Research article

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Plasmonic hot-electron photodetection with quasi-bound states in the continuum and guided resonances

<https://doi.org/10.1515/nanoph-2021-0069>

Received February 16, 2021; accepted March 18, 2021;
published online April 8, 2021

Abstract: Hot electrons generated in metallic nanostructures have shown promising perspectives for photodetection. This has prompted efforts to enhance the absorption of photons by metals. However, most strategies require fine-tuning of the geometric parameters to achieve perfect absorption, accompanied by the demanding fabrications. Here, we theoretically propose a Ag grating/TiO₂ cladding hybrid structure for hot electron photodetection (HEPD) by combining quasi-bound states in the continuum (BIC) and plasmonic hot electrons. Enabled by quasi-BIC, perfect absorption can be readily achieved and it is robust against the change of several structural parameters due to the topological nature of BIC. Also, we show that the guided mode can be folded into the light cone by introducing a disturbance to become a guided resonance, which then gives rise to a narrow-band HEPD that is difficult to be achieved in the high loss gold plasmonics. Combining the quasi-BIC and the guided resonance, we also realize a

multiband HEPD with near-perfect absorption. Our work suggests new routes to enhance the light-harvesting in plasmonic nanosystems.

Keywords: bound states in the continuum; guided resonance; hot electrons; photodetector; plasmonics.

1 Introduction

Plasmonic nanostructures can support coherent electron oscillations known as surface plasmons (SP), a phenomenon that has triggered various research and applications in the fields of photonics and optoelectronics. Following its optical excitation, a SP can nonradiatively decay into a population of excited single-electron states. Some of these energetic, or hot, electrons can be injected into neighboring molecules and semiconductors and be harnessed for applications ranging from photocatalysis [1–3], photovoltaics [4], and photodetection [5–13]. In a metal/semiconductor (MS) system, hot electrons excited in the metal can generate photocurrents when they overcome the Schottky barrier, which can, in turn, extend the photoresponse to frequencies with energies below the bandgap of the semiconductor. The overall hot electron generation and collection process can be described with a three-step model [9, 14, 15]: (i) hot electrons are generated in the metal through nonradiative plasmon decay after the absorption of photons, (ii) part of hot electrons diffuse to the MS interface before thermalization by electron-electron and electron-phonon scattering, (iii) hot electrons with sufficient energy are injected into the semiconductor via internal photoemission and collected by an external circuit. Therefore, a direct and efficient way to enhance hot electron photodetection (HEPD) is to improve photon absorption and boost the generation of hot electrons. Metamaterial perfect absorbers (MPAs) offered an ideal platform for HEPD since they can achieve unity absorption at the resonant wavelength [11, 16, 17]. To realize perfect

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absorption (PA), various structures and material configurations have been proposed. For example, Li et al. demonstrated an MPA-based photodetector by depositing a Au film on a pre-patterned Si substrate. Through careful design, the localized surface plasmon resonance (LSPR) of the structured top layer and a Fabry-Pérot (FP) resonance can overlap, leading to near unity absorption and high photoresponsivity [6]. Metal-insulator-metal (MIM) configuration in chiral plasmonic metamaterials has also been reported to reach near PA in a particular circular polarization hence realizing circularly polarized HEPD [8]. Recently, Tamm plasmons, introduced by a distributed Bragg reflector (DBR) and MS layer, are also utilized to enhance photodetection. By moving plasmonic resonance into the forbidden band of DBR, the incident light can be strongly confined and absorbed by the metal layer and eventually contributes to enhanced photocurrent [10, 12]. However, to satisfy PA condition, structure fine-tuning is usually required, especially the thickness of the intermediate dielectric layer, which is one of the key parameters in all of the configurations mentioned above. The geometric parameters-sensitive PA of the device is accompanied by the high requirement of fabrication. Therefore, it is desired to obtain a PA that is robust to structural parameters. In addition, due to the intrinsic high optical losses and radiative damping in metallic nanosystems, it is challenging to realize narrow-band HEPD, hindering the applications of spectrally selective photodetection in biomedical sensing, imaging, and communications systems [18].

