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NATURE OF COUPLING AND DIMENSIONAL CROSSOVER IN SUPERCONDUCTING MULTILAYERS

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ABSTRACT

A comparison of the temperature dependent upper critical fields in Josephson and proximity coupled multilayers is presented. The results are in good agreement with theoretical expectations which predict that the main determining factor is the spatial variation of the electronic density of states.

INTRODUCTION

The study of the critical field of superconducting multilayers and superlattices has been a field of recent intense activity[1-5]. Interesting effects have been observed which include the observation of dimensional crossover in Josephson and proximity effect coupled multilayers[2-4], the study of the interaction of superconductivity and magnetism[5-6], anomalous critical fields around the order-disorder transition in superlattices[7] and reflections of fractal structure in the critical exponents of specially engineered multilayers[8-9]. Since all these studies rely on studying the upper critical fields of a series of two dimensional (2D) superconducting layers separated by a semiconductor (Josephson coupled)[1,9] or metal (proximity coupled)[2-8] it is important to understand the differences and similarities between these two types of multilayers. We present here a comparison of critical fields in the Josephson coupled Pb/Ge system with earlier, published data, of the proximity coupled Nb/Cu[2,3].

THEORY

The temperature dependence of the upper critical field reflects quite clearly the presence of dimensional effects in superconducting multilayers. It is quite easy to understand the expected behaviour as a function of the thickness of the non superconducting separator. From flux quantization the critical fields in an anisotropic superconductor are given by

$$H_{c\perp}(T) = \frac{\phi_0}{2\pi} \frac{1}{\xi_{\parallel}^2(T)} \qquad (1)$$

$$H_{c\parallel}(T) = \frac{\phi_0}{2\pi} \frac{1}{\xi_{\parallel}(T)\xi_{\perp}(T)} \qquad (2)$$

where $\xi_{\parallel}$ and $\xi_{\perp}$ are the temperature dependent coherence lengths in the parallel and the perpendicular directions respectively. If the thickness d_S of the superconductor is decreased, the electronic mean free path decreases and therefore $\xi_{\perp}(T)$ approaches d_S. Therefore for a single 2D($d_S \lesssim \xi_{\perp}$) superconductor

$$H_{c\parallel}(T) = \frac{\phi_0}{2\pi} \frac{1}{\xi_{\parallel}(T) d_S} \qquad (3)$$

Except of numerical factors, this temperature dependence is identical with that obtained using the Ginsburg-Landau theory for a thin film[10].

Since the temperature dependence of the coherence length $\xi(T) \propto (T - Tc)^{-1/2}$, according to equation 2 the temperature dependence of $H_{c\parallel}$ in 3D is expected to be linear whereas in 2D it is expected to be square root like (equation 3).

For a sample composed of 2D superconducting layers separated by non superconducting elements, the dependence is 2D if the thickness of the separator $d_N \gtrsim \xi$ and 3D if $d_N \lesssim \xi_{\perp}$. Moreover, since the coherence length is strongly temperature dependent, close to T_c where $\xi_{\perp}(T) \gtrsim d_N$, the 2D layers will be strongly coupled and the temperature dependence will be linear (i.e. 3D like), whereas for $\xi_{\perp}(T) \leq d_N$ the 2D layers will be decoupled and the temperature dependence will be square root like. These ideas have been developed and quantified using a more rigorous treatment earlier[11-13].

EXPERIMENTAL

The Pb/Ge samples were prepared in a load locked, molecular beam epitaxy (MBE) system, on liquid nitrogen cooled, 90° sapphire substrates[14]. The structural properties of these multilayers were determined using extensive x-ray diffraction and transmission electron microscopy. For example, the high quality of the layered structure is shown by the appearance of a large number of small angle x-ray peaks due to the Bragg diffraction from the large periodicity (Fig. 1). The fact that the intensities of the even order reflections are smaller than the odd ones shows that minimal interdiffusion exists in these equal thickness multilayers. The details of the strucutral studies will be published elsewhere[15-17]. The Nb/Cu superlattices were prepared at room temperature using a sputtering technique which together with the structural studies[17] was published elsewhere[2-3].

