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Determination of the magnetic field penetration depth in $YBa_2Cu_3O_7$ superconducting films by polarized neutron reflectometry

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Abstract

Polarized neutron reflectometry was used for the direct measurement of the magnetic-field penetration depth in a high-temperature (HT_c) superconducting film. Two scattering geometries were used. The deduced neutron scattering length density profile gave an exact picture of the composition of the film. The fit to the spin-asymmetry yielded a magnetic-penetration depth of 1400 ± 100 Å at a temperature of $T = 4.8$ K along the c-axis oriented perpendicular to the film surface. The model included an intrinsic exponential decay of the penetration depth. For the first time the spin-asymmetry was determined with high resolution over an extended Q-range for a HT_c-film. Nb-films were investigated as reference.

Keywords: High-T_c superconducting films; Nb films; Magnetic penetration depth; Polarized neutron reflection

1. Introduction

One of the fundamental parameters of superconductors is the London penetration depth λ_L [1]. Polarized neutron reflectometry (PNR) offers the unique possibility to measure the absolute value of the penetration depth and the shape of the magnetic flux profile. Several studies of Nb-films have already been performed with this technique and values of $\lambda_L = 410$ Å [2] and 900–1450 Å [3] for different thicknesses of the film have been obtained. The high difference in the values can be explained by the fact that it was not the magnetic penetration depth that was measured but the screening length $l > \lambda_L$. The screening length takes into account electron scattering at the defects in the sample [4]. This effect is discussed in Ref. [5], in which the measured value for l was corrected for electron scattering and $\lambda_L = 430$ Å was obtained, which is

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the best result today for Nb-films. Also the HT_c-films ($YBa_2Cu_3O_7$) measured up to now [5–8] have defects as discussed in Ref. [9]. Here the defects or roughnesses do not perturb the penetration depth itself because the correlation length is small in the HT_c-films, but perturb the reflectivity curves so that e.g. the oscillations of the reflectivity curves are not visible [5].

In order to test the possibilities of PNR and to optimize the experimental conditions for HT_c-film studies we performed firstly model-calculations and experiments on Nb-films. In particular care was taken to get HT_c samples showing low or no off-specular scattering as a sign of good quality.

2. Model calculation and Nb/Si experiment

If the external field, which is oriented parallel to the film surface, is lower than the critical field $\boldsymbol{H}_{c1}$, then the flux penetrates from both sides of the film with decaying magnitude. Assuming an exponential law for the intrinsic profile the following formula is obtained for the film [10]:

$$\boldsymbol{B}(x) = \boldsymbol{H} \cosh\left(\frac{2x-d}{2\lambda}\right) \Big/ \cosh\left(\frac{d}{2\lambda}\right), \qquad (1)$$

where $\boldsymbol{H}$ is the external field, λ the penetration depth, d the thickness of the film and x the distance from the middle of the film. The neutron scattering length density (NSLD) profile $Nb(x)$, given by

$$Nb(x) = Nb_n \pm cH \cosh\left(\frac{2x-d}{2\lambda}\right) \Big/ \cosh\left(\frac{d}{2\lambda}\right), \qquad (2)$$

consists of two parts, the nuclear part Nb_n (N is the number density and b_n the neutron scattering length of atom n) and the magnetic part from Eq. (1) with $c = 2.31 \times 10^{-8}\ \mathrm{nm}^{-2}/\mathrm{Oe}$. Consequently, two reflectivity curves R^+ and R^- will be obtained with the neutron magnetic moment parallel and anti-parallel with respect to the external field.

In Fig. 1a the reflectivity curves are shown for a HT_c(YBaCuO)-film calculated for the two cases of the scattering geometry: reflection from the air–film interface (1) and substrate–film interface (2). For the reflection from the air–film interface (1)

