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TERAHERTZ SPECTRA EMITTED FROM HOT CARRIERS IN TWO-DIMENSIONAL SEMICONDUCTORS*

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We propose a simple method to calculate the spectrum of spontaneous terahertz (THz) emission from hot carriers in two-dimensional semiconductors by means of transport quantities, which are easily obtained during the process of solving the transport problem using the recently developed balance-equation approach for THz-driven transport. The method has been applied to examine the surface emission from a GaAs/AlGaAs heterojunction and the edge emission from a GaAs-based multiple quantum-well system subjected to strong dc biases. The theoretical results obtained are in reasonably good agreement with measurements.

Keywords: terahertz emission, two-dimensional semiconductors, hot electrons, balance equations
PACC: 7230, 7220H, 7865, 7830

I. INTRODUCTION

Although most optoelectronic devices with quasi-two-dimensional semiconductors rely on the direct transition process of electrons between different size-quantized subbands of the system, the emission and absorption of light due to indirect carrier intrasubband transitions, which always exist and exhibit broad band spectra, play an important role in the design and operation of optoelectronic devices especially in the far-infrared range. The intraband absorption and emission of terahertz (THz) electromagnetic waves are intimately related to the transport properties of two-dimensional (2D) electron gas. They can be studied by means of transport measurement, and their spectra can be used as characterization of transport properties of the underlying low-dimensional semiconductor.

Experimentally, Hirakawa *et al.*[1] detected the broadband far-infrared radiation (surface emission) from hot 2D electrons in a selectively doped $Al_xGa_{1-x}As/GaAs$ single heterojunction. Vorobjev *et al.*[2,3] measured the THz emission from the edge of multiple GaAs/AlGaAs quantum wells subject to an in-plane electric field. The emission spectra observed in these two cases exhibited quite different behaviour. In the case of surface emission, photons emitted from any part of 2D electrons immediately escape out of the surface of the 2D sheet without being absorbed, while in the case of edge emission, the electromagnetic waves emitted from inside the quantum well will be damped due to self-absorption during their propagation towards the edge. Because of this, only photons emitted from an inner place located at a distance less than the inverse of the absorption coefficient from the edge can contribute to the detected radiation. Hirakawa *et al.*[1] explained the radiation spectra using a method which relates the emissivity with the classical Drude conductivity and the electron temperature model. Although their theoretical analyses are in fairly good agreement with the measured radiation spectra in the most (higher) part of the frequency range, the predicted trend deviates strongly from the observation when the frequency becomes lower. On the other hand, the edge emission spectra calculated in Refs.[2] and [3] for the experimental sample, though exhibiting a roughly correct behaviour, were too crude to yield a reasonable electron temperature, as compared with the measured emission spectra.

As in the case of free-carrier absorption, the spontaneous photon emission due to intraband transition of carriers in semiconductors, is an indirect (impurity, phonon, or other scattering mechanism assisted) process. In principle, the emission spectra of a system can be obtained by calculating the transition rate using the second-order perturbation theory[4] after solving the transport problem. It is, of course, preferable to obtain these properties in the process of trans-

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port calculation, taking account of the main scattering mechanisms. In this paper we suggest a simple method to calculate THz spectra emitted from the surface and from the edge of quasi-two-dimensional semiconductors, based on the transport investigation using the balance-equation approach recently developed for semiconductors subject to a dc and a THz electric field.

II. ABSORPTION COEFFICIENT OF A THz RADIATION IN A QUASI-2D SEMICONDUCTOR

We assume N_s electrons forming a quasi-2D system (e.g. a semiconductor quantum well or heterojunction) with a unit area in the x-y plane and a small (nonzero) effective extension d in the z direction. The single electron state is described by a 2D wave vector $\boldsymbol{k}_\parallel = (k_x, k_y)$ and a subband index s, and the energy dispersion is given by $\varepsilon_s(\boldsymbol{k}_\parallel) = \varepsilon_s + k_\parallel^2/2m$ (where ε_s represents the bottom of the sth subband, and m is the electron band effective mass of the background material).

