Investigation of metastable current states in superconducting Al, Sn, and In films

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The kinetics of superconductivity destruction is investigated in "soft" semiconducting films Al, Sn, and In in the thickness range from 500 to 2800 Å. Variation of the mean free path by changing the film sputtering conditions made it possible to vary to Ginzburg-Landau parameter $\varkappa$ in a wide interval from 0.14 to 400. It was observed that starting with $\varkappa \sim 10$ the metastable resistive current states and the multiple-valuedness of the current-voltage characteristic are observed most distinctly. The analysis has shown that the presence of a small number of edge defects leads to stratification of the film in the course of superconductivity destruction and is, in final analysis, the reason why the current-voltage characteristic is multiply valued.

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1. INTRODUCTION

The destruction of superconductivity in bulky type-I superconductors by a transport current exceeding the critical value J_c' (the pair-braking current) was investigated in many studies.[1] Similar measurements were carried out subsequently also on "hard" type-II superconductors.[2] At the present time particular attention is being paid to the investigation of the resistive state in "one-dimensional" and "two-dimensional" superconductors produced in the form of long thin whiskers, thin films, and foils, since their properties differ substantially from the properties of "bulky" superconductors. Thus, Roderick and Wilson[3] have advanced the hypothesis that the current in thin wide films in the superconducting state is distributed over the width not uniformly but predominantly at the edges. This was experimentally proved in Ref. 4 for type-I superconducting films (the material investigated was Sn) of width $w \gg \xi$ where ξ is the coherence length. Because of this current distribution, the magnetic field associated with the current reaches its critical value primarily on the edges of the film, where local normal regions are produced in the form of seeds of individual rows of magnetic-flux tubes.[5] With increasing current, they begin to move away from the edges and annihilate at the center of the film. The instant when the motion start corresponds to the appearance of a voltage step on the current-voltage characteristic (CVC).[6]

The steplike structure on the CVC is observed also in "one-dimensional" and "two-dimensional" type-I superconductors[7,8] with transverse dimensions smaller than or of the order of the depth of penetration λ of the magnetic field. In these experiments the steplike structure on the CVC is due to the presence of phase slippage centers. The principal distinguishing feature of this mechanism is that the differential resistances are approximately equal for phase-slippage centers in one and the sample sample, and are independent of the temperature, while the phenomenon itself takes place at currents exceeding the pair-breaking current. In investigations of the CVC of microstrips made of hard superconductors of type II (Pb+5 at.% Bi), Huebner and Gallus[9] observed, besides the steplike structure, also a negative differential resistance.

The voltage jumps (up to hundreds of mullivolts) are most strongly pronounced when current flows in quasi-granulated superconductors made of aluminum with $\varkappa = 2.8$,[10,11] where $\varkappa$ is the Ginzburg-Landau parameter. These samples are "soft" type-II superconductors,[12] therefore the voltage jumps were attributed to motion of vortices of opposite sign across the film. The presence of steps on the CVC in a soft type-II superconductor (Nb film 1.5 mm wide made in the form of a short cylinder) was previously observed by London and Clark,[3] who used an induction method of measuring the critical current.

We report here the results of an investigation of resistive current states in soft thin-film superconductors (flat and cylindrical) made of Al, Sn, and In. The investigated films were polycrystalline. The effective mean free path of the electrons l_e varied in a wide range because the films were produced with different crystallite dimensions. Consequently, $\varkappa$ ranged between 0.14 and 400. This made it possible to regard samples made of one and the same material, depending on the value of $\varkappa$, as type-I, or type-II superconductors. Using several potential leads placed along the investigated films, it was established that when the films carry current they are in a nonequilibrium state. This state consists of a partial (local) destruction of the superconductivity in only individual locations in the film. The obtained theoretical temperature dependence of the critical current, on the basis of the local theory, agrees well with the experimental value. An effect of dissipation on the form of the CVC was observed.

2. EXPERIMENT

A. Preparation of samples

Flat film samples of Al, Sn, and In, with widths w from 4×10^{-2} to 5×10^{-1} cm, lengths L from 1.0 to 2.0

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cm, and thicknesses d from 500 to 2800 Å were evaporated on cover-glass substrates. Thin-wall cylindrical films of 1.5 mm diameter, 1.5 cm length and ~1000 Å thickness were evaporated on glass rods. The sample thickness was measured by three methods: 1) with a microinterferometer of type MII-4, 2) by measuring the electric resistance of the film in the course of sputtering, 3) by measuring the electric resistance of the films when cooled from room temperature to heating temperature, using the formula[14]

$$d=(L/w)(d\rho/dT)/(dR/dT),$$

where $d\rho/dT$ is the temperature coefficient of the resistivity and dR/dT is the observed change of the electric resistance of the sample with temperature. The same formula was used to estimate film thicknesses lower than 500 Å. The material for the sputtering had a purity 99.999%. The substrate temperature at sputtering was 77 K. The rate of sputtering was 5–10 Å/sec. The vacuum during sputtering was maintained constant between 1×10^{-5} and 5×10^{-6} Torr under various sputtering conditions. The samples, while in the vacuum sputtering chamber, were heated immediately after the sputtering at a rate of 10 K/min to a temperature 300–372 K. The resistance of the freshly deposited Al, Sn, and In films decreased when heated from 77 K, passed through a minimum at ~200 K, and then assumed the shape of a saturation curve (see also Ref. 15). After the heating, commercially pure O_2 was fed into the sputtering chamber and a high voltage gas discharge was turned on. The aluminum was sputtered from a tungsten wire, while Sn and In were sputtered from a tungsten basket coated with Al_2O_3, i.e., the sample of production technology was similar to that used to prepare granulated film semiconductors by Abeles.[16] Pettit and Silcox[17] investigated in detail films produced by this technology, and established (see also Ref. 12) that each crystallite in such a film is surrounded by an oxide layer.

