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Flux pinning characteristics in NbTi/Nb superconductor/superconductor multilayers

Y. Obi[a,*], M. Ikebe[b], H. Fujishiro[b], H. Fujimori[a]

[a]Institute for Materials Research, Tohoku University, Katahira, Aoba-Ku, Sendai 980-8577, Japan
[b]Faculty of Engineering, Iwate University, Morioka 020-8551, Japan

Abstract

Flux pinning characteristics have been investigated for superconductor(S)/superconductor(S′) NbTi/Nb multilayers. The maximum of the perpendicular pinning force ($F_{\mathrm{p}\perp\mathrm{max}}$) as a function of the structure modulation length Λ has a peak in the quasi-two-dimensional superconductivity region. The large perpendicular pinning force observed in the S/S′ multilayer is caused by Nb layers, which act as the repulsive pinning centers.

Keywords: Multilayers; Niobium–titanium; Pinning strength

In superconductor(S)/normal metal(N) multilayers, the perpendicular pinning force $F_{\mathrm{p}\perp}$ acting in the perpendicular direction to the layer plane is usually much enhanced compared to the parallel pinning force $F_{\mathrm{p}||}$. In S/N multilayers, the N layer works as an attractive pin center for vortices. Recently, Matsushita et al. [1,2] suggested that in S/S' structures ($\xi_{\mathrm{s}} < \xi_{\mathrm{s}'}$), the large enhancement is possible in $F_{\mathrm{p}||}$, where the boundary works as a repulsive pinning center. We investigate $F_{\mathrm{p}\perp}$ in NbTi/Nb (S/S′) multilayers in this note. We discuss about the size of $F_{\mathrm{p}\perp}$ with respect to the GL coherence length ξ_{s} of NbTi layer.

Three series of NbTi/Nb ($Nb_{65}Ti_{35}$/Nb(N1), $Nb_{28}Ti_{72}$/Nb(N2) and $Nb_{50}Ti_{50}$/Nb(N4)) multilayers have been fabricated by an RF dual sputtering onto quartz substrates. Samples have equal sublayer thicknesses, $d_{\mathrm{NbTi}} = d_{\mathrm{Nb}} = (1/2)\Lambda$, where d_{NbTi} and d_{Nb} denote the thickness of NbTi and Nb layer, respectively, and Λ is the modulation wavelength. The critical current density J_{c} was determined resistively at 1.5 K for the three series of N1, N2 and N4. $F_{\mathrm{p}\perp}$ and $F_{\mathrm{p}||}$ were estimated from J_{c} as $F_{\mathrm{p}\perp} = J_{\mathrm{c}} \times H_{||}$ and $F_{\mathrm{p}||} = J_{\mathrm{c}} \times H_{\perp}$, where $H_{||}$ and $H_{\perp}$ are applied fields parallel and perpendicular to the layer. The current J is always applied along the layer.

Our recent experimental study [3] revealed that in S/S′ multilayers, the maximum pinning force F_{pmax} is comparable to that of S/N multilayer NbTi/Ti. These results indicate that in NbTi/Nb, Nb layers actually act as equally strong repulsive pinning centers as Ti layers in NbTi/Ti which act as attractive pinning centers. We define $F_{\mathrm{p}\perp\mathrm{max}}$ as the maximum value of the $J_{\mathrm{c}} \times H_{||}$ curve and $F_{\mathrm{p}\perp\mathrm{max}}$ as a function of Λ is shown in Fig. 1. All $F_{\mathrm{p}\perp\mathrm{max}}$ versus Λ curves have a broad peak at around $\Lambda = 200$–300 Å. The peak value of $F_{\mathrm{p}\perp\mathrm{max}}$ is the largest for $Nb_{28}Ti_{72}$/Nb. The difference in the peak values should originate from the difference in the coherence length ξ_{s} of each NbTi layer. According to the H_{c2} measurement [4], $\xi_{\mathrm{s}}(0)$ of each material at 0 K is estimated as 100.0, 63.4, 58.9 and 42.4 Å for Nb, $Nb_{65}Ti_{35}$, $Nb_{50}Ti_{50}$ and $Nb_{28}Ti_{72}$, respectively.

The energy of a single vortex line per unit length is made up of contributions from inside and outside of the core. In a parallel flux configuration to the layer, the contribution from outside of the core is averaged over several S and S′ layers and may roughly be independent of the vortex core site. The superconducting condensation energy is almost the same for Nb and NbTi sublayers. Then the main difference in the vortex core energy of S and S′ layers comes from the kinetic energy term,

* Corresponding author. Tel.: + 81-22-215-2097; fax: + 81-22-215-2096.

E-mail address: obi@imr.tohoku.ac.jp (Y. Obi)

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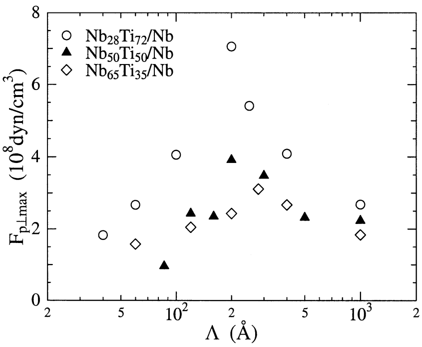

Fig. 1. $F_{p\perp max}$ for $Nb_{65}Ti_{35}$/Nb, $Nb_{50}Ti_{50}$/Nb and $Nb_{28}Ti_{72}$/Nb as a function of Λ at 1.5 K.

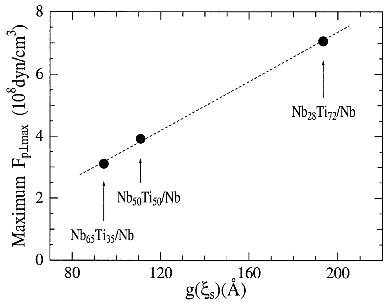

Fig. 2. Maximum $F_{p\perp max}$ as a function of $g(\xi_s)$ for three NbTi/Nb series at 1.5 K. The broken line is a guide to the eye.

$\hbar^2(\nabla|\Psi|)^2/2m^*$, in the GL free energy density, which is approximately equal to $\pi B_c^2\xi^2/\mu_0$. Dividing the energy difference by $2\xi_s$, the elementary pinning force $f_{p\perp}$ by this term is estimated to be

$$f_{p\perp} \simeq 0.5\pi \frac{B_c^2}{\mu_0}\frac{(\xi_{s'}^2 - \xi_s^2)}{\xi_s}, \tag{1}$$

where B_c is the thermodynamic critical field and μ_0 is the permeability of vacuum. Thus, $f_{p\perp}$ and, as a result, the maximum macroscopic pinning force $F_{p\perp max}$ is expected to depend linearly on $g(\xi_s) = (\xi_{s'}^2 - \xi_s^2)/\xi_s$. In Fig. 2, we plot the maximum $F_{p\perp max}$ as a function of $g(\xi_s)$. We can see from the plot that $F_{p\perp max}$ versus $g(\xi_s)$ approximately follows a linear relation.

In summary, the S/S' multilayer, NbTi/Nb, has a large $F_{p\perp max}$ which is comparable to that of NbTi/Ti [3]. Three series of NbTi/Nb having different Ti compositions show a broad peak in their $F_{p\perp max}$ versus Λ curve in the quasi-2D superconductivity region. The peak value of $F_{p\perp max}$ as a function of $g(\xi_s)$ has nearly a linear relation. This should originate from the Nb sublayers which act as repulsive pinning centers in the parallel flux configuration.

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