Under the influence of a dc electric field $\boldsymbol{E}_0$ and a high-frequency ac electric field of frequency ω and amplitude $\boldsymbol{E}_\omega$ (parallel to the 2D plane),

$$\boldsymbol{E}(t) = \boldsymbol{E}_0 + \boldsymbol{E}_\omega \sin(\omega t), \tag{1}$$

the balance equations for the time-dependent steady transport state read[5]

$$N_s e\boldsymbol{E}_0 + \boldsymbol{F} = 0, \tag{2}$$

$$S_p - \boldsymbol{v}_0 \cdot \boldsymbol{F} - W = 0. \tag{3}$$

Here e is the electron charge, $\boldsymbol{v}_0$ is the average drift velocity, $\boldsymbol{F}$ is the frictional force of electrons, W is the rate of electron energy-loss due to the nonradiative process, and S_p is the rate of electron energy-gain from the radiation field. The expression for S_p is[5]

$$\begin{aligned} S_p = & \sum_{s,s',\boldsymbol{q}_\parallel} |U_{s,s'}(\boldsymbol{q}_\parallel)|^2 \sum_{n=-\infty}^{\infty} J_n^2(\boldsymbol{q}_\parallel \cdot \boldsymbol{r}_\omega)\, n\omega\, \Pi_2(s, s', \boldsymbol{q}_\parallel, \boldsymbol{q}_\parallel \cdot \boldsymbol{v}_0 - n\omega) \\ & + 2 \sum_{s,s',\boldsymbol{q},\lambda} |M_{s,s'}(\boldsymbol{q}, \lambda)|^2 \sum_{n=-\infty}^{\infty} J_n^2(\boldsymbol{q}_\parallel \cdot \boldsymbol{r}_\omega)\, n\omega \\ & \times \Pi_2(s, s', \boldsymbol{q}_\parallel, \Omega_{\boldsymbol{q}\lambda} + \boldsymbol{q}_\parallel \cdot \boldsymbol{v}_0 - n\omega) \left[n\left(\frac{\Omega_{\boldsymbol{q}\lambda}}{T}\right) - n\left(\frac{\Omega_{\boldsymbol{q}\lambda} + \boldsymbol{q}_\parallel \cdot \boldsymbol{v}_0 - n\omega}{T_e}\right) \right]. \end{aligned} \tag{4}$$

The expression for $\boldsymbol{F}$ is obtained from the right-hand side of Eq. (4) by replacing the $n\omega$ factor with $\boldsymbol{q}_\parallel$ in both terms, and the expression for W is obtained from the second term of the right-hand side of Eq. (4) by replacing the $n\omega$ factor with $\Omega_{\boldsymbol{q}\lambda}$, the energy of the phonon having wave vector $\boldsymbol{q}$ in branch λ (assuming 3D bulk phonon modes). Here, $\boldsymbol{r}_\omega \equiv e\boldsymbol{E}_\omega/(m\omega^2)$, $J_n(x)$ is the Bessel function of order n, $n(x) \equiv [\exp(x) + 1]^{-1}$ is the Bose function, T is the lattice temperature, $\boldsymbol{q} = (\boldsymbol{q}_\parallel, q_z)$ is the 3D wave vector, $U_{s,s'}(\boldsymbol{q}_\parallel)$ is an effective impurity potential, $M_{s,s'}(\boldsymbol{q}, \lambda)$ is the electron–phonon matrix element, and $\Pi_2(s, s', \boldsymbol{q}_\parallel, \Omega)$ is the imaginary part of the electron density correlation function related to subbands s and s' in an equilibrium state at the electron temperature T_e. For the expressions of these quantities please refer to Ref. [6].

The quantity S_p depends on the strengths and the relative direction of the dc and THz electric fields, as well as on the frequency of the latter. For a given configuration (frequency, strength and polarization of the electromagnetic radiation, and the dc bias), the effective absorption coefficient α for a quasi-2D system of thickness d, can be written as[7]

$$\alpha = \frac{2}{\sqrt{\kappa}\epsilon_0 c} \frac{S_p}{E_\omega^2 d}, \tag{5}$$

in which c is the light speed, and κ is the dielectric constant of the material.

