Current-voltage characteristic during extrinsic breakdown in the semimagnetic semiconductor p-Mn$_x$Hg$_{1-x}$Te

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A mechanism is proposed for the occurrence of the S-shaped current-voltage characteristic which has been observed in p-Mn$_x$Hg$_{1-x}$Te. The mechanism involves the development of a nonequilibrium carrier distribution in an impurity band during impact ionization.

Research on the low-temperature conductivity of compensated semiconductors in strong electric fields E indicates that this conductivity is very sensitive to a number of parameters which characterize the hopping charge transport: the degree of compensation K, the width of the impurity band ($\Delta\epsilon$), and the impurity activation energy ϵ_1. In particular, our measurements of the current-voltage characteristics of p-Mn$_x$Hg$_{1-x}$Te ($x \approx 0.1$–0.2) in strong fields E at liquid-helium temperatures revealed that the characteristics of several samples had a region of a negative differential resistance during impact ionization. For the samples of this type, there was a pronounced broadening of the impurity band ($\Delta\epsilon \approx \epsilon_1$ at $K \approx 0.4$). On the other hand, it was possible to distinguish a group of samples with similar values $K \approx 0.4$ but with $\Delta\epsilon \ll \epsilon_1$ for which the characteristic was vertical (Fig. 1) during breakdown.

Analysis of the existing mechanisms[1,2] for the onset of S-shaped current-voltage characteristics along with the particular parameter values found for the samples fails to explain the entire set of experimental results. We accordingly suggest the consideration of a new model, which is based on the possibility of a heating of not only free carriers but also carriers localized at impurity centers by the external electric field.

For a quantitative description of the model, we introduce some simplifying assumptions. We approximate the function $g(\epsilon_i)$, i.e., the density of impurity states, by the constant value $g = N_i/\Delta\epsilon$ in the energy interval $\bar{\epsilon} - \Delta\epsilon/2 < \epsilon_i < \bar{\epsilon} + \Delta\epsilon/2$ and by zero outside this interval ($\bar{\epsilon}$ is the average energy of the impurity levels) (Fig. 2). We describe the nonequilibrium distribution of free carriers and of those localized at impurity centers by standard functions with the temperatures T_c and T_i, respectively. At voltages below the breakdown level ($n_c/n_i \to 0$, where n_c and n_i are the densities of free and localized carriers), the temperature T_i of the localized carriers, which partially fill the impurity band (to an energy $\epsilon_F < \bar{\epsilon} + \Delta\epsilon/2$), is close to the lattice temperature T_L ($T_L \ll \Delta\epsilon$). As a result, the impact ionization is determined by the energy threshold $\epsilon' = \epsilon_b - \epsilon_F$ (ϵ_b is the bottom of the conduction band or the top of the valence band), which corresponds to the breakdown voltage $E_{\rm br}^{(1)}$. In the case $n_c/n_i \to \infty$ the temperature T_i, which corresponds to the carrier distribution among impurity states, approaches T_m, which may even be higher than the temperature of the heated carriers, T_c. The minimum ionization energy tends toward $\epsilon'' = \epsilon_b - (\bar{\epsilon} + \Delta\epsilon/2) < \epsilon'$, which corresponds to a breakdown field $E_{\rm br}^{(2)} < E_{\rm br}^{(1)}$.

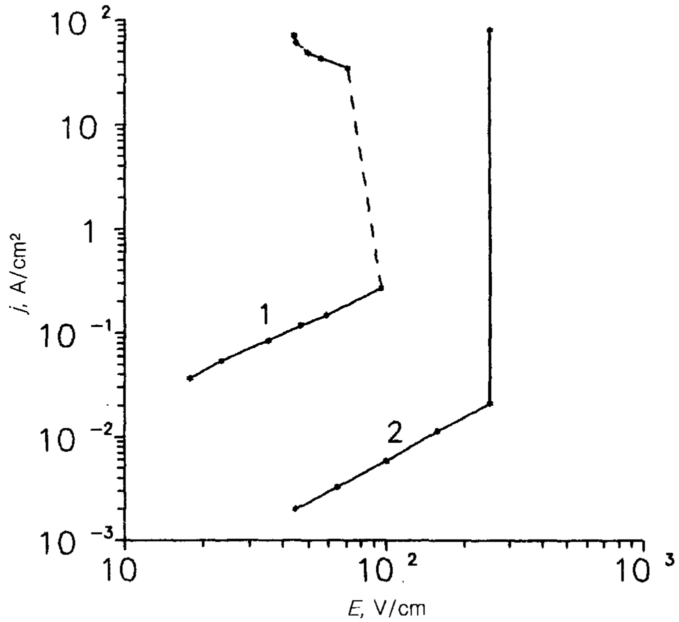

FIG. 1. Current-voltage characteristics of samples of (1) p-$Mn_{0.118}Hg_{0.882}Te$ and (2) p-$Mn_{0.147}Hg_{0.853}Te$.

