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Parallel and Perpendicular Field Dependence of J_C of NbTi-Cu Multilayer Films

Minoru Takeda and Kazu Nishigaki

***Abstract*—The critical current density, J_C, of NbTi-Cu multilayer films has been measured in parallel fields and in perpendicular fields at 4.2 K, as a parameter of thickness of the NbTi monolayer, d_S. The thicknesses d_S are 100 nm, 200 nm, 300 nm, and 500 nm, while the thickness of the Cu monolayer is 200 nm. It is found that the cross field B^* where J_C in perpendicular fields exceeds that in parallel fields clearly decreases as d_S increases. As a result of analyses of scaling parameters, the pinning force density of NbTi-Cu multilayer films in both parallel fields and perpendicular fields may be explained by the scaling law as a parameter of thickness d_S with different values of scaling parameters.**

***Index Terms*—critical current density, pinning force density, scaling law, superconducting films**

I. INTRODUCTION

SUPERCONDUCTING multilayer films such as NbTi-Cu and NbTi/Nb/Cu have been applied for magnetic field shielding [1]-[4]. In order to understand the shielding capability of the multilayer films, it is important to clarify the field strength dependence and orientational dependence of the pinning force density, which is closely related to the critical current density. From this point of view, we have been conducting studies on the critical current density J_C [5], [6].

In our previous work on NbTi-Cu multilayer films, which consist of 200-nm-thick NbTi layers and 200-nm-thick Cu layers, it was observed that the J_C value obtained in a perpendicular field exceeds that in a parallel field at a certain field B^*. This B^* value was related to the thickness of the NbTi monolayer d_S in the case of a constant thickness of the Cu monolayer. However, no systematic studies of the relationship between the thickness d_S and B^* have been carried out.

The present paper reports on the parallel and perpendicular field dependence of J_C of NbTi-Cu multilayer films as a parameter of thickness of the NbTi monolayer and the number of layers. On the basis of new data, the thickness dependence of B^* for NbTi-Cu multilayer films is discussed. Focusing on the global pinning force, we also qualitatively discuss the difference between the flux pinning mechanism in parallel fields and that in perpendicular fields through analyses of scaling parameters.

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II. EXPERIMENTAL

Multilayer films with Nb-46.5 wt% Ti and Cu were fabricated by RF sputtering onto a 17 mm×14 mm×0.5 mm glass substrate. No thermal or mechanical treatment was done on these films. The thicknesses of the NbTi monolayer, d_S, were 100 nm, 200 nm, 300 nm, and 500 nm, while the thickness of the Cu monolayer was 200 nm. The number of NbTi-Cu layers, n_L, ranged from 1 to 7. The critical temperatures T_C were 6.5 K for film with d_S = 100 nm, 7.8 K for d_S = 200 nm, 7.7 K for d_S = 300 nm, and 8.0 K for d_S = 500 nm. It was observed that these T_C values were almost independent of the number of layers.

A simple multipurpose cryostat [7] was used for the experiment. The samples were set at the center of the magnet, and were immersed in liquid helium. The critical current density J_C was measured at 4.2 K in parallel and perpendicular fields with respect to the film plane. The J_C value was calculated as I_C / A, where I_C is the critical current and A is the total cross-sectional area of the NbTi layers. The I_C value was determined by a four-probe method using a 1 μ V/cm criterion.

III. RESULTS AND DISCUSSION

A. Parallel and Perpendicular Field Dependence of J_C

First, measurements of J_C were carried out as a function of the thickness of the NbTi monolayer d_S, and the number of NbTi-Cu layers (n_L = 2) was fixed. The J_C values were obtained for the samples with thicknesses of 200 nm and 300 nm. Fig. 1 shows the parallel and perpendicular field dependence of J_C for the sample with d_S = 200 nm. Both $J_{C\parallel}$ (J_C in parallel fields) and $J_{C\perp}$ (J_C in perpendicular fields) gradually decreased with increasing magnetic flux density, B. It was observed that $J_{C\perp}$ exceeds $J_{C\parallel}$ at a certain magnetic flux density B^*, which was 6.25 T. A similar result of the B^* value was obtained for the sample with different thickness. Fig. 2 shows the relationship between J_C and B for the sample with d_S = 300 nm. In this case, the B^* value was 2.75 T. This value was clearly smaller than that of the sample with d_S = 200 nm.

