# Metal-insulator transition in gallium antimonide caused by the disordering of the crystal structure

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The metal-insulator transition in a system consisting of a single-crystalline and amorphous GaSb is studied as the content of the amorphous phase increases gradually. At $T \lesssim 10$ K the metal-insulator transition is accompanied by a decrease in the conductivity by a factor of $10^9$ and its behavior is in qualitative agreement with the scaling theory.

**1.** A procedure for synthesizing amorphous bulk samples of gallium antimonide was recently developed.[1] This procedure involves a rapid hardening of the melt under a high pressure. Samples comprised of a mixture of a single-crystalline phase ($m$-GaSb) and an amorphous phase ($a$-GaSb) can be obtained by changing the initial conditions of the synthesis (the melt temperature and the external pressure) (Fig. 1), and the content of the amorphous phase, $x$, can be smoothly varied over a wide range $0 \leqslant x \leqslant 1$.

This situation raises the possibility of studying the gradual transition from the ordered single-crystalline state to the amorphous state as another version of the metal-insulator transition, since at low temperatures the amorphous phase has generally a

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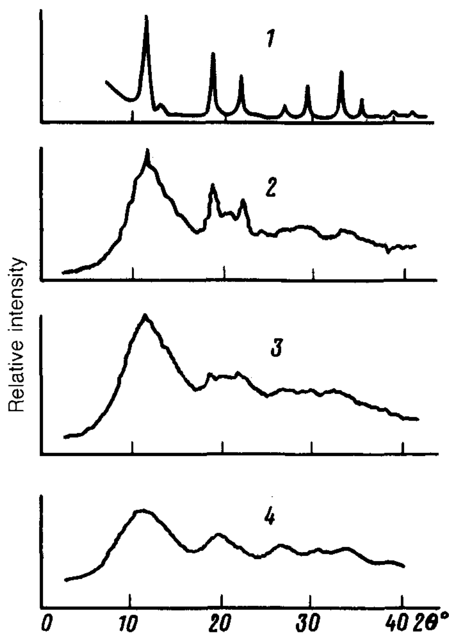


FIG. 1. Transformation of the Debye diagrams upon increase in the content $x$ of the amorphous phase. 1—$x = 0$ (single crystal); 2—$x = 0.36$; 3—$x = 0.7$; 4—$x = 1$ (amorphous sample).

considerably lower conductivity than a single crystal. Analysis of the localization of the electronic states is simplified considerably because of the bulk nature of the ($a$-GaSb)$_x$ ($m$-GaSb)$_{1-x}$ samples.[2]

In the physics of semiconducting glasses the metal-insulator transition caused by changing the content of the amorphous phase has so far, to the best of our knowledge, not been studied experimentally. In this letter we study the feasibility of such an experiment. To render a sample amorphous, we used as starting samples the $n$-type GaSb single crystals with $n \sim 10^{18}$ cm$^{-3}$.

**2.** An accurate determination of the order parameter, which in our case is the amorphous phase, is important in the study of the metal-insulator transition. Estimates based on the use of the data obtained in the study of Raman spectra[1] and x-ray photographs (see Ref. 1 and Fig. 1) have shown that the size of the regions of crystalline order is $\sim 100$ Å even for samples with $x \sim 0.6$–$0.8$. Furthermore, it was found that the densities of single-crystalline and amorphous GaSb are the same. The parameter $x$ is therefore proportional to the heat of crystallization, which is reduced to unit mass of the sample. To determine $x$ quantitatively, we have calculated the heat of crystallization from the area of the exothermic peak on the thermograms of the samples which were recorded with a scanning DSM-2M microcalorimeter (Fig. 2).

**3.** An increase in $x$ of the system ($a$-GaSb)$_x$ ($m$-GaSb)$_{1-x}$ causes a substantial change in the low-temperature asymptotic behavior of the temperature dependence of the resistivity $\rho(T)$ (Fig. 3): a quasimetallic behavior of $\rho(T) \approx$ const (curves 1–6) gives way to a semiconducting behavior (curves 7 and 8). At $T \lesssim 10$ K the value of $\rho$ increases by a factor of $\sim 10^9$ in this case. Such a change in the $\rho(T)$ curves is characteristic for a metal-insulator transition in a Fermi glass.[2] Assuming that the conductiv-

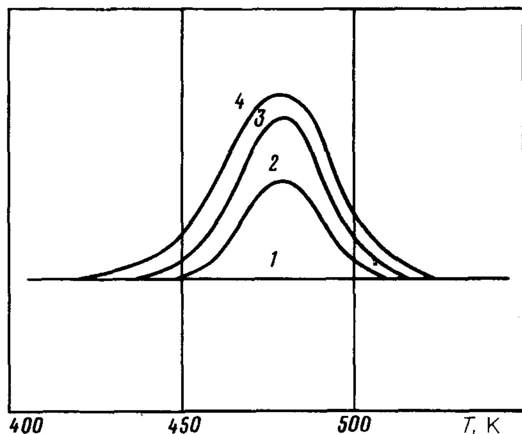


FIG. 2. Thermograms of the samples with different contents of the amorphous phase. The values of $x$ for curves 1–4 are the same as in Fig. 1.

ity $\sigma(x)$, which corresponds to the $\rho(T) \approx$const part of the curve, vanishes in accordance with

$$\sigma(x) = \sigma_0(1 - x/x_c)^t, \tag{1}$$

we can determine the critical concentration $x_c$ and the exponent $t$ (see the inset in Fig.

