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Depth-Dependent Magnetism of Layered Superconductors: Nb/Si

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ABSTRACT

We have studied magnetic field penetration and vortex line formation in a $[\text{Nb}(100 \text{ \AA})/\text{Si}(15 \text{ \AA})] \times 20$ multilayer by magnetization and polarized neutron reflection. With the magnetic field applied parallel to the surface, the magnetization revealed the presence of a kink above H_{c1} indicative of transitions between one row of fluxoids and two rows of fluxoids parallel to the surface. The spin-dependence of neutron reflectivity below H_{c1} was consistent with a penetration depth of $1200 \text{ \AA}$, substantially larger than that of bulk Nb. In the mixed phase ($H_{\text{ext}} > H_{c1}$) the field was found to penetrate the surface, with a slope as found in the case of $H_{\text{ext}} < H_{c1}$. At $H_{\text{ext}} > H_{c1}$ vortex forms in addition to surface penetration. A modulation of the vortex fields was found with the periodicity of the Nb/Si bilayers as evidenced by the spin dependence of the reflectivity at the first Bragg peak of the multilayer.

Artificial superlattices composed of alternating superconducting/metallic layers have been found in recent years to exhibit novel magnetic properties. These layered superconductors have a coherence length shorter than the overall film thickness. When a magnetic field H_{ext} is applied parallel to such layered structures a series of maxima occurs in the magnetization measurements at specific field strengths H_N ($H_{C1} < H_N < H_{C2}$).^{1,2} These maxima in M_z have been explained in terms of transitions between specific multichain configurations of in plane vortices.² Above H_{c1} a first row of vortices is said to be formed close to the center of the film. An increase of the the field causes a compression of this one-dimensional lattice until it becomes unstable, to be replaced by two rows of fluxoids with wider spacings. This process might be repeated for any transition from n rows of fluxoids to $n+1$. This description is fundamentally different from that given by Bean for the distribution of magnetization in a layer of type II superconductor, where the fluxoids are trapped by impurity centers.

Scope of the present work is to attempt to observe the vortex configuration by polarized neutron reflection, in a system - Nb/Si multilayers - whose magnetic properties closely resembled those of the aforementioned Nb/Cu multilayers.^{1,2}

The $[\text{Nb}(100\text{\AA})/\text{Si}(15\text{\AA})]_{\times 20}$ multilayer was grown by reactive d.c. magnetron sputtering on silicon (15 Å) and protected by a silicon cap (30 Å). The films were deposited onto 1" silicon wafers. From these a small piece was cut for magnetization measurements, while the remaining surface was used for neutron reflectivity. The good layering of the material was confirmed by x-ray reflectivity measurements. Magnetization measurements as a function of temperature (at a very low fixed applied field) indicated that the $[\text{Nb}(100)/\text{Si}(15)]_{20}$ system becomes superconducting below 7.5K (T_c). Previous transport studies have found that for 15 Å Si layers, Nb/Si behave as a coupled 3-D superconductor.³

Longitudinal magnetization (M_z) measurements were carried out using a SQUID magnetometer. The field was applied parallel to the layer planes in the zero field cooled (ZFC) condition. Figure 1 shows the magnetization M_z as a function of applied field at temperatures of 5, 3 and 2K for the $[\text{Nb}(100)/\text{Si}(15)]_{\times 20}$ multilayer. Two distinct features are present in Fig. 1. At low applied magnetic field a flux repulsion with a constant M_z/H_{ext} value (Meissner effect) is evident. At higher fields the flux expulsion is not complete. At 2K, the first maximum occurs at ~ 500 Oe; a second maximum at ~ 900 Oe. In analogy with the interpretation of the Nb/Cu data we inferred that, at the lowest temperature, 300 Oe was below H_{c1} ; at 700 Oe one row of fluxoids was close to the film's center; at 1200 Oe the film contained two rows of fluxoids.

Polarized neutron reflectivity study gives information on the laterally averaged depth profile (both chemical and magnetic) as a function of the neutron momentum $Q = 2\pi\sin\theta/\lambda$, where λ is the neutron's wavelength and θ its angle of incidence with the surface.⁴ At large Q (large compared to the critical value at which the reflectivity is complete) the reflectance is the Fourier transform of the depth profile.

The instrument ("POSY I") used to record the polarized neutron reflection data is located at the Argonne Pulsed Neutron Source as described in ref. 5. The sample temperature, in the experiments described here, was kept at 1.6 K. An electromagnet provides a vertical (perpendicular to the scattering plane) magnetic field up to 5 kOe parallel to the sample's surface. All measurements were taken in the ZFC condition.

