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Far-Infrared Emission from Population-Inverted Hot-Carrier System in *p*-Ge

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Experimental evidence is presented for radiative transitions of light holes accumulated in a limited area in momentum space to the heavy-hole band. Also reported is the observation of cyclotron resonance emission from the accumulated light holes. The possibility of far-infrared amplification is discussed.

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Streaming motion[1] and population inversion[2] of hot carriers in crossed electric and magnetic fields have been established in Hall-effect measurements on silver halides[3-5] and p-Ge[6,7] at 4.2 K. Here I report the first observation of far-infrared emission from the population-inverted hot-carrier system.

The experiments are performed on p-Ge crystals doped with In of concentration $1.2\times10^{14}/\text{cm}^3$. Specimens are of simple rectangular shape ($0.4\times3\times12$ mm^3) with end contacts prepared by alloying with Au-In (2 at.%). Prior to the radiation experiment, Hall-effect measurements are carried out to confirm streaming motion and carrier accumulation. A pulsed electric field E with an amplitude 5 V/cm $< E <$ 1 kV/cm and a duration 40 nsec–2 μsec is applied at a repetition rate of 30 Hz as in previous experiments.[8] Sample heating is confirmed to be insignificant by Hall-effect measurements. The magnetic field B is applied perpendicularly to the current. The specimen and a far-infrared detector are mounted at either end of a metal light pipe of 30 cm length in a similar configuration to that described in Refs. 9 and 10. The whole system is immersed in liquid helium. Two types of detector are used; a Ge/Ga photoconductive detector and an n-InSb cyclotron resonance detector. The Ge/Ga detector,[11] containing Ga of $\sim1\times10^{15}/\text{cm}^3$ density, is used to investigate integrated radiation intensities. The n-InSb detector ($n\sim2\times10^{13}$ cm^{-3} at 77 K), used under magnetic field B_d, yields a sharp spectral response at $\epsilon\sim\hbar\omega_c\equiv\hbar eB_d/m^*$ with the effective mass of electrons $m^*=0.013m_0$.[10] The spectral resolution is determined to be typically 1 meV by the observation of H_2O laser lines.

At $B=0$, far-infrared emission is observed in the whole range of E and is interpreted as due to transitions of hot light holes to the heavy-hole band. The radiation spectrum consists of a single broad peak which shifts towards higher energies with increasing E until the shift is saturated to give the maximum intensity point around $\epsilon\sim18$ meV above $E\sim100$ V/cm. The saturation of shift indicates the onset of streaming motion of light holes above 100 V/cm. This interpretation is supported by the following consideration. The collision time $\bar{\tau}_{\text{imp}}$ of light holes due to ionized acceptor scattering averaged over the energy range below the optical-phonon energy $\epsilon_{\text{op}}=37$ meV is estimated to be ~12 psec. For $E>100$ V/cm this $\bar{\tau}_{\text{imp}}$ is longer than the traveling time, $T_{\text{op}}^1\equiv(2m_1^*\hbar\omega_{\text{op}})^{1/2}(eE)^{-1}$, for light holes initially at $\epsilon=0$ to reach $\epsilon=\hbar\omega_{\text{op}}$, where $m_1^*=0.043m_0$ is the light-hole effective mass. ($T_{\text{op}}^1\sim12$ psec at $E=100$ V/cm.) Thus streaming motion is expected above 100 V/cm. No indication is found at any levels of E for recombination radiation from impact-ionized impurities,[12-14] which would yield a sharp emission at $\epsilon\sim10$ meV. This fact can be explained by the relatively low concentration of acceptors in the specimen used.

To explore the effects of light-hole accumulation on radiation, the total radiation intensity is studied as a function of B at different levels of dissipative electric field E_x. Typical results are

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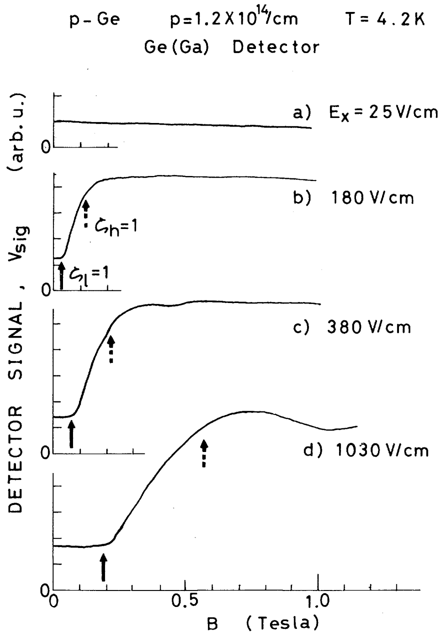

FIG. 1. Ge/Ga detector signals as a function of sample magnetic field B at different levels of E_x.

