Effect of magnetic flux penetration on the magnetic hysteresis loops of a Pt/Co/Pt triple layer on Nb(110)

N Joshi\textsuperscript{1,2}, C Sürgers\textsuperscript{1}, H v Löhneysen\textsuperscript{1,3}, W Löffler\textsuperscript{4,5} and H Kalt\textsuperscript{4}

\textsuperscript{1}Physikalisches Institut and Center for Functional Nanostructures, Universität Karlsruhe, D-76128 Karlsruhe, Germany
\textsuperscript{2}Physikalisches Institut, Universität Karlsruhe, D-76128 Karlsruhe, Germany
\textsuperscript{3}Forschungszentrum Karlsruhe, Institut für Festkörperphysik, D-76021 Karlsruhe, Germany
\textsuperscript{4}Institut für Angewandte Physik and Center for Functional Nanostructures, Universität Karlsruhe, D-76128 Karlsruhe, Germany
\textsuperscript{5}Present address: Huygens Laboratory, Leiden University, P.O. Box 9504, 2300 RA Leiden, The Netherlands

E-mail: christoph.suergers@pi.uka.de

Abstract. The magnetic properties of a (20 Å Pt/15 Å Co/20 Å Pt) triple layer deposited on a thick Nb(110) substrate are measured by vibrating sample magnetometry and the polar magneto-optical Kerr effect (p-MOKE). Above the superconducting transition temperature $T_c = 9.1$ K of Nb an out-of-plane magnetization curve $M(H)$ is observed by p-MOKE due to the perpendicular magnetic anisotropy of the Pt/Co/Pt triple layer. Cooling the sample below $T_c$ gives rise to a modification of the $M(H)$ hysteresis with a sudden change of the magnetization for magnetic fields smaller than the coercive field $H_{coerc}$ of the ferromagnetic triple layer. This is due to the penetration of magnetic vortices into the center of the weak-pinning superconducting Nb disk for fields above the lower critical field. These vortices generate an enhanced local magnetic field at the Nb surface which is larger than $H_{coerc}$ of the Pt/Co/Pt triple layer and locally switches isolated domains already for applied fields smaller than $H_{coerc}$.

1. Introduction

The magnetic interaction between a ferromagnet (F) and a superconductor (S) has been studied intensely in recent years [1]. In F/S systems with metallic contact the superconductor might modify the domain structure and/or the domain-wall width by the proximity effect [1]. Besides the proximity effect, the purely orbital contribution, i.e., the electromagnetic coupling between S and F plays an additional role. In hybrid structures where F and S are separated by a thin insulating layer the electromagnetic coupling between the magnetic domain structure of F and the superconductor gives rise to a number of effects such as domain-wall guided superconductivity [2], enhanced vortex pinning [3, 4].

For a F/S bilayer in a perpendicular magnetic field, which is often considered by theory, demagnetization effects are strong, leading to an immediate penetration of vortices even in very weak magnetic fields. In order to study the effect of diamagnetic screening currents on the domain structure in F, thick superconducting substrates are more suitable. For a F film with perpendicular anisotropy on top of a thick S substrate a shrinkage of the equilibrium domain size

\textsuperscript{2} Present address: Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland
\textsuperscript{5} Present address: Huygens Laboratory, Leiden University, P.O. Box 9504, 2300 RA Leiden, The Netherlands
by a factor $\sqrt{1.5}$ due to Meissner screening currents has been predicted [5, 6, 7]. The detailed behavior depends on the domain size, domain-wall width, and penetration depth $\lambda$.

A drawback when using a thin F film on a thick S substrate is the fact that the magnetic response measured by standard magnetometry is dominated by the screening behavior of S for $T < T_c$. However, the magnetization curve $M(H)$ of the thin F film can be studied without a contribution from S by means of the magneto-optical Kerr effect (MOKE) where the polarization axis of linearly polarized light is slightly rotated after reflection from a metallic ferromagnetic film [8]. Although magneto-optic techniques (Faraday rotation) have been employed during the last decades to investigate the magnetic flux structure of superconductors [9] special care was taken in order to avoid ferromagnetic ordering of the magneto-optically active layer that would distort the magneto-optic image of the flux structure. In the present case, where interest is focused on the effect of a bulk S on the magnetic properties of a thin F layer, MOKE is a perfect tool to measure the magnetization loop $M(H)$ of F on S via the Kerr-rotation $\phi(H) \sim M(H)$.

