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Dimensional effects in V/Cu superconducting superlattices

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The superconductor-normal-metal phase transitions in V/Cu superlattices have been studied in parallel and perpendicular magnetic fields. Two crossovers from three-dimensional to two-dimensional and from two-dimensional to three-dimensional have been observed in magnetoresistance $R(H,T)$ and in dependencies of the fluctuating conductivity $\sigma'(T)$ in a parallel magnetic field. The crossover in low magnetic field is caused by the fact that the superconducting coherence length $\xi_S(T)$ becomes of the order of the superstructure period Λ. The crossover in high magnetic field is due to the competition of the normal-metal coherence length ξ_N and magnetic length L_H. The experimental results are in good agreement with numerical solution of the Ginzburg-Landau equation for superconductor-normal-metal-superconductor (SNS) superlattices.

INTRODUCTION

The artificially prepared superconducting superlattices (SSL's) can be used as suitable objects for investigating the effects of dimensionality changes. The SSL dimensionality is connected with the ratio of the superlattice period Λ and superconducting coherence length $\xi_S(T)$. For $\Lambda \ll \xi_S(T)$ the superconducting nucleus overlaps with many layers and the three-dimensional (3D) state is realized. For $\Lambda \sim \xi_S(T)$ the nucleus is localized in the superconductor (S) and the two-dimensional (2D) state occurs. For further increase of Λ, another dimensional crossover may take place at $d_S \gg \xi_S(T)$, where d_S is the thickness of the superconducting layer. In this case the superconducting nucleus does not interact with layer boundaries.

Taking into account the temperature dependence of the coherence length

$$\xi_S(T)=\xi_S(0)/\sqrt{1-T/T_c} ,$$

one can easily change the SSL dimensionality by varying the temperature. Such dimensional crossover leads to an upturn in $H_{c2}^{\parallel}(T)$ curves of SSL's from 3D linear dependence near T_c to 2D square-root dependence at low temperatures. It has been observed in both SSL's with Josephson coupling [Nb/Ge,[1] Pb/C,[2] Pb/Ge, (Ref. 3), and in SNS SL's, with proximity coupling [Nb/Cu],[4] Nb/Ta,[5] V/Ag,[6] Nb/Ag,[7] Mo/V (Ref. 8)]. At temperatures $T>T_c$ the dimensional crossover can be observed in the temperature dependencies of the fluctuating conductivity $\sigma'(T)$. The effect of changing the $\sigma'(T)$ behavior from 2D- to 3D-like when $T\rightarrow T_c$ has been observed in Nb/Si SSL's.[9]

The theoretical models describing the variety of SSL properties have been developed for Josephson coupled structures,[10,11] and for proximity coupled structures.[12,13] The models dealing with SNS SL will be discussed in detail below.

We present here the results of an investigation of artificially prepared V/Cu superlattices. As the SSL properties are very sensitive to the choice of both the components, the investigation of V/Cu structure in addition to previous investigations seems to be of interest. In the following experimental part we present resistive transition dependencies $R(H,T)$ for different geometries of the samples. A theoretical model is proposed to describe both the high-temperature and the low-temperature properties of V/Cu superlattices in parallel magnetic fields.

EXPERIMENTAL DETAILS

The V/Cu SSL's have been prepared on the "Leibold-Heraeus" Z-400 high-vacuum installation by rf-cathode sputtering. The single-crystal highly oriented (100) silicon substrates were held at room temperature during the deposition. Eleven copper layers were separated by ten vanadium layers to provide a superconducting symmetry across the SSL. The thicknesses of the vanadium layers (d_V) are 20–25 nm, and those ones of copper layers, (d_{Cu}) are 10–20 nm. The periodicity of the structures and the sharpness of the interfaces between layers (less than 1.5 nm) have been confirmed by Auger- and mass-spectroscopy, respectively. The characteristics of some samples are listed in Table I.

