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Terahertz-driven nonlinear electrical transport in semiconductor nanostructures

C. Zhang
University of Wollongong, czhang@uow.edu.au

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C. Zhang

Department of Engineering Physics, University of Wollongong, New South Wales 2522, Australia

ABSTRACT

In this work, we used the quantum transport equation and density matrix formalism to calculate the frequency dependent electrical current of a two-dimensional electron gas directly driven by an intense terahertz laser. It is found that due to increased electron-photon coupling, the electron-impurity scattering decreases rapidly with the electric field.

1. INTRODUCTION

Terahertz (THz) radiation has been applied to experimental investigation of nonlinear transport and optical properties in electron gases such as low dimensional semiconductor systems. Interesting new phenomena have been found in recent years, including resonant absorption[1], photon enhanced hot-electron effect[2,3], THz photon-induced impact ionization[4], LO-phonon bottleneck effect[5], THz photon assisted tunneling[6], THz cyclotron resonance[7], THz switching effects in tunneling diode[8-10]. Despite the rapid development of terahertz phenomena, a theoretical formalism describing the quantum transport in strongly coupled electron-photon systems is lacking. In this paper, we present a theoretical investigation of the electrical current directly driven by the intense THz radiation field in the presence of electron-impurity scattering. We calculate the density matrix of the electron-photon system to the second order of impurity potential. The total current consists of contributions of successively electron-photon side bands. The strong nonlinear dependence of the real part of the current on the laser field indicates that as the electron-photon coupling becomes stronger, the electron-impurity scattering decreases rapidly.

2. FORMALISM OF NONLINEAR ELECTRICAL CURRENT

Our model system is a two dimensional electron gas under an intense laser radiation. We choose the laser field to be along the x-direction, $\mathbf{E}(t) = E_0 \cos(\omega t)\mathbf{e_x}$, where E_0 and ω are the amplitude and frequency of the laser field. For the notational convenience, both $\hbar$ and the speed of light c have been set to unity. We shall also neglect the effect of the magnetic field component of the laser field since it is smaller than the electrical field component by the factor of c. Let us choose the vector potential for the laser field to be in the form $\mathbf{A} = (E_0/\omega)\sin(\omega t)\mathbf{e_x}$. The time-dependent Schrödinger equation for a single electron is given as,

$$i\frac{\partial}{\partial t}\psi(\mathbf{r},t) = H\psi(\mathbf{r},t) = \frac{(\mathbf{p}-e\mathbf{A})^2}{2m^*}\psi(\mathbf{r},t). \tag{1}$$

The time-dependent wavefunction can be written as,

$$\psi_{\mathbf{k}}(\mathbf{r},t) = \exp(-i2\gamma_1\omega t)\exp(i\gamma_0 k_x(1-\cos(\omega t)))\exp(i\gamma_1\sin(2\omega t))\exp(-i\epsilon_k t)\exp(i\mathbf{k}\cdot\mathbf{r}). \tag{2}$$

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where $\gamma_0 = (eE_0)/m^*\omega^2$ and $\gamma_1 = (eE_0)^2/(8m^*\omega^3)$. The effect of electrical field is included in this wavefunction exactly. These wavefunctions satisfy the orthonormal condition and can be used as the basis for constructing the quantum field operator,

$$\Psi(\mathbf{r},t) = \sum_{\mathbf{k}} a_{\mathbf{k}}\psi_{\mathbf{k}}(\mathbf{r},t), \qquad \Psi^\dagger(\mathbf{r},t) = \sum_{\mathbf{k}} a_{\mathbf{k}}^\dagger\psi_{\mathbf{k}}^*(\mathbf{r},t), \tag{3}$$

where $a_{\mathbf{k}}^\dagger(a_{\mathbf{k}})$ is the creation (annihilation) operator for the electronic state with momentum $\mathbf{k}$. These field operators satisfy the equal time commutation relation, $\{\Psi^\dagger(\mathbf{r},t), \Psi(\mathbf{r}',t)\} = \delta(\mathbf{r}-\mathbf{r}')$. The field operators can also be written in terms of eigenfunctions of a free electron,

$$\Psi(\mathbf{r},t) = \sum_{\mathbf{k}} b_{\mathbf{k}}(t)e^{i\mathbf{k}\cdot\mathbf{r}}, \qquad \Psi^\dagger(\mathbf{r},t) = \sum_{\mathbf{k}} b_{\mathbf{k}}^\dagger(t)e^{-i\mathbf{k}\cdot\mathbf{r}}, \tag{4}$$

where $b_{\mathbf{k}}(t) = a_{\mathbf{k}}\exp(-i2\gamma_1\omega t)\exp(i\gamma_0 k_x(1-\cos(\omega t)))\exp(i\gamma_1\sin(2\omega t))$.