At different sputtering rates and at different residual air-pressures in the vacuum chamber, different crystallite dimensions were obtained, as well as different values of the resistivity of the films ρ_n in the normal state. In the superconducting state the films had a small bulk pinning force (see also Refs. 18 and 19). The pinning force was influence by the amount of oxygen introduced into the film in the course of sputtering, which varied with the residual air pressure (actually O_2 pressure) in the vacuum chamber during the time of sputtering and during the subsequent oxidation in the gas discharge. The presence of oxygen during the sputtering time had a stronger influence on the electric and superconducting properties of Al films than on films of Sn and In.

Microphotographs obtained with an electron microscope for Al, Sn and In films, revealed a tendency of the critical temperature T_c to increase with decreasing crystallite dimensions. Electron-diffraction measurements have established that all films are polycrystalline and structureless. No additional rings corresponding to impurities were recorded on the electron diffraction patterns.

B. Measurements of the CVC and of the critical parameters, and the cryogenic equipment

The resistive current states of superconducting Al, Sn, and In films was investigated by measuring their CVC by a four-probe method using a dc source. The internal resistance of the source was much higher than that of the superconducting films in the resistive state.

The value of T_c was determined by two methods: 1) extrapolation of the $J_c(T)$ curve from the temperature $T < T_c$ at which no contributions are made as yet to the current by the fluctuation pairing, 2) from the plot of the fluctuation resistance against the temperature in the region $T > T_c$.[20] Both methods of determining T_c yielded comparable results within the limits of the measurement error.

In the interval $\tau=0.01$–0.1, where $\tau=1-T/T_c$, the experimental value of the critical current $J_c(T)$ correponds to the current at which the first kink appears on the CVC curve. For lower temperatures, the value of $J_c(T)$ was set equal to the current at which the voltage step appears on the CVC. The measurement accuracy was higher when $J_c(T)$ was determined near T_c than far from this temperature, as much as the metastability of the nondissipative state in the region of low temperature gives rise to fluctuation jumps to different resistive parts of the characteristics in a rather large current interval. Consequently, the most probable $J_c(T)$ was determined from a run consisting of 10 plots of the CVC obtained for the same external parameters. The $J_c(T)$ dependence for Al films was investigated in the temperature region from 1.5 to 0.6 K, while for Sn and In films it was determined from 4.2 to 1.5 K. In addition, control measurements were made of the CVC of superconducting Al films situated in superfluid helium, and these measurements demonstrated that the CVC obtained in measurements in ^{3}He at identical temperatures are identical. The edges of some flat films were cut on both sides with the diamond needle of the instrument used to measure the microhardness. This operation did not change substantially the general form of the CVC, but decreased the critical current. For cylindrical thin-wall films, the qualitative appearance of the CVC was the same as for flat ones, but their critical current was higher. The temperature stability for thin CVC at the measurement point was in the range 2×10^{-2} K. On going to larger measuring currents, however, the temperature stabilization was disturbed. We therefore do not consider the region of registered states with large energy dissipation. The temperature was determined with a carbon resistor of the Allen-Bradley type calibrated with an ac bridge in each experiment. During the measurement time the Al films were immersed in liquid ^{3}He and the Sn and In films in liquid ^{4}He. The carbon resistance thermometer was located 4 mm away from the samples and on the same level with them. To exclude the influence of the magnetic field of the earth, of the pumps, etc., the internal metallic dewar with ^{3}He, in which the samples were located, was surrounded by a superconducting layered screen, while the outer helium dewar was surrounded by several layers of transformer iron.

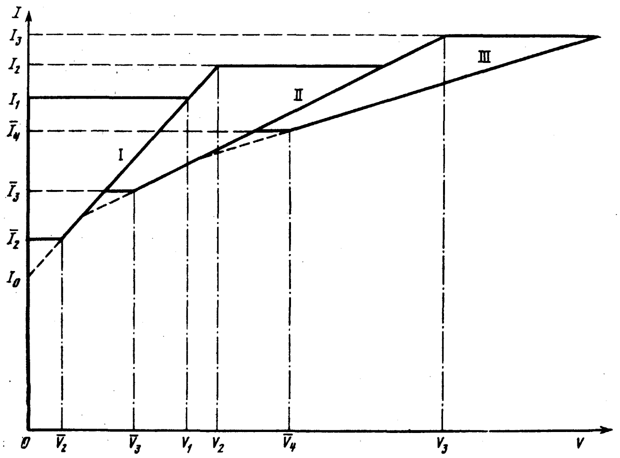

FIG. 1. Typical CVC of films in the resistive state in the presence of MSCS. (The quantity I_1 corresponds to the critical current J_c for concrete samples).

3. RESULTS AND THEIR DISCUSSION

A. Properties of metastable states

The CVC of superconducting Al films from 500 to 2600 Å thick and of Sn and In films 500–2800 Å thick revealed metastable current states (MSCS) similar to those previously obtained for aluminum films 700 Å thick.[11] The current in this case was a multiply valued function of the voltage (see Fig. 1), i.e., at a fixed value of the current the voltage had a number of values corresponding to different energy-dissipation levels. The term "metastable states" is therefore used here not in its thermodynamic meaning but as a reflection of the circumstance that the transition from one branch of the CVC to another is impossible (within the limits of the stability region of the given state) without an external perturbation of finite magnitude.

