Critical currents in niobium-based layer structures

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The critical currents in niobium-based ($Nb-NbO_x$) layer structures were measured. A strong anisotropy of the critical currents and of the pinning forces was observed for the parallel and perpendicular directions of an external magnetic field. In a field parallel to the layers a transition took place from pinning due to a flux-lattice shearing mechanism to a mechanism of direct summation of elementary pinning forces on reduction in the layer structure period.

1. INTRODUCTION

The critical current I_c in type-II superconductors is governed by the balance between the Lorentz force, acting on Abrikosov vortices during the flow of a transport current I, and the pinning force, i.e., the force that locks vortices to inhomogeneities. The phenomenological equation describing the critical state is[1]

$$[\mathbf{j}_c\mathbf{B}]+\mathbf{P}_v=0, \tag{1}$$

where j_c is the critical current density, $\mathbf{B}$ is the magnetic induction vector, and P_v is the total pinning force per unit volume. In fields much higher than the first critical value we can ignore the Meissner effect and assume that $B\approx\mu_0H$, where μ_0 is the magnetic constant and H is the intensity of the external magnetic field. Active investigations are proceeding of the mechanisms of the elementary pinning forces f_p, i.e., the forces of the interaction of a single vortex with a single inhomogeneity, and a search is being made for the procedure of summation of these forces in order to determine the volume pinning force.

The procedure of summation of the elementary pinning forces depends on the Ginzburg–Landau parameter $\varkappa$, on the magnetic induction $\mathbf{B}$, and the dimensions of the inhomogeneities, so that in general it should be considered separately for each specific case. At a high density of strong pinning centers, when the vortex lattice is destroyed and each vortex interacts with a pinning center, we encounter the case of direct summation of the elementary pinning force. Then, the volume pinning force is[2,3]

$$P_v=N_pf_p\propto h(1-h), \tag{2}$$

where N_p is the density of the pinning centers, $h=H/H_{c2}$ and H_{c2} is the upper critical magnetic field. The factor $1-h$ appears because of suppression of the order parameter by the magnetic field.

If the density of the pinning centers is low, we must allow for the elastic properties of a vortex lattice[4,5] which can be described conveniently by a matrix of the elastic moduli C_{ij} relating the stress tensor τ_i to the strain tensor ε_i:

$$\tau_i=C_{ij}\varepsilon_j. \tag{3}$$

When the vortex lattice interacts with the pinning centers, the important moduli are the shear modulus C_{66} and the modulus C_{44} responsible for bending of the vortices. The shear strains in strong fields give rise to a characteristic dome-shaped dependence $P_v\propto h^{1/2}(1-h)^2$ with a maximum at $h=0.2$.

Synthetic superconducting layer structures are particularly convenient objects for the investigation of this topic. It has been shown[6,7] that the dominant pinning centers are plane boundaries separating superconducting and nonsuperconducting layers. The procedure of finding the volume pinning force can be simplified by preparing layer superconductors with a rigorous periodicity of their properties. This opens up new opportunities for the investigation of the current-carrying capacity of type II superconductors. A change in the thickness of the superconducting layer then allows us to model superconductors with different grain diameters and to study the transition from the case when the shear strains in the lattice need to be allowed for to the procedure of direct summation of the elementary pinning forces. The mixed state and pinning in layer semiconductors have not yet been given sufficient attention. For example, to the best of our knowledge, the linear law $I_c(H)$ obeyed in strong fields and typical of the direct summation case is not exhibited by layer superconductors. Therefore, an investigation of pinning in such superconductors is an urgent task.

We investigated structures of the superconductor–insulator (S–I) type consisting of niobium layers separated by thin oxide spacers. In structures of this type we can expect a weak coupling between the layers, so that the order parameter is strongly modulated[8,9] and, consequently, such spacers should act as effective vortex-pinning centers.