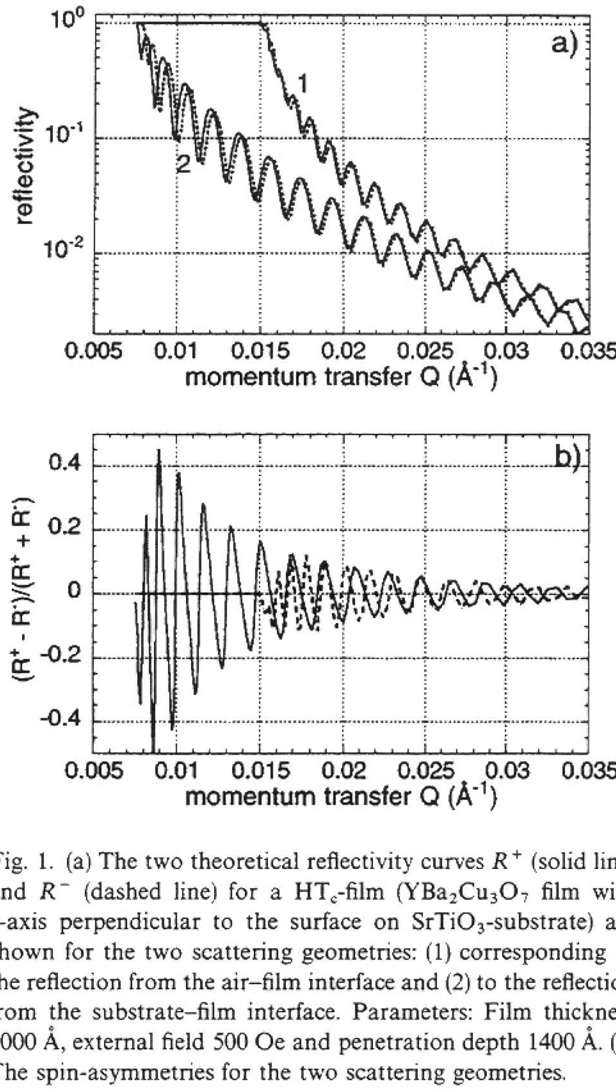

Fig. 1. (a) The two theoretical reflectivity curves R^+ (solid line) and R^- (dashed line) for a HT_c-film ($YBa_2Cu_3O_7$ film with c-axis perpendicular to the surface on $SrTiO_3$-substrate) are shown for the two scattering geometries: (1) corresponding to the reflection from the air–film interface and (2) to the reflection from the substrate–film interface. Parameters: Film thickness 3000 Å, external field 500 Oe and penetration depth 1400 Å. (b) The spin-asymmetries for the two scattering geometries.

the critical Q is given by the NSLD-difference between YBaCuO and air. This difference is larger than the NSLD-difference between YBaCuO and the $SrTiO_3$ substrate. Thus, the Q_c for the reflection from the substrate–film interface (2) is lower compared to Eq. (1). In order to get an image of such an NSLD profile look in anticipation to the inset in Fig. 3. Secondly the scattering through the substrate (2) shows much higher oscillations because of the high NSLD-difference at the second interface (the film–air interface) compared to the case of the scattering from the air side (1), where the second interface is the film–substrate interface.

The magnetic effect shows up in the difference between R^+ and R^- which is demonstrated in the plot of the spin-asymmetry $SA = (R^+ - R^-)/(R^+ + R^-)$ in Fig. 1b. The advantage of the scattering through the substrate is obvious. However the disadvantage is that an intensity factor of 5 is lost when the neutrons traverse the $SrTiO_3$-substrate.

The experiments for the Nb- and HT_c-films have been performed on the spectrometers SPN/Dubna [11] and D17/ILL [12].

The results of the measurement of the Nb-film on an Si-substrate at room temperature are depicted in Fig. 2. As predicted in Fig. 1, the Q_c shifts to a lower value if the scattering is done from the substrate side (marked 1 in Fig. 2a). Also the oscillations are higher compared to the scattering from the air side. The result of the fit is plotted in the inset of Fig. 2a. The NSLD profile shows a 50 Å thick NbO-layer at the surface and a 100 Å thick interdiffusion region at the substrate interface. The total film-thickness is 3310 Å. This thickness was chosen in view of the HT_c-films for which such a high thickness will be necessary due to the expected high penetration depth. Also the surface area of the Nb-film was about 2 cm^2 comparable to HT_c-film surfaces for which one can expect homogeneous surface properties.

The reflectivities R^+ and R^- of the Nb-sample at a temperature of 5.8 K were obtained with an applied external field of 556 Oe. The result is shown in Fig. 2b in the form of the SA. In the fit to the data presented in Fig. 2b only the magnetic penetration depth was the variable. The NSLD profile in Fig. 2c represents the complete result including the surface NbO layer, the interdiffusion layer and the magnetic effect due to the penetrating field. Eq. (1) was used as a flux profile. The screening length was determined to 650 Å in agreement with 550 Å from Ref. [5]. It was not the purpose of this study to perform further resistivity measurements to deduce λ_L for the Nb film.

