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Detection of X-ray photons by niobium Josephson tunnel junctions with trapped Abrikosov vortices

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Abstract. The high atomic number of niobium (Z=41) can be exploited to develop a high efficiency superconducting gamma-ray detector based on a novel detection principle, namely, the interaction of a single gamma-ray photon with Abrikosov vortices trapped inside a niobium bulk absorber. To study the feasibility of this principle, niobium type Josephson tunnel junctions with the aluminium oxide as a tunnel barrier and with a thick (0.3 mm) niobium base electrode have been fabricated. The devices have been tested at T = 4.2 K in terms of the current-voltage characteristic and of the magnetic field dependence of the Josephson critical current. The feasibility of the detection principle has been tested under X-ray irradiation from the ^{55}Fe source. The time dependence of the Josephson critical current of the junction with trapped Abrikosov vortices has been recorded without and with X-ray irradiation. The data analysis of obtained experimental curves has confirmed the effect of the X-ray photon absorption on the Josephson critical current caused by jumping of Abrikosov vortices.

1. Introduction

An innovative detection principle - based on the interaction of a single gamma-ray photon with the Abrikosov vortices trapped inside a type II superconducting absorber with high atomic number Z - has been proposed and theoretically explained in [1], with the aim of developing a gamma-ray superconductor single photon counter with high intrinsic detection efficiency in the energy range up to 100 keV. The gamma-ray absorption results in a photoelectronic hot-spot formation and produces a variation of the magnetic inductance around the absorber surface. The high sensitivity of the Josephson tunneling to weak magnetic field can be exploited to readout this variation. Two device designs were proposed in [1] for readout the detection events. The first one consists of a single Josephson tunnel junction device. In this case the superconducting absorber is one of two electrodes of the junction and the Abrikosov vortex jumps are revealed by step-like variations of the Josephson critical current (I_c). The second design is based on a superconducting quantum interference device (SQUID) magnetometer with the pickup loop placed in proximity of the absorber site where Abrikosov vortices are trapped. The motion of Abrikosov vortices, caused by gamma-ray absorption, results in the variation of the magnetic inductance around the absorber surface which, in turn, can be revealed by the SQUID.

As regards the absorber material, superconducting Nb (Z=41) is a good material for practical realization of a detector with high detection efficiency based on Abrikosov vortices [1]. First, the gamma-ray detection efficency of Nb with thickness as great as 0.3 mm is of 65 % for gamma-ray energy of 60 keV while the gamma-ray absorption of Si (Z=14) detector with the same thickness and for the same gamma-ray energy is only of 2 % [1]. Second, Nb is a type II superconductor and the magnetic field penetrates inside it spontaneously in form of Abrikosov vortices which occupy the whole volume. In addition, Nb absorber permits the detector to operate at liquid Helium temperature at normal pressure (T=4.2 K), facilitating the practical use of the device.

The operation principle requires that Abrikosov vortices have to be trapped on pinning centers in the Nb absorber by field-cooling process. For this reason it is preferable to choose a polycrystalline bulk Nb as device absorber because the grain boundaries between grains are itself effective pinning centers for vortices [2]. It is worth noting that spurious signals in absence of radiation might occur in a detector based on Abrikosov vortices (dark counts) due to thermally activated flux creep [3]. In [4], a low temperature magnetic force microscopy was used for experimental evaluation of the vortex depinning threshold temperature for a 0.3 mm thick Nb polycrystalline foil. This foil is analogous to the absorber chosen for fabrication of the Josephson tunnel junctions as vortex sensor element in the present research. As demonstrated in [4], the thermal activated dark counts of a thick (0.3 mm) Nb polycrystalline bulk absorber at T=4.2 K is negligible.

The present paper is devoted to the experimental test of the feasibility of the single Josephson tunnel junction device configuration based on the detection principle based on the Abrikosov vortices. X-ray irradiation from the ^{55}Fe source with energy of 5.9 keV was used in the present experiment in order to test the working principle in the case of absorption of low energy gamma-ray photons.