Driven by the mathematically infinite quality (Q) factor and exotic topological properties in the far-field, optical bound states in the continuum (BIC) have been extensively studied in dielectric systems. BICs were firstly introduced in quantum mechanics [19] and then were developed in acoustics [20, 21], hydrodynamics [22], and electromagnetics [23–25]. For a symmetry-protected BIC, the coupling between a resonant mode and channels radiating to the environment vanishes due to symmetry mismatching, leading to an infinite lifetime and Q factor in systems without dissipation. This novel nonradiative state can also be excited by the destructive interference of several leakage channels, in what is known as accidental BIC [25]. However, a true BIC can only exist in lossless and perfect infinite structures or for extreme values of parameters [26]. In practice, BIC can be realized as a quasi-BIC when both the Q factor and resonance width become finite due to the dissipations in materials and fabrication imperfections while BIC conditions are still satisfied. Besides, BICs can be transformed into quasi-BICs by breaking the symmetry or changing the coupling between resonances to make BIC conditions not satisfied [27]. Although BICs have been experimentally demonstrated and used for various

applications based on dielectric structures, research on BICs in plasmonic systems is limited due to their intrinsic losses. Recently, Liang et al. demonstrated an anisotropic plasmonic metasurface composed of a back Ag film and arrays of pairs of connected, vertically oriented pillar resonators [28]. Governed by quasi-BICs, the plasmonic metasurface supports high- Q factor resonances and PA. Moreover, the quasi-BICs induced high- Q resonance has been demonstrated to be robust to fabrication imperfections or disorders due to the topological nature of BIC [29]. Guided modes are another type of nonradiative states, which lie below the light cone and cannot leak out owing to total internal reflection [30]. By utilizing probe grating as a disturbance [31] or introducing compound lattices [32], several works have shown that guided modes can be folded into the light cone and become detectable guided resonances.

Here, we propose a new type of hot electron photodetector that combines quasi-BICs and plasmonic hot electrons. BICs are demonstrated through the theoretical calculations of angle-resolved absorption spectra and far-field polarization maps. The plasmonic structure can obtain PA in the quasi-BIC regime, and the Q factor mainly depends on the dissipation losses. Owing to the correspondingly large optical absorption and the relevance of the grating facets in efficiently generating hot electrons, enhanced HEPD can be predicted with a photoresponsivity of 9.12 mA/W. Importantly, the PA of this photodetector is robust against the change of geometric parameters that preserve the symmetry of the system, as it is originated from the topological nature of the BIC. One might notice that there is an interesting and relevant work that was done by Kildishev's group [33]. Specifically, they theoretically demonstrated symmetry-protected BICs and Friedrich-Wintgen BICs, which is induced by the destructive interferences of resonances and can also be considered as accidental BICs, in hybrid plasmonic-photonic systems. Compared with that work, we utilize quasi-BICs to achieve robust PA and show its potential in the applications of HEPD. By changing the gap between two ridges of the grating in the unit cell, thus introducing a disturbance, we also show that guided modes can be folded into the light cone, becoming guided resonances and leading to narrow-band HEPD with a Q factor of 475. Moreover, through breaking the in-plane inversion (C_2) symmetry of the plasmonic structure, a three-band HEPD is demonstrated. Compared with quasi-BICs, guided resonances show slower decay in the momentum space and give rise to less angle-affected optical absorption and photodetection. Our work provides new schemes to improve the optical absorption and engineer the resonance number of plasmonic structures.

2 Model and formalism of hot electron photodetector

The proposed plasmonic structure consists of a Ag grating and a 100 nm thick Ag film on a SiO₂ substrate, covered by a TiO₂ layer (Figure 1a). Such Ag/TiO₂ system has been widely studied in photodetection [7, 34, 35]. The back Ag film serves as a reflector to prevent transmission at the near-infrared wavelengths. The ridge edges of Ag grating were rounded to more closely reproduce actual experimental conditions, in which the edges of fabricated grating structure were rounded to adhere to realistic experimental features [18]. Since Ag grating is fully embedded in the semiconductor layer, a Schottky barrier is formed across the whole top metal surface, maximizing the possibilities for hot electron injection in this device. The plasmonic structure can be fabricated by standard electron beam lithography and evaporation process [36].

