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Superconductivity in Coupled Pb/Ge and Pb/C Multilayers

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We report on measurements of the dimensional crossover effect in superconducting Pb/Ge and Pb/C multilayers. The critical field data indicate the presence of a proximity effect at the interface between the Pb and the Ge or C. Using the model of Tachiki and Takahashi, we calculate the finite density of states near the Fermi-level in the Ge and C layers.

1. INTRODUCTION

The study of superconducting multilayers and superlattices has been a field of recent intense activity. The upper critical fields of two-dimensional superconducting layers separated by normal metal layers (proximity-coupled system) [1-4], as well as by semiconductor layers (Josephson coupled system) [5,6] has been investigated in detail. Since the perpendicular coherence length diverges near the transition temperature T_c, a crossover from three-dimensional (3D) towards two-dimensional (2D) occurs with decreasing temperature.

2. EXPERIMENTAL RESULTS

The Pb/Ge and Pb/C samples were condensed using an UHV, molecular beam epitaxy system [7], on liquid nitrogen cooled, sapphire substrates. The structural properties of these multilayers were determined using x-ray diffraction and transmission electron microscopy [8-10]. The presence of a large number of small angle x-ray peaks in Fig. 1, clearly illustrates the high quality of the resulting layered structure.

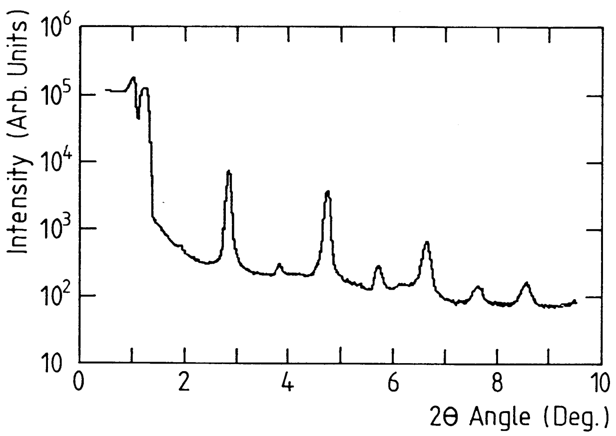

Fig.1 Small angle X-ray diffraction spectrum from a Pb(50 Å)/Ge (50 Å) multilayer. Note that the even order peaks are of considerably smaller amplitude than the odd ones.

The influence of the semiconductor layer thickness (d_{Ge}) on the critical temperature T_c is shown in Fig. 2. For a fixed d_{Pb} and an increasing thickness of the separator layer, T_c initially decreases and saturates for d_{Ge} = 30 Å (Fig. 2). Similar results are obtained in the Pb/C system (saturation for d_C = 20 Å). Apparently the proximity effect is still important in these semiconductor-superconductor multilayers.

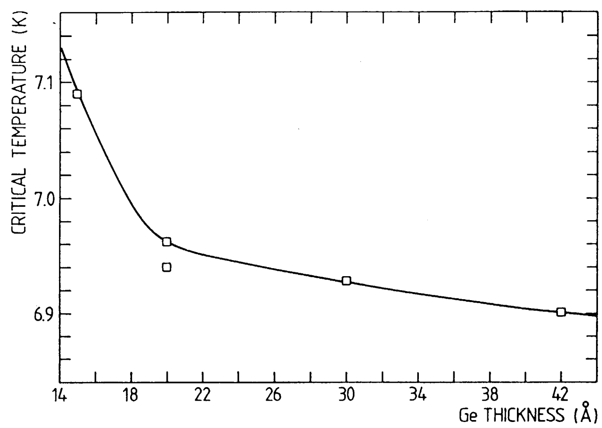

Fig. 2 Critical temperature versus thickness of the Ge separator for a Pb thickness of 140 Å.

The critical field parallel and perpendicular to the film plane were studied systematically as a function of the separator thickness. For a small separator thickness d_{Ge} < 15Å, d_C < 7Å, the temperature dependence of the parallel upper critical is linear, indicating a strongly coupled or 3D, anisotropic system. For a large separator thickness d_{Ge} > 30Å, d_C > 15 Å, the H_c (T) varies proportional to $(1-T/T_c)^{-1/2}$, characteristic of a 2D superconducting system : the superconducting layers are totally decoupled. For a Pb(140Å)/Ge(20Å) (Fig. 3a) and Pb(140Å)/C(12Å) (Fig. 3b) multilayer, the 3D-2D dimensional crossover is clearly visible in the critical field curves. The linear temperature dependence of H_c near T_c becomes square root like at lower temperatures.