We now calculate the electrical current of system driven by the terahertz laser due to electron-random-impurity scattering. The Hamiltonian of the system, in the second quantized notation, can be written as, $H = H_0 + H_{ee} + H_{eI}$. Here H_0 is the Hamiltonian of a non-interacting many-electron system,

$$H_0 = \frac{1}{2m^*}\sum_{\mathbf{p}}\left[\mathbf{p}+e\mathbf{A}\right]^2 b_{\mathbf{p}}^\dagger(t)b_{\mathbf{p}}(t), \tag{5}$$

H_{ee} is the electron-electron interaction[11],

$$H_{ee} = \frac{1}{2}\sum_{\mathbf{p},\mathbf{p}',\mathbf{q}} V_q b_{\mathbf{p}+\mathbf{q}}^\dagger(t)b_{\mathbf{p}'-\mathbf{q}}^\dagger(t)b_{\mathbf{p}'}(t)b_{\mathbf{p}}(t) = \frac{1}{2}\sum_{\mathbf{p},\mathbf{p}',\mathbf{q}} V_q a_{\mathbf{p}+\mathbf{q}}^\dagger(t)a_{\mathbf{p}'-\mathbf{q}}^\dagger(t)a_{\mathbf{p}'}(t)a_{\mathbf{p}}(t), \tag{6}$$

where $V_q = 2\pi e^2/q$ is the Fourier transform of electron-electron interaction in two dimensions. H_{eI} is the interaction between the electrons and random impurities,

$$H_{eI} = -\sum_{\mathbf{p},\mathbf{q}} V_q b_{\mathbf{p}+\mathbf{q}}^\dagger(t)b_{\mathbf{p}}(t)\sum_i e^{i\mathbf{q}\cdot\mathbf{R}_i}, \tag{7}$$

where we assumed that impurities are singly charged. $\mathbf{R}_i$ is the position of i^{th} impurity. The total average 2D current density of the system is defined as,

$$\mathbf{j} = \left\langle\frac{\delta H}{\delta\mathbf{A}}\right\rangle = \frac{e}{m^*}\sum_{\mathbf{p}}\langle\left[\mathbf{p}+e\mathbf{A}\right]b_{\mathbf{p}}^\dagger(t)b_{\mathbf{p}}(t)\rangle = \mathbf{j}_1 + \mathbf{j}_0. \tag{8}$$

Since $\mathbf{A} = (E/\omega)\sin(\omega t)\mathbf{e}_x$,

$$\mathbf{j}_0 = \frac{e^2}{m^*}e\mathbf{A}\sum_{\mathbf{p}}\langle b_{\mathbf{p}}^\dagger(t)b_{\mathbf{p}}(t)\rangle = \frac{e^2 n}{m\omega}\sin(\omega t)E_0\mathbf{e}_x, \tag{9}$$

where n is the 2D electron concentration. The electrical field is oscillating as $\cos(\omega t)$. Therefore $\mathbf{j}_0$ is in the direction of the laser field but its phase is behind the phase of the electrical field by π. All effects on the electrical current due to the laser field is contained in the current density

$$\mathbf{j}_1 = \frac{e}{m^*}\sum_{\mathbf{p}}\langle\mathbf{p}b_{\mathbf{p}}^\dagger(t)b_{\mathbf{p}}(t)\rangle. \tag{10}$$

We will use the density matrix method to evaluate $\mathbf{j}_1$. The equation of motion for the single-electron density matrix $F(\mathbf{p}, \mathbf{p}+\mathbf{k}) = \langle b^\dagger_{\mathbf{p}}(t) b_{\mathbf{p}+\mathbf{k}}(t)\rangle$ is given as

$$i\frac{\partial}{\partial t}F(\mathbf{p},\mathbf{p}+\mathbf{k}) = [\epsilon_{\mathbf{p}+\mathbf{k}} - \epsilon_{\mathbf{p}} + k_x\gamma_0\omega\sin(\omega t)]F(\mathbf{p},\mathbf{p}+\mathbf{k})$$

$$+\sum_{\mathbf{q}} V_q\left[n(\mathbf{q},t) - \sum_i e^{i\mathbf{q}\cdot\mathbf{R}_i}\right][F(\mathbf{p},\mathbf{p}+\mathbf{k}-\mathbf{q}) - F(\mathbf{p}+\mathbf{q},\mathbf{p}+\mathbf{k})]. \tag{11}$$

Here $\epsilon_{\mathbf{p}} = p^2/2m^*$ is the kinetic energy of an electron having momentum $\mathbf{p}$, and $n(\mathbf{q},t) = \sum_{\mathbf{p}} F(\mathbf{p},\mathbf{p}+\mathbf{q})$. The time-dependent current density $\mathbf{j}_1(t)$, is now given as

$$i\frac{d\mathbf{j}_1(t)}{dt} = \frac{-e}{m^*}\sum_{\mathbf{q}} V_q \mathbf{q} n(-\mathbf{q},t)\sum_i e^{i\mathbf{q}\cdot\mathbf{R}_i}. \tag{12}$$