We have investigated a thin ferromagnetic (20 Å Pt/15 Å Co/20 Å Pt) triple layer with perpendicular magnetic anisotropy, deposited on a superconducting Nb (110) single crystal. Here we report on the magnetic characterization by vibrating sample magnetometry and polar MOKE (p-MOKE) in a magnetic field orientated perpendicularly to the sample surface.

### 2. Experimental

A single-crystalline Nb (110) disk (6.4 mm diameter, 1.35 mm height) was mechanically polished followed by electrochemical etching. The substrate was cleaned by several cycles of 2-keV Ar$^+$ ion bombardment and subsequent heating to 1000 °C in ultrahigh vacuum. A buffer layer of 200 Å Nb was deposited by electron-beam evaporation at a substrate temperature $T_S = 650$ °C. After cooling to $T_S = 300$ °C a triple layer of 20 Å Pt/15 Å Co/20 Å Pt was deposited with growth rates of 0.2 Å/s.

Magnetization curves $M(H)$ were recorded in a vibrating sample magnetometer (VSM) with the field applied perpendicularly to the sample surface. Kerr-rotation loops $\phi(H)$ were recorded by means of a p-MOKE setup with the sample cooled in a $^4$He flow cryostat reaching a minimum temperature of $\approx 3.5$ K. Red light from a laser diode (beam diameter $\approx 0.5$ mm) passed through a linear polarizer and was focused perpendicularly to the sample surface through the pole shoe of an electromagnet. The reflected light passed through a Wollaston prism and the intensities $I_1$ and $I_2$ of the two orthogonally polarized beams were recorded with two photodiodes while sweeping the magnetic field $H$. The ratio $(I_1 - I_2)/(I_1 + I_2)$ is proportional to the Kerr rotation $\phi(H)$ and, hence, to the magnetization $M(H)$. The magnetic field at the sample (maximum $\approx 150$ mT) was measured with a Hall probe.

### 3. Results and discussion

Figure 1 (a) shows the magnetization curves $-M$ vs. $H$ of the sample measured by VSM. Due to the dominant diamagnetic signal of S a contribution from the Pt/Co/Pt was not observed. In the mixed state of the superconductor, $M$ is composed of the equilibrium magnetization and the irreversible magnetization $M_{irrev}$ arising from the surface (Bean-Livingston) barrier as well as from bulk pinning of magnetic vortices at various defects in S [10, 11, 12]. The lower critical field $H_{c1}$ above which flux starts to enter the superconductor from the outer boundary is directly obtained as the field where $M(H)$ has a maximum in Fig. 1(a). $H_{c1}(T)$ can be reasonably described by a square-root behavior $H_{c1}(T) = H_{c1}(0)[1 - (T/T_c)]^{1/2}$ with $H_{c1}(0) = 49$ mT and $T_c = 9.1$ K, see Fig. 1(c). The upper critical field $H_{c2}$ is obtained from the sudden drop of the $M_{irrev} = (M^+ - M^-)/2$ ($M^+$, $M^-$ correspond to ascending and descending branch of the loop, respectively) [13] plotted in Fig. 1(b) with an estimated $H_{c2}(0) = 660$ mT. The temperature dependence of the critical fields is plotted in Fig. 1(c). Within Ginzburg-Landau theory the following superconducting parameters are estimated [14]: Ginzburg-Landau
Figure 1. (Color online) (a) Magnetization loops $M(H)$ of Nb(110)/Pt/Co/Pt in perpendicular magnetic field $H$ at various temperatures $T$ measured by VSM. (b) Irreversible magnetization $M_{irrev}(H)$ calculated from $M(H)$. Arrows indicate $H_{c2}$. (c) Critical fields $H_{c1}$ and $H_{c2}$ and penetration field $H^*$ vs. temperature $T$. Dashed-dotted line shows a square-root behavior, see text. Dashed line indicates a linear behavior and the solid lines (inset) serve as guides to the eye.