The resistive transitions $R(T,H)$ were measured using a standard four-probe dc technique. The temperature below 4.2 K was changed by helium vapor pumping and measured by monitoring the vapor pressure. Above 4.2

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TABLE I. V/Cu-superlattice sample parameters.

d_V (nm)	d_{Cu} (nm)	T_c (K)	ρ_{300} ($\mu\Omega$ cm)	$R_{300\,K}/R_{5K}$
25	10	4.69	15.59	2.6
25	15	4.55	23.21	3.0
25	20	4.43	28.17	3.1
20	15	4.32	16.11	2.5
20	10	4.11	14.16	2.1

K the temperature was changed by increasing the helium vapor pressure above 1 bar and was measured by a GaAs thermometer placed in a helium bath out of the solenoid. The temperature was changed in the interval 1.6–5 K with an accuracy ~0.003 K, and the solenoid creates a magnetic field up to 40 kOe.

EXPERIMENTAL RESULTS

A. Magnetoresistance

We have studied the resistive superconducting transitions $R(H,T)$ of V/Cu structures over a large interval of temperatures and magnetic fields. Figure 1 shows the $R(H)/R_N$ curves for the V (25 nm)/Cu(10 nm) structure in parallel fields. The remnant resistance R_N was measured in strong magnetic fields suppressing the superconductivity. Near $T_c(H=0)$ the $R(H)$ transitions are rather narrow. With decreasing temperature the transition widths increase. Such a broadening is evidence of 3D-2D crossover, as the 2D fluctuation contribution appears.

An unusual behavior has been observed, however, at lower temperatures, where transition widths decrease again. The region of magnetic fields with a steep decrease of resistance gradually spreads over the entire transition as the temperature is lowered (the arrows on the Fig. 1). This effect was observed on structures with different ratios of the vanadium and copper layer thicknesses.

The diagrams of $H_{c2}^{\parallel}(T)$ extracted from $R(H,T)$ curves appear as follows: the linear part near T_c turns into the square-root one in some region around T^+ (T^+ is the temperature of 3D-2D crossover); at lower temperatures, a new upturn can be observed, where the curves become linear again. Figure 2 shows the temperature dependencies of the parallel and perpendicular critical fields of the superstructure V(25 nm)/Cu(15 nm). The $R=0.5R_N$ resistance vlaues were used to determine the critical field. Determination from other resistances produced qualitatively the same results.

As the thicknesses of the copper layers, d_{Cu}, are increased, the narrowing of the $R(H)$ transitions begins at lower temperatures, but does not move in accordance with the change of d_V. We have analyzed the values of T^*/T_c and $\xi_S(T)/d_V$, where T^* is the temperature of the second upturn on the $H_{c2}^{\parallel}(T)$ dependencies. The T^*/T_c values decrease with the increase of d_{Cu}; $T^*/T_c=0.59$ ($d_V=25$ nm, $d_{Cu}=10$ nm), $T^*/T_c=0.51$ ($d_V=25$ nm, $d_{Cu}=15$ nm), $T^*/T_c\leq 0.40$ ($d_V=25$ nm, $d_{Cu}=20$ nm). On the other hand, the randomness of $\xi_S(T^*)/d_V$ values is observed: $\xi_S(T^*)/d_V=0.71$ ($d_V=25$ nm, $d_{Cu}=10$ nm), $\xi_S(T^*)/d_V=25$ nm, $d_{Cu}=15$ nm), $\xi_S(T^*)/d_V=0.51$ ($d_V=15$ nm, $d_{Cu}=15$ nm). Thus the effect of narrowing of $R(H)$ is not a consequence of the bulklike behavior of the superconducting layer $[d_S \gg \xi_S(T)]$, but is strongly connected with normal layer thicknesses. No such anomalies have been observed in perpendicular fields.

