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ABSTRACT

Upper critical field and its anisotropy have been measured on two very short wavelength Mo-Ni heterostructures of different degrees of perfection, λ = 13.8Å (disordered structure) and λ = 16.6Å (layered structure). In both cases the parallel critical field has an unexpected temperature dependence, a large and temperature dependent anisotropy, and over 60% enhancement over the Clogston-Chandrasekhar limit. Data are fit to the Werthamer-Helfand-Hohenberg theory and the spin-orbit scattering times are found to be 1.79×10^{-13} sec and 2×10^{-13} sec, respectively.

INTRODUCTION

Artificial modulated heterostructures provide a convenient medium for the study of physical phenomena which are otherwise difficult to realize. Among them belong investigations of collective effects in the restricted geometry of thin films and interfaces and the competition between cooperative phenomena of superconductivity and magnetism. A bimetallic heterostructure composed of Mo and Ni is one such example.

We have shown recently [1,2] that Mo-Ni heterostructures with a very short modulation wavelength undergo a dramatic change in their physical properties. Ni strata, which possess bulk ferromagnetic character well above 100Å, loose their permanent magnetic moment when their thickness falls below 10Å and, simultaneously, superconductivity sets in near 2K. At a still shorter modulation wavelength, λ<15Å for structures of equal layer thickness, layering collapses and the structures are more akin to a glassy system. Superconductivity persists in this case but T_c's are suppressed down to near 0.5K. Thus, superconductivity is detected in both layered and collapsed Mo-Ni structures provided the Ni strata are paramagnetic, i.e., nominal λ is sufficiently small. To gain insight into the nature of the superconducting state and to ascertain how the structural order affects it, we have carried out detailed studies of the upper critical field and we report on these measurements in this paper.

EXPERIMENTAL

Mo-Ni heterostructures were prepared by sequential sputtering using a technique described in detail elsewhere [3]. Deposition was made on a 90° sapphire held at room temperature and the total thickness of the structure is about 1 μm. Standard photolithographic techniques were used to etch out a bridge pattern suitable for in-plane resistance measurements. Out of several samples investigated in Ref. 1, for this study we have chosen two equal-layer superconducting structures: one with the modulation wavelength λ=16.6Å in which layering is preserved, and one with λ=13.8Å where X-rays indicate a collapsed (glassy) structure. Cooling was achieved with the aid of a dilution refrigerator provided with a custom-made reduced tail-section to incorporate an 8T

superconducting solenoid. Samples were attached to an oxygen-free high-conductivity copper sample holder with a thin coating of Apiezon M grease and fastened with dental floss. In addition to the 50% resistive transition point we have also monitored 10% and 90% resistance changes to probe the width of the transition. Two separate runs were made, one for the parallel orientation of magnetic field with respect to the film surface, and the other one for the perpendicular configuration. Temperature was monitored by a combination of a calibrated Ge sensor and a Speer carbon resistance thermometer. The latter is known to possess a small and reproducible magnetoresistance while the Ge sensor serves to provide its zero-field calibration curve. Current densities used in the measurements were very small, $J=0.1A\ cm^{-2}$, to avoid any heating of the structures at subkelvin temperatures.

RESULTS AND DISCUSSION

Temperature dependence of the upper critical fields for the two Mo-Ni heterostructures studied is shown in Figs. 1 and 2. While the

