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Dimensional crossover and commensurability effect in V/Ag superconducting multilayers

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Using V/Ag superconducting multilayers prepared by vacuum evaporation we have observed dimensional crossover from anisotropic three-dimensional to two-dimensional behavior in terms of the upper critical field versus temperature. At a higher temperature we have also observed an anomalous turning in the curve of the critical field, which implies the existence of a commensurability effect between the lattice of vortices and the periodic superstructure.

Superconducting layered compounds such as transition-metal dichalcogenides and their intercalation complexes have aroused interest because of their large anisotropy and the possible quasi-two-dimensional characteristics.[1] Viewed from the upper critical field H_{c2}, the anisotropy is caused by the different superconducting coherence lengths $\xi_\perp$ and $\xi_\parallel$, perpendicular and parallel to the layer. In particular, if $\xi_\perp$ becomes comparable to the layer repeat distance, unusual behavior not seen in conventional superconductors could be expected.

Theoretically, the system composed of Josephson-coupled superconducting layers was initially investigated in the Ginzburg-Landau regime.[2,3] This investigation revealed that near the transition temperature, the system behaves like an anisotropic three-dimensional superconductor. However, the theory advanced by Klemm and co-workers[4] showed that when interlayer coupling is appropriate, the upper critical field parallel to the layer ($H_{c2\parallel}$) drastically increases at a certain temperature, and it shifts to the value typical of two-dimensional superconductors. This is called "dimensional crossover."

Recently, as a model system of layered structure, synthetic layered superconductors, which are prepared by alternate deposition of two different elements, have been developed,[5-14] and systematic experimentation to examine this unusual behavior has become possible.[15,16]

Ruggiero, Barbee, and Beasley[15] studied Nb/Ge superlattices and confirmed the temperature-dependent dimensional crossover expected in Josephson-coupled quasi-two-dimensional superconductors. Using Nb/Cu superlattices, Schuller and his co-workers[16] observed the dimensional crossover, and pointed out that the qualitative ideas put forward in theories of Josephson-coupled superconductors are valid also for proximity-coupled ones.

In the present work, V/Ag proximity-coupled superlattices have been investigated by means of upper critical field measurements. Observations showed that dimensional crossover clearly appears in $H_{c2\parallel}$. In addition, at a higher temperature, we also found anomalous turning in the curve of $H_{c2\parallel}$, depending on the period of multilayer.

Multilayered V/Ag films were prepared in an ultrahigh-vacuum deposition system, where two electron guns alternately evaporate V and Ag sources. The pressure during deposition is in the range of 10^{-9} torr and the deposition rate is about 0.3 Å/s. Individual thicknesses are regulated with shutters, located in front of each source and controlled by thickness monitors. We prepared 13 samples with different V-to-Ag thickness ratios (1:1,1:2,2:1,3:1). Both sides of each sample end with Ag layers. For samples reported here, deposition onto a Mylar substrate (at ambient temperature) is repeated typically 10 times, and their nominal periods are 200–720 Å.

In order to see the artificial periodicity by means of x-ray diffraction, we had previously examined several samples with nominal periods of 60 Å and less. The results showed that the difference between the designed and the observed periods is less than 5%. This guarantees the quality of artificial superstructures with longer period of compositional modulation.

Measurements of the upper critical field, parallel ($H_{c2\parallel}$) and perpendicular ($H_{c2\perp}$) to the layer, are made with the four-terminal ac resistance method down to 1.5 K. The current density ranges from 0.15 to 0.4 A/cm^2. H_{c2} is defined as the midpoint of the transition to the normal state when the magnetic field is swept at a fixed temperature. The transition width is 0.1 kG at best. However, for a few samples, the transition curve showed appreciable broadening in the field perpendicular to the layer, where the resistance rises sharply up to a certain portion of the normal resistance and then grows gradually with the field increased. We found that these samples (evaporated on thin Mylar substrates) have bent edges. Therefore, we consider that this rather gradual change in resistance versus field curves is caused by such edges and has no essential meaning. Thus, in such a case, the midpoint which determines $H_{c2\perp}$ is reasonably chosen by extending the rising linear section.

