New mechanism for current instability in narrow-gap semiconductors

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A new current-instability effect and the excitation of oscillations in the course of a magnetoconcentration effect have been studied experimentally and theoretically in a narrow-gap semiconductor under conditions such that Auger processes are predominant.

The literature reveals the description of only one mechanism for the formation of an *N*-shaped current-voltage characteristic in the course of a magnetoconcentration effect. That mechanism stems from the extrinsic nature of the semiconductor.[1–3] For that mechanism to be manifested, there must be a pronounced difference in the lifetimes and/or mobilities of the electrons and holes, and the carrier generation rate must be independent of the carrier density. This mechanism has been observed[2,3] in InSb at temperatures of 195–220 K: Current oscillations arose in a circuit containing the sample. The peak-to-peak amplitude observed for these osciliations reached a maximum of 20% of the average value of the current.

In the present letter we describe a current-instability effect in $Cd_{0.2}Hg_{0.8}Te$ films in the course of a magnetoconcentration effect in the temperature interval 300–380 K, where the bulk generation and recombination of carriers are caused by Auger processes.

In some cases the peak-to-peak amplitude of the current oscillations reached 50% of the average current flowing through the sample. The reason for the formation of an *N*-shaped current-voltage characteristic under these conditions is a decrease in the rate of Auger generation of carriers during a depletion of electron-hole pairs in the semiconductor. A sample typically has a wide depletion region, in which generation is predominant in the course of the magnetoconcentration effect. Accordingly, if this depletion region, rather than the narrow enriched layer, determines the current-voltage characteristic of the sample, the I-V characteristic can have an *N*-shaped region if Auger generation is predominant in the depletion region. This mechanism for the formation of an *N*-shaped negative differential conductivity on the I-V characteristic is not a consequence of the extrinsic nature of the semiconductor, although it does operate in extrinsic semiconductors also. Furthermore, this mechanism does not require a pronounced difference between the lifetimes or mobilities of the carriers, although it is manifested if such differences do prevail.

Under conditions corresponding to a well-developed magnetoconcentration effect, the sample breaks up into two regions: a region which is enriched in electron-hole pairs (the "pinch layer"), whose thickness is much smaller than the bipolar diffusion length and which is adjacent to one face of the sample; and a depletion region, which

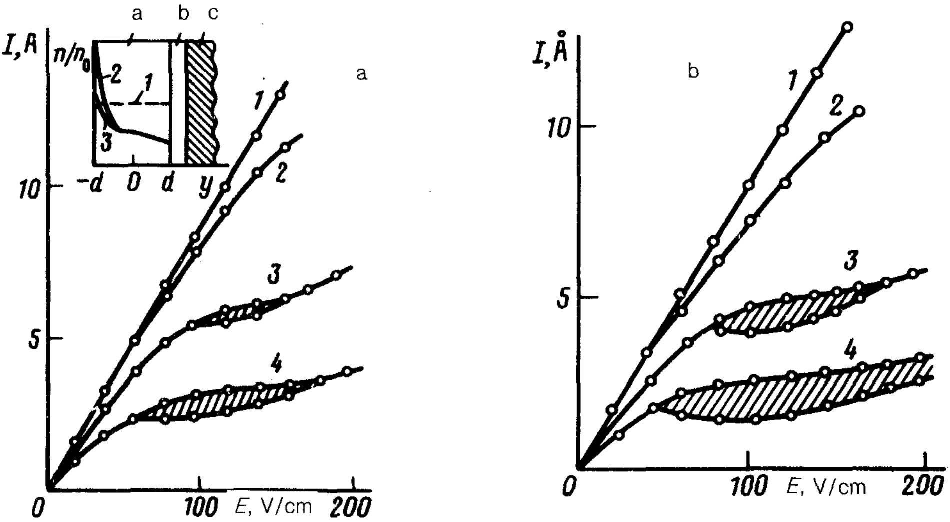

FIG. 1. Current-voltage characteristics of epitaxial Cd$_{0.2}$Hg$_{0.8}$Te films. *H*, kOe: 1–0; 2–5; 3–10; 4–20. a) $s^- \approx 10^4$ cm/s; b) $s^- \approx 5\times 10^5$ cm/s. The inset shows the profile of the charge-carrier density along the cross section of the homogap layer of the Cd$_{0.2}$Hg$_{0.8}$Te film. a) Homogap layer of film; b) transition layer; c) CdTe substrate. 1—Equilibrium charge-carrier distribution; 2—s^- at surface d is low; 3—s^- at surface d is high.

