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Magnetic-field penetration depth and material parameters of V-Ag multilayered superconductors

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We have made measurements of the magnetic field penetration depth λ of V-Ag proximity-coupled multilayers for the first time. The layer-thickness dependence of λ exhibits a nonmonotonic behavior (existence of a minimum λ). This is interpreted as a crossover from a single superconductor to a composite one. When the Ag layer becomes thicker, the temperature dependence of λ begins to deviate from that of usual superconductors, showing that the proximity effect is involved. In addition, from λ and our previously found upper-critical-field parameters, the Ginzburg-Landau parameter, the thermodynamic critical field at 0 K, and the electronic coefficient of the normal-state specific heat are obtained. The variation of these parameters with layer thickness is also discussed.

I. INTRODUCTION

Due to recent developments in thin-film technology, a variety of multilayers have become available, arousing interest in novel properties unseen in conventional materials. Especially, many superconducting multilayers have been fabricated and investigated.[1]

Concerning the thermodynamic properties, the variation of the transition temperature T_c has been studied for various multilayers.[1] The specific heat has also been studied in the Nb-Zr systems.[2] As to the electromagnetic properties, the upper critical field H_{c2} has been most extensively studied because H_{c2} can probe the superconducting dimensionality. Indeed, dimensional crossover and related phenomena have been observed with Nb-Ge,[3] Nb-Cu,[4] V-Ag,[5] V-Ni,[6] and V-Fe (Ref. 7) multilayers. However, to the authors' knowledge, the magnetic field penetration depth λ, which is one of the fundamental electromagnetic quantities, has not yet been studied.

We have made measurements of λ for V-Ag proximity-coupled multilayers. This work consists of two stages. First, we study the layer-thickness and temperature dependences of λ. Second, combining the above results with our previously measured H_{c2} parameters, we obtain several material parameters, such as the Ginzburg-Landau (GL) parameter, the thermodynamic critical field at 0 K, and the electronic coefficient of specific heat. We believe that the present work provides a comprehensive understanding of the magnetic properties of proximity-coupled superconducting multilayers. A brief account of the λ results was given earlier.[8]

II. EXPERIMENTAL

The samples were prepared by ultrahigh-vacuum electron-beam evaporation. Since the field penetration is sensitive to the surface state, both surfaces of each sample end were covered with Ag layers, which are stable in air and have a lustrous surface. The artificial periodicity was examined by means of x-ray diffraction. The difference between the designed and the observed periods was found to be less than 5%. Details of the sample preparation as well as the structural quality were given in our previous report.[9] The parameters of the multilayers studied here are listed in Table I.

The penetration depth λ was determined by means of ac susceptibility ($\chi_{\parallel}=\chi'_{\parallel}-i\chi''_{\parallel}$) with the field parallel to the films. In this geometry, field penetration takes place both from the surfaces in a direction perpendicular to the layers and from the edges in the parallel direction (see inset of Fig. 1). Considering the sample dimension, the former penetration is principally responsible for $\chi_{\parallel}$, and hence λ derived from $\chi_{\parallel}$ is in the perpendicular direction.

The measurements of ac susceptibility were performed with a Hartshorn-type mutual inductance bridge.[10] Two or four sheets of samples (8×20 mm^2) are mounted in the cryostat coil. They were placed directly into liquid He,

TABLE I. Sample parameters of V-Ag multilayers.

d_V/d_{Ag} (Å/Å)	D (Å)	T_c[a] (K)	ρ[b] ($\mu\Omega$ cm)	$\xi_{Ag}(T_c)/d_{Ag}$
30/15	1985	2.31	20.9(31.7)	12.8
40/20	1980	2.86	18.7(26.5)	9.9
100/50	3150	3.64	12.8(14.2)	5.6
100/100	3100	3.33	8.37	4.1
100/200	4700	2.44	4.15	3.4
160/320	5120	2.86	3.01	2.5
200/400	6400	3.34	2.36	2.1
240/480	5520	3.38	2.03	1.9

[a]The transition temperatures are determined from measurements of $\chi_{\parallel}$, and are slightly lower (58 mK on an average) than those from the resistive transition.

[b]For multilayers with the Ag layer thickness less than 100 Å, the covering Ag layers are 100 Å thick. In the calculation of Eq. (2), the observed ρ was directly used, because the contribution of the outermost Ag layers are involved in the observed λ. Note that in our previous paper on H_{c2} (Ref. 9), we used ρ corrected by subtracting the contribution from the covering layers (given in parentheses).

