The effect of a nonuniform electric field on the pinning of vortices in superconducting films

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A theoretical model is proposed to describe the effect of a nonuniform electric field on the pinning of magnetic vortices in superconducting films. The model shows that a nonuniform electric field can create additional energy barriers in the superconductor, which are pinning potentials for magnetic vortices. The interaction between the superconductor and the field arises from the spatial nonuniformity of the latter, which can be generated by a nonuniform configuration of artificial gate electrodes. The possibility of using this effect in structures resembling a superconducting field-effect transistor with a spatially nonuniform gate is discussed. This method of probing superconducting films can also be used to clarify the role of surface pinning in superconducting films. © *1996 American Institute of Physics.* [S1063-7761(96)01808-2]

1. INTRODUCTION

For a number of years after the discovery of high-temperature (high-T_c) superconductivity, there were investigations of the possibility of using an electric field to change the properties of high-T_c superconducting films (in geometries resembling that of a field-effect transistor, see, e.g., Refs. 1 and 2), for example, the resistive state or the value of the critical field. Applying an electric field to a high-T_c superconducting film is an interesting alternative way to create nonequilibrium states in superconductors, in addition to such traditional methods as, e.g., injection of a transport current, applying an external magnetic field, or subjecting it to electromagnetic radiation (see, e.g., Ref. 3). As mentioned in Ref. 1, there are two reasons why investigating the effect of an electric field on a superconductor is so interesting.

1. The carrier concentration in a sample can be changed in a controlled way without changing the stoichiometry of the compound. This can be an additional instrument for studying the mechanism of superconductivity in high-T_c compounds. In general, the action of an electric field on a film of superconductor is analogous to the action of microwave or optical radiation. An applied electric field acts like optical radiation[3] in that it changes the distribution function and concentration of quasiparticles,[4] and thus the magnitude of the superconducting order parameter.

2. When the electric-field-induced changes in the resistivity of the high-T_c superconducting film are sufficiently strong, the effect can be used in applications to create devices resembling field-effect transistors.

In low-temperature superconductors the effect of this mechanism on the system is very small, due to the high carrier concentration and hence the strong screening of the external electric field. Furthermore, in low-temperature superconductors the coherence length ξ is quite large. Therefore, in order to observe the effect of an electric field on the superconductor it is necessary, on the one hand, to use a film with thickness $d\sim\lambda_E$, where λ_E is the length over which the electric field is screened, but, on the other hand, d cannot be smaller than ξ, because in this case the film's superconducting properties are usually destroyed. For high-T_c materials, where the concentration of carriers is relatively small compared to that of metals, the screening length of an electric field is considerably larger: $\lambda_E\sim 10$ Å, while at the same time $\xi\sim 10$ Å, so that $\kappa=\xi/\lambda_E\sim 1$.[2] Because of this, thin films of high-T_c material can be prepared whose thickness d is several times ξ, and an electric field can penetrate such films appreciably. It is in this connection that there is interest in studying the action of an electric field on high-T_c superconducting films. There has been considerable progress toward this goal (see, e.g., Refs. 1 and 2), largely connected with successes in the technology of creating high-quality thin high-T_c superconducting films.

In this article a theoretical model is proposed for describing the effect of a nonuniform electric field on such superconducting films. In order for an electric field to affect a superconductor,[1,2,5] it must change the electrophysical characteristics of the superconducting film (for example, its resistivity and critical current j_c). Let us recall that first and foremost among the resistivity mechanisms in high-T_c superconducting films (see, e.g., Ref. 6) are the dissipative mechanisms associated with the motion of magnetic vortices[6–8] (in particular, vortices generated by a transport current). In thin films, the "washing-out" factor $w/d\gg 1$ (where w is the width of the film and d its thickness), which destroys the Bean–Livingston barrier to magnetic vortices created by a transport current even for very small values of the latter. However, in this case the resistive state does not appear for small currents, because the vortices that penetrate the film are pinned[9] by their interaction with nonuniformities of the crystal lattice. That is, electrophysical characteristics of a high-T_c superconducting sample such as its critical current and resistivity are to a considerable degree determined by the pinning of vortices, i.e., their attachment to points within the sample due to interaction with nonuniformities. Therefore, there is interest in investigating various artificial ways to modify the pinning of vortices. This article will focus on the way an external electric field affects vortex pinning in a superconducting film.

As a starting point we will use the methodology of Ref.

