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Vortex phases and energy dissipation in narrow Nb strips: Reduction of collective pinning

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A novel size effect in narrow Nb strips in relation to the width w was found in perpendicular fields much higher than H_{c1}; upon decreasing the width, even at 4.2 K, a linear resistivity at low current densities appeared for $w \leq 1.12$ μm, and the linear resistivity showed an enhancement with decreasing w. This behavior was explained by the reduction of collective pinning which occurs when w becomes comparable to the size of a hopping bundle of vortices. However, if w is further reduced, vortices are pinned individually and the surface barrier acts as a deep pinning potential, which resulted in a recovery of a high J_C. In zero field, these strips showed a clear increase in the critical current density with decreasing w, which agrees well with a calculation which takes into account the current concentration near the edges.

Dissipation in superconducting microbridges or strips was a subject of intense study more than ten years ago. Physically interesting problems in these systems were weak-link properties due to phase-slip events[1] or the periodic motion of vortices.[2] These studies were done mainly in zero applied magnetic field and in the presence of microwaves. However, properties in high magnetic fields ($H \gg H_{c1}$), where a considerable number of vortices exist, have not been studied intensively. Therefore, size effects in a mesoscopic vortex system, which is formed in a superconducting narrow strip in the mixed state, are interesting problems to investigate.

After the discovery of high-T_c superconductors, significant progress in the understanding of the mixed state in type-II superconductors has been achieved. For example, the collective-pinning theory,[3] the vortex-glass theory,[4] and the vortex-lattice melting theory[5] have introduced important ideas. Based upon these understandings, we have tried to study the size effects, in relation to the transverse size of a system, on the formation of vortex phases and energy dissipation in narrow strips of a type-II superconductor. We have already found a size effect in the vortex-glass transition in $YBa_2Cu_3O_7$ strips with widths of 0.54–5.6 μm.[6] We used Nb strips here, because it is expected that damage in the milling process is far smaller for metallic superconductors than for high-T_c oxides. Strips with the width down to 0.2 μm were successfully patterned without significant damage. In this paper, we deal with three subjects: (a) the surface effect on the critical current when the strip is in the Meissner state, (b) vortex phases in relation to the strip width, and (c) reduction of collective pinning of vortices for narrower strips.

The Nb films used here were deposited on a silicon wafer by rf magnetron sputtering with a 15-cm-diam Nb target (99.98%) using Ar gas.[7] The total gas pressure was 8.0 mTorr. The rf power was 400 W, and the deposition rate was 90 nm/min. The film thickness d was 0.1 μm. The wafer was cut into many pieces with sizes of about 1×1 cm^2. All the strips used here were patterned on pieces taken from a single wafer. The film on one piece was photolithographically patterned into six bridges which are 14 μm wide, 20 μm long with 1-mm-wide contact pads on both ends. A focused-ion beam (FIB) with Ga ions was used to further mill the bridges into strips with various widths. The length of the narrowest part was 10 μm. As in Ref. 6, the photoresist on the microbridges was left to protect Nb from suffering damages from the top surface. The current and voltage leads were attached onto the contact pads with indium solder. A standard dc four-probe method was used, and the voltage was read with a Keithley 182 nanovoltmeter for both current directions. The magnetic field was applied perpendicular to the substrate. No magnetic shield was used. The sample was soaked in liquid helium during the I-V measurements.

The onset temperature of the superconducting transition was 8.1 K for all strips. The zero-resistivity temperature T_{c0} was 8.0 K for strips wider than 0.67 μm, 7.9 K for 0.45-μm- and 0.67-μm-wide ones, 7.8 K for a 0.33-μm-wide one, and 7.6 K for a 0.18-μm-wide one. For these strips, we judged from the critical-current data described later that the damage produced by the process was not significant. For a strip with a width w of 0.10 μm, T_{c0} was 6.0 K and the critical current density in zero field showed some decrease. Therefore, we mainly report on the strips with widths $w \geq 0.18$ μm. The residual resistivities of the strips were in the range 8–18 $\mu\Omega$ cm, and no correlation with width was observed. The upper critical field H_{c2} at 4.2 K, defined by the resistivity midpoint, was 1.7 T. This gives the Ginzburg-Landau (GL) coherence length ξ of ~ 14 nm at 4.2 K. The penetration depth λ for films prepared in the same way has been measured by a transmission line method[8] to be ~ 80 nm at 4.2 K, which gives the lower critical field $H_{c1} \sim 0.045$ T for the bulk.

