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Pauli Paramagnetic Effect and Parallel Critical Field of Nb/Al_2O_3 Multilayers

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The parallel critical field $H_{c2//}(T)$ of Nb/Al_2O_3 multilayer superconductors has been analyzed as a function of Nb layer thickness using Maki's theory for a two-dimensional superconductor. $H_{c2//}$ was found to be significantly affected by the Pauli paramagnetic effect. A reliable estimation of the spin-orbit scattering time τ_{so} was made for the Nb layers.

1. Introduction

As is well-known, the Ginzburg-Landau (GL) theory predicts that the parallel critical field $H_{c2//}$ of a thin film superconductor is inversely proportional to the film thickness d [1,2]. Accordingly, the parallel critical field can be made arbitrarily large by making the film thickness small enough. For superconductors with such a large orbital, however, the Pauli paramagnetic effect is expected to become the main origin to limit $H_{c2//}$. In dirty superconductors with strong electron scattering, the paramagnetic limiting is controlled by the strength of the spin-orbit scattering. In this paper, we develop a method to evaluate τ_{so} of Nb layers by analyzing $H_{c2//}(T)$ of Nb/Al_2O_3 multilayers as a function of Nb sublayer thickness d_{Nb}.

Nb/Al_2O_3 multilayer films were prepared by the dual magnetron sputtering technique. The thickness of each sublayer (d_{Nb} and d_{AlO}) was selected over a range from 5 to 100Å. The layer numbers were so adjusted that the total thickness of the films became about 5000Å. The details of the sample preparation are presented elsewhere [3]. The list of the multilayers studied in this report is given in Table I together with important material parameters.

2. Results and Discussion

The sheet resistance $R_\square$ was measured by a standard four lead method. Fig. 1 shows the conductance per square, $G_\square$, at 10K as a function of d_{Nb}. The definition of $G_\square$ is given by

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Table I. Material and superconducting parameters of Nb/Al_2O_3 composites.

d_{Nb}/d_{AlO} (Å/Å)	R ($\Omega_\square$)	T_c (K)	H_{c2}/H_{c2} (at 1.5K)	$\xi(0)$ (Å)	dH_{c2}/dT (kG/K)	D (cm^2/s)
30/30	161	2.49	12.8	145	6.90	1.44
50/30	47.3	5.02	5.79	107	4.03	2.31
70/30	21.3	6.30	5.55	108	4.63	2.09
100/30	11.6	7.27	4.38	110	3.83	2.41
50/50	56.6	4.60	5.91	110	6.25	1.47
100/50	10.7	7.13	4.09	110	3.87	2.48
70/70	20.4	6.06	4.84	107	4.99	2.00
100/100	11.2	6.92	4.33	107	4.27	2.31

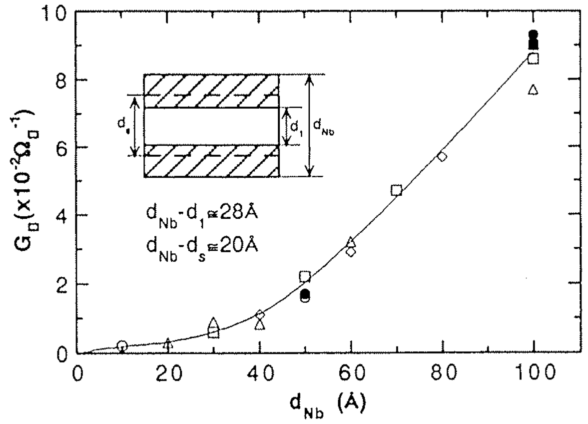

Fig. 1. $G_\square$ vs. d_{Nb}. Each symbol stands for d_{AlO} O: 10Å, Δ: 20Å, □: 30Å, ◇ :40Å, ●: 50Å, ▮: 100Å. The inset schematically shows the proposed trilayer structure inside of Nb layers. The shaded regions indicate the degraded parts of the Nb layer and d_1 is the intact part of the Nb layer. d_s is the effective superconducting layer (see text).

