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The effect of symmetry on resonant and nonresonant photoresponses in a field-effect terahertz detector

Abstract

The effect of the symmetries in the terahertz (THz) field distribution and the field-effect channel on THz photoresponse is examined. Resonant excitation of cavity plasmon modes and nonresonant self-mixing of THz waves are demonstrated in a GaN/AlGaIn two-dimensional electron gas with symmetrically designed nanogates, antennas, and filters. We found that the self-mixing signal can be effectively suppressed by the symmetric design and the resonant response benefits from the residual asymmetry. The findings suggest that a single detector may provide both high sensitivity from the self-mixing mechanism and spectral resolution from the resonant response by optimizing the degree of geometrical and/or electronic symmetries.

Keywords

terahertz, field, photoresponses, detector, nonresonant, symmetry, resonant, effect

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The effect of symmetry on resonant and nonresonant photoresponses in a field-effect terahertz detector

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The effect of the symmetries in the terahertz (THz) field distribution and the field-effect channel on THz photoresponse is examined. Resonant excitation of cavity plasmon modes and nonresonant self-mixing of THz waves are demonstrated in a GaN/AlGaIn two-dimensional electron gas with symmetrically designed nanogates, antennas, and filters. We found that the self-mixing signal can be effectively suppressed by the symmetric design and the resonant response benefits from the residual asymmetry. The findings suggest that a single detector may provide both high sensitivity from the self-mixing mechanism and spectral resolution from the resonant response by optimizing the degree of geometrical and/or electronic symmetries. © 2015 AIP Publishing LLC.

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In the terahertz (THz) portion of the electromagnetic spectrum, many sensing applications, such as security screening, near-field microscopy, and spectroscopy, are being studied and developed.¹ Sensitive, tunable, and compact semiconductor detectors are one of the key elements for such applications.² In the early 1990s, Dyakonov and Shur theoretically predicted that plasmon waves in the field-effect electron channel can be applied for THz emission and detection.^{3,4} For detection, specifically, plasmon waves can be excited either resonantly or nonresonantly (self-mixing) upon THz irradiation.⁴ It is naturally expected that a resonant response would allow for more sensitive detection and also allow for spectral resolution.^{4–12} However, experimental results reported so far show that the resonant response is much weaker than the nonresonant response and the former is usually submerged into the latter.^{5–7} The amplitude of the resonant response is limited by the quality factor ($Q = \omega_p \tau_p$, where ω_p is the plasmon's angular frequency and τ_p is the plasmon's relaxation time) of the plasmon resonance. Understanding the physics in plasmon damping would allow us to control the plasmon cavity with proper boundary conditions and to develop high-performance plasmon-based THz devices.

In the resonant case ($\omega_p \tau_p \gg 1$), a plasmon wave is excited resonantly at a proper gate voltage and induces an unidirectional photocurrent which has a Lorentzian line shape^{4–7}

$$i_R = I_R \frac{f_p^2}{(f - f_p)^2 + (1/4\pi\tau_p)^2}, \quad (1)$$

where prefactor I_R is a complex function of the incident THz power, channel conductance, the geometry, and the boundary

conditions, f is the incident THz frequency, and f_p is the plasmon frequency which, according to Refs. 3 and 4, can be tuned by the gate voltage

$$f_p = \frac{1}{4L_{eff}} \sqrt{\frac{eU_g}{m^*}}, \quad (2)$$

where L_{eff} is the effective length of the plasmon cavity, and e and m^* are the electron charge and effective mass, respectively. In the nonresonant case ($\omega_p \tau_p \ll 1$), the photoresponse comes from self-mixing of the THz electric field in the electron channel and is effective over a wide range of the electron density, i.e., has a broadband response with the bandwidth determined by the THz antenna.^{13–19} The short-circuit self-mixing current can be written as¹⁸

$$i_M = \frac{E_0^2}{4} \bar{z} \int_0^L \frac{dG}{dU_g} \xi_x \xi_z \cos \phi dx, \quad (3)$$

where E_0 is the free-space electric field induced by the incident THz wave, $G = G(x)$ is the local conductance of the gated channel, $\bar{z}$ is the effective distance between the gate and the channel, L is the length of the channel. $U_g = V_g - V_{th} - V_x$ is effective gate voltage, V_g , V_{th} , and V_x are the applied voltage, the threshold voltage, and the local channel potential, respectively. ξ_x , ξ_z , and ϕ are the horizontal and perpendicular THz field enhancement factors, and the phase difference between the induced fields, respectively. In an antenna coupled field-effect detector, both responses are expected to take place and the total photocurrent can be expressed as

$$i_T = i_M + i_R. \quad (4)$$

Both self-mixing and resonant responses rely on the asymmetries in the THz field distribution or the plasmon