occupies all the rest of the sample volume. There is always a depletion region in a sample except if the rate (s^-) of surface generation at the face from which the pairs are removed is infinite. The inset in Fig. 1a shows a sketch of the density of electron-hole pairs in the sample for various rates of surface recombination at the face to which the pairs are removed.

We will consider only the depletion region, assuming that the surface-recombination rate s^- is so high that the current in the sample is determined primarily by the depletion region. We assume that the applied field is so strong that the processes in the depletion region can be described in the drift approximation, i.e., disregarding the diffusion. For simplicity we assume that the sample is a purely intrinsic semiconductor and that the generation-recombination term is $-[(n^3 - n_0^2 n)/\tau_A n_0^2]$, where n is the density of electrons, n_0 is the equilibrium density of electrons, and τ_A is the lifetime in the Auger process. The continuity equation for the depletion region then takes the form[3]

$$\frac{2D\gamma}{L}\,\frac{dn}{dy} = \frac{n^3 - n_0^2 n}{\tau_A n_0^2}\,, \tag{1}$$

where D is the ambipolar diffusion coefficient, y is the coordinate which is transverse with respect to the current, and the current is flowing in the x direction ($-d \leqslant y \leqslant d$; the sample is assumed to be a wafer with infinite dimensions along x and z). Here $L^2 = D\tau_A$, and γ is the dimensionless field applied to the sample, which is given by

$\gamma = eaE_xL/4kT$, where a is the anisotropy coefficient,[3] and E_x is the field applied along the x axis. To the right side of (1) we can add terms which stem from quadratic recombination, $(n^2 - n_0^2)/n_0\tau_R$, and linear recombination, $(n - n_0)/\tau_0$. These generation laws describe a flux of carriers in the depletion region which does not depend on the electric field; consequently, a current-saturation region appears on the current-voltage characteristic. The Auger generation decreases with increasing electric field because of the decrease in the carrier density with increasing field. An N-shaped region of a negative differential conductivity thus appears on the current-voltage characteristic when Auger-generation processes are predominant; necessary conditions for the occurrence of this effect are the inequalities $\tau_A \ll T_0, \tau_R$. Solving Eq. (1) with the customary boundary condition at the $y = +d$ face, where the surface-generation rate is S^+, we find the following results for the current-voltage characteristic of the sample. In the limit $\gamma \to 0$, the I-V characteristic is ohmic, and the current i is proportional to $2\delta\gamma$, where $\delta = d/L$. As γ increases, the current growth slows down, and the current reaches a maximum at a value $\gamma_{\max} \approx S^+$, where $S^+ = s^+L/D$ at $S^+ \gg \delta$, and we have $\gamma_{\max} \approx \delta/(\ln 2\delta/S^+ - \ln\ln 2\delta/S^+)$, if $S^+ \ll \delta$. At $\gamma \gg \gamma_{\max}$ we have

$$i \sim S^+\gamma\left(\frac{\exp(\delta/\gamma)}{(1+S^+/\gamma)^{1/2}} - \frac{1}{1+S^+/2\gamma}\right). \qquad (2)$$