Before discussing the details of our theoretical model, it would be appropriate to discuss some general theoretical points related to the excitation of high-energy carriers in metals. To excite electrons to states with sufficient energy to traverse the energy barrier requires a large change in their linear momentum due to the dispersion of metallic conduction bands. However, this is not possible in the bulk of the metal, as the photon carries negligible momentum, unless phonon scattering provides it. Another mechanism that provides the needed momentum is electron scattering at the surface of plasmonic nanostructures so that carriers can be excited to high energies [37]. It provides the additional advantage of exciting such carriers near the metal-environment interface, increasing the injection likelihood. As shown in Figure 1b, carriers are excited inside the metal

through optical excitation, and most of them are excited to low energies in the bulk of Ag. These carriers, which arise from the dephasing of the plasmon and can be described by the Drude model, only have limited energy, and they do not contribute to the photoinduced currents for typical values of Schottky barriers. It is then, as a consequence of the surface effect, that hot electrons are preferentially generated instead near the metal surfaces, creating a nonthermal population profile for the excited carriers [38]. When hot electrons have sufficient energy to cross the barrier formed in the Ag/TiO₂ interface, that is, $\epsilon > E_F + \Delta E_b$, where ϵ denotes the energy of the electrons, E_F and ΔE_b represent the Fermi level and barrier height, they can be injected into the TiO₂. By depositing a transparent conductive indium tin oxide (ITO) bar as an electrode onto the TiO₂ [39], hot electrons can be then collected through the outside circuits formed by wire bonding to the Ag film and ITO, and contribute to a detectable photocurrent (Figure 1c). For an incident plane wave, its energy flux I_0 can be expressed as

$$I_0 = \frac{c_0 \epsilon_0 \sqrt{\epsilon_{\text{env}}}}{2} \cdot |E_0|^2 \quad (1)$$

where c_0 is the speed of light in vacuum, ϵ_0 is the vacuum permittivity, ϵ_{env} is the dielectric constant of the environment, and $|E_0|^2$ represents the electric field amplitude of the incident electromagnetic wave. The incident energy flux is set as $I_0 = 10^5 \text{ W/cm}^2$. Since there is no transmission in the system, the absorption of the plasmonic structure can be calculated by $A = 1 - R$, where R is the optical reflectivity. The photoresponsivity can be obtained by the following equation:

$$\text{Res} = \frac{I}{P_0} \quad (2)$$

Figure 1: Plasmonic structure for HEPD.

(a) Schematic of plasmonic structure supporting perfect absorption enabled by quasi-BIC. The structure comprises a Ag grating (lattice constant $a = 300 \text{ nm}$) and TiO₂ cladding (thickness $H = 300 \text{ nm}$). The ridges of the grating are $t = 30 \text{ nm}$ high and $w = 120 \text{ nm}$ wide. The back Ag film is 100 nm thick. Inset shows that the edges of the grating are rounded with a radius $r = 6 \text{ nm}$. (b) Mechanisms of the generation and injection of hot electrons at the interface of Ag/TiO₂. Since the excitation does not extend to the bottom of the metal (left interface), hot electrons are only generated near the interface of Ag/TiO₂. (c) Schematic of the HEPD integrated with indium tin oxide (ITO) electrodes. The circuit can be formed by wire bonding to the Ag film and ITO.

