**Planar narrowband Tamm plasmon-based hot-electron photodetectors with double distributed Bragg reflectors**

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**Abstract**

Hot-electron photodetectors (HE PDs) are attracting a great deal of attention from plasmonic community. Many efficient HE PDs with various plasmonic nanostructures have been demonstrated, but their preparations usually rely on complicated and costly fabrication techniques. Planar HE PDs are viewed as potential candidates of cost-effective and large-area applications, but they likely fail in the simultaneous achievement of outstanding optical absorption and hot-electron collection. To reconcile the contradiction between optical and electrical requirements, herein, we propose a planar HE PD based on optical Tamm plasmons (TPs) consisted of an ultrathin gold film (10 nm) sandwiched between two distributed Bragg reflectors (DBRs). Simulated results show that strong optical absorption (>0.95) in the ultrathin Au film is realized. Electrical calculations show that the predicted peak photo-responsivity of proposed HE PD with double DBRs is over two times larger than that of conventional single-DBR HE PD. Moreover, the planar dual-DBR HE PDs exhibit a narrowband photodetection functionality and sustained performance under oblique incidences. The optical nature associated with TP resonance is elaborated.

**1. Introduction**

Energetic carriers (i.e., hot electrons and holes) generated in metal nanoparticles and nanostructures due to the optical absorption promise considerable benefits in a variety of applications, such as nanoplasmonic sensing [1, 2], photocatalysis [3, 4], solar energy harvesting [5, 6], surface imaging [7, 8], and photodetection [9–15]. During the past decade, hot-electron photodetection has been extensively studied due to the capability of band gap-free detection [16], high tunability of working wavelength [17], and the possibility of room-temperature operation [18]. Hot-electron photodetectors (HE PDs) collect the hot electrons with sufficient energy that surmount the Schottky barrier in the metal–semiconductor (M/S) junction, forming a steady-state photocurrent. Given the extremely low internal quantum efficiency (IQE), several strategies have been proposed to boost IQE of HE PDs, such as adoption of multi Schottky junctions [19], reduction of Schottky barrier height [20], manipulation of interface roughness [21], use of bias voltage [22], and desings of various plasmonic nanostructures [23]. Indeed, a number of patterned metal nanostructures [24–29] that support the excitation of surface plasmons have been integrated within HE PDs to improve the performance of devices because enhanced localized electric field around M/S interface associated with surface plasmons can boost hot-electron generation efficiency [30].

In practice, despite the great progresses in nanofabrication technologies, the fabrication of HE PDs with patterned metal nanostructures is accompanied by complicated (usually costly) preparation procedures and difficulties of large-area application. The planar HE PDs, on the other hand, suffer from either weak photon...
absorption or poor hot-electron collection. For a planar HE PD, as the thickness of metal film increases, more photons would be absorbed in metal in the visible and near infrared regimes, whereas the thermalization loss inevitably raises during the hot-electron transport process, resulting in the reduction of hot-electron collection efficiency. In other words, the dilemma for enhancing planar hot-electron photodetection lies in the lack of successful light trapping approaches for ultrathin metal films. Additionally, narrowband photoelectric response is highly desired in some applications that involve hot-electron photodetection, such as hot electron-assisted sensors [1, 2] and spectrally selective plasmonic nanodiodes [31]. However, the full width at half maximum (FWHM) of photoelectric response for planar HE PDs is relatively large compared with that of HE PDs with patterned metal nanostructures [2, 32]. In order to promote the development of planar hot-electron photodetection, both drawbacks must be addressed.

