2019

Strong tunable photomixing in semi-Dirac materials in the terahertz regime

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Abstract

We demonstrate a strong and anisotropic photomixing effect in an electronic system whose energy–momentum dispersion is parabolic in the ? direction and linear in the ? direction, such as a TiO_2/VO_2 multilayered structure. The third-order photoresponses along the linear and parabolic directions have been analyzed and determined quantitatively. We have found a remarkable tunability of the mixing efficiency along the parabolic direction by a small electric field in the linear direction, up to two orders of magnitude. In the terahertz (THz) regime, the third-order response is comparable to the linear response under an applied field of 10^3–10^4 V/cm. Additionally, the nonlinear response persists at room temperature. The results may have applications where different current responses are required along different directions in the THz regime. We demonstrate a strong and anisotropic photomixing effect in an electronic system whose energy–momentum dispersion is parabolic in the ? direction and linear in the ? direction, such as a TiO2/VO2 multilayered structure. The third-order photoresponses along the linear and parabolic directions have been analyzed and determined quantitatively. We have found a remarkable tunability of the mixing efficiency along the parabolic direction by a small electric field in the linear direction, up to two orders of magnitude. In the terahertz (THz) regime, the third-order response is comparable to the linear response under an applied field of 103–104 V/cm. Additionally, the nonlinear response persists at room temperature. The results may have applications where different current responses are required along different directions in the THz regime.

Disciplines

Engineering | Science and Technology Studies

Publication Details

Huang, S., Tran, M., Zuber, J., Wang, Q., Zhu, Y. & Zhang, C. (2019). Strong tunable photomixing in semi-Dirac materials in the terahertz regime. Journal of the Optical Society of America B: Optical Physics, 36 (2), 200-203.

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Strong tunable photomixing in semi Dirac materials in terahertz regime

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We demonstrate a strong and anisotropic photomixing effect in an electronic system whose energy-momentum dispersion is parabolic in the x direction and linear in the y direction, such as a TiO_2/VO_2 multilayered structure. The third order photo response along the linear and parabolic directions have been analysied and quantitative determined. We have found a remarkable tunability of the mixing efficiency along the parabolic direction by a small electric field in the linear direction, up to two orders of magnitude. In the terahertz regime the third order response is comparable to the linear response under an applied field of $10^3 - 10^4$V/cm. Additionally, the non-linear response persists at room temperature. The results may have applications where different current response is required along different directions in THz regime.

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I. INTRODUCTION

Terahertz (THz) technology has been proven to have promising applications in obtaining molecular spectral and material information due to the energy matching among them[1,2]. A number of mechanisms have been developed to emit THz radiation[3–6]. The lack of high performance of THz resource has limited the application of THz technology[7]. Various non-linear processes such as down conversion and up conversion have been used for achieveing THz radiation[8]. It has been demonstrated that graphene is a strong non-linear material due to its massless Drac Fermion energy-momentum dispersion[8–11]. It also has been shown that the bulk state of topological insulator HgTe/CdTe quantum wells exhibits strong non-linear effect[12]. The non-linear effect arises from the non-parabolic energy-momentum dispersion.

While Dirac systems generally show stronger nonlinear optical effect and better photomixing efficiency, such systems usually have low density of states near the Dirac point. In the case of graphene, the density of states vanishes at the Dirac point. The low density of states has limited the power generated in the nonlinear process. On the other hand, the normal electronic materials with parabolic energy dispersion have a weaker nonlinear response but the power output of nonlinear processes is much higher due to the high density of states. It will be extremely useful if the low efficiency but higher power output in parabolic system can be significantly enhanced with the use of Dirac dispersion in some way. In this work we will employ the so called semi-Dirac system to achieve this purpose.

Recently, a unique energy-momentum dispersion was found in a VO_2-TiO_2 interface[13] and attracted enormous attention[14–17]. The new $2D$ state has a semi-Dirac point that behaves like a conventional semiconductor (effective-mass) along x axis but behaves like graphene (massless) along the y axis. For monolayer graphene with artificially designed hopping, a semi-Dirac energy dispersion can also occur[14]. Physical properties such as Faraday rotation, heat capacity, plasmon frequency[18], dynamical polarization[19] and optical conductivity[20] were investigated in the unique system. As a result, the plasmon frequency and optical conductivity are found to be highly anisotropic.