where P_0 is the incident power over the effective area S and can be calculated as $P_0 = I_0 \cdot S$. Since the model built in COMSOL has a square lattice, $S = a^2$. The photocurrent I generated by the plasmonic hot electrons can be approximated as

$$I = \frac{T}{2} \cdot e \cdot \text{Rate} = \frac{T}{2} \cdot e \cdot \frac{1}{4} \frac{2}{\pi^2} \frac{e^2 E_F^2}{\hbar} \frac{(\hbar\omega - \Delta E_b)}{(\hbar\omega)^4} \int_S |E_{\text{normal}}|^2 dS \quad (3)$$

where e is the elementary charge, and Rate is the generation rate of total excited high energy carriers in Ag, which is obtained from our quantum formalism [37, 40–42]. Briefly, the electric field strength in Ag's inner surface close to TiO_2 drives the surface scattering of electrons, which in turn allows the excitation of carriers with up to the total incident photon energy, thus providing electrons with sufficient energy to traverse the Schottky barrier. After their excitation, we consider that half of the hot electrons will go to the MS contact, while the remaining will move away from the interface, based on simple symmetry considerations on flat boundaries. A fraction of the hot electrons reaching the MS contact will traverse the energy barrier and move to the semiconductor, which we account for through a transmission coefficient, T , while the rest of them are reflected back to the metal. Here, $T = 0.2$ is considered, by comparing our model with Fowler model [9, 43] and photoemission probability model [44] (details can be found in the Supplementary Material). The integral is taken over the Ag/ TiO_2 interface, and E_{normal} is the electric field component normal to the metal surface, taken immediately at the inner surface of Ag. The barrier height ΔE_b is considered as 0.9 eV [34]. The product of the reduced Planck constant and the photon angular frequency, $\hbar\omega$, represents the total energy of the incident photon. One should note that Equation (3) highlights the central idea of the process that the generation of hot electrons is a surface quantum effect which stems from the nonconservation of the electron's linear momentum caused by the scattering of electrons on the metal surface.

The eigenmodes, optical absorption, and photoresponsivity of the plasmonic structure have been calculated using commercial software COMSOL Multiphysics. The optical constants of Ag and TiO_2 are taken from Ref. [45] and [46], respectively. The dielectric constant ϵ_r is set as 1 and 2.1 for air and SiO_2 , respectively. The eigenmode analysis is performed within a 2D model of the structure's cross-section, while the remaining calculations are conducted in a 3D model, defining a unit cell with a square boundary in the xy plane. Detailed information about modeling and computational setup can be found in Supplementary Material Figure S1.

3 Results and discussion

To analyze the properties of the modes supported by our grating structure, it is useful to study the response of the system in the momentum space generated along with the x -direction, on which the grating shows its periodical structure. Figure 2a shows the band diagram of the plasmonic structure depicted in Figure 1a. Two transverse magnetic (TM) modes, noted as TM_1 and TM_2 , are observed at 940 and 844 nm at Γ point ($k_x = 0$), respectively. Under the incidence of an electromagnetic wave with TM polarization, these two modes are excited. This can be clearly seen from the angle-resolved absorption spectra (Figure 2b), which can be practically obtained by polarization-resolved momentum-space imaging spectroscopy [47]. The wavelengths of excited modes, which is the position of resonance peaks, match well with eigen results shown in Figure 2a. Notably, the linewidth of TM_1 mode becomes narrower with a smaller incident angle and totally disappears at normal incidence, presenting the feature of symmetry-protected BIC. In plasmonic structures, the total Q factor, Q_{tot} , is defined as $Q_{\text{tot}}^{-1} = Q_R^{-1} + Q_N^{-1}$, where Q_R and Q_N are radiative and nonradiative Q factors. The intrinsic dissipations in the metal arouse the latter term. The Q_{tot} of TM_1 mode changing with the incident angle θ is extracted by $Q_{\text{tot}}^{-1} = \lambda/\Delta\lambda$, where λ is the resonant wavelength and $\Delta\lambda$ is the full-width at half-maximum (Figure 2c). At BIC point (normal incidence), the Q_R goes to infinite, and Q_{tot} is entirely determined by the nonradiative losses $Q_{\text{tot}} = Q_N \approx 270$. After tilting the incidence with an angle, the in-plane symmetry of the TM polarized field is broken. Therefore, BIC is transformed into quasi-BIC, and the Q_{tot} decreases as the incident angle increases. To achieve PA in plasmonic structures, the critical coupling condition, $Q_R = Q_N$, should be satisfied [48, 49]. Since Q_N can be considered unchanged and Q_R drops dramatically from infinite as incident angle increases, PA can be readily obtained by matching Q_R with Q_N in the quasi-BIC regime. As shown in Figure 2d, in the region near the BIC, the optical absorption of TM_1 mode increases with the incident angle since Q_R decreases and approaches Q_N . When $\theta = 8^\circ$, Q_R and Q_N are matched and PA is achieved. As θ further increases, Q_R becomes smaller than Q_N and the mismatching appears, leading to the decreases of absorption. The quasi-BIC regime also provides an ideal platform to investigate the PA associated strong field enhancement in plasmonic structures and the Q factor of PA resonance is mainly limited by the dissipative losses of metal, which can be further reduced by using conductors with relatively low intraband damping, such as alkali metals [50, 51].