Expression (2) demonstrates the basic effect: a decrease in i with increasing γ terminating in the attainment of a saturation value of δ. An expression like (2) of course cannot give an accurate description of the current-voltage characteristic observed experimentally, since other carrier-generation mechanisms come into play when a pronounced depletion is reached in the sample. The current described by (2) is proportional to S^+. This point demonstrates the need for a flux of carriers which are produced at the face $y = +d$ for a calculation of the effect in the drift approximation. The drift approximation is good at $\gamma \gg 1$. An expression of the type in (2) is found under an inequality of the type $S^+ > \gamma$, as we will show in a more-detailed future publication. At $S^+ = 0$, the N-shaped negative differential conductivity apparently occurs at $\gamma < 1$, where the drift approximation breaks down. In order to observe the effect, however, one would have to use samples with low values of S^+, since an increase in S^+ shifts the region of the N-shaped negative differential conductivity into the region of strong electric fields, where the negative differential conductivity may be masked by carrier-heating and impact-ionization effects.[1)]

To study the magnetoconcentration effect in samples with small values of S^+, we used a heterostructure of isomorphic semiconductors, CdTe and $Cd_{0.2}Hg_{0.8}Te$ (this is the first time this approach has been taken in a study of the magnetoconcentration effect). The approximately equal lattice constants of these compounds made it possible to achieve a low state density at their interface. Since the carrier density in CdTe is several orders of magnitude lower than that in $Cd_{0.2}Hg_{0.8}Te$, there was essentially no flux of carriers across the heterojunction during the magnetoconcentration effect. This circumstance is equivalent to a low value of s^+.

The samples were wafers with dimensions of 2×5 mm^2. Ohmic contacts were soldered with indium to the $Cd_{0.2}Hg_{0.8}Te$ film, with a thickness of 30 μm. An electric field was applied in the form of square pulses 2–10 μs long.

At temperatures above room temperature we have $\tau_A \sim 10^{-8}$ s, $\tau_R \sim 10^{-6}$ s, and $\tau_0 \gg \tau_R$, so the Auger generation is the primary process for densities over the range to two orders of magnitude below the equilibrium density.

Figure 1a shows current-voltage characteristics of the samples at 340 K. At a magnetic field $H = 0$, the characteristic is linear, providing evidence that the ohmic contacts are of good quality and that the experiments are free of carrier heating, impact ionization, and contact injection. If the magnetic field deflects the plasma toward the outer surface of the narrow-gap film, at which the surface-recombination rate is about 2×10^4 cm/s, the characteristic becomes sublinear. With a further increase in the magnetic field, a region of an N-shaped negative differential conductivity forms on the I-V curve, and oscillations appear in the current pulse. The hatched regions on the curve correspond to the oscillation region. The oscillations, when they appear, are sinusoidal with a period of 1 μs. With increasing electric field, the oscillation frequency increases; the oscillations then become a noise and disappear. Oscillations are observed over the temperature interval 300–380 K. Figure 1b shows current-voltage characteristics of the same sample when the surface-recombination rate at the free surface of the film was increased to $s^- \approx 5.10^5$ cm/s. An increase in s^- leads to a decrease in the voltage at which the oscillations appear and to an increase in the oscillation amplitude. The reason is a decrease in the current which flows through the pinch layer.

In experiments carried out in $Cd_{0.2}Hg_{0.8}Te$ single crystals under the same conditions, the N-shaped negative differential conductivity on the I-V characteristic and the current instability were not manifested. This result confirms the suggestion (above) that a very low surface-recombination rate at the depletion face of the sample is required for a manifestation of the effect. At high temperatures, $Cd_{0.2}Hg_{0.8}Te$ single crystals have a high surface-recombination rate, 10^4–10^5 cm/s.

The effect studied here might be utilized to study Auger generation of carriers; only Auger recombination has been studied previously in semiconductors. The effect might also be used to develop active elements for high-power (up to 1-kW) sources of regular and noisy oscillations from narrow-gap semiconductors. These sources could operate at room temperature and above.

[1)] The existence of an N-shaped negative differential conductivity is a consequence of the finite value of S^+. In the limit $S^+ = \infty$, the current-voltage characteristic has only an ascending region, regardless of the value of γ.

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