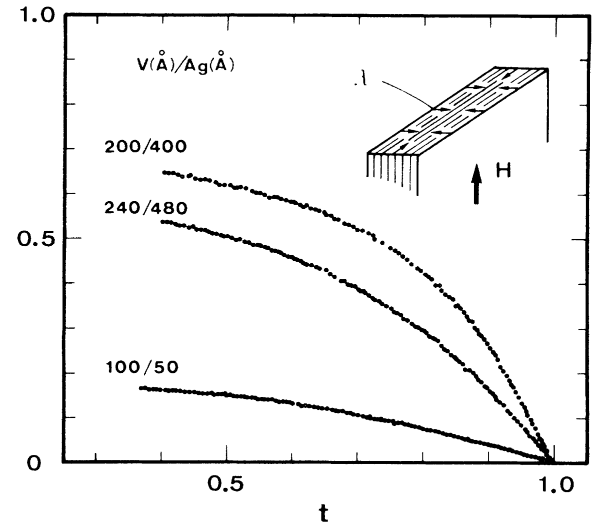

FIG. 1. Typical results of ac susceptibility (real part) vs reduced temperature. Inset shows the sample geometry against applied field. λ is the penetration depth perpendicular to the layers.

because $T_c < 4.2$ K for all samples. Null adjust and phase settings are made above T_c. The off-balance signal is detected by a two-phase lock-in as a function of temperature. The change in mutual inductance resulting from superconductive diamagnetism of the films is very small (typically of the order of 0.1 μH). Therefore, when the temperature is lowered, the contribution of the surroundings (including the coils) to $\chi_{\parallel}$ becomes crucial. However, since no discernible phase shift was found in the bridge throughout the experimental temperature range, we can extract $\chi_{\parallel}$ for the samples by subtracting the background from the raw data. The absolute values of $\chi'_{\parallel}$ and $\chi''_{\parallel}$ are deduced with reference to the complete diamagnetism of Sn films (7–500 μm thick).

For all samples, $\chi''_{\parallel}$ is nearly zero at all experimental temperatures. Henceforth we focus our discussion only on $\chi'_{\parallel}$. Figure 1 shows typical results of $\chi'_{\parallel}$, where $-4\pi\chi'_{\parallel}$ grows gradually as the temperature is lowered, reflecting the temperature-dependent λ. Assuming the field penetration to be exponential on a macroscopic scale, we obtain[8]

$$-4\pi\chi'_{\parallel} = 1-(2\lambda/D)\tanh(D/2\lambda)\ , \tag{1}$$

where D is the total thickness of multilayer.

Note that in the measurement of λ for a thin film with a thickness comparable or smaller than λ, one must be careful to include the effect of film thickness. In such a system, if the electron mean free path is restricted by the film thickness, the field penetration also depends on the thickness.[11] In our samples, the mean free path is much less than D (see below). Therefore the calculated λ represents the intrinsic value, regardless of its total thickness.

III. PENETRATION DEPTH

A. Layer-thickness dependence

In discussing the electromagnetic properties, we need to know the transport properties of the V and Ag layers. For this purpose, we measured the normal-state resistivity ρ parallel to the layers and obtained the electron mean free path in each layer (l_V and l_{Ag}). Since details of this analysis were reported previously,[9] we merely give the results here. (a) In thin V layers, l_V depends on the V layer thickness d_V, reflecting the V-Ag boundary scattering. But for $d_V > 100$ Å, l_V is saturated to the intrinsic value of about 22 Å. (b) In contrast, l_{Ag} is restricted almost completely by boundary scattering and is approximately $1.3d_{Ag}$, where d_{Ag} is the Ag layer thickness.

The above results imply that the V layers are certainly dirty. A comparison of l_{Ag} with the coherence length ξ_{Ag} in the Ag layers shows that for all samples ξ_{Ag} is longer than l_{Ag}, where $\xi_{Ag} = (\hbar v_{Ag} l_{Ag}/6\pi k_B T)^{1/2}$ and v_{Ag} is the Fermi velocity in Ag. This indicates that the Ag layers should also be considered to be dirty in a sense of superconductivity.

We first compare λ for multilayers of the same thickness ratio ($d_V{:}d_{Ag} = 2{:}1$). Figure 2 shows λ at several reduced temperatures t as a function of multilayer period d ($= d_V + d_{Ag}$). At all measured t, λ increases sharply with

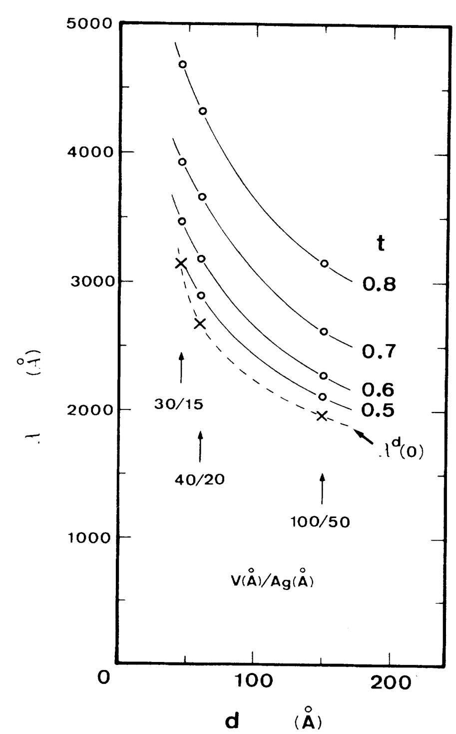

FIG. 2. Penetration depth vs multilayer period for samples with the same thickness ratio at several reduced temperatures t. $\lambda^d(0)$ is the calculated values for a homogeneous superconductor in the dirty limit at $t = 0$. Solid and dashed curves are guides for the eye unless otherwise denoted.

the decrease of d, and even seems to diverge at $d \sim 0$.

