Electron cooling due to terahertz irradiation in polar semiconductors

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It is shown that in a realistic two-dimensional polar semiconductor the irradiation of an electromagnetic field of terahertz frequency may induce a drop of the electron temperature in a rather wide lattice temperature range around 77 K. A magnetic field in Faraday geometry can give rise to the cyclotron resonance of this electron cooling effect: the sensitivity of the temperature response to the terahertz field strength is greatly enhanced when the cyclotron frequency ω_c of the magnetic field is close to the radiation frequency ω.

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It is generally believed that an electron gas irradiated by a far-infrared (FIR) or terahertz (THz) electromagnetic field will be heated due to its absorption of energy from the radiation field. This electron heating has been considered to be the primary origin of cyclotron resonance in FIR photoresistivity of two-dimensional electron systems since its discovery 20 years ago.[1–4] Such an intuitive conjecture, however, may not be true. The reason lies in the fact that a FIR radiation in a semiconductor has simutaneously two effects: (1) giving energy to electrons and (2) pushing electrons to transfer energy to phonons. The former is proportional to the frequency of the FIR field and the latter is related to the frequency of phonons. When polar optical phonon scattering dominates and FIR frequency is not too high the irradiation-induced electron energy loss to phonons may be greater than the energy absorption from the radiation field and may result in electron cooling.

In fact different kinds of possible electron cooling were previously observed in theoretical analyses for transport. Electron temperature descending below the lattice temperature in semiconductors during the electronic transport driven by a strong dc electric field was predicted when the system is subject to one kind of inelastic (phonon) scattering.[5–7] Possible radiation-induced cooling of electrons was also pointed out for the case assuming polar optic phonons to be the only scatterers.[8,9] However, electron cooling is a scattering-mechanism-dependent and temperature-sensitive phenomenon. Impurity and acoustic phonon scatterings in a realistic system generally heat the electrons under FIR irradiation. Therefore the appearance and role of irradiation-induced electron cooling and its implication in the cyclotron resonance cannot be fully understood without a careful examination of the electron temperature change, taking account of all important scattering mechanisms in a realistic system.

To proceed we model a polar semiconductor in which no direct interband transition can take place under a FIR radiation of frequency ω as a single-band system consisting of $N_{\rm e}$ electrons having effective mass m and charge e in a unit volume. These electrons are interacting with each other through the Coulomb potential, coupled with acoustic phonons and polar optic phonons, and scattered by randomly distributed impurities in the lattice. Under the influence of a THz electromagnetic radiation of amplitude $\mathbf{E}_\omega$ and angular frequency ω, the electron system approaching a steady state requires the energy balance that

$$S_{\rm p} - W = 0. \tag{1}$$

Here $S_{\rm p}$ is the average rate of the energy transfer from the radiation field to the electron system—i.e., the net absorption rate of the radiation energy by the electrons—and W is the average rate of the energy transfer from the electron system to the phonon system. A careful analysis of the electron intraband transition induced by direct impurity and phonon scatterings as well as by all orders of THz-photon-assisted impurity and phonon scatterings leads to the following results:[8] $W = W^0 + W_{\rm p}$,

$$W^0 = \sum_{\mathbf{q}} J_0^2(\xi)\Omega_{\mathbf{q}}|M(\mathbf{q})|^2\Lambda(\mathbf{q},\Omega_{\mathbf{q}}), \tag{2}$$

$$W_{\rm p} = \sum_{n=1}^{\infty}\sum_{\mathbf{q}} J_n^2(\xi)\Omega_{\mathbf{q}}|M(\mathbf{q})|^2[\Lambda(\mathbf{q},\Omega_{\mathbf{q}}-n\omega) + \Lambda(\mathbf{q},\Omega_{\mathbf{q}}+n\omega)], \tag{3}$$

$$S_{\rm p} = \sum_{n=1}^{\infty}\sum_{\mathbf{q}} J_n^2(\xi)n\omega|U(\mathbf{q})|^2 2\Pi_2(\mathbf{q},-n\omega) + \sum_{n=1}^{\infty}\sum_{\mathbf{q}} J_n^2(\xi)n\omega|M(\mathbf{q})|^2[\Lambda(\mathbf{q},\Omega_{\mathbf{q}}-n\omega) - \Lambda(\mathbf{q},\Omega_{\mathbf{q}}+n\omega)], \tag{4}$$

with

$$\Lambda(\mathbf{q},\Omega) \equiv 2\Pi_2(\mathbf{q},\Omega)[n(\Omega_{\mathbf{q}}/T) - n(\Omega/T_{\rm e})]. \tag{5}$$