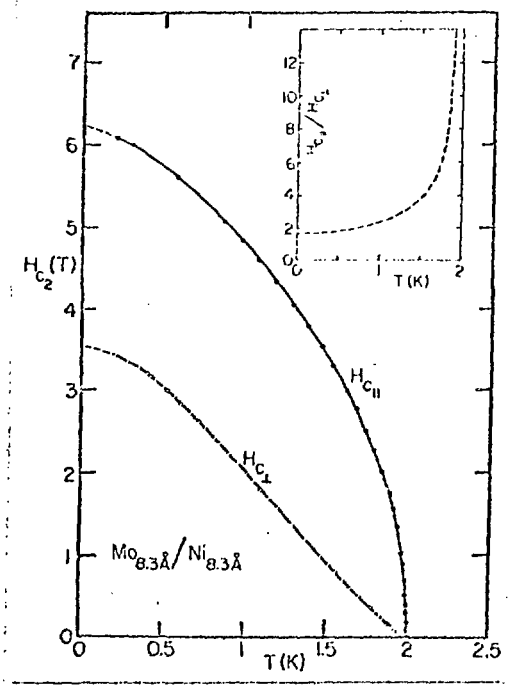

Fig. 1. Temperature dependence of the parallel, $H_{c_\parallel}$, and perpendicular, $H_{c_\perp}$, upper critical fields for Mo-Ni heterostructures with $\lambda=16.6Å$. Inset shows critical field anisotropy. X-ray strucural data indicate (Ref. 1) that layering is preserved in this structure.

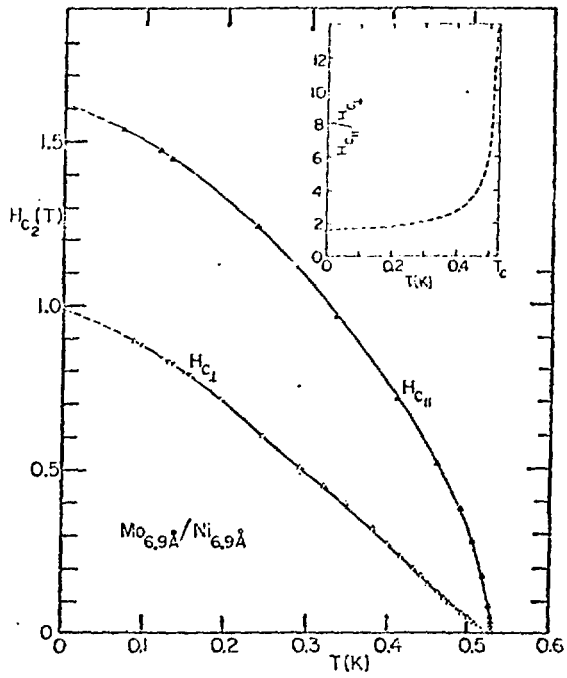

Fig. 2. Temperature dependence of the parallel, $H_{c_\parallel}$, and perpendicular $H_{c_\perp}$, upper critical fields for a structure with $\lambda=13.8Å$. Insert shows critical field anisotropy. X-ray structural data reveal (Ref.1) a typical glassy-like diffraction pattern, signaling a structural collapse.

perpendicular fields are, as expected, substantially linear over most of the temperature range (a tendency to saturate is noticeable at the lowest temperatures) this cannot be said about the parallel critical fields. In fact, pronounced and rather similar nonlinear profiles of $H_{c_\parallel}$ on both heterostructures are very surprising and unexpected. A plot of $H_{c_\parallel}$ vs. $(T_c-T)^{1/2}$, Fig. 3, shows that the temperature dependence is square root over a wide temperature range. This variation is similar

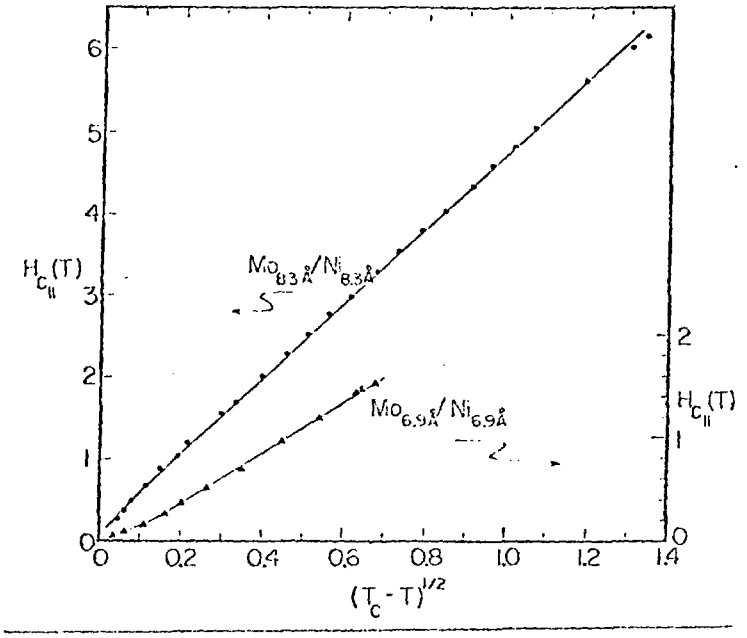

Fig. 3 Parallel upper critical fields plotted versus $(T_c-T)^{1/2}$.