Such a characteristic is qualitatively understood by considering the fact that the system becomes dirtier for smaller d. Since there exists no theoretical treatment of λ for multilayered systems, we discuss the above feature in the framework of the conventional theory for homogeneous superconductors.

The zero-temperature penetration depth in the dirty local limit is given by[8]

$$\lambda^d(0) = 1.05 \times 10^{-2} (\rho / T_c)^{1/2} \text{ cm} , \tag{2}$$

where ρ is in units of Ω cm. This equation includes only experimentally determined quantities so that discussion can be made without any fitting parameters. $\lambda^d(0)$ evaluated using ρ and T_c (tabulated in Table I) is shown in Fig. 2. $\lambda^d(0)$ reproduces well the expected λ at $t=0$, and in particular its d dependence is in good agreement with the observed λ. This means that the short-period multilayers behave like a homogeneous superconductor.

The above homogeneous nature like that of a single superconductor was examined by changing d_{Ag} (d_{V} is fixed at 100 Å). In general, the penetration depth of a normal metal in contact with a superconductor is longer than that of the isolated superconductor. Therefore, if the multilayer is considered to be a composite material, λ should increase with increasing d_{Ag}. Contrary to the expectation, our observations showed that λ decreases with increasing d_{Ag}, being similar to the d_{Ag} dependence of $\lambda^d(0)$.

For the samples with longer d, the behavior of λ becomes unusual. Figure 3 shows λ versus d at several t for samples with the same thickness ratio ($d_{\mathrm{V}}:d_{\mathrm{Ag}} = 1:2$). As d increases, λ first decreases like thinner samples. However, when d exceeds ~ 600 Å, λ starts to grow. This peculiar feature is seen at all measured t. Note that the surface Ag layers are not responsible for this peculiarity, because a similar behavior of λ versus d holds even up to the high reduced temperature ($\lambda \gg d_{\mathrm{Ag}}$). The calculated $\lambda^d(0)$ is also shown in the figure. $\lambda^d(0)$ decreases monotonically with increasing d, and begins to deviate from the experimental λ at $d \sim 600$ Å.

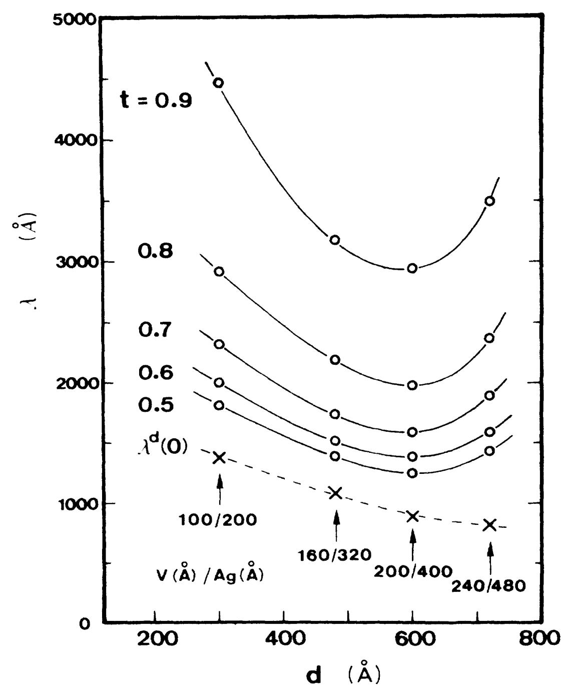

FIG. 3. Penetration depth vs multilayer period for samples with the same thickness ratio at several reduced temperatures t. For $\lambda^d(0)$, see Fig. 2.

The observed peculiarity can be interpreted as a kind of crossover from a single superconductor to a composite one. In other words, for λ, the coupling between the V layers weakens above the turnover thickness. The weakness of the interlayer coupling is known to appear as the dimensional crossover in $H_{c2\parallel}$, the upper critical field parallel to the layers. We emphasize here that the manner in which a composite nature appears on λ is qualitatively different from the case of $H_{c2\parallel}$. Even for a system which exhibits dimensional crossover in *high field*, at *zero field* superconductivity extends all over the sample at all temperatures. Consequently, multilayers always behave as three-dimensional from the point of view of the weak-field penetration depth. This is the reason why λ does not exhibit the drastic temperature dependence like $H_{c2\parallel}$.

