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Flux pinning in NbTi-based multilayers

Y. Obi, H. Fujimori
Institute for Materials Research, Tohoku University, Sendai 980, Japan

M. Ikebe, H. Fujishiro
Faculty of Engineering, Iwate University, Morioka 020, Japan

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Critical current density J_c and pinning force density F_p have been investigated for the superconductor/superconductor multilayers NbTi/Nb and superconductor/normal metal multilayer NbTi/Ti under parallel and perpendicular magnetic fields. The layered structure itself has been confirmed to play as an effective flux pinning centre enhancing $F_{p\perp}$ under parallel magnetic fields.

Key words: niobium-titanium, multilayer, critical current, flux pinning.

1. Introduction

Parallel critical fields $H_{c2\parallel}$ of multilayer superconductors are usually enhanced in comparison with perpendicular fields $H_{c2\perp}$ as confirmed by many reports [1]. The multilayer structure is also expected to enhance the critical current $J_{c\parallel}$ under parallel magnetic fields, because the vortex driving force is perpendicular to the layers and the vortex motion should be impeded by the multilayer structure itself [2, 3]. Then the pinning force density $F_{p\perp}$ in the perpendicular direction may be strongly affected by the kind of the metal of intervening sublayer and the structural modulation wavelength λ.

By using dual sputtering technique, we have fabricated $Nb_{65}Ti_{35}/Nb$ and $Nb_{65}Ti_{35}/Ti$ multilayers in order to compare the behavior of J_c and F_p of superconductor/superconductor (NbTi/Nb) and superconductor/normal metal (NbTi/Ti) multilayers. The details of the sample preparation was reported elsewhere [4]. The thickness of each sublayer was designed to be equal, i.e. $\lambda/2 = d_{NbTi} = d_{Nb}$ (or d_{Ti}). The J_c measurement was performed by a 4-terminal resistive method mainly at 1.5 K using a 10 T superconducting magnet.

2. Results and discussion

Figure 1 shows the field dependence of critical current J_c at 1.5 K under parallel ($J_{c\parallel}$) and perpendicular ($J_{c\perp}$) magnetic fields. The absolute values of J_c are slightly larger for NbTi/Nb multilayers ($7 \sim 10 \times 10^5$ A cm^{-2}) than for NbTi/Ti ($5 \sim 8 \times 10^5$ A cm^{-2}). Because both sublayers of NbTi/Nb are superconductive, the electrical current flows through both sublayers, while the current can flow only through NbTi sublayers in NbTi/Ti. This may explain the smaller J_c values of NbTi/Ti multilayers at low fields.

From the measured values of $J_{c\parallel}$ and $J_{c\perp}$ we can calculate the macroscopic pinning force densities $F_{p\parallel}$ and $F_{p\perp}$, which are defined as $F_{p\perp} = J_{c\parallel} \times H_\parallel$ and $F_{p\parallel} = J_{c\perp} \times H_\perp$, respectively. In Fig. 2 we plot the maximum

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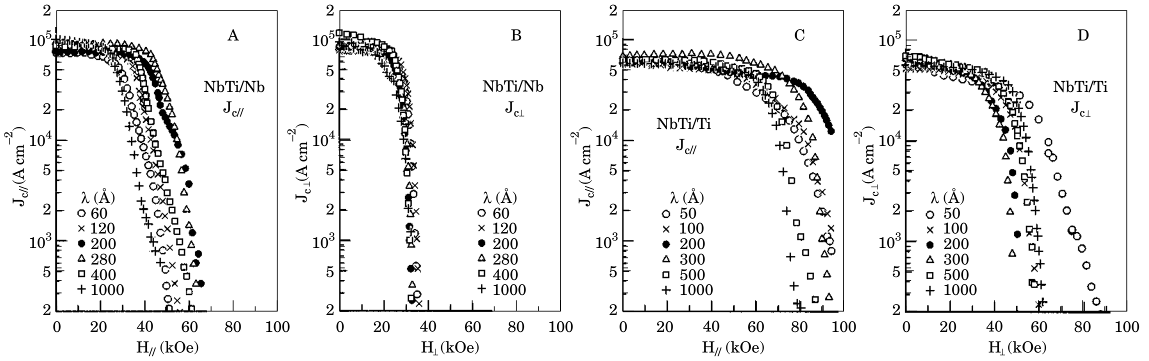

Fig. 1. Critical current versus magnetic field. A, $J_{c\parallel}$ of NbTi/Nb in parallel field; B, $J_{c\perp}$ of NbTi/Nb in perpendicular field; C, $J_{c\parallel}$ of NbTi/Ti in parallel field. D, $J_{c\perp}$ of NbTi/Ti in perpendicular field. H_{c2} can be estimated as the field in small J_c limit.