10, where it was shown that the presence of an electric field in the near-surface layer of the superconductor leads to the appearance of an additional energy barrier (along with the Bean-Livingston barrier) to the penetration of magnetic vortices into the sample. Our basic idea is that the surface energy barrier obtained in Ref. 10 is, in essence, a local nonuniformity for a magnetic vortex. In other words, the free energy of a magnetic vortex is changed in the presence of an electric field. Therefore, it is obvious that if the distribution of electric field in the plane of the superconducting film is somewhat nonuniform, the free energy of a magnetic vortex will be different depending on where this vortex is located (more precisely, on what the magnitude of the electric field is in the vicinity of the point where the vortex is located). Thus, a spatially nonuniform electric field should play the role of an additional pinning potential.

It is clear that the electric field can be nonuniform for two reasons. First of all, the gate in a traditional field-effect transistor configuration[2] need not take the form of a continuous film; it can also have a nonuniform structure (e.g., a grating, metallic strip, etc.). Secondly, even if the gate is uniform in the plane of the film, nonuniformity can exist either in the high-T_c film itself (e.g., nonstoichiometry of composition, interruption of the film continuity), in the dielectric substrate, and/or in some interlayer between the gate and the film. Material nonuniformity can also be involved, e.g., either natural or artificial modulation of the dielectric permittivity.

For simplicity we will neglect the interaction of vortices, and consider a single-particle problem as in the classical theory of creep.[9] In order to find the value of the energy barrier we compute the free energy as in Refs. 10–12, with the difference that the configuration of fields we will discuss is somewhat different, namely that of a thin-film field-effect transistor.[2]

Note also that in our discussion of the interaction of a magnetic vortex with the pinning potential created by the gate electric field we will neglect the presence of edge potential barriers in the superconducting film, such as the Bean-Livingston and geometric barriers.[13] The geometric barrier, which is associated with the nonuniform distribution of magnetic field,[13] and the surface Bean-Livingston barrier, whose role is enhanced in bulk samples, can play a significant role in determining the conditions for entry of a vortex into the superconductor. Thus, in Refs. 13 and 14 it was shown that these energy barriers can determine the hysteresis of the magnetization in superconducting samples in which the bulk pinning potential is comparatively small or even absent. It is clear why the bulk pinning potential must be small in this case. The fact is that in the most general case the entry of a vortex into the sample, and its subsequent motion, are significantly affected by all the energy barriers: the Bean-Livingston, geometric, and bulk (structural) pinning potential barriers, as well as potential barriers discussed in this article.

The behavior of vortices is determined by "collisions" with all of these barriers. Under different conditions, different kinds of energy barriers can play the most important role. Thus, for example, under the conditions discussed in Refs. 13 and 14, the bulk pinning potential is small and the edge energy barriers are of most interest (geometric or Bean-Livingston, depending on the conditions). The situation we will discuss here requires that we have effective control over the motion of vortices via artificial pinning potentials created by a nonuniform electric field, so that we must ensure that this pinning potential be the strongest, i.e., that the overall effect of this potential on the vortex system be no smaller than the action of the other energy barriers. To satisfy these conditions in experiment it is obviously necessary to use films whose structural quality is sufficiently high (so that structural pinning will not be too strong); the gate of the field-effect transistor must be made in the form of a large number of parallel strips (so that there will be many potential wells). Furthermore, the electric field created by the gate should be strong (the strength of the pinning potential, as we will see, is proportional to the magnitude of this field). However, when the gate electric fields are weak, the strength of the pinning potential created by this field will be small, and the motion of vortices will be determined by their interaction with edge energy barriers and structural pinning potential barriers.

In this case the gate strips should extend along the direction of the transport current in the superconducting film (i.e., perpendicular to the direction of motion of the vortices). The geometric configuration of the gate is arranged so that the potential barriers caused by the gate electric field are a more serious obstacle to the vortices than barriers from structural pinning potentials. This is because the structural nonuniformities are usually localized in spaces over scales much smaller than the size of the film, whereas the strip structure of the gate creates a quasi-one-dimensional potential relief for vortices in the superconducting film in the direction of their motion.

Experimental evidence that the potential created by the nonuniform electric field affects the vortex system is found in changes in the resistive state of the superconducting film as the value of the gate electric field changes.