Taking into account the dependencies of $R(H,T)$ and $H_{c2}^{\parallel}(T)$ the assumption about two different crossovers from 3D to 2D in low magnetic fields and from 2D to 3D in high magnetic fields can be suggested. Thus, the linear behavior for $H_{c2}^{\parallel}(T)$ together with narrow transitions $R(H)$ in this region are usual for the 3D case, while the square-root critical fields behavior and broad transitions can be caused by 2D localization of the nucleus.

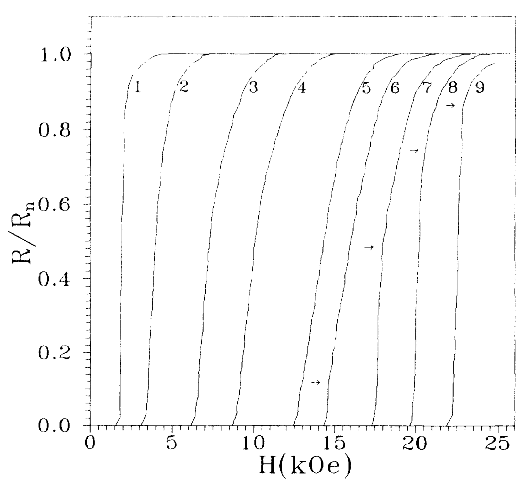

FIG. 1. The curves of $R(H)$ for the V(25 nm)/Cu(10 nm) plotted for various temperatures. 1: 4.62 K; 2: 4.22 K; 3: 3.77 K; 4: 3.42 K; 5: 2.84 K; 6: 2.54 K; 7: 2.21 K; 8: 1.74 K; and 9: 1.45 K. The arrows separate the wide and the narrow regions on the $R(H)$ curves.

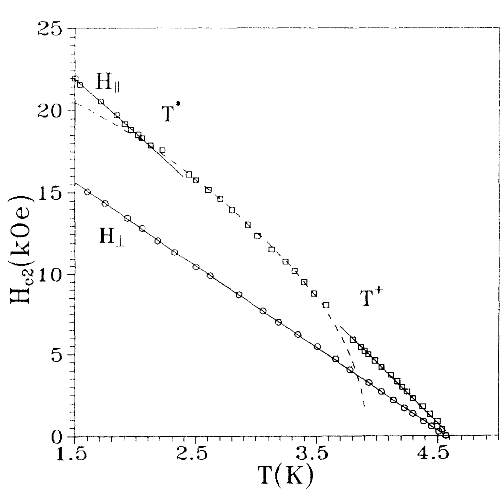

FIG. 2. The $H_{c2}(T)$ curves for the V(25 nm)/Cu(15 nm) SSL. The (T^+) and (T^*) on $H_{c2}^{\parallel}(T)$ are the temperatures of first and second upturns.

B. Fluctuating conductivity

The Aslamazov-Larkin (AL) fluctuation theory[14] describes the influence of fluctuation Cooper pairing on conductivity σ at temperatures above T_c. The fluctuation range and the form of excess conductivity curves $\sigma'(T)$ depend on superconductor dimensionality:

$$\sigma'=\sigma-\sigma_N \sim (T/T_c-1)^{D/2-2} , \qquad (1)$$

where σ_N is normal state conductivity and D is the superconductor dimensionality.

Figure 3 shows the resistance curves of V (25 nm)/Cu(10 nm) structure at the different parallel magnetic fields. In zero field (curve 1) resistive transition $R(T)$ is narrow. The broadening of the transition takes place when the field increases (curve 2), and then the transition narrows again in strong magnetic fields (curve 4). Curve 3 represents an intermediate transition between curves 2 and 4.

Figure 4 shows the comparison of the experimental results on $\sigma'(T)$ with calculations within the framework of the AL theory (solid curves). It was found that fluctuations in weak magnetic fields [Fig 4(a)] are of 3D type. In the middle range of fields [Fig. 4(b)] 2D-type fluctuations take place, and in strong fields they become 3D type again [Fig. 4(c)].

Thus, two different crossovers have been observed also on the fluctuating conductivity.