Figure 1 shows the electric field E vs the current density $J(\equiv I/wd)$ of the strips with various widths in 0.5 T at 4.2 K. Three different regimes can be distinguished: (a) the narrowest-width regime (0.18–0.33 μm) where the E-J curve shows upward curvature, (b) the intermediate-width regime (0.45–1.12 μm) where linear resistivity is observable at low current densities, and (c) the wide-width regime (2.13–10.54 μm) where the onset of dissipation with increasing current is very sharp. It should be emphasized that we have systematically changed the width and no exception to the above classification was found. The change in the E-J curve at 4.2 K with magnetic fields is shown in Fig. 2 for the 0.73-μm-wide strip which is in the intermediate-width regime. The linear E-J relation observed at higher current densities corresponds to the normal-state resistivity. In 0.02 T and in zero field, the onset of dissipation is so sudden that the voltage jumps from below the noise level to that of the normal state. We suppose this behavior is caused by a sudden breakdown of the Meissner state. In fields well below H_{c1}, the strip is in the Meissner state and no vortex exists inside at low current densities. Current distribution in this state can be calculated,[9] which shows some enhancement of local current densities near the edges. With increasing current, the potential barrier for the entry of vortices disappears when the local current density at the edges reaches approximately one-half of the depairing current density.[10] This leads to the entry of vortices and the breakdown of the Meissner state. Since the current density is already very high ($\sim 10^7$ A/cm^2) when the vortices begin to enter, the vortices are not pinned and the dissipation due to the motion of these vortices results in quenching the superconductivity, which is observed as the sudden onset of the normal-state resistivity.

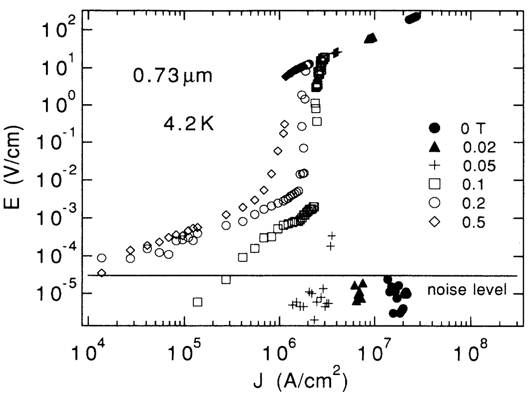

FIG. 2. E-J curves of the 0.73-μm-wide strip in various fields at 4.2 K. The solid line shows the noise level.

The above scenario for the sudden onset of dissipation can be checked quantitatively by comparing the observed critical current density $J_c(\equiv I_c/wd)$ in zero field with a calculation which takes into account the current distribution[9] inside the strip. The result is shown in Fig. 3, where the criterion electric field E_c for determining J_c in zero field was 3×10^{-5} V/cm. The solid line shows the calculated J_c in our picture. Here, only the local depairing current density J_{dp} was the fitting parameter, which was taken to be 1.26×10^8 A/cm^2. The agreement between the measurement and the calculation is very good. Moreover, the GL theory gives $J_{\mathrm{dp}}^{\mathrm{GL}} = \Phi_0/(3\sqrt{3}\mu_0\pi\xi\lambda^2) = 1.13\times10^8$ A/cm^2, which is consistent with the fitted J_{dp}. Note that the above scenario cannot be applied to the 10-μm-wide strip, because it did not show the sudden onset.

Very recently, Worthington *et al.* reported observation of separate vortex-melting and vortex-glass transitions in defect enhanced $YBa_2Cu_3O_7$ single crystals.[11] They argued that melting occurs at the melting tempera-

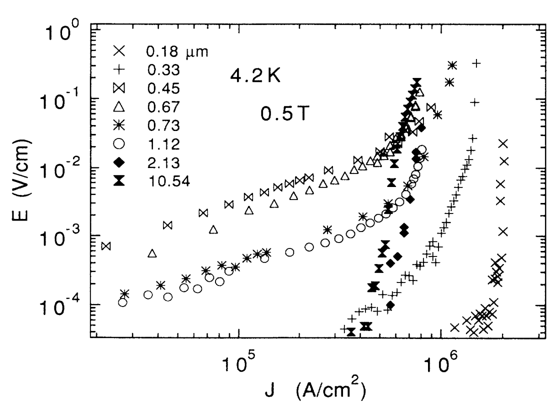

FIG. 1. E-J curves for strips with various widths in 0.5 T at 4.2 K.