2. PREPARATION OF SAMPLES AND METHOD USED IN CRITICAL-CURRENT MEASUREMENTS

Layer $Nb-NbO_x$ structures were formed by magnetron sputtering in a high-vacuum system with diffusion pumps. The rate of deposition of Nb was $\sim$20–25 Å/s in an atmosphere of spectroscopically pure (99.997%) Ar at a pressure of 30–60 Pa The residual pressure in the vacuum chamber was $P_{\min}\approx10^{-4}$ Pa. The substrates were polished single-crystal sapphire or silicon plates. Diffusion of oxygen into the layers was prevented by ensuring that the temperature of the substrates during sputtering did not exceed 70 °C. An Auger analysis of a control sample, carried out using layer-by-layer ion etching, confirmed the presence of a periodic structure. The film thickness was controlled by the deposition time. The constancy of the film thickness was ensured by stabilization of the niobium evaporation regime.

The selection of the thickness d of the individual layers

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TABLE I.

No.	d, Å	Substrate material	T_c, K	γ	$\varkappa$
1	1000	silicon	6.3	1.2	32
2	600	sapphire	6.4	1.6	19
3	300	sapphire	6.95	1.94	13

Note. Here, γ is the ratio of the resistance of a sample at room temperature to the residual resistance; T_c is the critical superconducting temperature.

was not accidental. In the case of either magnetron[10] or cathodic[11] sputtering, the thickness of a separate niobium film amounting to 450 Å is critical because thicker films have a columnar structure. This has been confirmed by electron microscopy. Therefore, we investigated the critical current and the pinning force in layer niobium films with $d = 300$ Å and 600 Å, so as to find the influence of the structure of the individual layers on the pinning in layer superconductors. The formation of an oxide layer was the result of admission of oxygen to the working chamber. In the case of the first film the pressure was 10^5 Pa and the oxidation time was 10 min; in the case of the second and third films the pressure was 2×10^{-3} Pa and the oxidation time was 5 min. In each case a total of 10 films was deposited. The parameters of the films used in our experiments are listed in Table I.

The critical-current measurements were made on narrow strips 100-μm wide, which were formed by photolithography and electrically isolated. In the case of narrow films the magnetic field created by the current through a sample was low and it could be ignored in an analysis of the experimental results. The strip width W was varied within the range 5–50 μm. Indium solder was used to attach contacts to the samples. Damage to the films due to their transition to the normal state (they could burn up) was avoided by employing a low-resistance shunt which was connected to the potential contacts. In the course of these measurements we were able to vary not only the intensity of the external magnetic field, but also its direction relative to the surfaces of the layers as well as the temperature of the sample. The critical current was determined in the course of recording of the current-voltage characteristic of a sample subjected to a voltage of 1 μV; the value of the critical magnetic field H_{c2} was deduced from the middle of the resistive transition from the superconducting to the normal state.

A magnetic field up to 70 kOe was created in a superconducting solenoid. An inhomogeneity of the film at the position of a sample did not exceed 0.04%. The angular dependences $I_c(\theta)$ and $H_{c2}(\theta)$, where θ is the angle between the film surface and the magnetic field direction, were determined at $T = 4.2$ K using a rotation mechanism based on a conical gear system made of stainless steel and enclosed in a helium-filled casing. The angle could be set to within $\Delta\theta = 0.5°$. The temperature was controlled by placing a sample inside an evacuated low-temperature chamber fitted with a microheater. The temperature of a sample was measured with a germanium thermometer to within $\Delta T = 0.005$ K.

3. MEASUREMENT OF THE CRITICAL MAGNETIC FIELDS AND CRITICAL CURRENTS IN LAYER STRUCTURES

The angular and temperature dependences of the upper critical magnetic field provided extensive information on the film structure. In the case of an ideal single-crystal film these dependences can be found from[12]

$$\left[\frac{H_{c2}(T,\theta)}{H_{c2}^{\parallel}(T)}\cos\theta\right]^2+\frac{H_{c2}(T,\theta)}{H_{c2}^{\perp}(T)}\sin\theta=0, \qquad (4)$$

where $H_{c2}^{\perp}(T)$ and $H_{c2}^{\parallel}(T)$ are the perpendicular and parallel critical fields. A calculation of $H_{c2}(T,\theta)$ for layer structures using the differential-difference Ginzburg–Landau equations[13] gave dependences of a different type:

$$H_{c2}(T,\theta)=H_{c2}^{\perp}(T)\left[\sin^2\theta+\left(\frac{H_{c2}^{\perp}(T)\cos\theta}{H_{c2}^{\parallel}(T)}\right)^2\right]^{-1/2}. \qquad (5)$$

