Unusual Vortex Dynamics in Nb–a-Si Multilayers with Strong Interlayer Coupling

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We observe an unexpected, new dissipation peak as a function of magnetic field orientation in Nb–a-Si multilayers. This peak depends differently on current, anisotropy, and magnetic field to the usual dissipation in layered anisotropic superconductors which is also seen. This new peak is most easily visible for thin a-Si layers and is consistent with a crossover from 3D to 2D vortex behavior as the field direction approaches the plane of the layers. [S0031-9007(96)01986-2]

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The discovery of superconductivity in the anisotropic high-T_c oxides has triggered renewed interest in investigations of other naturally anisotropic [1] superconductors as well as artificially layered stacks [2–9] regarding, e.g., the dimensionality of the flux dynamics. Recently, some very interesting, nonlinear, vortex dynamics were reported [1] in $NbSe_2$ which has extremely weak pinning. Multilayer studies suggest that vortex lattice rearrangements result in peak effects in the critical current density [5,6]. In addition, data on anisotropic high-T_c superconductors demonstrate that they behave as a stack of tunnel junctions [10–12], and that the in-plane vortex dynamics can be affected by the interplanar coupling in these systems [13]. Investigations of superconductor/insulator multilayers offer "tunable" interlayer coupling to investigate its effect on vortex dynamics, in analogy to natural layered superconductors.

We report in-plane transport measurements on niobium/amorphous silicon (a-Si) multilayers in which the interplanar coupling is modified by varying the nominal [14] thicknesses of the insulating a-Si spacer, $d_{\rm Si}$. For stronger coupling (small $d_{\rm Si}$), we find two distinct types of dissipation peaks as a function of magnetic field angle which are shown clearly in Fig. 1. The first type (U) is a peak centered about the angle ($\phi = 0°$) at which the magnetic field is perpendicular to the Nb layers, and this U type is usually found in anisotropic superconductors, e.g., high-T_c cuprates [15]. However, when the field is nearly aligned with the Nb planes, there emerges a second, previously unobserved peak [16], which we denote as N. The new peak shows up as an unexpected dissipation maximum (located in Fig. 1 at roughly $\phi \sim 84°$, i.e., with the field directed out of the Nb layers by $\sim 6°$). This N peak is the focus of our paper, and it is easily identified in multilayers with $d_{\rm Si} \leq 2.5$ nm. The second curve in Fig. 1, which is typical for samples with $d_{\rm Si} \geq 3$ nm, shows only the U peak and no evidence of the N peak for the same values of temperature, field, and current. After summarizing our data, we will suggest a potential explanation which is consistent with our experimental findings.

Our multilayers were fabricated by dual-target sputtering using techniques which give high-quality multilayers [17]. The key for smooth interfaces is in using Ar gas at 3 m Torr; deviations from this pressure result in nonuniform layers [17]. Our samples consist of 20 layers each of Nb (6 nm thick) and a-Si ($d_{\rm Si}$ was varied from 1–10 nm), which were patterned into 50 μm $\times$ 1 mm microbridges. Electrical transport measurements were performed in a high-uniformity, 7 T, split-access superconducting magnet with a stepper motor to rotate the sample.

The angular variation of dissipation for the multilayer ($d_{\rm Si} = 2$ nm) which showed both peaks in Fig. 1 will now be discussed in more detail. It was seen in each of four samples made in two batches about one year apart. For other values of $d_{\rm Si}$, only one sample was measured. We now describe the significantly different dependences of these two peaks on anisotropy, current, field, and Lorentz force.