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cavity's boundary conditions. For resonant detection, the source/drain ohmic contacts usually serve as the boundaries for the plasmon cavity and also as part of the THz antennas. The asymmetric boundary conditions for plasmon wave were achieved by biasing the device with a direct current source.^{8–10} For self-mixing detection, the asymmetric condition is reached either by using asymmetric antennas or biasing the electron channel with a proper current.^{13,17} Here, we report the effect of symmetry on THz photoresponse in a GaN/AlGaIn THz detector. The detector is based on GaN/AlGaIn two-dimensional electron gas with symmetrically arranged nanogates, antennas, and filters. The three gates form a tunable plasmon cavity with nearly symmetric boundaries. The metallic source/drain contacts are set 1.5 μm away from the plasmon cavity to maintain the degree of symmetry. Both self-mixing response and resonant response are observed. By suppressing the self-mixing response, the resonant response is clearly resolved at 77 K. The THz response as a function of the gate voltage and the source-drain bias is mapped for the verification of the symmetric design.

A scanning-electron micrograph of the detector is shown in Fig. 1. Three nanogates are defined as G_1 , G_2 , and G_3 . A plasmon cavity is formed between gates G_2 and G_3 . Gate G_1 applied with voltage V_G is used to control the carrier density and thus tune the plasmon frequency. Antennae A_1 and A_2 are designed to have a resonant frequency at 900 GHz and is connected to gate G_1 and G_2/G_3 , respectively. The meander-shaped low pass filters are used to connect the antennas with the corresponding wire-bonding pads.²⁰ The gate length is 150 nm, 100 nm, and 100 nm for gates G_1 , G_2 , and G_3 , respectively. The distance between the inner edges of gate G_2 and gate G_3 is about 330 nm. The width of the electron channel (mesa) is $W = 3 \mu\text{m}$, and the distance between the source and drain contacts is 3.5 μm . At 77 K, the electron mobility and the electron density are $\mu = 1.58 \times 10^4 \text{ cm}^2/\text{Vs}$ and $n_s = 1.06 \times 10^{13} \text{ cm}^{-2}$, respectively. The effective electron mass is $m^* = 0.2m$, where m is the free electron mass. The radiation from a backward wave oscillator (BWO) was modulated by a mechanical chopper at frequency $f_M = 317 \text{ Hz}$. The short-circuit photocurrent was measured using a current preamplifier and a lock-in amplifier. More experimental details can be found in Ref. 18. The

photocurrent is maximized when the polarization of the THz wave (linearly polarized) emitted from the BWO becomes in parallel with the antennas along direction y .

As shown in Fig. 2, we present numerical calculations of the THz electric field and the phase distributions at 900 GHz by a finite-difference time-domain (FDTD) method. To obtain the fine field distribution in the gated 2DEG, the grid constant is set as 5 nm and 20 nm in direction x and direction y in FDTD simulations, respectively. The field enhancement factors for the horizontal and perpendicular fields are shown in Figs. 2(a) and 2(b), respectively. The horizontal field is concentrated in the extended areas between gates G_1 , G_2 , and G_3 , while the perpendicular field is mainly distributed under gate G_1 . The simulation confirms that, unlike the asymmetric detector in Ref. 18, the source and drain sides have the same electric field distribution. The horizontal field changes its phase by 180° at the center of the three gates, while the perpendicular field changes its phase at the center of the gaps between the gates (Figs. 2(c) and 2(d)). In Fig. 2(e), the simulated mixing factor ($\xi_x \xi_z \cos \phi$) is plotted to reveal the spatial distribution. Strong mixing symmetrically occurs only at the left and right edges of gate G_1 . However, the mixing at the source side generates a positive current, opposite to that induced at the drain side. This inversion of polarity comes from a phase flips as shown in Figs. 2(c) and 2(d). Since the device structure is symmetric along the electron channel, the self-mixing response is expected to be suppressed effectively according to Eq. (3).

