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DIMENSIONAL AND MAGNETIC EFFECTS IN SUPERCONDUCTING SUPERLATTICES*

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The superconducting properties of superconductor/normal metal (Nb/Cu) and superconductor/magnetic metal (V/Ni) superlattices are presented. The superconducting and magnetic transition temperatures are found to be strongly thickness dependent. The superconducting critical fields show dimensional crossover in the Nb/Cu superlattices and an anomalous reversed anisotropy in V/Ni superlattices.

1. Introduction

Superconducting superlattices are model systems in which it is possible to study the behavior of superconductors in restricted dimensionality and the interaction of competing mechanisms. The characteristic length which determines the behavior of superconductors is the coherence length which typically is of the order of a few hundred ångströms. Superconducting superlattices can reliably be prepared with thicknesses ranging from much smaller to much larger than the coherence length and thus to span the whole range from two dimensional to three dimensional behavior. In addition, since the coherence length is strongly temperature dependent dimensional behavior can be observed as a function of temperature. The superconducting transition temperature (T_S) and the magnetic transition temperature (T_M) can be changed by changing the individual thickness of the superconducting or magnetic component. This allows the preparation of materials in which the superconducting ordering occurs at a higher temperature than the magnetic ordering. To study the interaction between the two competing phenomena (i.e., magnetism and superconductivity) superlattices are prepared so that $T_M < T_S$ and the superconducting coherence length (ξ) is close to the thickness of the superconducting layer. In this paper we present the study of dimensional crossover in a superconductor (Nb)/normal metal(Cu) superlattice and preliminary results on the behavior of a superconductor (V)/magnetic (Ni) superlattice.

2. Preparation and characterization

The samples are prepared using a sputtering technique described earlier [1]. Briefly, the samples were deposited on temperature controlled single crystal 90° orientation, sapphire substrates. Two rate controlled beams (Nb and Cu or V and Ni) of sputtered particles are prepared at typically 5–10 mTorr pressure after long bakeout to ~100°C and after pump down to a base pressure of $(5–10) \times 10^{-8}$ Torr. The substrates are alternately moved from one beam to the next thus depositing alternating layers.

Extensive low and high angle X-ray diffraction [1, 2], in the direction parallel and perpendicular to the layers, has been performed to determine chemical and structural modulation. The structure consists of well segregated bcc (110) and fcc (111) planes with an interfacial width of less than two interatomic planes and undergoes an order–disorder transition at ~8–10 Å layer thickness for equal layered samples.

Contamination can drastically affect the superconducting transition temperatures of Nb and V.

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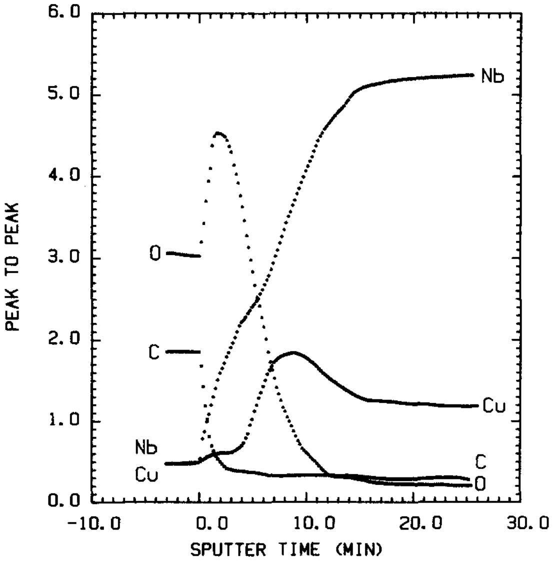

Fig. 1. Peak to peak ion mill Auger intensity as a function of sputter time for a Nb/Cu superlattice.

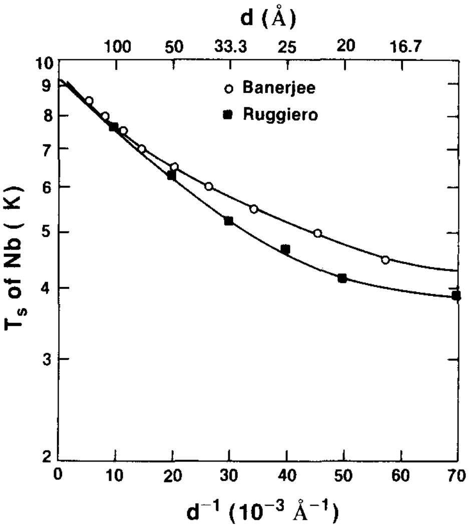

Fig. 2. Superconducting transition temperature for pure Nb as a function of thickness as extracted from Nb/Ge multilayers and Nb/Cu superlattices.