2. STRUCTURE OF THE MAGNETIC FIELD

Consider the magnetic field structure created by the transport current in an experiment where a constant electric field is applied to a thin high-T_c superconducting film (see, e.g., Refs. 1 and 2). For the reasons pointed out above, experiments where the electric field penetrates into the high-T_c superconducting film require that rather thin films be used.[1,2] In this case the experimental geometry and magnetic-field structure are qualitatively similar to the picture shown in Figs. 1 and 1b. It is obvious that the lines of force of the magnetic field have maximum curvature at the edges of the film, as shown in Fig. 1b. Under these conditions the geometric factor w/d plays an important role. Because of this geometric factor the first critical field is renormalized:

$$H_{c1} \sim H_{c1}^{\text{bulk}} d/w,$$

where H_{c1} is the critical field in the film, H_{c1}^{bulk} is the critical field in a bulk sample. Consequently, the magnetic field penetrates from the edges, and the lines of force of the magnetic

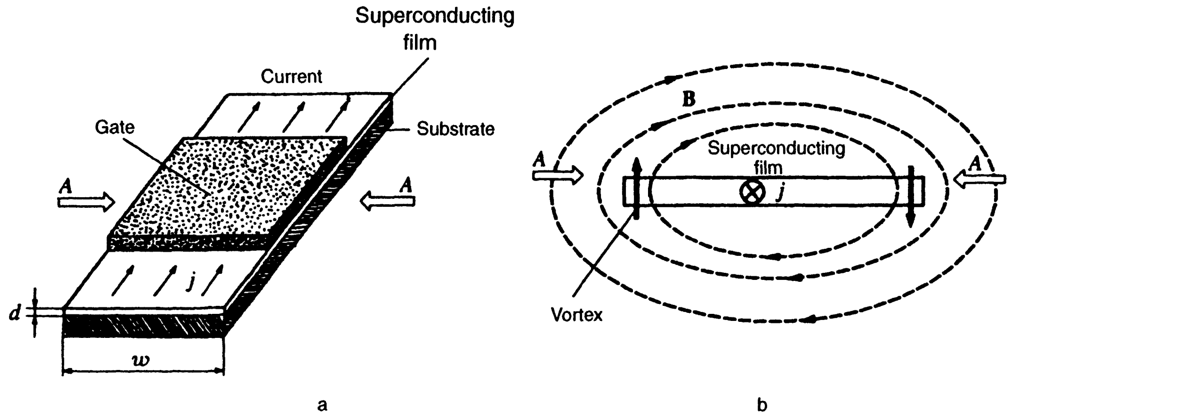

FIG. 1. a—Schematic illustration of a superconducting field-effect transistor structure. A layer of dielectric is placed between the gate and the superconducting film, so that the experimental current in the gate circuit is small. b— Sketch of magnetic field lines of force in the transverse cross section AA of a film with current. The curvature of the lines of force is largest at the edges of the film, which ensures that the entry of magnetic vortices from the edges of the film is energetically favored (as shown schematically).

field in the vortices are perpendicular to the plane of the film. The gate used in the experiments of Refs. 1 and 2 was located above the film, and its planes were parallel to the film. Because of this, the electric field was parallel (or antiparallel) to the induction vector **B** in the vortices.

These facts clearly show that the magnetic induction vector **B** intersects the layer in which the electric field penetrates during the entire motion of the vortex from the edges to the center of the film. Therefore, even though the effect of the electric field is a surface effect, it influences the transport properties (creep) of the magnetic vortices.

It is important to note that this mechanism for electric-field- induced changes in the vortex pinning potential is not the same as the mechanism in which the superconducting properties of the film (for example, the order parameter) are changed by electric-field-induced changes in the carrier concentration. It is well known[6,8,9] that the resistivity of a superconducting film associated with thermally activated creep depends exponentially on the value of the pinning potential. Therefore, even rather insignificant changes in the vortex pinning potential can, in principle, lead to large changes in the magnitude of the resistance of the critical current.

3. CHANGES IN PINNING POTENTIAL CAUSED BY AN ELECTRIC FIELD

Following Ref. 10, we next discuss the difference in free energies of the two states—with and without a vortex—in a film with an electric field. In this way we determine the value of the energy barrier for a vortex. Without including anisotropy of the coherence length ξ, the Ginzburg-Landau free energy has the form[10]

$$G=\int\left\{\frac{(\mathbf{B}-\mathbf{H})^2}{8\pi}+\nu\left[\left|\xi\left(\nabla-\frac{2ie}{c}\mathbf{A}\right)\Delta\right|^2-\alpha|\Delta|^2+\frac{\beta}{2}|\Delta|^4\right]\right\}d^3r, \tag{1}$$

where Δ is the order parameter, **B** and **H** are the magnetic induction and external magnetic field vectors respectively, and ν is the density of states. Let us assume that the electric field is perpendicular to the plane of the film and is directed along the z axis, while the coordinate axes for x and y lie in the plane of the film.