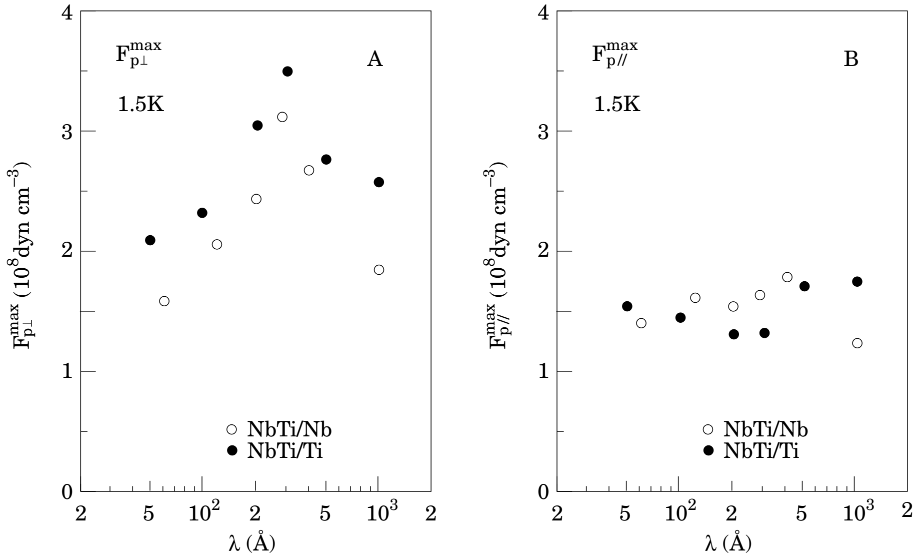

Fig. 2. Maximum pinning force F_p^{max} as a function of structural modulation wavelength λ. A, $F_{p\perp}^{max}$ in parallel field; B, $F_{p\parallel}^{max}$ in perpendicular field.

values of F_p^{max} as a function of the modulation wavelength λ for both multilayer systems. The characteristic results for F_p^{max} are summarized as follows: (i) $F_{p\parallel}^{max}$ values under the perpendicular field $H_\perp$ are almost independent of λ for both systems. (ii) $F_{p\perp}^{max}$ values are between 1×10^8 dyne cm^{-3} and 4×10^8 dyne cm^{-3} depending on λ. These values are about one order smaller than those of commercial NbTi wires. (iii) In contrast to $F_{p\parallel}^{max}$, $F_{p\perp}^{max}$ values, which are always larger than $F_{p\parallel}^{max}$, show a broad maximum around $\lambda = 300$ Å. (iv) The dimensionality of superconductivity changes from quasi-two-dimension ($\lambda < 300$ Å) to two-dimension ($\lambda > 300$ Å) around this λ value [4]. These results indicate that the multilayer structure really acting as an effective pinning center in both systems.

Figure 3A shows the λ dependence of the maximum F_p field $H(F_p^{max})$ at which the maximum pinning occurs. In Fig. 3A we see that $H(F_{p\perp}^{max})$ ($= H_\parallel^{max}$) values are larger than $H(F_{p\parallel}^{max})$ ($= H_\perp^{max}$) irrespective of λ, i.e. $F_{p\perp}^{max}$ always occurs at a higher field than $F_{p\parallel}^{max}$ in both systems. $H(F_p^{max})$ values are smaller for NbTi/Nb

