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Electron density of states in terahertz driven two-dimensional electron gases

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Abstract. In this paper, a detailed theoretical study of the density of states (DOS) is presented for free electrons in terahertz (THz) driven two-dimensional electron gases (2DEGs). Using the Green's function approach and including the electron-photon interaction exactly, we have derived the electronic DOS in a THz driven 2DEG. The results obtained show that: (1) in the presence of intense THz electromagnetic radiations, the maximum DOS in the system will be shifted to the high-energy regime; (2) a stronger effect of the radiation on electron DOS and Fermi energy can be observed at relatively low-frequency and/or high-intensity radiations where the energy shift induced by the radiation field plays an important role in determining the DOS and the Fermi energy; (3) the processes of the multiphoton absorption and emission will lead to a small increase in DOS; and (4) as a consequence of (1) and (2), an intense THz radiation will drive electrons in a 2DEG to occupy higher electronic subbands.

1. Introduction

With the development of novel means of investigation, such as free-electron-lasers (FELs), it has become possible to study the nonlinear transport and optical properties of two-dimensional electron gases (2DEGs) driven by intense terahertz (THz) electromagnetic (EM) fields. FELs can provide the tunable source of linearly polarized THz radiations with which one can study the dependence of the physical properties in an electronic device on the frequency and strength of the EM radiation. Recently, experimental measurements have been carried out in investigating the nonlinear response of a 2DEG to the THz EM fields [1,2]. Some interesting phenomena, such as resonant absorption of the THz radiation [1], radiation enhanced electron temperature [2], etc., were observed in different two-dimensional semiconductor systems. These experimental observations have impelled further theoretical study [3]. Moreover, the current availability of measurements at THz EM fields has resulted in proposals for observing photon-induced novel quantum resonance effects such as magneto-photon-phonon resonances [4]. It can be foreseen that the study of THz-driven 2DEGs will be of significant impact on the investigation and characterization of condensed matter materials, such as low-dimensional semiconductor systems and nanostructures.

Like in other studies, in the study of THz-driven 2DEGs the density of states (DOS) is one of the central quantities to determine and to understand almost all physically measurable properties. Therefore, it is of value to examine how an EM radiation affects such a fundamental quantity like the DOS, and is the motivation of this study. In the presence of electromagnetic radiation, the electron DOS in 3DEG and *ideal* 2DEG structures has been investigated very recently [5] by using the approach of the gauge-invariant spectral function. For the case of a *quasi*-2DEG, the presence of the confining potential $U(z)$ along the growth direction makes it difficult to derive the DOS using the gauge-invariant spectral function. In this paper we consider a simple theoretical treatment to calculate the electron DOS in a THz-driven 2DEG. The derivation of the electron DOS in the presence of the EM radiation field is presented in section 2. The main theoretical results are presented and discussed in section 3, and the conclusions obtained from this study are summarized in section 4.

2. Model

In the absence of an EM radiation and scattering, the DOS for a 2DEG at a fixed subband n is characterized by a step-function and given simply by

$$D_n(E) = D_0\Theta(E - \varepsilon_n) \tag{1}$$

where $D_0 = g_s m^*/2\pi\hbar^2$, $g_s = 2$ is the factor for spin degeneracy, m^* is the effective electron mass, ε_n is the energy for the n^{th} electronic subband, and $\Theta(x)$ is the unit-step-function. For a 2DEG subjected to an intense THz EM field, the nature of the electron-photon interaction

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will result in a strong modulation of the electronic DOS by the radiation. We start by studying this problem from a time-dependent Schrödinger equation for noninteracting electrons within a single-electron approximation, namely

$$i\hbar\frac{\partial\Psi}{\partial t}=\left(\frac{(\boldsymbol{P}-e\boldsymbol{A})^2}{2m^*}+U(z)\right)\Psi \tag{2}$$

where $\boldsymbol{P}=(p_x,p_y,p_z)$ is the momentum operator with $p_x=-i\hbar\partial/\partial x$, $\boldsymbol{A}$ is the vector potential induced by the EM radiation, and $U(z)$ is the confinement potential energy for the 2DEG. For a THz-driven 2DEG, the EM radiation is polarized along the 2D-plane of the 2DEG (taken along the x-direction), and so $\boldsymbol{A}=(A,0,0)$. Furthermore, after using the dipole approximation for the radiation field and taking $A=A_0\sin(\omega t)$, with ω being the frequency of the radiation, the solution of equation (2) is