In this case the anisotropy of the fields could be described on the basis of the anisotropy of the effective mass of an electron. In the course of motion along a film the mass is equal to the mass m of an electron in a homogeneous superconductor, but then increases to M in the course of its motion across the films (layers) in such a way that $(H_{c2}^{\perp}/H_{c2}^{\parallel})^2 = mM$.

In the case of our Nb–NbO_x layer structures we determined the dependences $I_c(H,T,\theta)$ and $H_{c2}(T,\theta)$. For each thickness d we prepared several strips of different width and investigated them. We found no significant dependence of the properties on the strip width W. The geometry in our measurements was such that the magnetic field was always perpendicular to the current. Examples of the $H_{c2}(\theta)$ dependences obtained for $d = 300$ Å and $d = 600$ Å at $T = 4.2$ K are shown in Fig. 1. In the case of the sample with $d = 300$ Å (Fig. 1a) the results were in good agreement with Eq. (4) for a thin film (in the figure the theoretical dependence is represented by the continuous curve). This was evidence of a weak coupling between individual layers. This was confirmed also by the temperature dependences of the upper critical magnetic field.

We demonstrated earlier[8] that in structures of this type there was no "crossover," i.e., there was no transition from quasitwo-dimensional behavior (far from T_c) to the three-dimensional case (near T_c). The $H_{c2}^{\parallel}(T)$ dependence for the thickness range $d = 100$–400 Å was close to the law $H_{c2}^{\parallel} \propto (T_c - T)^{1/2}$, which applies to layer superconductors with a weak coupling between the layers.[14] The dependence $H_{c2}(\theta)$ obtained for the sample with $d = 600$ Å had two maxima at $\theta = 0$ and 90°, again in agreement with the results obtained by us earlier for single-layer niobium films.[8] The maximum at $\theta = 90°$ could be attributed, by analogy with layer structures, to the mass anisotropy because of the weak interaction between column-shaped grains. An important feature was that the microstructure of the samples was not influenced by the total thickness, but by the thickness of the individual layers.

Figure 1 shows examples of the dependences $I_c(\theta)$ obtained in a constant magnetic field for our samples. A steep

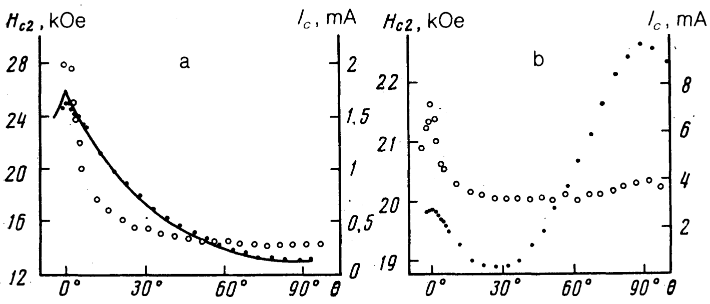

FIG. 1. Dependences $H_{c2}(\theta)$ (●) and $I_c(\theta)$ (○) for a layer structure: a) $d = 300$ Å, $H = 5$ kOe, $W = 5$ μm; b) $d = 600$ Å, $H = 5$ kOe, $W = 12$ μm.

maximum exhibited by all the samples at $\theta = 0°$ indicated that pinning in a parallel field occurred at the oxide spacers. Measurements of $I_c(\theta)$ gave information on the geometric characteristics of the pinning centers. The half-width of the peak at 0° was small, amounting to 3–5°, which indicated that the quality of the layer structure in our samples was high (i.e., that the layers were plane and parallel). The maximum at $\theta = 90°$ was due to the pinning by grain boundaries. Its considerable width and small amplitude were due to the scatter of the directions of grain growth and the small thickness of the grains. It was interesting to analyze the dependences $I_c(\theta)$ and $H_{c2}(\theta)$ for a sample with $d = 600$ Å (Fig. 1b). It is clear from $H_{c2}(\theta)$ that the average interaction between the grains was weaker $[H_{c2}(90°) > H_{c2}(0)]$ than the interaction between the layers. However, the peak of I_c at 0° was stronger than at 90°. This was due to the much larger size of the pinning planes in the parallel direction.