$$G_\square \equiv 1/R_\square = d_{Nb}/\rho \qquad (1)$$

where ρ is the resistivity determined under an assumption that the electrical current passes only through Nb sublayers. $G_\square$ exhibits a linear dependence on d_{Nb} in both the large and small d_{Nb} regions. But the slope of the linear dependence changes remarkably around d_{Nb}=30Å. A similar behavior of $G_\square$ was first observed for Nb/Ge composites [4]. This d_{Nb} dependence of $G_\square$ can be understood in a trilayer model. We assume that thin layers of degraded high resistivity Nb (probably a mixture of Nb with Al and O) are formed on both interfacial sides of each Nb sublayer. From the slopes of the linear parts of the $G_\square$ vs. d_{Nb} line, the resistivities of the degraded side layers (ρ_{deg}) and the central intact Nb layers (ρ_{Nb}) are estimated to be ρ_{deg}=49.5μΩcm and ρ_{Nb}=7.3μΩcm at 10K. From the turning point of the slopes, the thickness of the degraded Nb layer d_{Nb}^{deg} is estimated to be above 14Å (totally 28Å per Nb sublayer). This value of d_{Nb}^{deg} was found to be consistent with the λ (=structural modulation wavelength) dependence of the transition temperature T_c of Nb/Al_2O_3 multilayers as reported in our previous paper [3].

Nb/Al_2O_3 multilayers with d_{AlO} ≥30Å showed two-dimensional (2D) superconducting characteristics irrespective of d_{Nb} values [3]. In these multilayers each Nb sublayer behaves almost independently and the theory for the upper critical field of a thin film can be applied. We apply Maki's theory [5] to 2D Nb/Al_2O_3 composites. Maki's calculation is valid in the dirty limit, $l < d < (l\xi_0)^{1/2}$, where l is the electron mean free path, d is the film thickness and ξ_0 is the BCS coherence length. From the much larger perpendicular critical fields $H_{c2\perp}$ observed in Nb/Al_2O_3 than H_{c2} of bulk Nb and the estimated very small values of l, Nb is very small and Nb sublayers are surely in the dirty limit. Then the equations to determine critical fields parallel ($H_{c2//}$) and perpendicular ($H_{c2\perp}$) to the larger plane are given by

$$\ln(T/T_c) = \Psi(\tfrac{1}{2}) - \Psi\{\tfrac{1}{2} + (\tfrac{1}{2}\pi k_B T)(DeH_{c2\perp}/C)\} \tag{2}$$

$$\ln(T/T_c) = \Psi(\tfrac{1}{2}) - \Psi\{\tfrac{1}{2} + (\tfrac{1}{12}\pi k_B T)(De^2 H_{c2//}^2 d_s{}^2/\hbar C^2) + (\tfrac{1}{2}\pi k_B T)(3\tau_{so}\mu_B^2 H_{c2//}^2/2\hbar)\} \tag{3}$$

where k_B is the Boltzman constant, D the diffusion constant of electrons, d_s the thickness of the superconducting layer, μ_B the Bohr magnetron and $\Psi(x)$ is the di-gamma function. In Eq.(3) we took account of the paramagnetic effect by adding a new pair-breaking term $3\tau_{so}\mu_B{}^2H_{c2//}{}^2/2\hbar$. Eq.(3) is valid under the condition $\tau_{so}\mu_B H/2\pi\hbar < 1$.

Based on the equations (2) and (3), the fitting of the upper critical fields was made in the following way. At first, Eq. (2) was numerically solved to fit $H_{c2\perp}$. with D and T_c as adjustable parameters. Then Eq.(3) was solved to fit $H_{c2//}(T)$ by use of the D values which had been determined by the $H_{c2\perp}(T)$ fitting. Excellent fitting is obtained for both $H_{c2//}(T)$ and $H_{c2\perp}(T)$, as several examples in Fig. 2 show.

As can be seen from Eq. (3), the orbital effect becomes very small with decreasing d_s and the paramagnetic effect plays a dominant role to limit $H_{c2//}$ of small λ films. Thus we expect that $H_{c2//}(T)$ fitting for the small d_{Nb} specimens provides a reliable estimation of the spin-orbit scattering time τ_{so}. Fig. 3 shows estimated τ_{so} values as a function of d_{Nb}. If we put $d_s = d_{Nb}$, however, the d_{Nb} dependence of τ_{so} proves to be somewhat unreasonable; τ_{so} increases with decreasing d_{Nb}. Fig. 3 also shows the total scattering time τ which was evaluated from the determined D values from $H_{c2\perp}(T)$. Because τ decreases with decreasing d_{Nb}, we expect τ_{so} should also decrease with d_{Nb}. In order to remedy this contradiction, we regarded d_s as an effective thickness of the superconducting layer in the