In this work, we propose a design of planar narrowband HE PDs based on Tamm plasmon (TP) resonance which FWHM is less than 20 nm. It is reported that the mean free path of hot electrons in Au is about 20 nm [33]. However, previously reported TP-based HE PDs with single DBR used a relative thick Au film with thickness larger than 20 nm to realize strong optical absorption [32–36]. Therefore, hot-electron loss during the transport process is considerable because of the probability of a hot electron reaching the metal-semiconductor interface being reduced to a value less than 37%. In order to suppress transport loss, the thickness of Au film needs to be reduced further. Meanwhile, in order to guarantee the reliability of experimental preparation and characterization, the thickness of a continuous and ultrasmooth film Au film should be larger than 5 nm [37, 38]. Our device employs an ultrathin gold (Au) film (10 nm) sandwiched between two properly engineered distributed Bragg reflectors (DBRs), simultaneously guaranteeing prominent photon absorption and hot-electron collection. Benefitting from strong optical absorption (>0.95) in the ultrathin Au film, the peak photoresponsivity (PR) of planar HE PD with double DBRs at the TP resonance is significantly improved from that of conventional single-DBR HE PD. Detailed optical evaluations were performed to unveil the physics behind the TP resonance.

2. Simulation method and theoretical calculation

With the optical constants from Palik [39], optical responses of the designed device were examined by solving Maxwell’s equations in a finite-element platform (COMSOL Multiphysics) [40]. Considering the planar symmetry geometry of the planar HE PDs, two-dimensional (2D) computational domains with bounded boundaries were modelled to reduce the simulation time. The propagation of the incident signal wave is set along the negative direction of z axis. Two perfectly matched layers were used along the positive and negative directions of z axis to truncate the simulation region. Adopting the assumption of the infinite planes for the device, the periodic boundary condition was used along x direction. The triangles with characteristic size of 5 nm are used to mesh the 2D simulation region. After convergence test for the simulated results, we obtained the optical absorption in the ultrathin Au film.

Based on the simulated optical results, the performance of the proposed HE PD could be assessed by the probability-based analytic calculations. Several theoretic studies have been addressed how to calculate the PR spectrum of a planar HE PD [17, 34, 35]. These calculations usually evaluate four quantities that quantify hot-electron dynamic process within M/S junction, namely, hot-electron energy distribution, spatial hot-electron generation rate, hot-electron transport probability, and energy-dependent injection probability. The detailed descriptions and formula about these quantities are present in the following.

Upon the photon absorption, a hot electron is excited with relative energy \( E - E_0 \) over the Fermi energy level (\( E_0 \)). Hot-electron energy distribution \( D(E) \) is calculated and normalized [41].

\[
D(E) = \frac{\rho(E-h\nu)f(E-h\nu)\rho(E)[1-f(E)]dE}{\int \rho(E-h\nu)f(E-h\nu)\rho(E)[1-f(E)]dE}
\]  

where \( \nu \) is the energy of incident light, \( \rho(E-h\nu) \) [\( \rho(E) \)] the parabolic electron density of states at the initial [final] energy level, and \( f(E-h\nu) \) [\( f(E) \)] the corresponding Fermi–Dirac distribution function. The spatial hot-electron generation rate \( G(z) \) is calculated by [35]

\[
G(z) = \text{Im}(\varepsilon_m) |E_{elec}|^2/(2\hbar)
\]

where \( \text{Im}(\varepsilon_m) \) is the imaginary part of metal dielectric function (\( \varepsilon_m \)), \( E_{elec} \) is the spatial electric field strength, and \( \hbar \) is the reduced Planck constant. The chance that hot electrons with different generation positions reach the M/S interface is quantified by spatial transport probability \( P_{\text{trans}} \) that can be written as [42]
where \( l(E) \) is hot-electron mean free path that determined by electron-electron and electron-phonon scatterings, \( \varphi \) is the moving angle, and \( d(z) \) is the distance from the hot-electron generation position to the M/S interface.