$$\Psi_{n,\boldsymbol{k}}(\boldsymbol{R},t)=\Psi_{n,\boldsymbol{k}}(\boldsymbol{R},0)e^{-i[E_n(\boldsymbol{k})+2\gamma\hbar\omega]t/\hbar}\times e^{ir_0k_x[1-\cos(\omega t)]}e^{i\gamma\sin(2\omega t)} \tag{3a}$$

and

$$\Psi_{n,\boldsymbol{k}}(\boldsymbol{R},0)=e^{i\boldsymbol{k}\cdot\boldsymbol{r}}\psi_n(z) \tag{3b}$$

which should be normalized. Here, $\boldsymbol{R}=(\boldsymbol{r},z)=(x,y,z)$, $\boldsymbol{k}=(k_x,k_y)$ is the electron wavevector along the 2D-plane, $E_n(\boldsymbol{k})=\hbar^2k^2/2m^*+\varepsilon_n$ is the energy spectrum of the 2DEG, $r_0=eF_0/m^*\omega^2$ with F_0 being the strength of the radiation electric field, $\gamma=(eF_0)^2/(8m^*\hbar\omega^3)$, and $2\gamma\hbar\omega$ is the energy of the radiation field. We have used the relation $\boldsymbol{F}=\partial\boldsymbol{A}/\partial t=F_0\cos(\omega t)$ with $F_0=\omega A_0$. Furthermore, $\psi_n(z)$ and ε_n along the growth direction are determined from the following time-independent one-dimensional Schrödinger equation

$$\left[-\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial z^2}+U(z)-\varepsilon_n\right]\psi_n(z)=0. \tag{4}$$

From the time-dependent electron wavefunction given by equation (3), we can calculate the probability amplitude, which describes a process that if one adds an electron in a state $|\boldsymbol{k}',n'>$ at time t' to the system then the system will be in a state $|\boldsymbol{k},n>$ at time t, through

$$\int d^3\boldsymbol{R}\;\Psi^*_{n',\boldsymbol{k}'}(\boldsymbol{R},t')\Psi_{n,\boldsymbol{k}}(\boldsymbol{R},t)=\delta_{n',n}\delta_{\boldsymbol{k}',\boldsymbol{k}}R(n,\boldsymbol{k};t,t'), \tag{5a}$$

and

$$R(n,\boldsymbol{k};t,t')=e^{-i[E_n(\boldsymbol{k})+2\gamma\hbar\omega](t-t')/\hbar}e^{-ir_0k_x[\cos(\omega t)-\cos(\omega t')]}e^{i\gamma[\sin(2\omega t)-\sin(2\omega t')]}. \tag{5b}$$

Here we have used a condition: $\int d^3\mathrm{R}e^{-i(\boldsymbol{k}'-\boldsymbol{k})\cdot\boldsymbol{r}}\psi^*_{n'}(z)\psi_n(z)=\delta_{n',n}\delta_{\boldsymbol{k}',\boldsymbol{k}}$. Whence, by definition [6], the corresponding retarded propagator or Green's function in $(n,\boldsymbol{k};t)-$space for noninteracting electrons is given by

$$G^+(n',\boldsymbol{k}';n,\boldsymbol{k};t>t')=\delta_{n',n}\delta_{\boldsymbol{k}',\boldsymbol{k}}G^+(n,\boldsymbol{k};t>t'), \tag{6a}$$

where

$$G^+(n,\boldsymbol{k};t>t')=-\frac{i}{\hbar}\Theta(t-t')R(n,\boldsymbol{k};t,t'). \tag{6b}$$

Equation (6) is a two-time Green's function, due to the shift caused by the radiation field. Moreover, equation (6) satisfies (noting $d\Theta(t-t')/dt=\delta(t-t')$)

$$\left[i\hbar\frac{\partial}{\partial t}-\frac{(\hbar\boldsymbol{k}-e\boldsymbol{A})^2}{2m^*}-\varepsilon_n\right]G^+(n,\boldsymbol{k};t>t')=\delta(t-t') \tag{7a}$$

in the $(n,\boldsymbol{k};t)-$space and

$$\left[i\hbar\frac{\partial}{\partial t}-\frac{(\boldsymbol{P}-e\boldsymbol{A})^2}{2m^*}-U(z)\right]G^+(n,\boldsymbol{k};t>t')\Psi_{n,\boldsymbol{k}}(\boldsymbol{R},0)=\delta(t-t')\Psi_{n,\boldsymbol{k}}(\boldsymbol{R},0) \tag{7b}$$

in the real space where n and $\boldsymbol{k}$ are the quantum numbers. It can be seen that when equation (4) can only be solved in real space, which is in contrast to the case of 3DEG and ideal 2DEG, $G^+(n,\boldsymbol{k};t>t')$ is the actual Green's function in the $(n,\boldsymbol{k};t)-$space.