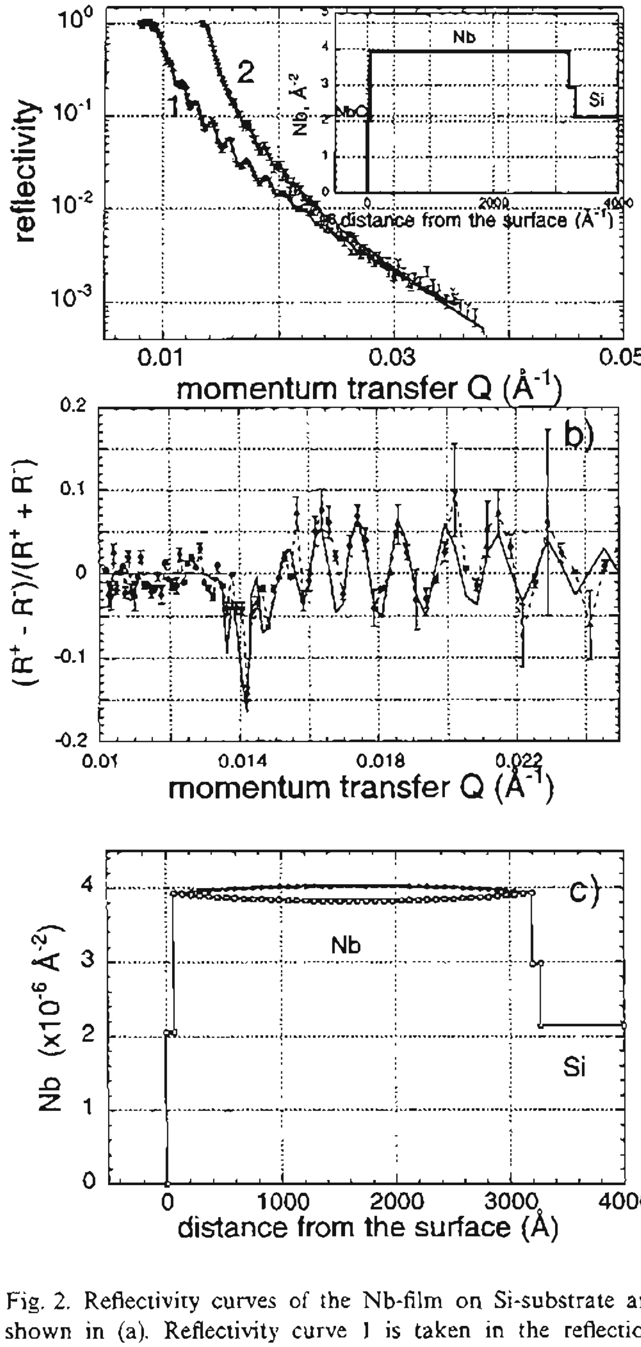

Fig. 2. Reflectivity curves of the Nb-film on Si-substrate are shown in (a). Reflectivity curve 1 is taken in the reflection geometry from the substrate–film interface and 2 from the air–film interface, respectively. In the inset the NSLD-profile is shown. (b) The spin asymmetry is shown for the reflection at the substrate-film interface marked 1 in Fig. 1a. (c) The NSLD-profile including the splitting of the Nb-potential due to the penetrating field.

3. $HT_c/SrTiO_3$ experiment

The HT_c films of $YBa_2Cu_3O_7$ were epitaxially grown on $SrTiO_3$ with a CeO_2 seed-layer. The c-axis was perpendicular to the film surface. The quality of the samples was tested by various methods (AFM, X-ray and electron diffraction). The neutron experiments were performed in two steps, first with the reflection from the substrate side and then with the reflection from the air side after half a year. In Fig. 3, the two measured

