Physica B 194–196 (1994) 1867–1868
North-Holland

PHYSICA B

Flux dynamics in submicron superconducting NbTi wires

X.S. Ling,[1] J.D. McCambridge,[1] D.E. Prober,[1] L.R. Motowidlo,[2] B.A. Zeitlin,[2] and M.S. Walker[3]

[1]Department of Applied Physics, Yale University, P.O. Box 2157, New Haven, CT 06520-2157
[2]IGC Advanced Superconductors, Inc., Waterbury, CT 06704
[3]Intermagnetics General Corporation, Guilderland, NY 12084

We find that the diameter of a superconducting filament plays a major role in the pinning and depinning of flux lines as the diameter is reduced to the submicron scale. We attribute this behavior to a finite-size effect of flux pinning.

1. INTRODUCTION

Present superconducting wire technology utilizes NbTi in the form of fine filaments embedded in a copper matrix. In this study, we find that the diameter of an individual isolated filament plays a crucial role both in the pinning and the dynamics of the flux lines when the filament diameter is less than one micron. These effects are not seen in multifilamentary wire with similar-size filaments.

2. EXPERIMENT and RESULTS

Our superconducting filaments have an artificial-pinning-center (APC) structure.[1] The alloy is Nb52wt%Ti with 25vol.% Nb; the Nb forms the pinning centers. The APC filaments were formed by drawing a billet with thin layers of Nb in a NbTi matrix. The details of sample fabrication are described in Ref. 1. Multifilamentary wire was formed by drawing APC filaments in a Cu matrix. We measured multifilamentary wires and also individual filaments taken from the multifilamentary wire by etching away the Cu matrix. Fig. 1(a) shows the E-J characteristic of a multifilamentary wire with a filament diameter of 0.33 μm, for 4.2 K and 5 T. The E-J curve is somewhat rounded for this wire at this field; nevertheless, it still gives a well defined J_c using a resistivity criterion of 10^{-12} Ωcm to define J_c. After etching away the Cu matrix, we noticed two results. First, the measured J_c went up by about 20% (compare Fig. 1 (a) and 1 (b)). Second, a linear resistivity becomes visible at 5 T and above, as shown in Fig. 1 (b). This behavior is not seen in the 1 μm filament, Fig. 1 (c). The data shown here are representative. The increase of J_c at 5 T seen for the single filament, Fig. 1 (b), can be easily understood. In the multifilamentary wire the proximity effect of the copper matrix reduces the effective cross-

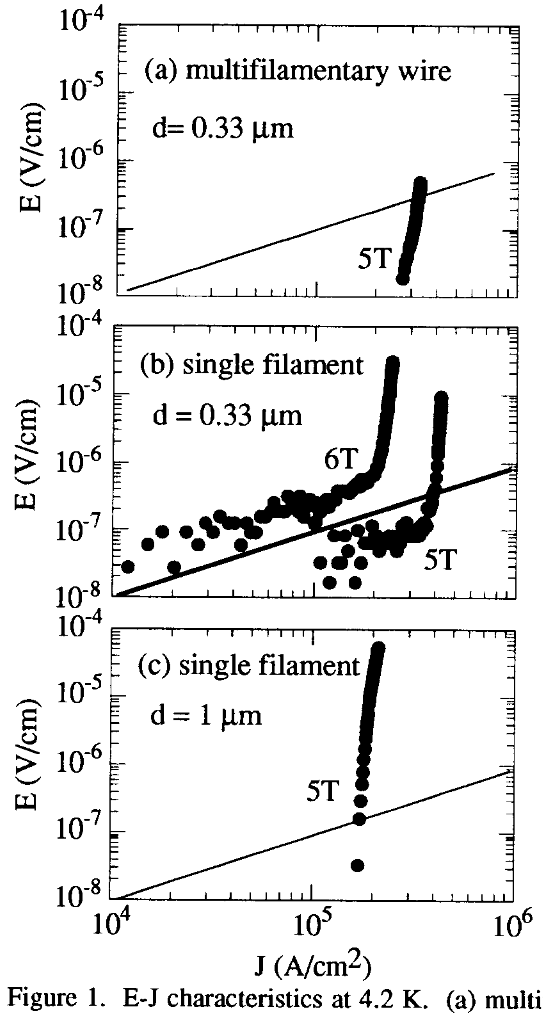

Figure 1. E-J characteristics at 4.2 K. (a) multifilamentary wire with filament diameter d = 0.33 μm, J=I/area of superconducting filaments; (b) single filament d = 0.33 μm; (c) single filament d = 1 μm. The straight lines indicate 10^{-12} Ωcm. Filament material: Nb52wt%Ti with 25vol.% Nb APC.