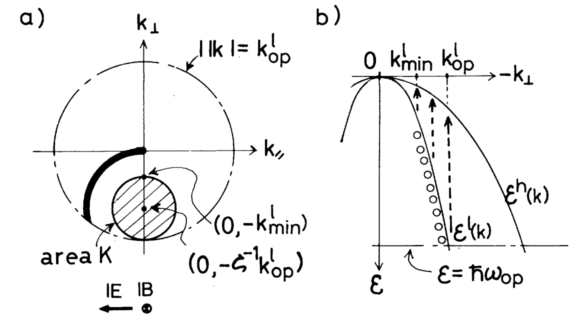

FIG. 2. (a) Momentum distribution of light holes in the range $\zeta_1 > 1$, and (b) a sketch of the dispersion relation of light- and heavy-hole bands, and possible radiative transition of accumulated light holes to the heavy-hole band.

shown in Fig. 1. At low E_x levels, the detector signal $V_{\rm sig}$ decreases slightly with increasing B as shown in Fig. 1(a). The decrease in radiation intensity is considered to be caused by a decrease in average energy of hot light holes with B. At higher E_x levels ($E_x > 100$ V/cm) where light holes are supposed to be streaming, distinct features emerge in the curve of $V_{\rm sig}$ vs B as shown in Figs. 1(b)–1(d). Arrows in Fig. 1 indicate the magnetic field where the relation

$$\zeta_{1,\rm h} \equiv V_{\rm op}{}^{1,\rm h}/V_y = 1 \qquad (1)$$

is satisfied. Here $V_{\rm op}{}^{1,\rm h}$ and V_y are defined by $\frac{1}{2}m_{1,\rm h}{}^*(V_{\rm op}{}^{1,\rm h})^2 = \hbar\omega_{\rm op}$ and $V_y = (E_x{}^2 + E_y{}^2)^{1/2}/B$ with the heavy-hole effective mass $m_{\rm h}{}^* = 0.35 m_0$ and the Hall electric field E_y. Values of E_y obtained from the Hall-effect measurements were used to calculate $\zeta_{1,\rm h}$. At each E_x level, the radiation intensity remains unchanged in the small B range $\zeta_1 < 1$. Then the intensity begins to increase abruptly at $\zeta_1 = 1$. The increase continues until it levels off above $\zeta = 1$.

I can interpret these results as follows. First, the radiation in the range $\zeta_1 < 1$ is due to radiative transition of streaming light holes to the heavy-hole band. It has been confirmed[6,7] that the feature of streaming motion does not change with B in the range $\zeta_1 < 1$. Therefore the radiation remains unchanged. Next, as evidenced in Hall-effect measurements[6,7] when B increases to cover the range $\zeta_1 > 1$, there arises accumulation of light holes into a limited round area K in momentum space as shown in Fig. 2(a). As pointed out by Andronov *et al.*,[15] the accumulation of light holes causes strong far-infrared emission through the radiative transition of these light holes to the heavy-hole band [Fig. 2(b)] and gives rise to the steep rise in the curve of $V_{\rm sig}$ vs B above $\zeta_1 = 1$ (Fig. 1). The curve of $V_{\rm sig}$ vs B continues to rise with increasing B up to $\zeta_{\rm h} = 1$ since the number of accumulated light holes increases. Finally, the steep rise of the curve levels off above $\zeta_{\rm h} \sim 1$ since heavy-hole accumulation sets in to reduce the number of accumulated light holes.[6] Thus all the observed features are consistently explained.

To confirm further that the radiation in the range $\zeta_1 > 1$ does indeed come from accumulated light holes, the following measurements are carried out by use of the n-InSb detector. The detector signal is studied as a function of B with B_d as a parameter. It is found that the kink position in the curve of $V_{\rm sig}$ vs B is a function of B_d as shown in the inset of Fig. 3. The kink positions B are converted to ζ_1 and plotted against B_d in Fig. 3. Generally the energy $\epsilon(k)$ of a photon emitted by the transition of a light hole with a wave vector k to the heavy-hole band is $\epsilon(\boldsymbol{k}) = \epsilon^1(k) - \epsilon^{\rm h}(k)$, where $\epsilon^{1,\rm h}(k) = \frac{1}{2}(m_{1,\rm h}{}^*)^{-1}\hbar^2 k^2$. As readily understood from Fig. 2, the minimum energy of photons coming from accumulated light holes is $\epsilon(\boldsymbol{k}_m{}^1)$, where $k_{\rm min}{}^1 = \boldsymbol{k}_{\rm op}{}^1(2\zeta_1{}^{-1} - 1)$ with $\boldsymbol{k}_{\rm op}{}^1 = m_1{}^* V_{\rm op}{}^1/\hbar$ the minimum wave vector in the accumulation area. The energy $\epsilon(\boldsymbol{k}_{\rm min}{}^1)$ is expressed in the form

$$\epsilon(\boldsymbol{k}_{\rm min}{}^1) = (1 - m_1{}^*/m_{\rm h}{}^*)(2\zeta_1{}^{-1} - 1)^2 \hbar\omega_{\rm op}, \qquad (2)$$