In these equations $\xi \equiv \mathbf{q}\cdot\mathbf{v}_\omega/\omega$ with $\mathbf{v}_\omega \equiv e\mathbf{E}_\omega/(m\omega)$ being the velocity amplitude of the electron oscillation under THz radiation, $J_n(x)$ is the Bessel function of order n, $U(\mathbf{q})$ and $M(\mathbf{q})$ stand for effective impurity and phonon scattering potentials, $\Pi_2(\mathbf{q},\Omega)$ the imaginary part of the electron density correlation function at electron temperature $T_{\rm e}$, $\Omega_{\mathbf{q}}$ the phonon energy of wave vector $\mathbf{q}$, $n(x) \equiv 1/(e^x+1)$ the Bose function, and T the lattice temperature. The contributions from different kinds of elastic scattering and from different phonon branches are implicitly included in the summation over wave vector $\mathbf{q}$.

W_0 is the electron-energy-loss rate due to direct electron-phonon scattering, which is existent without the radiation field but may be somewhat affected by the irradiation. $W_{\rm p}$ is the irradiation-induced electron-energy-transfer rate to the lattice. Both $S_{\rm p}$ and $W_{\rm p}$ are due to photon-assisted scattering processes. In the absence of the radiation field $S_{\rm p}=0=W_{\rm p}$ and the energy balance $W^0=0$ requires $T_{\rm e}=T$. Irradiation of a THz field though always transfers energy to electrons, $S_{\rm p}\geqslant 0$, at the same time gives rise to a nonzero $W_{\rm p}$. The electron temperature $T_{\rm e}$, which is generally not equal to T when the system is subject to a radiation field, should be determined according to the energy balance equation (1) by the competition of these two factors. In the case of a weak radiation field, the electron temperature change $\Delta T_{\rm e}\equiv T_{\rm e}-T$ can be written as

$$\Delta T_{\rm e}=\frac{N_{\rm e}m}{2}v_\omega^2[M_2(\omega)-N_{\rm p2}(\omega)]\left(\frac{\partial W^0}{\partial T_{\rm e}}\right)^{-1}, \tag{6}$$

where $M_2(\omega)$ stands for the imaginary part of the momentum memory function (due to impurity and phonon scatterings without radiation) which is proportional to the energy absorption rate from the radiation field, and $N_{\rm p2}(\omega)$ represents the imaginary part of the energy memory function (due to phonon scatterings) in the absence of radiation:[10]

$$N_{\rm p2}(\omega)=\frac{1}{N_{\rm e}m\omega^2}\sum_{\mathbf q}\Omega_{\mathbf q}\,q_x^2|M(\mathbf q)|^2[\Lambda(\mathbf q,\Omega_{\mathbf q}-\omega)+\Lambda(\mathbf q,\Omega_{\mathbf q}+\omega)]_{T_{\rm e}=T}, \tag{7}$$

which is proportional to the photon-induced electron-energy-loss rate to the lattice. The above expressions are written for an isotropic three-dimensional system. For quasi-two-dimensional semiconductors the equations and expressions remain essentially the same as long as the relevant correlation functions and scattering matrix elements are given in terms of two-dimensional wave vectors and subband indices.

As an example we calculated the electron temperature change induced by normally incident terahertz radiations for a GaAs-based *n*-type quantum well having well width 12.5 nm, electron sheet density $N_{\rm e}=5.5\times10^{15}\ {\rm m}^{-2}$, and low-temperature linear mobility $\mu_0=31\ {\rm m}^2\,{\rm V}^{-1}\,{\rm s}^{-1}$. This is quite a realistic system. We consider both the electron–polar-optic-phonon scattering (via the Fröhlich coupling) and the electron–acoustic-phonon scattering (via the deformation potential and the piezoelectric couplings) as well as the elastic scattering due to charged impurities. Phonons are considered to be the same as those of a bulk GaAs and remain in equilibrium at the lattice temperature T during the irradiation process. Two lowest electron subbands, with energy separation between their bottoms being 69 meV, are taken into account. Typical values of GaAs material and electron-phonon coupling parameters are used in the calculation.[11]

