Critical current enhancement in NbN/AlN multilayers

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Measurements are presented of the critical current density, J_c, and parallel upper critical field, $H_{c2\|}$, for the refractory superconductor/insulator multilayer system NbN/AlN. A dramatic increase in J_c, together with an increase of $H_{c2\|}$, is observed with decreasing NbN layer thickness. The J_c enhancement arises from flux pinning in the AlN or at the NbN-AlN interface, not at defects in the NbN structure. The results indicate that the development of superconductor/insulator composites is a viable strategy to increase the critical current. Thermal stabilization which does not degrade the very high J_c values was also accomplished in a novel structure by addition of copper layers within the superlattice.

The critical current density (J_c) of high-field superconductors in a magnetic field is a measure of a superconductor's ability to successfully pin the flux-line lattice. Kramer[1] has shown that this flux pinning at low reduced fields can be increased by the introduction of crystalline imperfections. The introduction of crystal defects into a superconductor is a standard approach to raise J_c[2]; however, this may not significantly affect the high-field value of J_c, which has been shown to be dependent on the shearing of the flux-line lattice about strong pinning points (pins) or on the strength of those pins. Moreover, these defects may have undesirable effects on other superconducting properties, such as the critical temperature.[3] Another method of increasing the critical current density has been to produce thin films[4] which, in niobium nitride (NbN), show an increased critical current density down to 100 Å; however, the total critical current is limited because of sample size.

In this letter we report a dramatic enhancement of the critical current density of superconducting NbN and suggest a method to increase the total critical current by the fabrication of thin layers of NbN alternated with insulating AlN in a superconductor/insulator superlattice. The AlN layers provide periodic pinning centers which greatly increase the flux pinning density allowing higher critical current densities to be achieved. This might also provide a method for enhancing the critical current of the newly discovered oxide superconductors.

Samples of NbN/AlN were prepared, as described earlier,[5] using dc reactive magnetron sputtering for both NbN and insulating AlN. The samples discussed in this letter have AlN layer thicknesses (d_{AlN}) of 20 Å, except for samples used in H_{c2} measurements by pulsed field for which $d_{\mathrm{AlN}} = 32$ Å. NbN thicknesses ranged from 30 to 350 Å; 30 layers of NbN and 31 layers of AlN were deposited for each sample. The multilayers were grown on $(10\bar{1}0)$ and $(11\bar{2}0)$ sapphire substrates held at a temperature of 300 °C in a precisely controlled mixture of argon (6 mTorr) and nitrogen (2 mTorr) atmosphere. Proper preparation of the Al target between sample fabrications was necessary to prevent target poisoning and to assure uniform deposition of the AlN. The preparation conditions were varied until AlN and NbN grew in a basally oriented wurtzite and (111) rock-salt structures, respectively. This results in an in-plane interlayer lattice mismatch of only 0.27%, which, in turn, is expected to minimize interfacial strain. The high melting temperature and the common nitrogen in each compound, which is expected to limit interdiffusion, makes this an ideal system for study. Evidence of modulation and textured growth is observed in both x-ray diffraction and microcleavage transmission electron microscopy[6] (MTEM) measurements (Fig. 1).

As the NbN layer thickness decreases below 60 Å, an increased disorder is observed from structural and transport measurements. MTEM shows an interfacial roughness approaching the layer thickness dimension at 30 Å or less.[5]

FIG. 1. Transmission electron micrograph of a NbN/AlN multilayer. The NbN (dark layers) thickness is 102 Å and the AlN (light layers) thickness is 40 Å.

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Critical temperatures, parallel critical field, and resistivity ratios ($\rho_{293\,K}/\rho_{20\,K}$) all show disorder increasing as d_{NbN} decreases below 60 Å. For NbN layer thicknesses greater than this value, the transport properties and structural characterization show no evidence of substantial disorder. Multilayers with $d_{NbN} > 100$ Å have critical temperatures as high as 16 K and low parallel critical field values indicative of clean, ordered NbN.