Figure 2 shows the experimental CVC curves of an In film at $T = 2.6$ K and different energy dissipation levels.[1)] The MSCS are produced in the following manner. A current that increases with time is made to flow through the superconducting film. So long as the film remains in the superconducting state, the operating point moves along the vertical line that coincides with the current axis. When the critical value J_c of the given film is reached, a jumplike transition takes place through the first dissipative state. In Fig. 2 it is marked by the number I. After the first MSCS is reached, further increase of the current produces a jumplike transition to the next curve with a higher dissipation level. It is marked II in Fig. 2. This is followed by a transition to the next curve—III, etc.

Starting with $\tau \sim 0.1$ and higher, hysteresis is observed between the forward and reverse branches of the CVC. The current at which the transition to the preceding dissipative curve takes place is lower than the current at which the voltage step in the forward direction was observed. The hysteresis increases with increasing number of MSCS, as illustrated in Fig. 2.

In the course of the experiment, after multiple passes through one and the same state, it was found that the stability region is located between the points I_n, V_n, and $\bar{I}_n$, $\bar{V}_n$, (see Fig. 1). The outermost points are unstable, and when they are approached a transition to neighboring MSCS can occur somewhat earlier. In the case of strong external perturbations, a jump past one or two neighboring MSCS is also possible. Figure 3 shows a transition from one dissipative state to another under the influence of single random pulses of duration ~ 10^{-6} sec and of amplitude up to 1 mV. It is seen that outside the limits of the stability region on the CVC, when the working point jumps over to a new state, it does not stay there but returns. The virtual jump continues only to the current J_0. At lower currents the superconducting state is stable to this perturbation.

It must be emphasized that the multiply valued char-

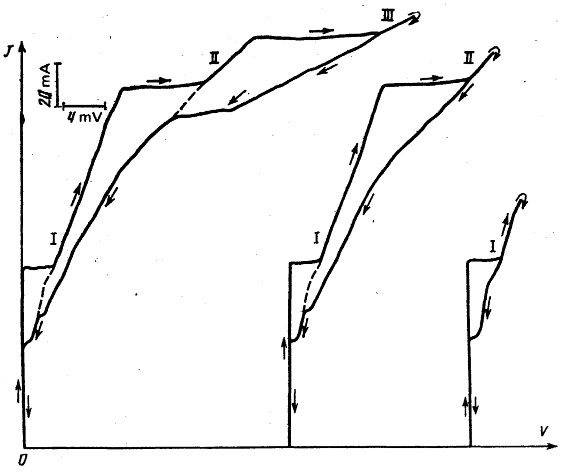

FIG. 2. Variation of the form of the CVC of an In film with changing return current.

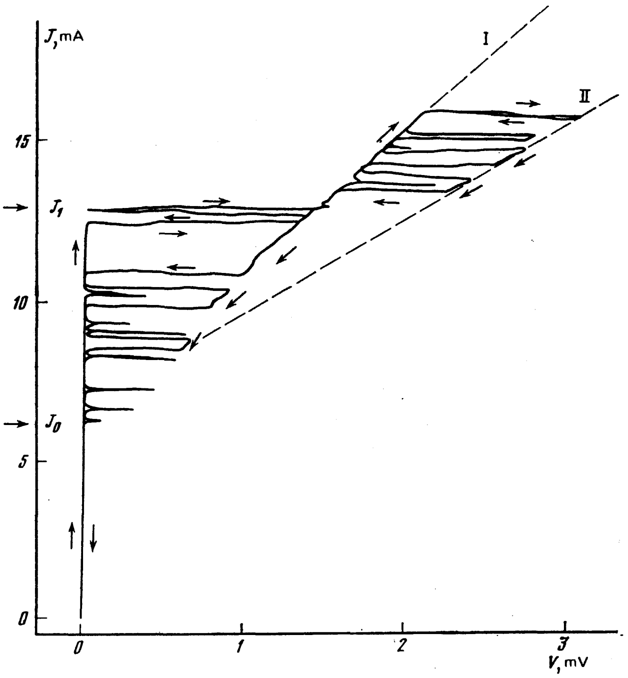

FIG. 3. Form of the CVC of an aluminum film acted upon by single perturbing voltage pulses.

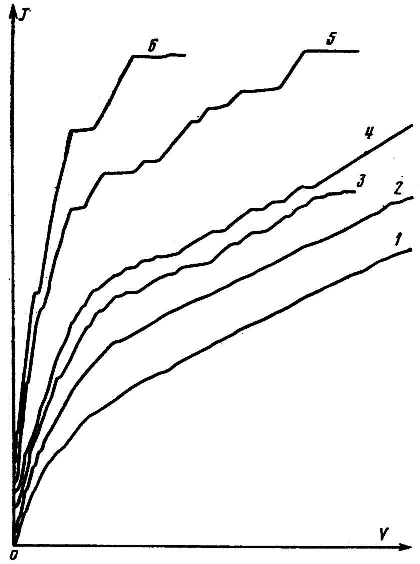

FIG. 4. CVC of an aluminum film near $T_c = 2.03$ K at different τ: -0.03 (1); -0.01 (2); 0.002 (3); 0.005 (4); 0.03 (5); 0.04 (6).

acter of the CVC is most strongly pronounced for samples with sufficiently large $\varkappa \sim 10$ at temperatures noticeably lower than T_c. On the whole, however, the variation of the CVC is the following. At temperatures noticeably lower than critical $\tau < -1$ the CVC is linear. Starting with $\tau \approx -0.2$ and higher, linearity is violated because of the contribution made to the conductivity by the fluctuation pairing (Fig. 4, curves 1 and 2). In the vicinity of the critical temperature, when τ changes from 0 to 0.01, voltage steps appear on the CVC, with sizes from several dozen microvolts to several millivolts (Fig. 4, curves 3 and 4). Their appearance can apparently be attributed to the phase slipping mechanism.[8] At lower temperatures, the resistive state is manifest on the CVC in the form of several MSCS. The voltage-switching jumps on going from one MSCS to another increase gradually with decreasing temperature and reach values from several millivolts to hundreds of millivolts (Fig. 4, curves 5 and 6, and also Fig. 2).

