Millimeter-range emission from hot electrons in *n*-type Ge in crossed electric and magnetic fields

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An emission from hot electrons has been observed in strong electric fields when the ratio of the magnitudes of E and H corresponds to closure of the principal trajectory of electrons in momentum space. The emission is attributed to the formation of an inverted carrier distribution among Landau levels.

It has been predicted theoretically that the carrier distribution functions may change substantially in strong electric and magnetic fields, to the point at which an inversion forms in the distribution of carriers among states.[1–4] Under "streaming" conditions, i.e., when the scattering of carriers by optical phonons is predominant, the redistribution of carriers in fields $\mathbf{E}\perp\mathbf{H}$ results from the appearance of regions in p space in which the effective carrier collision rates are substantially different. In addition to the region of streaming carriers, with a collision rate

$$\nu_{\rm opt} = \nu_0\sqrt{\epsilon / \hbar\omega_0 - 1}\ , \tag{1}$$

a region of closed trajectories (a "trap") forms at $p_{\rm dr} < p_0$. In this trap the carriers have a far lower collision rate, $\nu_{\rm i/ac}$, determined by the scattering by acoustic phonons, impurities, etc. Here ϵ is the carrier energy, $\hbar\omega_0$ is the energy of an optical phonon, $\nu_0 \sim 10^{12}\ {\rm s}^{-1}$ in the case of Ge, $p_0 = \sqrt{2m\hbar\omega_0}$, and $p_{\rm dr} = mc(E/H)$ is the carrier drift momentum in the direction perpendicular to $\mathbf{E}$ and $\mathbf{H}$. The nature of the accumulation effects depends on the magnitude of the source, i.e., magnitude of the region in p space to which the carriers return after emitting an optical phonon: $\Delta p = \sqrt{2m(\epsilon - \hbar\omega_0)}$. In most of the studies carried out to date, including those in p-type Ge, involving the observation of an inversion and of lasing during optical transitions between subbands of the light and heavy holes, the dimensions of the source have been quite large[4] $(\Delta p \approx p_0)$.

In the present letter we report a study of the problem of inverted states in a hot-carrier system for the case in which the source is quite small $(\Delta p \ll p_0)$. The case of most interest in this regard arises in fields $\mathbf{E}\perp\mathbf{H}$ under conditions such that $p_{\mathrm{dr}} \cong (1/2)p_0$, i.e., such that the principal orbit is closed (this is the orbit that passes through the point $p = 0$).[1-3] The satisfaction of the condition $\nu_{\mathrm{opt}} \gg \nu_{\mathrm{i/ac}}$ in this situation means that the carriers are concentrated near the principal trajectory; i.e., they fill the higher-lying Landau levels, $n \approx \hbar\omega_0/4\hbar\omega_c$. It is of course extremely difficult to induce emission on cyclotron transitions under ordinary conditions because of the equivalence of the transitions to lower-lying and higher-lying states. To some extent, the situation in strong fields $\mathbf{E}\perp\mathbf{H}$ is free of these limitations, since the state density for transitions to higher-lying levels with energies $\epsilon > \hbar\omega_0$ is lower than for transitions to lower-lying levels, $\epsilon < \hbar\omega_0$, because of an interaction with optical phonons. It is, on the other hand, extremely difficult to arrange a carrier distribution of this sort, primarily because at small dimensions of the source (corresponding to the condition $\epsilon - \hbar\omega_0 \ll \hbar\omega_0$) it is a difficult matter to satisfy the main condition $\nu_{\mathrm{opt}} \gg \nu_{\mathrm{i/ac}}$, which must be satisfied if carriers are to accumulate on the principal trajectory. This circumstance can be seen directly from expression (1). For a sufficiently high collision rate $\nu_{\mathrm{opt}} \cong \nu_0$ the carrier energy ϵ must be significantly greater than $\hbar\omega_0$ ($\epsilon - \hbar\omega_0$ must be on the order of $\hbar\omega_0$).

In the present experiments we use n-type Ge crystals with an antimony impurity $(3\times 10^{13}$–$2\times 10^{14}\ \mathrm{cm}^{-3})$. The samples, with dimensions of $5\times 3\times 0.5$ mm, are immersed in liquid helium in a superconducting solenoid in a lightguide at whose end there is an n-type InSb detector. Measurements are taken over the range $H = 0$–17 kOe. An electric field up to 2 kV/cm in the form of pulses 2–4 μs long is applied to the ends of the sample. The pulses produce a hot electron plasma in the semiconductor as a result of ionization of the donor impurity. The basic problem is to detect the cyclotron radiation, whose intensity might carry information about changes in the carrier distribution in strong fields $\mathbf{E}\perp\mathbf{H}$. The probability for spontaneous transitions between Landau levels is proportional to the level index; i.e., the intensity is given by

$$P \sim \dot{r}^2 \sim (\omega_c v)^2 \sim \omega_c^2 \hbar\omega_c \left(n + \frac{1}{2}\right). \tag{2}$$

The redistribution of carriers to higher-lying states should be accompanied by an increase in the intensity of the cyclotron-resonance emission. The experimental apparatus is described in Ref. 4. When this apparatus is connected to a backward-wave-tube spectrometer, it becomes possible to simultaneously measure the spectra of the electron cyclotron-resonance absorption.