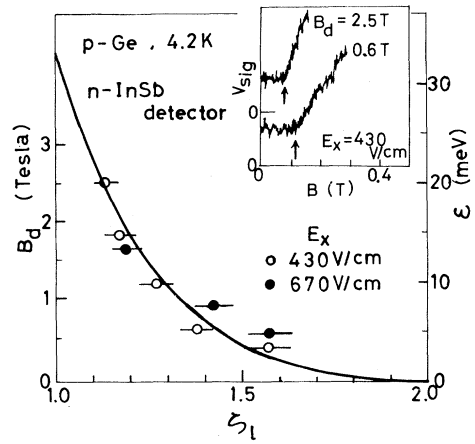

FIG. 3. Kink position ζ_1 in the V_{sig} vs B curve, taken with n-InSb detector, as a function of detector magnetic field B_d. A solid line is drawn according to Eq. (2). Curves of V_{sig} vs B at different B_d are shown in the inset.

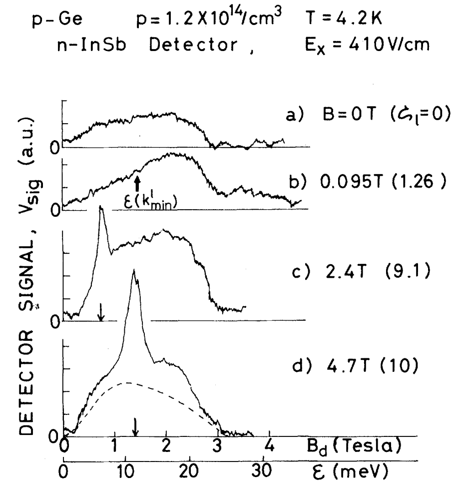

FIG. 4. n-InSb detector signals as a function of B_d. The dotted line in (d) indicates spectral response of the detector. Arrows in (c) and (d) indicate the energy position $\epsilon = \hbar eB/m_1^*$.

and is shown as a function of ζ_1 with a solid line in Fig. 3. In the measurements with the n-InSb detector, where only those photons with energy ϵ corresponding to B_d are detected, the contribution of radiation from accumulated light holes to the detector signal sets in only when $\epsilon > \epsilon(k_{\min}^1)$. Thus the satisfactory agreement of the data points with the calculation in Fig. 3 assures that the radiation does come from accumulated light holes.

To survey the spectrum of radiation and to seek for cyclotron resonance emission,[14,16] the n-InSb detector signal is studied as a function of B_d with B as a parameter. Shown in Fig. 4 are examples of the result at $E_x = 410$ V/cm. The detected signals are weighted by the spectral response of the detector, a rough measure of which[10] is indicated by a dotted line in Fig. 4(d). At every level of B, a broad spectrum is observed. The steep decrease of each curve above $\epsilon \sim 22$ meV reflects the rapid decrease in detector sensitivity and we are not able to see the expected cutoff at $\epsilon(k_{op}^1) = 32.5$ meV in the spectrum. The results below $\zeta_1 = 3$ reconfirm our interpretation: The intensity of radiation remains unchanged with B in the range $\zeta_1 < 1$ while it begins to increase above $\zeta_1 = 1$. An expected kink at $\epsilon(k_{\min}^1)$ in Fig. 4(b) at $\zeta_1 = 1.26$ cannot clearly be discerned because the rate of accumulation is not significant enough at $\zeta_1 = 1.26$ as readily seen from results in Fig. 1. At higher B range above 2.4 T, a relatively sharp peak appears as a superposition on the broad spectrum. The peak is identified, from the peak position $\epsilon = \hbar\omega_c^1 \equiv \hbar eB/m_1^*$, as due to cyclotron resonance emission from light holes. Thus in the high-B range, both the transition of light holes to the heavy-hole band and the transition between Landau levels within the light-hole band are observed.

The total radiation power is roughly estimated, from the magnitude of detector signals, to be of the order of microwatts at $\zeta_1 > 2$ and $E_x > 600$ V/cm. The most interesting question that arises from the present experiment is the possibility of far-infrared amplification, though the emission observed here is almost certainly spontaneous. There are two possibilities. The first one is the cyclotron resonance amplification at $\zeta \sim 2$.[17,18] However, the cyclotron amplification is not expected here since it should appear only at $\zeta_1 \sim 2$. The investigation of the cyclotron emission line at $\zeta_1 \sim 2$ was impossible because of the limitation of detector sensitivity at lower photon energies. Second, if the ratio of light-hole accumulation is high enough, it may cause population inversion between the light- and heavy-hole bands and this directly leads to a broadband far-infrared amplification as pointed out by Andronov *et al.*[15] In the present experiment, the ratio in number of accumulated light holes to streaming heavy holes can be estimated from the data as shown in Fig. 1. For instance the ratio is (6–8)% at $\zeta_h = 1$ above $E_x = 600$ V/cm. This amount of accumulation together with a likely momentum distribution of heavy holes[1] and the densities of state in the two bands makes it likely that the present carrier system lies close to the population inversion. Thus the amplification is quite probable for purer crystals in which stronger accumulation is expected.

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