Effects of fluxoid trapping on signal creation in superconducting tunnel junction X-ray detectors

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Abstract

Trapping of fluxoid quanta influences the performance of tunnel junction X-ray detectors. It has been found that the trapped vortices corresponding to a terrestrial magnetic field are enough for charge output and quasiparticle losstime to decrease by factors of two and three, respectively. This result leads to an effective vortex radius of $R_{\text{eff}} = 3\xi$, which is in a good agreement with a Golubov's calculation. Magnetic images by a scanning SQUID microscope show that the trapping takes place at junction edges or inside the junction at random. The random trapping may cause an instability of the detector performance. On average, the cooling in a perpendicular magnetic field results in the trapping of the corresponding vortex density, that is $B/\Phi_0$. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

It is known that the performance of superconducting tunnel junction X-ray detectors strongly depends on loss processes of the quasiparticles created by photon absorption. One of the loss processes is due to fluxoid quanta or vortices trapped in junction electrodes. The vortices cause local quasiparticle trapping associated with normal cores, and thus spatial nonuniformity of the charge output [1–3]. In polycrystalline-niobium-based junctions, the vortex trapping may easily occur at grain boundaries when an environmental magnetic field as small as $\sim 10$ mG is present during cooling. It is therefore very important to study the performance change due to the vortices and to observe the vortex trapping pattern.

In this study, the detector performance change was studied by using a $^{55}$Fe X-ray source. The experimental results are compared with a Golubov's model for the vortex quasiparticle trapping [4]. There are several methods to observe vortices; decoration techniques, scanning tunneling microscope, magnetic force microscope, Lorentz microscope, etc. In addition, for tunnel junctions it was demonstrated that the vortices were imaged by a low-temperature scanning electron microscope.
2. Experiment

The junctions have a square geometry with dimensions of 50 × 50 and 100 × 100 μm², and a layer structure of Al(2)/Nb(200)/Al(40)/AlOₓ/Al(40)/Nb(200)/MgO(20)/Si in nm. The transparency of the barrier is represented by a normal resistivity of 12 μΩ cm².

The X-ray detection experiments using the ⁵⁵Fe source were performed at 0.35–0.4 K, after the junction was cooled at a zero field in a magnetic shield having an attenuation factor of over 1000, or at about 350 mG in a terrestrial field. The scanning SQUID microscope developed by Seiko Instrument was employed for vortex observations [5].

3. Results and discussion

3.1. Effects of terrestrial magnetic field on X-ray detection

The difference between cooling at the zero field and at 350 mG is obvious in Fig. 1. The scatter plots were recorded at a bias point of 0.2 mV. The event groups near the maximum charge outputs are the total absorption events of the 6 keV X-rays. The total absorption events and the low charge output substrate events are connected by photoelectron escape events [6].

The photoelectron escape events display the dependence of the quasiparticle losstimes on energy deposited in the electrodes. In the zero-field cooling, the risetimes rapidly shorten above 5 × 10⁶ electrons. This implies a strong energy nonlinearity because of self-recombination. The response ratio of Mn-Kᵢ/Mn-Kᵢ was 1.04, which is considerably smaller than an ideal value of 1.10. In the cooling at 350 mG, on the other hand, the risetimes are greatly shorter than those in the zero-field cooling. However, since the curve is rather flat, the energy nonlinearity must be small. In fact, the Mn-Kᵢ/Mn-Kᵢ ratio was improved to 1.06. As mentioned below, the better linearity is consistent with a fast vortex quasiparticle loss that masks the self-recombination.

The quasiparticle total losstime τᵣ may be expressed by 1/τᵣ = 1/τ₀ + 1/τᵣAV, where τ₀ is the quasiparticle losstime without vortices and τᵣAV is the quasiparticle trapping time in vortices. The measured quasiparticle losstimes are 1.0 μs (the total absorption events) and 2.2 μs (the low charge events) in the zero-field cooling, and 0.5 μs (the total absorption events) and 0.6 μs (the low charge events) in the cooling at 350 mG. From these losstimes, the τᵣAV is calculated to be 1.0 μs. In the Golubov’s expression [4], 1/τᵣAV = 1.82npR² eff /τ₀, where n is the vortex density and τ₀ is the material-dependent characteristic time, the experimental τᵣAV value leads to an effective vortex radius of R eff = 3ζ, where ζ is the coherence length and equals to 10 nm in our niobium films. The factor three is in a good agreement with the Golubov’s calculation [4].

The corresponding X-ray spectra are shown in Fig. 2. The spectrum in the terrestrial field cooling is normalized so that the higher peak position...
becomes the same as that in the zero-field cooling. In the terrestrial field cooling, the 6 keV X-rays produce the double peaks originating from the absorption events in two superconducting electrodes \[7\]. In the zero-field cooling, on the other hand, the single peak appears. This may be explained by quasiparticle mixing between two electrodes because of the long quasiparticle losstime.

### 3.2. Observations of trapped vortices

In order to elucidate the above discussion, it is necessary to observe the vortices directly. The SQUID microscope images are shown in Fig. 3. At the zero applied field (b), the twelve black dots are visible. The flux of each black dot is equal to \(\Phi_0\), so that the black dots indicate the trapped vortices. In Fig. 3(b), the 12 vortices are equivalent to a residual field of about 20 mG. The two vortices are just on the upper edge, while the others are inside the junction.

By counting the black dots, it is revealed that the vortex density is expressed by \(B/\Phi_0\), where \(B\) is the sum of the applied field and the residual field. Above 100 mG, counting vortices becomes difficult by a spatial resolution limit. Nonetheless, it is reasonable that, in the cooling at the terrestrial field that is negligibly low for the interaction between vortices, the trapped vortex density is 0.02\(\Phi_0/\mu\text{m}^2\).

The \(B/\Phi_0\) trapping is a consequence of a type II superconductor with flux pinning sites. Our niobium films have a coherence length \(\xi\) of 10 nm and a penetration depth \(\lambda\) of 90 nm \[3,8\]. Since \(\kappa = \lambda/\xi\) is well larger than \(1/\sqrt{2}\), the niobium films are type II superconductors. The grain sizes of the niobium films are larger than \(\xi\), so that the grain boundaries can be the pinning sites. Therefore, the pinning site density should be extremely larger than the vortex density. It also seems that the pinning forces are uniform. These explain the fact that the trapping sites are practically at random in Fig. 3.

Additionally, it is observed that there are no vortices in the contact hole at any fields and in the leads at 20 mG. These will be discussed in future publications.

### 4. Conclusions

The trapped vortices corresponding to the terrestrial magnetic field are enough for the charge output to decrease by a factor of two, and for quasiparticle losstime to shorten by a factor of three. This experimental result leads to an effective vortex radius of \(R_{\text{eff}} = 3\xi\), which is in a good agreement with the Golubov’s calculation. Unexpectedly, the quasiparticle loss in the vortices improves the energy linearity.
The SQUID microscope images exhibit that, as expected for a tape II superconductor with pinning sites, the trapped vortex density is equivalent to the perpendicular magnetic field. The trapping takes place at the junction edges or inside the junction at random.

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