The effects of changes in anisotropy are seen in Fig. 1. Although no sharp N peaks, comparable to Fig. 1, have been found in samples with $d_{\rm Si} \geq 3$ nm, much weaker, qualitatively similar features have been seen over a much smaller part of the B-T plane field for $d_{\rm Si} = 3$–4 nm, but not for $d_{\rm Si} \geq 6$ nm. Interestingly, the upper critical fields, B_{c2}, are qualitatively different for $d_{\rm Si} \geq 3$ nm (see

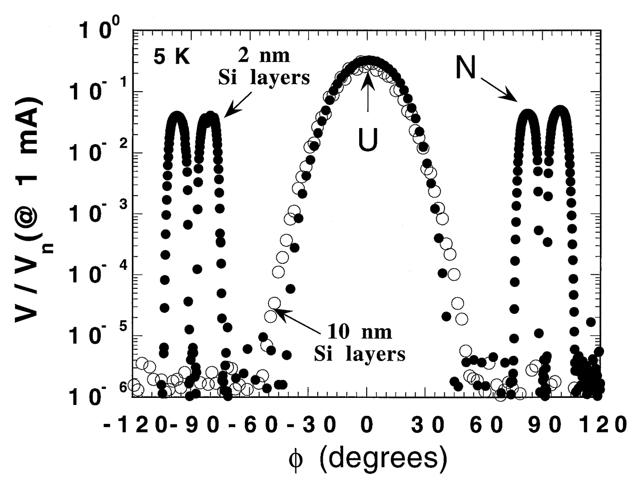

FIG. 1. Dissipation vs field direction ($B = 1.05$ T) for multilayers with $d_{\rm Si} = 2$ nm (solid) and 10 nm (open). Both show the usual peak (U) while the new peak (N) is only found in the multilayer with $d_{\rm Si} = 2$ nm.

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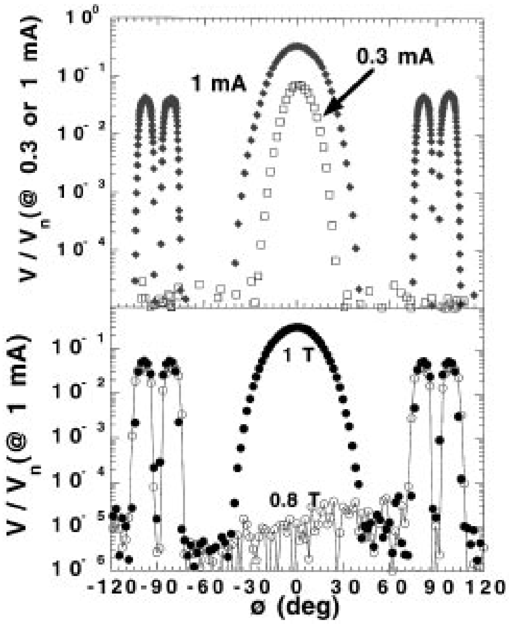

FIG. 2. (top) Dissipation vs field direction for the $d_{\mathrm{Si}} = 2$ nm multilayer showing the different dependences of N and U on current: 0.3 mA (open); and 1 mA (solid). (bottom) Same type of data for the $d_{\mathrm{Si}} = 2$ nm multilayer showing the different dependences of N and U on field: 0.8 T (open); and 1 T (solid).

Fig. 4), while the 2D limit for fields less than B_{c2} is apparently found only for $d_{\mathrm{Si}} > 4$ nm (see Fig. 5).

In Fig. 2 (top), a reduction of *current* by a factor of $\sim$3 is shown to reduce N by over 4 orders of magnitude, while U is only slightly reduced. Surprisingly, if, instead, the *field* is reduced by only 20%, Fig. 2 (bottom) shows relatively little change in N, while U is reduced by over 4 orders of magnitude. Finally, the direction of the current with respect to the in-plane component of field affects N. In the case shown in Fig. 3, N is reduced by 4 orders of magnitude when they are colinear, i.e., with the Lorentz force acting only on the pancake vortices.

The effects shown in Figs. 1–3 which span 4 orders of magnitude appear very dramatic—in actuality they correspond to more modest changes in the critical currents (which are typically $\sim$1 mA, corresponding to 1.7×10^4 A/cm^2) because the voltages are highly nonlinear with the current, well away from $B_{c2}(T)$. For example, if the current is doubled for the case of Fig. 3, N reappears for the minimum Lorentz-force configurations, albeit with a somewhat reduced magnitude relative to the maximum Lorentz-force configuration. Taken together, the data in Figs. 1–3 imply that N and U have independent origins, or, at the very least, their critical currents depend quite differently on anisotropy, current, field, and Lorentz force.

