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Anisotropic pinning enhancement in Nb films with arrays of submicrometric Ni lines

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Arrays of submicrometric Ni lines have been fabricated in superconducting Nb films by electron beam lithography. In the mixed state, these arrays induce strong anisotropy in the dissipation behavior. The dissipation is reduced several orders of magnitude, in the whole applied magnetic field range, when the vortex motion is perpendicular to the Ni lines (applied current parallel to them) in comparison with dissipation of vortices moving parallel to the lines. In addition, for the samples studied in this work, a change in the slope of the $\rho(B)$ curves is observed when the vortices move perpendicular to the lines and the vortex lattice parameter matches the width of the Ni lines. [DOI: 10.1063/1.1512947]

The control and reduction of the dissipation produced by vortex motion in superconductors is one of the main issues for the potential applications of these materials in the presence of magnetic fields. The introduction of artificial pinning centers in the superconductor is a very useful method to modify, in a controlled way, the vortex lattice motion, and, therefore, to reduce the dissipation.[1–4] The recent development of lithography technologies has provided the method for the preparation of such controlled structures not only with size comparable to important pinning length scales, but regular arrays too.[5,6] These pinning centers lock the vortex lattice[3] and, as a consequence, can reduce the dissipation. Although these structures are of technological interest by themselves, for instance antidot arrays have been already applied to the reduction of flux noise in superconducting quantum interference devices of high temperature superconductors,[7] they are also used as a powerful tool to get a further understanding of the fundamental properties of vortex lattice dynamics.[8]

Arrays of magnetic dots seem to be one of the best choices as pinning centers for the vortex lattice.[9] They can provide a reduction in the vortex motion dissipation and an increase in the critical current density when the vortex lattice matches the geometrical parameters of the array.[3] These arrays have been used to analyze basic properties of the mixed state too; for example elastic properties.[10]

In this work, we have studied how a very anisotropic array of extended pinning centers (Ni lines) modifies the dissipation in superconducting Nb films. The field dependencies of resistivity and critical current have been measured in the mixed state for different temperatures, array periods, current densities, and the most crucial, relative orientations between driving current and Ni lines. Combination of these experiments has been used to get a further insight in the anisotropic behavior of vortex lattice dissipation induced by the presence of a channeled pinning potential.

Magnetic Ni lines of width $d=200$ nm and thickness $t=40$ nm, with line periods of $L=0.5$ μm (sample I) and 0.8 μm (sample II) were prepared on oxidized Si (100) substrates using electron beam lithography. The pattern was defined on a poly(methylmethacrylate) resist layer; then magnetic (Ni) layer was sputtered on top. A lift-off process follows and, after this, a 100-nm-thick Nb film was sputtered. Finally, standard optical lithography and ion beam etching defined a bridge for transport measurements. The pattern is a 40 μm wide Nb crosscentered on the Ni line array, so that, the current can flow along two orthogonal paths aligned along the two principal directions of the Ni line array. Magnetotransport measurements were performed in a helium cryostat with a 9 T superconducting magnet, with the magnetic field always applied perpendicular to the substrate. Then, depending on the selected current path, the Lorentz force, $F_L = J \times B$, can point along two perpendicular directions relative to the array of Ni lines. Two geometries have been used in this work: geometry A: J parallel to Ni lines and therefore, vortex velocity perpendicular to them; and geometry B: J perpendicular to magnetic lines and vortex velocity parallel to Ni lines.

Figure 1 shows the results obtained from $\rho(B)$ measurements performed on sample I ($L=0.5$ μm). Current was applied parallel [Fig. 1(a)] and perpendicular [Fig. 1(b)] to Ni

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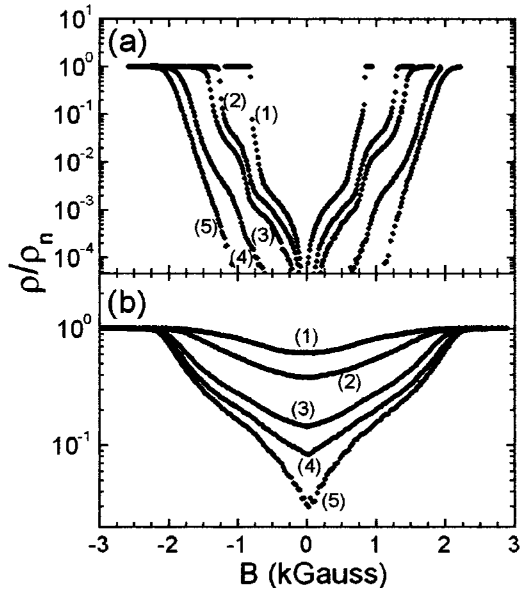

FIG. 1. Field dependence of normalized resistivity at $T=0.94\ T_c$. 2(a) and 2(b) correspond to geometry A (vortex motion perpendicular to the Ni lines) and geometry B (vortex motion parallel to the Ni lines) respectively. In Fig. 2(a) applied currents were $J=22$, 12, 8.7, 5, and 2.5×10^4 A/cm^2 for (1), (2), (3), (4), and (5) curves, respectively. In Fig. 2(b) applied currents were $J=50$, 25, 12, 8, and 2×10^3 A/cm^2 for (1), (2), (3), (4), and (5) curves, respectively.