In this kind of experiment, it is often important to consider the surface superconductivity. However, this effect is believed to be substantially suppressed by the following reasons: First, both sides of each sample end with Ag layers.[17] Second, in a proximity sandwich, as the conductivity of the normal metal is larger than that of the superconducting metal, the surface superconductivity tends to be strongly suppressed.[18] This is the case in the present samples. Third, in our samples, $\xi_\perp(T)$ becomes comparable to the period of the multilayer immediately below the zero-field transition temperature, so that the pair amplitude (or the order parameter) undulates on the scale of the multilayer period and is expected to deteriorate on the free surfaces (Ag layers).

In Fig. 1, we show the typical results of H_{c2} measured as a function of temperature, where four samples have the same thickness ratio of V and Ag (1:2). As expected, the curve of $H_{c2\perp}$ varies with temperature in a manner similar for all samples. On the contrary, $H_{c2\parallel}$ shows particular behavior when the period of multilayer exceeds a certain

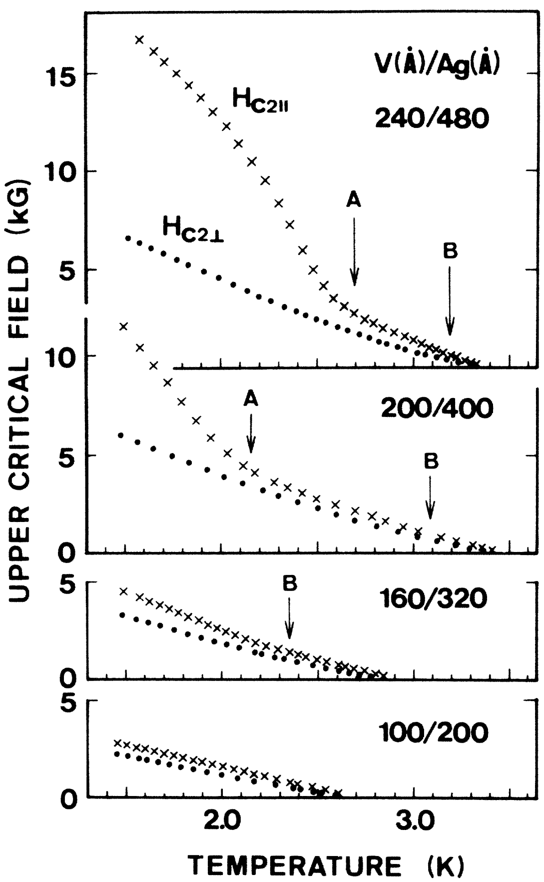

FIG. 1. Temperature dependence of upper critical field. Thickness ratio of V and Ag is the same for all samples (1:2). A and B indicate temperatures at which upturns start.

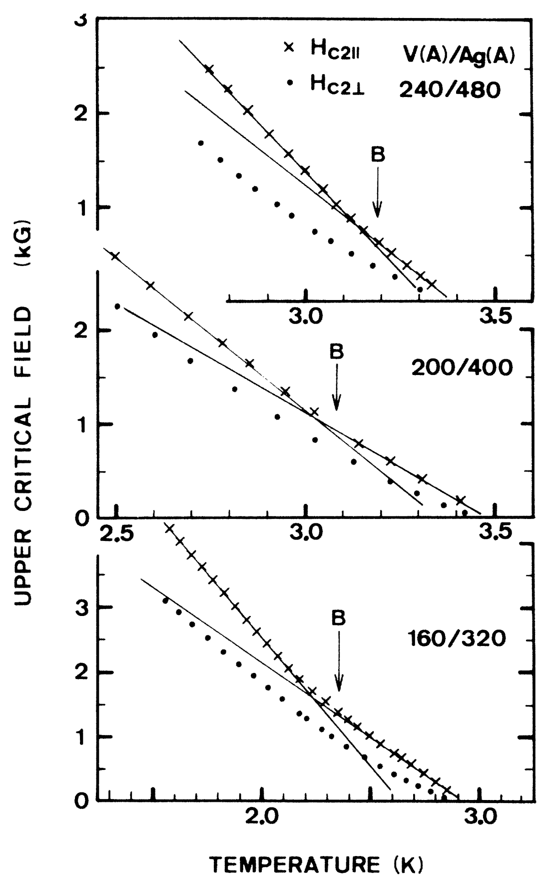

FIG. 2. Expanded figure of upper critical field around temperature B in Fig. 1. Solid lines are guides for the eye.

limit. Thus we confine our discussion to the temperature dependence of $H_{c2\parallel}$.

