Dimensional crossover 3*D*–2*D*–3*D* in superconducting layered V/Cu structures

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A temperature-dependent nonmonotonic variation of the superconducting transition width has been observed in multilayer vanadium-copper structures in a magnetic field. The critical field H_{c2} was also observed to vary as a function of temperature. These variations can be attributed to a dimensional crossover, 3*D*–2*D*–3*D*, in the structure due to the change in the temperature and the magnetic field.

The anisotropy of critical magnetic fields and the presence of a 3*D*–2*D* dimensional transition (crossover) have now been detected in synthesized superconducting layered structures[1–3] and in multicomponent superconductors, including high-T_c superconducting single crystals.[4] Depending on the period (d) of the layered structure and the temperature, Banerjee and Shuller[3] have classified superconducting layered structures as follows: strongly coupled 2*D* structures, coupled 2*D* structures, and 3*D* structures. In superconducting layered structures with a crossover, the 3*D* states have heretofore been ovserved only at temperatures near the critical temperature, in particular, in *SNS* structures with normal-metal intermediate layers. An inverse 2*D*–3*D* transition can, however, occur in *SNS* structures at low temperatures if the thickness of the normal layers, d_N, is small in comparison with the coherence length in a normal metal, $\xi_N(T)$. In the case of a valid relation between the normal conductivities and the coherence lengths in the *S* and *N* layers, the order parameter in the *N* layer is largely not suppressed compared with that in the adjacent superconductor. In the present letter we consider a 2*D*–3*D* dimensional crossover in layered V/Cu structures at low temperatures.

We have studied the resistive superconducting transitions $R(H,T)$ of V/Cu structures over a broad interval of temperatures and magnetic fields. The structures were synthesized by the method of *rf* ion-plasma sputtering in a high-vacuum system; as substrates we used single-crystal silicon wafers. The thickness d_V of the vanadium layers was 250 Å and the thickness of the copper layers varied from 100 Å to 250 Å in various samples. All of the samples had ten vanadium layers and eleven copper layers. To suppress the surface superconductivity and to prevent the formation of V–Si compounds, we made the first and the last layers of the structures copper layers. Figure 1 shows the $R/R_{\rm res}(H)$ curves for the structure V/Cu (250 Å/100 Å) in a parallel field; $R_{\rm res}$ was measured in strong magnetic fields which suppressed the superconductivity. Near $T_c(0)$ the $R(H)$ transitions are rather narrow. With increasing distance from $T_c(0)$, along with increasing H_{c2}, the transitions increase in width, which is accompa-

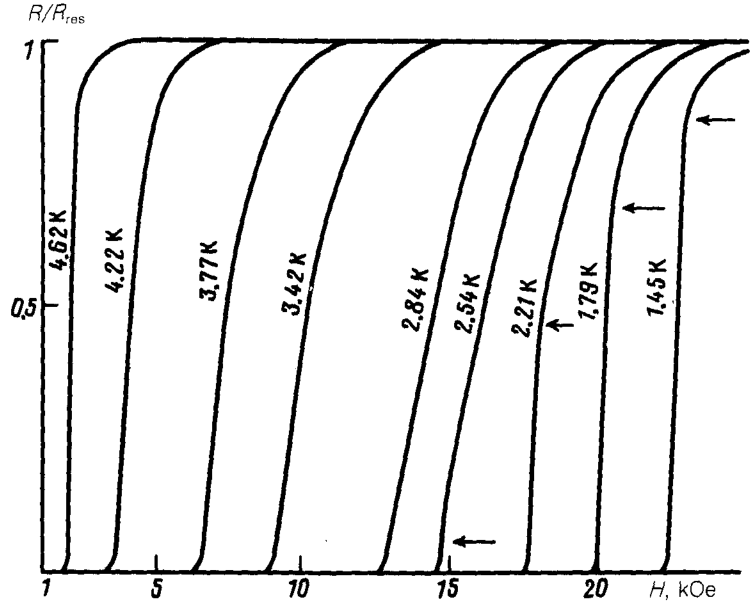

FIG. 1. The curves of $R(H)$ for the V/Cu structure (250 Å/100 Å) plotted for various temperatures.

nied by a crossover of the structure to a $2D$ state with separated $2D$ superconducting layers. At low temperatures, however, the $R(H)$ transitions again decrease in width. A region in which the resistance decreases anomalously rapidly, which gradually spreads over the entire transition as the temperature is lowered, can be clearly identified on the $R(H)$ curves at the end of the transition. The structures with different ratios of the vanadium and copper layer thicknesses were found to behave similarly. As the thickness of the copper layers, d_{Cu}, is increased, the narrowing of the $R(H)$ transitions begins at lower temperatures. The $R(H)$ curves exhibit no anomalies in perpendicular fields.

