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Pauli paramagnetic effect and spin-orbit scattering time in Nb/Al_2O_3 superconducting multilayers

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Abstract

The parallel critical field $H_{c2}||(T)$ of the Nb/Al_2O_3 two-dimensional (2D) multilayer superconductors has been analyzed by developing the 2D-version of the WHH theory and by utilizing the Takahashi–Tachiki formalism. A reliable method to estimate the spin-orbit scattering time τ_{S0} of thin films has been provided.

Keywords: Nb/Al_2O_3 multilayers; Parallel critical field; Spin-orbit scattering time

The parallel orbital critical field $H_{c2\|}(T)$ of thin films is inversely proportional to the thickness d and can be made arbitrary large in principle. Then instead, the spin paramagnetic effect counteracted by spin-orbit scattering limits $H_{c2\|}$. Accordingly, a reasonable estimation of the spin-orbit scattering time τ_{S0} can be made if we properly analyze the $H_{c2\|}(T)$ of thin films. In this paper, we determine τ_{S0} of Nb by analyzing $H_{c2\|}$ of the Nb/Al_2O_3 multilayers.

The Nb/Al_2O_3 multilayers were prepared by a dual sputtering method [1]. The transition temperature T_c and the critical fields $H_{c2\|,\perp}$ were determined resistively. The list of the multilayers analyzed in this report is given in Table 1.

Fig. 1 shows the conductance per square, $G_\square$, at 10 K as a function of the Nb layer thickness d_{Nb}. $G_\square$ exhibits a linear dependence on Nb in both the large and the small d_{Nb} regions, but the slope of the linear dependence radically changes around $d_{Nb} = 30$ Å. A similar behavior was first observed in Nb/Ge multilayers [2] and was understood on the basis of a trilayer model. We assume that thin layers of disordered and degraded high resistivity Nb are formed on both interfacial sides of each Nb layer (see the inset in Fig. 1). From the slopes of the linear dependences of the $G_\square$ vs. d_{Nb} line, the resistivities of the degraded layers (ρ_{deg}) and the genuine Nb layer (ρ_{Nb}) are estimated to be $\rho_{deg} = 49.5$ μΩcm and $\rho_{Nb} = 7.3$ μΩcm, respectively. From the turning point of the slopes, the thickness of each degraded Nb layer, d_{Nb}^{deg} is estimated to be about 14 Å (totally 28 Å per Nb layer).

Fig. 2 presents $H_{c2\|}(T)$ and $H_{c2\perp}(T)$ as a function of T.$H_{c2\|}(T)$ rises with an infinite slope at T_c, showing the two-dimensional (2D) character. The present Nb/Al_2O_3 multilayers are surely in the dirty limit but not dirty enough to satisfy the condition, $\lambda_{S0} = 2\hbar/3\pi k_B T_c \tau_{S0} \gg 1$ ($\lambda_{S0} \sim 0.5$, for present samples). Then the simplified Maki's theory [3] is not applicable and the 2D version of the full WHH theory [4] must be invoked. The 2D formalism of the WHH theory has been accomplished by Ebisawa [5] and $H_{c2\|}(T)$ of a thin film with the thickness d is given by the following equations:

$$\ell n(t) = \psi\left(\frac{1}{2}\right) - \frac{1}{2}\left\{\left(1 - \frac{\lambda_{S0}}{2G}\right)\psi\left(\frac{1}{2} + \frac{h^2}{t} + \frac{\lambda_{S0}}{4t} + \frac{G}{2t}\right) + \left(1 + \frac{\lambda_{S0}}{2G}\right)\psi\left(\frac{1}{2} + \frac{h^2}{t} + \frac{\lambda_{S0}}{4t} - \frac{G}{2t}\right)\right\}, \quad (1)$$

where $G = \sqrt{(\lambda_{S0}/2)^2 - 4fh^2}$, ψ is the di-gamma function, $f = \alpha^2(d_0/d)^2$, $d_0 = \pi\hbar D/2k_B T_c$, $\alpha = \hbar/2mD$, $h^2 = \pi\hbar d^2 H^2/12\Phi_0^2 k_B T_c$, $t = T/T_c$, $\Phi_0 = \pi\hbar/e$, D =electron diffusion constant, m =electron mass, H =applied field (other notations are of standard style). Eq. (1) allows us

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Table 1
Material and superconducting parameters of Nb/Al_2O_3

$d_{Nb}/d_{Al_2O_3}$ (Å/Å)	$G_\square$ ($\Omega_\square^{-1}$)	T_c (K)	$\xi(T=0K)$ (Å)	$dH_{c2\perp}/dT$ (kG/K)	D (cm^2/s)
10/10	9.52×10^{-4}	1.87	87	16.2	0.60
40/40	1.07×10^{-2}	3.51	101	6.55	1.50
50/50	1.77×10^{-2}	4.60	110	6.25	1.47
60/40	2.92×10^{-2}	6.18	109	4.50	2.26
70/70	4.90×10^{-2}	6.06	107	4.90	2.00
80/40	5.71×10^{-2}	6.55	107	4.11	2.38
100/100	8.93×10^{-2}	6.92	107	4.27	2.31

