Magneto-concentrating effects in unnatural semiconductors with substantially different electron and hole mobilities

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Magneto-concentrating effects are studied experimentally in p-type indium antimonide. Strong magnetic tuning by the current is observed—limited by "ohmic" contact exclusion—during enrichment and the generation of current oscillations during depletion.

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It is generally assumed that Welker's magneto-concentrating effect (MCE)[1] and similar bipolar anisotropic effects (see reviews[2,3]) that occur during thermal generation of current carriers are most prominent in intrinsic semiconductors. This holds only at near-identical values of the electron μ_n and hole μ_p mobilities; when the latter are substantially unequal, the above effects may also be significant in unnatural semiconductors. For example, at $b=\mu_n/\mu_p \gg 1$—a condition common to many materials—

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these effects are prominent over a wide range of equilibrium concentrations of electrons n_0 and holes p_0 expressed by the following inequalities

$$b n_0 \gtrsim p_0 \gtrsim n_0 , \tag{1}$$

moreover, the optimum—in a certain sense—in fact occurs in a strongly unnatural case when $p_0 \approx bn_0 \gg n_0$. (A similar situation also arises in a material with near-identical values of μ_n and μ_p in which due to deep-level capture it is possible to have, for example, $b_{\text{eff}} = \mu_n \tau_n / \mu_p \tau_p \gg 1$, where $\tau_{n,p}$ are lifetimes of electrons and holes, respectively; b_{eff} plays the role of an effective mobility ratio[4]).

This paper deals with the experimental study of MCE in p-type indium antimonide with an excess concentration of acceptors $p_0 - n_0 = N = (2\text{–}7)\times 10^{14}$ cm^{-3} at temperatures of 100–230 K. Volt-ampere characteristics (VAC) were measured in thin plates with the thickness of the order of the diffusion length in the transverse magnetic fields H applied in the plane of a plate, in the pulsed mode ($\tau_{\text{pul}} = 2\times 10^{-6}$ sec$\gg \tau_n \simeq \tau_p = \tau$) Plate processing of opposing surfaces was accomplished in several ways: mechanical, which results in a higher reconstruction rate $S^- > 10^5$ cm/sec, and chemical etching, which yields $S^+ \sim 10^3$ cm/sec in the low-temperature range of measurements. The cross section of the test specimen was 0.005×0.1 cm^2.

In addition to the identification of effects under these conditions, we also paid attention to two circumstances. First, unlike an intrinsic semiconductor, a bipolar drift in the longitudinal field E_x takes place in an unnatural semiconductor, such that any deviation from equilibrium is accompanied by deep-drawing secondary contact enrichment or depletion which must be eliminated. Second, as shown theoretically,[4] in the unnatural case—within the range of Eq. (1)—upon fulfillment of appropriate conditions (one of which is homogeneity of current direction) there occur sections of N-type negative differential resistance (N-NDR) with which Gunn-type current oscillations may be associated. Qualitatively, the occurrence of N-NDR follows from an expression for the transverse carrier drift fluxes:

$$j_{py} = j_{ny} = a E_x \frac{\mu_p \mu_n p n}{\mu_n n + \mu_p p} , \tag{2}$$

where n and p are electron and hole concentrations, respectively, and $a = \mu_{yx}^{(n)}/\mu_{yy}^{(n)} - \mu_{yx}^{(p)}/\mu_{yy}^{(p)}$ is the anisotropy parameter,[2] moreover $\mu_{np} = \mu_{yy}^{(np)}$. For high fields E_x, fluxes [Eq. (2)] are on the average equal to carrier generation fluxes and are independent of n and p. At $n = p$, Eq. (2) indicates that $n \approx C/E_x$, where C in a certain constant, and the longitudinal current j_x proportional to nE_x is saturated. However, if $bn \gg p \gg n$, according to Eq. (2), $p \approx C/E_x$, such that $n \approx (C/E_x) - N$, and the current proportional to $nE_x = C - NE_x$, decreases.