In this work, we analyze the photomixing properties of a semi-Dirac system. By using a semi-classical approach where the quantum mechanically calculated energy dispersion is used to derive the velocity in the presence of an applied field along the x or y direction, we calculated the third order current response involving three photons. We demonstrate

that the third order current exhibits much stronger anisotropy than the linear response. At room temperature the mixing efficiency along the linear direction is at least one order of magnitude higher than that along the parabolic direction.

II. MODELS AND CURRENT RESPONSE

The energy-momentum dispersion of the Semi-Dirac system is given as[20,21],

$$\epsilon_{\mathbf{k}} = \pm 2mv_F^2 \sqrt{\frac{p_x^4}{(2mv_F)^4} + \frac{p_y^2}{(2mv_F)^2}} \tag{1}$$

where $\pm$ is the index of valence and conduction bands, m is the mass of free electron, $v_F = 10^6$ m/s is the Fermi velocity, p_x and p_y are the momentums in x and y directions, respectively. We assume that the Fermi level is in the conduction band and and transport is solely due to electrons. The velocity operator can be obtained from $\mathbf{v} = \partial H/\partial \mathbf{p}$. The expectation value of $\mathbf{v}$ is simply given by, $\langle \mathbf{v} \rangle = \frac{\partial \epsilon}{\partial \mathbf{p}}$. We obtain the velocity components,

$$v_x = \frac{\partial \epsilon_{\mathbf{k}}}{\partial p_x} = \frac{p_x^3}{mF}, \tag{2}$$

and

$$v_y = \frac{\partial \epsilon_{\mathbf{k}}}{\partial p_y} = \frac{p_y \epsilon_0}{F} \tag{3}$$

where $\epsilon_0 = 2mv_F^2$ and $F = \sqrt{p_x^4 + 2m\epsilon_0 p_y^2}$. We now consider that the system is under a non-monochromatic electric field,

$$E = \sum_n E_0 \exp[i(\mathbf{q}_n \cdot \mathbf{r} - w_n t)], \tag{4}$$

where E_0 is the amplitude of the external field, q_n and w_n are the n-th wave vector and frequency. The semi-Dirac system is now coupled to the field via the minimal coupling scheme, $\mathbf{p} \to \mathbf{p} + e\mathbf{A}(\mathbf{r}, t)$, where $\mathbf{A}(\mathbf{r}, t)$ is the vector potential, $\mathbf{E}(\mathbf{r}, t) = -\partial \mathbf{A}(\mathbf{r}, t)/\partial t$ and the speed of light c is set to 1. Let $\mathbf{u} = e\mathbf{A}(\mathbf{r}, t)$ and substitute $\mathbf{p}$ by $\mathbf{p} + \mathbf{u}$ in Eqs.(2-3), we expand the velocity component in successive orders of the electric field. The first order velocity terms are given as,

$$v_x^{(1)} = \frac{3p_x^2 u_x}{mF} - \frac{2p_x^6 u_x}{mF^3} \tag{5}$$

$$v_y^{(1)} = \frac{\epsilon_0 u_y}{F} - \frac{2m\epsilon_0^2 p_y^2 u_y}{F^3} \tag{6}$$

We will not show the explicit form of the second order velocity terms. Due to the inversion symmetry, the second order terms do not contribute to the current. The third order velocity terms are given as,

$$v_x^{(3)} = G_{xx}u_x^3 - G_{xy}u_x u_y^2 \tag{7}$$

and

$$v_y^{(3)} = -G_{yx}u_x^2 u_y - D_{yy}u_y^3 \tag{8}$$

where $G_{xx} = \frac{1}{mF} - \frac{17p_x^4}{mF^3} + \frac{36p_x^8}{mF^5} - \frac{20p_x^{12}}{mF^7}$, $G_{xy} = \frac{3\epsilon_0 p_x^2}{F^3} - \frac{18m\epsilon_0^2 p_x^2 p_y^2}{F^5} - \frac{6\epsilon_0 p_x^6}{F^5} + \frac{60m\epsilon_0^2 p_x^6 p_y^2}{F^7}$, $G_{yx} = (\frac{3\epsilon_0 p_x^2}{F^3} - \frac{18m\epsilon_0^2 p_x^2 p_y^2}{F^5} - \frac{6\epsilon_0 p_x^6}{F^5} + \frac{60m\epsilon_0^2 p_x^6 p_y^2}{F^7})$, and $G_{yy} = (\frac{m\epsilon_0^2}{F^3} - \frac{12m^2\epsilon_0^3 p_y^2}{F^5} + \frac{20m^3\epsilon_0^4 p_y^4}{F^7})$. Here the terms in the third order velocity that do not contribute to the current have been omitted. The second order terms are not explicitly given since they will not result in a finite current due to the inversion symmetry of the system.