Investigations of the CVC of a film with several potential leads distributed along the film have established that each part of the film has its own CVC which differs from CVC of the other parts, i.e., to each part there correspond several MSCS (or one MSCS), and the MSCS of the entire film is the sum of the MSCS of its individual parts. Thus, conditions are realized wherein one or several parts of the film go over into the resistive state, while the remaining parts are superconducting. This phenomenon is apparently possible only in the case of weak coupling the individual granules or crystallites,[21] when the fluctuation effects cannot be neglected. An additional check on the presence of superconductivity was effected with the aid of the tunnel effect. A lead film was evaporated above the oxidized aluminum film. (For details see Ref. 11.) In the region of the first 3–5 dissipative MSCS curves the energy gaps of Al and Pb remained practically unchanged. Therefore the onset of MSCS can be attributed to generation of vortices of opposite sign on the "weak spots" of the films, and to motion of these vortices under the influence of the current in a direction perpendicular to the current.

B. Temperature dependence of critical current

The greater part of the investigated films can be regarded either as granulated or as "dirty" type-II superconductors,[22] since their value of $\varkappa$ exceeds $1/\sqrt{2}$. We can therefore regard the destruction of the Meissner state under the influence of the current flowing through the superconductor as the result of the onset of vortices (which carry a magnetic flux quantum $\Phi_0 = ch/2e$) through the weak spots of the film. In this case there exists a lower (I_{c1}) and an upper (I_{c2}) value of the critical current.[11] The current I_{c1} is due to instability of the Meissner state according to Likharev,[23] while I_{c2} is the current at which the potential barrier to the vortex vanishes. Thus, the destruction of the Meissner state is local and occurs at the place where the potential barrier to the vortex into the film is lowest (this in fact is the so-called weak spot of the film). The critical current J_c determined from the CVC should apparently be close to I_{c2} and located within I_{c1} and I_{c2}. To estimate I_{c2} we must take into account the fact that the current is not uniformly distributed over the width of the film, even if it is assumed that it is homogeneous over the thickness.[11] To calculate the width distribution of the current we use the London equations in the form

$$\operatorname{rot} \mathbf{j} = -(c/4\pi)\lambda^2(T)\mathbf{H}, \quad \operatorname{rot} \mathbf{H} = (4\pi/c)\mathbf{j}. \tag{1}$$

Eliminating the magnetic field $\mathbf{H}$ from (1), with account taken of the fact that the first equation holds only for in the sample, we obtain in the limit $\lambda \gg d$ an equation that describes the distribution of the surface density of the current $J(x) = jd$ over the width:

$$\frac{\partial J}{\partial x} = \frac{1}{2\pi\lambda_0}\int_0^{w} dx' \frac{J(x')}{x - x'}, \tag{2}$$

where $\lambda_0 = \lambda^2(T)/d$. For the case when $w \gg \lambda_0$, we have a solution suitable everywhere except for regions with width of the order of λ_0 near the edges of the film, namely,

$$J(x) = I/\pi[x(w-x)]^{1/2}. \tag{3}$$

Here I is the current flowing through the cross section of the film

$$I = \int_0^w dx\, J(x).$$

If $w \ll \lambda_0$, the current is uniformly distributed. All the investigated films, however, had $w \gg \lambda_0$.

To calculate the critical current it is necessary to know the behavior of $J(x)$ in the vicinity of the edges of film. The solution near the edges can be obtained in the following manner. We take $x \ll w$, and then the upper limit of integration in (2) can be extended to infinity, and the obtained equation can be solved by the Wiener-Hopf method. Selecting a suitable form of the solution such that the asumptotic form (at $x \gg \lambda_0$) corresponds to relation (3), we get

$$J(x) = \frac{I}{(2\pi w\lambda_0)^{1/2}}\frac{1}{\pi}\int_0^\infty \frac{dk}{k^{1/2}}\frac{1}{(1+k^2)^{3/4}}\exp\left[-\left(\frac{kx}{2\lambda_0} + \int_0^k \frac{dy \ln y}{1+y^2}\right)\right]_{x \ll w} \tag{4}$$

Since the current and the normal component of the magnetic field reach a maximum value on the edges of the film, it is there that the production of the vortices is most likely. To determine the critical current I_{c2} it is necessary to ascertain the current at which the vortices can penetrate through the edge of the film. To this end we present an expression obtained by the method developed by Pearl[24] and de Gennes[25] for the energy $F(x)$ of a vortex in a current-carrying film in the region $\lambda_0 \ll x \ll w$:

$$F(x)=\left(\frac{\Phi_0}{4\pi}\right)^2\frac{1}{\lambda_0}\left(\ln\frac{2\lambda_0}{\xi}+\frac{\pi}{2}N_0\left(\frac{x}{\lambda_0}\right)+\frac{\pi}{2}E_0\left(\frac{x}{\lambda_0}\right)\right]-\frac{2\Phi_0 I}{\pi c}\left(\frac{x}{w}\right)^{1/2}, \tag{5}$$