As shown in Fig. 3(a), the source-drain conductance G and its derivative dG/dV_g as a function of the gate voltage are characterized at 77 K. The derivative is maximized at -4.00 V . Fig. 3(b) shows the photocurrent versus V_g at different THz frequencies of 850 GHz ($\square$), 861 GHz ($\circ$), 907 GHz ($\triangle$), and 940 GHz (∇). For the sake of clarity, the curves are shifted in the vertical scale. Two peaks are observed with one of them fixed at -4.00 V and the other at a lower gate voltage around -3 V , depending on the THz frequency. The frequency-independent response at the same location where the derivative of the conductance is maximal comes from the self-mixing as described by Eq. (3). The frequency-dependent response is induced by the excitation of cavity plasmons and can be well described by Eq. (1). The higher the THz frequency, the lower the peak gate voltage (i.e., the higher the electron density) will be. When we tune the THz frequency from 850 GHz to 940 GHz, the position of the resonant response shifts from -3.12 V to -2.60 V . Solid curves in Fig. 3(b) are calculated photoresponses based on Eq. (4) and agree well with the experiments. By normalizing the total photoresponse and subtracting the self-mixing response, the net resonant responses at different THz frequencies are shown in Fig. 4(a). The resonant frequency as a function of the gate voltage fits well with Eq. (2), as shown in Fig. 4(b). In the fitting, the size of the plasmon cavity is chosen to be $L_{\text{eff}} = 330 \text{ nm}$, i.e., the gap size between gate G_2 and G_3 . As a comparison, the dashed line shown in Fig. 4(b) represents the gate-voltage-tuned plasmon frequency with a cavity size of 150 nm, i.e., the length of gate G_1 . This implies that the plasmons are excited and confined in the 2DEG enclosed by G_2 and G_3 instead of in the 2DEG right beneath the control gate G_1 .^{5–7}

FIG. 1. (a) Scanning-electron micrograph of the field-effect THz detector. (b) Zoom-in view of the central active region including the plasmon cavity, the nanogates, and the 2DEG channel.

FIG. 2. Spatial distribution of the THz electric field and the phase from a FDTD simulation at 900 GHz. (a) Field enhancement factor ξ_x . (b) Field enhancement factor ξ_z . (c) and (d) The phases ϕ_x and ϕ_z at $y=0$. (e) Mixing factor $\xi_x \xi_z \cos \phi$.

FIG. 3. (a) Channel conductance and its derivative as a function of the gate voltage. (b) THz response at different incident THz frequencies ($\square$: 850 GHz, $\circ$: 861 GHz, $\triangle$: 907 GHz, and ∇ : 940 GHz). The solid curves are calculated responses based on Eq. (4). The arrows mark the locations of plasmon resonances.

As can be seen in Fig. 3(b), the resonant response is much weaker than the nonresonant self-mixing response. The current responsivity is estimated to be 540 mA/W and 59 mA/W for the self-mixing response and the resonant response, respectively. The corresponding noise-equivalent powers are 3 pW/ $\sqrt{\text{Hz}}$ and 45 pW/ $\sqrt{\text{Hz}}$. Comparing to those detectors with a 2- μm gate at room temperature reported previously,¹⁷ this nano-gated detector exhibits an unexpectedly low responsivity in the self-mixing mode at 77 K. It is the symmetric antenna design that strongly suppresses the self-mixing response. The amplitude of the

resonant response relies on how plasmons are effectively excited and how effectively the charge oscillations are converted into a direct current. The former can be characterized by the plasmon quality factor $Q = 2\pi f_p \tau_p$. The latter is a complex function of the boundary conditions of the plasmon cavity, and it is not yet specifically known. By substituting Eq. (2) into Eq. (1), we obtain the resonant response as a function of the plasmon frequency (Fig. 4(c)), and the plasmon quality factors can be extracted as shown in Fig. 4(d). We found a spectral resolution of better than 10 GHz can be achieved by tuning the gate voltage. By fitting the