The experimental results are shown in Figs. 1–3. In electric fields above a critical field $E_{\mathrm{cr}} \geqslant 1.5$ kV/cm the emission intensity increases sharply, by about two orders of magnitude from the level of the spontaneous emission, detected with a detector in the range $\lambda > 0.3$ mm in fields E near E_{cr}. Measurements with various filters between the sample and the detector revealed that the observed emission has a wavelength on the order of 1–3 mm. This wavelength corresponds to the energy spacing between Landau levels in these magnetic fields.

The emission intensifies in fields $E > 1.5$ kV/cm in a very narrow interval of conditions near the value

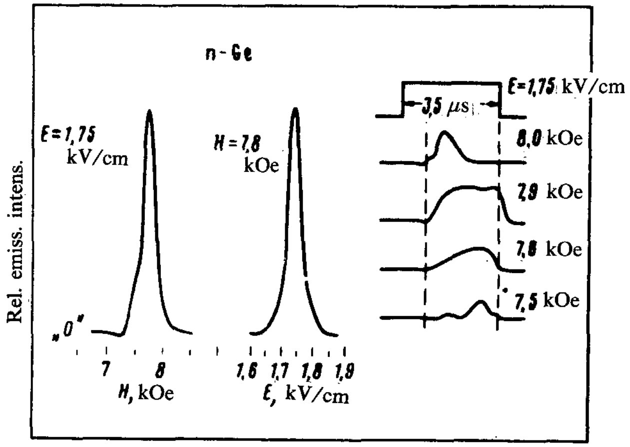

FIG. 1. Emission intensity versus *E* and *H*. Shown at the right is the time evolution of the emission intensity.

$$E / H = 0{,}22 \text{ kV/(cm kOe)}. \tag{3}$$

It can be seen from Fig. 1 that the emission is observed at fixed values of *E* in fields *H* differing from (3) by no more than 0.5 kOe, while at a fixed value of *H* it is observed in fields *E* which differ from (3) by no more than 0.1 kV/cm. Figure 2 demonstrates that the ranges of *E* and *H* in which the emission is detected conform well to line (3). Also shown here is the intensification of the emission with *E* and *H* according to measurements at the maxima. We see a clearly defined threshold in the intensification. Figure 1 also shows data on the kinetics of the emission buildup during the *E* pulse for various values of *H*.

The fact that the submillimeter emission corresponding to transitions between Landau levels is observed under conditions corresponding approximately to closure of

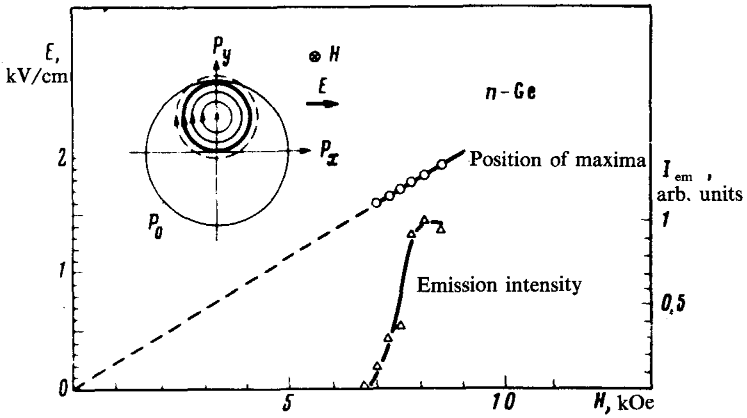

FIG. 2. Circles—Positions of the emission maxima on the *E*, *H* plane. Shown at the bottom is a curve of the emission intensity at the maxima versus *H*.

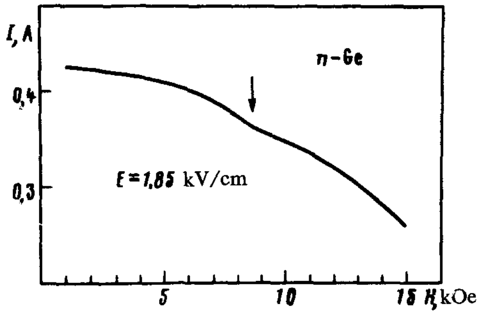

FIG. 3. Current versus the magnetic field. The arrow shows the value of H at which the emission is observed.

the principal trajectory is confirmed by calculations ($E/H = 0.2$ according to Ref. 1) and strongly suggests that in these experiments there was a toroidal carrier distribution inverted in terms of the low-lying Landau levels. According to Ref. 1, a structural feature should appear on the curves of the current versus the magnetic field under these conditions. We see from Fig. 3 that a structural feature of this type is in fact found on the $I(H)$ curves upon the appearance of emission in the present experiments. In principle, the intensification of the emission under these conditions should also occur for spontaneous transitions. According to estimates, however, this increase is much smaller than that observed. In view of the threshold required for the onset of the emission and other aspects of the phenomenon, it appears more likely that the observed emission is stimulated.

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