In Eq. (1), the presence of the electric field can be taken into account in the linear approximation[10,11] by renormalizing the value of α:

$$\alpha=\tau+\frac{1}{g}\frac{\delta n}{n_0}, \tag{2}$$

here we have set $\tau=(T_c-T)/T_c$ (where T_c is the critical temperature at $E=0$), g is the superconducting pairing constant, n_0 is the carrier density at $E=0$, and $\delta n=\delta n(E)$ is the change in carrier density in the near-surface layer due to the presence of the electric field. In this case, as was noted in Ref. 10, we assume that the value of $\Delta(\mathbf{r})$ and its change $\delta\Delta(\mathbf{r})$ are small.

In our geometry (see Fig. 2), we will assume for simplicity of calculation that the electric field is directed along

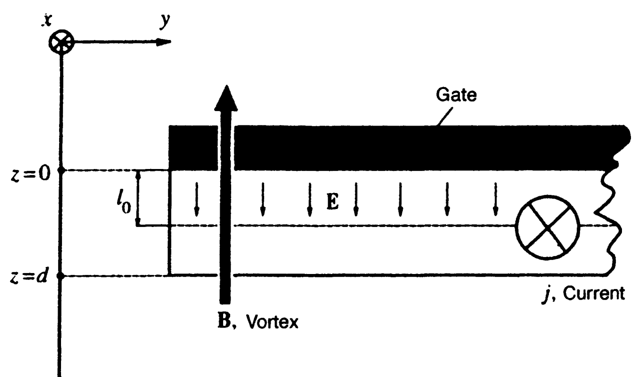

FIG. 2. Structure of the electric field **E** created by the gate; l_0 is the scale of Thomas-Fermi screening (the penetration depth of the field into the film). In this geometry the electric field vector **E** is parallel to the magnetic induction vector in the film **B** (the field in the vortices). A—Gate, B—Current, C—Vortex.

the z axis, and that the characteristic scale of variation of the field in the xy plane can be larger than the characteristic scales ξ, l_0, so that

$$E \equiv E_z = E_z(x,y,z). \tag{3}$$

In the Thomas-Fermi approximation we have (see Ref. 10)

$$\delta n/n_0 = (E/E^*)\exp(-z/l_0), \tag{4}$$

where $E^* = 4\pi e l_0 n_0/\epsilon$. We will assume that in the vortex $\Delta = \Delta(x,y)$ does not depend on the coordinate z. It should be noted that (4) is, in fact, the solution to the Poisson equation (see, e.g., Ref. 15) to first order in the field E.

By analogy with Refs. 10 and 12, we substitute (4) into Eq. (1) and find the variation of the Ginzburg-Landau functional. Then to first order in E we obtain the following expression for the potential barrier for a vortex in the electric field:

$$\Delta G = -\frac{\nu}{g}\int d^3r \frac{E(x,y,z)}{E^*}(|\Delta_0(x,y)|^2 - |\Delta_0(\infty)|^2), \tag{5}$$

where $\Delta_0(x,y)$ is the order parameter in the presence of a vortex for $E=0$, and $\Delta_0(\infty)$ is the order parameter in the uniform state of the superconductor, $\Delta_0^2(\infty) = \tau/2\beta$.

Taking into account the smoothness of the variation of $E(x,y,z)$ in x and y, we will assume that

$$E(x,y,z) \simeq E\exp(-z/l_0), \tag{6}$$

i.e., E can be approximately taken outside the integration sign with respect to x and y. Then

$$\Delta G \approx -\frac{\nu}{g}\frac{E}{E^*}\int_0^\infty \exp\left(-\frac{z}{l_0}\right)dz \int\int_{-\infty}^{+\infty} (|\Delta_0(x,y)|^2 - |\Delta_0(\infty)|^2)dx\,dy. \tag{7}$$

Unlike the corresponding expressions of Ref. 10, in Eq. (7) the field E and the bracketed quantity $(|\Delta_0(x,y)|^2 - |\Delta_0(\infty)|^2)$ are integrated separately. This is because in our problem the electric field $E(\mathbf{r})$ and order parameter $\Delta(\mathbf{r})$ vary mainly along different coordinates: $E(\mathbf{r})$ along the z axis, and $\Delta(\mathbf{r})$ in the xy plane.