As seen in the figure for V (100 Å)/Ag (200 Å), $H_{c2\parallel}$ varies linearly with temperature. This behavior is what the anisotropic three-dimensional Ginzburg-Landau theory predicts. For longer periods (upper three samples in Fig. 1), however, two kinds of anomalous characteristics appear in $H_{c2\parallel}$.

First, in V (200 Å)/Ag (400 Å) and V (240 Å)/Ag (480 Å), abrupt upturns are observed at about 2.1 and 2.7 K, respectively. Arrow A indicates the temperature at which the upturn starts. This phenomenon is quite similar to the dimensional crossover found in the proximity-coupled Nb/Cu multilayer system.[16] As expected theoretically,[19] the reduced temperature t_A of this upturn seems to increase for longer multilayer period (see Table I).

Second, at higher temperatures, a less prominent but appreciable upturn (designated by arrow B) is observed in V (160 Å)/Ag (320 Å), V (200 Å)/Ag (400 Å), and V (240 Å)/Ag (480 Å). This feature is expanded in Fig. 2. When the temperature decreases from the transition temperature, $H_{c2\parallel}$ increases linearly. Meanwhile, at the temperature indicated by B, the variation of $H_{c2\parallel}$ suddenly changes and gives a larger slope. As listed in Table I, the reduced tem-

TABLE I. Calculated values of characteristic parameters at temperatures indicated by arrows A and B in Fig. 1. The H_{c2} curves for V (150 Å)/Ag (50 Å) are not shown in the figure.

Thickness of V/ thickness of Ag (Å)	A: t_A	$\xi_\perp$ (Å)	$\xi_\parallel$ (Å)	$d_\perp^\Delta$ (Å)	$d_\perp^\square$ (Å)	B: t_B	$\xi_\perp$ (Å)	$\xi_\parallel$ (Å)	$d_\perp^\Delta$ (Å)	$d_\perp^\square$ (Å)
240/480	0.79	274	431	640	687	0.94	530	970	1237	1329
200/400	0.62	250	310	584	627	0.89	499	697	1163	1251
160/320	. . .	. . .	. . .	. . .	. . .	0.82	401	592	936	1005
150/50	. . .	. . .	. . .	. . .	. . .	0.61	163	191	380	409

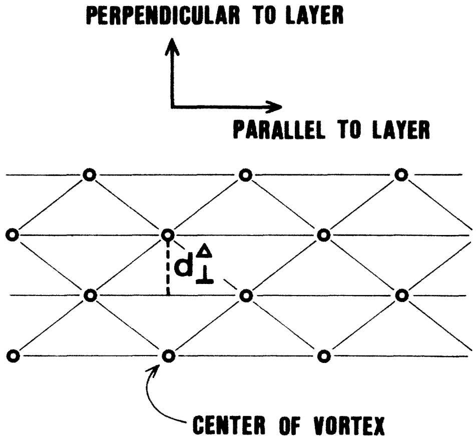

FIG. 3. Triangular configuration of vortex lattice. $d_\perp^\Delta$ is the distance between vortex trains parallel to the layer.

perature t_B increases with the multilayer period, similarly to t_A. Note this newly found upturn is not characteristic of this specific thickness ratio of V and Ag, but also found for V(150 Å)/Ag(50 Å) (see Table I).

Assuming that the anisotropic Ginzburg-Landau theory is valid down to the temperature at which upturn A occurs, one can express the upper critical field as[2]

$$H_{c2\perp}(T)=\frac{\phi_0}{2\pi\xi_\parallel(T)^2}\ , \tag{1}$$

$$H_{c2\parallel}(T)=\frac{\phi_0}{2\pi\xi_\parallel(T)\xi_\perp(T)}\ . \tag{2}$$

An additional assumption we use is that the vortices form a lattice deformed from an equilateral triangular with one side parallel to the layer,[20] of which the deformation factors are $(\xi_\parallel/\xi_\perp)^{1/2}$ parallel and $(\xi_\perp/\xi_\parallel)^{1/2}$ perpendicular to the layer (see Fig. 3). These factors correspond to the anisotropy of the vortices. So at $H_{c2\parallel}$, the distance between vortex trains parallel to the layer yields

$$d_\perp^\Delta=\left(\frac{3}{4}\right)^{1/4}\left(\frac{\phi_0}{H_{c2\parallel}}\right)^{1/2}\left(\frac{\xi_\perp}{\xi_\parallel}\right)^{1/2}\ . \tag{3}$$

Substituting Eq. (2) to Eq. (3), we get $d_\perp^\Delta=3^{1/4}\pi^{1/2}\xi_\perp$.