To gain further insight into this unusual behavior of the U and N peaks, we have measured B_{c2}, which is customarily used to address the interlayer coupling, e.g., to distinguish between 2D and 3D behavior. The resistive transitions were $\sim$0.04 K wide [(10–90)%] and the mid-

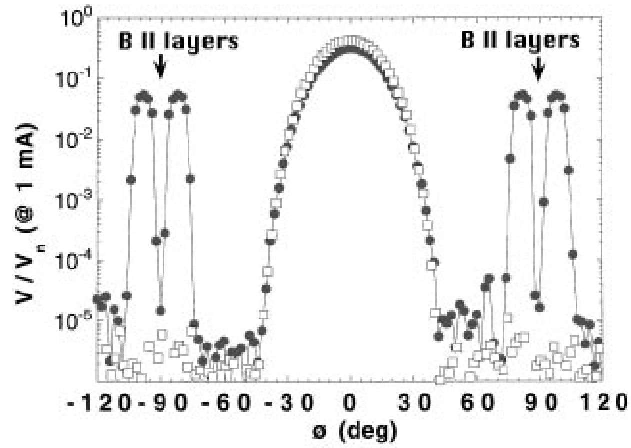

FIG. 3. Dissipation vs field direction for the $d_{\mathrm{Si}} = 2$ nm multilayer showing the different dependences of N and U on Lorentz-force configuration: maximum Lorentz force (solid); and minimum (open).

points, used to define B_{c2}, are plotted in Fig. 4 against the reduced temperature, $t = T/T_{c0}$, where the T_{c0} are the zero-field values which ranged from 6.79 to 6.93 K with no systematic dependence on insulator thickness, d_{Si}. At B_{c2}, the voltage-current data are linear up to currents of 10 μA, so another criterion for B_{c2} would only slightly change the quantitative, but not qualitative, results. As is expected for the field perpendicular to the layers, there is no dependence whatsoever of B_{c2} on d_{Si}. This result suggests that the in-plane coherence lengths are roughly equal for each d_{Si}, and thus, for similar defects, the pinning within the planes should be very nearly the same for all multilayers regardless of d_{Si}. For fields parallel to the layers, the B_{c2} data are also very systematic as a function of d_{Si}. The data of Fig. 4 show that the samples divide neatly into two categories: For $d_{\mathrm{Si}} \geq 3$ nm, B_{c2} displays the usual

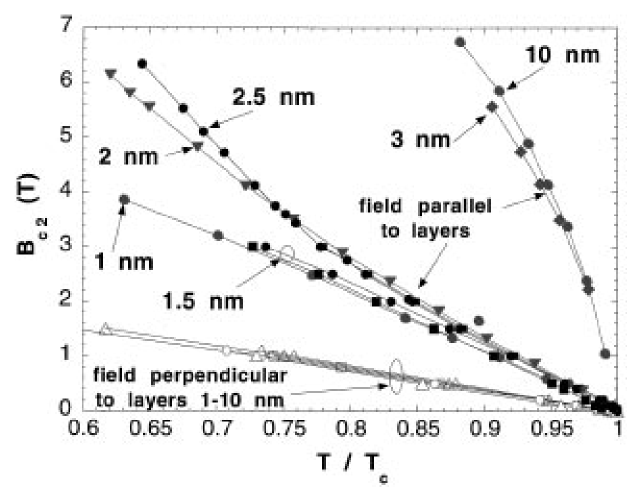

FIG. 4. Upper critical magnetic fields (defined by midpoints of resistive transitions) for various multilayers with different d_{Si}. Data are for fields both parallel (solid) and perpendicular (open) to the Nb layers.

temperature dependence of 2D (i.e., decoupled) layers with very minor differences up to the largest d_{Si} of 10 nm; for 1 nm $< d_{\mathrm{Si}} <$ 2.5 nm, the B_{c2} are considerably smaller and display the linear temperature dependence of 3D (coupled) layers. While curves bunch together at the highest temperatures, for the thickest for this latter category, the low-temperature B_{c2} show deviations which have been described by others as a crossover to 2D behavior [9]. All our B_{c2} data are virtually identical *quantitatively* with data on Nb-Ge multilayers [9], except that, in the case of Ge, the nominal spacer thickness [14] for the 2D-3D crossover was about 1 nm larger.