The integral over dz in (7) is calculated as follows:

$$\Delta G = \frac{\nu\tau l_0}{2\beta g}\frac{E}{E^*}\int\int_{-\infty}^{+\infty}\left\{1 - \left|\frac{\Delta_0(x,y)}{\Delta_0(\infty)}\right|^2\right\}dx\,dy, \tag{8}$$

while the remaining integral over $dx\,dy$ is a number that is not difficult to estimate.

When the coherence length ξ is isotropic in the xy plane, the order parameter $\Delta_0(x,y)$ is in a cylindrical geometry and depends only on the distance from the vortex axis. Let us set the origin of the cylindrical coordinate system on the vortex axis. Then

$$\int\int\left\{1 - \left|\frac{\Delta_0(x,y)}{\Delta_0(\infty)}\right|^2\right\}dx\,dy \to \int_0^{2\pi}d\varphi\int_0^\infty \rho\,d\rho\left\{1 - \left|\frac{\Delta_0(\rho)}{\Delta_0(\infty)}\right|^2\right\} = 2\pi\int_0^\infty \rho\,d\rho\,S(\rho/\xi) \sim 2\pi\xi^2, \tag{9}$$

because the characteristic scale of variation of $\Delta_0(\rho)$ is $\rho \sim \xi$.

Eventually, we obtain the following estimate for the change in free energy for a vortex in an electric field:

$$\Delta G \simeq \frac{\pi\nu\tau}{\beta g} l_0\xi^2\frac{E}{E^*}. \tag{10}$$

This is also the free-energy correction when the vortex moves through a transverse cross section of the thin superconducting film.

When the field E is uniform in the xy plane, we have $\Delta G = \mathrm{const}(x,y)$ and the correction ΔG leads to a renormalization of the origin from which G is measured. If, however, the field E is nonuniform in the xy plane, ΔG depends on positions and develops a certain potential relief—i.e., "peaks" and "valleys"—which create an additional pinning potential that depends on the electric field. Furthermore, ΔG depends on the carrier concentration n_0, i.e., the larger n_0 is, the smaller the penetration depth l_0 of the field into the sample is and the smaller ΔG is. In other words, ΔG is small when the field is strongly screened.

It is obvious that the total pinning potential is the sum of the potential formed by lattice inhomogeneities and the potential formed by the variation of the electric field. Whereas the electric field is concentrated (see Fig. 2) in a layer of thickness $\sim l_0$, the lattice varies throughout the volume. Therefore, in order for the effect of an electric field in this model to be significant, the superconducting film should, as a rule, be rather thin on the scale of l_0. However, if the film is sufficiently well characterized and there are a relatively small number of pinning centers in it, it can be much thicker than l_0.

Equation (10) gives an estimate of the magnitude of the modulation of the pinning potential by the electric field to first order in the field E.

Let us first estimate the value of the characteristic field for a high-T_c superconductor:

$$E^* = \frac{4\pi e l_0 n_0}{\epsilon}. \tag{11}$$

Here l_0 is the characteristic scale for screening the electric field (see Ref. 10), $l_0 \sim \xi \sim 10$ Å $\simeq 10^{-7}$ cm, $n_0 \equiv n_F = p_F^3/3\pi^2\hbar^3 \approx 1.5\cdot 10^{21}$ cm^{-3} is the carrier concentration (electrons at the Fermi surface), and $\epsilon \approx 20$–30 is the dielectric constant. Then, according to Eq. (11), $E^* \simeq 3\cdot 10^4$ statvolt/cm $\approx 10^7$ V/cm.

Since $\tau/2\beta = \Delta_0^2(\infty)$ is the order parameter in the region far from the core of the vortex, (10) can be written in the form

$$\Delta G \simeq \frac{2\pi}{g}\nu\Delta_0^2 l_0\xi^2\frac{E}{E^*}.$$

Here the density of states is

$$\nu(\mu)\sim\frac{n_F}{\varepsilon_F}\approx 1.5\times 10^{18}\ \mathrm{cm^{-3}K^{-1}}.$$

Let us assume that $2\pi/g\sim 1$; then

$$\Delta G\sim\nu(\mu)\Delta_0^2 l_0\xi^2 E/E^*\approx 10\ \mathrm{K}\cdot E/E^*.$$

Thus, the following estimate for the change in free energy is obtained:

$$\Delta G\sim 10\ \mathrm{K}\cdot\left(\frac{E}{10^7\,\mathrm{V/cm}}\right).$$

In magnetic flux creep, all quantities (for instance, the resistivity) are proportional to $\exp(-G/T)$, where G is the pinning potential; then for $\Delta G/G\ll 1$ the relative change is $\sim(10K/T)(E/E^*)$, which, e.g., in fields $E\sim E^*$ at $T\sim$ 80 K gives $\sim$ 10%.