The characteristics of λ described above should certainly be related to the proximity effect in the Ag layers. If the electron-electron interaction in Ag is negligible, the position-dependent penetration depth in the dirty limit is given by[12]

$$\lambda_{\mathrm{Ag}} = \frac{\hbar c}{2F(x)} N_{\mathrm{Ag}} \left[\frac{k_B T \rho_{\mathrm{Ag}}}{\hbar} \right]^{1/2} \propto \frac{1}{F(x)} \left[\frac{1}{l_{\mathrm{Ag}}} \right]^{1/2} , \tag{3}$$

where $F(x)$ is the pair-field amplitude as a function of distance x from the interface, N_{Ag} is the Ag density of states, and ρ_{Ag} denotes its resistivity. A profile of $F(x)$ is qualitatively obtained by estimating $\xi_{\mathrm{Ag}}/d_{\mathrm{Ag}}$, because ξ_{Ag} is considered to be a damping constant of hyperbolic cosine function $F(x)$. As listed in Table I, $\xi_{\mathrm{Ag}}(T_c)/d_{\mathrm{Ag}}$ is several times greater than unity for smaller d, meaning $F(x)$ is nearly constant.[13] On the assumption that $F(0)$ does not change appreciably with d_{Ag}, the dominant factor determining the d_{Ag} dependence of λ_{Ag} is $(1/l_{\mathrm{Ag}})^{1/2}$. Since l_{Ag} is proportional to d_{Ag}, λ_{Ag} decreases with increasing d_{Ag} for thin Ag layers. This qualitatively reproduces the results in Fig. 2 and in the region of $d < 600$ Å in Fig. 3.

When d_{Ag} becomes greater, however, simple proportionality of λ_{Ag} to $(1/l_{\mathrm{Ag}})^{1/2}$ is by no means relevant. As listed in Table I, $\xi_{\mathrm{Ag}}(T_c)/d_{\mathrm{Ag}}$ approaches unity. Hence $F(x)$ is no longer constant, but deteriorates at the center of the Ag layer. This effect eventually increases λ_{Ag} through the factor $1/F(x)$ in Eq. (3).

The competition of these two factors, the electron mean free path and the pair-field profile in the Ag layers, results in the appearance of the minimum λ at $d \sim 600$ Å. We emphasize that it is with multilayered samples that this remarkable feature of very thin normal metal in the proximity system could be found. It would be extremely difficult to find this feature with a bilayer sample.[14]

B. Temperature dependence

Three typical results are presented: V(100 Å)-Ag(50 Å), V(160 Å)-Ag(320 Å), and V(240 Å)-Ag(480 Å) as the multilayers with thin, intermediate, and thick Ag layers. Figure 4 shows $[\lambda(0.5)/\lambda(t)]^2$ versus t, where λ is normalized at $t=0.5$. For V(100 Å)-Ag(50 Å), the temperature dependence seems to be linear near $t=1$ and tends to saturate at lower temperatures. In contrast, V(240 Å)-Ag(480 Å) exhibits an upward curvature in the temperature region above $t \sim 0.7$ and increases almost linearly as the temperature is lowered further. V(160 Å)-Ag(320 Å) is located between them.

For reference, two curves for a homogeneous superconductor are also shown in the figure. One represents the empirical Gorter-Casimir law, $\lambda \propto (1-t^4)^{-1/2}$, which reproduces the behavior of clean, Pippard-limit superconductors. Since our system belongs to the dirty local regime, the large deviation of our results from this law is not surprising. The other is in the dirty local limit which is given as

$$\lambda \propto \{\Delta(t)\tanh[\Delta(t)/2k_B T]\}^{-1/2} ,$$

where $\Delta(t)$ is the gap parameter. Although this relation could be realistic for our systems, the results exhibit remarkable differences, in particular when the layers become thicker.

We notice that the present results cannot be reproduced by any other limiting curve for a homogeneous superconductor. In the clean local limit λ is equal to the London penetration depth. In the temperature region concerned, its temperature dependence does not differ remarkably from the dirty local limit. If the system goes to the nonlocal regime, the curve would approach the Gorter-Casimir law.[15] Taking account of these, we should insist that the observed temperature dependence reveals a peculiar character of multilayers and should be attributed to the proximity effect.

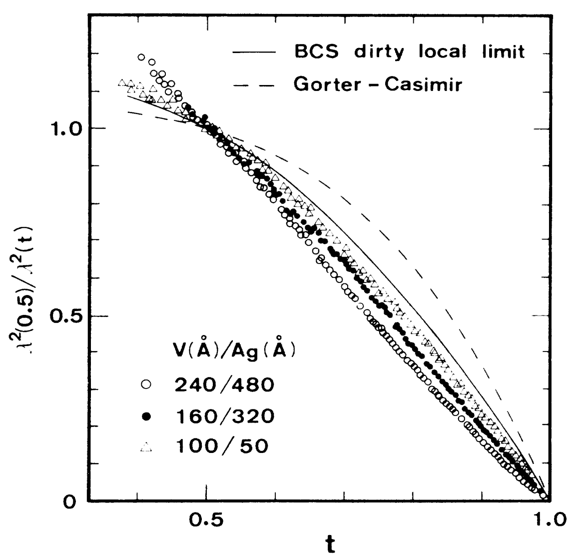

FIG. 4. Plots of $[\lambda(0.5)/\lambda(t)]^2$ vs reduced temperature for three typical multilayers.