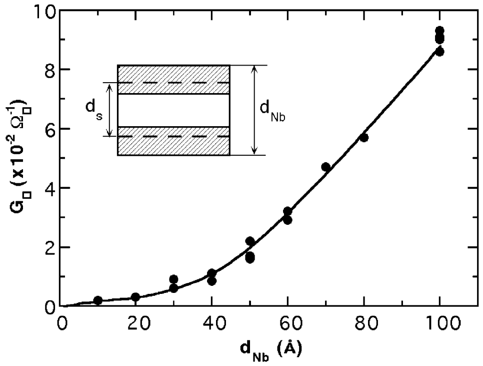

Fig. 1. $G_\square$ vs. d_{Nb}. The inset schematically shows the trilayer structure inside of Nb layers. The shaded parts indicate the degraded Nb layer. d_s is the effective superconducting layer.

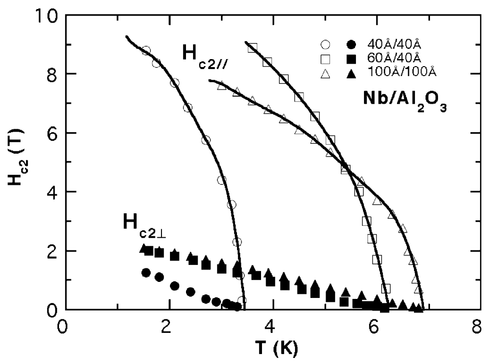

Fig. 2. Examples of measured critical fields and numerical fittings for $H_{c2\|}(T)$ on the basis of Eq. (1) and d_s.

to calculate $H_{c2\|}(T)$ of thin films in the dirty limit for arbitrary τ_{S0} on the basis of T_c, D, τ_{S0} and d values.

Because of the trilayer structure of the Nb sublayer, however, we cannot directly regard d_{Nb} as d in Eq. (1). To estimate the effective superconducting film thickness d_s, we utilized the Takahashi–Tachiki formalism [6] and calculated $H_{c2\|}(T)$ of the sandwiched Nb films (without the paramagnetic effect). The material parameters of Nb ($\theta_D = 277$ K, $N = 0.9\times10^{23}/\text{eVcm}^3$, $V = 0.315\times10^{-23}\text{eVcm}^3$, $D = 3.0\ \text{cm}^2/\text{s}$) were used for the central intact Nb layer and those for degraded Nb layer were modified ($\theta_D = 277$ K, $N = 0.77\times10^{23}/\text{eVcm}^3$, $V = 0.252\times10^{-23}\text{eVcm}^3$, $D = 0.60\ \text{cm}^2/\text{s}$) to best reproduce the T_c vs. d_{Nb} curve [1]. The obtained $H_{c2\|}(T)$ curve was approximated by the G–L result, $H_{c2\|}(T) = \sqrt{12}\Phi_0/2\pi\xi(T)d_s$ ($\xi(T)$ =coherent length), to get the effective d_s which is given in Fig. 3(a). Fig. 3(b) presents our final results, τ_{S0} as a function of d_{Nb}. We can conclude that the spin-orbit scattering accounts for 1.2–3% of the total scattering rate in the sputtered Nb. The authors wish to thank Prof. H. Ebisawa for the derivation of Eq. (1).

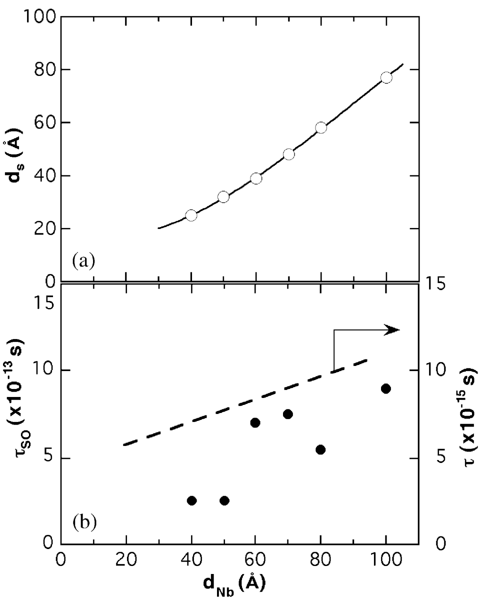

Fig. 3. (a) Calculated effective superconducting layer thickness d_s for a unit Nb trilayer as a function of d_{Nb}. (b) Calculated spin-orbit scattering time τ_{S0} vs. d_{Nb}. Total scattering time τ is shown by the dashed line ($v_F^{Nb} = 2.6\times10^7$ cm/s).

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