SSDI 0921-4526(93)1565-4

sectional area of each superconducting filament, by a fraction $(4\xi_{sc}/d) \sim 0.15$. The second effect, the linear resistivity seen in Fig. 1 (b), is the main issue of this paper. We have also tested some regular cold-drawn (non-heat treated) NbTi filaments with no APC structure; a linear resistivity also appeared in filaments thinner than 0.6 μm at 4.2 K and 5 T but not in larger filaments. Thus, we believe that the linear resistivity seen in the individual submicron filaments is not related to the APC structure, rather it is generic and is related to the size of a filament. We note that a similar size dependent E-J behavior was also observed recently in narrow Nb strips.[2]

3. DISCUSSION

We want to understand why a linear resistivity arises in the 0.33 μm filament at 4.2 K and $\gtrsim$ 5 T, and why it is not seen in a large filament and in the multifilamentary wire. The E-J characteristic of a type-II superconductor in a magnetic field is determined by the driven motion of flux lines. The pinning force density F_p is determined[3] by the incomplete averaging of elementary pinning forces f in a Larkin domain, $F_p = (nf^2/V_c)^{1/2}$ where n is the pin density. $V_c = R_c^2 L_c$ is the domain volume in a bulk sample. R_c and L_c are the transverse and longitudinal Larkin dimensions, with $L_c > R_c$. For a wire in a perpendicular field, if $d >> L_c$, F_p is independent of d (assuming n and f are independent of d). When $L_c > d > R_c$, one expects $F_p \sim d^{-1/2}$. When d is reduced further, below R_c, one expects $F_p \sim 1/d$. Therefore, one expects to get an enhancement in J_c by simply reducing the wire diameter, if n and f do not depend on d (One cannot apply this argument directly to the lower J_c value in our 1 μm filament, because the pin density is lower in this 1 μm filament).

The simple dependence of J_c on d given above is modified by magnetic interactions. In a bulk sample the energy cost for depinning one Larkin domain by the range of a pin, r_p, is[4] $C_{66}(r_p/R_c)^2 R_c^2 L_c \sim C_{66} r_p^2 L_c$ where C_{66} and C_{11} (discussed below) are the shear and compression moduli of the vortex lattice. Shifting a bundle of flux lines will also create lattice compression beyond a single domain.[4] The actual energy barrier is then $C_{66}(r_p/R_c)^2 R_c R_{||} L_c$, where $R_{||} = (C_{11}/C_{66})^{1/2} R_c$ is the range of lattice compression along the direction of hopping. Hence, the true energy barrier for depinning a domain in bulk is <u>increased</u> by a factor of $(C_{11}/C_{66})^{1/2}$ (~20 for Nb52wt%Ti at 4.2 K and 5 T) due to the presence of other flux lines along the direction of hopping. However, if the filament diameter is $d < R_{||}$, the energy barrier U will be <u>reduced</u> to $C_{66}(r_p/R_c)^2 R_c d^2$, due to the absence of neighboring vortices. For our Nb52wt%Ti wire at 4.2 K, B = 6 T, $B_{c2} \sim 10$ T, $\kappa \sim 70$, one finds[5] $C_{66} \sim 160$ J/m^3. At d ~ 0.33 μm, $r_p \sim 4$ nm, assuming $R_c \sim 0.29$ μm, one obtains an energy barrier $U/k_B \sim 70$ K. From the linear resistivity ~ 2.7×10^{-12} Ωcm at 6 T in Fig. 1 (b), $\rho_n \sim 70$ μΩcm, the energy barrier $U/k_B = -T\ln(\rho/\rho_{ff}) \sim 70$ K. This is consistent with the estimate above.

We can also understand why we do not see a linear resistivity in the 1 μm filament. The same estimate of U gives an energy barrier ~ 630 K which leads to a linear resistivity on the order of 10^{-65} Ωcm. The absence of a linear resistivity in the multifilamentary wire can also be understood. Because the separation between the filaments is less than 0.1 μm, it is likely that the vortex magnetic fields of different filaments are coupled so that the vortices are more difficult to move than they are in an isolated filament.

4. CONCLUSION

We find that an individual submicron NbTi filament can exhibit a large linear resistivity at low current density at 4.2 K and in a strong magnetic field. This linear resistivity is not seen in a large filament, nor when multiple filaments are closely packed in a multifilamentary wire. We suggest this effect arises when the filament diamenter is below $R_{||}$. Our results imply that in order to suppress this behavior, we should maintain a large filament diameter or close coupling of filaments.

This work was supported by Conn. Dept. of Economic Development, grant 92G036 and by the Intermagnetics General Corporation.

REFERENCES

1. L.R. Motowidlo, B.A. Zeitlin, M.S. Walker, P. Haldar, App. Phys. Lett. <u>61</u>, 991(1992) .
2. Y. Ando et al. Phys. Rev. B <u>47</u>, 5481 (1993).
3. A.I. Larkin, and Yu. N. Ovchinnikov, J. Low Temp. Phys. <u>34</u>, 409(1979).
4. M.V. Feigel'man et al. Phys. Rev. Lett. <u>63</u>, 2303(1989); M.P.A. Fisher, ibid.<u>62</u>, 1415(1989).
5. E.H. Brandt, J. Low Temp. Phys. <u>26</u>, 709(1977).