to the characteristic 2-d-behavior observed earlier in Nb-Cu [5] and Nb-Ge [6] superlattices. Note that a 3-d superconductor should exhibit a linear temperature dependence [7]. The factor that determines the dimensional behavior of a metallic superlattice is the ratio of the perpendicular coherence length ($\xi_\perp$) to the nonsuperconducting spacer (Ni in this case). In order to check whether a 2-d behavior was possible in our present superlattices we have calculated the coherence lengths using the experimentally measured critical fields in conjunction with the anisotropic Ginsburg-Landau theory (Table I). It is clear that in all

Table I. Some Relevant Parameters for the Two Mo-Ni Structures

Parameter	λ = 13.8Å	λ = 16.6Å
$H_{c_\perp}(0)$	0.98 T	3.5 T
$H_{c_\parallel}$	1.62 T	6.2 T
$\xi_\parallel(0)$	200Å	110Å
$\xi_\perp(0)$	130Å	60Å
$\tau_{s.o.}$	1.79×10^{-13} sec	2×10^{-13} sec

cases $\xi_\perp >> d_{Ni}$ and therefore the $(T_c-T)^{1/2}$ behavior cannot possibly be due to dimensional effect.

We would like to draw attention to another interesting feature of the data. Plotting anisotropy ratio, $H_{c_\parallel}/H_{c_\perp}$, see insets in Figs. 1 and 2, we note that as T approaches zero this ratio converges to 1.7±0.1, a number which is very close to the critical field associated with surface superconductivity [8], $H_{c_3}=1.69H_{c_2}$. The closeness of the two ratios might suggest that we are observing this surface contribution; however this agreement holds only in the limit of low temperatures. According to the theory of homogeneous superconductors [8], the ratio should be constant for all temperatures below T_c, i.e., H_{c_3} is supposed to be a linear function of T_c-T. Thus, either the agreement between the two numbers is fortuitous or one would have to consider modifications of the de Gennes-Saint-James theory to obtain other than linear variations of H_{c_3}.

Let us now examine the magnitude of the parallel critical fields. In the absence of the pair-breaking mechanisms associated with the effect of the field on the orbital motion of the electrons, the upper bound on the strength of the critical field is ultimately given by the Pauli paramagnetic limit, possibly modified by the presence of strong spin-orbit scattering. This paramagnetic limiting field is, according to Clogston [9] and Chandrasekhar [10], given by a simple formula

$$H_p = \frac{\Delta(0)}{\sqrt{2}\,\mu_B} = 1.85\ T_c\ (\text{Tesla}) \qquad (1)$$

where $\Delta(0)$ is the BCS superconducting gap and μ_B the Bohr magneton. Normalizing the data to Hp we note that both Mo-Ni structures show at least a 60% enhancement over the Clogston-Chandrasekhar limit. This rough estimate already suggests that spin-orbit scattering is an important process and should be considered in these materials. Recently there has been much progress in theoretical understanding of the upper critical field [11,12] including the effects of a strong spin-orbit scattering [13], dimensional considerations associated with layered structures [14,15], and the effect due to carrier localization [16]; various fitting procedures exist to extract the relevant physical parameters. We are particularly interested in the spin-orbit scattering time, $\tau_{s.o.}$, and we fit the Werthamer-Helfand-Hohenberg (WHH) model [13] to the data using a computational scheme developed by Fulde [17] and further refined at MIT [18] . We have chosen this procedure rather than a model applicable specifically for the layered structures basically because of the nature of our Mo-Ni samples; one having a collapsed structure and the other one indicating such a short modulation wavelength that it is inconceivable to assume its coherence length could be shorter than this modulation period.