The temperature dependence of field penetration into a normal-metal film (several thousands of angstroms thick or more) superimposed on a thick superconductor has been investigated both theoretically[16] and experimentally.[14] According to these, the penetration differs from that into usual superconductors. When the temperature is lowered, λ decreases more moderately, and continues to decrease even in the region where λ of the usual superconductors saturates. This behavior is mainly attributed to the temperature-dependent profile of the pair-field amplitude $F(x)$ in the normal metal.

The present feature of $\lambda(t)$ is qualitatively understood in this context. Due to thin Ag layers, $\lambda(t)$ for V(100 Å)-Ag(50 Å) bears a resemblance to the curve of usual superconductors in the dirty local limit. However, for the multilayers with thicker Ag layers, the proximity effect is reflected progressively on $\lambda(t)$. This explanation although qualitative is consistent with the layer-thickness dependence discussed in the preceding section. For quantitative understandings, a refined theoretical treatment is needed.[17]

IV. MATERIAL PARAMETERS

As discussed above, λ is in itself informative of the properties of multilayered superconductors. In addition, when combined with the H_{c2} parameters, a comprehensive understanding of the magnetic and thermodynamic properties is attainable. Using the anisotropic GL theory,[18] we can deduce the GL parameter κ, the zero-temperature thermodynamic critical field $H_c(0)$, and the electronic coefficient γ of the normal-state specific heat.

Our previous measurements of H_{c2} have revealed that for the thinner multilayers, H_{c2} behaves in an anisotropic GL manner throughout the experimental temperature range.[9] Therefore, the theory can be applied to them, at least phenomenologically. The H_{c2} parameters relevant to the GL analysis are listed in Table II.

Prior to the analysis, the GL penetration depth $\lambda_{\mathrm{GL}}(0)$ was determined. Near T_c, λ is given as

TABLE II. Upper-critical-field parameters involved in the Ginzburg-Landau analysis.

$d_{\mathrm{V}}/d_{\mathrm{Ag}}$ (Å/Å)	$(dH_{c2\perp}/dT)_{T_c}$ (kG/K)	$H_{c2\perp}/H_{c2\parallel}$	$\xi_{\mathrm{GL}\parallel}(0)$ (Å)	$\xi_{\mathrm{GL}\perp}(0)$ (Å)
30/15	10.7	0.82	113	92.4
40/20	9.12	0.82	112	91.9
100/50	6.49	0.88	117	103
100/100	4.15	0.86	153	132
100/200	1.99	0.78	254	199

TABLE III. Material parameters of V/Ag multilayers.

d_V/d_{Ag} (Å/Å)	$\frac{d}{dt}(4\pi\chi'_{\parallel})_{t=1}$	$\lambda_{GL}(0)$ (Å)	$\kappa_\perp$	$\kappa_\parallel$	$(dH_c/dT)_{T_c}$ (kG/K)	$H_c(0)$ (kG)	γ (10^4 erg/cm^{3}K^2)
30/15	0.0705	2160	19.2	23.4	0.395	0.54	0.87
40/20	0.0810	2010	17.9	21.9	0.360	0.60	0.72
100/50	0.375	1490	12.7	14.4	0.362	0.77	0.73
100/100	0.412	1390	9.14	10.6	0.321	0.63	0.58
100/200	0.900	1430	5.62	7.19	0.250	0.36	0.35

$\lambda = \lambda_{GL}(0)(1-t)^{-1/2}$. $\lambda_{GL}(0)$ can be obtained directly from the measured susceptibility. Near T_c, λ should be much greater than D, so that Eq. (1) reduces to

$$-4\pi\chi'_{\parallel} = (1/12)(D/\lambda)^2 \ . \tag{4}$$

Substituting the expression for λ into Eq. (4) and differentiating with respect to t, we obtain

$$\lambda_{GL}(0) = D\left[12\left[\frac{d}{dt}(4\pi\chi'_{\parallel})\right]_{t=1}\right]^{-1/2} \ . \tag{5}$$

Using the observed slope $4\pi(d\chi'_{\parallel}/dt)_{t=1}$ in Eq. (5), $\lambda_{GL}(0)$ is determined, of which the numerical values are tabulated in Table III.