It was expected that the B^* value would decrease with increasing d_S because of the results shown in Figs. 1 and 2. Thus, measurements were also carried out for the samples with thicknesses of 100 nm and 500 nm. In the case of the sample with d_S = 500 nm, the B^* value was about 0 T; $J_{C\perp}$ was larger than $J_{C\parallel}$ in all fields examined. On the

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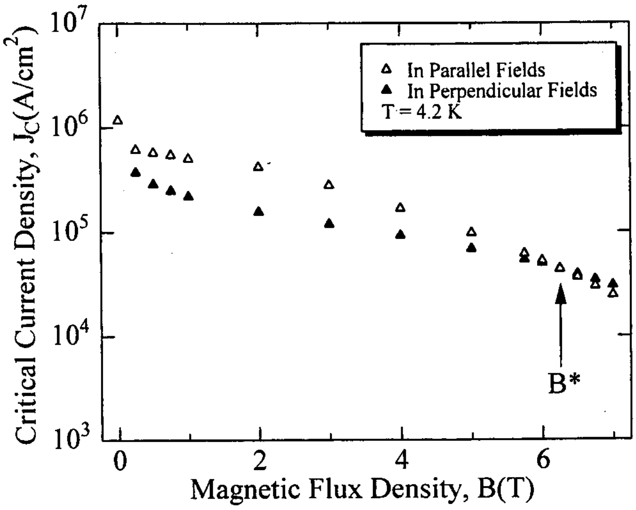

Fig. 1. Parallel and perpendicular field dependence of J_C for the sample with d_S = 200 nm and n_L = 2. In this figure, B^* shows a cross point at 6.25 T.

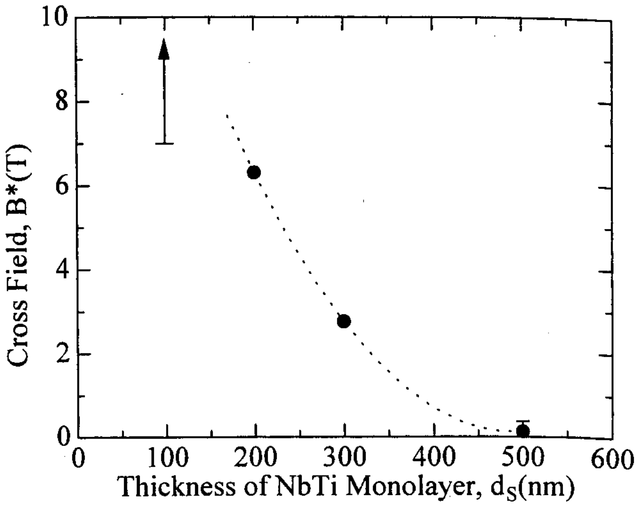

Fig. 3. Thickness dependence of B^* for the samples with n_L = 2. A dotted curve is drawn as a visual guide. An arrow indicates that the B^* value was much more than 7 T.

other hand, the B^* value was much more than 7 T for the sample with d_S = 100 nm; $J_{C\perp}$ was smaller than $J_{C\parallel}$ in all fields examined. The relationship between B^* and d_S for the samples with n_L = 2 is summarized in Fig. 3. In this figure, a dotted curve is a visual guide. It is found that the B^* value clearly decreases as d_S increases.

Next, measurements of J_C were carried out as a function of the number of NbTi-Cu layers n_L, with the thicknesses of the NbTi monolayer d_S fixed to 200 nm and 300 nm. Relationships between B^* and n_L, which were obtained from the J_C values, are shown in Fig. 4. In this figure, the maximum value of B^* was 6.8 T and the minimum value was 5.5 T for the sample with d_S = 200 nm, while the B^* value was approximately 3.0 T for the sample with d_S = 300 nm except for the data obtained at 5 layers. It was found that B^* did not depend significantly on n_L. The reason for this may be described as follows. The property that B^* does not depend significantly on n_L corresponds to the property that J_C does not depend significantly on n_L. In other words, J_C does not vary significantly, even when the number of interfaces between the superconductor and normal metal is changed.

In our previous paper on NbTi films [5], an empirical rule that $J_{C\perp}$ / $J_{C\parallel}$ is proportional to the square root of thickness was reported. According to this experimental result, the tendency of B^* to decrease with increasing d_S may be ascribed to the thickness dependence of J_C of the NbTi monolayer. In order to confirm this explanation, a similar experiment was carried out only on NbTi samples with thicknesses of 200 nm and 500 nm. As a result of this experiment, the relationship between B^* and thickness was similar to that for NbTi-Cu multilayer films, which agreed with our expectation.