In the limit of the weak high-frequency field (small E_ω), the argument $\boldsymbol{q}_\parallel \cdot \boldsymbol{r}_\omega$ of the Bessel functions on the right-hand side of the S_p expression (4) is small. It suffices to retain the single-photon process ($n = 1$ and -1) and keep the leading terms of the expansion of the Bessel function: $J_{\pm 1}^2 \approx \frac{1}{4}(\boldsymbol{q}_\parallel \cdot \boldsymbol{r}_\omega)^2$. As a result Eq. (5) reduces to

$$\alpha = \frac{1}{\sqrt{\kappa}\epsilon_0 c} \frac{N_s e^2}{m\omega^2 d} M_2(\omega, \boldsymbol{v}_0), \tag{6}$$

where $M_2(\omega, \boldsymbol{v}_0)$ is the imaginary part of the memory function under a dc bias velocity $\boldsymbol{v}_0$, which consists of contributions from impurity and phonon scatterings:

$$M_2(\omega, \boldsymbol{v}_0) = M_2^{(i)}(\omega, \boldsymbol{v}_0) + M_2^{(p)}(\omega, \boldsymbol{v}_0). \tag{7}$$

The expressions for the impurity part $M_2^{(\mathrm{i})}(\omega, \boldsymbol{v}_0)$ and phonon part $M_2^{(\mathrm{p})}(\omega, \boldsymbol{v}_0)$ have been given in Ref. [7]. Note that these memory functions depend not only on the strength of the dc bias (v_0 or E_0), but also on the direction of the high-frequency field $\boldsymbol{E}_\omega$ in reference to $\boldsymbol{E}_0$.

Ⅲ. SPECTRA OF SURFACE EMISSION AND EDGE EMISSION FROM A QUASI-2D SEMICONDUCTOR

It is known that the rate of spontaneous emission can be related to the rate of absorption in an equilibrium or quasi-equilibrium system. If the statistical distribution of electrons in a semiconductor is described in their centre-of-mass frame by an electron temperature T_e, the energy of photons spontaneously emitted through the intraband electron transition process within a unit time from the system of unit volume having a frequency in the range $\mathrm{d}\omega$ (around frequency ω), the wave vector direction in the solid-angle range $\mathrm{d}\Omega$ (around solid angle θ) and the polarization in $\hat{e}$ mode, can be written as $i_{\mathrm{se}}(\omega, \theta, \hat{e})\mathrm{d}\omega\mathrm{d}\Omega$. The spontaneous emission spectrum is given by[8]

$$i_{\mathrm{se}}(\omega, \theta, \hat{e}) = \frac{\kappa}{(2\pi)^3 c^2} \frac{\omega^3}{\exp(\omega/T_\mathrm{e}) - 1} \alpha(\omega, \theta, \hat{e}), \quad (8)$$

where $\alpha(\omega, \theta, \hat{e})$ is the net absorption coefficient of electrons in the system due to the nonzero photon process of the intraband transition for electromagnetic radiation with frequency ω, wave vector in the θ direction and polarization in $\hat{e}$ mode. This absorption coefficient should be the same as the absorption coefficient given by Eq. (6) in an appropriate configuration.

We first discuss the case of surface emission, i.e. the emitted electromagnetic wave escapes out off the 2D surface normally. The intensity spectrum of the normal emission from the 2D surface of area $A_{2\mathrm{d}}$ can be expressed as

$$I_{\mathrm{sur}}(\omega) = A_{2\mathrm{d}} \frac{\sqrt{\kappa} N_\mathrm{s} e^2}{8\pi^3 \epsilon_0 c^3 m} \frac{\omega}{\exp(\omega/T_\mathrm{e}) - 1} M_2(\omega, \boldsymbol{v}_0). \quad (9)$$

The spectrum of the 2D surface emission is relevant to the absorption coefficient, or to the imaginary part of the memory function. The latter depends strongly on the scattering mechanisms and also on the dc bias.

