Blackbody radiation from hot two-dimensional electrons in Al$_x$Ga$_{1-x}$As/GaAs heterojunctions

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We have studied the broad-band far-infrared (FIR) radiation from hot two-dimensional (2D) electrons in selectively doped Al$_x$Ga$_{1-x}$As/GaAs heterojunctions. The combination of a composite Si bolometer and a magnetic-field-tuned InSb cyclotron resonance filter allows a spectroscopic as well as an intensity analysis of the FIR emission from hot 2D electrons. It is found that the radiation spectra are well explained by the theory of blackbody radiation and the emissivity assuming a classical Drude conductivity. The behavior of the determined effective blackbody temperatures of hot 2D electrons is quantitatively explained by a theory of acoustic- and optical-phonon emissions.

The two-dimensional (2D) electrons in selectively doped Al$_x$Ga$_{1-x}$As/GaAs heterojunctions exhibit very high mobility,[1,2] because of the spatial separation of electrons from their parent donors in the Al$_x$Ga$_{1-x}$As. Advantages of using such a high-mobility system are well recognized and applied to high-speed field-effect transistors (FET's).[3] The high-mobility 2D electrons are, however, easily heated up by an external electric field, leading to a rapid rise in electron temperature and a reduction of electron mobility. Such a "hot electron" effect is one of the most important issues in practical device applications. The experimental approach which can characterize the electron temperature (T_e), however, has been limited so far; although the analysis of Shubnikov–de Haas (SdH) oscillations allows an accurate and sensitive determination of T_e,[4,5] it is applicable only up to $T_e \sim 20$ K. The analysis of the high-energy tail of photoluminescence (PL) spectra[6,7] is, on the other hand, good for high T_e's, but it becomes inapplicable below ~ 25 K due to finite nonthermal PL line width. Also, the PL method has a drawback that it cannot be used for the single interface structure, which is the more widely used structure in FET applications.

In this work, we have studied broad-band far-infrared (FIR) radiation from hot 2D electrons in selectively doped Al$_x$Ga$_{1-x}$As/GaAs heterojunctions. An electron system at temperature T_e is expected to emit blackbody radiation of equivalent temperature. Since blackbody radiation is a direct consequence of velocity fluctuation of electrons, it gives a good measure of *thermodynamic temperature* of the electron system without postulating a specific type of distribution function for the electrons. This fact is quite important in high electric-field transport, where electron distribution function could be strongly deformed from its equilibrium form, i.e., the Fermi-Dirac distribution function. The combination of a wide-band FIR detector and a magnetic-field-tuned InSb cyclotron resonance (CR) filter[8] allows a spectroscopic analysis of the FIR emission from hot 2D electrons. It is found that the radiation spectra are, indeed, well explained by the theory of blackbody radiation, which enables us to determine the effective blackbody temperature, or the 2D electron temperature T_e. The integrated

intensity of the blackbody radiation, I_b, is proportional to T_e^γ, the exponent γ gradually decreasing from 4 to ~ 2 with increasing electron mobility μ. Since I_b is strongly dependent on T_e, T_e has been determined sensitively for a wide temperature range (5–100 K). We also discuss the dominant energy relaxation mechanism of a hot 2D electron system.

The samples used in this study are Al$_x$Ga$_{1-x}$As/GaAs single interface heterojunctions grown by either molecular-beam or liquid-phase epitaxy. Each sample was cut into $\sim 2.5 \times 3.5$ mm^2 pieces and Ohmic contacts for source, drain, and voltage probes were made by alloying InSn. The low-field transport parameters (electron densities N_s and mobilities μ) at lattice temperature $T_L = 4.2$ K were determined by *in situ* magnetotransport measurement and are listed in Table I. A composite Si bolometer operated at 1.5 K was used as a wide-band FIR detector to measure the broad-band FIR emission from the samples. The CR absorption of a high-purity InSb slab was used as a tunable filter for spectroscopy.[8] The energy position E_{CR} and the line width $\Delta\hbar\omega$ of the InSb CR were calibrated by using a Fourier transform spectrometer. $\Delta\hbar\omega$, which limits our spectral resolution, is 3 meV (5–7 meV) when E_{CR} is below (above) the Reststrahl band (22.8–24.4 meV) of InSb. The responsivity of the measurement system, including FIR waveguides and a sapphire window, was calibrated to be 1×10^5 V/W by measuring the blackbody radiation from a NiCr-film heater/AuGe thermometer device.[9] Because of the presence of a sapphire window, our system is sensitive up to ~ 370 cm^{-1} (~ 45 meV). In the experiment, hot electrons were excited by applying 0.7-ms-long voltage pulses[10] to the Ohmic contacts on two ends of the samples and the bolometer signal was detected by using a

TABLE I. Electron densities and low-field mobilities of the samples at 4.2 K.

