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Thermal depinning of Abrikosov vortices in a Nb polycrystalline bulk absorber for gamma-ray superconducting detector

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Abstract

The threshold temperature at which the thermal depinning of Abrikosov vortices starts to be pronounced, defines the upper temperature limit for secure operation of a gamma-ray superconducting detector based on Abrikosov vortices. Indeed, because of the flux creep phenomenon, unwanted spontaneous vortex jumps can take place concurrently with those resulting from the gamma-ray photon absorption, resulting in the appearance of dark counts. Low temperature magnetic force microscopy (MFM) was applied for the evaluation of the threshold temperature for a 0.3 mm thick Nb polycrystalline bulk absorber with dimensions of 5×5 mm^2, which was chosen for the fabrication of Josephson tunnel junctions serving as vortex sensor element of the gamma-ray detector. Vortices were generated by cooling the sample to 4.3 K in a small magnetic field. A field of 0.1 mT was chosen in order to produce more than two vortices within the 7×7 μm^2 scan area, but with sufficiently large inter-vortex spacing such that vortex-vortex interactions would be negligible. The threshold temperature associated with the thermal depinning of a single vortex was found to be 6.3 ± 0.2 K, whereas the threshold temperature associated with the thermal depinning of half of vortices was found to be 7.2 ± 0.2 K.

Keywords: Abrikosov vortices, pinning, gamma-ray superconducting detector, magnetic force microscopy

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1. Introduction

Recently, a new detection principle based on the interaction of a single gamma-ray photon with the Abrikosov vortices, trapped inside a type II superconducting absorber, was proposed [1]. Magnetic flux variation on the absorber surface is registered by the Josephson effect, which is extremely sensitive to the magnetic field. Contrary to the quasiparticle collection principle, which requires thin film superconducting tunnel junction device with the film thickness < 1 μm, the detection mechanism based on Abrikosov vortices permits to utilize bulk superconductor absorber (with the thickness of the order of 1 mm) and, hence, increase substantially the detection efficiency. Therefore this new detection mechanism permits to exploit niobium as a high Z (Z=41) type II superconductor with larger thickness for utilization as a gamma-ray absorber.

Before operation, Abrikosov vortices have to be trapped on pinning centers in the Nb absorber by field-cooling process. Therefore a polycrystalline bulk Nb absorber is chosen because the grain boundaries between grains are effective pinning centers for vortices. An essential part of the detection principle is the requirement that the trapped Abrikosov vortices remain fixed on the pinning centers after its introduction and after turning off the external magnetic filed, otherwise unwanted vortex jumps (dark counts) would appear.

The main reason of the dark counts of the detector based on Abrikosov vortices is the flux creep [2]. Indeed, at finite temperature ($T \neq 0$), the thermal energy may activate a jump of a single Abrikosov vortex from one pinning center to another with the jump rate described, in accordance with the Anderson theory [2] by the Arrhenius expression

$$R = \omega_0 e^{-F_b/k_B \ T} \tag{1}$$

where ω_0 is a vibration frequency (or characteristic attempt frequency) of the vortex trying to escape from the pinning site, k_B is Boltzman's constant, and F_b is an effective activation energy (or barrier energy) which depends on the nature of the pinning centres and the sample type (bulk or thin film). Because of the flux creep phenomenon, unwanted spontaneous vortex jumps can take place concurrently with the gamma-ray photon absorption, resulting in the appearance of dark counts. Because of the exponential character of the dependence of the jump rate on the temperature (see Eq. 1) it is possible to introduce the threshold temperature at which the thermal depinning of Abrikosov vortices starts to be pronounced inside the time interval required for measurements (usually some hours). Namely the threshold temperature defines the upper temperature limit for secure operation of a gamma-ray superconducting detector based on Abrikosov vortices. In order to avoid dark counts, the device must be operated at a temperature below the threshold temperature. Up to the present, the thermal depinning of a single trapped vortex was experimentally estimated only for thin film Nb sample by Sok and Finnemore in [3]. These authors have found that, in Nb film with a thickness of 0.4 μm, the thermal depinning of a single Abrikosov vortex consistently occurs when the reduction in superconducting order parameter Δ/Δ_0 is lower than 0.22. Taking into account the superconducting transition temperature T_c =9.2 K for clean Nb and using the Bardeen, Cooper and Schriffer (BCS) dependence of Δ/Δ_0 on temperature [4], it is possible to demonstrate that in terms of the temperature the condition Δ/Δ_0=0.22 corresponds to the threshold temperature in the order of 9.05 K.