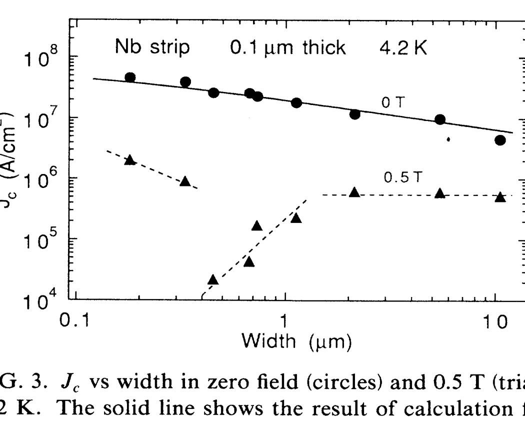

FIG. 3. J_c vs width in zero field (circles) and 0.5 T (triangles) at 4.2 K. The solid line shows the result of calculation for the J_c in zero field. The dashed lines are guides for the eye.

ture T_m of a clean system and the vortex glass is formed at the glass transition temperature T_g which lies below T_m. Also they referred to the intermediate phase between the two transition temperatures as the "vortex-slush" phase which has a finite but much smaller linear resistivity than in the vortex liquid phase above T_m. Suenaga *et al.* reported[12] that T_m of a Nb specimen lies just below the superconducting transition temperature $T_c(H)$. Therefore, according to the interpretation of Worthington *et al.*, the linear resistivities observed at low current densities in Figs. 1 and 2 are that of the vortex slush. The vortex-glass state is expected to be formed below the vortex-slush state; the experimental evidence for the existence of the vortex-glass state in our Nb strips was given in Ref. 13. It should be noted that there is another interpretation for the phases above the vortex glass; Vinokur *et al.* have argued[14] that a thermally assisted flux-flow[15] (TAFF) regime, where the linear resistivity is determined by a current-independent activation barrier, is formed between the vortex glass and the pinning-free liquid. However, in both cases, such an intervening regime can certainly be considered as a pinned fluid.

Now we discuss the size effect in the formation of vortex phases. As is evident in Fig. 1, the onset of dissipation with increasing current in the strips in the wide-width regime (2.13–10.54 μm) is very sharp, suggesting that the vortex systems in these strips are in a solid state (possibly the vortex glass). On the other hand, the vortex systems in strips in the intermediate-width regime (0.45–1.12 μm) are in the pinned-fluid (vortex-slush or TAFF) state at 4.2 K. This means that a transition from a vortex glass to a pinned fluid occurs with decreasing width at 4.2 K. Moreover, the linear resistivity in the pinned-fluid state is enhanced for narrower strips in the intermediate-width regime. These experimental results can be understood if one supposes that the collective-pinning effect[16] is reduced in narrower strips. As discussed by Worthington *et al.*,[11] the vortex-glass transition temperature T_g is decreased for weaker pinning; therefore, it is probable that T_g is decreased for narrower strips if the collective pinning is reduced. Also it is expected that the linear resistivity in the pinned-fluid state is enhanced for weaker pinning, which explains the behavior in the intermediate-width regime.