Figure 1 shows the electron temperature $T_{\rm e}$ as a function of the amplitude of the radiation field E_ω having frequency $\omega/2\pi=0.67$, 1, 2, 3 and 4 THz at lattice temperature $T=77$ K. We see that, for a given frequency, the electron temperature always descends with increasing the strength of the radiation field before it reaches a minimum and then rises rapidly with further increase of the THz field strength. The range of the radiation field amplitude exhibiting electron cooling and the maximum cooling field amplitude increase with (roughly proportional to) frequency in the THz region. Note that the maximum $T-T_{\rm e}$ value goes down with increasing frequency, indicating that electron cooling does not appear with a radiation of sufficiently high frequency.

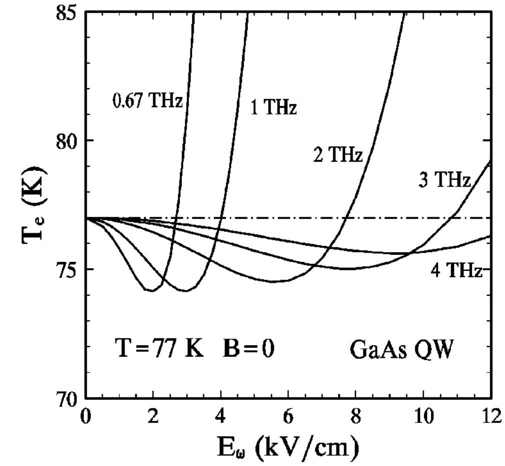

FIG. 1. The electron temperature $T_{\rm e}$ of a GaAs quantum well subject to FIR fields at lattice temperature $T=77$ K is shown as a function of the amplitudes E_ω of the radiation field having frequency $\omega/2\pi=0.67$, 1, 2, 3 and 4 THz.

This electron cooling phenomenon is strongly temperature dependent. Figure 2 shows the electron temperature change $\Delta T_{\rm e}\equiv T_{\rm e}-T$ induced by the irradiation of a weak field of 1 THz. For such a polar semiconductor with impurity scattering, electrons are heated ($\Delta T_{\rm e}>0$) upon irradiation at low temperatures ($T<50$ K) and high temperatures ($T>125$ K), but clear cooling appears in the medium temperature range between 55 and 125 K. The temperature range for electron cooling to appear depends on the amplitude and frequency of the radiation field. Figure 3 shows the temperature dependence of $\Delta T_{\rm e}\equiv T_{\rm e}-T$ at five radiation fields having different frequencies and amplitudes all in the vicinity of maximum cooling field strength for each given frequency.

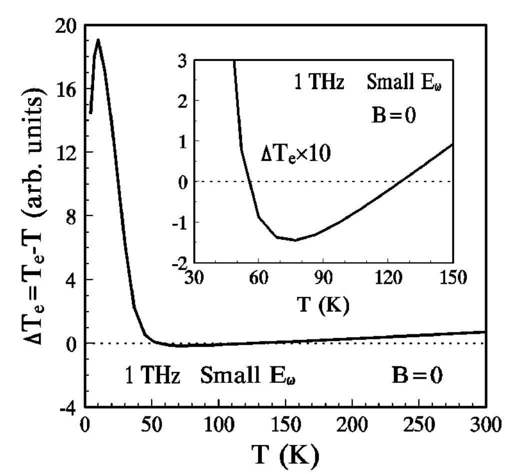

FIG. 2. The electron temperature change $\Delta T_{\rm e}\equiv T_{\rm e}-T$ induced by a weak FIR field of frequency 1 THz. The inset shows the part between 30 and 150 K with enlarged scale.

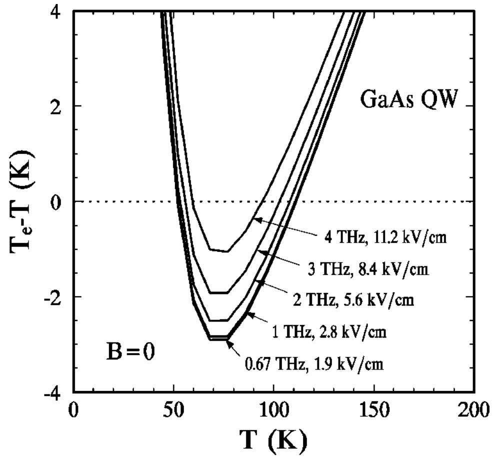

FIG. 3. Temperature dependence of the electron temperature change $\Delta T_e \equiv T_e - T$ induced by five FIR fields of different frequencies and amplitudes.