To determine the extent of contamination ion mill Auger Electron Spectroscopy (AES) and ion scattering spectroscopy have been performed. Fig. 1 shows the results from an ion mill AES experiment for a Nb (16.5 Å)/Cu (16.5 Å) superlattice. The results show that after approximately 40 Å (12 min sputtering time) the oxygen and carbon contamination fall below the detection limit. It is also interesting to notice that due to the finite escape depth of the Auger electrons ($\geqslant$10 Å) and the intermixing by the ion milling the layering is barely discernable for this small modulation period although X-ray diffraction studies show well-defined superlattice peaks.

3. Transition temperature

The superconducting transition temperatures (T_S) were measured both resistively and inductively, with no appreciable difference in the results. The transitions are found to be sharp ($\leqslant$60 mK wide) and for a single film the Nb, $T_S \simeq 9$ K, and the V, $T_S \simeq 5$ K, are very close to the bulk transition temperatures. This also indicates that the contamination is minimal.

Fig. 2 shows a comparison of the superconducting transition temperatures for a Nb film as obtained from an extrapolation ($d_{Ge} \rightarrow 0$) of Nb/Ge multilayers [3] and a proximity effect analysis of Nb/Cu superlattices [4]. Both results are in reasonably close agreement showing a decrease of T_S of Nb, which has been previously assigned [5] to a broadening of the Nb density of states at the Fermi surface.

The magnetic transition temperature (T_M) of Ni (fig. 3) is strongly affected by the decrease in thickness in similar Ni/Mo superlattices [6]. T_M was obtained from Arrot plots of the magneti-

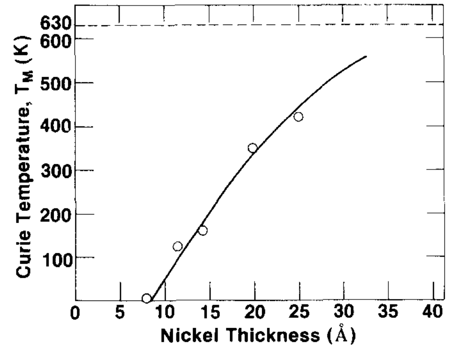

Fig. 3. Curie temperature obtained from Arrot plots as a function of Ni thickness obtained from Ni/Mo superlattices.

zations measured in parallel fields using SQUID magnetometry in the temperature range 5–300 K and in fields up to 10 kG. Whether this decrease is due to the existence of dead layers of Ni or an interfacial intermixing is a subject of much controversy and not clear at this time.

4. Superconducting critical fields

The superconducting critical fields are strongly affected by the dimensionality and the magnetic effects.

The characteristic length that determines the behavior of Nb/Cu superlattices is the coherence length, which in the parallel direction was determined to be $\xi_{\parallel} = (161 \pm 17)$ Å, independent of layer thickness. When the superlattice wavelength is matched to this coherence length (at fixed temperature, $T \sim 1.1$ K) the parallel critical field increases as shown in fig. 4 [7]. This has been explained by a preferential penetration of the vortex lattice into the Cu normal metal. In this situation, the magnetic field has a less destructive effect on the superconductivity of the Nb and therefore the critical field in this region is considerably enhanced.

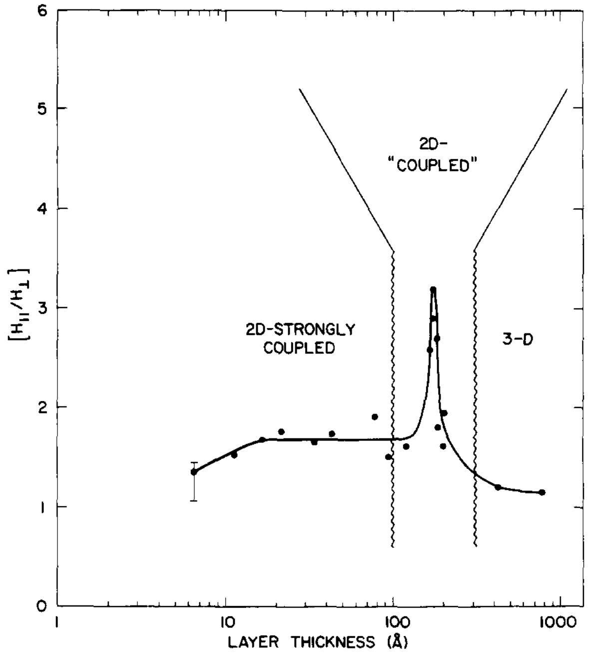

Fig. 4. Critical fields as a function of layer thickness for equal layered Nb/Cu superlattices. Reproduced from Phys. Rev. B28 (1983) 5037, by permission of the American Physical Society.