The Fourier transform (or average over time $t-t'$) of the retarded Green's function is given by, after generating $e^{ix\cos y}$ and $e^{ix\sin y}$ into the Bessel functions [7],

$$G^+_{n,\boldsymbol{k}}(E,t')=\int_{-\infty}^{\infty}d(t-t')\;e^{i(E+i\delta)(t-t')/\hbar}G^+(n,\boldsymbol{k};t>t')=\sum_{m=-\infty}^{\infty}\frac{\mathcal{F}_m(k_x,t')}{E-E_n(\boldsymbol{k})-2\gamma\hbar\omega-m\hbar\omega+i\delta}, \tag{8a}$$

where an infinitesimal quantity $i\delta$ has been introduced to make the integral converge. Here,

$$\mathcal{F}_m(k_x,t')=(-1)^mF_m(k_x)\sum_{n=-\infty}^{\infty}i^nJ_{m+n}(r_0k_x)e^{i[n\omega t'-\gamma\sin(2\omega t')]} \tag{8b}$$

where $\mathrm{Re}\,\mathcal{F}_m(-k_x,t')=\mathrm{Re}\,\mathcal{F}_m(k_x,t')$, $\mathrm{Im}\,\mathcal{F}_m(-k_x,t')=-\mathrm{Im}\,\mathcal{F}_m(k_x,t')$, $J_m(x)$ is a Bessel function, and

$$F_m(k_x)=\sum_{n=0}^{\infty}\frac{J_n(\gamma)}{1+\delta_{n,0}}[J_{2n-m}(r_0k_x)+(-1)^{m+n}J_{2n+m}(r_0k_x)]. \tag{8c}$$

For studying the steady-state properties, we can average over the initial time t'. After averaging t' over a periodicity of the radiation field [5], the averaged Green's function then becomes

$$G^*_{n,\boldsymbol{k}}(E)=\frac{\omega}{2\pi}\int_{-\pi/\omega}^{\pi/\omega}dt'\;G^+_{n,\boldsymbol{k}}(E,t')=\sum_{m=-\infty}^{\infty}\frac{F_m^2(k_x)}{E-E_n(\boldsymbol{k})-2\gamma\hbar\omega-m\hbar\omega+i\delta}. \tag{9}$$

One can find that the energy sum rule for this Green's function is exhausted by the imaginary part alone, i.e., $\int_{-\infty}^{\infty}dE\;\mathrm{Re}G^*_{n,\boldsymbol{k}}(E)=0$ and $\int_{-\infty}^{\infty}dE\;\mathrm{Im}G^*_{n,\boldsymbol{k}}(E)=-\pi$ (noting $\sum_{m=-\infty}^{\infty}F_m^2(k_x)=1$).

The DOS for electrons in the n^{th} subband is determined by the imaginary part of the Fourier transform of the Green's function

$$D_n(E)=-\frac{g_s}{\pi}\sum_{\boldsymbol{k}}\mathrm{Im}G_{n,\boldsymbol{k}}(E)=D_0\sum_m\Theta(E-\varepsilon_n-2\gamma\hbar\omega-m\hbar\omega)\times R_m(E-\varepsilon_n-2\gamma\hbar\omega-m\hbar\omega) \tag{10a}$$

where

$$R_m(x) = \frac{2}{\pi}\int_0^1 \frac{\mathrm{d}y}{\sqrt{1-y^2}} F_m^2\left(y\sqrt{\frac{2m^* x}{\hbar^2}}\right). \qquad (10b)$$