After arriving at the M/S interface, the hot electron has an injection probability \( P_{\text{inj}} \) to cross the interface which is calculated by

\[
P_{\text{inj}}(E) = \int_{k_{\text{inj}}}^{k_{\text{out}}} \frac{4 \sqrt{(k_m^2 - k_y^2)(k_m^2 - k_{\text{out}}^2)}}{\left( k_m^2 - k_{\text{inj}}^2 + \sqrt{k_m^2 - k_y^2} \right)^2} \frac{k_y}{k_m \sqrt{k_m^2 - k_y^2}} dk_y
\]

where \( k(E) \) is the electron wave vector, \( k_{\text{inj}} \) and \( k_{\text{out}} \) are the incident and transmitted electron wave vectors, respectively.

\[
k_{s}(E) = \sqrt{2m_e(E - E_F - \Phi_0)}/\hbar
\]

\[
k_{\text{inj}}(E) = \sqrt{2m_m E}/\hbar
\]

where \( m_e \) and \( m_m \) are the effective electron masses in the semiconductor and metal, respectively. It is noted that the calculation of \( P_{\text{inj}} \) considers the hot-electron interfacial reflection and the continuity of tangential hot-electron momentum component parallel to the M/S interface [18]. In our calculations, the power of the incident light for any wavelength was normalized to be 1 W. Therefore, we obtain wavelength-dependent PR(\( \lambda \)) of the proposed HE PDs that can be written as

\[
\text{PR}(\lambda) = \int \frac{eA(\lambda)}{hc} G(z) D(E) P_{\text{trans}}(E, z) P_{\text{inj}}(E) dE dz
\]

where \( A(\lambda) \) is the simulated absorption spectrum, \( h \) is the Planck constant, \( e \) is the electron charge, and \( c \) is the light speed.

3. Results and discussion

Figure 1 shows the schematic and structure parameters of the proposed device. The device consists of a dual-DBR structure with an ultrathin Au film, two DBRs, and a silica substrate. The DBRs with identical central wavelengths (\( \lambda_{\text{central}} = 800 \) nm) are composed of periodically alternating TiO\(_2\) and SiO\(_2\) films. The thickness of the absorbable layer of Au is denoted as \( d_1 \). The thickness of the TiO\(_2\) film adjacent to Au in bottom DBR (bot-DBR) is denoted as \( d_2 \). The optical thicknesses of TiO\(_2\) and SiO\(_2\) films in both DBRs are the same as a quarter of the central wavelength. The numbers of pairs of top and bottom DBRs are denoted as \( N_{\text{top}} \) and \( N_{\text{bot}} \), respectively. Figure 1(b) shows the operation of HE PDs relies on three consecutive electronic processes that occur within the Au-TiO\(_2\) junction: hot-electron generation, transport, and injection. When the device is illuminated by a light signal, photon energies are deposited in Au film through the excitation of TPs. Consequently, electrons below Fermi level are excited to higher unoccupied levels. The generated hot electrons with relative energy of \( E - E_F \) diffuse to Au-TiO\(_2\) interface, experiencing electron-electron and electron-phonon scatterings. Upon arriving at the Au-TiO\(_2\) interface, the over-barrier hot electrons can be injected into TiO\(_2\) with interfacial reflections. Below-barrier hot electrons are blocked by Schottky barrier.
with height of $\varphi_p$ (1 eV for Au-TiO$_2$ contact) [23]. It is noted that the tunnelling effect in Au-TiO$_2$ junction is negligible even for heavy-doping TiO$_2$ film [43]. The injected hot electrons are collected by an electrode, contributing to a detectable photocurrent. When $N_{\text{top}} = 2$, $N_{\text{bot}} = 12$, and $d_1 = 10$ nm, figure 1(c) plots the absorption ($A_{\text{PD}}$, black solid line), transmission ($T_{\text{PD}}$, blue solid line), and reflection ($R_{\text{PD}}$, red solid line) spectra of the planar dual-DBR HE PD. The black dashed line in figure 1(c) presents the reflection spectrum ($R_{\text{bare}}$) of the bare DBR with DBR pair numbers of 14. Red solid line shows that there is a narrow reflection dip with incident light wavelength ($\lambda$) of 936 nm appears in the forbidden band of DBR by using the dual-DBR + Au structure, revealing the presence of TP resonance. As shown in figure 1(d), the strength ($A_{\text{TP}}$) and position ($\lambda_{\text{TP}}$) of TP resonance peak are strongly related with $N_{\text{top}}$ and $N_{\text{bot}}$. With different numbers of bot-DBR pairs, as $N_{\text{top}}$ increases from 0 to 15, $A_{\text{TP}}$ increases first and then decreases to rather small absorption ($\sim$0). Meanwhile, $\lambda_{\text{TP}}$ shifts towards shorter wavelength first and then remains nearly unchanged. We found that top DBRs with small $N_{\text{top}}$ (such as $N_{\text{top}} = 1$) assist light trapping in the ultrathin Au film. However, with further increasing $N_{\text{top}}$, top DBRs prevent incident light from permeating into device, leading a weak absorption. In this study, optimal numbers of $N_{\text{top}} = 2$, $N_{\text{bot}} = 12$ were chosen for an optically superior and ultrathin Au film.

