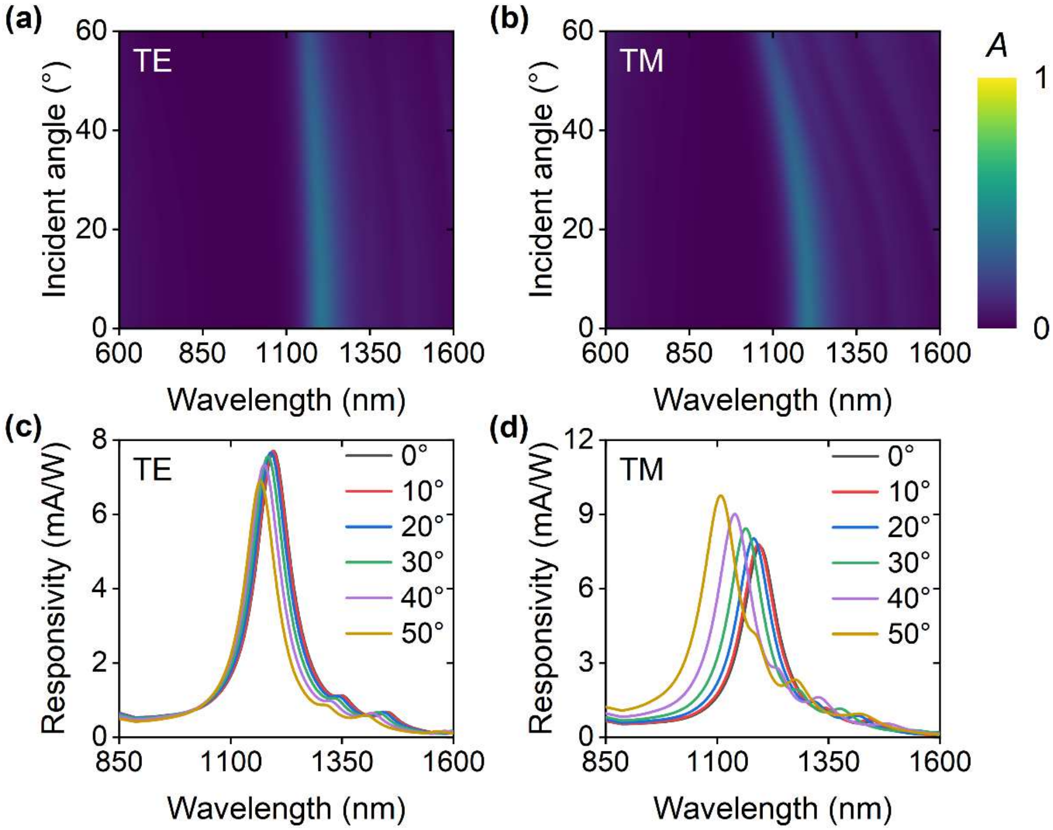

Fig. 3 Absorption spectra of Au layer as a function of incident angle when incident light is (a) TE- and (b) TM-polarized. In the cases of (c) TE and (d) TM incidences, wavelength-dependent responsivity when incident angle is increase from 0° to 50° with a step of 10°.

3. Conclusion

To summarize, a purely planar design of HE PDs has been proposed to realize the relatively stable working wavelength when the incident angle is variable. The deigned device relies on the excitation of Ge-involved TP. Detailed studies show that TE-polarized incident light can satisfy the demand on the insensitivity of resonance wavelength to incident angle. High refractive index of Ge in DBR is responsible for the observed minimum shift of TP wavelengths. Using Fowler equation, the photoelectric studies on the designed device was accomplished.

Acknowledgments

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