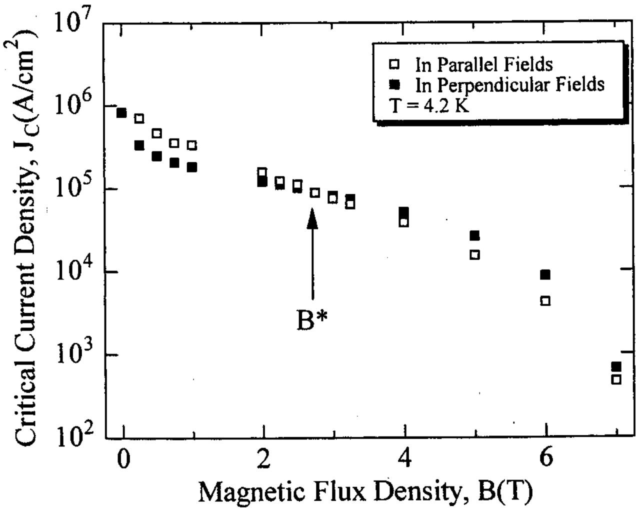

Fig. 2. Parallel and perpendicular field dependence of J_C for the sample with d_S = 300 nm and n_L = 2. In this figure, B^* shows a cross point at 2.75 T.

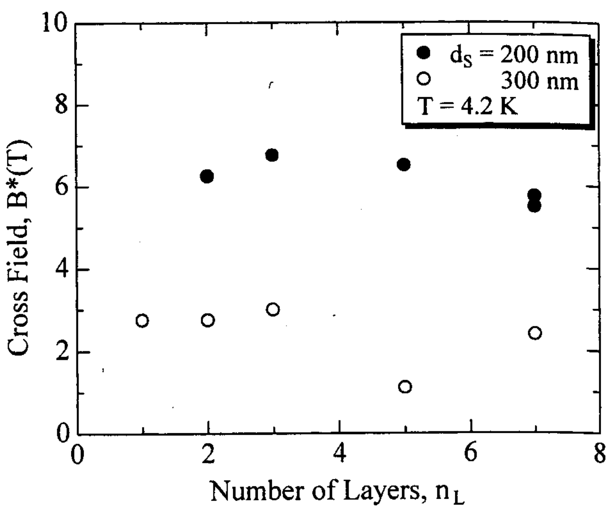

Fig. 4. Dependence of B^* on number of layers n_L for the samples with d_S = 200 nm and 300 nm.

It can be concluded that the tendency of B^* to decrease with increasing d_S for NbTi-Cu multilayer films is believed to be due to the thickness dependence of J_C of the NbTi monolayer, not that of the Cu monolayer. In addition, the reason why B^* shows such a tendency is qualitatively explained as follows. In general, with increasing the thickness of the superconducting layer, it has been accepted that $J_{C\parallel}$ decreases due to the weak surface barrier [8]. On the other hand, it is known that $J_{C\perp}$ increases relatively due to the collective pinning by comparison with $J_{C\parallel}$ [9]. Therefore, it may be understood that the cross field B^* where $J_{C\perp}$ exceeds $J_{C\parallel}$ decreases as d_S increases.

B. Analysis of Scaling Parameter

It has been known that the scaling law of the pinning force density, F_P, as a parameter of temperature, can be applied to superconducting materials such as Pb-Bi [10]. The scaling law taking into account the thickness is discussed as follows: In this case, since F_P is considered to be a function of magnetic flux density B, temperature T, and thickness d_S, the scaling equation of F_P can be expressed as

$$F_P(B,T,d_S) = J_C(B,T,d_S)B = AB_{C2}(T,d_S)^m b^\gamma (1-b)^\delta, \quad (1)$$

where A, m, γ and δ are scaling parameters, B_{C2} is the upper critical magnetic flux density, and $b = B / B_{C2}$ is the reduced magnetic flux density. On the assumption that the maximum pinning force density, $F_{P,\max}$, is proportional to $B_{C2}{}^m$, a nondimensional equation of reduced pinning force density, $F_P / F_{P,\max}$, can be obtained from (1) as

$$F_P / F_{P,\max} = Cb^\gamma (1-b)^\delta, \quad (2)$$

where C is constant.