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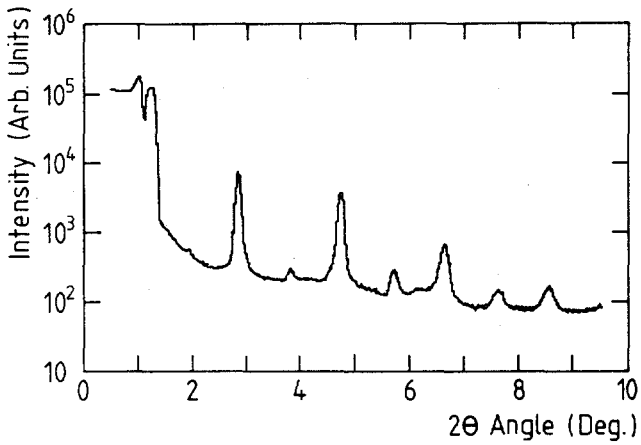

Figure 1. Small angle X-ray diffraction spectrum from a Pb(50 Å)/Ge(50 Å) multilayer. Note that the even order peaks are of considerably smaller amplitude than the odd ones.

Critical fields were resistively measured down to 1 K and up to 5 Tesla in the parallel and perpendicular directions. Care was exercised to assure the absence of inhomogeneities due to sample edges or instabilities in the preparation method, which may give rise to temperature dependent normal to superconducting transition widths.

Fig. 2 shows the temperature dependence of the critical fields in typical Pb/Ge multilayers in the three regimes; three-dimensional (3D), 2D and crossover. In the 3D regime (Fig. 2a) for Pb (140 Å)/Ge(15 Å) the dependence of parallel ($H_{c\parallel}$) and perpendicular ($H_{c\perp}$) upper critical fields is linear with temperature. Note also the presence of surface superconductivity indicated by the large anisotropy present. In the 2D regime (Fig. 2b) for a Pb(140 Å)/Ge(42 Å) multilayer $H_{c\parallel}$ exhibits a square root like temperature dependence whereas $H_{c\perp}$ is linear. In the crossover region (Fig. 2c) for a Pb(140 Å)/Ge(20 Å) multilayer the dependence $H_{c\parallel}$ is linear close to T_c and then it crosses over to the typical square root like 2D dependence. However, $H_{c\perp}$ again is linear. Further studies as a function of Ge layer thickness shows that the crossover occurs for 20 Å $\lesssim d_{Ge} \lesssim$ 30 Å.

In contrast, fig. 3 shows the critical fields for 3D, 2D and crossover behaviour for typical samples in the Nb/Cu proximity coupled system, in the absence of surface superconductivity.

An 8500 Å Nb film exhibits the typical 3D linear temperature dependence in $H_{c\parallel}$ (Fig. 3a), an 191 Å Nb film shows a square root like dependence (Fig. 3b) and a Nb(172 Å)/Cu(333 Å) multilayer illustrates dimensional crossover (Fig. 3c) by a linear temperature dependence close to T_c which changes to a square root like dependence at low temperatures. As expected, for a proximity coupled system the crossover occurs for a thicker separator, in this case 150 Å $\leqslant d_{Cu} \leqslant$ 200 Å. Again $H_{c\perp}$ remains linear as expected.