In reality these changes can be even larger if, as in Ref. 10, we take $g\simeq 1/3$. Then $2\pi/g\sim 10^1$ (and not $\sim$ 1, as we asserted above) and the change in resistivity, critical field, etc., can be $\sim$ 100 % in fields $E\sim E^*$.

From this model of the effect of an electric field on a superconducting film, it is clear that the largest change in the resistive state of the film can be achieved by modulating its superconducting properties in the direction of motion of the magnetic vortices (i.e., perpendicular to the direction of current flow). To do this, we can use a gate made, e.g., in the form of a strip.

4. CHANGE IN PINNING POTENTIAL AND A SUPERCONDUCTING FIELD-EFFECT TRANSISTOR

In order to illustrate the effect of a nonuniform electric field on the pinning of vortices and the resistive state of a superconductor, let us consider the following superconducting structure along which a transport current flows. We will assume that the gate is made in the shape of a longitudinal strip (parallel to the film and the direction of current flow), whose width is smaller than the film width. Then the potential arising from the gate electric field (normal to the film surface) that determines the motion of the vortices has the shape of a step barrier at the center of the film (for an electric field of opposite polarity the shape will be a well). The height of the step U_E can easily be estimated from Eqs. (10) and (11). Note that the potential $U_E(x)$ is accompanied by the "ordinary" pinning potential in the film, and also a certain viscosity connected with vortex flow;[9] however, these do not depend on the value of the gate voltage.

In this section we compute the current-voltage characteristics of this structure as a function of the potential U_E, or, which is the same thing, the gate voltage. It should be noted that rigorous calculation of the current-voltage characteristics of a superconducting film, even one that is uniform on the average, is a rather complicated problem (see, e.g., Ref. 16). Let us first pause to discuss qualitatively the structure under study. It is well known that the resistive state of a superconducting film is associated with the motion of magnetic vortices generated by a transport current at the edges of the film. At the edges of the film, vortices arise of opposite polarities. Under the action of the Lorentz force,[9] these vortices move to the center of the film and are annihilated there. When a potential barrier U_E appears in their path whose value is not small, it will be an obstacle to the vortex motion. And because the probability for a vortex to "hop" over the barrier is proportional to $\exp(-U_E/T)$, for $U_E\gg 1$ the dependence of the "hopping" rate for the vortex over the barrier will be steep (exponential).

The problem of finding the current and magnetic field distributions in a thin uniform film has been treated previously (see, e.g., Ref. 16). Qualitatively, its solution leads to a current $j(x)$ with a minimum at the center of the film and a maximum at its edges. The resistive state of such a film is associated with motion of vortices under the action of the Lorentz force exerted by the transport current. The Lorentz force acting on an isolated vortex[9] equals

$$\mathbf{f}=\frac{\phi_0}{c}\left[\mathbf{j}\frac{\mathbf{B}}{|\mathbf{B}|}\right],\tag{12}$$

where ϕ_0 is a flux quantum.

The current density j has its smallest value at the center of the film (see Ref. 16); therefore, the Lorentz force is a minimum at this point as well. Consequently, the change in pinning force in the central part of the film should have the largest effect on the current-voltage characteristics. Even a slight change in the pinning can change the latter significantly (this fact was noted in Ref. 16). Therefore, it is interesting to consider a structure with a gate in the shape of a metallic strip located above the film center. We will assume that the current is rather strong and the film is in its resistive state, and find rough estimates of the effect of the gate electric field on the current-voltage characteristics.

In this structure it is obvious that a finite resistance arises because vortices of different polarity can hop over the barrier at the center and annihilate there. If this hopping is impossible (e.g., in the limit $U_E\rightarrow\infty$), the vortices cannot annihilate, and therefore they cannot move. Some of them will simply accumulate at the "banks." However, the probability of hopping over the potential barrier equals

$$\nu=\nu_0\exp(-U_E/T),\tag{13}$$

and U_E in turn depends linearly on the gate field E_G, as we showed previously. Thus, by changing the gate voltage, it is possible in principle to obtain an exponentially strong modulation of the voltage across the superconducting structure for sufficiently large values of U_E.

From this point of view, our structure is a prototype of a new kind of field-effect transistor, in which the gate electric field creates a narrow region with a barrier to magnetic vortices whose height is regulated by the gate voltage.