where c is the speed of light, and $N_0(z)$ and $E_0(z)$ are Neumann and Weber functions.[26] The term in the square brackets in (5) is the energy of the vortex interaction with the edge of the film. This expression is suitable also at small $x \gtrsim \xi$. The second term in (5) is the energy of interaction with the current and is valid only at $x \gg \lambda_0$, since it was calculated by using the solution (3). An analysis of (5) shows that before a vortex can penetrate the film it must overcome a potential barrier whose value at small currents is of the order of the vortex-formation energy (the first term in the square brackets). To determine the current at which the barrier vanishes it is necessary, when calculating the energy of interaction with the current (the second term in the square brackets), to use relation (4), inasmuch as in this case the values $x \sim \xi$ turn out to be essentially small. Without presenting the cumbersome expressions for the interaction energy, we write down the final result for the critical current:

$$I_{c2}=(g/16)(c\Phi_0/\xi\lambda)(dw/\pi)^{1/2}, \tag{6}$$

where g is a constant of the order of unity

$$g^{-1}=\int_0^\infty \frac{dk}{k^{1/2}}(1+k^2)^{-3/4}\exp\left[-\int_0^k \frac{dy\ln y}{1+y^2}\right].$$

Formula (6), apart from a coefficient ~1, agrees with the current at which the critical current is reached on the edges of the film in accordance with Ginzburg.[27]

It should be noted that when a sufficient number of macroscopic inhomogeneities are present in the films (with characteristic dimensions $\sim\lambda$) and contribute to the local destruction of the superconductivity, the current density averaged over these inhomogeneities is constant over the width of the film. It is therefore of interest to determine the critical current I'_{c2} at which the barrier to the entry of the vortex vanishes in the case of uniform distribution of the current over the sample width. It is desirable here to find out the degree to which I'_{c2} will differ from the experimental value J_c, since this difference characterizes the degree of the macroscopic inhomogeneity of the films. I'_{c2} can be calculated with the aid of relation (5), in which, however, it is necessary to replace the term with the current by $\Phi_0 Ix/wc$. We then obtain in explicit form for I'_{c2} the expression

$$I_{c2}'=\frac{c\Phi_0}{(4\pi)^2}\frac{wd}{\lambda^2\xi}. \tag{7}$$

To compare the temperature dependences of $I_{c2}(T)$ and $I'_{c2}(T)$ with $J_c(T)$ we must know the values of $\lambda(T)$ and $\xi(T)$.

For a dirty superconductor the values of λ and ξ near T_c are given, according to Gor'kov,[28] by

$$\lambda=0.615\lambda_L(0)(\xi_0/l_e)^{1/2}\tau^{-1/2}, \tag{8}$$

$$\xi=0.85(\xi_0 l_e)^{1/2}\tau^{-1/2}, \tag{9}$$

Where l_e is the effective electron mean free path and $\tau = 1-T/T_c$.

In the case of a granulated superconductor (see the Appendix), λ and ξ near T_c are equal to

$$\lambda=0.49\lambda_2(0)[\xi_0/l_e]^{1/2}\tau^{-1/2}, \tag{10}$$

$$\xi=0.67(l_e\xi_0)^{1/2}\tau^{-1/2}. \tag{11}$$

Although the relations for the quantities λ and ξ in the case of dirty and granulated superconductors are very similar, it must be remembered nevertheless that in a granulated superconductor l_e is much smaller than in a dirty one, since it is determined by the tunnel conductivity between the individual granules. In addition, the formulas for λ and ξ are given for a cubic close-packed lattice in the continual limit. The packing in the experiment, however, is random and the value of λ is larger.

Together with Eqs. (6) and (7), Eqs. (8), (9) and (10), (11) make it possible to estimate the dependence of the critical current on the temperature near the transition point. For both a dirty and granulated superconductor with uniform distribution of the current over the width, the theory yields

$$I_{c2}'\sim\tau^{3/2}, \tag{12}$$

and in the case of a nonuniform distribution

$$I_{c2}\sim\tau. \tag{13}$$

Figure 5 shows the experimentally obtained $J_c(T)$ for films made of different materials and having different geometrical parameters.[2)] The linearity of $J_c(T)$ near T_c means that a situation is realized wherein the current is not uniformly distributed over the width of the film, and the films have a relatively small numbers of microinhomogeneities. The degree $k = I_{c2}(T)/I_c(T)$ of the deviation of the theoretical value of the critical cur-

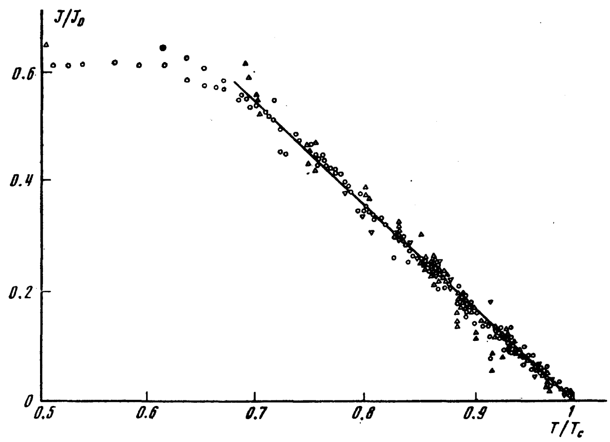

FIG. 5. Temperature dependence of the critical current of the first voltage step. The following symbols are used: ○—In; △—Sn; ▽—Al.