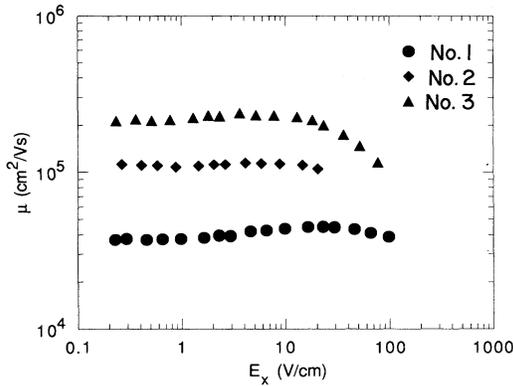| Sample	N_s (cm^{-2})	μ (cm^2/V s)
No. 1	4.4×10^{11}	3.7×10^4
No. 2	3.3×10^{11}	1.1×10^5
No. 3	3.1×10^{11}	2.2×10^5

FIG. 1. The dependence of electron mobilities μ on applied electric fields E_x.

boxcar averager. The duty ratio of the pulses was maintained below 1/100 to minimize lattice heating. All the experiments were performed at $T_L = 4.2$ K.

First, we characterized the electron mobilities μ as a function of applied electric field E_x by *in situ* pulsed *I-V* measurements. As shown in Fig. 1, μ initially increases slightly with increasing E_x, suggesting that the ionized impurity scattering becomes less effective as T_e rises.[11] However, μ eventually starts to decrease with E_x and asymptotically approaches the line limited by a saturation velocity.[11]

We measured the spectra of FIR emission from hot 2D electrons excited by applying voltage pulses. Between the samples and the Si bolometer, a wedged InSb slab was inserted at the center of the superconducting solenoid and its CR energy was swept by applying a magnetic field. The samples were mounted 25 cm above the center of the magnet (see the inset of Fig. 2); the residual magnetic
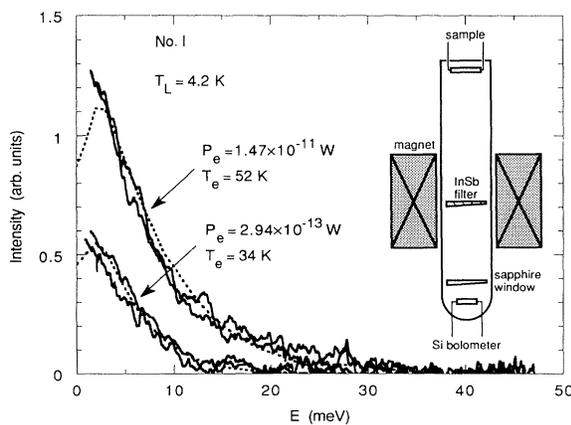

FIG. 2. Far-infrared emission spectra from hot two-dimensional electrons measured by using a magnetic-field-tuned InSb cyclotron resonance (CR) filter. The magnetic field applied to the filter has already been converted to the CR energy. Also plotted by dotted lines are the theoretical curves for black-body radiation which are calculated by Eq. (3) and convoluted with the InSb filter transmission function. The inset shows a schematic illustration of the experimental setup for the spectroscopic measurement.

field at the sample position was kept less than 600 G. Figure 2 shows typical FIR emission spectra from the hot 2D electrons. In the figure, the magnetic field applied to the InSb filter is converted to its CR energy. It is found that the FIR emission spectra from hot 2D electrons are broad and, for higher excitations, both the intensity and the width of the emission increase.