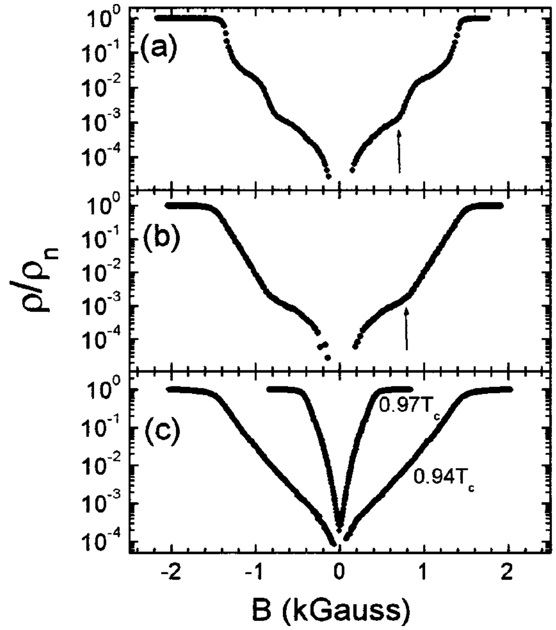

FIG. 2. Field dependence of normalized resistivity at $T=0.94\ T_c$ obtained for sample I, 2(a), and sample II, 2(b). Figure 2(c) shows the field dependence of normalized resistivity at $T=0.94\ T_c$ and $T=0.97\ T_c$ obtained for sample III (line period of 1.4 μm with 800 nm Ni linewidth). Applied current was 1×10^5 A/cm^2 parallel to Ni lines. Arrows indicate the matching field values.

lines. Temperature was set to 8.2 K, corresponding to a reduced temperature of 0.94 T_c. When driving current is applied parallel to Ni lines [Fig. 1(a), vortex motion perpendicular to the lines] two clear changes in the $\rho(B)$ slope are observed. On the other hand, monotonic behavior was obtained when current was applied perpendicular to Ni lines [Fig. 1(b), vortex motion parallel to the lines]. Magnetic fields, at which these slope changes occur, are B_1, and $B_2 \cong 2B_1$, being $B_1 \cong 0.7$ kG corresponding to a density of vortices $n_v = B/\Phi_0 \cong 3\times10^9$ cm^{-2}. Considering a triangular vortex lattice, this density would induce a distance between adjacent vortices of 190 nm, very close to the Ni line width (200 nm). This fact suggests that the observed enhanced vortex pinning is produced at the edges of magnetic lines due to the enhancement of proximity effect in the Nb film on top of line edges. Matching effects in the $\rho(B)$ curve for magnetic fields corresponding to Ni line periods are not observed. In particular for this sample I, the matching field for the period $L=500$ nm would be $\Delta B \cong 0.095$ kG, but at this field the measurements have not revealed any signature. These results can be understood in terms of the correlation length of vortex lattice, that is the characteristic distance where the translational order in the moving vortex lattice is actually kept.[11,12] Matching effects are only efficiently produced if correlation length of vortex lattice is larger than the distance between pinning centers. In our case, distance between line edges is smaller than line period, this could explain why matching effects take place when vortex distance matches line width, instead of array period that is probably larger than correlation length. Finally, it is worth to note that these pinning effects when the vortex lattice matches the line width have also been observed in experiments performed in NbN/Nb_3Ge bilayers with weak-pinning channels.[13] In this case the matching effects are observed when the vortex motion is along these very weak pinning channels. In our case the matching effects are observed for currents applied parallel to the channels and vortex motion perpendicular to them.