First, we attempted to determine the values of the scaling parameters γ and δ by means of a best fitting method between the experimental data and (2), in order to elucidate whether the scaling law taking into account the thickness can be applied to NbTi-Cu multilayer films. Fitting gives that $\gamma = 0.68$ and $\delta = 2.0$ in parallel fields, and $\gamma = 0.60$ and $\delta = 1.0$ in perpendicular fields. Fig. 5 shows the relationship between $F_P / F_{P,\max}$ and B / B_{C2} in parallel fields as a parameter of thickness. In this figure, the solid curve represents for the calculation from (2). The B_{C2} values were estimated by extrapolating the $J_{C\parallel}(B)$ values to zero. It was observed that the B_{C2} value was a function of thickness d_S. Fig. 6 shows the result obtained in a similar way for perpendicular fields. As is evident in Figs. 5 and 6, the calculation from (2) was in good agreement with the experimental data in perpendicular fields, while the scattering of data was more in parallel fields.

Next, we attempted to determine the value of the scaling parameter m in (1) by comparison with experimental data, on the basis of the linear relationship between $F_{P,\max}$ and $B_{C2}{}^m$, which was observed in Pb-Bi [10]. This relationship in parallel fields on a logarithmic scale is shown in Fig. 7. In this figure, slope m of the solid line, which was obtained as a data-fitting line, was 1.8. Fig. 8 shows the result obtained in a similar way for perpendicular fields. In this case, the value of m was 3.9, which was relatively large. It should be noted that the pinning force density of NbTi-Cu multilayer films in both parallel and perpendicular fields may be explained by the scaling law as a parameter of thickness with different values of scaling parameters. These scaling parameters are summarized in TABLE I .

Based on the values of the scaling parameters shown in TABLE I , the difference between the flux pinning mechanism in parallel fields and that in perpendicular fields is qualitatively discussed as follows. With respect to NbTi monofilamentary wires, Matsushita and Küpfer [11] reported that m = 2.2 to 2.9, γ = 0.95 to 1.76 and δ = 1.95 to 2.28, and that the result of $\delta \simeq 2$ indicates that the pinning force density F_P was saturated at high fields. Upon comparison of our scaling parameter values in parallel fields and their values,

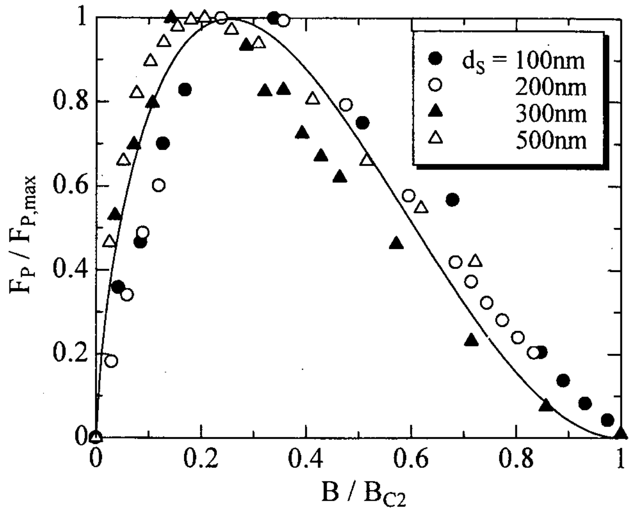

Fig. 5. Scaling properties as a parameter of thickness for NbTi-Cu multilayer films with n_L = 2 in parallel fields. A solid curve is calculated from (2) with $\gamma = 0.68$ and $\delta = 2.0$.

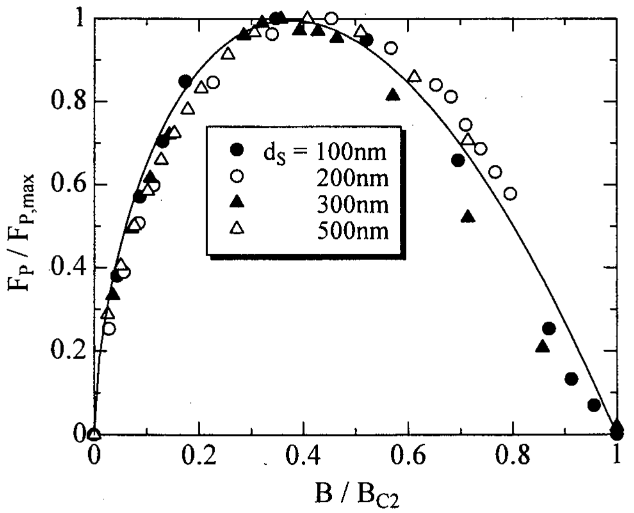

Fig. 6. Scaling properties as a parameter of thickness for NbTi-Cu multilayer films with n_L = 2 in perpendicular fields. A solid curve is calculated from (2) with $\gamma = 0.60$ and $\delta = 1.0$.