For the case of edge emission we consider a system consisting of N parallel quantum wells. Each quantum well extends in the 2D (x-y) plane to sweep a square area ($L \times L$) having a straight edge of length L in both x and y directions, and a nonzero well width d in the z direction. We consider the emitted THz electromagnetic wave which propagates along the x direction in the 2D plane with the electric field $\boldsymbol{E}_\omega$ polarizing in the y direction. The absorption coefficient for such a configuration is denoted by $\alpha(\omega, /\!/)$. Due to the absorption during the process of propagation, however, the strength of the radiation field emitted from a small volume located at a distance x from the edge will be damped to $\exp(-\alpha x)$ of its original value at the place of emission when it reaches the edge before escaping out. Therefore, the total intensity of the edge emission contributed from all parts of a well and from all N quantum wells, is

$$\begin{aligned} I_{\mathrm{edg}}(\omega) =& \frac{\kappa}{(2\pi)^3 c^2} \frac{\omega^3}{\exp(\omega/T_\mathrm{e}) - 1} \alpha(\omega, /\!/) LNd \\ & \times \int_0^\infty \exp[-\alpha(\omega, /\!/) x] \mathrm{d}x \\ =& A_{\mathrm{edg}} \frac{\kappa}{(2\pi)^3 c^2} \frac{\omega^3}{\exp(\omega/T_\mathrm{e}) - 1}, \end{aligned} \quad (10)$$

where $A_{\mathrm{edg}} = LNd$ is the total effective edge area. We see that the spectrum intensity of the edge radiation turns out to be the universal black-body type, depending only on the electron temperature. The role of the dc bias field and the scattering mechanisms lies in the determination of the electron temperature in the transport process.

Ⅳ. COMPARISON WITH EXPERIMENTS

Based on Eq. (9) we have calculated the surface-emission spectra from a GaAs/AlGaAs single interface heterojunction with parameters similar to sample No. 1 reported in Ref. [1]: electron sheet density $N_\mathrm{s} = 4.4 \times 10^{11}\,\mathrm{cm}^{-2}$ and low-temperature linear mobility $\mu_0 = 3.7 \times 10^4\,\mathrm{cm}^2/\mathrm{V\,s}$. We consider remote impurity, acoustic phonon and polar optic phonon scatterings. The system is heated by a dc bias field E_0. The transport properties (v_0 and T_e) in the case of a weak high-frequency field can be obtained from balance equations (2) and (3) with vanished S_p at a given lattice temperature. With v_0 and T_e thus derived, the emission spectra I_{sur} is readily calculated from Eq. (9) for a given polarization configuration of the emitted radiation field. The calculated surface emission intensity I_{sur} at lattice temperature $T = 4.2\,\mathrm{K}$, averaged over parallel ($\boldsymbol{E}_\omega /\!/ \boldsymbol{E}_0$) and perpendicular ($\boldsymbol{E}_\omega \perp \boldsymbol{E}_0$) configurations, is plotted in Fig.1 as small circles and dots respectively for the two cases of dc bias fields, which correspond to (i) drift velocity $v_0 = 2.0 \times 10^5\,\mathrm{cm/s}$ and electron temperature

$T_e = 34\,K$ and (ii) drift velocity $v_0 = 2.3 \times 10^6\,cm/s$ and electron temperature $T_e = 58\,K$. The theoretical predictions are in reasonably good agreement with the measured results of Ref. [1], shown in Fig. 1 as thin solid lines. For comparison, the theoretical results of Ref. [1] are also indicated in the figure as dotted curves. Based on the electron temperature model, their theoretical spectra depend only on the electron temperature, without being directly affected by the dc bias velocity.