THEORY

Theoretical analysis of the upper critical fields of SNS SL's have been the subject of detailed studies.[12,15,16] In the calculations[12] for SNS superlattices the spatial variation of density of states, diffusion coefficients and BCS electron-electron interaction have been taken into account. On the other hand, from phenomenological point of view there are three parameters $\xi_S(0)$, $\xi_N(T)$, and α which determine the behavior of SSL in magnetic field (α is the parameter which determines the step of the order parameter on the superconductor/metal boundary), and may be easily estimated from experimental data. Thus the phenomenological consideration seems to provide the simple way for comparing theory and experiment and is

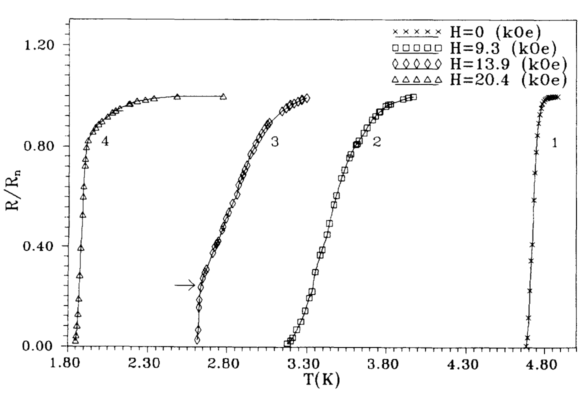

FIG. 3. The resistance curves $R(T)$ of V(25 nm)/Cu(10 nm) at various parallel magnetic fields.

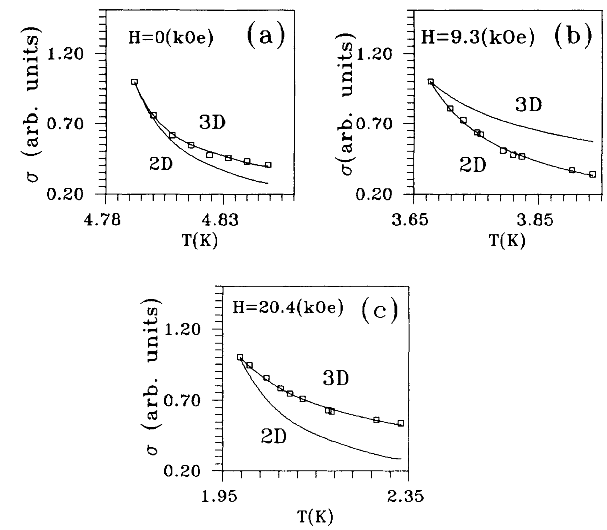

FIG. 4. The temperature dependences of excess conductivity of the structure V(25 nm)/Cu(10 nm) SSL.

supposed to give an acceptable qualitative description.

We consider the Ginzburg-Landau equations (GLE) to describe the spatial dependence of the order parameter in S and N layers:

$$-\frac{d^2\psi}{dx^2}+[(x-\kappa L_H^2)^2/L_H^4-\tau/\xi_S^2]\psi=0 , \qquad (2)$$

where $\Lambda n - d_S/2 < x \le \Lambda n + d_S/2$ for S layers;

$$-\frac{d^2\psi}{dx^2}+[(x-\kappa L_H^2)^2/L_H^4-1/\xi_N^2]\psi=0 , \qquad (3)$$

where

$$\Lambda(n+\tfrac{1}{2})-d_N/2 < x \le \Lambda(n+\tfrac{1}{2})+d_N/2$$

for N layers.

$\tau=(T_{c0}-T)/T_{c0}$, T_{c0} is the coherence length in the S layer for $T=0$, $\xi_N(T)=\xi_N/\sqrt{T/T_{c0}}$ is the normal metal coherence length, $L_H^2=c\hbar/eH$, $H\|z$ is magnetic field, κ is pseudowave vector, corresponding to the choice of the center of the superconducting nucleus. Since the system is invariant under translations, the critical field does not depend on κ, and we adopt $\kappa=0$.