The simplest functional dependence for T_i which satisfies the requirements listed above is a linear combination of T_c and T_L (analysis shows that a refinement of this approximation has no substantial effect on the results):

$$T_i = \frac{rn_cT_c + [(1-r)n_c + n_i]T_L}{n_c + n_i}, \tag{1}$$

where $r = T_m/T_c \approx 1$ (this is an adjustable parameter of the model).

In our approximation for the density of impurity states, the equation for the chemical potential of the impurity system, μ_i, has the analytic solution

$$\exp\left(\frac{\bar{\epsilon} - \mu_i}{T_i}\right) = \frac{\exp\left(\frac{\Delta\epsilon(1-n_i/N_i)}{T_i}\right) - 1}{\exp(\Delta\epsilon/2T_i) - \exp\left(\frac{\Delta\epsilon(1/2-n_i/N_i)}{T_i}\right)}. \tag{2}$$

We can find the equation that we need, which implicitly relates n_c and T_c, by substituting (1) and (2) into the balance equation for the impact excitation (with a cross section σ_i) of n_i localized carriers and for the trapping (with a cross section σ_t) at $N_i - n_i$ ionized impurity centers (N_i is their total density). For the steady state ($\dot{n}_c = 0$), the equation becomes

$$\int g(\epsilon_i)\frac{n_c\bar{v}\sigma_i(\epsilon_i)}{\exp\left(\frac{(\epsilon_i-\mu_i)}{T_i}\right)+1}\exp-\left(\frac{\epsilon_c-\epsilon_i}{T_c}\right)d\epsilon_i - n_c(N_i - n_i)\bar{v}\sigma_t = 0. \tag{3}$$

To deal with thermal activation, we should introduce a corresponding collision integral I_{ph} on the left side of Eq. (3). Figure 3a shows the results of a solution of (3).

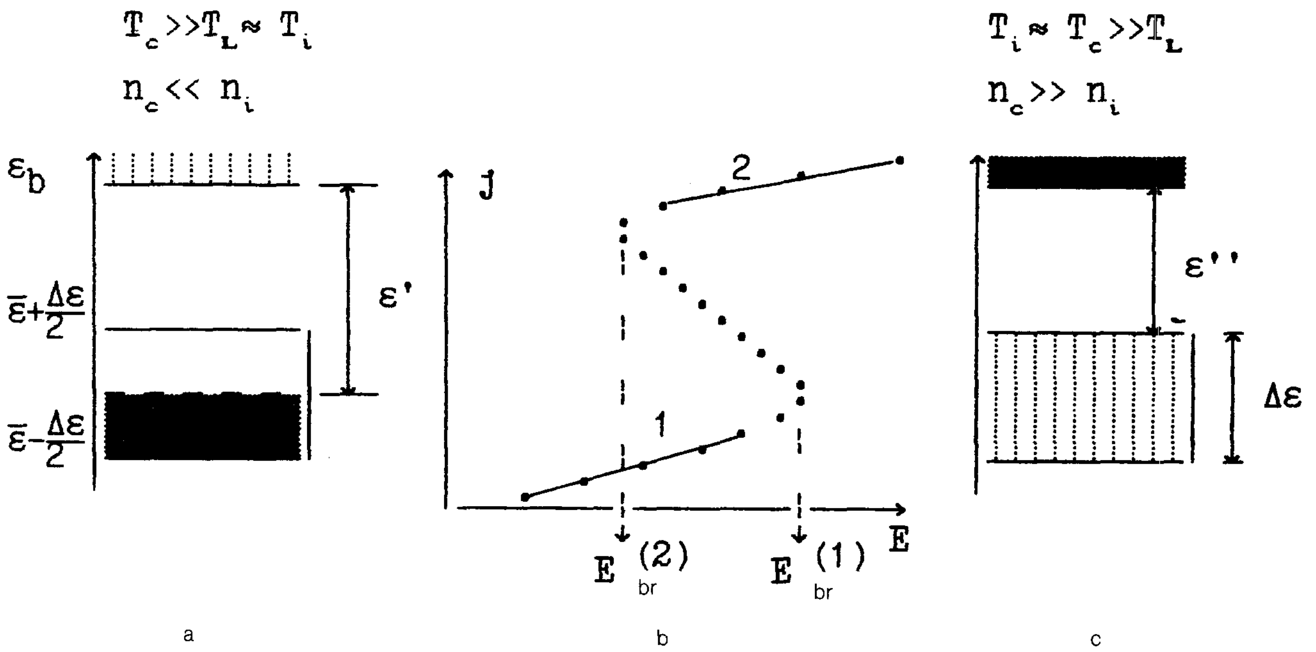

FIG. 2. a,c—Scheme of impurity and band states in the cases $T_i \approx T_L \ll T_c$ and $T_i \approx T_c \gg T_L$, respectively; b—current-voltage characteristic, on which regions 1 and 2 correspond to cases a and c.