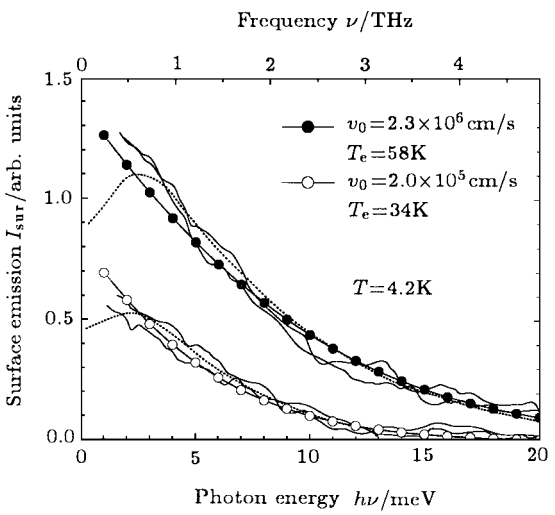


Fig.1. The THz spectra of surface emission from a GaAs/AlGaAs single interface heterojunction as described in the text. The small circles and the black dots are calculated spectra I_{sur} for two dc bias fields, which correspond to (i) drift velocity $v_0 = 2.0 \times 10^5\,cm/s$ and electron temperature $T_e = 34\,K$, and (ii) drift velocity $v_0 = 2.3 \times 10^6\,cm/s$ and electron temperature $T_e = 58\,K$. The wavy thin lines represent the measured spectra by Hirakawa *et al.*[1] The dotted lines are the theoretical results of Ref. [1].

We have also calculated the edge emission spectra from Eq. (10) at the lattice temperature $T = 4.2\,K$ for a GaAs-based quantum well similar to the experimental system discussed in Refs. [2] and [3]: well width $d = 6\,nm$, electron sheet density $N_s = 3 \times 10^{11}\,cm^{-2}$, and 77 K linear mobility $\mu_0(T = 77K) = 0.33\,m^2/Vs$, under the influence of four different dc bias electric fields—$E_0 = 0.29, 0.41, 0.143$ and $2.0\,kV/cm$. The electron temperature T_e is theoretically determined from force- and energy-balance equations (2) and (3) in the absence of the THz field with impurity, acoustic phonon and polar optic phonon (equilibrium phonon occupation assumed) scatterings included. The T_e thus obtained is shown in inset (a) of Fig. 2 as a function of bias electric field E_0, having values T_e=57, 64, 106, and 128 K (black squares) respectively, corresponding to the above four strengths of the dc electric field. They are used in Eq.(10) to calculate I_{edg}. The calculated edge emission spectra are plotted in arbitrary units in Fig.2, which are in reasonably good agreement with the experimental emission spectra reported in Ref. [3] (see inset (b) of Fig.2).

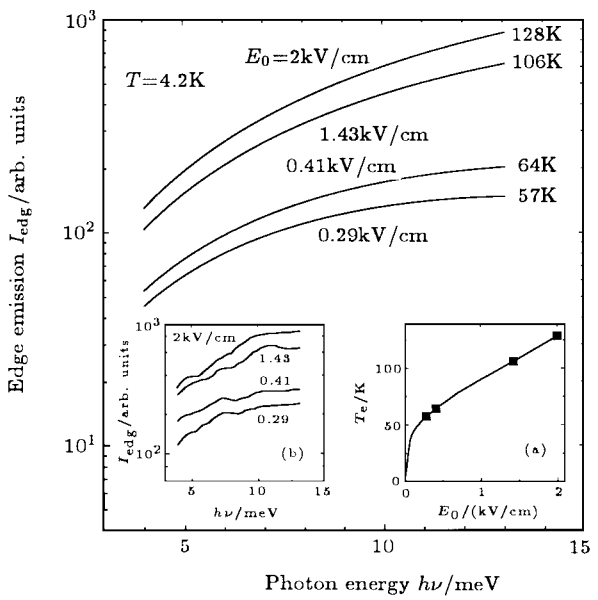


Fig.2. The calculated THz spectra of edge emission I_{edg} from a GaAs-based quantum well, as described in the text, subjected to several different dc bias fields $E_0 = 0.29, 0.41, 1.43$ and $2.0\,kV/cm$ at the lattice temperature $T = 4.2\,K$. Inset (a) shows the theoretical electron temperature T_e as a function of applied dc field E_0. The small squares indicate the positions of the above four bias fields. Inset (b) shows the experimental edge emission spectra reported in Ref. [3] under the four values of dc bias fields stated above.

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