A. Ginzburg-Landau parameter κ

The anisotropic GL parameters $\kappa_\perp$ and $\kappa_\parallel$ are given by

$$\kappa_\perp = \lambda_{GL}(0)/\xi_{GL\parallel}(0) \ , \tag{6}$$

$$\kappa_\parallel = \lambda_{GL}(0)/\xi_{GL\perp}(0) = \lambda_{GL}(0)/\epsilon\xi_{GL\parallel}(0) \ , \tag{7}$$

where $\xi_{GL\perp}(0)$ and $\xi_{GL\parallel}(0)$ are the zero-temperature GL coherence lengths perpendicular and parallel to the layers. ϵ denotes the anisotropy parameter, being equal to $H_{c2\perp}/H_{c2\parallel}$. Using the values of $\xi_{GL\perp}(0)$, $\xi_{GL\parallel}(0)$, and $\lambda_{GL}(0)$, we evaluated $\kappa_\perp$ and $\kappa_\parallel$ (listed in Table III). Figure 5(a) shows κ for samples of the same thickness ratio (d_V:d_{Ag}=2:1). Both $\kappa_\perp$ and $\kappa_\parallel$ decrease with increasing d. The variation should be attributed to $\lambda_{GL}(0)$ because $\xi_{GL\parallel}(0)$ for these three samples is insensitive to d (see Table II). In Fig. 5(b) is shown κ versus d_{Ag} for multilayers with the same d_V (=100 Å). Both $\kappa_\perp$ and $\kappa_\parallel$ decrease further with the increase of d_{Ag}, for which in turn the variation of $\xi_{GL\parallel}(0)$ is responsible because $\lambda_{GL}(0)$ is rather insensitive to d_{Ag} (see Table III).

According to Ref. 19, κ for V metal with a mean free path of about 22 Å, which corresponds to the value of 100-Å-thick layers in our samples, can be estimated at 10. In Fig. 5(b), one finds that multilayering with thin Ag layers raises κ over 10, while with thicker Ag layers κ is lowered below 10.

This result leads us to speculate upon the possibility of the synthesis of a type-I superconductor composed of a type-II superconductor and a normal metal. As seen in Fig. 5, the Ag-rich multilayers with rather large d would be a good candidate. Further suppression of κ could be attainable by improving the conditions of the sample preparation so that the V layer becomes structurally cleaner. In particular, if the condition $\kappa_\perp < 2^{-1/2} < \kappa_\parallel$ is satisfied, a very interesting material is to be realized; type I with the field perpendicular to the layers, but type II in the parallel field. Graphite intercalation compound C_8K has been known as such a material.[20]

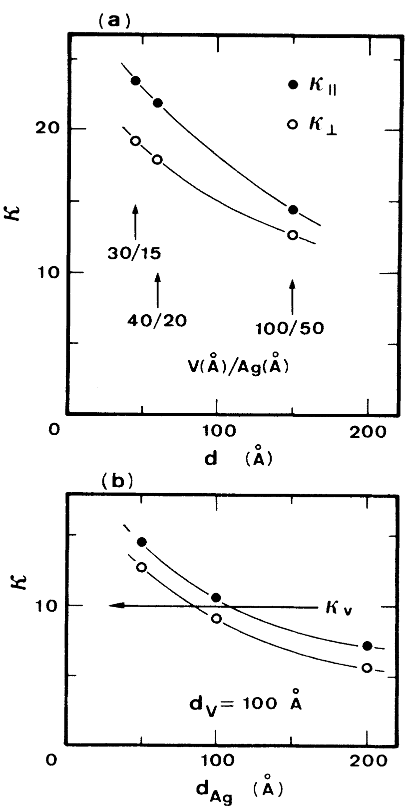

FIG. 5. Parallel and perpendicular GL parameters vs multilayer period (a) or Ag layer thickness (b). κ_V in (b) is for V metal with the mean free path of about 22 Å.

B. Thermodynamic critical field $H_c(0)$

The GL parameter κ was determined straightforward, since it is a phenomenological parameter in the anisotropic GL theory. However, for evaluation of the thermodynamic quantities in terms of H_{c2} and λ, one should examine the applicability of the theory to a multilayered system. This theory is originally for a homogeneous system in which the anisotropy appears at a level of the band structure. Thus the naturally occurring layered superconductors have been the subject.[21,22] In contrast, the superconductive anisotropy in an artificial multilayer comes from the different origin, related to the conductivity ratio and the layer-thickness ratio of constituent materials.[23]

Nevertheless, we have an ample reason to justify the application of the theory to our system. First, the multilayer in question behaves like a single three-dimensional superconductor, viewed from both H_{c2} and λ. Second, according to the theory treating a proximity-effect bilayer in the Cooper limit, the jump in the specific heat is equivalent to that of the BCS superconductor with the same T_c.[24] We therefore expect that this correspondence holds true for other thermodynamic quantities, such as H_c. Third, we made an internal check by examining the normal-state parameters deduced from H_{c2} and λ through the GL theory. γ from the magnetic measurements was found to agree well with the expected value (see below). This is the strongest evidence to support the applicability of the theory to our systems.

