Features of inhomogeneous current state in wide superconducting films

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A dc superconducting-transformer circuit is used to investigate the features of the current-voltage characteristics (CVC) of thin aluminum films of width $W \gg \lambda_\perp$. It is shown that in contrast to narrow channels, where phase-slippage centers are realized, the steplike structure of the CVC results in this case from the inhomogeneous entry of the vortex strings.

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The inhomogeneous current state realized in thin ($d<\xi$) and wide ($W>\lambda_\perp$) superconducting films was investigated in most cases by analyzing their current-voltage characteristic (CVC).[1-4] Even though the CVC reflect the dynamics of the transition of the superconductor into the resistive state under the influence of the current, the transition mechanism cannot always be uniquely interpreted on the basis of these characteristics. Thus, the qualitatively similar structures of the CVC for narrow and wide (in the scale of $\lambda_\perp$) films is described by essentially different mechanisms. In the former case the steplike CVC dependence is due to the onset of the phase slippage centers,[5,6] and in the later it is due to inhomogeneous current flow and the possibility of entry of vortices at the location of edge defects of the sample.[2-4] In addition, the formation of the CVC is attributed in Ref. 1 to thermal processes that develop under the influence of the transport current.

We present and discuss here the results of experiments performed on sandwich structures consisting of two granulated aluminum films (average grain dimension $\sim 5\times10^{-7}$ cm) separated by an SiO layer of thickness $d_i \sim 1\times10^{-6}$ cm. The lower film (film 1) had a width $W_1 = 0.3$ cm, a thickness $d_1 = 3\times10^{-6}$ cm, a length between the potential ends $L_1 = 0.6$ cm, and a resistance $R^n_\square = 10\ \Omega$. The dimensions and resistance of the upper film (Fig. 2) were $d_2 = 6\times10^{-6}$ cm, $L_2 = 0.6$ cm, $W_2 = 0.1$ cm and $R^n_\square = 2-5\ \Omega$. The samples were evaporated on glass substrates in an oxygen atmosphere at $P=10^{-4}$ Torr. The aluminum films prepared by this technique had a critical superconducting-transition temperature $T_c = 1.85-1.9$ K, $\xi = 5\times10^{-6}$ cm, and a Ginzburg-Landau parameter $\varkappa = 8-10$. The arrangement of the current and potential contacts is shown in the inset of Fig. 1(b). A specimen having this structure comprises a dc superconducting transformer[7] whose operating principle is based on the joint motion of the vortices of both films. The fluxoids in the first and second films are coupled by magnetic fields that penetrate through the dielectric liner of the sandwich, and the vortices of like polarity attract (i.e., tend to make their cores congruent), while those of unlike polarity repel. Any motion of the vortices in the lower film under the influence of the transport current I_1 causes the vortices to drag fluxoids in the upper film, on which there appears an induction emf $V_2 = L_2\varphi_0 n_2 \dot{X}_2/c$ (c is the speed of light, φ_0 is the magnetic-flux quantum, and n_2 and X_2 are the vortex density and velocity in the film). The amplitude and contour of this signal allow us to draw conclusions concerning the character of the distribution of the vortex structures of the films. Thus, the employed procedure of investigating the transition of a thin film from the superconducting into the resistive state under the influence of a transport current makes it possible to separate in the CVC of the investigated film the mechanisms connected with the transport of the flux quanta.

The experiments were performed in a cryostat shielded against external magnetic fields. The current-voltage characteristics, plotted at $T/T_c = 0.7-0.8$, have shown for the lower films the presence of a critical current I_c and of a large number of voltage steps in the resistive region [see Fig. 1(a)]. The smallest height of the steps was 200 μV, and the largest steps were multiples of the smallest. Extrapolation of the linear sections of the CVC to the current axis has shown that all lie on straight lines drawn from the point corresponding to the critical current, and have a differential resistance that is a multiple of a certain constant value R_F. Simultaneously with the CVC we registered the drag signal V_2, which was plotted as a function of the bias voltage on the lower electrode V_1 [Fig. 1(b)]. The voltage V_2 (V_1) appeared when the measuring current I_1 was made to flow and reversed sign when the direction of I_1 changed. The effect did not appear when the films were in the normal state, and was independent of the electric field $\sim 10^5$ V/cm applied to the sandwich. The drag signal was observed in the entire resistive region of the CVC and decreased monotonically when the curve reached the normal state. The V_2 (V_1) revealed small singularities in the region of the large CVC steps. The presence of the drag signal is evidence of a substantial contribution of the vortices to the formation of the resistive region of the CVC of the investigated film.