The parallel critical field measured at the National Magnet Laboratory by a pulsed field technique, a dc field, and Kramer extrapolations above 20 T, is shown as a function of the NbN layer thickness in Fig. 2. In the Ginzburg–Landau (GL) region the parallel upper critical field of a thin-film superconductor scales inversely with the superconductor thickness according to the relation[7]

$$H_{c2\|}(T)=\frac{\sqrt{12}\Phi_0}{2\pi d\xi_{\|}(T)}, \qquad (1)$$

where Φ_0 is the flux quantum, d is the film thickness, and $\xi_{\|} \propto (1-t)^{-1/2}$ is the in-plane GL coherence length with $t=T/T_c$. The experimental data in the region 70 Å $< d_{NbN} <$ 140 Å are in agreement with this temperature dependence where

$$\xi_{\|}(T)=\frac{\Phi_0}{2\pi H_{c2\perp}(T)^{1/2}}. \qquad (2)$$

For $d_{NbN} > 140$ Å the parallel critical field appears to converge to the thick-film NbN value prepared under similar conditions.

The parallel field dependence of the critical current density was also measured at the Francis Bitter National Magnet Laboratory in dc fields. The critical current I_c is defined as the current necessary to produce 1.5 μV/cm across the voltage leads of the sample at a temperature of 4.2 K. The critical current density J_c was calculated from the total cross section of the multilayer, *including* the AlN layers, and is shown in Fig. 3. At 20 T for a multilayer with $d_{NbN} = 62$ Å, J_c is an order of magnitude greater than for typical NbN films and ~6 times higher than thick NbN film deposited specifically to optimize J_c using structural modifications.[8] Data below ~10 T is absent because of thermal instabilities in the films at high currents.

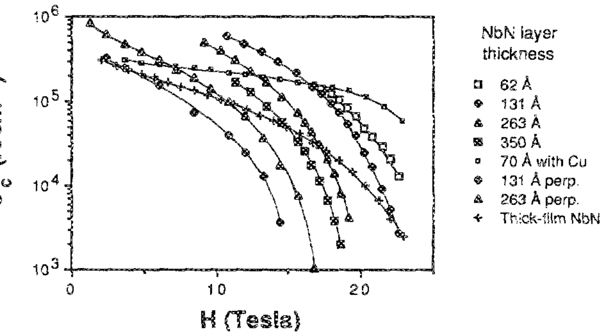

FIG. 3. Total critical current density (including AlN and Cu layers) vs magnetic field parallel to the sample with varied NbN thickness and constant AlN thickness of 20 Å. A NbN film is presented for comparison along with perpendicular field data of two multilayers.

In order to improve thermal stability of the multilayers, a novel structure was fabricated consisting of a 30-period NbN (70 Å)/AlN (20 Å) multilayer with the addition of a 300-Å copper layer inserted in the middle and on the top of this structure. Copper has a high thermal conductivity which serves to conduct the heat away from resistive hot spots before they propagate and quench the entire sample. This successfully allowed J_c to be measured to lower fields (higher currents) while at the same time maintaining high values of J_c at high fields. Indeed, as shown in Fig. 3, the J_c in parallel field of one of these structures had the greatest high-field value among all samples. The low-field J_c dependence differs from other multilayers and is not yet fully understood. The overall critical current density, *including* Cu and AlN layers, of this sample is 1×10^5 A/cm² at 21 T.

The difference between the optimized NbN film and NbN/AlN multilayers is clearly observed in the flux pinning density, $F_p = J_c^* H$, shown in Fig. 4. Note the increase in the flux pinning density, up to six times at a reduced field of $h = 0.46$. The reduced field was calculated from Kramer extrapolations of the critical field above 20 T. Possible sources for the flux pinning are: (1) the insulating layers, (2) the interfaces, and/or (3) microstructural defects in the superconducting layers. Although an increased disorder is observed in thin NbN multilayers, samples well outside of the region of disorder ($d_{NbN} > 60$ Å) also show J_c enhancement. This is an indication that the enhancement is not due to disorder within the superconducting layers but from pinning in the insulating layers or at the interfaces. Further evidence of this is given by J_c studies in transverse magnetic fields.