2. Experimental details

2.1. Sample description

A Nb foil with thickness of 0.3 mm and with 5x5 mm^2 size, identical to that investigated in [4], was used as a base electrode of the Josephson tunnel junctions with the following layer configuration: Nb(0.3 mm foil-base electrode)/Al(20 nm)/Al_2O_3/Al(20 nm)/Nb(100 nm-top electrode). Before the deposition of the first 20-nm thick Al layer, the native oxide of the Nb foil was removed by Ar-ion beam cleaning. A secure electric disconnection between the Nb wiring and the Nb foil was reached by growing of the Nb oxide by anodization process with consequent deposition of two SiO insulating layers. The sample contains Josephson tunnel junctions with circular geometry with diameters of 20 μm, 60 μm, 80 μm and 100 μm. The Josephson critical current density was of 3 A/cm^2.

2.2. Experimental cryogenic setup and measurement procedure

The special cryogenic setup was used for measurements of the Josephson critical current of the Nb Josephson tunnel junction with trapped Abrikosov vortices exposed to X-ray irradiation from a ^{55}Fe radioactive source (5.9 keV X-rays). The sample was mounted inside a vacuum cylindrical chamber of a cryogenic insert fabricated from a thin wall stainless steel tube. The cooper sample holder was attached to the thin wall stainless steel tube. The chamber was immersed in a liquid Helium bath. Helium exchange gas was introduced into the chamber. Besides the exchange helium gas, the sample holder stayed in a good thermal contact with the copper bottom of the cylindrical chamber in order to keep the stable temperature T=4.2 K. A 100 Ohm micro resistor was used as a heater in contact with the sample holder, in order to control the temperature of the sample with a high accuracy at values above the liquid Helium temperature. The temperature of the sample was measured by a Lake Shore Germanium thermometer. The junction plane was oriented perpendicular to the axis of the cylindrical chamber. Under the sample, the encapsulated ^{55}Fe disc source was mounted inside a copper box with an externally controllable mechanical copper shutter to shield the sample from X-ray irradiation. A special magnetic coil system was used to generate both the magnetic field perpendicular (B_{per}) and parallel (B_{par}) to the junction plane. The shielding of the earth magnetic field and of the electromagnetic noise was obtained by a superconducting lead shield and three coaxial μ-metal shields.

Abrikosov vortices were trapped by cooling the sample from a temperature $T>T_c$ down to $T<T_c$ in the presence of a perpendicular magnetic field (T_c is the superconducting transition temperature). The perpendicular magnetic field was turned off at T=4.2 K. The Josephson critical current was recorded in time by a data acquisition electronic system. The current-voltage (*I-V*) characteristic of the Josephson junction was measured by application of the triangle shape current through the junction with the frequency of 10 Hz and with the amplitude greater than I_c. The junction voltage was applied to a precise comparator which produced the digital signal when the non-zero voltage appeared on the junction. By acquiring and analyzing the output signal from the comparator, the acquisition system stored the current values when the non-zero voltage occurred on the junction. These current values represented the Josephson critical current I_c values. Both the parallel magnetic field dependences of the I_c and the dependences of the I_c on the time (t) were recorded by suitable software.