In Figs. 4 and 5 we show the resulting fits together with the corresponding fitted parameters. The data for the λ = 16.6Å structure can be fitted quite well and the fit for the λ = 13.8Å is a reasonable one. The spin-orbit scattering times obtained are $\tau_{s.o.} = 2\times10^{-13}$ sec and 1.79×10^{-13} sec, respectively. These values are two orders of magnitude larger than the transport time ($\tau_{tr} \sim 10^{-15}$ sec) established from the resistivity data using the free electron approximation. Again we observe a very little difference in the behavior of the two structurally dissimilar Mo-Ni samples.

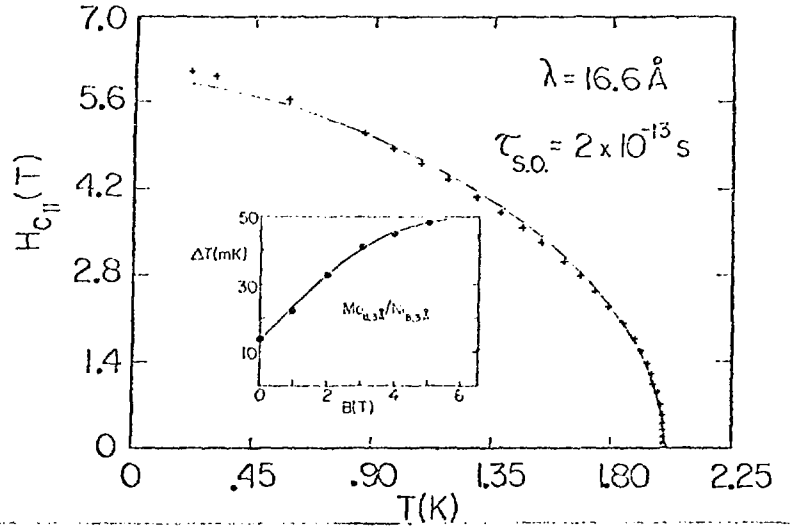

Fig. 4. A fit of the WHH theory to the data of λ=16.6Å structure. Inset shows the width of the transition.

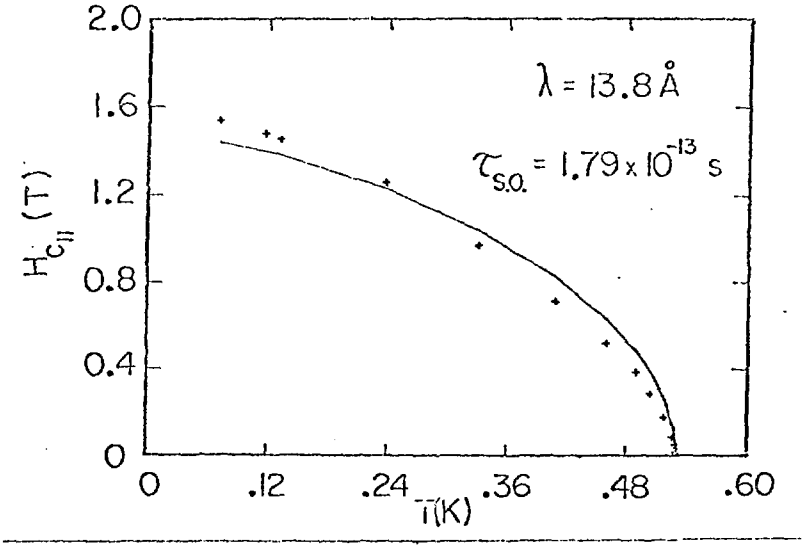

Fig. 5 A fit of the WHH theory to the data of λ=13.8Å structure.

CONCLUSION

We have measured both perpendicular and parallel upper critical field on two short wavelength Mo-Ni heterostructures, one in which layering is preserved and the other one which shows a collapsed structure. In both cases we observe a surprising square-root temperature variation on the parallel critical field data, a large and temperature-dependent anisotropy of the critical field, and a significant enhancement over the Pauli paramagnetic limiting field. Fitting the data to the WHH theory yields spin-orbit scattering times in the low 10^{-13} sec range. While the superconducting transition temperatures appear strongly affected by the degree of perfection of the heterostructure, the shape of the critical fields and the spin-orbit times are quite comparable for the two structures. We are puzzled by the unexpected square-root temperature dependence of the upper critical field, perhaps the strong paramagnetic Ni centers play a role here.

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