The temperature dependence quite clearly shows the existence of dimensional effects [8]. A thick Nb film ($\xi_{\perp}(0) < d_{\mathrm{Nb}}$) shows typical three dimensional (3D) behavior, in the parallel critical field (linear temperature dependence) (fig. 5a). A single thin ($\xi_{\perp}(0) > d_{\mathrm{Nb}}$) Nb film shows characteristic two dimensional (2D) behavior (fig. 5b) as a function of temperature. At intermediate normal metal "separation" thicknesses ($\xi_{\perp}(0) \sim d_{\mathrm{Cu}}$) the behavior changes from 3D at high temperature to 2D at low temperature as the coherence length becomes shorter, thereby progressively decoupling the layers (fig. 5c). The perpendicular critical field $H_{\perp}$ is not affected by the layering and therefore it is linear in all regimes. This qualitative picture can readily be understood in terms of the Ginzburg–Landau theory [8]; however detailed microscopic theoretical studies have been lacking and are only now starting to emerge [9].

In the rest of this paper we present preliminary results on the interaction of superconductivity and magnetism in V/Ni superlattices. In order to study these phenomena it is necessary to keep the thickness of Ni low enough so that $T_{\mathrm{M}} < T_{\mathrm{S}}$ and the thickness of V comparable to its coherence length so that the weak magnetism in Ni has a strong effect on the superconductivity. A thick V film ($d_{\mathrm{V}} \sim 1.15$ μm) shows again the typical 3D linear temperature dependence as shown in fig. 6a. A stack of thin V films ($d_{\mathrm{V}} \sim 500$ Å) shows the typical 2D square root-like temperature dependence (fig. 6b). It should be emphasized that in this case a ferromagnetic Ni film of 20 Å is sufficient to decouple the layers in contrast to the large Cu thicknesses ($\gtrsim$400 Å) necessary for this decoupling. If d_{Ni} is decreased further, close to the thickness for which the ferromagnetism is strongly weakened the critical field anisotropy is reversed (i.e., $H_{\perp} > H_{\parallel}$). This behavior is extremely anomalous and has only been observed in $\mathrm{ErRh_4B_4}$ thin films [10], where the local Er moment interacts with the superconductivity. We

