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Bunching of streaming carriers in p-type Ge at intense microwave fields

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Small dc current response J of carriers in p-type Ge crystals under high microwave fields at 9.4 GHz up to $E_\omega = 1$ kV/cm and magnetic fields up to 1.5 kG is studied at 4.2 K. In the range of magnetic field 0.3–0.8 kG, there appears in the J vs E_ω curves a new plateau structure which indicates bunching of heavy holes in momentum space.

Streaming motion of carriers and resulting peculiar distributions of hot carriers in crossed high electric and magnetic fields have recently been studied extensively in several semiconductors including AgBr and p-type Ge.[1–4] One of the most interesting features of streaming motion is its possibility of bunching carriers in momentum space.[5,6] According to theory,[5,6] bunching is expected when a strong enough (linearly polarized) microwave field and a weak perpendicular magnetic field are applied, so that the average interval of successive optical-phonon emissions by a streaming carrier is shorter than the half period of the applied microwave field. In previous cyclotron resonance experiments on photocarriers in AgBr at intense microwave fields, the occurrence of streaming motion in microwave fields was confirmed, but bunching of carriers was not concluded, since the dependence of the conductivity on the strength of microwave field was not studied in detail in the photoexcitation measurements.[7,8] In the present work we have used ultrapure p-type germanium crystals with Ohmic contacts to study dc conductivity in the presence of strong microwave fields. The experimental results here provide for the first time definite evidence for the carrier bunching in momentum space.

The specimens are cut out of a p-type Ge crystal containing a net acceptor concentration of $N_A - N_D \sim 2\times10^{12}/\text{cm}^3$ into rectangular parallelepipeds ($10\times3\times0.34$ mm^3), with each face normal to one of the [100] crystallographic axes [Fig. 1(a)]. One long face has at both ends B^+ implanted and metallized contacts with an interelectrode distance 6.6 mm. Hall-effect measurements made prior to the present experiments and cyclotron resonance experiments proved the contacts to be Ohmic and free from minority-carrier injection at 4.2 K up to the highest electric fields studied (1 kV/cm). The mobility of carriers μ_0 as derived from the width of cyclotron resonance lines at 4.2 K and weak microwave field is as high as 8×10^5 cm^2/V sec for heavy holes (corresponding to a scattering time of $\tau_0 = 120$ psec). The current-voltage characteristic studied at 4.2 K for static electric fields indicates streaming motion of heavy holes to take place already at a relatively low electric field about 30 V/cm, which is consistent with the high value of μ_0 in this specimen.

Microwave power generated by a pulsed magnetron operating at 9.4 GHz is fed to the specimen by using a standard reflection-type spectrometer. The specimen is placed inside the waveguide along the direction of the microwave electric field as shown in Fig. 1(a). The size of the waveguide in the electric field direction is reduced to 2 mm by use of a part of a wedge-shaped transition, so that the contacts are well outside the waveguide. The guide walls are fitted to the specimen with insulating foils sandwiched between the walls and the specimen, so that the capacitance formed between them shunts off the microwave currents. The waveguide with the specimen is directly immersed in liquid helium. Time sequence of the pulse operation is shown in Fig. 1(b). A pulsed dc voltage V_{dc} with amplitude of 50 V and duration of 1 μsec is applied to generate free carriers through impact ionization of acceptors. For probing dc current response, this carrier-generating pulse is followed by a weak voltage pulse with amplitude 0.5 V and duration 1 μsec. A microwave field pulse E_ω with duration 0.5 μsec is applied immediately after the carrier-generating voltage pulse.