A direct and important application of the DOS is to determine the Fermi energy in an electronic system. Using the condition of electron number conservation, the Fermi energy E_F for a 2DEG subjected to an EM radiation can be determined by, after assuming that the total electron density n_e in the 2DEG is not varied by the presence of the radiation field, by

$$n_e = \sum_n \int dE\ f(E) D_n(E), \qquad (11)$$

where $f(E) = [e^{(E-E_F)/k_B T} + 1]^{-1}$ is the Fermi–Dirac function. In the low-temperature limit (i.e., $T \to 0$), we have $f(E) \to \Theta(E_F - E)$ and, consequently,

$$n_e = D_0 \sum_{n,m} \Theta(E_F - \varepsilon_n - 2\gamma\hbar\omega - m\hbar\omega) \times (E_F - \varepsilon_n - 2\gamma\hbar\omega - m\hbar\omega) \times S_m(E_F - \varepsilon_n - 2\gamma\hbar\omega - m\hbar\omega) \qquad (12a)$$

where

$$S_m(x) = \frac{4}{\pi}\int_0^1 \mathrm{d}y\ \sqrt{1-y^2} F_m^2\left(y\sqrt{\frac{2m^* x}{\hbar^2}}\right). \qquad (12b)$$

3. Results and discussions

When a 2DEG is subjected to an EM radiation field polarized along the 2D-plane, like in the case of the 3DEGs, the electron wavefunction is characterized by a Floquet state [8] which is the analog to a Bloch state when replacing a spatially periodic potential with a time periodic one. As can be seen in equation (3a), the coupling of the radiation field to the electronic system results in that: (i) the energy of a 2DEG system becomes $\mathcal{E} = E_n(\boldsymbol{k}) + 2\gamma\hbar\omega$ shifted by a positive energy arisen from the EM radiation: $2\gamma\hbar\omega = (eF_0)^2/(4m^*\omega^2)$. This has been observed in, e.g., dynamical Franz–Keldysh effect [5]; (ii) the time evaluation of the electron wavefunction will no longer be in the form of $\Psi \sim e^{iEt/\hbar}$; and (iii) an anisotropic nature of the wavefunction along the 2D-plane can be present. The physical reason behind this is that the polarized radiation field has broken the symmetry of the sample geometry. As a consequence of (iii), the Green's functions given above are also anisotropic, i.e., depending on k_x.

In equations (8)–(12), $m = 1, 2, 3, \ldots (-1, -2, -3, \ldots)$ corresponds to the absorption (emission) of $1, 2, 3, \ldots$ photons with the frequency ω. This implies that the electrons in a 2DEG system can interact with the radiation field, which will be accompanied by the processes of photon emission and absorption.

When $F_0 = 0$ (i.e., $r_0 = \gamma = 0$), due to the feature $J_m(0) = \delta_{m,0}$, the Green's functions given above become the well-known results obtained in the absence of the EM radiation and the DOS given by equation (10) becomes that given by equation (1).

The theoretical approach employed in the present study is a generalization of those documented in reference [9]. We find that this approach is of great convenience in dealing with quasi-low-dimensional electron gases. It should be noted that the results shown in this paper are obtained from using the Coulomb gauge [10] which allows us to choose the vector potential $\boldsymbol{A}$ and the scalar potential ϕ for the radiation field such that $\nabla\cdot\boldsymbol{A} = 0$ and $\phi = 0$. The Coulomb gauge corresponds to a situation where the charge density $\rho = 0$ and the current density $\boldsymbol{j} = 0$, which is true for the case of free electrons in a 2DEG subjected to EM fields polarized along the 2D-plane. It can be verified that the Green's function given by equation (6) and the DOS given by equation (10) are gauge-invariant in the Coulomb gauge.

The numerical results of this paper pertain to GaAs-based 2DEG structures. For GaAs, the effective electron mass is $m^* = 0.0665m_e$ with m_e being the rest electron mass. To calculate $F_m(x)$ given by equation (8c), we have taken $n = 0, 1, 2, \ldots$ and 20. Furthermore, we have included the contributions from $m = 0, \pm1, \pm2, \ldots$ and ±10 to calculate the DOS and the Fermi energy.

