Features of the resistance change in phase transitions in bismuth and gallium films

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An anomalous increase of the electric conductivity of bismuth and gallium films was observed during the initial stages of the "amorphous" Bi→rhombohedral Bi and β-Ga→α-Ga phase transitions. The conductivity peak reaches ∼4% of the electric conductivity of the initial phase.

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It was suggested in[1] that in phase transitions the region of restructuring of the crystal lattice should be characterized by large electron-phonon interaction, i.e., it should have properties that differ significantly from the properties of the initial and of the produced phases. In this paper we report experimental results that seem to indicate that the interphase boundary regions make an appreciable contribution to the character of the change of the resistance in the phase transition. The experiments were performed on bismuth and gallium films prepared at low temperature.

When molecular bismuth beam is deposited on a substrate at liquid-helium temperature, a disordered practically amorphous condensate is produced, having superconductivity with $T_c = 6$ K and a higher conductivity (at $T > T_c$) than crystalline films of rhombohedral bismuth.[2] The relatively high conductivity of low-temperature bismuth films is ensured by the metallic concentration of the electrons in this phase, and the change of resistance with temperature is well described, within the framework of the model of almost free electrons, by the changes of the coordination structure of the "amorphous" metal.[3] Heating to a certain temperature T_L (or else increasing the thickness[4]) produces a phase transition into the rhombohedral modification of bismuth, accompanied by a jumplike increase of the resistance (by 5–10 times). The temperature T_L increases with decreasing film thickness.[2,3]

In low-temperature gallium films, the phase transition accompanying the heating is from the state of the "amorphous" condensate (with $T_c \approx 8.4$ K) to the crystalline phase of β-Ga ($T_c \approx 6$ K), which has a monoclinic lattice, and then into α-Ga ($T_c = 1.1$ K) with orthorhombic lattice. For films of sufficiently large thickness ($L > 1000$ Å) the first of these transitions occurs at ~ 15 K and the second at ~ 60 K.[5,6] In the first phase transition, the resistance decreases jumpwise by a factor 3–4. In the second phase transition (β-Ga → α-Ga) the resistance, just in the case of bismuth films, increases by several times.

The low-temperature bismuth and gallium films were prepared by condensing the metal in a vacuum of ~ 10^{-8} mm Hg on the surface of a polished sapphire plate attached with indium-gallium alloy to a copper block with liquid helium. This system ensured good thermal contact between the film and the cryogenic block. The temperature of the sapphire plate could be varied smoothly by turning on a heater. The film resistance was registered with an x–y potentiometer (with sensitivity $(2-5) \times 10^{-3}$ Ω per millimeter of scale). The x-input was used either for time scanning corresponding to a certain average heating rate of the sample (Figs. 1 and 2) or to record the signal from a semiconductor temperature pickup (Fig. 3).

In the case of relatively rapid heating (average rate faster than 2–3 deg/min), a small dip (conductivity peak) is observed, against the background of the preceding temperature variation of the resistance, in the

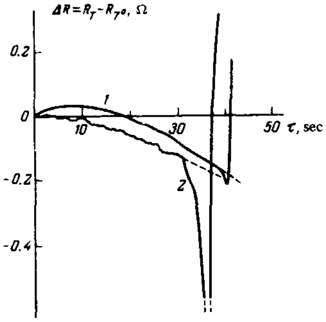

FIG. 1. Change of the resistance of low-temperature bismuth films by heating. Film thickness, Å: 1—415, 2—380. Initial resistance $R_{7°}$ at 7 K (directly after the superconducting transition), Ω: 1—111.4; 2—109.7. Average heating rate 20 deg/min. The phase transition was observed at 25—30 K.

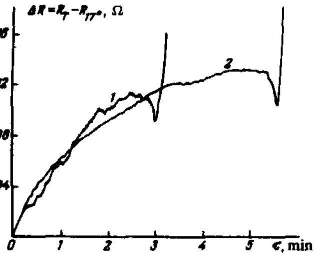

FIG. 2. Plot of the change of the resistance of low-temperature β-gallium films in the course of heating. Film thickness, Å: 1—1200, 2—1300. The initial resistance $R_{17°}$ at 17 K (directly after the phase transition of the "amorphous" gallium into β-Ga), Ω: 1—0.96; 2—0.74. Average heating rate, deg/min: 1—20, 2—11. The phase transition was observed in the region of 67 K.

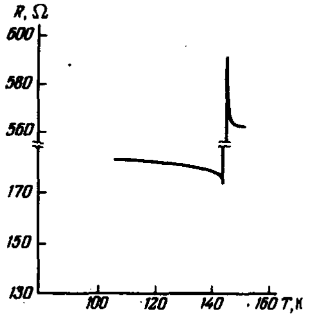

FIG. 3. Plot of the change of the resistance in the region of the β-Ga → α-Ga phase transition as a function of the temperature. Gallium film thickness 60 Å. Heating rate approximately 5 deg/min.

region of the resistance pump in the phase transition from the "amorphous" bismuth to the rhombohedral bismuth. The characteristic value of the dip is on the average ~ 0.05 Ω (curve 1 on Fig. 1). In one case the dip turned out to be so large in comparison with the recording interval that the minimum went off the potentiometer scale (curve 2 of Fig. 1).

A similar dip was observed also near the resistance jump in the phase transition of the monoclinic β-Ga phase into the orthorhombic α-Ga phase (Fig. 2). In contrast to bismuth, the phase transition takes place in this case in crystalline films with a perfect structure (the β- and α-Ga phases in the films have a texture). In addition, for sufficiently thick gallium films, the temperature dependence of the resistance of the β-phase has a metallic character, making the appearance of the dip of the resistance near the phase-transition temperature sufficiently pronounced (Fig. 2). The depth of the resistance dip for gallium films is 0.01–0.03 Ω. The relative change of the resistance in the dip for gallium films reaches 3–4%.

Decreasing the gallium film thickness makes it possible to increase the phase-transition temperature. The resistance dip is preserved when the temperature of the transition is increased to 147 K ($L \approx 60$ Å) and seems to vanish at higher temperature. Measurement of the change of the resistance not only at the start but also at the end of the phase transition has shown that the resistance peak is observed before the resistance reaches the level corresponding the properties of the new phase (Fig. 3). The relative size of the peak can reach 5%.

Special measurements with alternating current duplicate fully the direct-current poles, thus indicating that the observed effects are not the consequence of a possible influence of the change of the thermoelectric power.

The most interesting feature of the presented curves, from our point of view, is the electric-conductivity peak which appears at the start of the phase transition. We note that the electric-conductivity peak cannot be connected with thermal effects that occur in the phase transition, since it is observed at all types of variation of the resistance in the temperature interval preceding the phase transition.

It can be assumed that the appearance of the peak of the electric conductivity is due to the contribution made to the conductivity by the boundary interphase regions with anomalously high conductivity. If it is assumed that the thickness of these regions is several periods of the crystal lattice, then a 3–5% increase of the electric conductivity of the film calls for a conductivity of the boundary regions that is at least one order of magnitude larger than for the initial phase, which is more conducting than the final phase. It was indicated in[1] that superconductivity can appear when the lattice changes as a result of a strong increase of the electron-phonon interaction constant. The onset of real superconductivity in the boundary regions during the phase transition seems unlikely to us, since the superconductivity can be suppressed by the "proximity effect" in the thin interlayer adjacent to the normal phases. This, however, does not exclude the possibility of the appearance of an anomalously high conductivity of interphase regions also in the absence of macroscopic coherence, for example as a result of mechanisms that are analogous to the fluctuation-superconductivity mechanism.

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