The density of generated carriers n at the time of gate 1 shown in Fig. 1(b) (duration 0.2 μsec) was determined by the current-voltage characteristic to be $n = 8.5\times10^{11}/\text{cm}^3$, when $B = 0$ and $E_\omega = 0$. The density n was found to vary

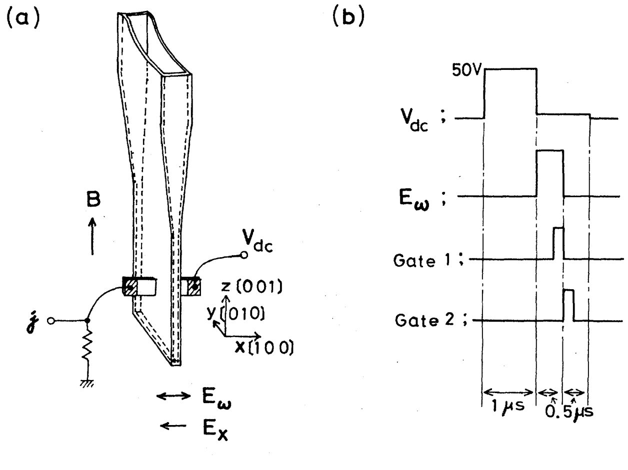

FIG. 1. (a) The p-type Ge sample mounted in the waveguide. (b) Time sequence of the dc voltage pulse V_{dc} and the microwave pulse E_ω, with the gates 1 and 2 of duration 0.2 μsec.

with B and E_ω within the range $n \lesssim 2\times10^{12}/\mathrm{cm}^3$, as will be described later. The sample heating due to the application of the pulses of the dc voltage and the microwave field can be estimated on the assumption of adiabatic heating. Since the carrier density is low, the estimated temperature rise is small, such that $T=4.2$ K rises only to 5.4 K even at $E_\omega=1$ kV/cm. The repetition rate of the pulses is about 100 Hz, which was confirmed to be low enough to avoid the accumulation of heat in the specimen. The amplitude of the microwave field E_ω (i.e., half of the peak-to-peak value) in the specimen was calculated with an accuracy ±15% from the incident microwave power and the dimensions of the waveguide.

Figure 2 shows typical recorder traces of the cyclotron resonance absorption line at different levels of E_ω. The dc voltage after the carrier-generating pulse is set to be zero in these measurements. The relatively sharp resonances at $B=0.14$ and 0.95 kG are, respectively, those of light holes of effective mass $m_l^*=0.043m_0$ (m_0 is the free electron mass) and of heavy holes of $m_h^*=0.28m_0$, respectively. The absorption line gets remarkably broad with increasing E_ω. The overall feature of the change in the line shape with increasing E_ω above 70 V/cm is similar to that observed for electrons in AgBr,[7,8] and suggests the occurrence of streaming motion of heavy holes at higher E_ω. However, the anisotropy in the heavy-hole band and the variation in the carrier density with E_ω and B complicate the quantitative analysis of the line shape.

For the more detailed study, we have measured dc current response of the carrier system to a small dc voltage (0.5 V). The dc electric field along the current direction, $E_x=0.5$ V/0.66 cm $=0.76$ V/cm, is much smaller than the large values of E_ω of interest here.[9] The assumption that this small field can be regarded as a weak perturbation to the carrier system was supported by the measurements of absorption lines, in which no appreciable difference was noted on the application of 0.5 V. Hence we suppose that, apart from the variation in n, the dc current J gives a measure for the average scattering time τ of the carrier system under given E_ω and B. Most simply considered, J may be expressed as[10]

$$J=nev_x=(ne^2\tau/m_h^*)E_x\ , \tag{1}$$

by neglecting a small contribution from light holes. Figure 3 shows the current density J_1, measured at the time of gate 1, as a function of E_ω for several fixed values of B. The magnitude of J_1 at $B=0$ and low E_ω (5 V/cm) is explained by Eq. (1) with the values $\tau=\tau_0=120$ psec and $n=8.5\times10^{11}/\mathrm{cm}^3$, which agree with the results of measurement of the cyclotron resonance lines and the current-voltage characteristic. The current J_1 at $B=0$ decreases rapidly with increasing E_ω in the range from 100 V/cm up to 1 kV/cm without exhibiting remarkable structures except for a change in slope at about 250 V/cm, indicating a rapid decrease of μ (or τ) in the high-E_ω range. When B is applied, the feature of the J_1 vs E_ω curve changes significantly. Firstly, J_1 decreases with B at fixed low E_ω. This is attributed to a decrease in n with B, since μ (or τ) must be substantially independent of B in the limit of low E_ω. Secondly, a distinct plateau structure appears in the range of E_ω from 150 to 250 V/cm for the B values satisfying $\omega_c/\omega=0.3$–0.8, where ω is the angular frequency of microwave field and $\omega_c=eB/m_h^*$. The plateau disappears at higher values of B where $\omega_c/\omega\gtrsim1$. A plateaulike structure is also noted in the curve of J_1 vs B at an E_ω fixed in the above range, as shown by an example for $E_\omega=180$ V/cm in the inset of Fig. 3. The plateau suggests the scattering time τ to become constant there and indicates the occurrence of carrier bunching, as discussed later.

