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Multiple maxima in the field dependent magnetisation of superconducting Nb/Cu multilayers

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Abstract

Measurements of the magnetic moment of superconducting niobium/copper multilayers show a well defined series of maxima at specific field strengths. They are observed when the angle between the applied magnetic field and the superconducting layers is small (less than 10^{o}). Only the total thickness and the anisotropy are of influence on the fields at which they occur . The results can be explained by consecutive entering of chains of vortices into the sample.

1. Introduction

Superconducting metallic multilayers can be used as a model system for high-T_c compounds in the search for a complete description of the phenomena involved. Over the last few years it has been predicted [1..4] that a lock-in of vortices can occur in high-T_c superconductors when the perpendicular coherence length ξ_c is comparable to the interlayer distance d, and the applied magnetic field H_a is almost parallel to the CuO_2-planes. The vortices will consist of long in-plane parts separated by relatively short kinks. In this case a matching of the vortex lattice, formed by the parallel parts of the vortices, with the modulation of the multilayer can occur. This results in an increase of the pinning and thus of the critical current. So far these predictions could not be confirmed experimentally in high-T_c superconductors.

2. Experiment

The multilayers, used in the torque experiments, are grown in an ultra-high vacuum system (FISONS, V.G.) (Fig. 1). In the bottom part of the chamber two electron beam evaporation cells produce copper and niobium particle beams with thermal velocities. The actual growth takes place in the upper part of the chamber where substrates can be entered through a fast entry lock. They are positioned on an XYZΘΦ-manipulator that supports growth of thin films at elevated temperatures and the use of masks. The two parts of the chamber are separated by H_2O and LN_2-shields that, combined with differential pumping

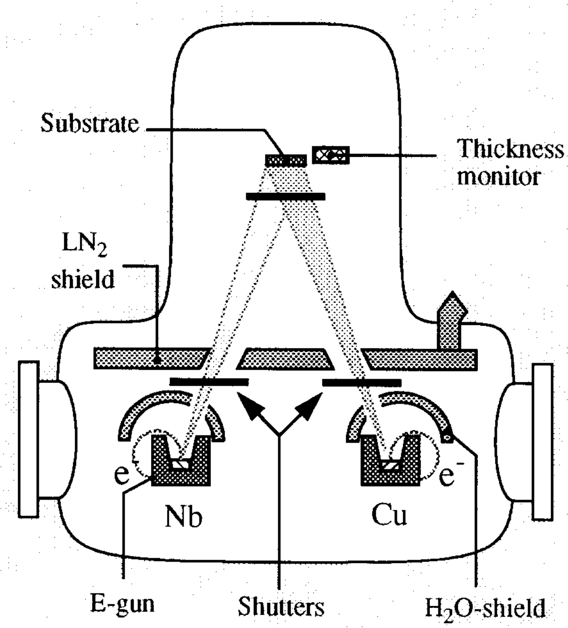

Figure 1. Schematic drawing of the deposition chamber used for growing niobium/copper multilayers. Shutters in front of both substrate and E-gun evaporation cells are used for alternating growth of Nb and Cu.

techniques, guarantee a base-pressure of 10^{-8} Pa at the substrate surface. This is achieved by using two ion pumps (60 and 400 l/s, MECA 2000), one turbomolecular pump (TPU 520, Balzers), and two titanium sublimation pumps

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(FISONS, V.G.). Shutters have been installed in front of both sources and substrate which enable the alternate growth of niobium and copper layers. The QCTM (Intellemetrics, IL 400), calibrated with Rutherford Backscattering Spectroscopy (RBS) measurements, is used in a feedback system to control the deposition rates and the shutters, and in that way the thicknesses of the individual layers as well as their number.

2.1 Sample properties

The films are grown on sapphire substrates (Al_2O_3 $11\bar{2}0$) at ambient temperatures with a typical growth rate of 0.15 nm/s. The sample used in the experiments described below consists of eleven Cu layers separated by 10 Nb layers. All layers have thicknesses of 10 nm yielding a total thickness of 210 nm. A surface area of (10x0.75) mm^2 is obtained by using a mask during the growing process. The critical temperature is T_c=5.9K which is in agreement with data of Banerjee and Schuller [5] for Nb/Cu multilayers. Surface superconductivity is suppressed by the outer Cu layers.