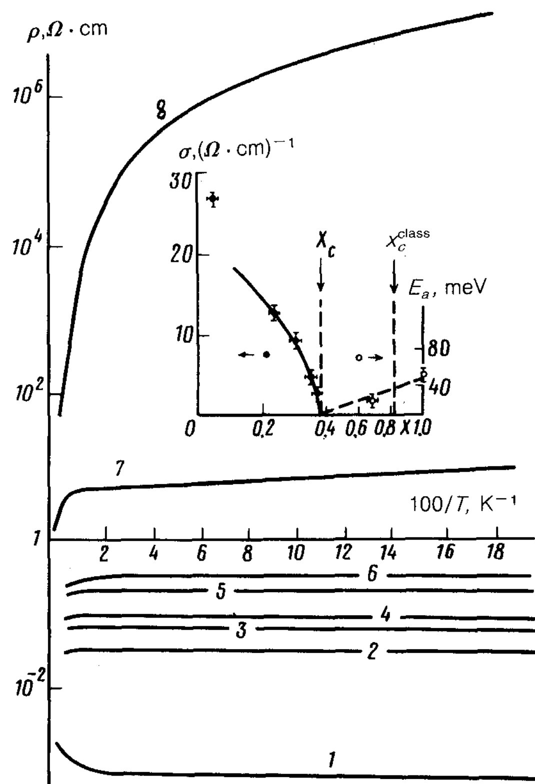


FIG. 3. Temperature dependences of the resistivity for different values of $x$. 1—$x = 0$;2—$x = 0.05$; 3—$x = 0.24$; 4—$x = 0.31$; 5—$x = 0.34$; 6—$x = 0.36$; 7—$x = 0.7$; 8—$x = 1$. The solid curve in the inset corresponds to curve 1 with the parameters $x_c = 0.37$, $t = 0.6$, and $\sigma_0 = 23$ $(\Omega \cdot \mathrm{cm})^{-1}$.

3). We estimated $x_c$ to be $\sim 0.37$ and the exponent $t$ to be $\sim 0.6$. On the insulator side of the transition, $x > x_c$, the activation energy $E_a$ for functions of the type $\ln\rho \sim E_a / k_B T$, which are seen at $T \gtrsim 150$ K, increases with increasing $x$ (see the inset in Fig. 3).

**4.** Interestingly, $x_c \approx 0.37$ is markedly different from the value predicted by the semiclassical theory,[3] in which the metal-insulator transition should occur in a 15–17% conducting phase. Since the conductivities of the metallic and dielectric phases differ by approximately nine orders of magnitude (curves 1 and 8 in Fig. 3) and therefore the system $(a\text{-GaSb})_x (m\text{-GaSb})_{1-x}$ is approximately the same as that analyzed in the theory of percolation of a mixture of a conducting and a nonconducting phase, we find the classical percolation level to be $x_c = x_c^{\text{class}} \approx 0.83$. We see from the inset in Fig. 3 that the conductivity vanishes much sooner than $x_c^{\text{class}}$ and that the experimental value of $t$ is at variance with the semiclassical value, $t \approx 1.5$–$1.7$ (Ref. 3).

The scaling theory in which $t \approx 0.6$–$0.7$ seems to be more suitable for the description of the metal-insulator transition in this system.[2] An increase in the fraction of the metallic phase, which is necessary in order to delocalize the electronic states, also corresponds to a scaling approach and probably stems from quantum effects such as above-the-barrier reflection from a random potential relief.[4]

Both of these results—estimate of the value of the critical exponent and the displacement of the mobility threshold relative to the classical percolation level—are in agreement with the data obtained in the study of the metal-insulator transition in doped semiconductors.[4–7] The values of the critical exponent for silicon[5] and gallium antimonide,[6] for example, were found to be $t = 0.6 \pm 0.1$, while a displacement of the mobility threshold was observed in GaSb⟨Se⟩ (Ref. 4) and $Pb_{1-x}Sn_xTe$ (Ref. 7). We wish to emphasize in this connection that the behavior of the metal-insulator transition in the $(a\text{-GaSb})_x (m\text{-GaSb})_{1-x}$ system does not change, despite the fact that the random potential, which is caused by the disordering of the crystal structure rather than by a random impurity field, as in the case of a doped semiconductor, has a different physical nature.

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