The contribution from different optical processes to electron DOS is shown in figure 1 at a fixed radiation field. From equation (10a), we see that with increasing electron energy E, a contribution from the process of m-photon absorption ($-$) or emission ($+$) to the DOS becomes possible when the condition $E - \varepsilon_n - 2\gamma\hbar\omega \mp m\hbar\omega \geq 0$ is satisfied. The opening up of the new channel for optical absorption or emission leads to an increase in DOS. In contrast to the case of $F_0 = 0$ (see figure 2) where the DOS is given by equation (1), in the presence of the EM radiation the electron DOS in a 2DEG can be present in the energy regime $E - \varepsilon_n < 0$ and $D_n(E)$ can be larger than D_0. This arises from the processes of the photon emission. From figure 1, we note that: (i) the maximum DOS appears when $E - \varepsilon_n$ is around $2\gamma\hbar\omega$ for the case of $m = 0$ (because $\lim_{x\to0} J_m(x) = \delta_{m,0}$); (ii) in the energy regime $E - \varepsilon_n \sim 2\gamma\hbar\omega$, the contribution to the DOS from a process of $m+1$-photon emission is smaller than that from a m-photon emission process; and (iii) the contribution from multiphoton absorption processes can only be observed in high-energy regime.

The influence of the strength and frequency of the THz radiation field on the DOS for electrons in a fixed subband is shown in figures 2 and 3. With increasing radiation intensity F_0 and/or decreasing radiation frequency ω, the maximum DOS shifts to the high-energy side due to the increase in γ. For the case of very low-frequency radiations (e.g., $\omega/2\pi = 0.7$ THz in figure 3), the contributions from multiphoton emission and absorption to the DOS can become larger in comparison to the situation of high-frequency radiations. Under the low-frequency radiations, the electrons can interact with the radiation field via multiphoton processes because of relatively small energy transfer. The theoretical results obtained in this paper agree with those observed in dynamical Franz–Keldysh effect in an ideal 2DEG (see figure 4 in reference [5]). The results presented in figures 1 – 3 have given a more clear physical picture regarding the effect of the EM radiation on the DOS in a 2DEG and on the dynamical Franz-Keldysh effect.

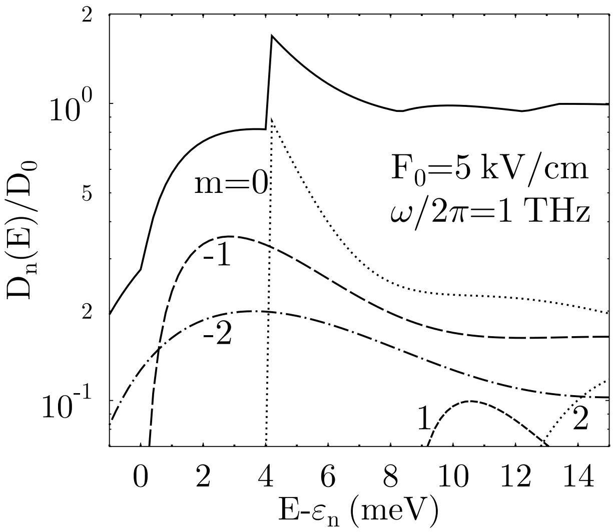

Figure 1. The contribution from different optical processes to electron density of states at a fixed radiation field with intensity F_0 and frequency ω. $m > 0$ and $m < 0$ correspond, respectively, to the channels of m-photon absorption and emission. When F_0 = 5 kV/cm and $\omega/2\pi$ = 1 THz, $\hbar\omega \simeq$ 4.14 meV and $2\gamma\hbar\omega \simeq$ 4.19 meV.

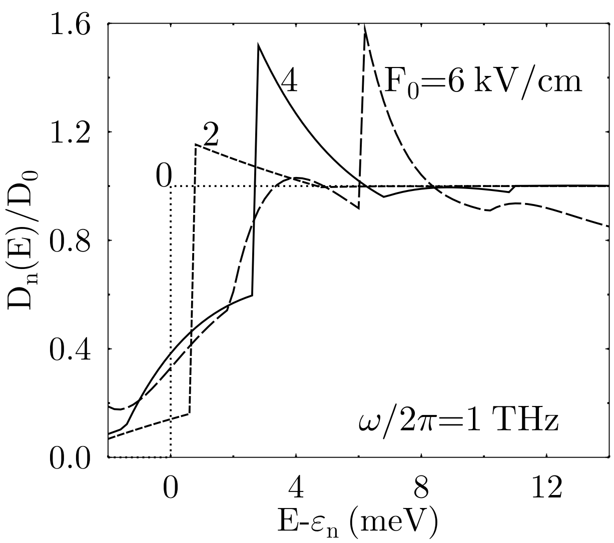

Figure 2. Density of states for electrons in the n^{th} subband as a function of electron energy E at a fixed radiation frequency ω for different strengths of the radiation field F_0. Here, ε_n is the electronic subband energy and $D_0 = g_s m^*/(2\pi\hbar^2)$.