4.1. ESTIMATE OF CURRENT-VOLTAGE CHARACTERISTICS

Let us consider a high barrier U_E such that the hopping of a vortex over the barrier is an exponentially rare event. We will assume that in this case the vortices are distributed rather uniformly at the edges of the film with a certain average concentration n.[1)] They cannot annihilate due to the presence of the infinitely strong potential U_E at the center of the film. Therefore, even if we consider a current that is so strong that the vortices are driven to the banks, the voltage V across such a structure will equal zero.

In what follows, in order to obtain a simple estimate we will assume that the current and vortex concentrations are distributed uniformly, although in reality the spatial distribution of carrier concentration and current depends on whether the film is thick or thin (on a scale of λ_L), and also on the amplitude and structure of the pinning potential. Therefore, the form of these distributions is not universal.

In the case where the cross section of the film is $S=wd$ (where w is the width of the film, d its thickness), the average current density equals

$$j=\frac{I}{wd}. \tag{14}$$

The average density of vortices is estimated as follows. Let us assume that the film is in its Meissner state. Then the lines of force near the surface approximately match the transverse contour of the film. As usual,

$$\oint \mathbf{B}\cdot d\mathbf{l}=\frac{4\pi}{c}I.$$

In this case, we have for the field B_s at the surface

$$B_s 2(w+d)\cong\frac{4\pi I}{c},$$

$$B_s\simeq\frac{2\pi I}{c(w+d)}\approx n_s\phi_0\approx n\phi_0,$$

where n is the average concentration in the "banks," or (because $w\gg d$)

$$n\simeq\frac{2\pi I}{c\phi_0 w}. \tag{15}$$

In steady state, a certain distribution of vortices (lattice) is set up in the banks with an average planar vortex density $\sim n$, so that the average distance between them is $l\sim n^{-1/2}$. Only when a vortex hops from the bank over the barrier will the entire distribution (all the vortices) shift by a distance $\sim l$, and then once again return to the original state, resulting in only one vortex moving into the film. Hops at the barrier are exceptionally rare events, so that the distribution is quasi-steady-state. Then the flux of vortices in each of the banks is

$$q_1\simeq n_1 v_1=n_1\nu l\simeq n\nu_0\exp(-U_E/T)n^{-1/2}$$
$$=n^{1/2}\nu_0\exp(-U_E/T). \tag{16}$$

The quasi-steady-state condition implies that this should also be the flux of vortices in the neighborhood of the barrier q_2, i.e., $q_2=q_1$, and therefore that the concentration of vortices in the barrier n_2 depends on the effective viscosity of vortex flow in this region.

Thus, the average flux of vortices is determined by Eq. (16). The electric field E_j induced by the motion of the vortices is determined by the general expression[9]

$$\mathbf{E_j}=\mathbf{B}\times\mathbf{v}/c, \tag{17}$$

i.e., E_j is parallel to the direction of the current j. From (17) we have

$$E_j=Bv/c=n\phi_0 v/c=\langle q\rangle\phi_0/c.$$

Thus, the electric field induced across the structure, taking into account Eq. (16), equals

$$E_j=n^{1/2}\frac{\nu_0\phi_0}{c}\exp\left(-\frac{U_E}{T}\right).$$

Finally, taking (15) into account, we obtain the expression for the electric field due to motion of vortices in the film:

$$E_j=\left(\frac{2\pi\phi_0 I}{c^3 w}\right)^{1/2}\nu_0\exp\left(-\frac{U_E}{T}\right). \tag{18}$$

Thus, we have obtained a completely understandable result: the current–voltage characteristics depend on the gate potential exponentially ($\propto\exp(-U_E/T)$). This is associated with the exponential probability of overcoming the barrier to the vortices created by the electric field. As we showed previously, the order of magnitude of the change connected with this exponential can be as large as 100% for electric fields achievable in experiments ($E\sim10^7-10^8$ V/cm). Note that the width of the gate strip does not enter into this solution (i.e., the shape of the current–voltage characteristics). This is explained by the approximation we have used: rather than find the profile of the current distribution or density distribution, we took a certain average value. Therefore, our result is only an estimate that illustrates the exponential dependence of the current-voltage characteristics on the magnitude of the gate field.

It is clear that the larger this effect is, the more effectively vortices are pinned at the barrier created by the gate electric field. In order to ensure a large pinning efficiency, the gate can be made in the form of a series of parallel strips instead of a single strip (as in the case discussed here). Then in the course of its motion, a vortex will be successively "hooked" by these strips, causing an effective braking of the vortex motion through the film.