Besides the numbers of both DBR pairs, the dependences of optical absorption on $d_1$ and $d_2$ were also investigated, as depicted in figures 2(a) and (b), respectively. Figure 2(a) shows that: (1) as $d_1$ increases from 10 to 70 nm, resonance wavelength displays a blue shift; (2) with an appropriate $d_1$ (10–20 nm), almost all the incident light energy can be absorbed by the thin Au film; (3) further increasing $d_1$, most of the incident light is directly reflected by the top DBR and Au film. For the tunability of the working wavelength, we break the constraint that the optical thickness of TiO$_2$ layer adjacent to Au is a quarter of $\lambda_{\text{central}}$. It is clear from figure 2(b) that, as $d_2$ increases from 20 nm to 400 nm, device shows three absorption bands from visible to near infrared band and device keeps strong optical absorption at TP resonance. This multiband response of the device increases the flexibility of the device preparation because more than one values of $d_2$ can realize a TP resonance at a targeted wavelength. Overall, it is convenient for one to obtain targeted optical responses by adjusting the planar thicknesses. To get more insight into TP resonance, phase accumulation ($\phi_{\text{PD}}$) at the interface between Au+top-DBR and bot-DBR+substrate was examined by using the optical transfer-matrix method [17]. $\phi_{\text{PD}}$ can be expressed as.

$$ P_{\text{PD}} = (P_1 + P_2) / 2\pi $$

where $P_1$ ($P_2$) is the phase shift due to the reflection for the wave incident on Au+top-DBR (bot-DBR+substrate) from TiO$_2$ medium. $P_{\text{PD}}$ was normalized by $2\pi$. Figures 2(c) and (d) depict the maps of wavelength-dependent $P_{\text{PD}}$ as a function of $d_1$ and $d_2$, respectively. One can see in figure 2(c) that there is a contour lines corresponding to $P_{\text{PD}} = 0$. Moreover, in figure 2(d) there are three contour lines corresponding to $P_{\text{PD}} = 0$, $\pi$, and $2\pi$. The absorption profiles presented in figures 2(a) and (b) indicate that TP resonances of the device occurs when the phase matching condition (i.e., $P_1 + P_2 = 2\pi m$, in which $m = 0, 1, 2\ldots$) is satisfied [36]. The absorption band in figure 2(a) presents zero-order TP resonance. The absorption bands in figure 2(b) present zero-, first-, and second-order TP resonances.