Based on the above consideration, we discuss $H_c(0)$ with the anisotropic GL theory, where H_c and H_{c2} are related by

$$\left[\frac{dH_c}{dT}\right]_{T_c}=\frac{1}{2^{1/2}\kappa_\perp}\left[\frac{dH_{c2\perp}}{dT}\right]_{T_c} . \tag{8}$$

From the Bardeen-Cooper-Schrieffer (BCS) temperature dependence of H_c, one obtains

$$H_c(0)=-\frac{1}{1.73}\left[\frac{dH_c}{dT}\right]_{T_c}T_c , \tag{9}$$

of which the numerical values are listed in Table III.

Figure 6(a) shows $H_c(0)$ versus d for samples with the same thickness ratio (d_V:d_{Ag}=2:1). From the result, two features should be noticed. First, $H_c(0)$ is always smaller than the value for pure V metal, ~ 1.4 kG; and second, as d becomes smaller, $H_c(0)$ decreases.

The smallness of $H_c(0)$ can be due to two reasons. One is that the superconductive condensation energy is, so to say, diluted by multilayering with normal Ag layers. Another reason probably comes from the effect of disorder on the V-layer band structure. For a system having a sharp density of states at the Fermi level, the band parameters are affected by the electron mean free path. Consequently the thermodynamic properties are altered.[19,25] Indeed, l_V is less than 22 Å and the preliminary analysis of T_c of the V layers shows a considerable decrease from its clean value (5.4 K). Thus we reasonably expect that the thermodynamic critical field of the V layers also deteriorates.

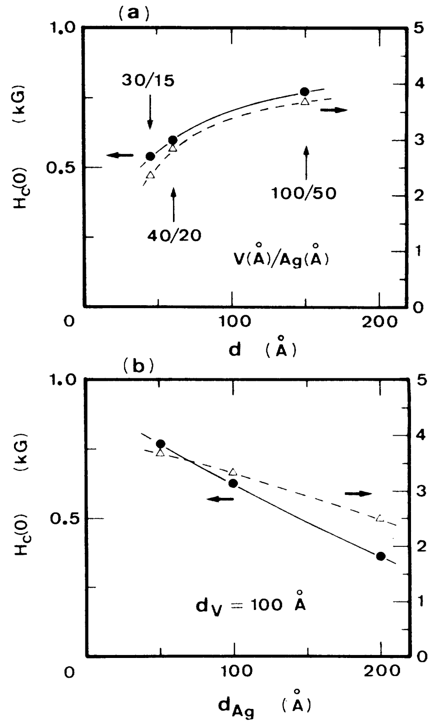

FIG. 6. Thermodynamic critical field (solid circles) and transition temperature (open triangles) as a function of multilayer period (a) or Ag layer thickness (b).

Concerning the variation of $H_c(0)$ with d, the disorder effect seems again to play an essential role, because l_V depends on the layer thickness. If the thermodynamic properties such as $H_c(0)$ and T_c in each layer do not change with thickness, those of multilayers should not depend on d in the Cooper-limit system with the same thickness ratio. As shown in Fig. 6(a), $H_c(0)$ and T_c vary similarly with d, implying the thickness-dependent disorder effect in the V layers.

Figure 6(b) shows $H_c(0)$ for samples with only d_{Ag} varied. $H_c(0)$ lowers with increasing d_{Ag} due to further dilution of the condensation energy $H_c(0)^2/8\pi$. When d_{Ag} increases, the depression in $H_c(0)$ becomes more remarkable than in T_c, as seen in the figure. The BCS superconductors have the condensation energy of $H_c(0)^2/8\pi=(\frac{1}{2})N\Delta(0)^2$. Therefore, $H_c(0)\propto N^{1/2}T_c$, where N is the electronic density of states at the Fermi level and $\Delta(0)$ is the energy gap at 0 K. The same relation is expected to hold in the Cooper-limit system. In this case, N is replaced by the volume average N_{eff} of the constituent materials; $H_c(0)\propto N_{\text{eff}}^{1/2}T_c$. Since the density of states of V is far greater than Ag (about 20 times for the clean metals), N_{eff} decreases with increasing d_{Ag}. This leads to a more rapid depression in $H_c(0)$ than in T_c.

C. Electronic coefficient γ of the normal-state specific heat

Generally speaking, γ of a multilayered system is given by the volume average of the constituent layers.

Meanwhile, in the GL theory γ can be deduced from magnetic measurements, where γ is directly related to superconductive quantities. Thus a comparison of γ's obtained by the volume average and by the GL theory is a strong probe to examine whether the theory can be applied to our system.