Figure 2: BIC in plasmonic grating structure.

(a) The band structure of plasmonic structure. (b) Angle-resolved absorption spectra under TM polarization. BIC can be found in TM_1 mode at normal incidence. (c) Dependence of the Q factor of TM_1 mode on the angle of incidence. (d) Absorption of TM_1 and TM_2 modes for different angles of incidence. (e) Electric-field E_z profiles of the BIC (TM_1) and leaky (TM_2) mode. (f) The angle of the polarization vector of TM_1 mode in k space. BIC is protected by a topological charge $q = +1$ at Γ point. (g) Absorption spectra of plasmonic structure with different H . (h) Incident angle and wavelength of the PA for different H .

To further investigate the mechanism of the symmetry-protected BIC, E_z field profiles of TM_1 and TM_2 modes at Γ point are calculated (Figure 2e). The eigenmode TM_1 (TM_2) possesses even (odd) character. When illuminating the plasmonic structure with TM (E_x) polarized wave, which is an odd polarized source with respect to the yz plane, TM_2

mode with the same type of symmetry is excited, while TM_1 mode decouples from free space and do not decay due to symmetry mismatching. BICs have also been proved as vortex centers in the polarization directions of far-field radiation [52]. It is characterized by an integer topological charge of q , which is defined as:

$$q = \frac{1}{2\pi} \oint_C d\mathbf{k} \cdot \nabla_{\mathbf{k}} \phi(\mathbf{k}) \quad (4)$$

where $\phi(\mathbf{k}) = \arg[E_x(\mathbf{k}) + iE_y(\mathbf{k})]$ is the angle of the polarization vector and C is a simple closed path (black circle in Figure 2f) in $\mathbf{k}$ space that goes around the BIC in the counterclockwise direction. As shown in Figure 2f, the $\phi(\mathbf{k})$ of TM_1 mode forms a vortex around the Γ point, where the polarization direction is ill-defined, and we have a BIC characterized by a positive topological charge $q = +1$. Recently, it was known that symmetry-protected BICs are related to the C_2 , C_4 , C_6 and other symmetries of the structure [27, 53–55]. For C_2 symmetry-protected BICs, they are robust against the change of structural parameters if the system's C_2 symmetry is preserved. The absorption spectra of the plasmonic structure are calculated for different dielectric thickness H (Figure 2g), which is a key parameter to achieve PA in various plasmonic structure configurations [6, 8, 10]. By tuning the incident angle from

4.3 to 10.9°, PA can be robustly obtained as H changes from 250 to 350 nm. Figure 2h shows the incident angle and the wavelength of the PA at each H value. The resonance only shifts ~11 nm and PA is preserved. The PA driven by quasi-BIC is also robust against the change of the width and height of Ag gratings (Supplementary Material Figure S2). Importantly, compared with other strategies to achieve PA, such as using MIM structure [8], or overlapping different resonant modes [6], quasi-BIC governed PA is free of fine-tuning of structural parameters and is readily obtained when inspecting the response of the system in momentum space.

