Large reduction of the Gunn-effect threshold field in a strong magnetic field

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(Submitted 12 May 1980; resubmitted 22 October 1980)

Pis'ma Zh. Eksp. Teor. Fiz. **32**, No. 11, 628–632 (5 December 1980)

The results of numerical experiments to investigate the intervalley transport of hot electrons in *n*-GaAs in a strong magnetic field are presented. A strong magnetic field ($B \approx 50$ kG) reduces the threshold field of the decreasing portion of the volt-ampere (V-A) characteristic and the Gunn effect in long, pure samples by more than a factor of 2 at a temperature $T = 77$ K. It is established that this is a consequence of the "runaway" electron energy in a strong magnetic field, which is caused by the strong Hall field in the sample.

PACS numbers: 72.20.My, 72.80.Ey

A strong transverse magnetic field **B** exerts a strong influence on intervalley electron transport in *n*-GaAs. In short samples it suppresses the decreasing portion of the volt-ampere (V-A) characteristic at values as low as $B \approx 20$–30 kG. The most detailed numerical and experimental studies of short samples were performed in Ref. 1.

The situation changes significantly in long samples (see inset in Fig. 1). Here, in addition to the field $\mathbf{E}_{\rm ap}$ applied to the sample, the Hall field $\mathbf{E}_H$, which facilitates the transfer of electrons to heavy valleys and the appearance of a decreasing part of the V-A characteristic, is produced in a strong magnetic field. Figure 1 shows the results of a numerical modeling of the V-A characteristic in long samples by using the Monte-Carlo method. The applied threshold electric field $E^t_{\rm ap}$, at which the decreasing part appears in the V-A characteristic, is reduced significantly in a strong magnetic field (at 300 K the calculations reduce the threshold field $E_{\rm ap}$ by a factor of 1.2–1.5).$^{1)}$ According to current concepts,[2] the band structure of *n*-GaAs has the form in the inset in Fig. 1; however, the parameters of the X and L valleys are uncertain.[2] We selected a band-structure model with heavy valleys at the energy $\epsilon = \epsilon_h = 0.33$ eV with a field-independent mobility $\mu_h = 600$ cm^2/V·sec. Scattering by optical phonons and impurity scattering (at 77 K) were taken into account in the light (Γ) valley. The transition probability to the heavy valleys was assumed to be close to that now accepted[2] for X valleys. Heating of electrons in the heavy valleys was ignored; an electron that left the light valley with an energy ϵ returned to it with an energy $\epsilon' = \epsilon - 2\hbar\omega_0$, where $\hbar\omega_0$ is the optical-phonon energy.

The V-A characteristic varies in a strong magnetic field because of the escape of electrons in strong, crossed $\mathbf{E} \perp \mathbf{B}$ fields.[3] This is clearly evident in pure samples at low temperatures when the electron scattering is small in the light valley at energies $\epsilon < \hbar\omega_0$. In this case, a buildup of electrons in the spindle-shaped region of the closed trajectories,[4] in which the emission of optical phonons is impossible, can oc-

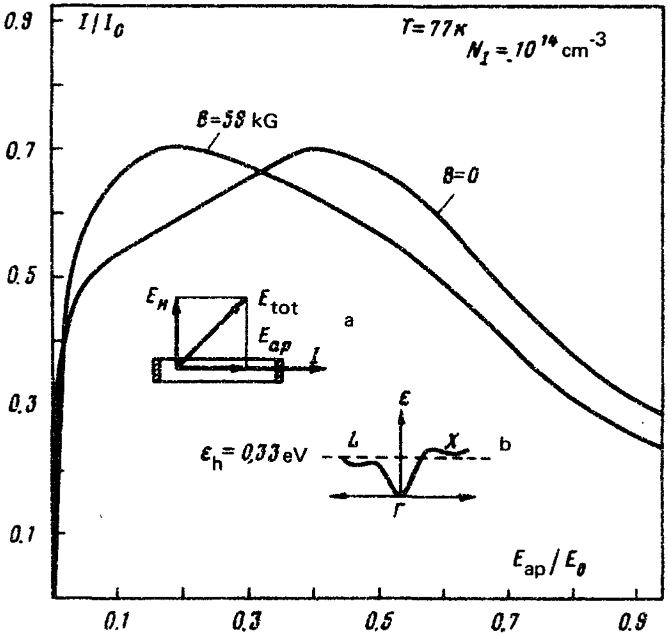

FIG. 1. Dependence of the electron current density I in n-GaAs on the applied electric field E_{ap} $I_0 = eV_0(n_l+n_h)$; $E_0 = m_l^* e\omega_0(1/\epsilon_\infty - 1/\epsilon_0)/\hbar = 6.5$ kV/cm. The insets show the field geometry (a) and the conduction-band diagram of n-GaAs (b); the dashed line represents the selected energy of the heavy valleys.