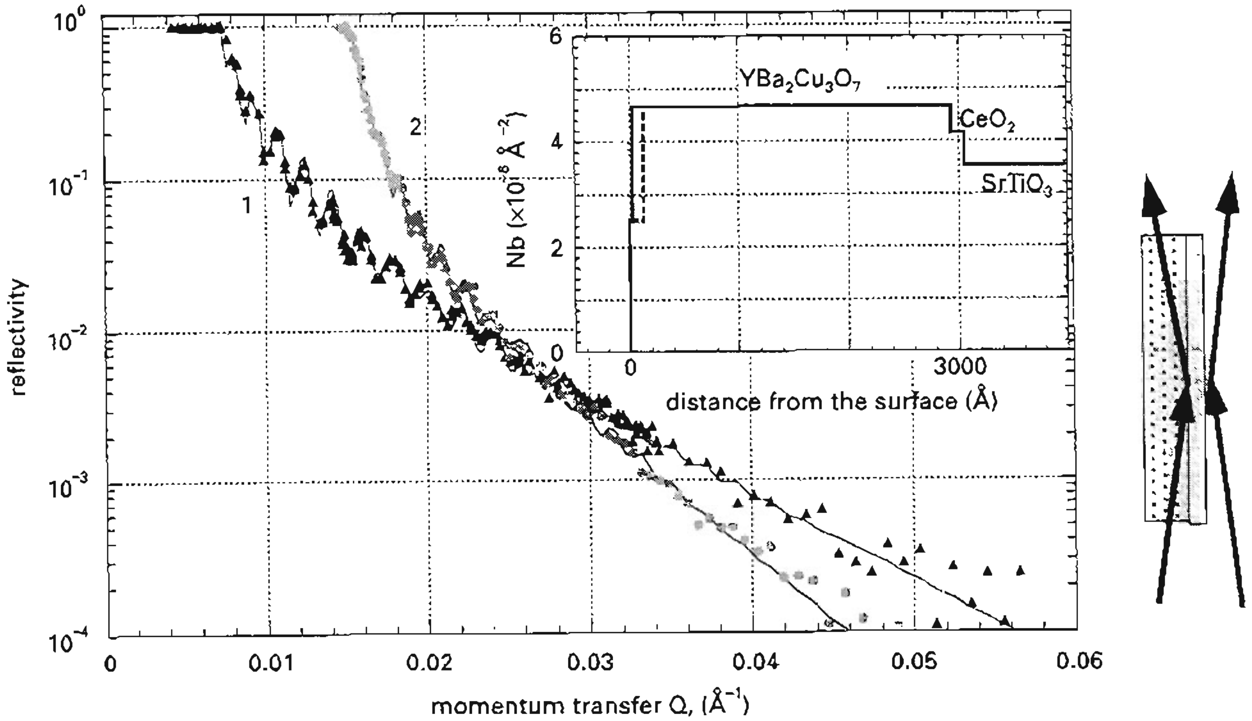

Fig. 3. Reflectivity curves of the YBaCuO-film on SrTiO-substrate. (1) is taken in the reflection geometry from the substrate–film interface and (2) from the air–film interface, respectively. The reflection geometries are shown in the sketch on the right side. In the inset the NSLD-profile is seen. The dashed line at the air–film interface represents the change at the air–film interface with time (see text).

reflectivity curves are depicted with the fit to the data. In the obtained NSLD diagram in the inset of Fig. 3 an additional surface layer is visible. This surface layer has grown during this half year from 25 to 125 Å and consists presumably of $BaCO_3$ formed through the humidity of air.

In the case of HT_c films the penetration depth is measured because the correlation length is very short and thus electron scattering at defects should be negligible. Nevertheless defects and the quality of the films can be probed by off-specular scattering. We did not detect any noticeable off-specular scattering in contrast to the rather huge off-specular scattering measured from the film in Ref. 5. This might be the reason why no oscillations were observed in the reflectivity curves [5].

Reflectivity curves were taken at low temperatures with an external field of 500 Oe at 4.8 K with scattering from the air side and 300 Oe at 2 K with scattering from the substrate side. The SA is shown in Fig. 4a and b for the two geometries. Again only the magnetic part of the NSLD profile was variable and the nuclear scattering part was taken from the fit to the room-temperature data. A penetration depth of 1400 ± 100 and 1350 ± 150 Å was obtained for the reflection from the air side and the substrate side, respectively, using again Eq. (1) with an intrinsic exponential profile. The complete result is depicted in Fig. 4c.

