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Tunable Far-Infrared Radiations from Hot Electrons in *n*-Type InSb

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We report tunable far-infrared radiation from *n*-type InSb under crossed magnetic and electric fields. The emission is interpreted in terms of the transitions of hot electrons between Landau sub-bands and the radiative capture by the impurity ground state.

In the course of studying the cyclotron resonance in *n*-type InSb under a pulsed electric field,[1] we have observed, for the first time, tunable far-infrared radiation from *n*-type InSb at 4.2 K under crossed magnetic and electric fields, due to the transitions of hot electrons between Landau sub-bands or associated impurity states. The experimental results are interpreted in terms of hot-electron effects in strong magnetic fields. There have been studies[2-5] of the microwave emission from *n*-type InSb in magnetic fields at low temperatures. For example, Bekefi, Bers, and Brueck[5] observed resonant structures (not interpreted) with varying magnetic field in the microwave emission from *n*-type InSb at 4.2 K when a sample was subjected simultaneously to dc magnetic and electric fields.

Their experiments were made in the intermediate magnetic field region where the quantization effects on conduction and impurity electrons are not so definite. In order to avoid the complicated phenomena which occur in the intermediate magnetic field region, the present experiment was made in the strong magnetic field region where each of four dimensionless parameters, $\omega_c\tau$, $\hbar\omega_c/kT$, $\hbar\omega_c/2R_y^*$, and $(\frac{4}{3}\pi a_\parallel a_\perp^2 N_{\rm imp})^{-1}$ is much greater than unity. Here $\frac{4}{3}\pi a_\parallel a_\perp^2$ and $N_{\rm imp}$ are the volume occupied by the impurity wave function and the total impurity concentration, respectively.

The specimens used in the present experiment were single crystals of n-type InSb containing free-carrier concentrations of $10^{13}\sim 10^{14}$ cm^{-3} at liquid-nitrogen temperatures. The experimental configuration is schematically shown in the inset of Fig. 1. Magnetic fields up to 20 kOe in strength were applied by a superconducting solenoid transverse to the sample current. An electric field of $0\sim 20$ V/cm with a duration of 400 μsec was applied at a repetition rate of 15 Hz in order to avoid heating up the lattice. So long as we stick to this duty ratio of 6×10^{-3}, no change in the IV characteristics has been observed up to the highest applied electric field. The radiation emitted from the sample was detected by a narrow-band Ge/Sb photoconductive-type detector containing Sb of 1×10^{14} cm^{-3} density. This type of detector has a maximum spectral response at a photon energy of 9.8 meV (photoionization energy) with a bandwidth of $\Delta\lambda/\lambda\sim 0.15$.[6] The output signal from the Ge/Sb detector was amplified and detected with a lock-in amplifier or a boxcar integrator. Measurements were made at 4.2 K.

The intensity of the observed radiation is shown in Fig. 1 as a function of the magnetic field with various electric field strengths. The widths of the peaks in Fig. 1 were determined mostly by the bandwidth of the Ge/Sb detector. Four peaks —1α, 1β, 2, and 3 from the high magnetic field side—are seen. The peak 1α shifts slightly toward the higher magnetic field side as the electric field increases, while the peak 1β becomes masked by the 1α peak. A plot of an assumed order number for each peak versus $1/H$ is shown in Fig. 2. The peaks 1α, 2, and 3 fall on a straight line, while 1β does not. Figure 3 shows

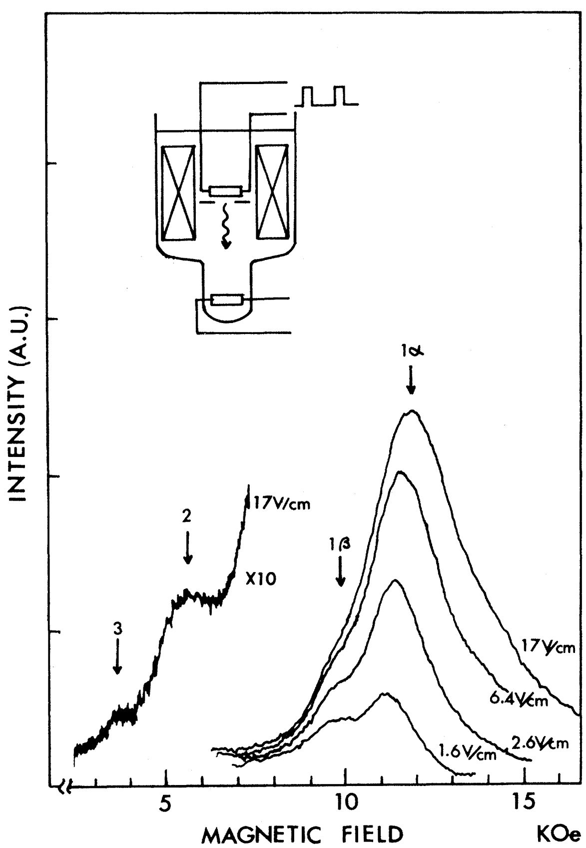

FIG. 1. Intensity of the far-infrared emission at different electric field strengths. The recorder trace in the lower magnetic field side is an enlarged scale to show structures clearly. The inset shows a schematic of the experimental setup. The electric fields indicated are measured at the magnetic field corresponding to the 1α peak.