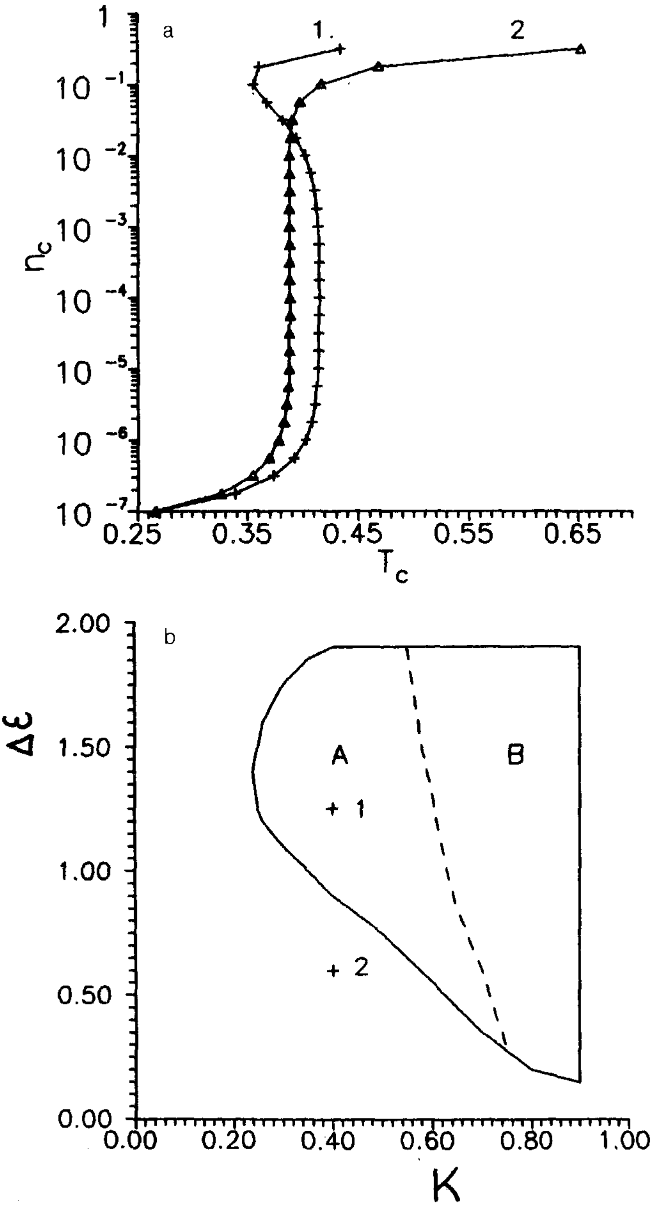

FIG. 3. a—Calculations of $n_c(T_c)$ for (1) $\Delta\epsilon = 1.25$ and $K = 0.4$ and (2) $\Delta\epsilon = 0.6$ and $K = 0.4$; b—diagram showing the boundary of the region in which an S-shaped characteristic exists at $T_c < 1$ (region A) and $T_c > 1$ (region B). The plus signs show the positions of samples 1 and 2.

In these calculations we assumed $k_B = 1$, and we normalized all the energy parameters by dividing them by ϵ_1.

If T_c is determined unambiguously by the external electric field E, so that this functional dependence can be approximated by a linear function in a comparatively narrow region near the breakdown field, the functional dependence $n_c = n_c(T_c)$ essentially reflects the current-voltage characteristic of this system. An important aspect of these solutions is that the function $n_c = n_c(T_c)$ is multivalued only in the case of large fluctuations ($\sim \Delta\epsilon$) and a sufficiently strong compensation (Fig. 3b); i.e., only in this case does the current control the generation rate.

In summary, the amplification of fluctuations in the energy of shallow impurity centers which stem from (for example) fluctuations in the composition of the semiconducting solid solution (as in the case of p-$\mathrm{Mn}_x\mathrm{Hg}_{1-x}\mathrm{Te}$, which we are considering here), promotes the formation of an S-shaped current-voltage characteristic.

This model applies to a long list of semiconductors in which fluctuations in the energy of impurity levels (associated with fluctuations in the concentration of the magnetic component in semimagnetic semiconductors, in the Coulomb interaction between impurity centers, etc.) can be described by a distribution function $g(\epsilon_i)$ with a width $\Delta\epsilon$ which is comparable to the ionization energy ϵ_1.

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