Figure 2 depicts the R_+ and R_- as a function of Q measured at 1.6K with $H_{\text{ext}} = 700$ Oe. Here R_+ and R_- represent, respectively, the reflectivities of neutrons with incident neutron spins parallel (+) and antiparallel (-) to the applied magnetic field on the sample. For small Q values a total reflection is observed up to the critical Q value. Beyond the critical Q value the reflectivities undergo several rapid oscillations which are due to the interference of reflections from the front and back surfaces of the multilayer. For yet larger Q -values the presence of a Bragg peak is seen due to an existence of periodicity of Nb/Si

layer structure with a period of 108 Å. The prominent feature of the reflectivities at and around the Bragg peak is the clear modulation of the spin asymmetry, $P = (R_+ - R_-)/(R_+ + R_-)$. This function is much more sensitive than the individual reflectivities to the magnetic depth profile. The spin asymmetry gives the most immediate signature of the magnetic character of the sample, being identically zero if the sample was nonmagnetic. The fact that non-zero P appears at the Bragg reflection indicates that the magnetic response is modulated with the Nb/Si period. No such spin-dependence was seen at the Bragg peak in 300 Oe applied field.

Open circles with error bars in Fig. 3 represent the spin asymmetry of reflected neutron beam as a function of neutron wave vector transfer Q measured at 1.6 K with $H_{\text{ext}} = 300$ Oe. The region of Q spanned here is that close to total reflection: this is the region most sensitive to the penetration depth of the external magnetic field in the superconductor.³ To calculate the reflectivities R_+ and R_- and hence P , a model profile for the chemical structure with the following parameters was used. The thicknesses of the Si and Nb layers are 15 Å and 93 Å, respectively. The scattering amplitude densities are $2.07 \times 10^{-6} \text{ Å}^{-2}$ and $3.96 \times 10^{-6} \text{ Å}^{-2}$, corresponding to the bulk values for Si and Nb, respectively. The solid line shows the polarization calculated assuming that the field penetration from both the surfaces of the multilayer has the exponential form $[B(x) = H_{\text{ext}} \exp(-x/\delta)]$, where x is the distance(depth) from the surface and δ is the penetration depth. The best-fitted penetration depth δ was found to be 1200 Å (with $\chi^2 = 1$); for comparison, the spin asymmetries for penetration depth of 800 and 1600 Å are also presented. It is to be mentioned that over this Q -region a similar oscillation of P was observed with 700 Oe field (not shown).

To recap the findings, for $H_{\text{ext}} < H_{\text{cl}}$ (=500 Oe) the Meissner effect has been observed with a characteristic penetration depth of 1200 Å at 1.6K. The value of the surface penetration depth is significantly larger than that of bulk Nb (4.2K) = 400 Å.⁶

When H_{ext} is increased to 700 Oe ($> H_{c1}$) we have observed a modulation of the magnetic field at the interior of the film in addition to the effect of surface penetration. The vortex field which causes the interior field has the periodicity of the Nb/Si layers. This does not necessarily rule out the longer wavelength modulations predicted for these multilayers. Those, if present, would give rise to further modulations of the spin asymmetry for which longer, more accurate measurements are required. What is remarkable is the detection of sizeable magnetic fluctuations over spacings as low as ~ 100 Å. If, in a very naive picture the fluxoids are considered to be centered at the silicon layers, and their size is given in all direction by the penetration depth (1200 Å - found for this material), the magnetic field should be practically uniform throughout the film.

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REFERENCES

- * Present address: IBM Almaden Research Center, San Jose, CA 95120-6099
- ¹ J. Guimpel, L. Civale, F. de la Cruz, J.M. Murduck, and I. K. Schuller, Phys. Rev. **B38**, 2342 (1988).
- ² S.H. Brongersma, E. Verweij, N.J. Koeman, D.G. de Groot, R. Griessen, and B.I. Ivlev, Phys. Rev. Lett. **71**, 2319 (1993).
- ³ J.D. Hettinger, B.R. Washburn, N.B. Remmes, D.G. Steel, K.E. Gray, E.E. Fullerton, and C.H. Sowers, Phys. Rev. Lett. **77**, 5280 (1996).
- ⁴ G.P. Felcher, Physica **B 192**, 137 (1993).
- ⁵ G.P. Felcher, R.O. Hilleke, R.K. Crawford, J. Haumann, R. Kleb, and G. Ostrowski, Rev. Sci. Instrum. **58**, 609 (1987).
- ⁶ J. Schelten, H. Ullmaier and W. Schmatz, Phys. Stat. Sol. (b) **48**, 619 (1971).

FIGURE CAPTIONS

FIG. 1. Magnetization(M_z) as a function of magnetic field H_{ext} applied parallel to the surface of the multilayer at 2, 3 and 5K. The first kink is shown by a vertical arrow.

FIG. 2. Spin dependent reflectivities at 1.6K and 700 Oe ZFC field. Solid dots indicate data for neutron spin parallel to the applied field(+); open circles for spins antiparallel to the field(-). In the insert: spin asymmetry $(R_+ - R_-)/(R_+ + R_-)$ in the region of the Bragg reflection.

FIG. 3. The spin asymmetry $P = (R_+ - R_-)/(R_+ + R_-)$ as a function of neutron momentum transfer Q at 1.6K and with 300 Oe ZFC field. The open circles shows the measured values with their error bars. The spin asymmetry calculated from the model profile discussed in the text and a penetration depth of 1200 Å is shown by a solid curve. For comparison, the spin asymmetries are calculated for 800 Å (dashed line) and 1600 Å (dotted line) penetration depths.

FIG. 1

FIG. 2

Spin Asymmetry

FIG. 3
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