It is well known that GLE's are not valid as one moves from $T_c(H=0)$. To analyze the upper critical field in this region it is necessary to use the de Gennes–Werthammer formulation.[13] However, to understand the qualitative changes in H_{c2} curves we can use this simplified phenomenological model. Boundary conditions for GLE can be written as[17]

$$\alpha\psi(\Lambda n+ds/2-0)=\psi[\Lambda(n+\tfrac{1}{2})-d_N/2+0] , \qquad (4)$$

$$\frac{d\psi(\Lambda n+d_S/2-0)}{dx}=\frac{d\psi[\Lambda(n+\frac{1}{2})-d_N/2+0]}{dx} , \qquad (5)$$

where

$$\alpha \propto D_N(N_N(0)/D_S N_S(0) ,$$

D_N and D_S are the diffusion coefficients of N and S layers, and $N_N(0)$ and $N_S(0)$ are the densities of electronic states on the Fermi surface in N and S layers. Here we do not take into account the influenced of the vacuum/metal interface on $H_{c2}(T)$ dependences[13] and consider the volume properties of superlattices only.

The general solution of the GLE's (2) and (3) is a linear combination of Weber functions (see also Ref. 12). The coefficients in the linear combination have to be chosen to satisfy boundary conditions (4) and (5) (see also Ref. 12).

We first consider a single superconducting layer between two thick normal metal films. The solution of the GLE's (2) and (3) with boundary conditions (4) and (5) shows the following temperature dependence of H_{c2} (Fig. 5). For a large enough value of ξ_N we have found the change in the dependence of H_{c2} on temperature from $H_{c2} \propto \sqrt{T_c - T}$ (T_c is the critical temperature of the NSN three layers) at high temperature to $H_{c2} \propto (T_{c0} - T)$ at low T. This phenomenon is connected with the fact that a slope of the order parameter in normal metal in the low field region ($L_H \gg \xi_N$) is determined by the normal metal coherence length ξ_N: $\psi \propto \exp(-x/\xi_N)$. The increase of the magnetic field leads to the decrease of L_H, and in the high field region ($L_H < \xi_N$) a slope of the order parameter in the normal metal is determined by L_H: $\psi \propto \exp(-x^2/2L_H^2)$. It means that ξ_N does not contribute to the spatial dependence of the order parameter. Therefore, in a high magnetic field normal metal layers do not affect the order parameter distribution in the superconducting layer. The derivative of the order parameter near the boundary is determined by the magnetic length L_H: $\psi' \sim \psi/L_H$. The spatial distribution of ψ depends only on L_H and ξ_S.

Figure 6 shows the results of comparison of the model (2)–(5) with the experimental data of Chun *et al.*[4] for three layers of the *N-S-N* structure. These data show 2D

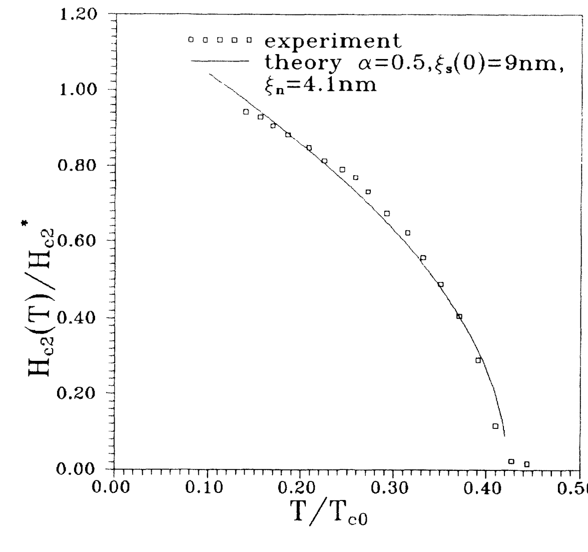

FIG. 6. The temperature dependence of $H_{c2}(T)$ of NSN three layers (100 nm/19 nm/100 nm). Comparison with experimental results (Ref. 4).

behavior in all regions of temperature. Note that $T_c = 4$ K of the structure is lower than $T_{c0} \sim 9$ K for pure Nb. This means that ξ_N is small ($\xi_N \ll \xi_S$). Since the deviation from 2D behavior in the temperature dependence of H_{c2} corresponds to $L_H \sim \xi_N$ the discussed experiment[4] does not show it.