The most important dependences in the study of pinning were $I_c(H)$ and $P_v(H)$. The use of H instead of B was justified because in the case of our structures the field was $H_{c1} \approx 10^2$ Oe and throughout the investigated range of magnetic fields we found that $H \gg H_{c1}$. Figure 2 shows examples of the dependence of the critical current density j_c on the magnetic field for layer structures with $d = 300$ Å and $d = 600$ Å. It is clear from Fig. 2b that in the case of samples with a granular structure subjected to strong fields the inequality $j_c^\perp > j_c^\parallel$ was obeyed because $H_c^\perp > H_c^\parallel$.

A characteristic feature of the dependence $j_c(H)$ in a perpendicular field was a steep fall in weak fields. A graph of the dependence $j_c^\parallel(H)$ for the sample with $d = 300$ Å could be divided into two regions. In weak magnetic fields there was a large scatter of the values of the critical current. This scatter of $j_c^\parallel(H)$ was exhibited by samples with all thicknesses d and it was due to the influence of the intrinsic magnetic field created by the current flowing through the sample. Near the film this field was directed perpendicular to its surface and it bent the vortices when the external magnetic field had the parallel orientation and intensity not much greater than the field created by the current. A transition of a sample to the normal state could alter the proportion of the vortices interacting with the nonsuperconducting spacers. In the range of strong fields the dependence $I_c(H)$ was linear.

This linear dependence indicated that all the vortices (or their majority) were located in the superconducting region and participated in depairing processes and in suppression of the order parameter. A direct summation of the elementary pinning forces then occurred. As pointed out at the

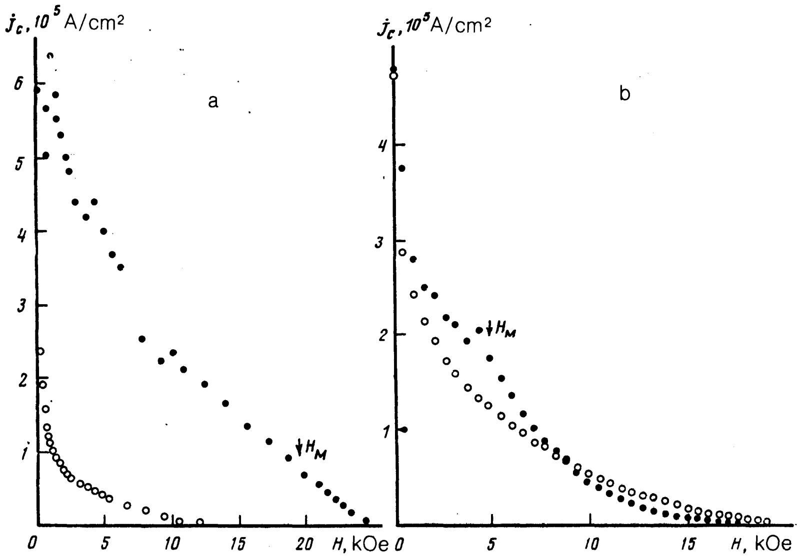

FIG. 2. Dependences $j_c(h)$ obtained for a layer structure: (●) in a parallel magnetic field; (○) in a perpendicular magnetic field; a) $d = 300$ Å, $W = 5$ μm; b) $d = 600$ Å, $W = 4$ μm.