Finally, we anticipate the value of comparing the *magnitude* of dissipations for the 3D-coupled multilayers with data on the weakly coupled 2D ones ($d_{\mathrm{Si}} \geq 3$ nm) taken under the "same" conditions. Clearly, one should not compare at the same values of field and temperatures due to their quite different B_{c2}, but even using the same reduced values, i.e., t and $B/B_{c2}(T)$, may introduce some uncertainty since the superconducting order parameter, ψ, varies differently with field for 2D and 3D systems. We propose that appropriate comparisons should keep constant the values of temperature, current, ψ, and the perpendicular component of field, $B|\cos\phi|$, i.e., the areal density of vortices in the Nb layers. To test this, we check for scaling of the dissipation with $B|\cos\phi|$ in our most weakly coupled multilayer ($d_{\mathrm{Si}} = 10$ nm). In Fig. 5, dissipations are plotted against $B|\cos\phi|$ at $t = 0.9$, and the top panel shows comparisons between (i) rotations in a field of 3.2 T (solid symbols) which are indistinguishable for $d_{\mathrm{Si}} = 4$, 6, and 10 nm and (ii) the use of much smaller fields applied perpendicular to the layers (open symbols). While case (ii) does depends on d_{Si}, it does not for $d_{\mathrm{Si}} \geq 6$ nm, implying that by any measure the 2D limit has been reached for $d_{\mathrm{Si}} \geq 6$ nm, and that the remaining discrepancy with (i) must then be due to the parallel field affecting ψ. At these small angles, the parallel component of the field, $B_{\parallel}$, in (i) is ~3.2 T which should reduce ψ by

$$\left(\frac{\psi}{\psi_0}\right)^2 = 1 - \left(\frac{B_{\parallel}}{B_{c\parallel}}\right)^2, \tag{1}$$

where, from Fig. 4, $B_{c\parallel} \sim 6.2$ T for $t = 0.9$. In order to test this idea, the decrease can be simulated at $B_{\parallel} = 0$ by using a higher temperature since $\psi^2 \sim \psi_0^2\,(1 - t)$. Then we calculate that $t_x \sim 0.926$ and $B_{\parallel} = 0$ should simulate $t = 0.9$ and $B_{\parallel} \sim 3.2$ T. The best match at $B_{\parallel} = 0$ is shown as open squares in Fig. 5 (top) for $t = 0.923$, which can be considered within experimental error to be the same as t_x. Thus we verify that Eq. (1) adequately describes $\psi(B)$ for the 2D multilayers with $d_{\mathrm{Si}} = 6$ and 10 nm.

Armed with this result, we can now compare data on 3D-coupled multilayers in the region of the new peak with data on the weakly coupled 2D multilayers. In Fig. 5 (bottom panel), data are shown for the 3D-coupled multilayer ($d_{\mathrm{Si}} = 2$ nm) at $t = 0.9$ and $B = 0.41$ T. Excellent agreement is found with the weakest-coupled 2D multilayer ($d_{\mathrm{Si}} = 10$ nm) by changing only the field (from 0.41 to 5.7 T). To determine if this is reasonable requires the equivalent to Eq. (1) for the 3D-coupled multilayer. We expect the Abrikosov solution, $\psi^2 \sim \psi_0^2\,(1 - B/B_{c2})$, to be a good starting point for the 3D case, although it is strictly valid only for extreme type-II superconductors close to B_{c2}, and it does not explicitly consider layering effects. Following the analysis, as above, the match is expected for a field of 3.5 T, which is smaller than the experimentally determined 5.7 T. Given the uncertainties in $\psi(B)$ for the 3D case, the ability to account for most of the shift in field (of a factor of 14), demonstrated by the fit in Fig. 5, could be taken as evidence that the dissipation at the new peak mimics that of a weakly coupled 2D multilayer with the same ψ.