What is the characteristic length for the reduction of collective pinning in narrow strips? Experimentally, the characteristic length is about 1 μm, where the transition from the wide-width regime to the intermediate-width regime occurs at 4.2 K, as shown in Fig. 1. This length scale is larger than λ, and differs from the case for $YBa_2Cu_3O_7$.[6] We show below that the characteristic length is given by the size of a hopping bundle of vortices[16] for our Nb strips. In the collective-pinning theory,[16] vortices move in a unit of a hopping bundle with the sizes L (along the field), $R_\parallel$ (in the direction of hopping), and $R_\perp$ (in the transverse direction). Since the vortex bundle hops across the strip, the size which is relevant to the problem is $R_\parallel$. In a wide strip where many hopping bundles exist within the width w of the strip, shifting of a hopping bundle by the hopping distance induces both shear and compression deformation, and the energies of shear and compression deformations are in the same order of magnitude.[16] On the other hand, in a narrow strip where only one hopping bundle exists within the width, the shifting of the hopping bundle induces only shear deformation, which means that the activation energy for hopping is smaller than that in the wide ones. Therefore, the collective-pinning effect is reduced for strips with $w \sim R_\parallel$. This explanation may be far too simple and, actually, some deformation of the hopping bundle occurs for $w \sim R_\parallel$;[17] nevertheless the activation energy will still be decreased. If $H \gg H_{c1}$, $R_\parallel$ is given by[16] $R_\parallel \approx (C_{11}\xi/J_c B)^{1/2} \approx 1.1$ μm for $B = 0.5$ T and $J_c = 5\times10^5$ A/cm^2, where $C_{11} = B^2/\mu_0$ is the bulk modulus in the local limit. This is consistent with the length scale observed experimentally. It should be mentioned that the formulas used here were derived for weak pinning, and a collective theory for strong pinning is not available yet except for the special case of columnar defect.[18] It is not clear whether our Nb strips are in the weak-pinning regime, however, judging from the value of the J_c and its field dependence, it seems to be not in the strong-pinning limit.

The last subject to be discussed is the origin of the crossover from the intermediate-width regime to the narrowest-width regime. In the latter regime, dissipation suddenly drops with decreasing width, which is not expected from the above-described picture. We suppose this behavior comes from two effects. First, upon decreasing the width, a crossover from the collective-pinning regime to a single-pinning regime occurs, which results in stronger pinning because a vortex can be trapped in the deepest pinning potential available.[19] Second, the surface barrier[10] becomes effective when the width approaches 2λ, which also results in stronger pinning for a trapped vortex. In strips where the width is comparable to 2λ or narrower, effective magnetic induction contributed by the vortices in the strip decreases due to the penetration of the field from the edges, which also raises H_{c1}.[10] Taking this effect into account, it is concluded that only one vortex exists within the width in the 0.18-μm-wide strip at 0.5 T. Therefore, the E-J curve of the 0.18-μm-wide strips in Fig. 1 represents the depinning of a single vortex from the strong pinning potential. The 0.33-μm-wide strip possibly showed a crossover to the single-pinning regime.

Based upon the above-discussed interpretation of the vortex states in the narrow strips, a phase diagram at 4.2 K in the w-H plane is schematically shown in Fig. 4. The behavior of J_c in 0.5 T shown in Fig. 3 can be explained in conjunction with this phase diagram (note that E_c was taken to be 7×10^{-4} V/cm for J_c in 0.5 T for convenience): In the wide-width regime (2.13–10.54 μm), the vortex system is in the vortex-glass state and J_c shows little dependence on the width.[6] In the intermediate-width regime (0.45–1.12 μm), J_c is not at all a true *critical* current density and it reflects the linear resistivity in the pinned-fluid state; namely, the larger resistivity in narrower strips leads to a smaller J_c. The sudden increase in J_c in the narrowest-width regime (0.18–0.33 μm) is a consequence of the crossover to the single-pinning regime

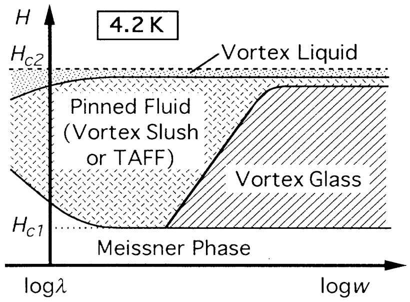

FIG. 4. Schematic vortex-phase diagram of narrow Nb strips at 4.2 K in perpendicular fields. The demagnetization effect was neglected.

and the stronger surface barrier. Although not shown here, a decrease in the vortex-lattice melting temperature is also expected in this width regime[6] in higher magnetic fields.

In conclusion, we have investigated the size effects in narrow Nb strips. It was shown that the origin of the size effect in zero and very low applied fields is the current distribution inside a strip, which leads to an apparent increase in J_c. In higher fields, it was found that reduction of collective pinning occurs below the length scale given by the size of a hopping bundle in the direction of hopping, which leads to both the transition from the vortex glass to the pinned fluid with decreasing width and an enhancement of the linear resistivity. If the width is further decreased to a value comparable to 2λ, vortices are pinned individually and the surface barrier acts as a deep pinning potential, which results in a recovery of a high J_c. These complicated size effects manifest themselves both in the qualitative change in the E-J characteristics and in the dip in the width dependence of J_c in 0.5 T.

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