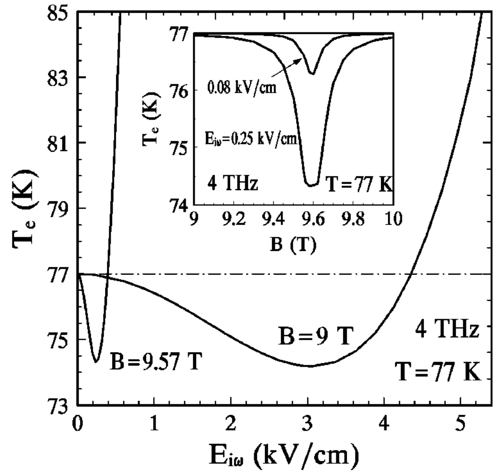

FIG. 4. The electron temperature T_e of a GaAs quantum well subject to a FIR field of frequency 4 THz and a magnetic field B in Faraday geometry at lattice temperature $T=77$ K is shown vs the incident field amplitude $E_{i\omega}$ at $B=9.0$ and 9.75 T. The inset shows T_e vs the magnetic field B at $E_{i\omega}=0.08$ and 0.25 kV/cm.

In the presence of a magnetic field parallel to the linear polarized radiation field (Voigt geometry) the above formulation for zero magnetic field is still usable if the Landau quantization is included in the density correlation function $\Pi_2(\mathbf{q},\Omega)$. The role of a Voigt-geometry magnetic field is essentially equivalent to that of a transverse confinement of electrons. The electron temperature together with other quantities may exhibit oscillation with changing magnetic field strength at quite a large intensity of the radiation field.[12,13]

When the applied magnetic field $\mathbf{B}$ is in the propagating direction of the radiation field (Faraday geometry) the situation becomes completely different. In this configuration even the incident radiation field is linearly polarized: $\mathbf{E}_{i\omega}\sin(\omega t)$, the oscillatory field $\mathbf{E}$, and the electron velocity $\mathbf{v}$ inside the quantum well are elliptically polarized. We can write $\mathbf{E}=\mathbf{E}_s\sin(\omega t)+\mathbf{E}_c\cos(\omega t)$ and $\mathbf{v}=\mathbf{v}_1\cos(\omega t)+\mathbf{v}_2\sin(\omega t)$, and $\mathbf{v}_1$ and $\mathbf{v}_2$ satisfy the following force-balance equations:

$$\mathbf{v}_1=(1-\omega_c^2/\omega^2)^{-1}\left\{\frac{e}{m\omega}\left[\mathbf{E}_s+\frac{e}{m\omega}(\mathbf{E}_c\times\mathbf{B})\right]+\frac{1}{N_e m\omega}\left[\mathbf{F}_s+\frac{e}{m\omega}(\mathbf{F}_c\times\mathbf{B})\right]\right\}, \tag{8}$$

$$\mathbf{v}_2=(\omega_c^2/\omega^2-1)^{-1}\left\{\frac{e}{m\omega}\left[\mathbf{E}_c-\frac{e}{m\omega}(\mathbf{E}_s\times\mathbf{B})\right]+\frac{1}{N_e m\omega}\left[\mathbf{F}_c-\frac{e}{m\omega}(\mathbf{F}_s\times\mathbf{B})\right]\right\}, \tag{9}$$