If the enhanced J_c was caused by small-grain growth,

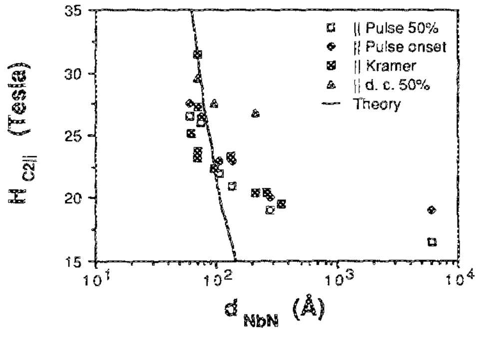

FIG. 2. $H_{c2\|}$ (4.2 K) vs NbN layer thickness. The solid line is a theoretical curve for a dirty 2D superconductor.

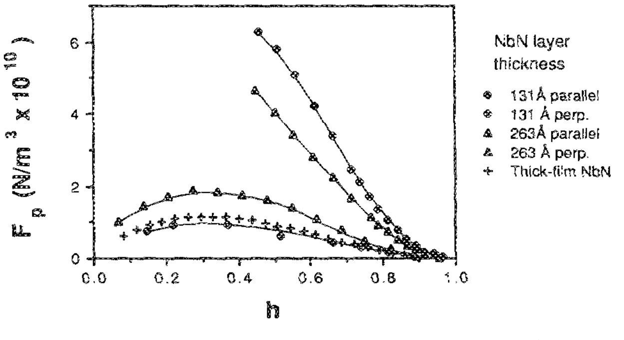

FIG. 4. Flux pinning density, $F_p = J_c H$, vs reduced field in parallel and perpendicular magnetic fields. The optimized NbN film of Fig. 3 is also presented for comparison.

pinning from the grain boundaries would cause enhancement in a transverse rather than parallel field as it does in thick-film NbN studies.[8] Figure 4 shows the opposite occurring in the multilayered samples; the enhancement in the critical current density in parallel rather than perpendicular magnetic fields verifies that the pinning occurs in the AlN layers or their interfaces rather than by grain boundaries or disorder within the NbN.

A comparison of multilayers with various NbN layer thicknesses in parallel field shows that the magnitude of the total flux pinning scales directly with the number of interfaces and is nearly independent of d_{NbN}; this is further evidence that pinning occurs at the AlN and not within the NbN.

In summary, we have used AlN to effectively constrain NbN into thin layers; the structure has been confirmed by x-ray diffraction and TEM analysis. At high magnetic fields the multilayers display more than an order of magnitude increase of J_c over comparable NbN films and an enhanced flux pinning density. Disorder is present in samples with NbN layer thicknesses less than 60 Å, as evidenced by T_c and TEM studies, but this is not solely responsible for the enhanced flux pinning. The insulating AlN and its interfaces are the primary pinning centers as verified by J_c measurements in transverse fields.

Finally, the addition of a third component to the superlattice, in the form (NbN/AlN)/Cu/(NbN/AlN), provides increased thermal stability while maintaining the high total critical current density.

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[1] E. J. Kramer, J. Appl. Phys. **44**, 1360 (1973).
[2] R. E. Enstrom and J. R. Appert, J. Appl. Phys. **43**, 1915 (1972).
[3] A. V. Narlikar and S. N. Ekbote, in *Superconductivity and Superconducting Materials* (South Asian, New Delhi, Madras, 1983), pp. 89–90.
[4] J. R. Gavaler, M. A. Janocko, A. Patterson, and C. K. Jones, J. Appl. Phys. **42**, 54 (1971).
[5] J. M. Murduck, J. Vicent, I. K. Schuller, and J. B. Ketterson, J. Appl. Phys. **62**, 4216 (1987).
[6] Y. Lepetre, I. K. Schuller, G. Rasigni, R. Rivoira, R. Phillip, and P. Dhez, Soc. Photo-opt. Instrum. Eng. Proc. **563**, 258 (1985).
[7] M. Tinkham, in *Introduction to Superconductivity* (McGraw–Hill, New York, 1975), p. 124.
[8] R. T. Kampwirth, D. W. Capone II, K. E. Gray, and A. Vicens, IEEE Trans. Magn. **MAG-21**, 459 (1985).