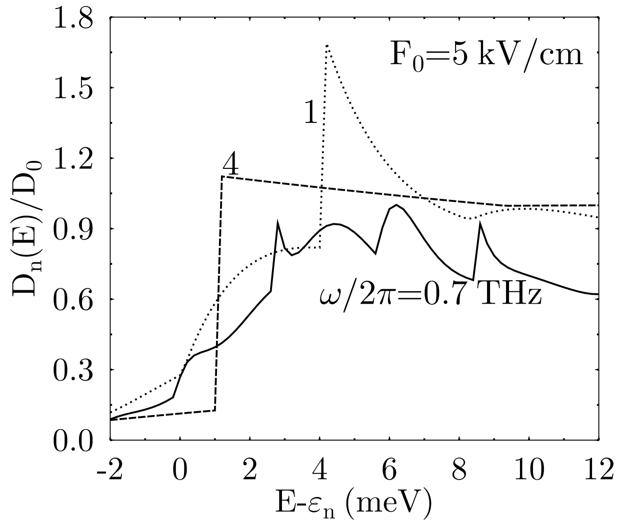

Figure 3. Density of states for electrons in the n^{th} subband as a function of electron energy E at a fixed radiation intensity F_0 for different radiation frequencies ω. $D_0 = g_s m^*/(2\pi\hbar^2)$.

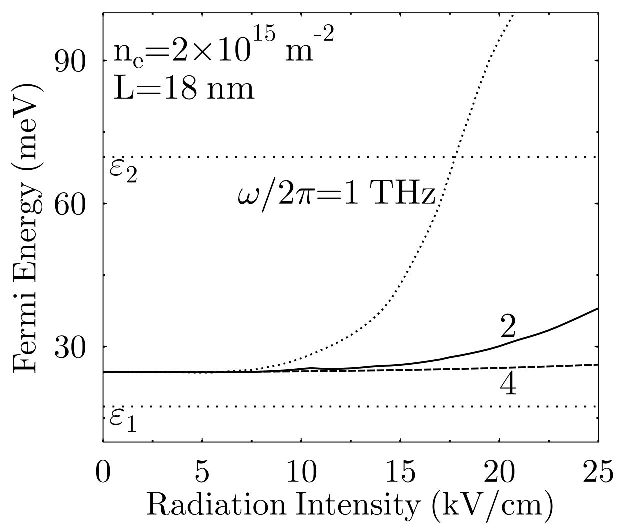

Figure 4. Fermi energy E_F in a single quantum well as a function of radiation intensity F_0 for different radiation frequencies. n_e is the electron density of the 2DEG, L is the width of the quantum well, and ε_n is the energy for the n^{th} electronic subband.

As can be seen from Figs. 1 - 3, the blue shift of the absorption edge arisen from the dynamical Franz-Keldysh effect is mainly caused by the energy of the radiation field $2\gamma\hbar\omega \sim (F_0/\omega)^2$ and the electron DOS presented in the lower-energy regime is mainly induced by the processes of the photon emission.

The results shown above indicate that the processes of optical absorption and emission may result in an increase in the DOS. However, due to the shift by the energy of the radiation field and to the nature $|J_m(x)| \leq 1$, the overall DOS for electrons in the low-energy regime will be reduced in comparison with that at $F_0 = 0$ (see figure 2). The DOS measures the maximum number of electrons which can occupy an energy range. The EM field applied will drive electrons out of the low-energy regime by a factor of $2\gamma\hbar\omega$, so that a reduced electron DOS in the lower-energy regime can be achieved. Due to the limiting feature $\lim_{x\to 0} J_m(x) = \delta_{m,0}$, for a radiation with relatively high-frequency (e.g., $\omega/2\pi = 4$ THz in figure 3) and/or low-intensity (e.g., $F_0 = 0$ in figure 2), which leads $r_0 \to 0$ and $\gamma \to 0$, the effects of the EM radiation on the DOS can be suppressed. Moreover, because $r_0 \sim F_0/\omega^2$ and $\gamma \sim F_0^2/\omega^3$, the radiation frequency has a stronger effect on the DOS.