To eliminate the effect of a variation of n on J_1, the current J_z was monitored immediately after the microwave field pulse [at the time of gate 2 in Fig. 1(b)]. The inset of Fig. 4 shows the ratio $r=J_2(B,E_\omega)/J_2(B,0)$ as a function of

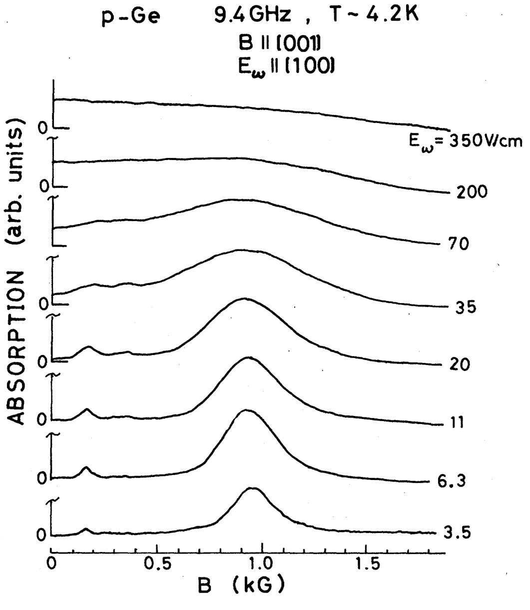

FIG. 2. Recorder traces of cyclotron resonance absorption lines at different levels of E_ω.

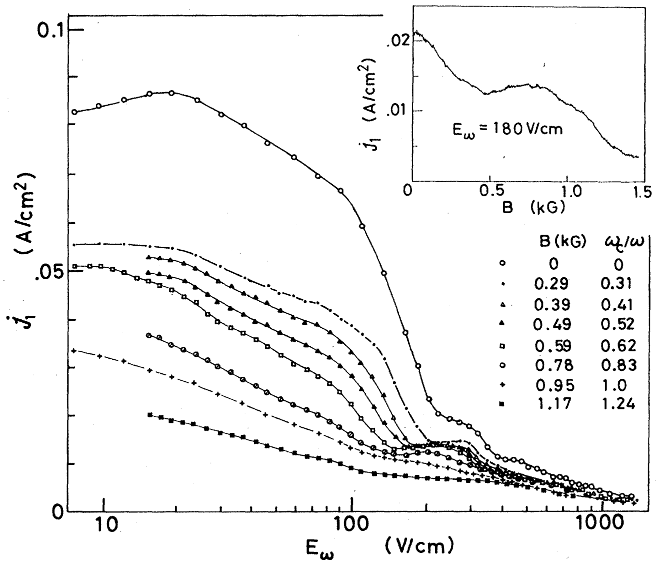

FIG. 3. dc current density J_1 as a function of E_ω. dc electric field is $E_x=0.76$ V/cm. The inset shows the B dependence at $E_\omega=180$ V/cm.