To determine the connection of the drag-signal amplitude and profile with the character of the vortex structures in the films, we shall analyze their equations of motion

$$d_1\eta_1\dot{X}_1 = I_1\varphi_0/W_1c - kF(X_1-X_2) - F_1^c,$$
$$d_2\eta_2\dot{X}_2 = F(X_1-X_2) - F_2^c, \quad k = a_1W_2/a_2W_1; \tag{1}$$

X_1 and X_2 are the coordinates of the vortex lattices. It

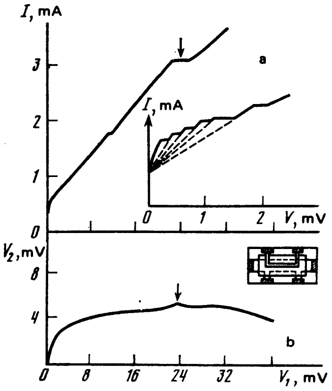

FIG. 1. a) Current-voltage characteristic of film 1. The inset shows the initial section of the CVC; $T=1.72$ K. b) Drag-signal voltage $V_2(V_1)$ and construction of the dc superconducting transformer. The arrows mark the step on the CVC (a) and the corresponding singularity in the drag signal $V_2(V_1)$ (b).

is assumed here that the lattices are ideal and have periods a_1 and a_2 in the direction perpendicular to the transport current I_1; η_1 and η_2 are the viscosity coefficients in the first and second films, F_1^c and F_2^c are the averaged volume and surface pinning forces, and F is the pinning force between the fluxoids in the sandwich.

The form of the function F depends on the unknown parameters of the vortex lattices in films and on their symmetry. However, Eq. (1) leads to a number of general conclusions concerning the drag-signal profile. It follows from them that the vortex velocities $\dot{X}_1$ and $\dot{X}_2$ in the films are equal if

$$|\dot{X}_1|\leqslant|\dot{X}_2|_{max}=(F_m-F_2^c)/d_2\eta_2=\dot{X}_m.$$

In this case they are "rigidly" pinned to each other and move together in the first and second films up to a voltage $V_1=V_{1m}=n_1\varphi_0L_1\dot{X}_m/c$ on the first film (here $F_m=\max\{F(x)\}$), after which the vortex structures in the film begin to "slip" relative to each other and the drag signal should decrease in the general case like I_1^{-1} and V_1^{-1}. If the vortex-density distribution is the same in the films, the voltages V_1 and V_2 should be equal up to values $V_1<V_{1m}$. This is satisfied, for example, if the entering current is uniform, or in external magnetic fields for films with $d\gg\xi$ (Refs. 7 and 8). In our experiments, however, the plot of $V_2(V_1)$ differs qualitatively from the curves calculated for a homogeneous distribution of the fluxoids in the film.[9]

The profile of the signal $V_2(V_1)$ and the CVC of the investigated samples is incontrovertibly explained by model in which the transition from the superconducting into the resistive state under the influence of the current is the result of formation of vortex strings. Each string constitutes a chain of moving vortices that appear in different sections of the film as the measuring current overcomes the entrance barriers for the vortices in a given place in the sample. Thus, the CVC of the investigated films is an integral characteristic of a large number of vortex chains in which the fluxoids move under the influence of a Lorentz force perpendicular to the transport current. The formation of individual strings gives rise to small (of the order of the energy gap of the superconductor) voltage jumps; larger voltage steps appear as a result of simultaneous inrush of a considerable number of strings at close values of the entry currents. The number n of the strings is determined from the relation $n=V_n/R_F(I_n-I_c)$, where R_F is due entirely to the vortex motion, and I_n and V_n are the current and voltage of the n-th string. The experimental conditions are chosen such that the normal component of the magnetic field due to the measuring current is minimal for the upper film [see the inset of Fig. 1(b)]. In this case the vortices in the upper narrow electrode are due mainly to the magnetic flux produced by the vortex structure of the wide film. In the absence of a transport current they are uniformly distributed, despite the sharply inhomogeneous character of the distribution of the vortices in the film 1. This is also indicated by the experimentally obtained ratio $V_2/V_1=10^{-3}$ as $V_1\to 0$. The large difference between the parameters of the vortex structures of the upper and lower films explains the low value of the observed drag signal V_2.

