Metal–semiconductor transition along thickness in an amorphous Sb layer

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A metallic state has been produced in a layer of amorphous antimony ~20 nm thick by depositing Sb on an amorphous Bi layer. With a further increase in thickness, the Sb condensate forms in the ordinary semiconducting state. The difference between the conductivities of these two states of the amorphous antimony is approximately six orders of magnitude (at $T=20$ K).

The electrical conductivity σ of amorphous antimony films condensed in ultrahigh vacuum ($\sim 10^{-10}$ Pa) on substrates cooled by liquid helium has been studied. The method for growing the films and the method for studying them are described in Ref. 1. Only a semiconducting state (a Fermi-glass state[2]) of amorphous antimony has been seen previously. This state is realized (for example) when glass substrates are used. Figure 1a shows the conductivity of an amorphous Sb film ~70 nm thick, condensed on a glass substrate, versus the temperature T. This behavior can be described by $\log \sigma = A - BT^{-1/4}$, where A and B are constants, and σ is expressed in S/cm. This behavior is similar to that which had been found previously[3] for amorphous antimony. It indicates that the electron states at the Fermi level are localized in this case and that the conductivity at low temperatures ($T<100$ K) results from thermally activated jumps of electrons from one localized state to another.[2]

In the present study we found that in addition to the semiconducting state (a-Sb) it is possible to realize a metallic state (a_m-Sb) in amorphous Sb condensates. The metallic state arises when Sb is condensed on an amorphous film of bismuth. In this case, the electrical resistance R of the Bi–Sb sandwich is observed to drop sharply as soon as the Sb begins to condense. This decrease slows down as time (t) elapses (at a constant Sb condensation rate). When the thickness of the antimony film is $d_{\mathrm{Sb}} \simeq 20$ nm, the change in R comes to a halt; i.e., the $R(t)$ curve becomes a horizontal straight line. Calculations based on the experimental $R(t)$ dependence show that an Sb layer ~4 nm thick bordering the amorphous Bi film has a resistivity $\rho \simeq 2\times 10^{-3}\ \Omega\cdot$cm, which is essentially independent of the thickness. With increasing distance from the bismuth substrate, the resistivity increases sharply layer by layer (at intervals of 2 nm, for example), reaching the value[1)] $\rho \simeq 3\times 10^{-2}\ \Omega\cdot$cm at an Sb condensate thickness ~16 nm. At $d_{\mathrm{Sb}} > 20$ nm, the surface layer of Sb forms in a semiconducting state instead. The average value of ρ for an a_m-Sb layer ~20 nm thick at $T=20$ K is ~ $(6 \pm 0.5)\times 10^{-3}\ \Omega\cdot$cm, about six orders of magnitude smaller than ρ for an a-Sb. The temperature dependence (at $T<70$ K) of the conductivity of this layer is linear: $\sigma = A_1 + B_1 T$ (A_1 and B_1 are constants; Fig. 1b), possibly because of quantum interference.[4,5]

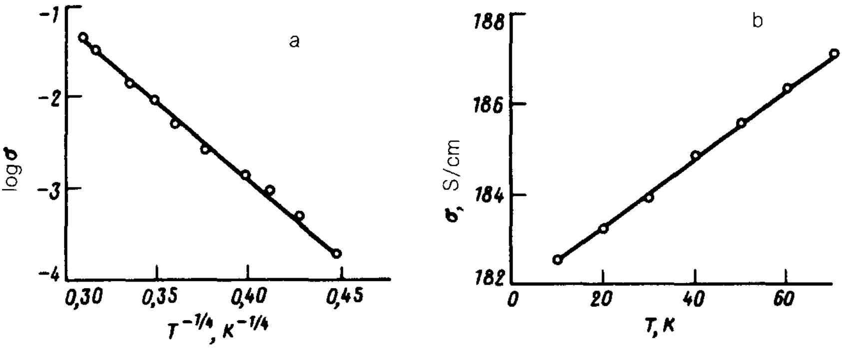

FIG. 1.