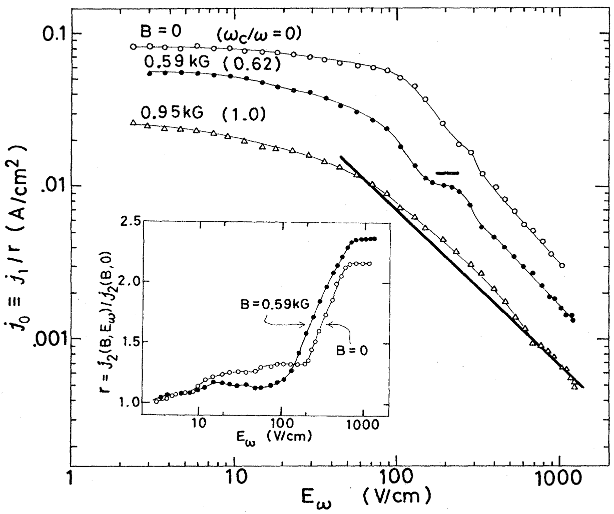

FIG. 4. E_ω dependence of the normalized current density, $J_0 \equiv J_1/r = n(B,0)ev_x$. The broad straight line corresponds to Eq. (1) with $\tau = T_{\rm op}/2$. The horizontal bar indicates the range of E_ω and the magnitude of J_0 theoretically predicted for the bunching of heavy holes. The inset shows E_ω dependence of r, indicating the variation of carrier density with E_ω.

E_ω for $B=0$ and 0.59 kG. Since the drift velocity v_x of carriers at the time of gate 2 must be independent of E_ω, this ratio represents that of the carrier density. Further, the carrier density n_z at the time of gate 2 is nearly equal to the density n_1 at the time of gate 1, as concluded from the observation of a pulse waveform of the current; hence,

$$r(B,E_\omega) = n_2(B,E_\omega)/n_2(B,0) = n_1(B,E_\omega)/n_1(B,0) \ .$$

We can therefore derive a normalized current density, $J_0 = J_1/r = n_1(B,0)ev_x$, which is independent of the variation in n_1 with E_ω. Shown in Fig. 4 are the curves of J_0 against E_ω for $\omega_c/\omega = 0$, 0.62, and 1.0. We should note that the distinct plateau remains in the curve of J_0 for $\omega_c/\omega = 0.62$, whereas a structure for $\omega_c/\omega = 0$ at $E_\omega \sim 250$ V/cm (Fig. 3) has become less remarkable. This implies that the variation of n plays a significant role in giving rise to the structure in the curve of J_1 at $\omega_c/\omega = 0$, while the plateau structure in the curves for $\omega_c/\omega \neq 0$ is primarily caused by the behavior of τ. Except for the plateau region, J_0 for every ω_c/ω is nearly proportional to the inverse of E_ω in the higher E_ω range, suggesting a scattering time τ proportional to $1/E_\omega$.

Under the resonance condition $\omega_c/\omega = 1$, a carrier initially at rest in a microwave field E_ω is accelerated to reach a state of optical phonon energy $\omega_{\rm op}$ at time[7,8]

$$T_{\rm op} = 2(2m_h^* \hbar\omega_{\rm op})^{1/2}/eE_\omega \ . \tag{2}$$

Therefore, streaming motion with the time interval of successive optical phonon emissions given by $T_{\rm op}$ is expected to occur when E_ω is so high that $T_{\rm op}$ is shorter than the scattering time, due to impurities and/or acoustical phonons τ_0. In the present condition ($\tau_0 = 120$ psec, $m_h^* = 0.28m_0$, and $\hbar\omega_{\rm op} = 37$ meV), $T_{\rm op}$ equals τ_0 when $E_\omega = 60$ V/cm. Substituting τ in (1) by $T_{\rm op}/2$, and using the value $n = 3.3 \times 10^{11}/\text{cm}^3$, as derived from the value $n(0,0) = 8.5 \times 10^{11}/\text{cm}^3$, together with the ratio

$$J_1(B,E_\omega)/J_1(0,E_\omega) = n_1(B,E_\omega)/n_1(0,E_\omega) = 0.38$$

at $B = 0.95$ kG and the limit of low E_ω (Fig. 3), we can evaluate J_0 under the resonance condition as a function of E_ω. The broad straight line in Fig. 4 represents the calculated values of J_0. The data points of J_0 for $\omega_c/\omega = 1.0$ lie close to the calculated values in the expected range of E_ω ($E_\omega \gtrsim 60$ V/cm), thus providing a reliable indication of streaming motion. Further, the data of J_0 at $\omega_c/\omega = 0$ give additional evidence for streaming motion as discussed in the following. In the absence of a magnetic field, free motion of a carrier initially at rest in E_ω is an oscillatory motion with angular frequency ω and the maximum kinetic energy given by $2(eE_\omega)^2/(m_h^*\omega^2)$. Therefore, with increasing E_ω at $\omega_c/\omega = 0$, the optical phonon emission is expected to set in abruptly at the E_ω satisfying $2(eE_\omega)^2/(m_h^*\omega^2) = \hbar\omega_{\rm op}$. This critical field is $E_\omega = 101$ V/cm in the present condition, and agrees with the field position at which J_0 for $\omega_c/\omega = 0$ starts to decrease rapidly. The features of J_0 for $\omega_c/\omega = 0$ and 1.0 thus guarantee the condition in which the bunching of carriers can be expected.