The n-th order nonlinear response (current density) can be obtained by following equation,

$$\mathbf{J}^{(n)} = e\int_0^\infty \int_0^\infty \mathbf{v}^{(n)}[f(\epsilon_k) - f(\epsilon_k + \delta)]dk_x dk_y \tag{9}$$

where $\mathbf{v}^{(n)}$ is the n-th order velocity to the applied electronic field, $f(\epsilon_k)$ is the Fermi-Dirac distribution function, δ is the total energy of the incoming photons.

Both the first and third order current density in the x and y direction can be obtained by inserting Eq.(5)-Eq.(8) into Eq.(9). Along the parabolic direction, the mixing current is given as,

$$J_x^{(3)} = \frac{4e}{\hbar^2}\int_0^{+\infty} \int_0^{+\infty} [G_{xx}u_x^3 - G_{xy}u_x u_y^2][f(\epsilon_k) - f(\epsilon_k + \epsilon_{ph})]dp_x dp_y. \tag{10}$$

The response contains two terms, first term is a direct response under the excitation of the fields along the parabolic direction. The second term is the response to field along the x-direction assisted by the field along the y-direction (the linear direction). In an isotropic system, the two terms can be combined to give an effective response under a total field along an arbitrarily direct. In what follows, we shall show that in a semi-Dirac system, the second term can play a role to enhance the x-response by many order of magntidue.

III. RESULTS AND DISCUSION

In the following, we make two assumptions. Firstly, we assume that the magnitude of three incoming photons in the x-direction are the same and in in the order of 10^3V/cm. The

y-component of the three fields are the tuning parameters. Only the y-component of the second and the third field contributes to the current in the x-direction. We treat E_{2y} and E_{3y} to be the same when tuning the field. Finally, we assume that the chemical potential is larger than 0.04 eV. The two assumptions guarantee that the value of u/p_0 is small enough to make the above velocity expansion, where p_0 is the Fermi momentum.We now consider a situation where three ultrafast fields (of the order of femtosecond, or frequency ω) incident on the semi-Dirac system to generate a photoresponse at a frequency ($\delta\omega$) in the terahertz regime. For $\omega_1 = \omega + \delta\omega/2$, $\omega_2 = \omega + \delta\omega/2$ and $\omega_3 = 2\omega$, the third order current at $\omega_1 + \omega_2 - \omega_3 = \delta\omega$ is given as,

$$J_x^{(3)}(\delta\omega) = \frac{ie^4}{(\omega^2+\delta\omega^2)2\omega}\int_0^{+\infty}\int_0^{+\infty}[G_{xx}E_{1x}E_{2x}E_{3x}^* - G_{xy}E_{1x}E_{2y}E_{3y}^*][f(\epsilon_k) - f(\epsilon_k+\epsilon_{ph})]dp_x dp_y. \tag{11}$$

The third order current in the parabolic direction is shown in Fig.1.

In conventional semiconductor systems with parabolic energy-momentum dispersion, the third order current density $J^{(3)}$ is much smaller than the first order current density $J^{(1)}$. The mixing efficiency, defined as $Q = J^{(3)}/J^{(1)}$,

$$Q = \frac{J^{(3)}}{J^{(1)}} = \frac{e\int\int v^{(3)}[f(\epsilon) - f(\epsilon+\hbar\omega)]\hbar\omega dk^2}{\hbar\omega J^{(1)}} = \frac{-e\hbar\omega\int\int v^{(3)}f'(\epsilon)dk^2}{J^{(1)}}. \tag{12}$$

For a parabolic systems, the Q-value is generally very low, in the order of 10^{-8}. One the other hand for materials withe Linear energy dispersion, The Q value can be much higher, in the order of 10^{-4}. For example in HgTe/DeTe quantum wells.