2.2 Sample analysis

The samples can be transferred, under ultra-high vacuum conditions, to an analysis chamber (VSW). Here techniques such as depth profiling with Auger Electron Spectroscopy (AES), Scanning Electron Microscopy (SEM), and Scanning Auger Microscopy (SAM) can be used to determine the quality of the film. The periodic structure of the films is checked with AES depth profiling, RBS, and θ–2θ X-ray Diffraction (XRD). The AES depth profile of Fig. 2 is measured without sample rotation while sputtering at a rate of 0.4 nm/min with 0.75kV Ar^+ atoms from a VSW AS20 argon source. The intensities of the Cu LMM (920 eV) and the Nb MNN (167 eV) peaks are plotted as a function of the sputtertime. The Auger electrons are induced by bombardment with 5 kV electrons from a VSW EG10 electron gun. It can be clearly seen that the sample consists of ten niobium and eleven Cu layers which all have thicknesses of 10 nm.

Contrary to AES depth profiling, samples are always exposed to atmospheric pressure for XRD and RBS measurements. XRD is done in our Rigaku 12 kW rotating copper anode diffractometer. With this technique low angle diffraction on the interfaces, as well as both first and second order Bragg peaks have been observed [6]. Both XRD and RBS have confirmed the periodic structure of the multilayer.

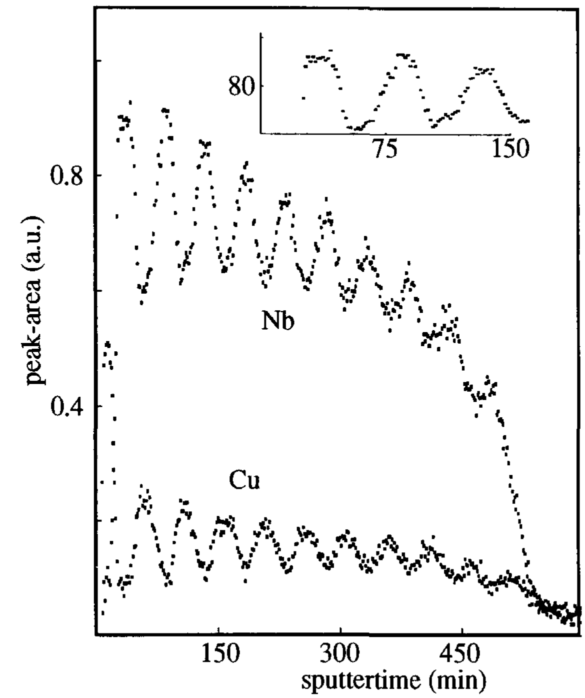

Figure 2. Peak areas of the copper and niobium AES-peaks while sputtering the multilayer. The maxima correspond to the internal layers. The inset is an enlargement of the first three peaks of the niobium signal. It demonstrates the plateaus in the curve.

2.3 Torque measurements

The torque

$$\tau = \mu_0 \mathbf{M} \times \mathbf{H}_a \qquad (1)$$

exerted on a sample with a magnetic moment M by the externally applied magnetic field H_a, is measured by means of a torque magnetometer. This apparatus consists of two parts that are connected by cross-springs [6]. The first is fixed while the second, to which the sample and a calibration coil are connected, can rotate over small angles (less than 0.01°). The rotation is measured as a change in capacitance, be tween two copper plates (one on each part), which is linearly dependent on the torque. Experiments are performed in a helium bath cryostat that is positioned in between the poles of a rotatable 1.5 Tesla electromagnet. Fieldsweeps at a rate of 0.2 Tesla/s can be made at temperatures down to 1.2 K. The torquemeter used in these experiments has a noise-level of 10^{-9} Nm.

3. Results & Discussion

When applying a current along the length of the sample and measuring the resistance while sweeping up the magnetic field, a clear transition to the normal state is observed at H_{c2}. This has been done for fields parallel as well as perpendicular to the layers over the temperature range of 1.8 K to 6.0 K (Fig. 3). The anisotropy γ is defined as the

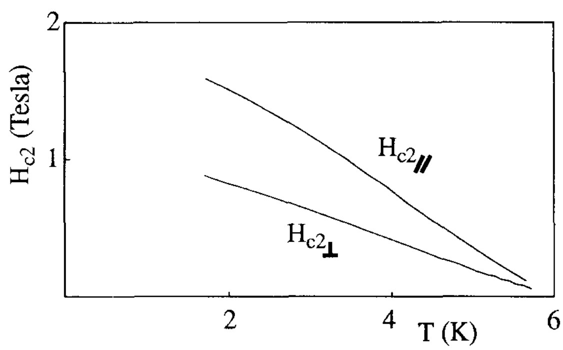

Figure 3. The critical magnetic field H_{c2} is plotted as a function of temperature for two configurations. One with the field parallel and the other with the field perpendicular to the layers. In both cases a current is applied along to the length of the sample.

ratio of the two critical fields $H_{c2//}/H_{c2\perp}$ which gives γ=1.85 +/- 0.05. This ratio is equal to ξ_{ab}/ξ_c, and with ξ_{ab}=16.1 +/- 1.7 nm [7] the coherence length perpendicular to the layers can be calculated to be ξ_c=8.7 nm.