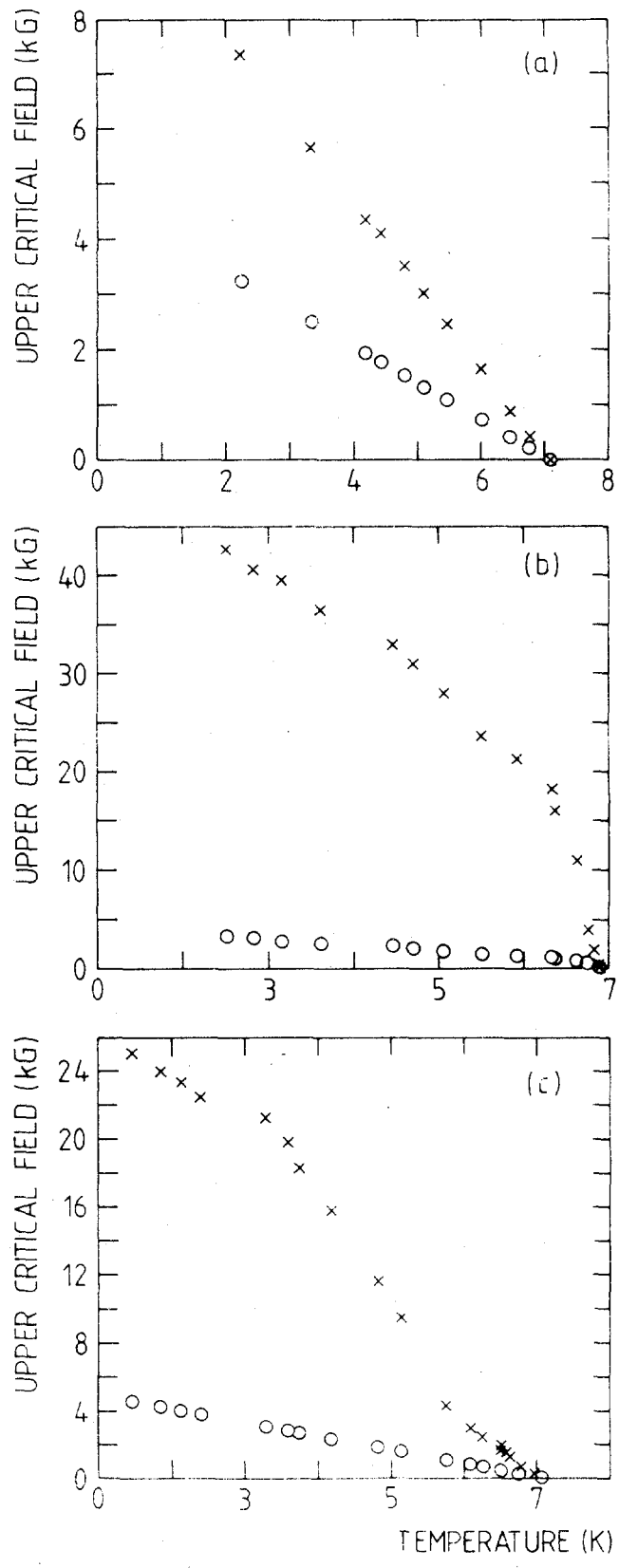

Figure 2. Critical fields for: a) a Pb(140 Å)/Ge(15 Å) multilayer (3D regime), b) a Pb(140 Å)/Ge(42 Å) multilayer (2D regime) and c) a Pb(140 Å)/Ge(20 Å) multilayer (crossover regime) $H_{c\parallel}$(x); $H_{c\perp}$(o).