It should be pointed out that in deriving Eq. (18), we have in fact ignored the presence of bulk pinning of vortices at structural nonuniformities. We have assumed that the pinning potential U_E created by the electric field is the most significant perturbation on the motion of the vortices. If this is not so (e.g., for films that are thick on the scale l_0, in which structural pinning is always significant), the effect we have obtained (changes in the current-voltage characteristics) will obviously be reduced by the ratio of the pinning energy at irregularities of the electric field to the pinning energy at structural irregularities. If we assume that the value of the pinning potential is proportional to the layer thickness in which the pinning centers are located, the change in current-voltage characteristics and critical current for a thick film will be smaller by $\sim d/l_0$ (where l_0 is the scale of penetration of the electric field and d is the film thickness). However, even in this case the effect may be significant, due to the abrupt exponential dependence in Eq. (18).

5. CONCLUSION

In describing the mechanism proposed here for the action of an electric field on a superconductor, we have demonstrated that a nonuniform electric field creates an additional pinning potential for magnetic vortices. It is clear that in this case the films need not be necessarily single-crystal or continuous. However, the films should be rather thin. In fact, the length of a vortex in the film is the same order as its thickness, and the largest effect should occur when the electric field acts over a large portion of the vortex. In the opposite case, if the film is thick and the electric field is concentrated near the surface, the electric field will bring about only surface pinning, and the vortex pinning will be determined by structural nonuniformities in the volume of the film.

The assumptions discussed here can facilitate the study of spatially nonuniform states created artificially by using a spatially nonuniform gate profile (e.g., by lithographic methods). In order to experimentally reveal this mechanism, it appears to us that a spatially nonuniform gate configuration must be used, in a geometry similar to that of a field-effect transistor. This will correspond to an artificially created pinning potential profile, whose strength can be controlled by an applied voltage. In addition, these structures can be used to clarify the role of surface pinning in superconducting films.

[1)]Of course, this is a rather strong assumption; however, it allows us to obtain the form of the current–voltage characteristics.

[1]J. Mannhart, J. G. Bednorz, K. A. Müller, and D. G. Schlom, Z. Phys. B (Condensed Matter) **83**, 307 (1991).

[2]J. Mannhart, Mod. Phys. Lett. B **6**, 555 (1992).

[3]V. F. Eselin and Yu. V. Kopaev, Usp. Fiz. Nauk **133**, 259 (1981) [Sov. Phys. Usp. **24**, 116 (1981)].

[4]J. Mannhart, D. G. Schlom, J. G. Bednorz, and K. A. Müller, Phys. Rev. Lett. **67**, 2099 (1981).

[5]V. V. Lemanov and A. L. Kholkin, Fiz. Tverd. Tela (St. Petersburg) **36**, 1537 (1994) [Solid State Phys. **36**, 841 (1994)].

[6]G. M. Genkin and A. V. Okomel'kov, Zh. Éksp. Teor. Fiz. **103**, 2072 (1993) [Sov. Phys. JETP **76**, 1030 (1993)].

[7]A. M. Kadin, J. Appl. Phys. **68**, 5741 (1990).

[8]E. Zeldov, N. M. Amer, G. Koren *et al.*, Phys. Rev. Lett. **62**, 3093 (1989).

[9]M. Tinkham, *Introduction to Superconductivity*, McGraw-Hill, New York, 1975.

[10]L. Burlachkov, B. Khalfin, and B. Ya. Shapiro, Phys. Rev. B **48**, 1156 (1993).

[11]V. M. Nabutovskiĭ and B. Ya. Shapiro, Zh. Éksp. Teor. Fiz. **75**, 948 (1978) [Sov. Phys. JETP **48**, 480 (1978)].

[12]V. B. Geshkenbeĭn, Zh. Éksp. Teor. Fiz. **94**(10), 368 (1988) [Sov. Phys. JETP **67**, 2166 (1988)].

[13]E. Zeldov, A. I. Larkin, V. B. Geshkenbeĭn *et al.*, Phys. Rev. Lett. **73**, 1428 (1994).

[14]Ming Xu, D. K. Finnemore, G. W. Crabtree *et al.*, Phys. Rev. B **48**, 10630 (1993).

[15]M. Ghinovker, V. B. Sandomirsky, and B. Ya. Shapiro, Phys. Rev. B **51**, 8404 (1995).

[16]L. G. Aslamazov and S. V. Lempitskiĭ, Zh. Éksp. Teor. Fiz. **84**, 2216 (1983) [Sov. Phys. JETP **57**, 1291 (1983)].

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