In the present work, the low temperature magnetic force microscopy was applied for the visualization of the temperature-induced depinning of vortices and evaluating the correspondent threshold temperature for a Nb foil. The Nb foil with a thickness of 0.3 mm was chosen as a polycrystalline bulk absorber for the fabrication of the gamma-ray detector‘s prototype with Josephson tunnel junctions as vortex sensor elements arranged on its surface.

2. Experiment

A Nb foil with a thickness of 0.3 mm and with dimensions of 5x5 mm^2, was used in the thermal depinning experiment. The sample had a purity of 99.9% and was one side polished with a roughness of less than 0.03 μm, according to the manufacturer (MaTecK, Material – Technologie & Kristalle GmbH, Germany). The superconducting transition temperature T_c of Nb foil was order of 8 K. This value was estimated from the temperature dependence of the Josephson critical current of the Josephson junctions fabricated on the surface of the identical Nb foil from the same fabrication part as the sample under MFM experiment.

Our low temperature MFM is based on cantilevers integrated with piezoresistive displacement detection [5]. The sensing element is a piezoresistor embedded in the arms of the cantilever [6]. The resistance change of the piezoresistor caused by stresses due to cantilever deflection can easily be measured. The fundamental resonance frequency is in the range 30–50 kHz, while the force constant is about 1 N/m. Molecular beam epitaxy (MBE) deposition is used to grow on top of the Si tips two 25 nm thick Co layers separated by a 2 nm thick Au layer. Oblique incidence deposition minimizes the coated area by restricting the magnetic-film growth to one side of the tip. This optimized Co/Au multilayer coating of the tip, as well as the relatively large tip-sample separation (70–100 nm), turn out to considerably decrease the stray field from the tip acting on the sample surface.

With the Nb foil sample in the superconducting state, force spectroscopy measurements were performed in order to ensure that no vortices are nucleated by the magnetic field from the tip. Usually the cantilever experiences a repulsive interaction when approached towards the surface due to the Meissner effect and the increase in the resonance frequency of the cantilever as a function of tip–sample separation is monotonic. On the other hand during vortex creation, the resonance frequency decreases discontinuously [7]. We observe the monotonic increase of the resonance frequency of the cantilever as a function of tip–sample separation in the range 200 – 30 nm. This suggests that no vortices are nucleated by the magnetic field from the tip at the indicated tip–sample separations. The separations were previously determined by approaching the tip to the sample surface at ~ 11 K, until tip-sample contact was made.

3. Results and Discussion

Vortices were generated by cooling the Nb polycrystalline foil in the presence of an applied magnetic field. This was done by heating the sample to ~ 11 K, and applying a small magnetic field perpendicular to the sample surface, using a Helmholtz copper coil system. A field of 0.1 mT was chosen in order to produce more than two vortices within the 7×7 μm^2 MFM scan area, but with sufficiently large inter-vortex spacing such that vortex-vortex interactions would be negligible. Next, the applied field was removed and MFM imaging cycles of the same scan region with increasing temperature (by steps of 0.1 K) were performed until a vortex was depinned and expelled from the region. Images as a function of temperature for the Nb foil are shown in Fig. 1, acquired with a chosen constant tip-sample separation of 100 nm, (see below for explanation).

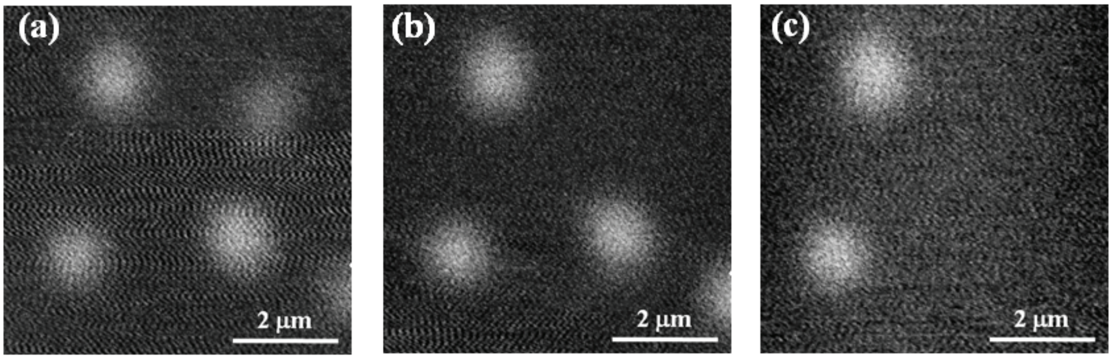

Figure 1: Temperature sequence of 7 × 7 μm^2 MFM images acquired at constant 100 nm tip-sample separation and illustrating vortex depinning. (a) T = 4.3 K; (b) as temperature increases to T = 6.3 K, the first vortex is depinned; (c) at T = 7.2 K half of the vortices were expelled from the scan region.