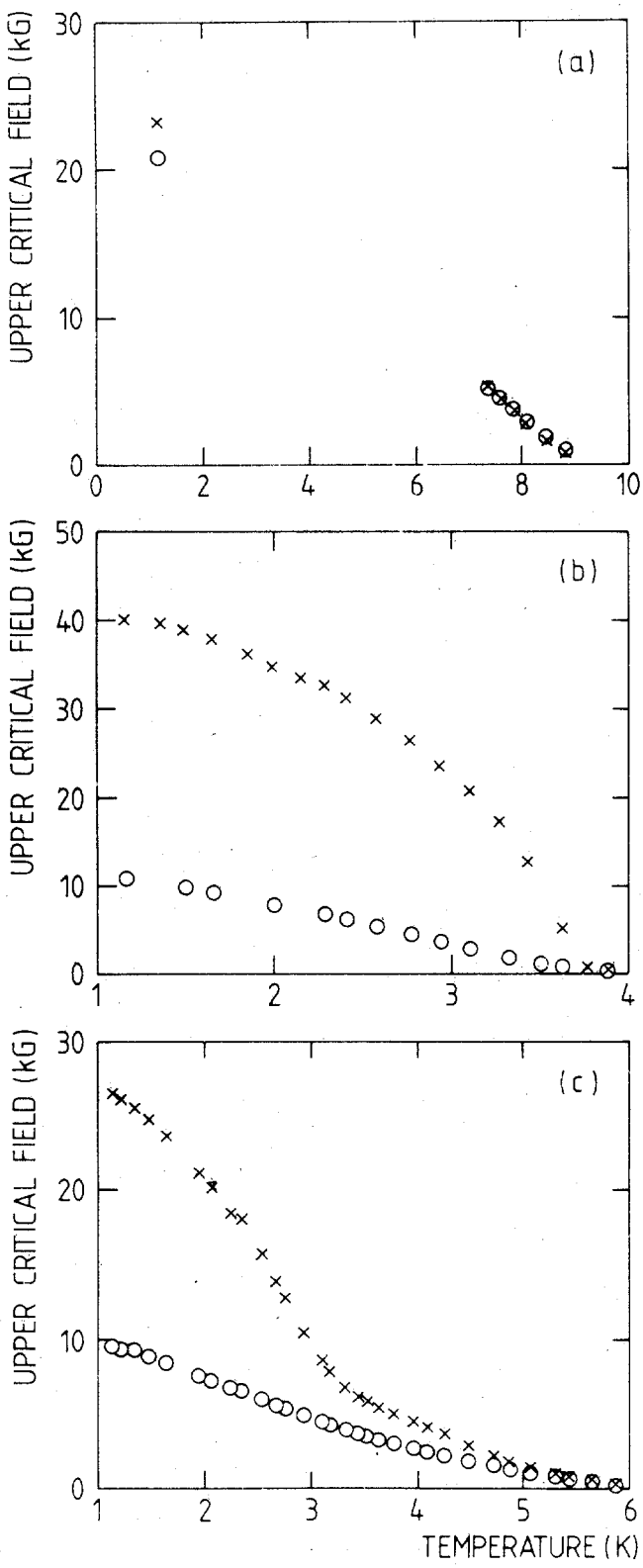

Figure 3. Critical fields for: a) a 3D thick (8500 Å) Nb film, b) a 2D thin(191 Å) Nb film and c) a Nb(172 Å)/Cu(333 Å) superlattice (crossover). In this case 1500 Å of Cu were added as the external layers to eliminate surface superconductivity $H_{c\parallel}$ (x); $H_{c\perp}$ (o).

DISCUSSSION

Qualitatively, the critical field versus temperature behaviour in the Pb/Ge and Nb/Cu multilayers is in good agreement with the theoretical ideas presented above. A detailed comparison of the two systems shows that the crossover behaviour is more pronounced in a proximity coupled than in a Josephson coupled system. Takahashi and Tachiki[13] have developed a theory for the upper critical fields in superconducting superlattices by taking into account the spatial variations of the density of states, the diffusion constants of conduction electrons, the attractive interaction constant responsible for superconductivity and spin polarization. Their conclusion is that the spatial variation of the density of states is the most important factor which determines the temperature dependence. As the ratio of the superconducting to separator density of states increases, the layers become progressively more and more decoupled and the break in the $H_{c\parallel}$ vs T curve is expected to shift to higher temperatures as shown in Fig. 4 of ref. 13. A fit to the Nb/Cu critical fields determines quite accurately the ratio of the density of states between Nb and Cu[13].

The present experiments give quite a direct confirmation of these theoretical results. The break in the $H_{c\parallel}$ vs T curves occurs at higher temperatures for Pb/Ge than for Nb/Cu in all the crossover thickness regime. This is so because the ratio of the Nb to Cu density of states is lower than the one for Pb and Ge. A rough comparison with the theoretical results of ref. 13 indicates that the ratio of the effective density of states between Pb and Ge is of the order of or smaller than 0.05. A further comparison of the Pb/Ge data with the Nb/Ge data of Ruggiero, Barbee and Beasley[1] points in the same direction; i.e. the temperature dependence in the crossover regime, is less pronounced for Nb/Ge than Pb/Ge (Fig. 4). Again, this is what one might expect based on the theoretical calculations of Takahashi and Tachiki[13] since Nb has a much higher density of states than Pb.

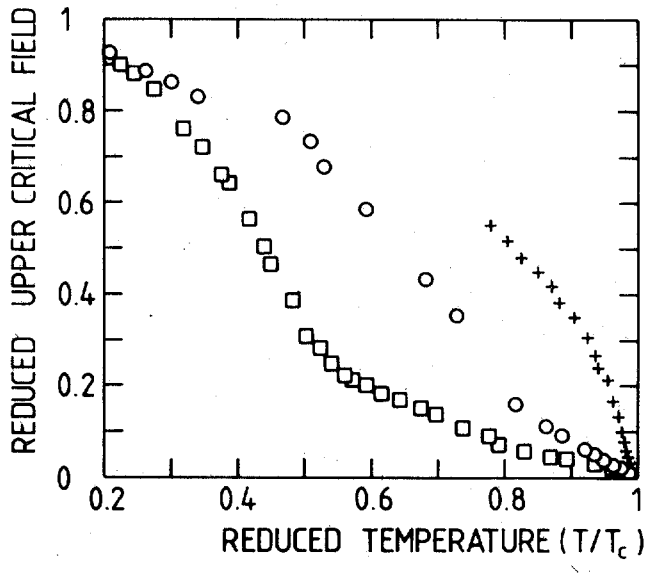

Figure 4. Critical field ratio $H_{c\parallel}(T)/H_{c\parallel}(0)$ for a Nb(172 Å)/Cu(333 Å) superlattice (□), a Pb(140 Å)/Ge(20 Å) multilayer (o) and a Nb(65 Å)/Ge(35 Å) multilayer (x).

CONCLUSIONS

In conclusion, we have compared the critical fields of Josephson and proximity coupled multilayers. We find that the experimental data are in good agreement with recent theoretical expectations. The present results in conjunction with earlier experiments show that the temperature dependence of $H_{c\|}$ can be modified drastically by changing the temperature and thickness of the separator as shown earlier[1-3] and by changing the density of states ratio, as shown here.

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