3. DISCUSSION OF THE EXPERIMENTAL RESULTS

The anomalous temperature dependence of the upper critical field in layered structures, has also been investigated theoretically. Lawrence

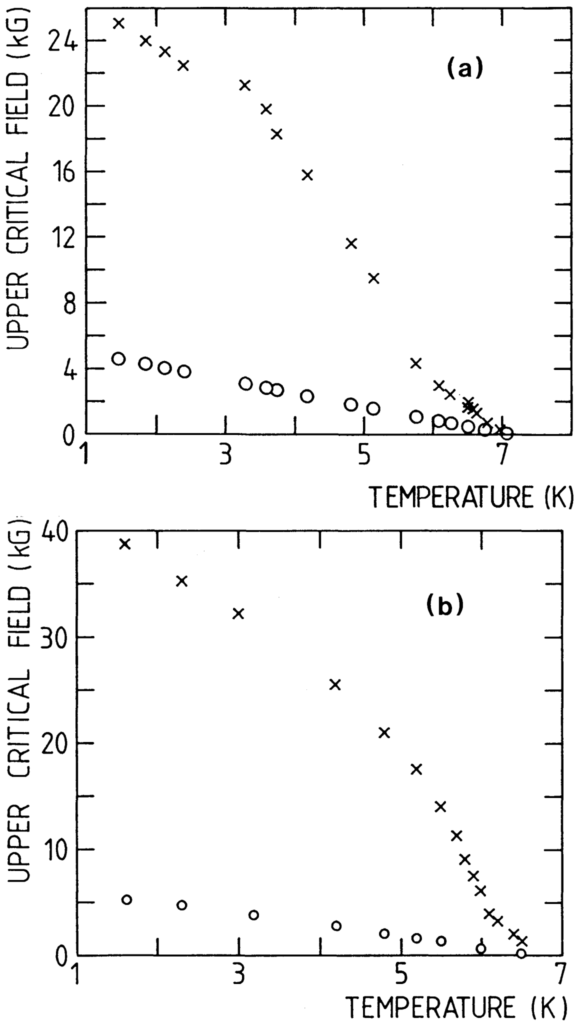

Fig. 3 Critical fields: a) Pb(140 Å)/Ge (15 Å), b) Pb(140 Å)/C (12 Å) $H_{c//}$(x); $H_{c\perp}$(o)

and Doniach [11] calculated the critical fields for thin superconducting layers coupled through insulating layers via Josephson tunneling. Their model was later extended by Klemm et al, [12] who predicted the presence of dimensional crossover for weakly coupled layers, a short mean free path and a strong spin-orbit scattering rate τ_{so}^{-1}. Ruggiero et al, [5] used this Josephson model to explain their critical field data for Nb/Ge multilayers. The obtained coupling strength was however too large to be consitent with Josephson coupling. In order to explain the variation of the critical temperature as a function of separator thickness, we had to invoke a model based on the superconducting proximity effect for our Pb/Ge and Pb/C multilayers. This proximity effect can also account for the important coupling between the layers.

Recently Takahashi and Tachiki [13] developped a theory for the upper critical fields, taking into account the spatial variation of the density of states, the diffusion constant, and the attractive electron-electron interaction. They concluded that the ratio of the density of states is the most important parameter for the description of the parallel critical field. The application of their model to the Nb/Cu case predicted the ratio of the density of states between Nb and Cu within 5 percent.

Using the theoretical curves of Tachiki and Takahashi, we can derive a rough estimate for the density of states in the Ge and the C layers. The value of $N(E_F)$ for Ge and C is approximately 1. $10^{+21}/cm^3/eV$, in agreement with the value reported for amorphous semiconductor layers deposited at liquid nitrogen temperature. One should keep in mind that this value is obtained using a model in which a uniform density of states in each layer is assumed. It is well known that the disorder in an amorphous layer is much larger at the surface (interface Pb/Ge) than in the bulk. Therefore, if the thickness of the separator is small, coupling essentially occurs via the disordered layers having a finite density of states. Increasing this thickness adds amorphous material with an almost zero density of states through which coupling can only occur via the Josephson effect. The fact that the Pb/C multilayers become decoupled at carbon thicknesses equal to half the thickness at which the Pb/Ge multilayers become decoupled, suggests that the disordered interface layer is thicker for the Ge than for the C.

4. CONCLUSIONS

High quality Pb/Ge and Pb/C multilayers were prepared. The upper critical fields and the critical temperature versus separator thickness show evidence of proximity coupling. Comparison with a theoretical model leads to an estimate for the density of states in the separator

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