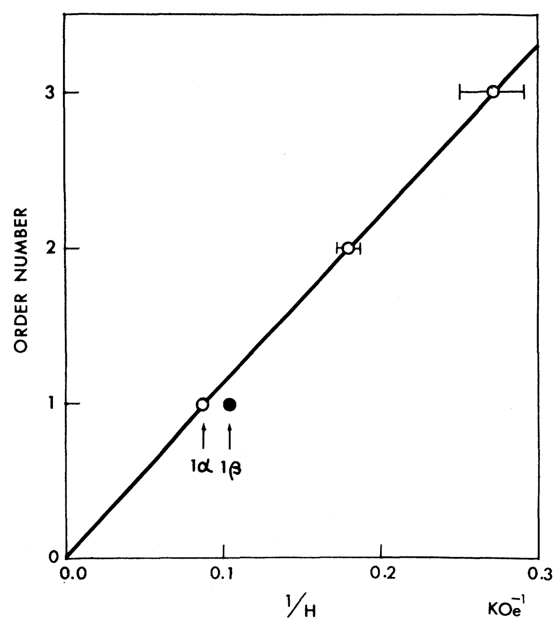

FIG. 2. Assumed order number versus $1/H$. The 1β peak is not in harmonic relation with other peaks.

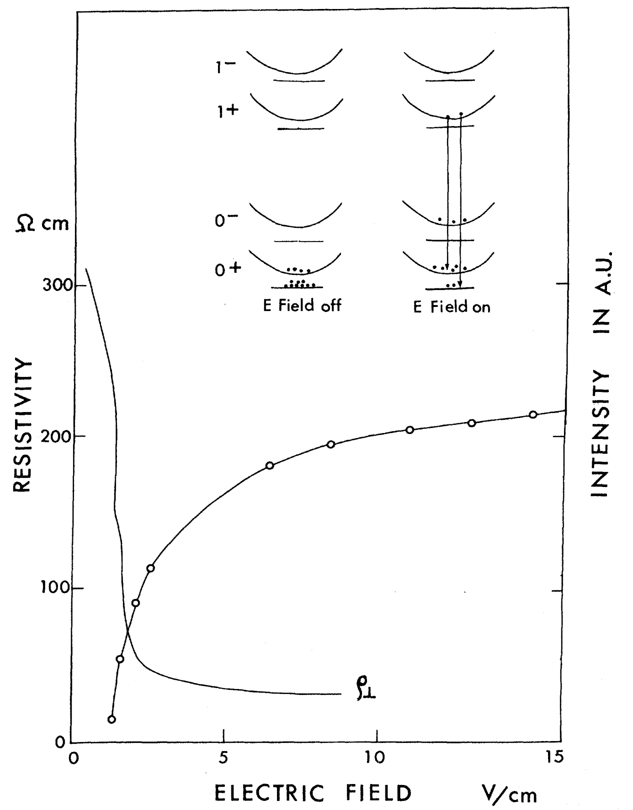

FIG. 3. Resistivity $\rho_\perp$ and peak intensity of the 1α emission as functions of electric field. The inset shows schematically the electron distribution with and without electric field.

the electric field dependence of the intensity of the 1α peak and the resistivity $\rho_\perp$ of the same sample in the transverse magnetic field. The resistivity $\rho_\perp$ was measured at the magnetic field where the 1α peak appears. The intensity of the radiation increases rapidly with increasing electric field. This increase of intensity continues even after the variation of $\rho_\perp$ is slowed down.

As shown in the inset of Fig. 3, the conduction band of InSb in the strong magnetic field is quantized into two series of Landau sub-bands, which correspond to spin-up and spin-down states, respectively, and shallow donor states associated with each Landau sub-band. Almost all the electrons are situated in the lowest Landau sub-band and the associated impurity states at liquid-helium temperatures without an applied electric field. When an electric field is applied, electrons are heated and transferred from the impurity states to the conduction band. They populate higher Landau sub-bands as the electric field increases. Because of the weak electron-acoustic phonon interaction, the energy gained from the electric field is stored in the electron system, and the electron temperature rises remarkably. Taking into account the strong electron-LO phonon interaction, Yamada and Kurosawa[7] calculated the distribution function of hot electrons in strong magnetic fields. They obtained strongly distorted distribution functions which are truncated at the LO phonon energy. Although most of the energy gained from the electric field is dissipated through acoustic or optical phonon emission, there is another possible energy dissipation process, that is, the emission of photons.