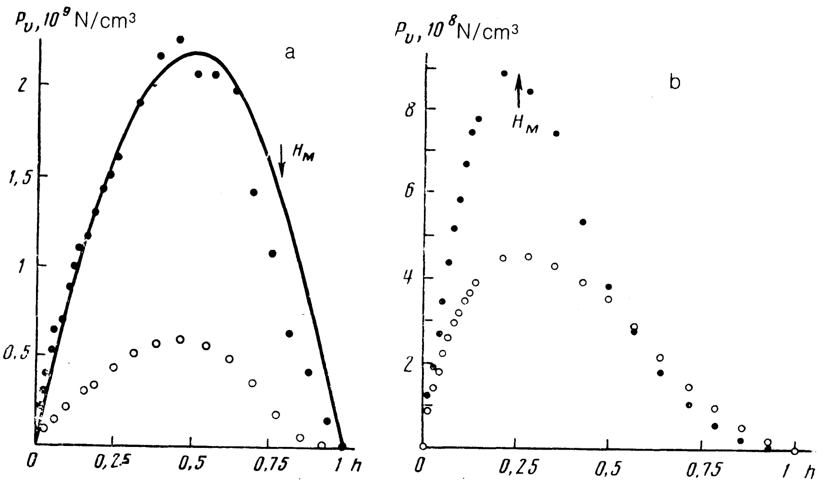

FIG. 3. Dependences $P_v(h)$ obtained for a layer structure: ●) in a parallel magnetic field; ●) in a perpendicular magnetic field; a) $d = 300$ Å, $W = 12$ μm, the continuous curve gives the dependence $P_v(h) \propto h(1-h)$; b) $d = 600$ Å, $W = 12$ μm.

beginning of this paper, this gave rise to linear field dependences of the critical current I_c and of the volume pinning force $P_v \propto (1-h)$ near H_{c2}. In the case of the samples with $d = 600$ Å and 1000 Å, a near-linear dependence $I_c(H)$ was observed in the range of fields not exceeding the matching field H_M defined by the relationship

$$H_M = \frac{3^{1/2}}{2\mu_0}\frac{\Phi_0}{d^2},$$

where Φ_0 is a magnetic flux quantum. In the field $H = H_M$ the vortex lattice was matched to the layer structure, which in the case of some samples with $d = 600$ Å and 1000 Å gave rise to a local maximum of the dependence $j_c^{\parallel}(H)$. An increase in the magnetic field to the range $H > H_M$ reduced strongly the critical current, indicating a change in the nature of pinning in this range of fields. Obviously, if $H > H_M$ we were dealing with a high density of the pinning centers, whereas when $H > H_M$ the density of these centers was low. In the former case the volume pinning force was determined by direct sunmation of the elementary forces, whereas near $H_{c2}^{\parallel}$ when $H \gg H_M$ it was governed by shear deformations of the vortex lattice. In the case of the samples with $d = 300$ Å the value of H_M was close to $H_{c2}^{\parallel}$, so that the linear law $j_c^{\parallel}(H)$ was observed right up to $H_{c2}^{\parallel}$.

These conclusions were confirmed by the dependence of the volume pinning force P_v on the magnetic field. Examples of such dependences are plotted in Fig. 3. The dependence of the pinning force shown in Fig. 3b for strong fields was close to $P_v(h) \propto h^{1/2}(1-h)^2$, typical of pinning governed by the shear deformation. This was facilitated by the interaction of the oxide layers with just a small proportion of the vortices, similar to that occurring at the boundaries of large grains. For example, in the case of the sample with $d = 600$ Å subjected to a parallel field close to $H_{c2}^{\parallel}$ only half the vortices interacted with the layer boundaries. In the case of these samples the maximum of $P_v(h)$ occurred at $H = H_M$. An increase in the layer thickness reduced the density of the pinning centers, which should reduce the value of max $P_v(h)$ in a parallel field. It is clear from Fig. 3 that this was indeed observed experimentally.