with $\omega_c \equiv |eB|/m$. The expressions of the oscillating damping force amplitudes $\mathbf{F}_s$ and $\mathbf{F}_c$, which also depend on $\mathbf{v}_1$ and $\mathbf{v}_2$, will be given elsewhere.[14] The energy-related equations (1)–(4) are still valid with ξ replaced by $[(\mathbf{q}\cdot\mathbf{v}_1)^2+(\mathbf{q}\cdot\mathbf{v}_2)^2]^{-1/2}/\omega$ in the argument of the Bessel functions and with $\Pi_2(\mathbf{q},\Omega)$ representing the electron density correlation function in the presence of a magnetic field. The electron temperature T_e and the oscillation velocity $\mathbf{v}_1$ and $\mathbf{v}_2$ can be obtained from energy- and force-balance equations (1), (8), and (9), together with the interface condition connecting the external and internal fields. Effects of a Faraday-geometry magnetic field on electron temperature change (heating or cooling) can be remarkable. This is not only because a strong magnetic field significantly changes the electron density correlation function due to Landau quantization and level broadening thus affects the transport of the electron system, but particularly because the cyclotron resonance also strongly shows up in electron heating and cooling.

We numerically studied the electron temperature change in a GaAs/AlGaAs heterostructure due to THz irradiations normal to the 2D plane in the presence of a magnetic field in Faraday geometry. Both electron heating and cooling can appear depending on the magnetic field, the radiation field, and the lattice temperature. Figure 4 shows T_e as a function of the amplitude $E_{i\omega}$ of the incident radiation field of frequency $\omega/2\pi=4$ THz at lattice temperature $T=77$ K subject to a magnetic field $B=9.57$ T satisfying the cyclotron resonance condition ($\omega=\omega_c$) and subject to a magnetic field $B=9$ T somewhat deviated from cyclotron resonance ($\omega_c/\omega=0.94$). We see that in both cases the electrons can be cooled due to FIR irradiation and, like the case without a magnetic field, with increasing the strength of the radiation the electron temperature first goes down before reaching a minimum and then rises with further increase of the radiation strength. The striking feature in the presence of a Faraday-geometry magnetic field is that the sensitivity of the electron temperature change is greatly enhanced by the cyclotron resonance. One can see that although the lowest electron temperatures attained are essentially the same in both cases, the critical field at which T_e reaches its minimum is an order of magnitude smaller for $B=9.57$ T than for $B=9$ T. This reflects the cyclotron resonance in the electron cooling as seen in the inset of Fig. 4 where, at each THz field, T_e exhibits sharp peak around $B=9.57$ T.

The appearance of electron cooling at medium temperature range indicates that the behavior of electron temperature versus radiation field is completely different from that of the

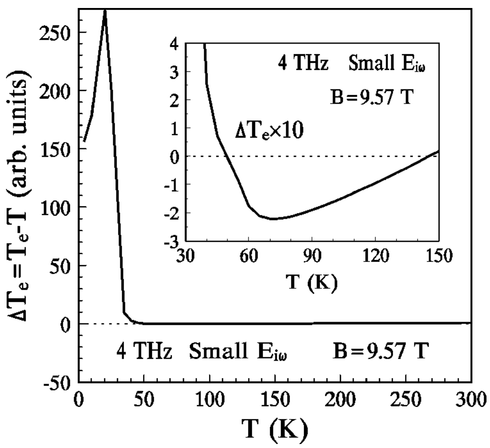

FIG. 5. The electron temperature change $\Delta T_e \equiv T_e - T$ induced by a weak FIR irradiation of frequency 4 THz. The inset shows the part between 30 and 150 K with enlarged scale.

resistivity induced by the irradiation: photoresistivity always increases with increasing strength of the radiation field. Therefore the cyclotron resonance of photoresponse cannot be attributed to the rise of the electron temperature at this temperature range.

In Fig. 5 we plot the electron temperature change $\Delta T_e \equiv T_e - T$ induced by a weak radiation field of 4 THz under the cyclotron resonance condition $B = 9.57$ T. Although electrons exhibit heating at both low and high temperatures, the absolute value of the radiation-induced ΔT_e is too small at high temperatures to account for the cyclotron resonance in photoresistivity.

In conclusion we have demonstrated that in a realistic two-dimensional polar semiconductor the irradiation of a THz electromagnetic field results in a moderate electron cooling in a rather wide temperature range around 77 K for radiation field up to a certain strength depending on the frequency and temperature. A magnetic field in Faraday geometry can induce the cyclotron resonance in the electron cooling which greatly enhances the sensitivity of electron temperature response to the THz field strength and greatly scales down the radiation intensity range for electron cooling to appear. The electron cooling phenomenon is not only observable through the measurement of noise, but is important in understanding the cyclotron resonance of THz photoresponse at medium and high temperatures.

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