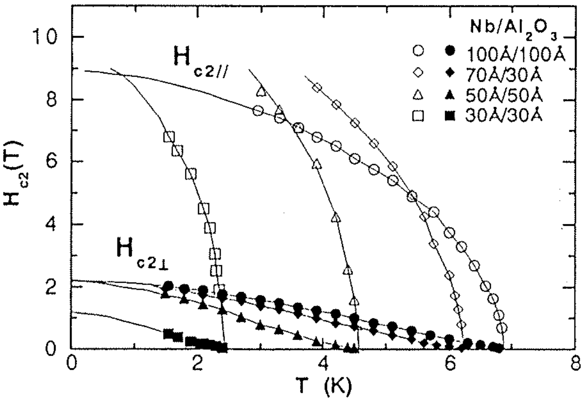

Fig. 2. Examples of numerical fitting of $H_{c2//}(T)$ and $H_{c2\perp}(T)$ by use of Eq. (2) and Eq. (3).

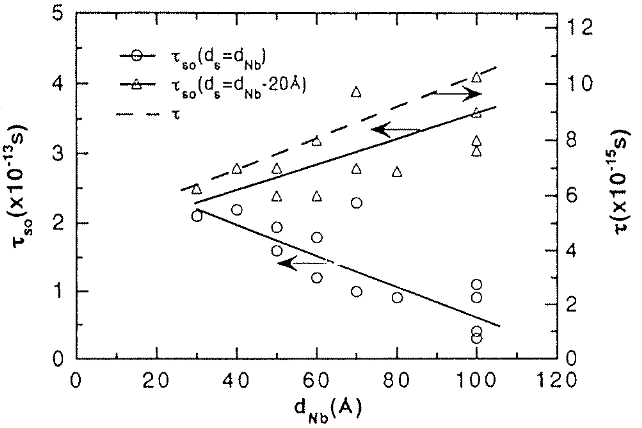

Fig. 3. Spin-orbit scattering time τ_{so} (O) vs. d_{Nb}. Total scattering time τ vs. d_{Nb} is also shown by the dashed line. τ is estimated from the diffusion constant $D=(v_F^{Nb})^2\tau/3$ ($v_F^{Nb}= 2.6\times10^7$cm/sec). By assuming $d_s=d_{Nb}$-20Å, τ_{so} (Δ) vs. d_{Nb} approximately scales to τ vs. d_{Nb}.

multilayer and put $d_s=d_{Nb}$-20Å. Then the d_{Nb} dependence of τ_{so} almost scales with that of τ as can be seen in Fig. 3, and the evaluated spin-orbit scattering accounts for about 1/30 of the total electron scattering in sputtered Nb metals.

As already mentioned, the analyses of the λ dependence of $\rho(T)$ and T_c indicated formation of the degraded (low T_c [3]) Nb side layers with total thickness 28Å sandwiching the central intact Nb layer. The proposed effective superconducting the layer thickness d_s in the Nb/Al_2O_3 multilayer is smaller than d_{Nb} by about 20Å but larger than that of the inner intact Nb layer thickness d_I by about 8Å (see the inset of Fig. 1). These relations between d_{Nb}, d_I and d_s seems reasonable but should be confirmed on the basis of microscopic theories. Recently, Kamiguchi, one of the present authors, has calculated the orbital critical fields $H_{c2//}(T)$ of the trilayer in Fig. 1 by use of Takahashi and Tachiki's formalism for superlattices [6]. The relation, $d_s=d_{Nb}$-20Å has been found to be consistent with the calculated $H_{c2//}$ in the region of $d_{Nb}\geq$50Å [7].

4. Summary

(i) Parallel ($H_{c2//}$) and perpendicular ($H_{c2\perp}$) critical fields of Nb/Al_2O_3 multilayers with Al_2O_3 layer thickness $d_{AlO}\geq$30Å can be well explained on the basis of Maki's theory for thin film superconductors if we also take account of the Pauli paramagnetic effect. (ii) From the analyses of $H_{c2//}(T)$, a reliable estimation of the spin-orbit scattering time τ_{so} can be made for Nb sublayers with small d_{Nb}. Spin-orbit scattering accounts for about 1/30 of the total electron scattering in the sputtered Nb films.

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