4. Conclusions

The Nb-films have been investigated as a prestudy for the HT_c films in order to optimize the parameters of the method. Sample quality, sample size, film thickness, reflection geometries and the film interfaces were investigated. The obtained screening length shows a value already near to the magnetic penetration depth but the difference indicates clearly an influence of electron scattering at the defects. The study of the HT_c-films showed that details of the film structure, in particular, at the interfaces, can be obtained. An appreciable Q-range

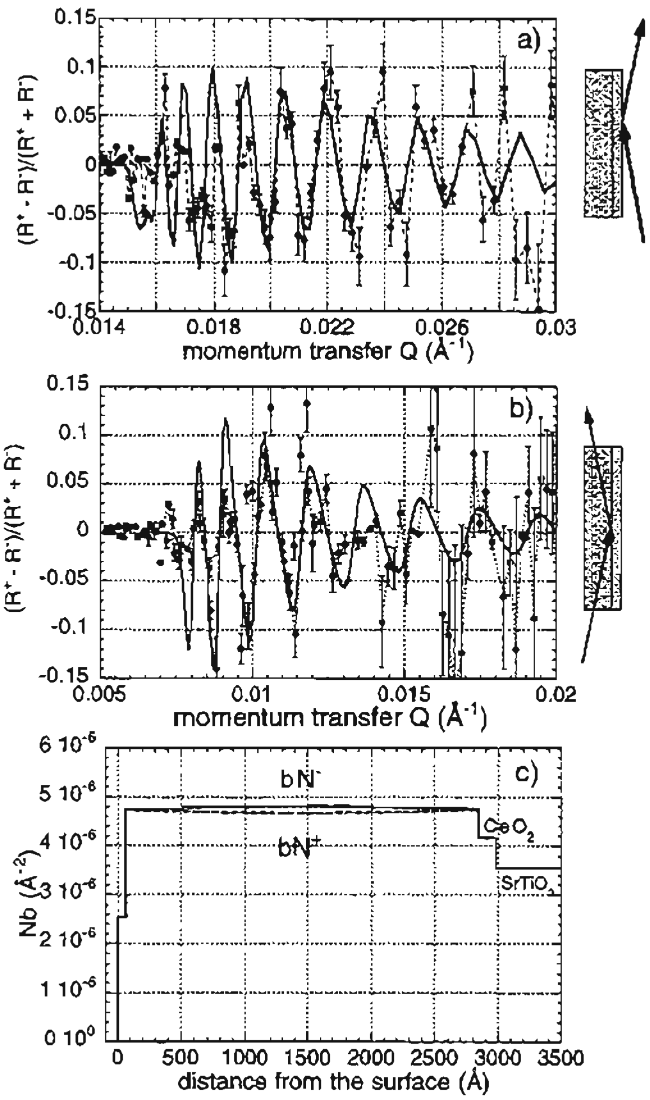

Fig. 4. Spin-asymmetry curves of the YBaCuO-film on SrTiO-substrate for the two reflection geometries sketched on the right side in a and b. In c the deduced NSLD profile is shown.

was available to determine the magnetic penetration depth. However the statistics must be still improved to study an eventual non-exponential character of the penetrating magnetic flux.

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References

[1] F. London, H. London, Proc. Roy. Soc. (Lond.) A 149 (1935) 71.
[2] G.P. Felcher, R.T. Kampwirth, K.E. Gray, Roberto Felici, Phys. Rev. Lett. 52 (1984) 1539.
[3] L.P. Chernenko, D.A. Korneev, A.V. Petrenko, N.I. Balalykin, A.V. Skripnik, Springer Proc. Phys. 61 (1992) 209.
[4] A.B. Pippard, Proc. Roy. Soc. (Lond.) A 216 (1953) 547.
[5] H. Zhang, J.W. Lynn, C.F. Majkrzak, S.K. Satija, J.H. Kang, X.D. Wu, PRB 52 (1995) 10395.
[6] R. Felici, J. Penfold, R.C. Ward, E. Olsi, C. Matacotta, Nature 329 (1987) 523.
[7] A. Mansour, R.O. Hilleke, G.P. Felcher, R.B. Laibowitz, P. Chaudhari, S.S.P. Parkin, Physica B 156 & 157 (1989) 867.
[8] S.V. Gaponov, E.B. Dokukin, D.A. Korneev, E.B. Kljuenkov, V. Lebner, V.V. Pasyuk, A.V. Petrenko, H. Rzany, L.P. Chernenko, Pis'ma Zh. Eksp. Teor. Fiz. 49 (1989) 277.
[9] G.P. Felcher, Physica B 192 (1993) 137.
[10] M. Tinkham, Introduction to Superconductivity, McGraw-Hill, New York, 1975.
[11] V.V. Pasyuk, D.A. Korneev, A.V. Petrenko, E.B. Dokukin, Proc. 2nd Int. Conf. on Surface X-ray and Neutron Scattering, Bad Honnef, Germany, 25–28 June 1991.
[12] Guide to neutron research facilities at the ILL, ILL, Grenoble, 1994, pg. 74.