3. Experimental results and discussion

As predicted in [1], the absorption of 5.9 keV X-ray photons in Nb results in the formation of a hot spot with dimension of order of 1 μm. In order to ensure a high probability of the interaction between a hot spot and an Abrikosov vortex, a perpendicular magnetic field B_{per} of 20 G was chosen for trapping the magnetic field. Indeed, the field cooling process in this magnetic field creates a flux structure with an average distance between vortices of order of 1 μm, which is close to the expected dimension of the hot spot. The Josephson tunnel junction with the diameter of 20 μm was employed in the experiment described in the present paper. After Abrikosov vortex trapping, the $I_c(B_{par})$ dependence was recorded. As expected from a previous research [5], the maximum value of the Josephson critical current was suppressed with respect to the vortex free state and oscillation in I_c occured. The Josephson critical current was tuned by applying a parallel magnetic field in order to achieve the maximum value of the dI_c/dB_{par} derivative of the $I_c(B_{par})$ dependence. At this point the measurement of the Josephson critical current in time was started and the data were recorded both with and without X-ray irradiation. A typical experimental time dependence of the Josephson critical current I_c without X-ray irradiation (first part of the time track) and then after X-ray irradiation is shown in Figure 1 by black points (raw data). Full color line in Figure 1 reports the signal after a denoising procedure made by a wavelet transform method (OriginPro 8 SR3 Software, wavelet type - Haar, thresholding level - 6, threshold of every level - 100%). The derivative of the denoised signal with respect to time was calculated. The threshold for event detection was considered as the mean value of the non-zero spikes of the derivative for the time interval without X-ray irradiation, plus its standard deviation multiplied by three. Open circles in Figure 1 are the denoised signal values at time moments where the derivative spikes exceed the threshold. As can be seen from Figure 1, the derivative spikes exceed the threshold mainly in case of the signal recorded under X-ray irradiation. Therefore for the part of signal stored under X-ray irradiation, the open circles indicate the variations of the magnitude of I_c which can be attributed to the jumps of trapped Abrikosov vortex/vortices caused by the absorption of single 5.9-keV X-ray photons. The measured average time interval between the events is 448 s while the expected time interval between absorption events of 5.9 keV X-photons inside 0.3 mm thick Nb foil is of 0.2 s (for the given source emission rate and measurement geometry). This discrepancy is taken as an indication of low observed detection efficiency, with respect to calculations. Based on these measurements we speculate that, for reasons still unclear, only thin part of Nb absorber just near the junction barrier are effectively producing a vortex jump to be recorded by the Josephson junction in critical current operation mode. The reason of the low detection efficiency will be studied in future experiments.

4. Conclusions

Josephson tunnel junctions with the 0.3-mm thick Nb polycrystalline foil as a base electrode were fabricated. Preliminary experiment was carried out under 5.9 keV X-ray irradiation from the ^{55}Fe source, namely, under absorption of single low energy gamma-ray photons. After Abrikosov vortex trapping, single X-ray photons were detected by registration of step-like changes of the Josephson critical current recorded vs. time.

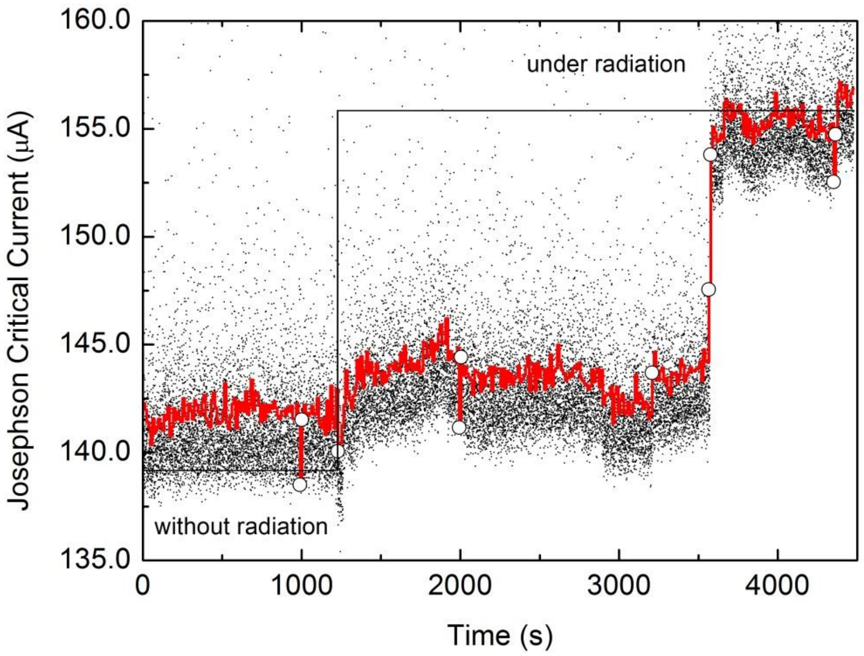

Figure 1. The $I_c(t)$ dependence for a 20 μm circular Josephson tunnel junction after field cooling process in B_{per}=20 G, without and with X-ray irradiation (black point). Red line shows the signal after a denoising procedure. Open circles are I_c changes which are attributed to the absorption events of single X-ray photons, by selection procedure described in the text.

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