The angle-resolved photoresponsivity of plasmonic structures was then calculated utilizing Equations (2) and (3) (Figure 3a). The Res of TM_1 mode increases first as incident angle increases, achieves the maximum at PA, and decreases as the incident angle further increases, which can be seen more clearly in Figure 3b. The photoresponsivity roughly follows the optical absorption,

Figure 3: Enhancing HEPD with quasi-BIC.

(a) Angle-resolved responsivity spectra of plasmonic structure under TM polarization. (b) Responsivity of TM_1 and TM_2 modes at different angles of incidence. (c) Absorption and responsivity spectra of plasmonic structure at an oblique incidence of 8°, where perfect absorption condition is satisfied at TM_1 mode. (d) Normalized absorption (black) and photocurrent (red) spectra of grating structure at an oblique incidence of 8°. (e) Electric field and P_{abs} distributions at TM_1 and TM_2 modes; they are marked as a brown circle and gray inverted triangle in c.

presenting similar features. Interestingly, the Res of TM_2 mode keeps growing as the angle of incidence increases and obtains the maximum of 10.5 mA/W near the light line $\omega = c \cdot (k_x^2 + k_y^2)^{1/2}$, above which mode can radiate to the environment. It is even larger than the maximum of Res of TM_1 mode. The Res of TM_1 and TM_2 modes present different tendencies when approaching the X point ($k_x = \pi/a$) because the Q_R of TM_1 mode keeps decreasing and the mismatching between Q_R and Q_N increases leading to the decrease of Res , while the Q_R of TM_2 mode keeps increasing and finally matches with Q_N near the light line, inducing unity absorption (Figure 2b) and high Res at large incident angles. Figure 3c shows the absorption and responsivity spectra of plasmonic structures illuminated by an oblique incidence of 8° . Two resonance peaks are observed at 844 (TM_2) and 943 (TM_1) nm, respectively. PA is obtained at TM_1 mode with a $Q_{tot} = 155$, and the maximum Res is 9.13 mA/W. This calculated photoresponsivity is comparable with that of practical MPA-based photodetectors, including using Au grating structure overlapping LSPR and FP resonance (measured Res_{max} is 3.37 mA/W) [6] and chiral metamaterial photodetectors based on the MIM configuration (measured Res_{max} is 2.2 mA/W) [8]. It's also comparable to that of the existing Ag/TiO₂ photodetector (measured Res_{max} is 7.4 mA/W at 450 nm), realized by depositing a porous Ag layer on an anatase porous TiO₂ membrane [7]. The Res obtained by our quantum formula is close to the responsivity obtained by Fowler [9, 43] and other models [44], demonstrating that our results are reliable (Supplementary Material Figure S3). Comparing the shapes of absorption and photocurrent spectra normalized at 943 nm, one can see that the photocurrent spectra is slightly larger than absorption spectra near 844 nm (Figure 3d). The difference between the absorption and photocurrent spectra is induced by the factor, $(\hbar\omega - \Delta E_b)/(\hbar\omega)^4$, in Equation (3). Similar quantum effect of absorption and photocurrent spectra has been experimentally observed in previous work [8]. Compared to the TM_1 mode, both the absorption and Res of the TM_2 mode are relatively low. To further reveal the mechanism of the different features of TM_1 and TM_2 modes, electric field and absorbed power of incidence (P_{abs}) distributions are calculated (Figure 3e). The upper panels show that the electric field is more strongly enhanced at TM_1 mode and is localized along the sidewalls of Ag grating. While for TM_2 mode, it is mainly confined at the ridge edges, leading to the distributions of absorbed incident power shown in the lower panel. Moreover, at a small incident angle, the dominant transverse components of the electric field provide a strong normal component to the internal field at the barrier

formed by the sidewalls of Ag grating. Therefore, in the TM_1 mode, the carriers are mainly generated along the sidewalls due to an intensive absorption of light. For TM_2 mode, photons are strongly absorbed near the top surface of Ag grating, which is consistent with the high responsivity of the TM_2 mode at large incident angles.