To explore the electrical responses of proposed device, three electronic processes described above were quantitatively analyzed [34], as presented in the following discussions. Figure 3(a) plots the spatial distributions

Figure 2. Contour map of absorption spectra as a function of (a) $d_1$ and (b) $d_2$. (c) and (d) $P_{\text{PD}}$ corresponding to (a) and (b). The black lines represent the phase accumulation of 0.
of the planar HE PD is strongly related with should originate from the dependence of IQETP on hot electrons boosted photocurrent output. Red curve in hot-electron spatial distributions are expected to significantly relieve thermalization loss and therefore to realize the further reduction of work function ($W = 5.1$ eV) of Au and the electron affinity ($\chi = 0.75$ eV) of SiO$_2$. Only generated hot electrons that reach the Au-SiO$_2$ interface will have enough energy to surmount the barrier of Au-SiO$_2$ contact with a value of 4.35 eV, i.e., the difference of interface between Au and bottom DBR. When hot electrons diffuse to the Au-TiO$_2$ and Au-SiO$_2$ interfaces. But the hot electrons that reach the Au-SiO$_2$ interface will not reach the Au-TiO$_2$ interface. Considering the adopted ultrathin Au layer, these favourable transport processes usually degrade the performance of HE PDs because the spatial optical absorption associated with TP resonance reduces the lifetime and mean free path of hot electrons in metals are inversely proportional to hot-electron energy.

Figure 3. Spatial distributions of $G$ and $P_{\text{tran}}$ with $\lambda_{\text{TP}}$ of 936 nm. (b) $N_{\text{gen}}$ and $N_{\text{tran}}$ as a function of $E - E_0$ at 936 nm. (c) The calculated energy-dependent $N_{\text{col}}$ at 936 nm. (d) The proportion ($\alpha$) of over-barrier hot electrons as a function of $\lambda_{\text{TP}}$. (e) The dependences of EQE$_{\text{TP}}$ (red line) and $A_{\lambda_{\text{TP}}}$ (blue line) on $\lambda_{\text{TP}}$. (f) IQE$_{\text{TP}}$ (solid line) and fitted peak IQE (dashed line) from Fowler equation as a function of $\lambda_{\text{TP}}$.

We obtained the external quantum efficiency (EQE$_{\text{TP}}$) of device with the different TP resonance wavelengths. Red line in figure 3(e) shows that EQE$_{\text{TP}}$ decreases with $\lambda_{\text{TP}}$. It is known that EQE describes the overall efficiency with which the device converts incident photons to collected hot electrons. However, EQE convolutes the effects of optical absorption with the subsequent three hot-electron electronic processes. Blue solid line in figure 3(e) shows that device maintains strong optical absorption with the red shift of $\lambda_{\text{TP}}$. Therefore, considering the relation between EQE and IQE (i.e., $\lambda_{\text{TP}} = A_{\lambda_{\text{TP}}} \times \text{IQE}_{\text{TP}}$), the reduction of EQE$_{\text{TP}}$ with red shift of $\lambda_{\text{TP}}$ should originate from the dependence of IQE$_{\text{TP}}$ on $\lambda_{\text{TP}}$. Solid line in figure 3(f) shows that the calculated IQE$_{\text{TP}}$ of the planar HE PD is strongly related with $\lambda_{\text{TP}}$. It is considered that the reduction of $\alpha$ with $\lambda_{\text{TP}}$ is responsible.
for the $\text{IQE}_{\text{TP}}$ reduction with $\lambda_{\text{TP}}$. Moreover, the calculated $\text{IQE}_{\text{TP}}$ was fitted with Fowler equation

$$\text{IQE}_{\text{TP}} = \frac{\eta (hc - \lambda_{\text{TP}} \Phi_0)^2}{\lambda_{\text{TP}} hc}$$

where $\eta$ is the coefficient that depends on device-specific details [10]. It is found that the fitted (dashed) line with coefficient of $\eta = 0.0227$ agrees well with the calculated (solid) line, suggesting the rationality of our electrical evaluations.