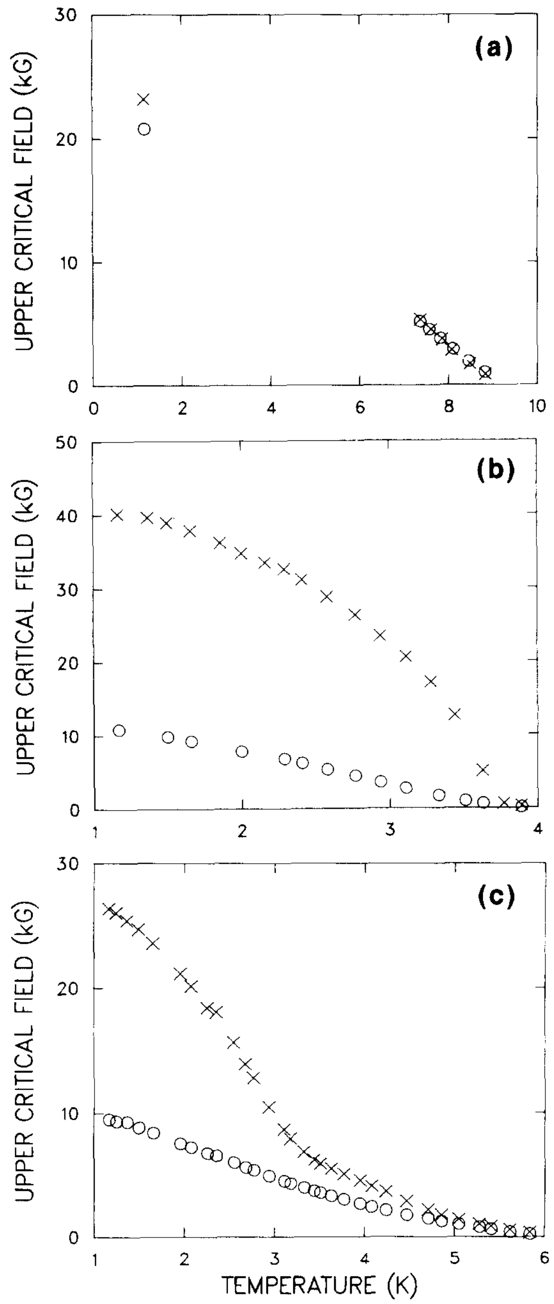

Fig. 5. Temperature dependence of perpendicular (○) and parallel (×) critical fields of (a) 3D niobium film [Cu (1500 Å)/Nb (8500 Å)/Cu (1500 Å)]; (b) 2D niobium film [Cu (1500 Å)/Nb (191 Å)/Cu (1500 Å)] and (c) Nb (172 Å)/Cu (333 Å) superlattice with Cu (1500 Å) as the surface layers. The thick Cu layers on the surface eliminate the nucleation of surface superconductivity.

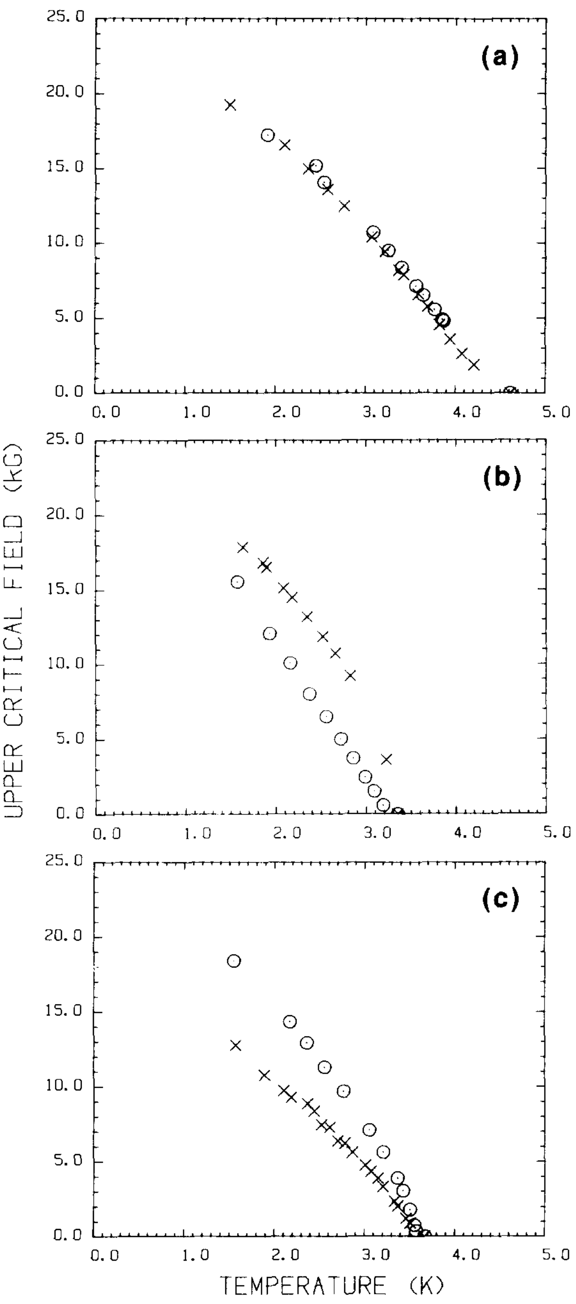

Fig. 6. Temperature dependence of perpendicular (⊙) and parallel (×) critical fields for (a) 3D vanadium film 1.15 μm thick; (b) 2D Ni (192 Å)/V (500 Å) superlattice and (c) Ni (10 Å)/V (750 Å) superlattice showing reversed anisotropy. The outside layers are Ni to eliminate the nucleation of surface superconductivity.

believe that this anomalous behavior is not due to some structural effect since very slight changes in the d_{Ni} have a very strong effect on the superconducting properties. The detailed study of the superconducting properties of these V/Ni superlattices is underway and will be the subject of future publications. We would like to point out however that to our knowledge there has been no published theoretical work which addresses the issues presented here.

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