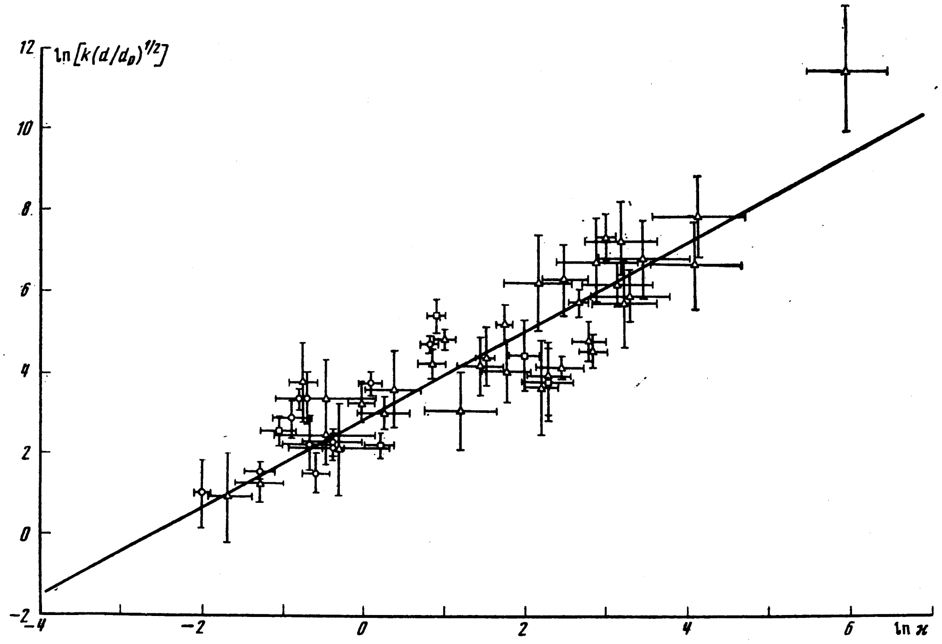

FIG. 6. Dependence of $\ln[k(d/d_0)^{1/2}]$ on $\ln\varkappa$ for 50 investigated samples. The straight line is a plot of the relation $\ln[k(d/d_0)^{1/2}]=\ln[\alpha(r_D/d_0)^{1/2}]+\ln\varkappa$, obtained from formula (14) with values $\alpha=1$, $r_D=1.81\cdot10^4$ Å. The scatter about this line, which exceeds the experimental error, is evidence of the random character of r_D. Points: ○—In; △—Al; □—Sn.

rent from the experimental value, as a function of $\varkappa$, is shown in Fig. 6 in a logarithmic scale. The parameter $\varkappa$ was calculated by Goodman's formula[29]: $\varkappa=0.96\lambda_L(0)\times(1/\xi_0+1/1.32l_e)$, and l_e was calculated from the value of the product $\rho_n l_e$ taken from the published data on the anomalous skin effect. In view of the error contained in the determination of the film thickness, a scatter arises in the values of $\ln\varkappa$, which is marked by horizontal lines in the figure. The vertical segment correspond to the scatter of the quantity at $\ln[k(d/d_0)^{1/2}]$, where $d_0=100$ Å.

It is seen from the figure that in the case of typical type-I superconductors the theoretical value of I_{c2} agrees with the experimental J_c. At first glance this agreement seems surprising, since the calculation presented is suitable only for type-II superconductors. However, if it is recognized that I_{c2} agrees, apart from a coefficient ~1, with the total current at which its density on the edges of the film reaches the pair-breaking current, then the results explains many factors in the behavior of the investigated samples. First, as shown by Clem *et al.*[30], in type-I superconductors there exists a barrier to the entry of the magnetic flux, and leads to an increase of the critical current by several orders compared with the pair-breaking current. The fact that at small $\varkappa$ the critical current in our case is close to the pair-breaking current indicates that macroscopic inhomogeneities (with characteristic dimension $\gtrsim\lambda$) are present in the investigated samples and lead to a local suppression of the carrier. Second, it is obvious that in case of type-II superconductors the role of the edge defects reduces to a suppression of the barrier, and if this is the case, then it is easy to estimate the coefficient k. For this it is necessary to stipulate that the width of the barrier at the experimental critical current be of the order of the characteristic dimension r_D of the edged effect. We then obtain for k

$$k\approx\alpha\varkappa(r_D/d)^{1/2}, \qquad (14)$$

where α is a numerical coefficient of the order of unity. It is of interest that r_D for all films is of the same order of magnitude, namely 10^4 Å. Finally, the third conclusion that follows from the foregoing is that the value of $J_{c2}(T)$ can be determined during the last step, after which a transition takes place to the characteristic corresponding to the normal state of the entire film. In practice, however, this cannot be realized, since the strong increase of the dissipation with increasing current causes either a substantial heating or an overheating of the samples.

We note also a singularity common to all the films. The plot of the critical current against temperature exhibit saturation with decreasing temperature earlier than would follow from the corresponding temperature dependences of λ and ξ. The reasons are not yet clear. One of the possible explanations is that when the dimensions of the vortex decrease with decreasing temperature the defects with smaller r_D which cannot be felt at higher temperatures, now come into play.

C. Analysis of the influence of dissipation on the form of the CVC

Since the appearance of the first MSCS is accompanied by energy dissipation, it must naturally be taken into account. Heat is released in a superconductor only in the region where the vortices move, after which it propagates further over the superconducting film. Therefore the released heat influences the value of the current at which the subsequent dissipative curves appear, i.e., the current values of the second, third, etc. voltage steps on the CVC. The influence of the heat release is easiest to investigate by constructing on a single plot $J-T$ diagrams on which the $J_i(T)$ lines (J_i is the current at which the ith step appears) separate from one another the regions with different numbers of resistive regions in the film. It turned out that the current of the second and subsequent steps are not the

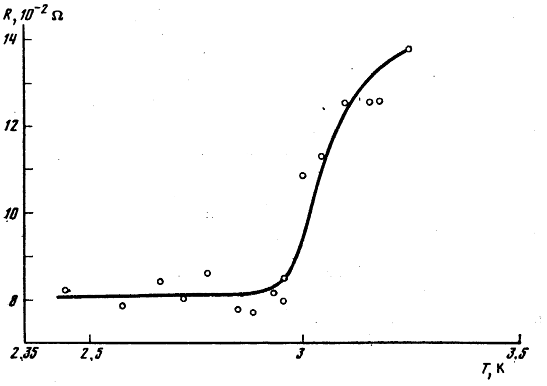

FIG. 7. Dependence of the resistance of the resistive section of the CVC of an indium film R on the temperature in the region of the anomalous increase of the current of the second step of the CVC.

same (apart from a coefficient) as the current of the first step, but tend to become smaller with decreasing temperature. The diagrams of In films (in contrast to Al and Sn) have a particularly intricate character. In addition, one of the last steps of the CVC of the In and Sn films show a clearly pronounced rise.