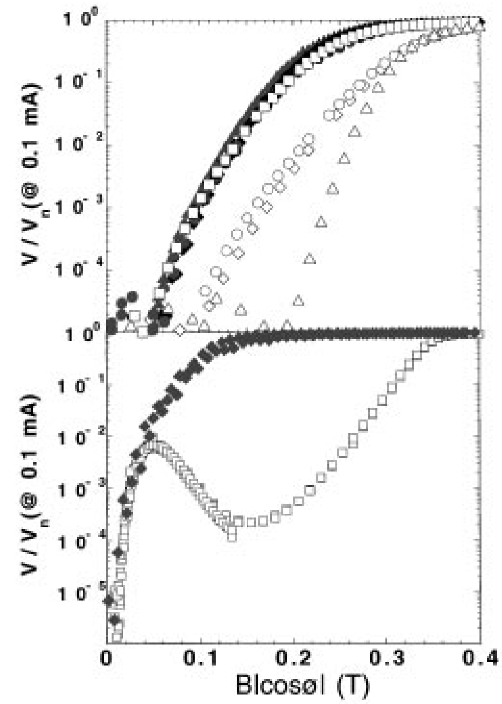

FIG. 5. (top) Comparison of dissipation vs $B|\cos\phi|$ at $t = 0.9$ between (i) rotations in an applied field of 3.2 T (solid) and (ii) much smaller fields applied perpendicular to the layers (open). Data are for $d_{\mathrm{Si}} = 4$ nm (triangles), 6 nm (diamonds), and 10 nm (circles). Data on the $d_{\mathrm{Si}} = 10$ nm multilayer (open squares) for case (ii) at $t = 0.923$ are shown to overlap cases (i) at $t = 0.9$. (bottom) Similar comparison at $t = 0.9$ for rotations in a field of 5.7 T for weakly coupled ($d_{\mathrm{Si}} = 10$ nm) multilayers (solid diamonds) and at 0.41 T for strongly coupled ($d_{\mathrm{Si}} = 2$ nm) multilayers in the region of the new peak (open squares).

In summary, the experimental facts which reflect strongly on the origin and nature of the new peak (N) are: (1) The peaks N and U have independent origins, or, at the very least, their critical currents depend quite differently on field, current, anisotropy, and Lorentz force; (2) it has been difficult to find convincing evidence for the new peak (N) in samples with $d_{\mathrm{Si}} \geq 3$ nm, which based on B_{c2} are weakly coupled (2D-like); and (3) there is evidence that the dissipation at the new peak mimics that of a weakly coupled 2D multilayer (with the same ψ).

The result (3) is intriguing: it implies an alternative to ascribing newness to the *peak* (N), by hypothesizing instead a *dip* in dissipation due to a 2D to 3D crossover occurring as the angle drops from 90°. In this model, the increased effective pinning provided by the 3D coupling [13] reduces the dissipation from the weakly coupled 2D case (although the increased pancake vortex density as ϕ goes to zero does cause a measurable dissipation). Such weak interlayer coupling for angles near 90° could, e.g., result from the very large distances between pancake vortices in adjacent layers. This model can clearly accommodate the different dependences of N and U on field and current, because of their different dimensionalities. Although otherwise appealing, at first sight, such a model cannot resolve the Lorentz-force dependence shown in Fig. 3; if the layers are truly decoupled, it is hard to see what role the Lorentz force would play. Perhaps, further theoretical guidance [18] can resolve that aspect of this intriguing and unexpected phenomenon, since the new peak is otherwise consistent with a crossover from 3D to 2D vortex behavior as the field direction approaches the plane of the layers.

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