In thermal equilibrium, the spectral emission intensity per solid angle $i_b(\omega)$ of the FIR radiation from a system with temperature T is given by[12]

$$i_b(\omega)d\omega\,d\Omega = i_{bb}(\omega)\,A\,(\omega,\theta)\cos\theta\,d\omega\,d\Omega \ , \qquad (1)$$

where $i_{bb}(\omega)$ is the spectral emission intensity of a real blackbody, Ω the solid angle, and $A(\omega,\theta)$ the incident-angle (θ)-dependent spectral absorptivity of the system; in equilibrium, the emissivity and the absorptivity are equivalent. For example, for an $Al_xGa_{1-x}As/GaAs$ single interface 2D electron system, $A(\omega,\theta)$ for normal incidence is expressed as[13]

$$A(\omega,\theta=0)=4\,\mathrm{Re}(F)/|1+\sqrt{\kappa}+F|^2 \ , \qquad (2)$$

where $F = \sigma(\omega)/\varepsilon_0 c$ with $\sigma(\omega)$ the dynamical conductivity of the 2D electrons, ε_0 the dielectric permittivity of vacuum, κ the dielectric constant of GaAs, and c the speed of light. The blackbody radiation intensity per unit area, $I_b(\omega)$, can be written as[12]

$$I_b(\omega)d\omega = \int \hbar\omega^3/4\pi^3c^2[\exp(\hbar\omega/k_B T)-1]$$

$$\times\,A(\omega,\theta)\cos\theta\,d\omega\,d\Omega \ , \qquad (3)$$

with k_B the Boltzmann constant. In the following discussion, we made two assumptions; (i) we assume that Eq. (3) is valid even in nonequilibrium steady-state condition, and (ii) we assume a classical Drude conductivity for $\sigma(\omega)$, i.e.,

$$\sigma(\omega)=e^2N_s\tau_m/m^*[1/(1-i\omega\tau_m)] \ , \qquad (4)$$

with e the electronic charge and τ_m the E_x-dependent momentum-relaxation time which is determined by *I-V* measurement.

We calculated the blackbody radiation spectra by using Eq. (3) and convoluted them with the line-shape function of the InSb CR peak. For the blackbody temperature of 2D electrons in Eq. (3), we used the values determined from the integrated intensity of the radiation, as described below. The calculated spectra are plotted as dotted lines in Fig. 2, and show a good agreement with the experimental data, which confirms that the broadband radiation from the hot 2D electrons is indeed of the blackbody radiation origin. This fact enables us to deduce the thermodynamic blackbody temperature, or the electron temperature T_e, of the hot 2D electrons from the FIR emission data.

We next measured the integrated intensity of the broadband FIR emission, I_b, to determine T_e more sensitively. I_b is defined as

$$I_b = \int_{\omega_{min}}^{\omega_{max}} I_b(\omega)d\omega \ , \qquad (5)$$

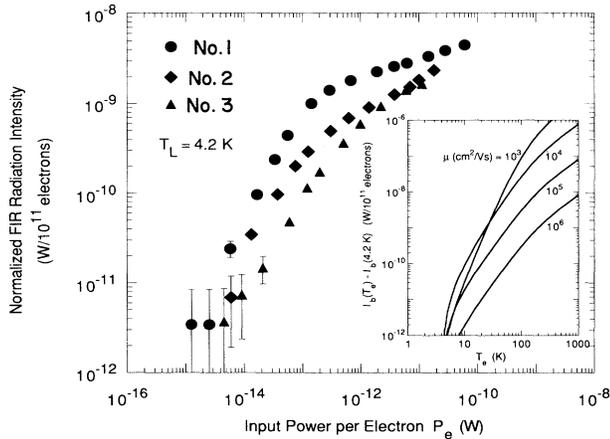where ω_{min} and ω_{max} are the low and high cutoff frequen-

FIG. 3. The normalized FIR emission intensities are plotted as functions of input electrical power per electron P_e. The inset shows the normalized blackbody radiation intensities calculated as functions of the electron temperature for different μ's.
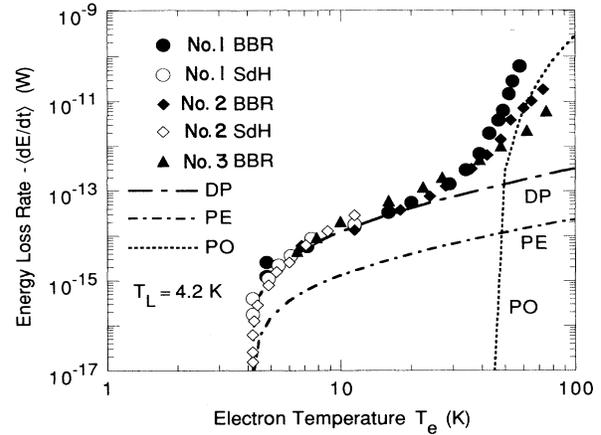