Guided resonances are similar to guided modes, in that they strongly confine the electromagnetic wave within the structure, but with the difference that they can also couple to external radiation [56]. They can thus be excited from the far-field. By introducing a disturbance, the guided mode can be folded into the light cone (see more information about band folding in Supplementary Material Figure S4). Figure 4b shows the evolution of the eigen wavelengths of unfolded (TM_{10} and TM_{20}) and folded (TM_{11} and TM_{21}) modes at Γ point as the gap changes. Under the illumination of a TM polarized wave at normal incidence, unfolded leaky mode TM_{20} and folded guided resonance TM_{11} are excited, which can be seen from the absorption (Figure 4c) and responsivity (Figure 4d) spectra. The unfolded TM_{10} and folded TM_{21} modes are symmetry-protected BICs, and they do not couple with the far-field since C_2 symmetry is still preserved. Consequently, these modes do not appear in the absorption and responsivity spectra. The eigenmode profiles are shown in Supplementary Material Figure S5. When the gap is 146 nm, PA is obtained at guided resonance with a $Q_{tot} = 475$, and the photoresponsivity is 7.2 mA/W (Figure 4e). The electric field distribution shows that the guided resonance TM_{11} is the hybridization of photonic mode in TiO₂ and plasmonic mode in Ag grating (Figure 4f).

Besides breaking the symmetry of the incident field, a BIC can also be turned into a quasi-BIC by breaking the C_2 symmetry of the structure, in this way becoming a detectable leaky mode. Figure 5a and b show the absorption and responsivity spectra of grating structure with different w_2 at normal incidence. Here, w_1 and gap are fixed at 120 nm. As w_2 increases from 120 nm, C_2 symmetry of the plasmonic structure is broken and TM_{10} and TM_{21} modes start to couple with free space. The Q_R of TM_{21} mode decreases faster than that of TM_{10} mode since the disturbance, which induces the folded mode TM_{21} , also increases as w_2 increases. It would further enhance the coupling of TM_{21} mode and leaky channels in the environment and lead to more easily detectable absorption and photoresponsivity near $w_2 = 120$ nm. When $w_2 = 200$ nm, three resonance with near-PA are induced by quasi-BICs and guided resonance, leading to an enhanced three-band hot electrons photodetector (Figure 5c). Therefore, the combination of quasi-BIC and guided resonance provides a new scheme to

Figure 4: Narrow-band HEPD driven by guided resonance.

(a) Schematic diagram of the unit cell of plasmonic structure when a disturbance is introduced ($gap \neq 180$ nm or $w_1 \neq w_2$). Here, a is 600 nm. (b) Eigenfrequencies of plasmonic structure with different gaps. The solid (TM_{10} and TM_{20}) and dashed (TM_{11} and TM_{21}) lines represent unfolded and folded modes, respectively. (c) Absorption and (d) responsivity spectra of plasmonic structure with different gaps. (e) Absorption and responsivity spectra of grating structure with gap = 146 nm. (f) Electric field and P_{abs} distribution at TM_{11} mode, which is marked as a purple diamond in e. The grating widths in b ~ f are $w_1 = w_2 = 120$ nm.

Figure 5: Multiband HEPD enabled by quasi-BICs and guided resonance.

(a) Absorption and (b) responsivity spectra of plasmonic structure with different w_2 at normal incidence. Symmetry-protected and accidental BICs are marked with white and blue dashed circles in b, respectively. (c) Absorption and responsivity spectra of grating structure with $w_2 = 200$ nm. Here, w_1 and gap are fixed at 120 nm.

achieve multiband light harvesting. As $w_2 = 213$ nm, the linewidth of TM_{10} mode disappeared due to the generation of an accidental BIC in a configuration without C_2 symmetry, marked as a blue circle in Figure 5b. When w_2 is

further increased to 240 nm while retaining a lattice constant $a = 600$ nm, C_2 symmetry is reobtained due to the continuous translational symmetry of the structure. In this condition, the distance separating the ridges is the same in

Figure 6: Effect of incident angle on the performance of three-band HEPD.