The effect of transparency of normal layers for the superconducting order parameter in a high magnetic field must be important for multilayered SNS superlattices as well. For $L_H < \xi_n$ the distribution of order parameters in superlattices depends only on two parameters: L_H and ξ_S. The competition of these two lengths determines the upper critical field $H_{c2} \propto (T_{c0} - T)$. Figures 7 and 8 show the temperature dependencies of upper critical fields for different values of α and ξ_N. If α decreases, H_{c2} increases

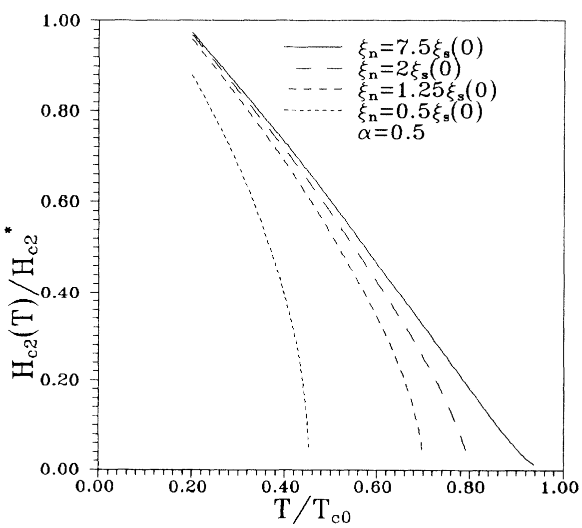

FIG. 5. The temperature dependence of $H_{c2}(T)$ of NSN three layers for various values of normal-metal coherence length.

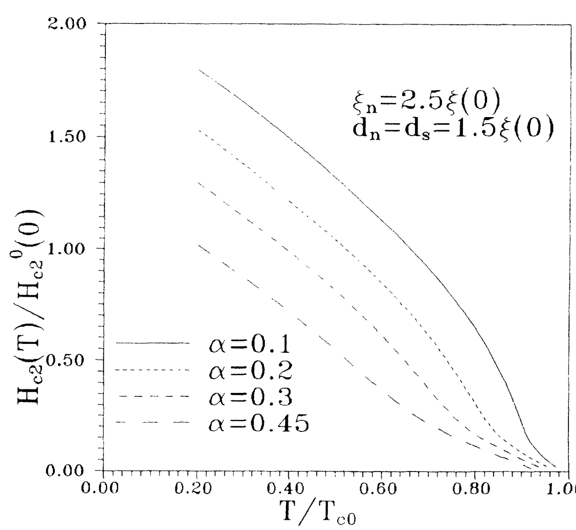

FIG. 7. The $H_{c2}(T)$ curves of SNS SL for various values of α.

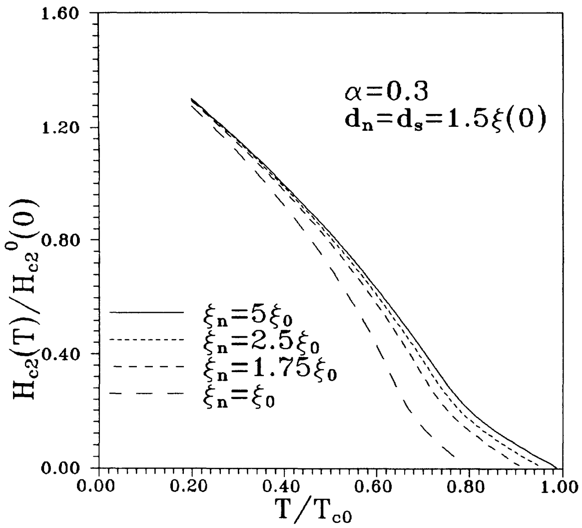

FIG. 8. The $H_{c2}(T)$ curves for various ξ_N values.