Now we apply a second electric field along the linear axis, E_y. The E_y field is much smaller compared to the field along the parabolic direction, E_x field. In the case of an isotropic system with parabolic energy dispersion, adding a small E_y only changes the total field from E_x to $E_t = \sqrt{E_x^2 + E_y^2}$. The Q_x-value is proportional to E_t^2 and its change is very small. For example, for $E_x = 5000$V/cm, adding $E_y = 1000V$/cm changes the E_t^2 (or Q_x-value) by only 4%, a negligible improvement.

The situation will drastically different in the present system. In Fig.2 we show the enhancement of of the mixing efficiency due the field E_y. The Q-value can still be approximated by $E_x^2 + AE_y^2$. The enhancement factor A is weakly dependent on the chemical potential and is of the order of 10^3. For $E_x = 5000$V, applying $E_y = 500$V will result an enhancement of 10 times, as shown in figure 2. The Q_x-value decreases with the increase of chemical

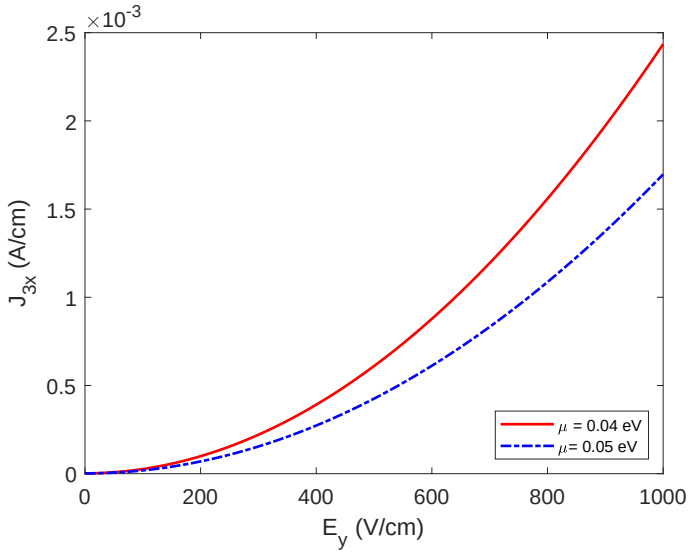

FIG. 1. (Color online) Plot of the Q-value as a function E_y for $E_{x0} = 5 \cdot 10^3$ V/cm, T = 0 K, $\mu =$ 0.04 eV and 0.05 eV, $\omega = 5$THz

potential μ. The reason is that the increase of chemical potential results in an increased Fermi momentum. Additionally, $v^{(1)}$ is proportional to $\frac{u}{p_0}$ and $v^{(3)}$ is proportional to $\frac{u^3}{p_0^3}$.

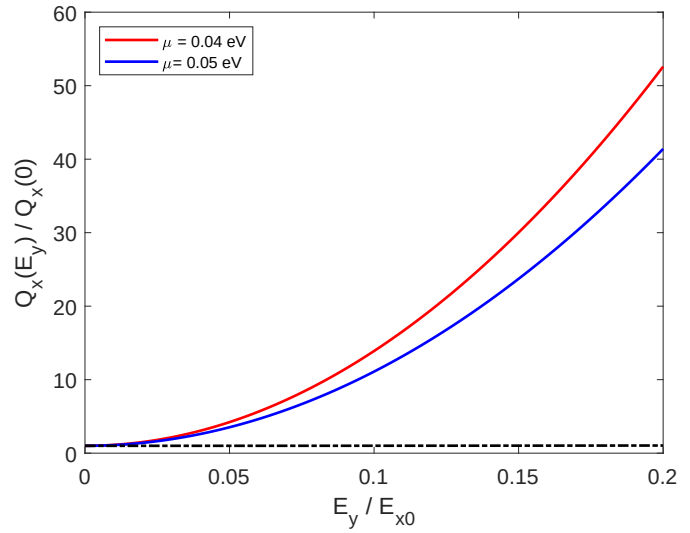

FIG. 2. (Color online) Dependence of Q_x on the electric field along the y-direction at two different chemical potentials, where $E_{x0} = 5000$V/cm and $T = 0K$.The dotted line is for an isotropic parabolic system.