It follows from the experimental curves that the differential resistance of the CVC sections in the gaps between the steps is a multiple of the dc resistance R_F of the strings. As new strings enter, the voltage on the film becomes uniformly redistributed among them. Therefore the contribution to the voltage V_1 from each string will decrease with increasing V_1 more slowly than V_1^{-1}; at the same time, addition of new strings increases the density of the fluxoids in the upper film, and it is this which leads to the monotonic growth of V_2. As a result, the dragging signal $V_2(V_1)$ changes little on the linear sections of the CVC. From the expression $\dot{X}_1=a_1cI_1R_F/\varphi_0$ at $R_F=0.1\ \Omega$, $I_1=2$ mA, and the distance between the vortices in the string $a_1\approx\xi\approx10^{-5}$ cm we find that their velocity in the strings $\dot{X}_1=10^6$ cm/sec $\gg\dot{X}_m=2\times10^4$ cm/sec, where $\dot{X}_m$ is the maximum possible velocity of the joint motion of the vortices, calculated from the expression for F_m (Ref. 9) and from the usual value of the viscosity coefficient of Abrikosov vortices. At $\dot{X}_1\gg\dot{X}_m$, the vortices in the strings would be unable to capture firmly the fluxoids in the upper film, and the dragging voltage from each string (V_2/n) would be smaller than that observed by two orders of magnitude.

This contradiction is resolved, if, following Larkin and Ovchinnikov,[10] it is assumed that the viscosity coefficient η_2 depends substantially on the vortex velocity and decreases considerably at $\dot{X}_2>\dot{X}_c$, where $\dot{X}_c$ is the

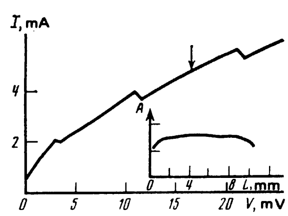

FIG. 2. Current-voltage characteristic of aluminum film at $T=1.71$ K. The inset shows the dependence of the second-sound signal amplitude in He II on the coordinate L along the aluminum film. The arrow indicates the region of the bias voltage on the film, at which the measurements on second-sound generation in helium were performed.

critical velocity at which the viscous-friction force is maximal. The value of $\dot{X}_c$ calculated from the equations of Ref. 10 is for our specimens 5×10^2 cm/sec < $\dot{X}_m$, i.e., the maximum viscous-friction force is much less than the vortex pinning force. Their joint motion is then possible at velocities that exceed $\dot{X}_m$.

An alternative mechanism, which interprets the stepwise structure of the CVC on the basis of thermal phenomena,[1] does not explain the observed drag effect, which is due entirely to the joint motion of the vortices in the films. It is possible also to interpret the CVC structure of the investigated aluminum films as being due to local superheating processes determined by the dissipative motion of the vortices in the weak spots of the specimen. To check on this possibility we mapped the topography of the thermal regions along the film with the aid of experiments on generation of second sound in He II by the investigated specimens. In this investigation we attempted to observe sections where the dissipative processes are localized. The second-sound receiver was an aluminum film 0.1 mm wide and 3 mm long, serving as the second-sound sensitive element at working currents higher than critical. The receiver was placed at a distance 3 mm from the investigated sample and could be displaced along it with a micrometer screw. The measurements were performed on the linear sections of the CVC between the voltage steps (Fig. 2). The transport current of the investigated film was modulated by pulses at a repetition frequency 10 kHz and with an amplitude that did not distort substantially the shape of the current-voltage characteristic. The film generated second sound which was registered by the receiver and was fed to the input of an amplifier. The dependence of the second-sound amplitude on the coordinate is shown in the inset of Fig. 2. Similar dependences were observed also on other sections of the CVC. The results of this experiment offer unambiguous evidence of the absence of a clearly pronounced localized heat-release section. This indicates that the energy dissipation from the vortex strings is approximately uniform over the length of the film under the experimental conditions.

Thus, the investigation shows that the destruction of the superconductivity of granulated aluminum films by current at $T < T_c$ proceeds via formation of a large number of vortex strings. The period of the vortex structure in the strings is much smaller than the distance between the strings, i.e., the fluxoids in the films are distributed quite inhomogeneously and their velocity exceeds greatly the critical value at which the viscous-friction force decreases substantially.

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