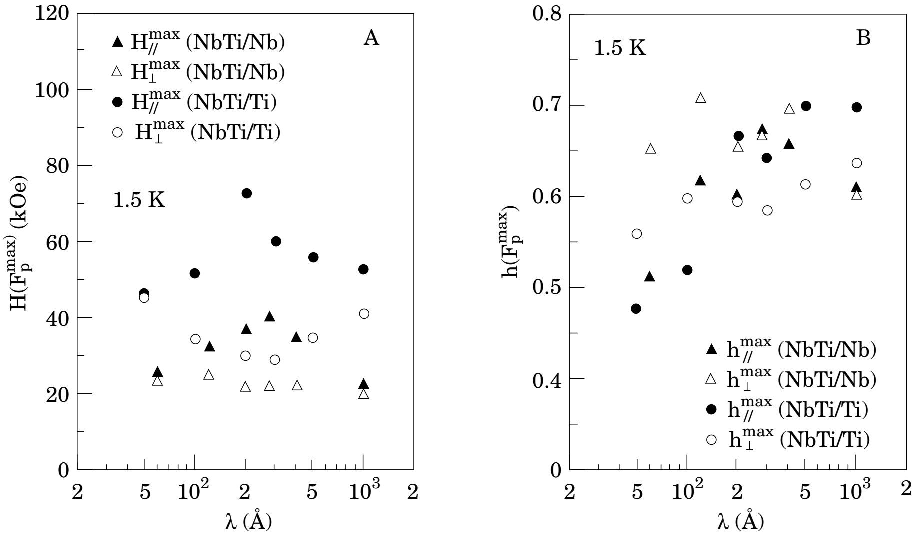

Fig. 3. A, Maximum pinning field H_{max} versus λ. ▲, $H_{p\parallel}^{max}$ of NbTi/Nb; △, $H_{p\perp}^{max}$ of NbTi/Nb; ●, $H_{p\parallel}^{max}$ of NbTi/Ti; ○, $H_{p\perp}^{max}$ of NbTi/Ti. B, Reduced maximum pinning field $h^{max} = H^{max}/H_{c2}$ versus λ. Symbols are the same as A.

Table 1: Parameters for various $Nb_{65}Ti_{35}/Nb$ and $Nb_{65}Ti_{35}/Ti$ multilayers.

λ (Å)	T_c (K)	$H_{c2\parallel}$ (kOe) 1.5 K	$H_{c2\perp}$ (kOe) 1.5 K	$F_{p\perp}^{max}$ (10^8 dyn cm^{-3}) 1.5 K	$F_{p\parallel}^{max}$ (10^8 dyn cm^{-3}) 1.5 K	λ (Å)	T_c (K)	$H_{c2\parallel}$ (kOe) 1.5 K	$H_{c2\perp}$ (kOe) 1.5 K	$F_{p\perp}^{max}$ (10^8 dyn cm^{-3}) 1.5 K	$F_{p\parallel}^{max}$ (10^8 dyn cm^{-3}) 1.5 K
$Nb_{65}Ti_{35}/Nb$						$Nb_{65}Ti_{35}/Ti$					
60	7.76	51	36	1.58	1.41	50	6.91	98	80	2.08	1.56
120	7.71	53	36	2.05	1.62	100	6.46	100	58	2.32	1.45
200	7.40	62	33	2.43	1.55	200	6.49	110	51	3.04	1.31
280	7.42	60	33	3.11	1.64	300	6.82	93	50	3.50	1.33
400	7.92	53	32	2.67	1.80	500	7.61	81	57	2.76	1.72
1000	8.59	38	34	1.84	1.26	1000	8.12	76	65	2.57	1.75

system than for NbTi/Ti system. The origin for the low $H(F_p^{max})$ is attributable to the lower H_{c2} values of NbTi/Nb than those of NbTi/Ti multilayers.

Figure 3B shows $h(F_p^{max}) = H(F_p^{max})/H_{c2}$ versus λ. In terms of the reduced field, $h(F_{p\parallel}^{max})$ $(= h_{\perp}^{max})$ values of NbTi/Nb are somewhat larger than corresponding values of NbTi/Ti. No systematic λ dependence of $h(F_p^{max})$ is confirmed except for $h(F_p^{max})$ of NbTi/Ti. The values of $h(F_p^{max})$ of NbTi/Ti increased with increasing λ up to λ = 500 Å and then saturated.

Finally we make a brief comment on the pinning mechanisms operating in these multilayer systems. For Nb/Ti, the superconductor/normal metal multilayer, the fluxoids are stabilized in Ti sublayers and the superconducting condensation energy is the main vortex pinning energy. The elementary pinning force f_p across the interface may be estimated from the core interaction formula, e.g. $f_p \approx 0.3\xi_{NT}H_c^2(1 - H/H_{c2})$ with thermodynamical critical field H_c and the coherence length ξ_{NT} of NbTi layer. In contrast, for NbTi/Nb, the superconductor/superconductor multilayer with almost the same condensation energy of both layers, the main origin of the pinning force comes from $\hbar^2(\nabla\psi)^2/2m^*$ term of the GL free energy (ψ: order parameter, m^*:

effective mass), which stabilizes the fluxoids in NbTi sublayers [5]. It is noteworthy that the overall features of $F_{p\perp}^{max}$ versus λ curve are similar for NbTi/Nb and NbTi/Ti multilayers in spite of the different vortex site and different pinning mechanisms between the two systems.

As a summary, the multilayer structures of NbTi/Nb and NbTi/Ti systems have been confirmed to enhance the pinning force density $F_{p\perp}$ perpendicular to the layer plane. Although the pinning mechanisms are different between these superconductor/superconductor and superconductor/normal metal multilayers, the most effective pinning occurs near the quasi-two-dimension to two-dimension transition of superconductivity in both systems. In comparison with NbTi/Ti, $F_{p\perp}$ in NbTi/Nb is enhanced at lower magnetic fields. Important superconducting material parameters are summarized in Table 1 for multilayers studied in this report.

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