The experiment showed a strong temperature dependence of VAC on the magnetic field. Figure 1 shows a plot of the current ratio I_H^+ with the magnetic field and without I_0 as a function of temperature (the index x denotes the linear branch of VAC: the magnetic field bends the carriers toward a surface with small $S = S^+$). The sharp maximum at $T = 160$ K may be readily explained in terms of a simple formula for

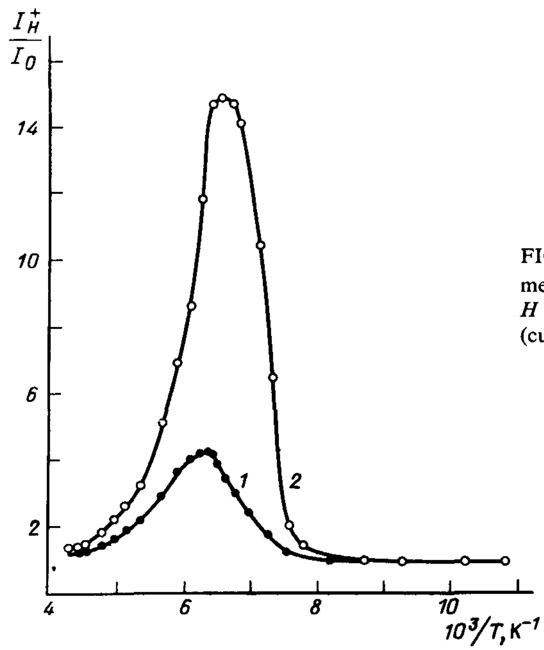

FIG. 1. Dependence of ratio I_H^+/I_0 on T in specimen with length $l = 0.78$ cm, $N = 7\times10^4$ cm^{-3} at $H = 0.3$ kOe and $V = 35$ V (curve 1) and 80 V (curve 2).

$S^+ = 0$, $S^- = \infty$. If the temperature dependence of all parameters except p_0 and n_0 is neglected, the shape of the curve in Fig.1 is expressed by the following fraction

$$\mu_n\mu_p p_0 n_0/(\mu_n n_0 + \mu_p p_0)^2,$$

which peaks at $p_0/n_0 = b$. Based on data in Fig. 1 we find $b \approx 35$, a result which is

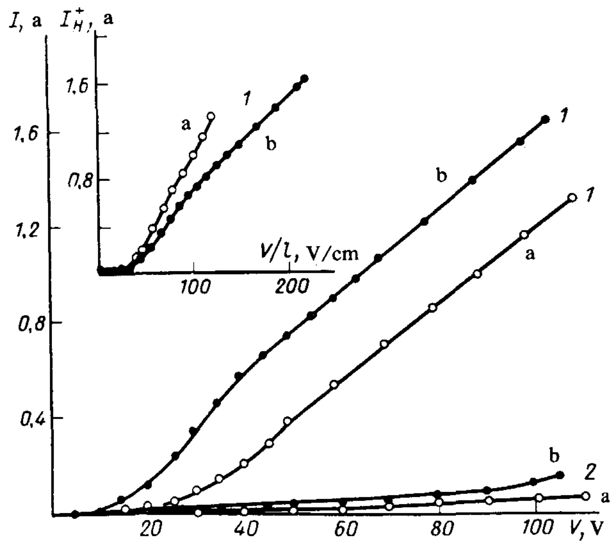

FIG. 2. VAC of two p-InSb specimen with $N = 7\times10^{14}$ cm^{-3}, $l = 0.78$ cm (curves a) and 0.4 (curves b) at $T = 160$ K and $H = 0.5$ kOe (curves 1) and 0 (curves 2).