At temperatures below 6.3 K vortices remain at the same positions (Fig. 1(a)). This indicates that pinning is sufficiently strong so as to prevent any temperature-induced motion of vortices. The first vortex depinning event occurs at T_1=6.3 K, (Fig. 1(b)), with expelling of half of vortices from the scan area as temperatures rise above $T_{1/2}$=7.2 K, (Fig. 1(c)). At temperatures above ~ 8 K all vortices are expelled from the scan area. Similar behavior was observed for others scanned 7×7 μm^2 areas with the ± 0.2 K scatter for the mentioned depinning temperaturs T_1 and $T_{1/2}$. . According to a simple statistical analyses of all MFM images acquired at T_1 ~ 6.3 K the probability of the “first” vortex depinning (within 7×7 μm^2 area) is < 5%. It might have been thought that T_1 is the threshold temperature at which the thermal depinning of Abrikosov vortices starts to be pronounced [8].

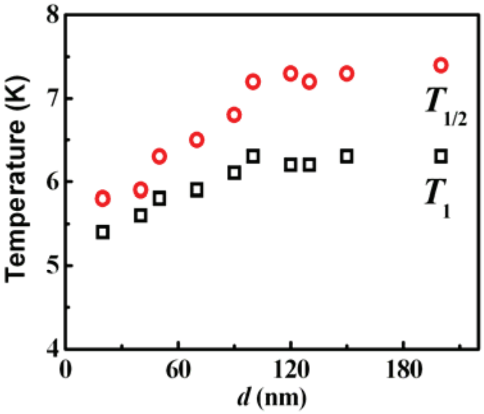

Figure 2: The average temperatures corresponding to the first vortex depinning events (T_1) and expelling of halve of vortices from the 7 × 7 μm^2 scan area ($T_{1/2}$) as a function of tip-sample separation (*d*) .

However, it should be emphasized that in our MFM experiments, vortices can also hop from one pinning site to another in response to a driving force, arising from the stray field of the tip [9]. With the aim of better understanding the influence of this tip-induced driving force we performed vortex imaging as a function of temperature at various tip-sample separations and determined correspondent depinning temperatures T_1 and $T_{1/2}$. Note that our MFM is sensitive enough to map vortices at tip-sample separations up to 200 nm although the signal-to-noise ration decreases considerably at larger separations. Results are illustrated in Fig. 2, which points are obtained by averaging T_1 and $T_{1/2}$ over three scan areas as a function of the tip-sample separation d. Noticeable decrease in the vortex depinning temperatures T_1 and $T_{1/2}$, indicative of stronger tip-induced driving forces, is observed at smaller tip-sample separations $d < 50$ nm. On the other hand the depinning temperature only slightly varies with distance at larger tip-sample separations $d > 70$ nm (Fig.2). This observation provides confirmation of the validity of our assumption that disappearance of vortices from the scanned areas above $T_1 = 6.3$ K ± 0.2 K is due to the thermal depinning rather than due to the stray field of the tip.

One immediate conclusion that can be drawn from the experimentally obtained vortex depinning temperatures is that vortices in the polycrystalline bulk Nb foil-absorber are pinned considerably weaker than in Nb thin films. The calculated normalized superconducting order parameter Δ/Δ_0 at the depinning threshold temperature $T_1 \sim 6.3$ K is of 0.8 which is higher than the correspondent parameter obtained in [3] for the polycrystalline Nb thin film. It has been naturally assumed that the threshold temperature $T_1 \sim 6.3$ K at which first events of vortex depinnig occur can be used as a reliable parameter for characterization of the Nb absorber.

4. Conclusions

Low temperature magnetic force microscopy was applied for evaluation of the vortex depinning threshold temperature for a 0.3 mm thick Nb polycrystalline bulk absorber, which was chosen for fabrication of Josephon tunnel junctions serving as vortex sensor element of the gamma-ray detector. The first vortex depinning events occur at threshold temperature $T_1 = 6.3 \pm 0.2$ K (with a probability < 5%). The temperature $T_{1/2}$ associated with the thermal depinning of half of vortices was found to be 7.2 ± 0.2 K. The obtained threshold temperature $T_1 = 6.3 \pm 0.2$ K corresponds to the superconducting order parameter $\Delta/\Delta_0 \sim 0.8$ which is considerably higher than Δ/Δ_0 measured for the polycrystalline Nb thin films. It is important to note that the thermal activated dark counts of Nb gamma-ray superconducting detector with thick (~0.3 mm) Nb polycrystalline bulk absorber will be negligible at the liquid helium temperature at normal pressure.

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