in the low-temperature region. It is connected with the fact that a small value of α corresponds to a small value of density of states $N_N(0)$. It leads to the suppression of the proximity effect and decoupling of the layers. The temperature interval of 2D behavior of H_{c2} increases. In the high-temperature region H_{c2} is very sensitive to the ξ_N value (Fig. 8). For $T \rightarrow T_c$, H_{c2} strongly depends on interlayer coupling. A decrease of ξ_N leads to the diminishing of the interlayer coupling and a smaller value of H_{c2}. In the low-temperature region H_{c2} is not sensitive to the change of ξ_N. ξ_N does not contribute into GLE's (2) and (3) and the spatial dependence of the order parameter is determined by ξ_S and L_H. Note that α changes only the absolute value of the order parameter in S and N layers but does not contribute to the spatial dependence (the size of the nucleus) of the order parameter.

To clarify this effect we plot in Fig. 9 $H_{c2}(T)$ dependence of the SNS superlattice in comparison with the critical field of thin film. The thickness and critical temperature of the film are chosen to describe the 2D behavior of the SSL. One can see from the Fig. 9 that the difference between these two curves increase with the increase of the magnetic field. This deviation is connected with the changing of the distribution of the order parameter in N layers.

Thus the upper critical field strongly depends on the parameters ξ_S, ξ_N, and α. Figures 10(a) and 10(b) show the results of the comparison of the experimental data for different superlattices with our calculations. One can see that it is possible to describe the experimental data in terms of GLE theory with a reasonable set of parameters.

It should be noted that real superlattices have the different widths of the layers and T_{c0} of superconducting layers. It leads to the correction to H_{c2} and broadening

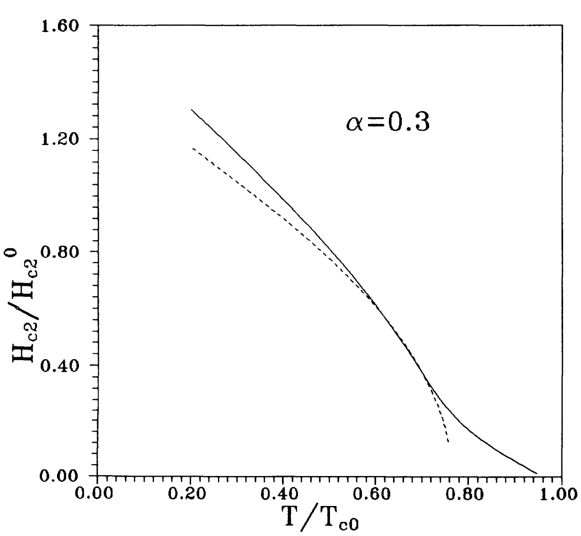

FIG. 9. The $H_{c2}(T)$ of SNS SL in comparison with $H_{c2}(T)$ (dashed line) of the single film with $d_{\text{eff}}=2.7\xi(0)$ and $T_c=0.765T_{c0}$.