Angle-resolved (a) absorption and (b) responsivity spectra of plasmonic structure. Dependence of (c) absorption and (d) responsivity of $TM_{10} \sim TM_{21}$ modes on the angle of incidence. Here, w_1 and gap are 120 nm and $w_2 = 200$ nm and the mirror symmetry of the structure is broken with respect to the yz plane.

both directions. Interestingly, a new symmetry-protected BIC in TM_{11} mode is generated while the original one in TM_{10} disappeared, leading to the linewidth of TM_{11} and TM_{21} modes to disappear in both the absorption and photoresponsivity spectra. This trend is originated from the evolution of the eigenmode field as w_2 changes (Supplementary Material Figure S6).

Finally, the dependence of the optical absorption and photoresponsivity of the three-band hot electrons photodetector on the incident angle is investigated. As shown in Figure 6a, the high absorption of guided resonance TM_{11} and TM_{21} remains as the incident angle increases in a wide range. The unfolded mode TM_{10} and TM_{20} , which merged at normal incidence and give rise to unity absorption, start to split, and the absorption drops with the increase of incident angle. The absorption of TM_{10} mode starts to increase while it keeps decreasing for TM_{20} mode as the incident angle further increases. The TM_{21} mode drops abruptly at $\theta = 23^\circ$ ($k_x a / 2\pi = 0.195$) because it couples with the diffraction modes near the folded light line [57]. Besides, the spectra show slight asymmetry in momentum space

since the mirror symmetry of the structure is broken with respect to the yz plane. The responsivity spectra present similar features (Figure 6b). It can be seen more clearly from Figure 6c and 6d that band folding induced guided resonances (TM_{11} and TM_{21}) is less dependent on the incident angle than unfolded modes (TM_{10} and TM_{20}).

4 Conclusion

In summary, we present a Ag grating/ TiO_2 cladding plasmonic nanostructure for hot electrons photodetection. Driven by quasi-BIC, PA can be readily obtained when inspecting the system's response in momentum space at which the radiation and dissipation losses can be matched. Unlike conventional strategies, our quasi-BIC assisted PA is free of the fine-tuning of structural parameters and is robust against the change of structure when C_2 symmetry of the system is preserved due to the topological nature of BIC. The continuous Ag/ TiO_2 interface surrounding the Ag grating improves the probability of photocurrents generation from

hot electrons injection at both vertical and horizontal Ag walls. We also show that guided mode can be folded into the light cone, becoming capable of supporting a guided resonance. The strongly confined electromagnetic wave and enhanced absorption give rise to a narrow-band HEPD with high responsivity. We should note that the Q_{tot} is mainly limited by the intrinsic dissipation of Ag since the Q_R in quasi-BIC and guided resonance regime can be very high and close to infinite. By breaking the C_2 symmetry, BICs are turned into quasi-BICs, and combined with guided resonance, a three-band hot electrons photodetector is obtained. Our work shows that quasi-BIC and guided resonance can be used to enhance light-harvesting and holds great potential for applications in hot-electron science.

5 Supplementary Materials

Details of modeling for simulation, photoresponsivity of grating structure obtained by different models, band folding induced by the introduction of disturbance, and eigenmode profiles.

Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: The authors acknowledge the support from the National Key Research and Development Program (No. 2019YFB2203400). P. Y. is supported by the China Postdoctoral Science Foundation (2019M663467), and the Sichuan Science and Technology Program (2020YJ0041), and NSFC (62005037). L. V. B is supported by the China Postdoctoral Science Foundation (2019T120820), the Xunta de Galicia (Centro singular de investigación de Galicia accreditation 2019–2022) and the European Union (European Regional Development Fund – ERDF).

Conflict of interest statement: The authors declare no conflict of interest.

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Supplementary Material: The online version of this article offers supplementary material (<https://doi.org/10.1515/nanoph-2021-0069>).