The dependence of the Fermi energy in a 2DEG on the

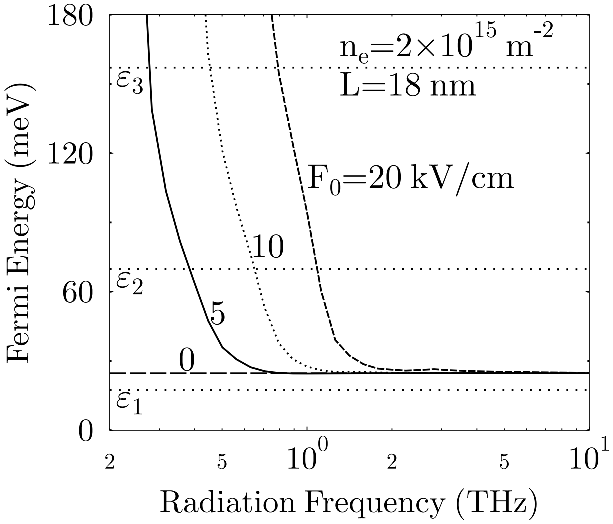

Figure 5. Fermi energy in a single quantum well as a function of radiation frequency $\omega/2\pi$ for different radiation intensities.

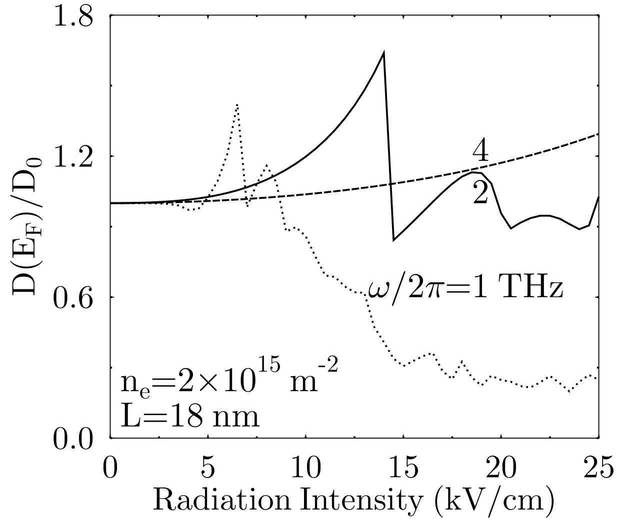

Figure 6. Total density of states at the Fermi energy, $D(E_F) = \sum_n D_n(E_F)$, as a function of radiation intensity for different radiation frequencies. The parameters are the same as in figure 4.

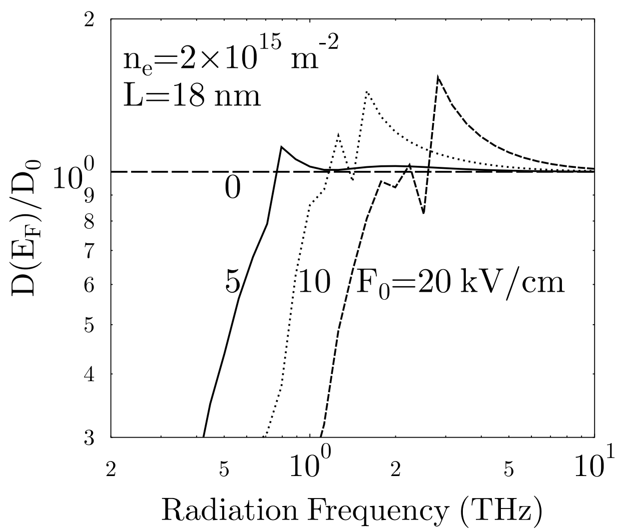

Figure 7. Total density of states at the Fermi energy as a function of radiation frequency for different radiation intensities. The parameters are the same as in figure 5.

frequency and strength of the THz driving fields is shown in figures 4 and 5. Here we consider an AlGaAs/GaAs single quantum well structure in which the electronic subband energy is given by $\varepsilon_n = n^2\pi^2\hbar^2/(2m^*L^2)$ where $n = 1, 2, 3, \ldots$ and L is the width of the quantum well. Because the reduction of the DOS in the low-energy regime by the radiation field, especially at the low-frequency and high-intensity radiations, the electron occupation of the higher subbands can be observed at a radiation with low-frequency and/or high-intensity. From equation (12), we can find that for a radiation field with very high-intensity and low-frequency so that $2\gamma\hbar\omega \gg \hbar\omega$ and $2\gamma\hbar\omega \gg \varepsilon_n$, the Fermi energy is of the feature $E_F \sim 2\gamma\hbar\omega \sim (F_0/\omega)^2$, which can be seen in figures 4 and 5. Under the high-frequency (e.g., $\omega/2\pi > 2$ THz in figure 5) and/or low-intensity (e.g., $F_0 < 7$ kV/cm in Fig. 4) EM radiations, the Fermi energy in a 2DEG depends very weakly on the radiation. A significant conclusion we draw from these results is that by varying the strength and frequency of the THz EM radiation, one can tune the electron population in different subbands and, consequently, the photon-induced quantum resonance effects, which are electrically analogous to the Shubnikov–de Haas effect, may be observed.