Let us define a critical field E_ω, above which the interval of successive optical phonon emissions becomes shorter than the half period of the microwave field, by

$$eE_\omega^C/\omega = 2(2m_h^*\hbar\omega_{\rm op})^{1/2}/\pi \ , \tag{3}$$

which implies $T_{\rm op} = \pi/\omega$. E_ω^C is 129 V/cm in the present condition. According to a Monte Carlo calculation,[5,6] the first-order bunching in which each carrier emits an optical phonon once per half cycle of the microwave field is expected to occur when $E_\omega/E_\omega^C = 1.1$–$1.6$ and $\omega_c/\omega = 0.4$–0.8.[11] When streaming carriers bunch in this situation, all the carriers naturally emit optical phonons concurrently at a fixed instant in each half cycle of the microwave field and the interval of the phonon emissions is consequently fixed rigidly to the half period of the microwave field

$$T_{\rm op}^B = \pi/\omega \ , \tag{4}$$

in contrast to the resonance case characterized by Eq. (2). The dc current response is accordingly expected to exhibit a plateaulike structure when measured in a sweep of E_ω or B. We should note that the region of E_ω and B in which the plateau structure has been observed (150–250 V/cm and $\omega_c/\omega = 0.3$–0.8) agree substantially with the expected range ($E_\omega/E_\omega^C = 1.1$–$1.6$ with $E_\omega^C = 129$ V/cm and $\omega_c/\omega = 0.4$–0.8). Furthermore, substituting τ and n in the relation (1) by $T_{\rm op}^B/2 = 26.6$ psec and $n(0.59 \text{ kG}, 0) = 5.7 \times 10^{11}/\text{cm}^3$, as derived from the data shown in Fig. 3 similarly as above, we estimate the current density in the case of bunching to be $J_0 = 12$ mA/cm. This value, together with the expected range of E_ω, is indicated by the position and the width of a horizontal bar in Fig. 4, which is close to the measured value in the plateau region, $J_0 = 10$ mA/cm. Thus we conclude to have obtained strong experimental evidence, for the first time, for the bunching of heavy holes in momentum space.

In addition to the first-order bunching so far considered, higher-order bunchings, in which a carrier emits an optical phonon many times during a half cycle of the microwave field, are also expected to occur in higher E_ω.[5,6] With the present experimental accuracy, however, additional steplike structures were not clearly discernible in the higher-E_ω range.

Recently, we have found a strong generation of the third harmonic (3 × 9.4 GHz) to occur coincidentally with the appearance of the plateau structure in the current density.[12] This is additional evidence for the (first-order) carrier bunching, in which the microwave response current is to contain a strong third harmonic component.

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[9] Hall electric field E_y also develops because the dc current is normal to B. However, E_y is expected to be small in comparison to E_x when E_ω is high, because the scattering time τ of the carrier system at high E_ω is strictly limited ($\omega_c\tau < 1$) due to streaming motion, as will be discussed below.

[10] This relation is not rigorously justified in the present condition in which $E_x \perp B$ and $E_x \parallel E_\omega$. However, we suppose it to be approximately valid in giving a rough measure, since the measurements are made in the presence of Hall field E_y.

[11] In Refs. 5 and 6, carriers in an isotropic band are considered. We have made calculations on heavy holes in p-type Ge by taking into account the band anisotropy on the basis of the DKK model, and confirmed that a strong bunching equally results for heavy holes in the present condition ($B \parallel$ [100]) in a similar region of E_ω and ω_c, as quoted above.

[12] S. Komiyama, H. Sukeda, and E. E. Haller (unpublished).