The temperature dependence of the Q_x-value is shown in Figure 3. The normalised value $Q(T)/Q(0)$ is directly determined by the normalised current $J^{(3)}(T)/J^{(3)}(0)$ if the linear current is nearly indepedent of the temperature. There exists an optimal temperature around 50K at which the mixing efficiency is highest. This optimal temperature increases with the chemical potential. At room temperature, the nonlinear terms persists, at about 50% strength of that at zero temperature. The variation tendency of the third order current density to temperature agree with the previous work[12].

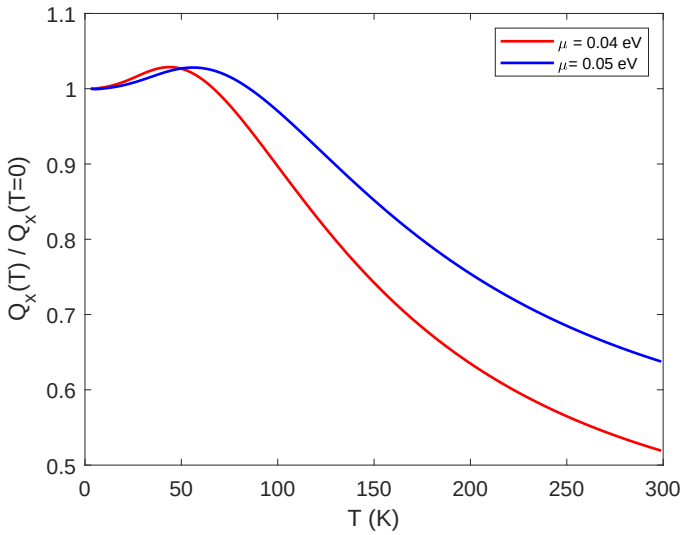

FIG. 3. (Color online) Temperature dependence of the mixing efficiency along the parabolic direction

For the completeness of our discussion, we present the mixing efficiency along the linear direction Q_y. Q_y is generally higher than Q_x for the reason discussed in the beginning. The E_x tunability of Q_y is only a few percent for $E_x/E_y < 0.1$.

IV. SUMMARY

We have shown that the lower photomixing efficiency for electrons with a parabolic energy dispersion can be significantly enhanced if the electron dispersion perpendicular to the parabolic direction is linear. A small electric field along the linear direction can improve the mixing efficiency by two orders of magnitude. Compared to graphene, the semi-Dirac system has a stronger nonlinear effect at room temperature. Our results suggest that the strength

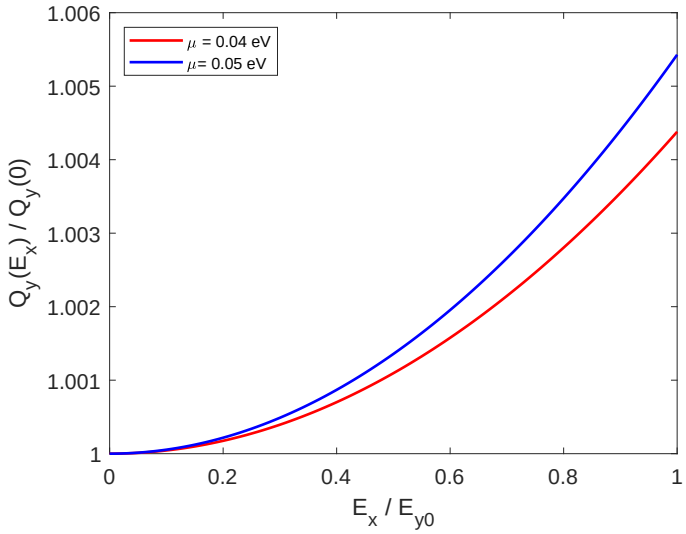

FIG. 4. (Color online) Dependence of Q_y on the electric field along the x-direction at two different chemical potentials, where $E_{y0} = 5000\text{V/cm}$ and $T = 0K$.

of non-linear electromagnetic response can be controlled by the weak field perpendicular to the direction of the third order current. This up to two orders of magnitude tunability is much greater than that in an isotropic parabolic system like normal semiconductors and in an isotropic linear system like graphene.

ACKNOWLEDGMENTS

The work is supported by the Australian Research Council Grant (DP160101474).

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