The pinning force behaved differently in samples with a small period. An example of the dependence $P_v(h)$ obtained in this case is shown in Fig. 3a, demonstrating that $P_v(h) \propto h(1-h)$, which was typical of direct summation of the elementary pinning forces. In the case of layer samples with a small thickness of the superconducting films the procedure of summation of the elementary pinning forces can be performed quite readily. Let us assume that the x axis is directed perpendicular to the layers. The elementary pinning force per unit length of a vortex is then found from the expression

$$f = \partial E/\partial x, \tag{6}$$

where $E = \frac{1}{2}\pi\mu_0 H_c^2\xi^2$ is the condensation energy per unit length of a vortex and H_c is the thermodynamic value of the critical magnetic field. Obviously, the pinning force is governed mainly by the value of $\partial H_c/\partial x$. In the case of Nb–NbO_x structures the value of H_c is maximal at the center of a niobium film and it vanishes in an oxide spacer. If we assume that H_c varies smoothly across the thickness of the films, we find that the elementary pinning force is given by

$$f \approx \frac{\pi}{2}\mu_0 d_I H_c^2(1-h), \tag{7}$$

where d_I is the thickness of the insulator (oxide) spacer and the factor $(1-h)$ allows for the reduction in the condensation energy in a magnetic field, exactly as in Eq. (2). The volume pinning force can be found by determination of the total length of the vortices per unit volume. Obviously, in our case it is governed by the intensity of the magnetic field and amounts to $\mu_0 H/\Phi_0$. We then have

$$P_v \approx \pi\mu_0^2 d_I H_c^2 \frac{H(1-h)}{2\Phi_0} = \frac{\pi}{4}\frac{\mu_0^2}{\varkappa^2\Phi_0} d_I H_{c2}^{\perp 2} H_{c2}^{\parallel} h(1-h), \tag{8}$$

where we have allowed for the fact that $H_{c2}^{\perp} = \Phi_0/2\pi\mu_0\xi^2 = 2^{1/2}\varkappa H_c$.

The experimental points in Fig. 3a are compared with the dependence $\overline{P}_v(h)$ plotted on the basis of Eq. (8) on the assumption that $\overline{P}_v(h) = \alpha P_v(h)$. The quantity α is a fitting parameter. We can see that the experimental and calculated results are in good qualitative agreement (because of similarity of the dome-shaped dependences). The factor α was found to vary within the range 0.5–3 for different samples with $d = 300$ Å. In view of the rough approximation for $\partial H_c/\partial x$ in the derivation of Eq. (8), the observed quantitative agreement should also be regarded as fully satisfactory.

Figure 3 gives also examples of the dependence of the pinning force on the perpendicular magnetic field applied to samples made of films Nos. 2 and 3. In all the measurements on the strips we found that the dependence $P_v \propto (1-h)^2$ was obtained in the limit $h \to 1$, so that the pinning due to the plastic shear deformation of the vortex lattice predominated. The disagreement between the positions of the maxima of $P_v(h)$ obtained for samples with different values of d was due to the influence of the elastic interaction of the vortex lattice with the pinning centers.[5] This pinning mechanism, important in weak magnetic fields, should be described by a dependence of the $P_v \propto h^{1/2}/(1-h)^2$ type and its effectiveness should be governed by the microstructure of a sample.

As shown in Ref. 5, the position of the maximum of $P_c(h)$ is governed by the ratio of the effectiveness of these two pinning mechanisms. In the case of weak pinning centers or because of their low density a small maximum should be observed at high values of h. Since niobium films with $d = 600$ Å had a columnar structure, the grain boundaries were strong pinning centers so that the maximum of $P_v(h)$ exhibited by such samples was located at a much lower value of h than for the samples with $d = 300$ Å.

4. CONCLUSIONS

A series of investigations of niobium-based layer structures was made. The nature of the dependences $H_{c2}(\theta)$ and $H_{c2}(T)$ demonstrated a regular geometric configuration of the structure: the oxide layers were parallel in the range $d < 450$ Å. This was supported also by a sharp maximum at $\theta = 0°$ exhibited by the dependences $I_c(\theta)$. The results obtained in an investigation of $P_v(h)$ were in agreement with the theoretical hypothesis of two pinning mechanisms. In the case of layer structures with a large period exposed to strong fields the critical current was governed by shear deformation of the vortex lattice. When the period of the layers of the magnetic field were reduced, such a lattice was destroyed and the vortices exhibited liquid-like flow so that the volume pinning force was the result of direct summation of the elementary pinning forces exerted by the oxide spacers. This was supported by the nature of the dependence of the volume pinning force on the magnetic field and on the thickness of the spacers, as well as by the magnitude of this force.

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