cur in crossed $\mathbf{E}\perp\mathbf{B}$ fields at $\epsilon<\hbar\omega_0$ (see inset in Fig. 2). In a strong magnetic field $\mathbf{B}$ (when the cyclotron frequency of electrons in the light valley is $\omega_c \gg \nu_0 \gg \nu$, where ν_0 is the characteristic optical-phonon emission frequency and ν is the scattering frequency at $\epsilon<\hbar\omega_0$) the buildup of a large fraction of electrons in the spindle-shaped region at $\epsilon<\hbar\omega_0$ results in the fact that the Hall field $E_H \gg E_{\text{ap}}$, and the distribution function can be inverted[5] (see below). As the buildup region decreases with increasing electric field, the electrons escape to the high-energy region and an intervalley transport occurs in a strong magnetic field ($\omega_c \gg \nu_0$) when the electron buildup region is still large and $E_H \gg E_{\text{ap}}$. This decreases the threshold field E_{ap}^t in a strong magnetic field. The number of electrons can be greatly increased in the heavy valley by slightly changing the location of the center of the trajectories $P_c = m_l^* c\,E/B$ in the buildup region relative to the momentum $P_0 = (2m_l^* \hbar\omega_0)^{1/2}$, where m_l^* is the effective electron mass in the light valley. As a result, the intervalley transport under these conditions resembles a "breakdown" of the buildup region, which is well illustrated by the curve in Fig. 2. If the buildup region still exists and the intervalley transport is in progress, then most of the electrons will be either in the buildup region or in a heavy valley; if the scattering is sufficiently weak at $\epsilon<\hbar\omega_0$, then the distribution function in the light valley will be inverted ($df/d\epsilon>0$) in the energy region that corresponds to the buildup region (Fig. 2). The distribution function f of the light valley near the energy ϵ_h of the heavy valleys has a "plateau" due to the electrons from the heavy valley that travel almost freely across the light valley (the

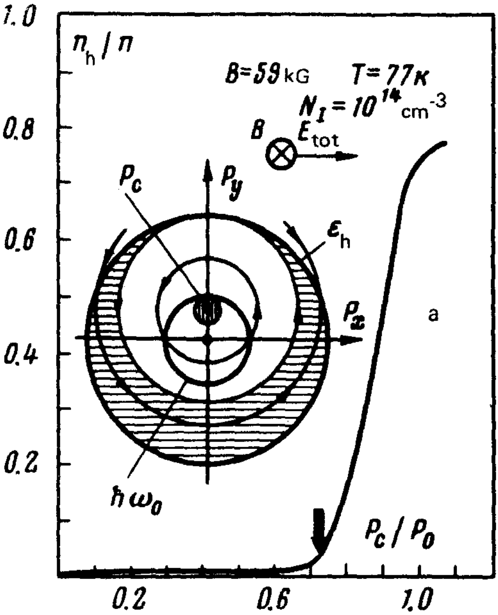

FIG. 2. Dependence of the relative number of electrons in the heavy valleys n_h/n, $n = (n_h + n_l)$ on the location of the center of trajectories $P_c = m_l^* cE_{tot}/B$. The phase trajectories in a light valley are shown in the inset. The vertically shaded area represents the spindle-shaped region of electron buildup; the horizontally shaded region represents the electrons that come from the heavy valleys and traverse this region without scattering before returning to the heavy valleys. The arrow indicates the P_c value at which a decreasing portion on the V-A characteristic appears.

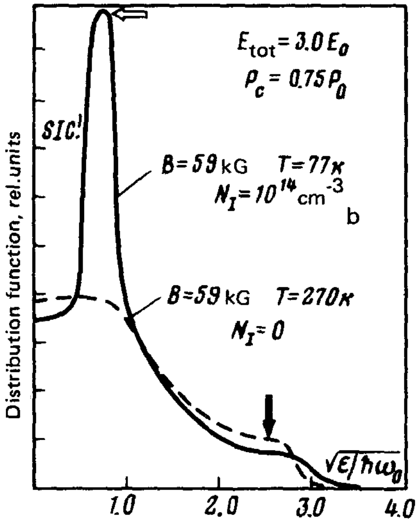

FIG. 3. Distribution function in the light valley; the arrows indicate the portions of the distribution function that correspond to the shaded regions in the inset in Fig. 2; this represents the population-inversion region.

electrons in the horizontally shaded region in the inset in Fig. 2).

The influence of the strong magnetic field on intervalley transport is analogous to the so-called transverse breakdown in *n*-InSb in a strong magnetic field,[6] which was investigated and explained by us[3] within the framework of analogous concepts.

A variation of the electron dynamics and escape in a strong magnetic field must influence not only the above-described, static characteristics of the electrons, but also their dynamic properties. In particular, a decrease of the electron lifetime τ in the light valley in a magnetic field, which decreases the threshold field, also increases (see Ref. 7) the limiting frequency f of the negative differential conductivity associated with the decreasing part of the V-A characteristic.

In addition, we note that in a strong magnetic field $\omega_c \gg \nu_0$ the electrons of the light valley acquire a new characteristic frequency—the cyclotron frequency ω_c, which determines the characteristic residence time of electrons in the region corresponding to the "plateau" in the distribution function when $\epsilon \approx \epsilon_h$ (Fig. 3). The new characteristic frequency in the electron system may significantly influence the frequency dependence of the differential conductivity (see Refs. 8 and 9).

A detailed numerical and experimental study of the decrease of intervalley-transport threshold field in a strong magnetic field and of the V-A characteristics and the dynamic properties of electrons associated with it is of interest for many reasons including the increase of the limiting frequency of the Gunn-effect oscillators.

We take this opportunity to thank L. Ya. Pavlov for his continuing help in numerical modeling.

[1)] A decrease of the Gunn-effect threshold field in a transverse magnetic field was reported in Refs. 10–12.

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Translated by Eugene R. Heath
Edited by S. J. Amoretty