We have recently developed a method to calculate the density matrix in a strongly coupled electron-photon system[11]. Making use of the generating function for the Bessel function, $\exp[i\alpha\cos(x)] = \sum_m i^m J_m(\alpha)\exp(imx)$ (where J_m is the Bessel function of first kind), the density matrix, the density fluctuation, the total current can be decomposed into a sum of successive harmonics. We solve for the electron density matrix up to the second order in electron-impurity interaction, F_1. The solution of the m-th order density matrix, $F_1^{(m)}$ is given as

$$F_1^{(m)} = -\frac{V_k}{2\pi D(k,m\omega)}\frac{f_{\mathbf{p}+\mathbf{k}} - f_{\mathbf{p}}}{\epsilon_{\mathbf{p}+\mathbf{k}} - \epsilon_{\mathbf{p}} - m\omega}\sum_i e^{i\mathbf{k}\cdot\mathbf{R}_i}, \tag{13}$$

where $D(q,m\omega) = 1 - V_q Q(q,m\omega)$ is the dielectric function in the random-phase-approximation and $Q(q,\omega)$ is the the polarizability for free electrons. The final result for the electric current can be written as

$$\mathbf{j}_1(\omega) = \frac{-ne}{m^*\omega}\sum_{\mathbf{q}} \mathbf{q} V_q \sum_m \frac{(-i)^m}{m} J_m(q_x\gamma_0) e^{iq_x\gamma_0}\frac{V_q Q(q,m\omega)}{D(q,m\omega)}. \tag{14}$$

For isotropic systems, the electric current is along the direction of polarization of the laser field. The real part of the electric current is given as

$$\Re e\,[\mathbf{j}_{1x}(\omega)] = -\frac{ne}{m^*\omega}\sum_{\mathbf{q}} q_x V_q \sum_m \frac{J_m(q_x\gamma_0)}{m}\times$$

$$\left\{\Im m\left[\frac{1}{D(q,m\omega)}\right]\sin(q_x\gamma_0 - m\pi/2) - \Re e\left[\frac{1}{D(q,m\omega)}\right]\cos(q_x\gamma_0 - m\pi/2)\right\}. \tag{15}$$

We now make use of the following facts: (a) The dielectric function is only dependent on the magnitude of q; (b) The Bessel functions are symmetric for even m, and antisymmetric for odd m with respect to the argument q_x. Therefore the integration over the direction of q will be nonzero for the second term in the curl brackets. The real part of the electric current is now written as,

$$\Re e\,[\mathbf{j}_{1x}(\omega)] = -\frac{ne}{m^*\omega}\sum_{\mathbf{q}} q_x V_q \sum_m \frac{J_m(q_x\gamma_0)}{m}\Im m\left[\frac{1}{D(q,m\omega)}\right]\sin(q_x\gamma_0 - m\pi/2). \tag{16}$$

3. RESULTS AND DISCUSSIONS

We have numerically calculated real part of the current. The parameters used in our calculation are those of GaAs, $m^* = 0.067m_0$, $r_s = m^*e^2/(\hbar^2 k_F) = 1.0$. $R = k_F e E_0/(m^*\omega^2)$ is the reduced electric field.

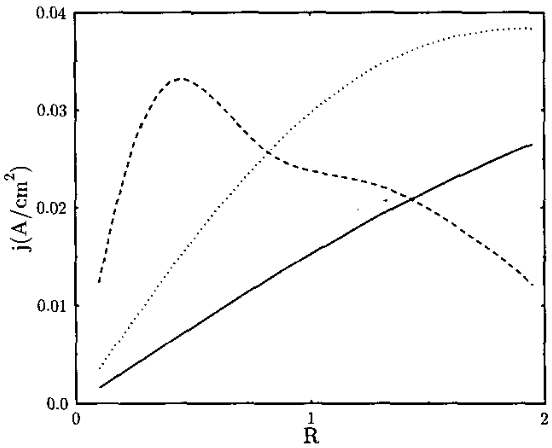

Fig.1. Electrical current as a function of the reduced electric field R for GaAs-based semiconductor quantum wells. The solid line is for ω=6 THz, the dotted line is for ω=4 THz, and the broken line is for ω=2 THz.

Fig.1 shows electric field dependence of the real part of the electric current. The real part of the current is a direct measure of the absorption of THz photons by the electronic system. At weak electric fields or high frequencies, the current is almost linear in the electric field. The electron-photon coupling is inversely proportional to ω^2. Therefore the absorption increases as frequency decreases. At fixed frequency, as the laser intensity increases, the current starts to deviate from the linear dependence, the absorption coefficient j/E starts to decrease with the field intensity. This behaviour is a direct consequence of the electron-impurity scattering time being affected by electron-photon coupling. At low field intensity or weak electron-photon coupling, the scattering time is independent of the electric field. As field intensity increases, electrons-photon coupling become stronger and as a consequence, the electron-impurity scattering becomes less effective. This reduced electron-impurity scattering is the origin of the reduction of the current at high fields.

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