FIG. 4. The determined electron temperatures T_e vs the energy loss rates of two-dimensional electrons, which is equivalent to P_e in a steady state. Full and open symbols denote FIR (plotted as BBR) and magnetotransport (plotted as SdH) results, respectively. Calculated energy loss rates due to phonon emissions are also shown by dashed and dotted lines; DP, the deformation potential interaction; PE, the piezoelectric interaction; and PO, the polar-optical-phonon interaction.

cies of the FIR detection system, ~ 5 and ~ 370 cm^{-1} in our case, respectively. As shown in the inset of Fig. 3, the calculated I_b is approximately proportional to T_e^{γ}, the exponent γ gradually decreasing from 4 to ~ 2 with increasing μ. The decrease of γ with μ is due to the high-frequency cutoff of the FIR radiation by longer τ_m. Since I_b is strongly dependent on T_e, sensitive determination of T_e is possible by comparing I_b with theoretical calculations. This method is more sensitive than that used by Hopfel and co-workers[13] and Okisu, Sambe, and Kobayashi;[14] they measured the spectral emission intensity $I_b(\omega)\Delta\omega$ at a fixed frequency by using narrow-band crystal detectors with band widths $\Delta\omega$ (~ 2 cm^{-1}) and $I_b(\omega)$ is approximately proportional to T_e.

To measure I_b, the InSb filter was removed and the FIR radiation was directly detected by the Si bolometer. In Fig. 3, the measured emission intensities which are normalized by N_s and the sample area S, I_{bn} ($\equiv I_b / N_s S$), are plotted as functions on input electrical power per electron P_e ($\equiv J_x E_x / N_s$ with J_x the current density). It is noted that I_{bn} increases rapidly with increasing P_e in the low excitation region and shows a saturation behavior for higher P_e. It is also noted that I_{bn} is larger for lower mobility sample, as expected from Eqs. (2) and (4); i.e., the lower mobility sample has higher emissivity in the FIR frequency range. By comparing the measured I_{bn} with theoretical values calculated by using Eqs. (2)–(5) and the calibrated detector responsivity, it is possible to determine T_e of hot 2D electrons. In Fig. 4, the determined T_e's are plotted by filled symbols versus the energy loss rate $-\langle dE/dt \rangle$, which is equivalent to P_e in steady states. In the figure, T_e's determined by analyzing the amplitude of SdH oscillations measured on the identical samples in the same experimental run are also plotted by open symbols. It is noted that the FIR emission method can detect a temperature rise as small as ~ 2 K and can cover up to ~ 100-K range.[15] It is also noted that the FIR emission data and the magnetotransport data agree well with each other where they overlap, suggesting the

accuracy of the FIR emission method.

As seen in Fig. 4, T_e rises rapidly with P_e and reaches 40 K when $P_e \sim 10^{-13}$ W. For $P_e > 10^{-13}$ W, however, T_e shows a drastic change in slope, indicating an onset of another energy relaxation mechanism. In order to understand the energy relaxation mechanisms, we calculated the energy loss rates due to acoustic- and optical-phonon emissions within a framework of the electron temperature model. In the calculation, we used the Fang-Howard variational wave function[16] and assumed that only the lowest subband is occupied. The detail of the calculation has been published elsewhere.[17] The calculated energy loss rates for $N_s = 5 \times 10^{11}$ cm^{-2} are also plotted in Fig. 4. The excellent agreement between the experimental and theoretical results indicates that the dominant energy relaxation mechanism for $T_e < 40$ K is the acoustic-phonon emission via deformation potential coupling, while optical-phonon emission becomes a much more efficient electron cooling mechanism when $T_e > 40$ K. It is also noted that the rise in T_e is almost independent of N_s when $T_e < 40$ K, which is a characteristic of the screened acoustic-phonon interaction.[17]

In summary, we studied the broad-band FIR radiation from hot 2D electrons in selectively doped $Al_x Ga_{1-x}As/GaAs$ heterojunctions. By using a wide-band Si bolometer and a magnetic-field-tuned InSb cyclotron resonance filter, we performed a spectroscopic analysis of the FIR emission from hot 2D electrons. It is found that the radiation spectra are well explained by the theory of blackbody radiation, and the thermodynamic temperature of the hot 2D electron system has been successfully determined from 5 to 100 K. The behavior of the determined electron temperature is quantitatively explained by a theory of acoustic- and optical-phonon emissions.

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