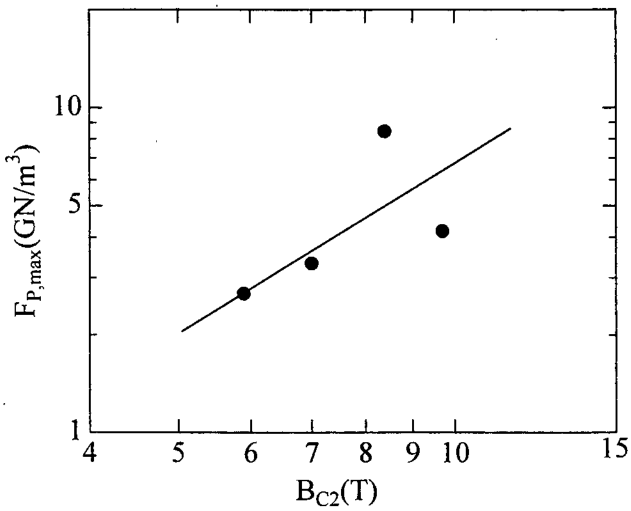

Fig. 7. Relationship between maximum pinning force density $F_{P,max}$ and upper critical magnetic flux density B_{C2} in parallel fields. The solid line has a slope of 1.8.

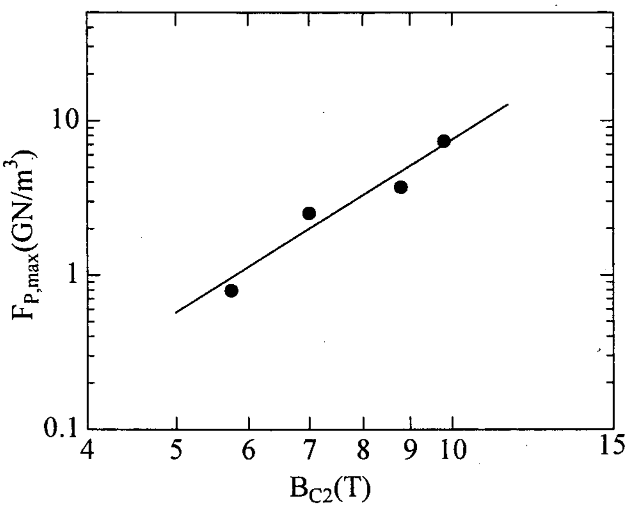

Fig. 8. Relationship between maximum pinning force density $F_{P,max}$ and upper critical magnetic flux density B_{C2} in perpendicular fields. The solid line has a slope of 3.9.

they were found to be similar. Thus, it may be understood that the flux pinning force was saturated at high parallel fields in NbTi-Cu multilayer films, because flux lines flowed through the grain boundaries. On the other hand, for Pb-Bi cylindrical specimens, Coote *et al.* [10] reported that $m = 2$, $\gamma = 0.5$ and $\delta = 1.0$, and that the result of $\gamma = 0.5$ and $\delta = 1.0$ indicates that three-dimensionally distributed precipitates act as pinning centers, where the size of the precipitates is much larger than the distance between flux lines. Upon comparison of our scaling parameter values in perpendicular fields and their values, they were found to be similar except for the value of m. Thus, a similar pinning model might be applied to the NbTi-Cu multilayer films in perpendicular fields.

TABLE I
SCALING PARAMETERS OF NBTI-CU MULTILAYER FILMS

Orientation	m	γ	δ
Parallel	1.8	0.68	2.0
Perpendicular	3.9	0.60	1.0

IV. SUMMARY

The parallel and perpendicular field dependences of the critical current density J_C of NbTi-Cu multilayer films have been studied as a parameter of the thickness of the NbTi monolayer d_S. It is found that the cross field B^* where $J_{C\perp}$ exceeds $J_{C\parallel}$ noticeably decreases with increasing d_S. This tendency of B^* is believed to be due to the thickness dependence of J_C of the NbTi monolayer. It is a consequence of analyses of scaling parameters that the scaling law of the pinning force density F_P as a parameter of thickness d_S may be applied to NbTi-Cu multilayer films in both parallel and perpendicular fields with different scaling parameter values.

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