Figure 2. (Color online) Polar Kerr loops recorded in the normal state at $T = 10$ K (a) and in the superconducting state below $T_c = 9.1$ K (b-d). Arrows indicate the field $H^*$ where magnetic flux penetrates into the center of the superconducting disk with a concomitant sudden jump of the Kerr signal.

Parameter $\kappa(0) = H_{c2}(0)/\sqrt{2}H_c(0) = 2.3$ with $H_c(0) = 200$ mT for bulk Nb, coherence length $\xi_S(0) = \sqrt{\hbar/2e\mu_0H_{c2}(0)} = 223$ Å, penetration depth $\lambda(0) = \kappa(0)\xi_S(0) = 513$ Å.

Figure 2 shows MOKE loops recorded in the normal state ($T = 10$ K) and in the superconducting state ($T < 9.1$ K) of the Nb(110) substrate. In the normal state, the loop shows the $M(H)$ behavior characteristic of the ferromagnetic Pt/Co/Pt triple layer with strong out-of-plane anisotropy and large coercivity due to strongly pinned magnetic domains. Similar loops have been obtained for Co/Pt multilayers on Nb (110) films by VSM for $T > T_c$ [15]. After magnetic saturation and reversing the field direction, $M(H)$ of the F triple layer starts to decrease for fields $|H| > 75$ mT and is reduced to zero at a coercive field $H_{coerc} \approx 100$ mT.

In the superconducting state a sudden change of the magnetization appears at fields $H^*$
smaller than $H_{\text{coerc}}$ for both sweep directions, indicating a partial reversal of the sample magnetization. $H^*$ increases with decreasing temperature and is larger than the lower critical field $H_{c1}$ determined from the VSM measurements, see Fig. 1(c). We mention that $H^*$ is lower in measurements with the light spot positioned near the edge compared to the center of the circular sample. This suggests that $H^*$ can be identified as the field for which magnetic flux penetrates into the center of S in the form of quanta $\phi_0 = h/2e$. $H^*$ usually exceeds the lower critical field due to the pinning force characterized by a critical current density $j_c$ [10, 16]. This flux penetration into the Nb disk locally reverses the magnetization of magnetic domains in the Pt/Co/Pt film and gives rise to a change of the Kerr signal. Hence, this demonstrates a local modification of the Pt/Co/Pt magnetization by the vortex pattern of the superconducting Nb substrate. The fact that $M(H)$ suddenly changes at a field $H^*$ smaller than the coercive field of the Pt/Co/Pt triple layer is attributed to the local compression of magnetic flux in the vortex core with respect to the normal state resulting in a local enhancement of magnetic field higher than the applied magnetic field $H$. For magnetic fields slightly above $H_{c1}$ the local magnetic field $H_{\text{loc}}$ in the vortex core is estimated to $H_{\text{loc}}(\xi) = \phi_0 (\ln \kappa + 0.12)/2\pi \lambda^2 = 115$ mT [14]. Hence, the local magnetic field in the vortex at the S/F interface is larger than $H_{\text{coerc}}$ even for applied fields $H < H_{\text{coerc}}$ and can locally flip the magnetic domains in the triple layer. This effect is stronger at lower temperatures due to the higher $H^*$ approaching $H_{\text{coerc}}$, c.f. Figs. 2 (b-d).

In conclusion, our measurements demonstrate that in F/S systems with perpendicular anisotropy the flux variation above the superconducting crystal in the mixed state can locally change the magnetization of the F layer on the scale of $2\lambda(0) \approx 100$ nm. The effect is due to the enhanced local field in the vortex core compared to the applied field. In the present experiments, $H_{\text{coerc}}$ of F is larger than $H_{c1}$ and $H^*$. Clearly, in order to investigate the change of the magnetic domain structure by screening currents in the Meissner state of S [5, 6, 7], future experiments have to be performed on F/S systems with $H_{\text{coerc}}$ of F lower than $H_{c1}$.

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