FIG. 4. (a) Resonant photocurrent as a function of the gate voltage. (b) Resonant plasmon frequency as a function of the gate voltage. The solid curve and the dashed curve correspond to an effective cavity length of $L_{eff} = 330$ nm and $L_{eff} = 150$ nm, respectively. (c) Resonant photocurrent as a function of the plasmon frequency. (d) Quality factor of the plasmon resonance extracted from (c) as a function of the plasmon frequency. The solid curve and the dashed curve correspond to a plasmon relaxation time of $\tau_p = 0.52$ ps and a transport relaxation time of $\tau_e = 1.80$ ps, respectively.

experimentally extracted quality factors, we found that the effective plasmon lifetime is $\tau_p = 0.52$ ps, which is about one third of the electron's relaxation time $\tau_e = \mu m^* / e = 1.80$ ps obtained from the Hall mobility at 77 K. This indicates that damping of plasmon due to strong electron-electron and electron-plasmon interactions take place in the cavity.⁷

To further verify the symmetric design, we use the same technique as that reported in Ref. 18. The degree of symmetry in the photoresponse mapped in a 2D color-scale plot as a function of V_{ds} and V_g at 907 GHz can be seen in Fig. 5(a). A strong self-mixing photocurrent is produced near -4.00 V and is marked by the dashed line. When the large positive bias is applied at the drain (source) side, the 2DEG under the gate at the drain (source) side is depleted, and the locally induced negative (positive) photocurrent is suppressed effectively, as schematically shown in the insets of Fig. 5(b). Along the dashed line in Fig. 5(a), the measured

photocurrent comes from the locally induced positive (negative) photocurrent at the source (drain) side of the gated 2DEG channel. The corresponding current responsivity increases from 0.54 A/W to 1.72 A/W as bias V_D changes from 0 V to 0.5 V. As shown in Fig. 5(b), the absolute THz photocurrent as a function of V_{ds} is extracted along the dashed line and is plotted in Fig. 5(a). The maximum photocurrent with the bias applied at the drain and at the source is 83 nA and 57 nA, respectively. The expected location of the minimal photocurrent is shifted from 0 V to $V_s = 0.1$ V. At $V_{ds} = 0$ V, the photocurrent is about 26 nA, which is about the difference between the observed maximal responses when the bias is applied at the drain and at the source. This confirms that a residual asymmetry exists in our symmetrically designed device. It is this asymmetry that allows us to bring up the resonant response with a suppressed self-mixing photoresponse as the background. Since the broadband nonresonant response is always expected to occur, it is difficult to separate the resonant response from the nonresonant response when both the gate voltage and the source-drain bias are applied. However, in our symmetrically designed detector, we can set the detector at a proper operation point so that the residual asymmetry in self-mixing response can be electrically cancelled and minimize the self-mixing response, in our case $V_s = 0.1$ V. On the other hand, by operating the detector with a large source-drain bias, the detector allows for THz detection with an enhanced sensitivity. Thus, a symmetrically designed detector could provide both high sensitivity and a spectral resolution.

In conclusion, we have demonstrated and analyzed both the resonant and nonresonant (self-mixing) THz photoresponses in a GaN/AlGaIn 2DEG detector with symmetrically arranged nanogates, antennas, and filters. Experiments confirm that the self-mixing response can be effectively suppressed by the symmetric design. The observed self-mixing response at zero bias suggests that a certain degree of asymmetry exists in the THz field distribution and/or in the field-effect electron channel. The observed resonant response

FIG. 5. (a) Examination of the degree of symmetry in the THz photocurrent mapped in a 2D color-scale plot as a function of V_{ds} and V_g at 907 GHz. (b) Absolute value of THz photocurrent as a function of V_{ds} extracted along the dashed line in (a).

agrees well with the quarter-wavelength plasmon mode defined by the nanogates. Although this resonant photoresponse may be induced by the residual asymmetry in our symmetrically designed device, more indepth research is required for further engineering the boundary conditions for cavity plasmon modes. The broadband self-mixing mechanism and the narrowband resonant detection integrated in one detector may provide both high sensitivity and spectral resolution.