For some flat films of In and Sn, an anomalous increase of the current of one of the last steps was observed at a temperature $T_a \approx 0.8 T_c$. An investigation of this anomaly by measuring the differential resistance of the resistive sections preceding the given step on the CVC, revealed a 40% decrease of the energy dissipation in the region $T < T_a$ (see Fig. 7). Therefore the increase of the current can be attributed to a decreased heating of the region where the vortices are produced in the film by a neighboring region in which the dissipation is less. This is probably due to the decrease of the differential resistance when the viscosity coefficient of the moving vortices changes with temperature (see, e.g., Ref. 31). In some films $J_c(T)$ has a maximum at τ values from 0.35 to 0.7; this agrees with the reports concerning the same situation for Sn and Nb in Refs. 22 and 13.

Thus, the appearance of MSCS is possible only in "soft" superconductors, i.e., in superconductors with small volume pinning, since the volume forces that inhibit the vortex motion are small in such superconductors. Therefore the vortex moves from one side of the film to the other with practically no scattering. The vortices penetrate into the film in those places where the surface barrier is lower than in other places. A situation arises wherein the superconductivity is destroyed first in only one region, and then (with increasing current) in several (width) regions of the film. Naturally, the transverse dimensions of these sections is $\approx \xi$, i.e., it is equal to the diameter of the normal core of the vortex. The foregoing pertains to the case when there are two or three (with a maximum of five) MSCS. At larger currents the picture becomes much more complicated because of the increased energy dissipation.

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APPENDIX

To estimate the values of λ and ξ in the case of a granulated superconductor, we use a model proposed by Parmenter.[33] In this model the superconductor constitutes a system of superconducting granules connected by Josephson bonds with energy

$$\varepsilon_D = (a l_e p_0^2 / 12\hbar^2 \pi \sqrt{2}) \Delta \operatorname{th} (\Delta/2T). \tag{A.1}$$

We represent the free energy of the sample in the form of its expansion in the order parameter:

$$F = \sum_f F_f - \sum_{f\delta} \frac{M}{2} (\Delta_f \Delta^*_{f+2a\delta} + \Delta^*_f \Delta_{f+2a\delta}), \tag{A.2}$$

where Δ_f is the order parameter of the f-th granule, and δ is the unit vector in the direction of the nearest neighbors of the granule. The first term is the sum of the energies of the unbound granules; the second is the sum of the binding energies between the nearest granules. In the case of Josephson bonds (assuming that the modulus of the order parameter is the same for all granules, Δ), we have $M = \varepsilon_D / 2\Delta_0^2$, where Δ_0 is the equilibrium value of the order parameter. Recognizing that the radius of the granule is $a \ll \xi_0$ we can neglect in the equation for the free energies F_f of the individual granules the terms that contain derivatives of the order parameter Δ_f with respect to the coordinates. It is then useful to change over to the continual approximation. Then

$$F = \int \frac{d\mathbf{r}}{\Omega} \frac{A^2}{B} \Omega\gamma \left\{ \frac{f^4}{2} - f^2 + \frac{2\varepsilon_D a^2 B}{\Omega\gamma A^2} \left(\frac{\partial f}{\partial \mathbf{r}} \right)^2 \right\}. \tag{A.3}$$

Here Ω is the volume of the unit cell of the superconductor, γ is the filling factor of the film volume by superconducting material,

$$f = \Delta/\Delta_0, \; A = H_c^2/4\pi\Delta_0^2, \; B = -H_c^2/4\pi\Delta_0^4.$$

Here H_c is the thermodynamic critical magnetic field of a bulky superconductor. Minimizing, as usual, F with respect to f, we arrive at the equation

$$-\xi^2(T) \frac{\partial^2 f}{\partial x^2} - f + f^3 = 0, \tag{A.4}$$

where the coherence length $\xi(T)$ is now defined as

$$\xi^2 = -(2\varepsilon_D a^2 B / \Omega\gamma A^2). \tag{A.5}$$

Making the appropriate substitutions, we find that near T_c

$$\xi = 0{,}67 [l_e \xi_0 / \tau]^{1/2}. \tag{A.6}$$

We obtain the depth of penetration by transforming Maxwell's equation

$$\operatorname{rot} \mathbf{H} = 4\pi \mathbf{j}/c$$

for the case of Josephson currents between the granules, and obtain

$$\lambda^2 = \left(\frac{\hbar c}{e} \right)^2 \frac{a}{8\pi \cdot 2^{1/2} \varepsilon_D} \tag{A.7}$$

or near T_c

$$\lambda = 0.49 \lambda_L(0) [\xi_0 / l_e \tau]^{1/2}. \tag{A.8}$$

[1]Since the stabilization of the temperature is disturbed in the region of strong energy dissipation, because of the large heat release, we investigated 2–3 (with a maximum of 5) MSCS.