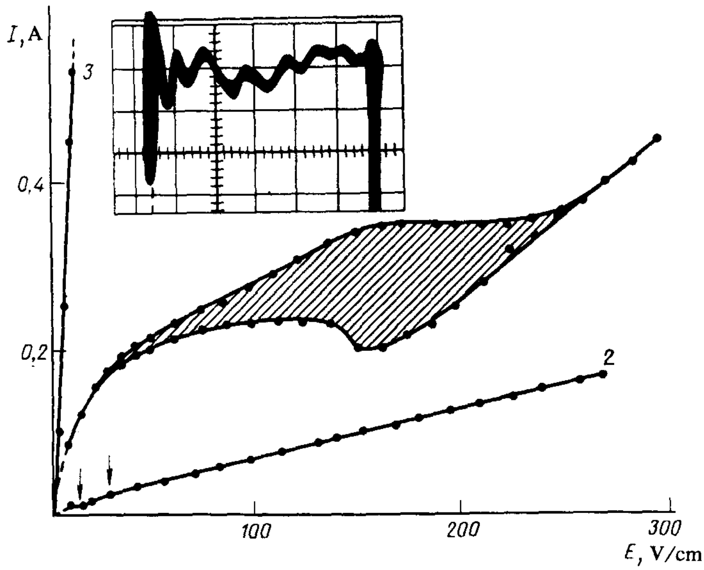

FIG. 3. Curve 1—p-InSb, $N = 7 \times 10^{14}$ cm^{-3}, $T = 215$ K, $H = 1.5$ kOe; region of oscillations cross-hatched. Curve 2—n-InSb, $N = 2 \times 10^{14}$ cm^{-3}, $T = 205$ K, $H = 9$ kOe; arrows indicate boundaries of oscillations region. Curve 3—same specimen as in curve 1 at $H = 0$; a—oscillogram of current oscillations in p-InSb specimen at $E_x = 150$ V/cm; horizontal scale 1 cm—10^{-8} sec.

acceptable considering the insufficient accuracy of temperature measurement and our knowledge of intrinsic concentration $n_i(T)$.

Of the two curves in Fig. 1, the first corresponds to that section of VAC for which $I_H^+ \sim V^2$ following the theory for $S^+ = 0$, $S^- = \infty$ and $\tau = \text{const}$, and the second corresponds to a linear slope section. To refine the nature of these sections and, also, to confirm that we are dealing with MCE involving intrinsic and not injected carriers, we measured VAC of two specimens of different length; these are shown in Fig. 2 in two different scales. At small voltages, field dependent currents in the specimen coincide which affirms the "intrinsic" origin of MCE. At high voltages field functions diverge, while the slopes of currents as a function of the total voltage coincide. This completely rules out an injection origin for VACs: the curve behavior at high voltages affirms the local depletion (clearly, contact exclusion) which limits current growth in the linear branch.

To identify N-NDR we measured VACs of the same specimen at higher temperatures, where $n_0 \approx N$. Figure 3 (curve 1) shows the reverse branch of VAC (bending of carriers toward a surface with high $S = S^-$) at $T \approx 215$ K where $n_0 \simeq 1.2 \times 10^{15}$ cm^{-3}. Statistical VAC may not be measured over a wide range of voltages due to the appearance of current oscillations [Fig. 3(a)]. The upper and lower current values read off the CRT screen are plotted in Fig. 3. To show a correspondence between the observed oscillations and theoretical predictions of N-NDR, we measured the field H and temperature T dependence of I_H^-. Disruption of the oscillations was observed outside the range of magnetic fields $H = 0.7$–3 kOe ($T = 215$ K) and outside the temperature interval $T = 195$–230 K ($H = 1.3$ kOe) which is in a qualitative agreement with theoretical values.

Growth in the magnetic field due to electron magnetization causes a sharp decrease in $b(H)$ which at $H \approx 3.5$–4 kOe becomes less than 1. Moreover, N-NDR should be expected in n-type rather than p-type material. Measurements carried out in n-type InSb have also identified portions of VAC perturbed by oscillations (Fig. 3 curve 2) with amplitudes and voltage duration considerably smaller than in p-type specimen. It is conceivable that VAC with N-NDR predicted by theory[4] is the cause of instability of a state that is homogeneous in the direction of the current, and leads to the observed oscillations.

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