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¹M. Tonouchi, *Nat. Photonics* **1**, 97 (2007).

²F. Sizova and A. Rogalski, *Prog. Quantum Electron.* **34**, 278 (2010).

³M. I. Dyakonov and M. S. Shur, *Phys. Rev. Lett.* **71**, 2465 (1993).

⁴M. I. Dyakonov and M. S. Shur, *IEEE Trans. Electron Devices* **43**, 380 (1996).

⁵W. Knap, Y. Deng, S. Rumyantsev, J. Q. Lü, M. S. Shur, C. A. Saylor, and L. C. Brunel, *Appl. Phys. Lett.* **80**, 3433 (2002).

⁶A. El Fatimy, F. Teppe, N. Dyakonova, W. Knap, A. Shchepetov, Y. Roelens, S. Bollaert, A. Cappy, and S. Rumyantsev, *Appl. Phys. Lett.* **89**, 131926 (2006).

⁷V. V. Popov, O. V. Polischuk, W. Knap, and A. E. Fatimy, *Appl. Phys. Lett.* **93**, 263503 (2008).

⁸S. Boubanga-Tombet, F. Teppe, D. Coquillat, S. Nadar, N. Dyakonova, H. Videlier, W. Knap, A. Shchepetov, C. Gardes, Y. Roelens, S. Bollaert, D. Seliuta, R. Vadoklis, and G. Valueis, *Appl. Phys. Lett.* **92**, 212101 (2008).

⁹X. G. Peralta, S. J. Allen, M. C. Wanke, N. E. Harff, J. A. Simmons, M. P. Lilly, J. L. Reno, P. J. Burke, and J. P. Eisenstein, *Appl. Phys. Lett.* **81**, 1627 (2002).

¹⁰G. C. Dyer, G. R. Aizin, S. J. Allen, A. D. Grine, D. Bethke, J. L. Reno, and E. A. Shaner, *Nat. Photonics*, **7**, 925 (2013).

¹¹T. Tanigawa, T. Onishi, S. Takigawa, and T. Otsuji, *68th Device Research Conference (DRC 2010)* (IEEE, 2010), p. 167.

¹²S. Kim, J. D. Zimmerman, P. Focardi, A. C. Gossard, D. H. Wu, and M. S. Sherwin, *Appl. Phys. Lett.* **92**, 253508 (2008).

¹³W. Knap, Y. Deng, S. Rumyantsev, and M. S. Shur, *Appl. Phys. Lett.* **81**, 4637 (2002).

¹⁴T. Otsuji and M. Shur, *IEEE Microwave Mag.* **15**, 43 (2014).

¹⁵A. Lisauskas, U. Pfeiffer, E. Öjefors, P. H. Bolivar, D. Glaab, and H. G. Roskos, *J. Appl. Phys.* **105**, 114511 (2009).

¹⁶R. A. Hadi, H. Sherry, J. Grzyb, Y. Zhao, W. Förster, H. M. Keller, A. Cathelinand, A. Kaiser, and U. R. Pfeiffer, *IEEE J. Solid-State Circuits* **47**, 2999 (2012).

¹⁷J. D. Sun, Y. F. Sun, H. Qin, B. S. Zhang, and D. M. Wu, *Appl. Phys. Lett.* **100**, 013506 (2012).

¹⁸J. D. Sun, H. Qin, R. A. Lewis, Y. F. Sun, X. Y. Zhang, Y. Cai, D. M. Wu, and B. S. Zhang, *Appl. Phys. Lett.* **100**, 173513 (2012).

¹⁹L. Vicarelli, M. S. Vitiello, D. Coquillat, A. Lombardo, A. C. Ferrari, W. Knap, M. Polini, V. Pellegrini, and A. Tredicucci, *Nat. Mater.* **11**, 865 (2012).

²⁰Y. F. Sun, J. D. Sun, Y. Zhou, R. B. Tan, C. H. Zeng, W. Xue, H. Qin, B. S. Zhang, and D. M. Wu, *Appl. Phys. Lett.* **98**, 252103 (2011).