Figure 2 shows the temperature dependences of the parallel and perpendicular critical magnetic fields, $H^{\parallel}_{c2}$ and $H^{\perp}_{c2}$, for the V/Cu structure (250 Å/150 Å). The value of H_{c2} was determined from the resistance $0.5R_{\mathrm{res}}$. Determination of H_{c2} from other resistances produced qualitatively the same result. $H^{\perp}_{c2}$ depends linearly on T over the entire temperature interval, a typical behavior for layered structures.[2] Three regions can, however, be clearly identified on the $H^{\parallel}_{c2}(T)$ curve. Near T_c the dependence is linear $[H^{\parallel}_{c2} \sim (T_c - T)]$. With increasing distance from T_c, it becomes a square-root dependence $[H^{\parallel}_{c2} \sim (T^*_c - T)^{1/2}]$, in agreement with the assumption that a dimensional crossover ($3D$–$2D$) occurs in this structure.[1–4] At lower temperatures $T \approx 0.4T_c$) we see a deviation from the square-root dependence, and the temperature dependence of $H^{\parallel}_{c2}$ again becomes nearly linear.

The behavior of $R(H)$ and $H^{\parallel}_{c2}(T)$ curves can be explained by assuming that a double crossover, $3D$–$2D$–$3D$, occurs in the system in the temperature interval under

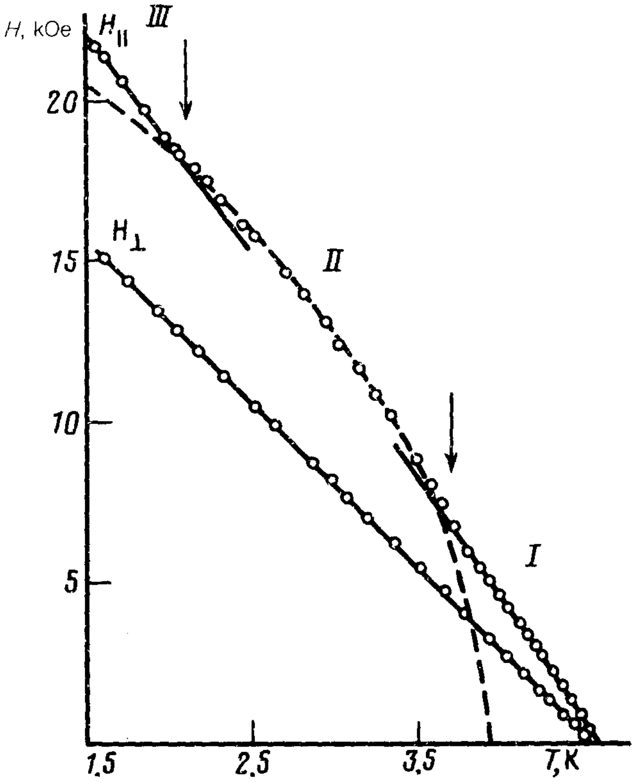

FIG. 2. The H_{c2} ()T) curves for the V/Cu structure (250 Å/150 Å).

study. The first transition occurs when the coherence length of the anisotropic 3*D* structure $[\xi^{\perp}(T) \sim (T_c - T)^{-1/2}]$ is equal, upon lowering the temperature, to the spacing between the *S* layers,[2,3] d_{Cu}. On the basis of the results shown in Fig. 2 we estimate $\xi^{\perp}(T = 3.6\ \mathrm{K})$ to be ≈ 170 Å at the temperature of the first crossover of the structure with $d_{\mathrm{Cu}} \approx 150$ Å. Upon further lowering of the temperature (to $T \approx 2$ K, in Fig. 2), the state with isolated superconducting 2*D* layers is apparently destroyed because of the increase in the coherence length in the *N* layers ($\zeta_N \sim T^{-1/2}$) and because of the appearance in them of a large order parameter. Without a detailed numerical simulation, such as that in Ref. 6, it is difficult to explain why a 2*D*–3*D* crossover in the *SN* structures we are analyzing occurs at these temperatures and thicknesses of the structure. Our estimates show that $\zeta_N(T)$ is much greater than d_{Cu} even at $T \approx 4$ K. We see, however, that in the similar experimental study[3] of Nb/Cu structures ($d_{\mathrm{Cu}} = d_{\mathrm{Nb}} \approx 170$ Å) an angular dependence of H_{c2} was observed at $T \approx 1.2$ K. This dependence, which corresponds to an anisotropic 3*D* case, was not clearly explained. The 3*D* state may be destroyed during the resistive transition because of the suppression of the order parameter; the corresponding points are shown by the arrows in Fig. 1. With an increase in the thickness of the copper layers, the 2*D*–

$3D$ crossover on the $H_{c2}^{\parallel}(T)$ curves shifts down the temperature scale, in agreement with the result discussed above.

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