The heating up of the conduction electrons causes strongly nonlinear current-voltage characteristics, as first predicted by Kazarinov and Skobov.[8] Kotera, Yamada, and Komatsubara[9] have experimentally investigated this effect using dc and microwave techniques to get results which were interpreted by the theory of Yamada and Kurosawa.[7] Kobayashi and Otsuka[10] used cyclotron resonance to study the relation between the distribution functions of hot electrons and the resistivity in pulsed electric fields. The latter authors showed that electrons begin to flow into higher Landau sub-bands at fields where $\rho_\perp$ decreases.

The rapid increase of emission intensity in Fig. 3 seems to imply that this emission comes from electrons populating higher Landau sub-bands. The peaks 1α, 2, and 3 satisfy the condition that

$$n\hbar\omega_c = 9.8\text{ meV},\quad n = 1, 2, 3,$$

where $\omega_c = eH/mc$, with effective mass of $m = 0.013m_0$. (As mentioned before, the Ge/Sb detector has a maximum spectral response at about its ionization energy of 9.8 meV.)

On the basis of the above discussion, we can identify the observed emission peaks labeled 1α, 2, and 3 to be the electronic transitions $(1^+ \to 0^+)$, $(2^+ \to 0^+)$, and $(3^+ \to 0^+)$, respectively. No clear-cut understanding is available at the present stage for the apparent shift of the 1α peak with applied electric field. The emission peak 1β should be the result of radiative capture of electrons from the 1^+ sub-band directly into the impurity ground state, because it appears on the low magnetic field side. The splitting between 1α and 1β peaks gives an ionization energy of ~1.4 meV which is somewhat smaller than the value calculated by the variational method.[11] The observation of these types of far-infrared radiation tells us that the distribution function is far from the equilibrium one. We believe this effect is a very useful tool for studying the impurity states and the profile of the hot-electron distribution function under strong magnetic fields. Furthermore, we have information of the cyclotron-resonance absorption in the pulsed electric field.[10] Assuming that the emission and absorption bandwidths are nearly equal, we can estimate the bandwidth of the emission line as $\Delta\lambda/\lambda \sim 10^{-2}$ at $\lambda = 119$ μm. Such a narrow bandwidth offers the possibility of application as a tunable far-infrared source.

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Measurement of Spin-Scattering Anisotropy and Exchange-Coupling Energy in Cu-Fe, Using the Wave Shape of the de Haas–van Alphen Effect*

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A linearly field-dependent and temperature-independent exchange energy and spin-scattering anisotropy has been measured in a Cu–93-ppm Fe alloy using wave-shape analysis of the de Haas-van Alphen effect for the ⟨111⟩ neck orbit over a field range of 30–45 kG and a temperature range of 1–2°K.

Landau quantum oscillations such as the de Haas–van Alphen (dHvA) effect provide an explicit measure of the interaction between conduction electrons and magnetic impurities. In contrast to bulk-property measurements[1] (resistance, NMR, etc.), only specific orbits are observed and comparison[2] with theory is more direct. Analysis of the amplitudes gives the local scattering rate directly,[3] and analysis of the wave shape gives spin-dependent information. Recently, Coleridge, Scott, and Templeton[4,5] have observed a shift in angular position of the dHvA spin-split zero in Cu doped with Cr and other transition-metal impurities, and have interpreted their data to obtain the sign (negative or antiferromagnetic) and estimated magnitude of the impurity-electron exchange energy $\epsilon_{ex} = \mu_B H_{ex}$. They also observed in some cases the disappearance of the spin-split zero, which they interpreted as due to anisotropy of scattering of spin-up and spin-down electrons by the magnetic impurity.[5]

We have developed a more general technique[6] using dHvA wave-shape analysis for the measurement of spin scattering anisotropy (SSA) and exchange energy, which does not require the (accidental) spin zero. The dHvA signal is resolved into the harmonic components contributed by spin-up and spin-down electrons. Since the harmonic amplitudes from each spin may be unequal in the presence of a magnetic impurity, the resultant wave shape is altered in magnitude and phase from the usual Lifshitz-Kosevich (LK) expression.[7]

Consider the four most dominant contributions to the dHvA magnetization M_r^σ, where σ is the spin index and r is the harmonic index. Using