We also investigated, for comparison purposes, the performances of the planar HE PDs with and without (w/o) top DBR. First, the device with parameters of $d_2 = 45$ nm and $d_1 = 10$ nm were exemplified. Figures 4(a) and (b) show the calculated $A_{\text{PD}}$ and PR spectra, respectively. It was found that: (1) the peak absorption of dual-DBR design (i.e., with top DBR) is enhanced by over 2-fold compared with that of single-DBR design (i.e., without top DBR) with a blue shift ($\sim 10$ nm) in position; (2) the peak photo-responsivity (PR $\sim 2.35$ mA W$^{-1}$ at $\lambda_{\text{TP}} = 843$ nm) of the device with top DBR increased by over 2-fold compared with that of the device without top DBR; (3) the FWHM of PR spectrum of dual-DBR HE PD is less than 20 nm, which is prominently smaller than that of single-DBR HE PD. For the sake of generality, the peak photo-responsivity ($\text{PR}_{\text{TP}}$) and spectral width (FWHM$_{\text{TP}}$) versus $d_1$ of the designs ($d_1 = 10$ nm) with and without top DBR are shown in figures 4(c) and (d), respectively. Obviously, both optical and electrical performances of dual-DBR system are better than those of the single-DBR design. It is noted that FWHM of dual-DBR HE PDs is only 11 nm at $\lambda_{\text{TP}} = 938$ nm when $d_2 = 80$ nm, which is comparable to the reported FWHM ($\sim 10$ nm) of HE PDs with patterned metal nanostructures [2].

Finally, we examined the angular performances of the proposed dual-DBR HE PD ($d_1 = 10$ nm), with which both the transverse electric (TE) and transverse magnetic (TM) incidences must be considered. As one can see in figures 5(a) and (b), with the increase of incident angle ($\theta$), TP resonance wavelength has a blue shift, but the amount of blue shift under TM incidence is larger than that under TE incidence. Besides the angular optical absorption, the angular electrical responses were also investigated. For TE illuminations, as shown in figure 5(c), PR at TP resonance increases with $\theta$ even if the value of $A_{\text{PD}}$ reduces slightly with $\theta$. For TM illumination, figure 5(d) shows that the high PR is maintained even when $\theta$ is as large as 60°, while the value of $A_{\text{PD}}$ decreases with $\theta$. The distinct behaviours between angular optical and electrical responses are ascribed to that the PR of a HE PD, or equivalently its EQE, is determined not only by optical absorption but also by IQE which is a function of working wavelength, as shown in equation (9). As one can see in figures 5(a) and (b), peak optical absorption reduces with the increase of $\theta$. However, the PR at TP resonance can be somewhat compensated for with the enhanced IQE due to the blue shift of $\lambda_{\text{TP}}$.

\section{4. Conclusion}

In summary, we have demonstrated a planar narrowband HE PD formed by inserting an ultrathin Au film into two DBRs. Our design can circumvent the conventional trade-off between optical absorption and hot-electron transport for planar hot-electron photodetection. Simulated results show that significantly enhanced optical absorption (>0.95) in ultrathin Au film is realized compared to that of single-DBR structure. Transfer-matrix

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure4.png}
\caption{Spectra of (a) $A_{\text{PD}}$, and (b) PR$_{\text{TP}}$ with and without (w/o) top DBR configuration when $d_1 = 10$ nm and $d_2 = 45$ nm. (c) PR$_{\text{TP}}$ and (d) FWHM$_{\text{TP}}$ as a function of $d_1$ when $d_1 = 10$ nm, where single- and dual-DBR systems are compared.}
\end{figure}
method was employed to reveal that TP resonances occur when the phase accumulation at the interface between top-DBR + Au and bot-DBR + substrate is an integer multiple of $2\pi$. Analytical probability-based electrical analysis demonstrated that compared with the single-DBR counterpart, boosted PR ($\sim 2.35 \text{ mA W}^{-1}$ at $\lambda = 843$ nm when $d_2 = 45$ nm) with narrowband spectral width (less than 20 nm) is obtained for the planar HE PDs with double DBRs. Furthermore, these outstanding optical and electrical responses are found to sustain over a broad range of the incident angles. Our work is expected to facilitate the efficient, low-cost, and large-area photodetection.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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