Figure 2 shows the $\rho(B)$ curves obtained in geometry A (vortex moving perpendicular to magnetic lines) for sample I [Fig. 2(a)] and sample II [Fig. 2(b)], both films with lines of 200 nm width and with separation between lines of 300 nm (sample I) and 600 nm (sample II). Temperature was $T=0.94T_c$ and applied current was 10^5 A/cm^2. The anomalies in the $\rho(B)$ curves are observed at similar magnetic fields in the same range for both samples. In particular, for sample II, they are at $\Delta B \cong 0.8$ kG, that corresponds to an intervortex distance of 175 nm (triangular vortex lattice), close to the line width, and for sample I $\Delta B \cong 0.7$ kG (intervortex distance of 190 nm). This fact supports the role played by the linewidth. To clarify even more this point, a third sample (sample III) was grown with separation between lines of 500 nm, but with line width four times larger (800 nm) than in the case of samples I and II. Therefore, if the separation is the crucial length, a slope change should appear at lower magnetic fields ($\Delta B \cong 0.1$ kG) than those observed in Figs. 2(a) and 2(b). Nevertheless, the experimental data obtained on sample III [Fig. 2(c)] show monotonic magnetic field dependence.

From Figs. 2(a) and 2(b) it is clear that changes observed in the $\rho(B)$ slope are more intense when the line period, L, is reduced. As a matter of fact, two slope changes (at fixed field intervals of $\Delta B \approx 0.7$ kG) are observed in sample I, whereas only one is observed in sample II. As the array period is reduced, the ratio [Ni lines]/[Nb] is increased and, as a consequence, the artificially induced pinning is enhanced with respect to Nb intrinsic pinning.

By inspection of Fig. 1 ($T=0.94\ T_c$), it can be noted that, in a wide field range, the overall resistivity values at the

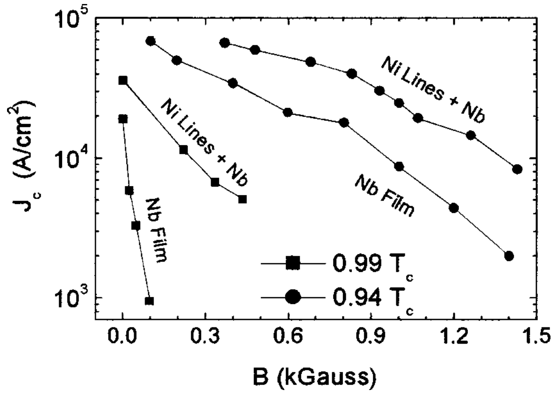

FIG. 3. Critical current vs magnetic field for sample I (period 0.5 μm and linewidth 200 nm), and for 100-nm-thick Nb film without array of Ni lines, at 0.99 and 0.94 T_c.

same magnetic field and for the same applied current are several orders of magnitude lower in geometry A [Fig. 1(a)] than in geometry B [Fig. 1(b)]. This enhancement in the pinning effect has been also observed in experiments performed on rectangular arrays of Ni dots.[14] Furthermore, previous theoretical simulations on rectangular arrays of point pinning centers predicted this anisotropic dissipation.[15] In Ref. 15, authors found that the main effect of changing the current direction relative to the rectangular array of defects is a clear anisotropy in the background pinning that is lower when the vortex lattice moves along the long dimension of the rectangular array than when it moves parallel to the shortest dimension of the array. In our case, the presence of magnetic lines in the Nb film defines a channeled pinning potential and, therefore, produces a very high anisotropic dissipation. In geometry B, the vortex lattice will flow along these easy paths (Ni lines) without any variation of the pinning potential in the direction of motion. On the other hand, in geometry A, vortex lattice crosses the channels in the pinning potential, leading to a slow down vortex lattice motion and reducing the induced dissipation. This effect will occur for any magnetic field, and it is further enhanced when the field values are such that the vortex lattice parameter matches the linewidth, as observed in Fig. 2.

Finally, using the same voltage criterion that Hoffmann *et al.*,[16] field dependence of critical current (J_c) has been measured on sample I (see Fig. 3) with driving current applied parallel to Ni lines (geometry A). We have found an increase of the critical current value and a smoother field dependence of J_c than in the case of Nb films with array of Ni dots[16] and Nb films. As was commented before, when the vortex lattice is moving perpendicular to Ni lines there is an enhancement in pinning force. This enhancement is produced in a wide field range (does not depend on the distance between vortices), in such a way that the array of Ni lines could be a good tool to reduce the sharp decrease of J_c with applied magnetic fields.

In summary, anisotropic pinning effects have been studied in Nb films with regular arrays of Ni lines. Matching effects in magnetoresistence have been observed when vortex lattice matches the Ni linewidth and they are only detected when the vortices move perpendicular to the Ni lines. Furthermore, a very significant decrease in dissipation, due to enhancement in pinning force, is observed for the whole range of applied magnetic fields for current applied parallel to the Ni lines. In fact, for this current configuration, the Nb films with the line arrays show a smoother magnetic field dependence of the critical current than observed on Nb films and patterned Nb films with similar dimensions of square arrays of Ni dots.

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