The electronic coefficient is given as

$$\gamma=\left[\frac{1}{4.23}\left[\frac{dH_c}{dT}\right]_{T_c}\right]^2 \text{ erg/cm}^3\,\text{K}^2 , \tag{10}$$

where $(-dH_c/dT)_{T_c}$ is in units of G/K. Figure 7 shows γ calculated by substituting the experimental values into Eq. (10). The solid curves in the figure are γ obtained by volume averaging, where we adopt $\gamma_V=1.15\times10^4$ erg/cm^3 K^2 (the value for clean V metal[26]) and $\gamma_{Ag}=0.63\times10^3$ erg/cm^3 K^2.[27] γ's obtained by the above two different ways agree well. This agreement proves that the anisotropic GL analysis is useful for the multilayers even in the relationship involved in the thermodynamic and the normal-state parameters.

One sees that the curves lie slightly above the experimental data, except V (30 Å)-Ag(15 Å). As mentioned in the discussion on $H_c(0)$, the difference may be caused by the density-of-state broadening resulting from short mean free path in the V layers. γ_V of the present samples should be more or less smaller than that of the pure metal, so that if we can use real values of γ_V, agreement would be better.

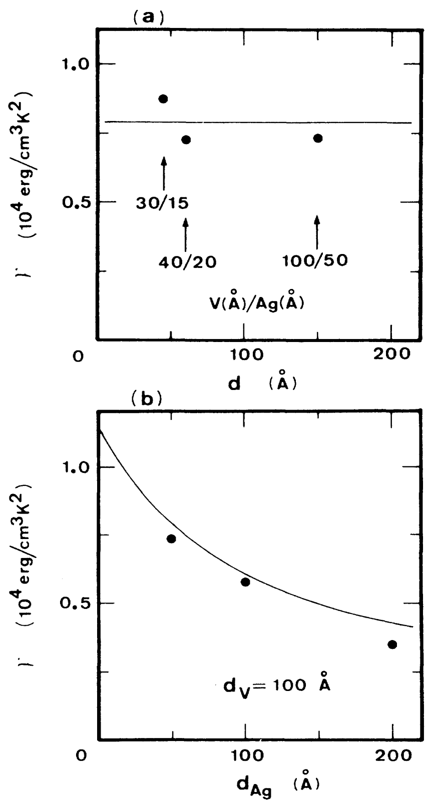

FIG. 7. Electronic coefficient of the normal-state specific heat (derived from the magnetic measurements) as a function of multilayer period (a) or Ag layer thickness (b). Solid curves are calculated by means of the volume average of V and Ag layers.

V. CONCLUSIONS

We have measured the magnetic-field penetration depth of V-Ag proximity-coupled multilayers. First, the layer-thickness dependence of λ was studied. For samples with thin layers, λ decreases with an increase of the layer thickness. In this region, the observed behavior is in good agreement with a homogeneous superconductor with the same transition temperature and resistivity. Such a correspondence has been theoretically pointed out only in the thermodynamic properties such as the specific heat.[24] Our result suggests that this can be generalized to the weak-field electromagnetic properties. When the layer thickness exceeds a critical value, however, λ in turn starts to increase. This feature is considered as a crossover from a single superconductor to a composite one, because the superconducting coupling between V layers becomes weaker when the Ag layer becomes thicker.

The above situation is also reflected on the temperature dependence of λ. For samples with thin layers, $\lambda(t)$ is rather similar to a homogeneous superconductor in the dirty local limit. When the layer thickness increases, however, $\lambda(t)$ deviates more and more from any limiting behavior of homogeneous superconductors, and exhibits the character of proximity effect.

The overall dependence of λ also sheds light on the proximity effect in the Ag layers. The main point which distinguishes a normal metal from a usual superconductor is the spatial variation of the pair amplitude. Therefore, roughly speaking, in the absence of spatial variation, a normal metal behaves like an ordinary superconductor, while otherwise it exhibits the specific nature of proximity effect. Indeed, test for the profile of pair amplitude in the Ag layers shows that it is nearly constant for short-period multilayers, but the spatial variation becomes appreciable for a longer period.

Next we discuss the Ginzburg-Landau parameter κ, the thermodynamic critical field $H_c(0)$, and the electronic coefficient γ of specific heat for short-period multilayers. Through the examination of γ, we confirmed the applicability of the GL theory to multilayers. We thus think that the GL analysis presented in this paper would be useful for other multilayers. In our system, κ is anisotropic and decreases with an increase of the multilayer period or the Ag-layer thickness. This feature reflects both the mean free path and the proximity effect. The remarkable points are the controlability of κ, and a possible synthesis of a superconductor of type I in the field perpendicular to the layers and of type II in the parallel field. Since $H_c(0)$ is directly related to the condensation energy density, its variation layer thickness gives us an intuitive picture; a multilayered superconductor is, so to speak, a diluted superconductor with a normal metal and has an effective density of states equivalent to the volume average of the constituent layers.

From the present work, the electron boundary scattering is found to play an important role for the electromagnetic properties of multilayers. We expect that the characteristics revealed in this study are general for proximity-coupled multilayers with electron-boundary scattering.

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