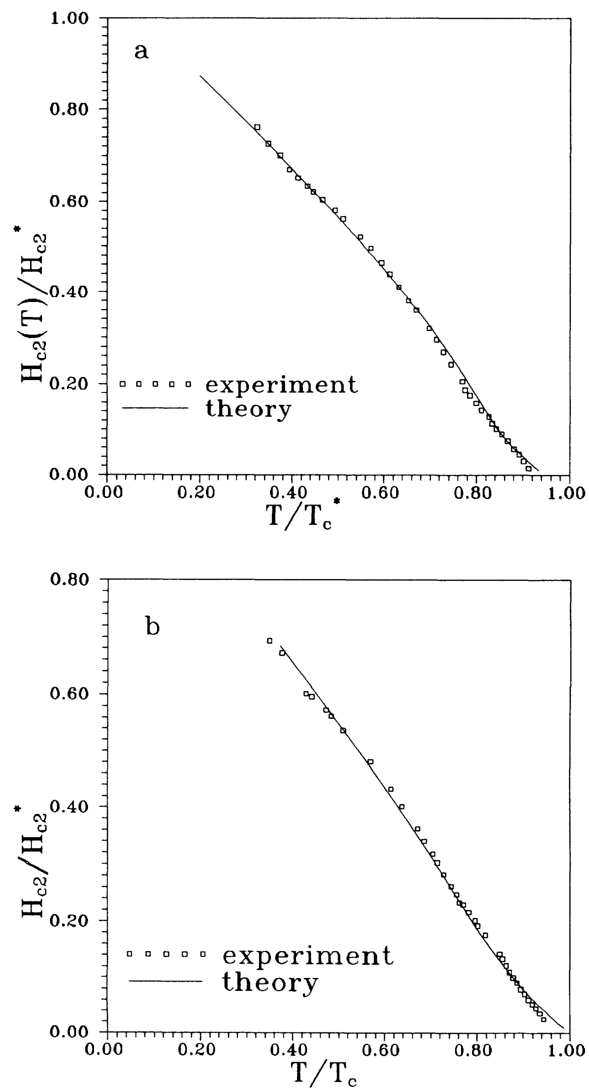

FIG. 10. Comparisons of theoretical calculation for $H_{c2}(T)$ of SNS SL with experimental results for (a) $d_S=25$ nm, $d_N=15$ nm, $\xi(0)=10$ nm, $\xi_N=22$ nm, $\alpha=0.55$ and (b) $d_S=25$ nm, $d_N=10$ nm, $\xi(0)=8$ nm, $\xi_N=20$ nm, $\alpha=0.6$.

of the superconducting transition. In the region of the low field where the nuclear size L_H is much larger than a period of the structure Λ, this disorder is not important due to the averaging of the parameters of the structure on length scale L_H. It leads to the restoration of the translational symmetry and the energy of the superconducting nucleus does not depend on its position. The superconducting transition is narrow. In the region of the intermediate field (2D behavior of H_{c2}) the energy of the nucleus is position dependent due to disorder. It leads to the broadening of the transition. In the high field region the spatial dependence of the order parameter is not sensitive to N layers. It means that the superconducting order parameter is not sensitive to the disorder on the superconductor/metal boundaries. The energy of the nucleus weakly depends on its position. It leads to the narrowing of the transition in the high magnetic field region.

CONCLUSION

In the present paper we have presented the results of the resistive superconducting transitions $R(H,T)$ of V/Cu superlattices. We have observed the increase of the $R(H)$ transition width with H in low magnetic fields connected with the 3D-2D crossover. Further increase of magnetic field leads to the decrease of the transition width and 3D behavior is restored. The $H_{c2}^{\parallel}(T)$ curves show 3D linear temperature behavior in regions of low and high magnetic fields. In the intermediate field region $H_{c2}^{\parallel}(T)$ has 2D character. Investigations of the fluctuating conductivity show a similar change of the dimensionality of the superlattices.

The temperature dependence of the upper critical field $H_{c2}(T)$ has been analyzed in terms of Ginzburg-Landau equations. It was shown that crossover is caused by the decrease of the superconducting coherence length and localization of the superconducting nucleus in the S layer. In the high magnetic field region ($L_H < \xi_N$) the decrease of the order parameter in the N layers is determined by the magnetic length L_H and ξ_N does not contribute to the order parameter distribution in the superlattice. The numerical solution of Ginzburg-Landau equations in high magnetic fields region shows 3D behavior in agreement with the experimental data.

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