[2)]The normalization of $J_c(T)$ to $J_c(0)$ and of T to T_c yields a universal function $J_c(T)$ for films having different geometrical parameters and made of different materials.

[1]L. M. Shubnikov and N. E. Alexeyevski, Nature **138**, 804 (1938).
[2]J. Lowell, Cryogenics 5, 185, 221 (1965).
[3]E. H. Roderick and E. M. Wilson, Nature **194**, 1167 (1962).
[4]W. J. Skocpol, Phys. Rev. **B14**, 1045 (1976).
[5]R. P. Huebener and R. T. Kampwirth, Phys. Stat. Sol. **A13**, 255 (1972).
[6]R. P. Huebener and D. E. Gallus, Phys. Rev. **B7**, 4089 (1973).
[7]W. W. Webb and R. J. Warburton, Phys. Rev. Lett. **20**, 461 (1968).
[8]W. J. Skocpol, M. R. Beasley, and M. Tinkham, J. Low Temp. Phys. **16**, 145 (1974).
[9]R. P. Huebener and D. E. Gallus, Appl. Phys. Lett. **22**, 597 (1973).
[10]A. A. Galkin, Yu. M. Ivanchenko, and V. F. Khirnyĭ, Fiz. Tverd. Tela (Leningrad) **20**, 1237 (1978) [Sov. Phys. Solid State **20**, 713 (1978)].
[11]Yu. M. Ivanchenko and V. F. Khirnyĭ, Fiz. Nizk. Temp. **4**, 969 (1978) [Sov. J. Low Temp. **4**, 456 (1978)].
[12]R. B. Pettit and J. Silox, Phys. Rev. **B13**, 2865 (1976).
[13]H. London and G. R. Clark, Rev. Mod. Phys. **36**, 320 (1964).
[14]W. Itther, Phys. of Thin Films, Acad. Press Inc., New York, 1963.
[15]I. O. Yanson and I. O. Kulik, Effekt Dzhosefsona v sverkhprovodyashchikh tunnel'nykh structurakh (Josephson Effect in Superconducting Tunnel Structures), Nauka, 1970.
[16]B. Abeles, R. W. Cohen, and G. W. Callen, Phys. Rev. Lett. **17**, 632 (1966).
[17]R. B. Pettit and J. Silcox, J. Appl. Phys. **45**, 2858 (1974).
[18]B. Abeles, R. W. Cohen, and R. W. Stowell, Phys. Rev. Lett. **18**, 902 (1967).
[19]J. W. Ekin, B. Serin, and J. R. Chem. Phys. Rev. **B9**, 912 (1974).
[20]W. E. Makser and R. D. Parks, Phys. Rev. **B1**, 2164 (1970).
[21]G. Deutscher, Rev. Phys. Appl. **8**, 127 (1973).
[22]N. Abeles, Sheng Ping, M. D. Courrs, and Y. Arie, Adv. in Phys. **24**, 407 (1975).
[23]K. K. Likharev, Izv. vyssh. ucheb. zav. Radiofizika **14**, 909, 917 (1971).
[24]J. Pearl, Appl. Phys. Lett. **5**, 65 (1964).
[25]P. de Gennes, Superconductivity of Metals and Alloys, Benjamin, 1965.
[26]I. S. Gradshteĭn and I. P. Ryzhik, Tablitsy intergralov, summ, ryadov i proizvedeniĭ (Tables of Integrals, Sums, Series, and Products), Nauka, 1971. [Academic, 1966].
[27]V. L. Ginzburg, Dokl. Akad. Nauk SSSR **118**, 464 (1958) [Sov. Phys. Dokl. **3**, 102 (1958).
[28]L. P. Gor'kov, Zh. Eksp. Teor. Fiz. **36**, 1918 (1959) **37**, 833, 1407 (1959) [Sov. Phys. JETP **9**, 1364 (1959), **10**, 593, 998 (1960)].
[29]B. B. Goodman, IBM J. Res. Developm. **6**, 63 (1962).
[30]J. R. Clem, R. P. Huebener, and D. E. Gallus, J. Low Temp. Phys. **12**, 449 (1973).
[31]R. A. Gasparyan and V. Z. Kresin, Zh. Eksp. Teor. Fiz. **69**, 377 (1975) [Sov. Phys. JETP **42**, 192 (1975)].
[32]J. E. Mercereau and L. T. Crane, Phys. Rev. Lett. **9**, 381 (1962).
[33]R. H. Parmenter, Phys. Rev. **154**, 353 (1967).

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Resonance between dipole oscillations of atoms and interference modes in crystalline films

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Investigation of the optical properties of $CdS_{1-x}Se_x$ films in the long-wave IR region of the spectrum has revealed resonance between the gap oscillations of selenium atoms and the interference modes of the films. This resonance leads to a sharp increase of the absorption at the frequencies of the gap oscillations. The experimental results agree well with the theoretical calculations. It is also shown that this resonance should always take place when the interference mode coincides with the weakly absorbing IR active oscillations, including those on the low-frequency wing of the dipole oscillation in the region of the anomalous dispersions of the dielectric constant of the layer.

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1. INTRODUCTION

The use of optical properties of thin crystalline films makes it possible, as is well known, to obtain by a rather easy direct method information on the dynamics of crystal lattices, to determine the frequencies and the damping constants of transverse and longitudinal optical phonons. What are investigated in the main are pure materials with low impurity concentrations.

Thin films of II-VI compounds were investigated by methods of long-wave IR spectroscopy in Refs. 1–5. The theory of the optical properties of thin crystalline films of compounds with fractions of ionic bond between the atoms was developed in Ref. 6, and it follows from it that these films contain, besides phonons, a rather