Experimentally, the DOS at low-temperatures can be obtained by measuring thermodynamic quantities such as specific heat [11], capacitance [12], etc. These low-temperature experiments measure the DOS at the Fermi energy, i.e., $D(E_F)$. For example, $D(E_F)$ can be determined by the data measured for specific heat via $C_v = \pi^2 k_B^2 T D(E_F)/3$. In figures 6 and 7 we plot the total DOS, $D(E_F) = \sum_n D_n(E_F)$, as a function of the frequency and strength of the THz radiation, respectively. By varying the radiation intensity and frequency, the Fermi energy changes, which is similar to the change of the electron energy shown in figures 1 – 3. Due to the opening up or closing down of the channels for different optical processes with varying the Fermi energy, the step changes in $D(E_F)$ can be observed. From the fact that the multiphoton effects on the DOS are more pronounced for low-frequency and high-intensity radiations, a stronger modulation of the DOS at the Fermi level can be seen at a radiation field with relatively high-intensity and low-frequency. Again, at high-frequency and/or low-intensity EM fields, $D(E_F)$ depends very little on ω and F_0.

We note that in the experiments carried out by references [1] and [2], the frequency and the strength of the THz radiations are, respectively, $\omega/2\pi$ ~THz and F_0 ~kV/cm. These parameters of the EM field may result in the strongest effect of the THz radiation on the DOS in a 2DEG, as presented and discussed in this paper. This may be one of the important reasons why some interesting and distinctive phenomena can be observed in their experiments.

The physical reason behind a strong effect of the EM radiation on electron DOS and on the Fermi energy in a 2DEG system can be understood by the fact that for a GaAs-based 2DEG driven by an EM field with $F_0 \sim$ kV cm^{-1} and $\omega \sim$ THz, the conditions such as $r_0[2m^*(E_F - \varepsilon_n - 2\gamma\hbar\omega \mp m\hbar\omega)/\hbar^2]^{1/2} \sim 1$ and $\gamma \sim 1$ can be satisfied. As a consequence, (i) the radiation field can couple strongly to the electronic system; (ii) the energy of the system is shifted to the high-energy regime by the energy of the radiation field $2\gamma\hbar\omega$; and (iii) the electrons in the system can interact with the radiation field via the processes of photon emission and absorption. Hence, the features distinctive for electron-photon interactions can be exposed.

4. Conclusions

In summary, in the present study we have derived the steady-state DOS for noninteracting electrons in a THz-driven 2DEG using the Green's function approach and including the electron-photon interaction exactly. Using the DOS obtained, we have studied the influence of the intense THz radiation on the quantities such as Fermi energy and the low-temperature DOS at the Fermi level. We found that: (1) the DOS and the Fermi energy for a THz-driven 2DEG will be strongly modulated by the frequency and strength of the radiation field; (2) applying an EM driving field to a 2DEG will result in a decrease in the DOS in the low-energy regime and, consequently, in an increase in the Fermi energy, due to the nature of electron-photon interactions; (3) a stronger effect of the radiation on the DOS and the Fermi energy can be observed at relatively low-frequencies and/or high-intensities where a large energy shift induced by the radiation field is present and the processes of the multiphoton emission and absorption are possible; (4) the processes of optical absorption and emission, including the multiphoton absorption and emission, have a relatively weak effect on the Fermi energy in comparison with those induced by the energy shift of the radiation field; and (5) by varying the frequency and/or strength of the THz radiation, the electron population in different subbands can be varied. Furthermore, the DOS for noninteracting electrons in a THz-driven 2DEG, obtained from this study, can be used for further derivation of the DOS or Green's function in the presence of electronic scattering mechanisms such as impurities and phonons.

The phenomena predicted and discussed in this paper may be observed within the radiation intensity and frequency regimes of recently developed free-electron lasers such as the UCSB FELs [1, 2] and the FELIX [13]. We hope those presented in this paper could be verified experimentally.

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