We studied about twenty amorphous Bi–Sb sandwiches with $d_{\mathrm{Bi}}=3$–30 nm and $d_{\mathrm{Sb}}=9$–150 nm. The results were completely reproducible and independent of the thickness of the amorphous Bi layer. The superconducting transition temperature T_c of an amorphous Bi film ~ 3 nm thick decreases very slightly, from 3.99 to 3.96 K, after an Sb layer > 20 nm thick is condensed on it. Such a small change in T_c of the extremely thin Bi film is evidence that bismuth does not mix with the antimony at the interface. In amorphous Bi–Sb alloys, T_c falls off sharply, and ρ increases with increasing Sb concentration.[6] We found no indications of this behavior in the present study.

Figure 2 shows the behavior of the resistance of a Bi–Sb sandwich ($d_{\mathrm{Bi}} \simeq 3$ nm, $d_{\mathrm{Sb}} \simeq 21$ nm) as it is heated to room temperature at a rate of ~2 K/min. It has been shown previously by electron diffraction[7] that sharp changes in the resistance during the heating of amorphous Bi or Sb layers, like those in Fig. 2, correspond to a crystallization of these layers. We thus conclude that the increase in R at $T=90$–110 K stems from the crystallization of a thin (~3-nm) layer of Bi. This conclusion is supported, in particular, by the loss of superconductivity of the layer after the sandwich is heated to $T\sim 110$ K. The decrease in the resistance at $T=210$ K stems from the crystallization of the amorphous Sb layer: At $T>210$ K, the value of ρ for this layer corresponds to the value of ρ for crystalline Sb films.[3,7]

The value of ρ for a_m-Sb layers corresponds to the minimum metallic conductivity in the Mott expression[2]

$$\sigma_{\min} \simeq 0.026 \frac{e^2}{\hbar a}, \tag{1}$$

where e is the electron charge, $\hbar$ is Planck's constant divided by 2π, and a is the distance between atoms. With $a=0.3$ nm we find $\sigma_{\min} \simeq 200$ S/cm from (1). For a_m-Sb, an extrapolation of the $\sigma(T)$ line to $T=0$ yields a nonzero conductivity (Fig. 1b). According to the Mott criteria,[2] the a_m-Sb layers behave as a metal, in contrast with the semiconducting behavior of a-Sb layers, for which we find $\rho \to \infty$ as $T \to 0$.

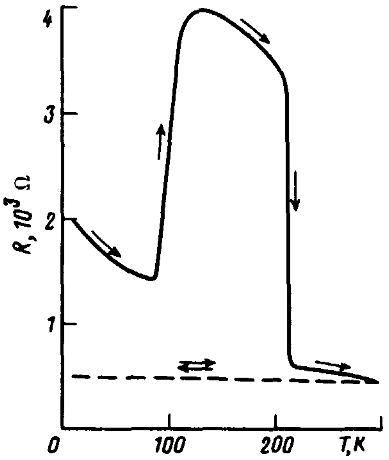

FIG. 2.

According to Ref. 2, a minimal metallic conductivity corresponds to the state of the electrons just before the onset of localization, i.e., as the Fermi level E_F approaches the mobility threshold E_c from the side of delocalized states. This state, with $E_F > E_c$, is apparently realized in a_m-Sb, in contrast with a-Sb, for which we have $E_F < E_c$. The reason for this behavior might be (for example) a difference between the short-range order in the arrangement of a-Sb atoms and that of a_m-Sb atoms.

When Sb condenses on a layer of amorphous Bi, the latter imposes its own short-range order on the Sb condensate (in accordance with the nature of pseudomorphism).[8] This bismuth-like short-range order is apparently responsible for the increase in the electron density (and in E_F) in amorphous Sb. Evidence for this suggestion comes from the fact that liquid Sb, whose short-range characteristics are approximately the same in magnitude as those of amorphous Bi,[9] is a typical metal. With increasing thickness of the Sb condensate, the orienting effect of the bismuth substrate on the structure of the Sb surface layer weakens,[2)] and at $d_{\text{Sb}} > 20$ nm amorphous antimony can form in the ordinary semiconducting state.

In addition to the bismuth, we used amorphous and crystalline films of ytterbium 20–30 nm thick for the condensation of Sb. In these cases, only the semiconducting amorphous modification of antimony forms.

[1)] For an upper layer ~2 nm thick.

[2)] We mean the mediated effect through the structure of the underlying layer of antimony.

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