The dependence of torque on applied field is measured in the configuration where the magnetic field is almost parallel to the length of the sample ($\theta=1^\circ$). This is done at a temperature of 1.8 K and a sweeprate of 0.01 T/s. The magnetic moment is obtained by deviding torque by field (Fig. 4). It starts at a non-zero value due to the magnetic flux that is initially present in the sample. Then three peaks are observed at 0.09 T, 0.20 T, and 0.36 T. The magnetic moment reduces to zero at 0.9 T, which is close to $H_{c2\perp}$. The position of these peaks has been studied as a function

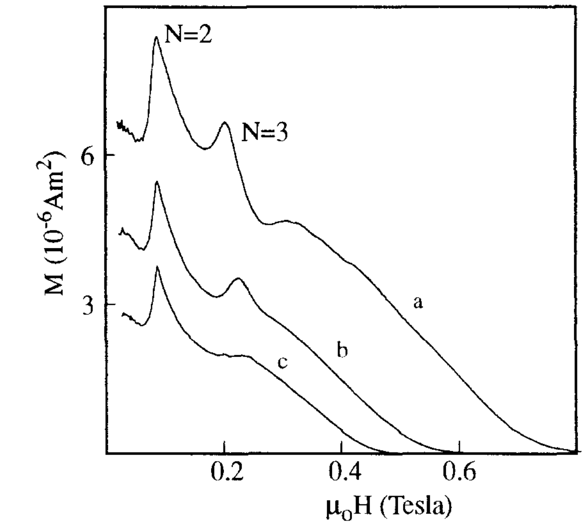

Figure 4. The magnetic moment M has a peaked dependence on the magnetic field H_a that is applied almost parallel to the layers ($\theta=1^\circ$). The three curves are measured at different temperatures. a: 2.1 K, b: 3.3 K, c: 3.8 K.

of both angle and temperature. In both cases no shift of the peaks has been found.

This result can be explained by the ideas presented in reference [8]. At small angles θ the vortices, with a coherence length close to the internal layer thickness, will consist mainly of long parts parallel to these layers which act as intrinsic pinning centers. These parallel parts may be separated by short kinks making an angle $\theta_k=7^\circ$ with the layers [2].

The thermodynamic potential per unit vortex length is given by [9]

$$F = \frac{1}{8\pi}\int (h^2 + \lambda_c^2 (\frac{\partial h}{\partial x})^2 + \lambda_{ab} (\frac{\partial h}{\partial z})^2 - 2hH_a)\, dxdz \qquad (1)$$

where λ_c and λ_{ab} are the penetration depths perpendicular and parallel to the layers and $\gamma \equiv \lambda_c/\lambda_{ab}$, the field is applied along the y direction, and h(x,z) is the microscopic field consisting of both the Meissner field and the field due to vortices. From this, first of all, the critical field H_{c1}, above which the field starts penetrating the sample, can be calculated by setting the energy of a vortex at the midplane equal to that of one at the surface. Above H_{c1} the parallel parts of the vortices will be situated in the film as a single chain in the middle of the sample as a result of the Bean-Livingstone barrier. When the applied field increases the vortex density in this chain will increase until the vortex interaction becomes too large and initiates a splitting of the chain, thus creating two chains that are only half as dense. This results in a quick increase of the total number of vortices in the film accompanied by a drop of the magnetisation. The distance between the chains will adjusts itself to the thickness of the multilayer. This process will repeat itself whenever the density in the chains present in the sample becomes too large, resulting in a step by step increase of the number of vortex chains N in the film. The peaks should occur at

$$\mu_o H_N = \frac{\sqrt{3}}{2} \cdot \frac{\phi_o}{\gamma} \cdot \left(\frac{N}{D}\right)^2 \qquad (2)$$

where N=2,3,... . With $\gamma = 1.85$ and D = 210 nm this gives $\mu_o H_N = 2.2 \cdot 10^{-2} \cdot N^2$ which is in perfect agreement with the maxima observed. It also follows that the positions of the maxima do not depend on temperature, which is indeed observed experimentally (Fig. 4).

4. Conclusions

In conclusion we can state that high quality multilayers can be grown in our present set-up. They are suitable for a detailed analysis of the penetration of vortices in layered compounds. A description in terms of consecutive entering of vortex chains yields good agreement with the experimental data.

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