In Table I are listed the calculated values of $\xi_\parallel$, $\xi_\perp$, and $d_\perp^\Delta$ at t_A and t_B for samples in question. At t_A, $d_\perp^\Delta$ is approximately equal to the multilayer period λ, so that the vortex lattice matches fairly well with the periodic structure. Besides, at t_B, $d_\perp^\Delta$ is nearly equal to twice the multilayer period for all the samples. This leads us to insist that upturn B is attributable to the doubly commensurate configuration between the vortex lattice and the periodic structure. $\xi_\perp$ at t_B is also twice of that at t_A. Figure 4 illustrates above situations.

We also examine the case of a rectangular lattice where the square lattice is deformed in a similar manner to the case of triangular lattice. We can express the distance between vortex trains at H_{c2} as $d_\perp^\square=(2\pi)^{1/2}\xi_\perp$. Calculated values of $d_\perp^\square$ at t_A and t_B are also listed in Table I. As given in the table, no substantial difference is found between $d_\perp^\Delta$ and $d_\perp^\square$, suggesting that the type of lattice (triangular or rectangular) of vortices does not matter (see Fig. 4). This indicates that these upturns at t_A and t_B are both related to the commensurability between the lattice of vortices (or

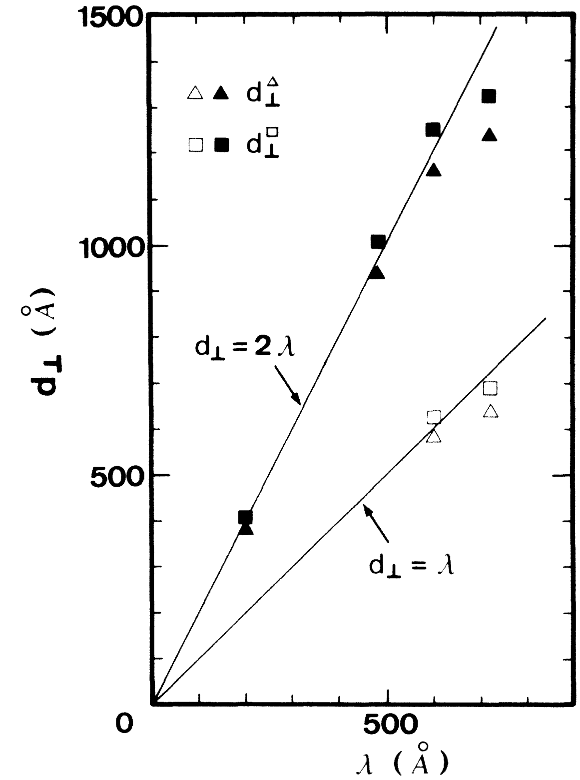

FIG. 4. $d_\perp^\Delta$,$d_\perp^\square$ vs period of multilayer λ. Open triangles and squares give the values at t_A, and solid ones give those at t_B. Deviations from the commensurate line for $\lambda=720$ Å are probably due to less repetition of deposition (seven times).

bulk superconducting nucleations) and the periodic superstructure. It should be noted that the commensurability at t_A is closely related to dimensional crossover, i.e., when the system goes from three-dimensional to two-dimensional, it necessarily undergoes singly commensurate vortex configuration. This means that the upturn at t_A is expected to appear as a superposition of both phenomena.

To see the effect of commensurability further, we give a brief qualitative discussion. When $\xi_\perp$ is larger than the period of the proximity-coupled multilayers, a superconducting nucleation spreads over several layers, including superconducting and normal regions. On the contrary, when $\xi_\perp$ becomes comparable to the period, each nucleation reduces and tends preferentially to stay in the superconducting region. However, this tendency should not always be expected, because we can expect that the nucleations (or vortices) are disposed to form the temperature-dependent regular lattice, as in a homogeneous superconductor. Thus, in superconducting multilayers, the nucleations probably result in the formation of a complicated lattice, and this effect arising from the commensurability should be reflected on $H_{c2\parallel}$, although at the present stage we cannot give theoretical corroboration of how this effect causes the *upturn* in $H_{c2\parallel}$.

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