Experimental imaging diagnosis of superconducting tunnel junction x-ray detectors by low-temperature scanning synchrotron microscope

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Imaging diagnosis of superconducting tunnel junction x-ray detectors has been performed by an apparatus called the low-temperature scanning synchrotron microscope (LTSSM) using an x-ray microbeam with a diameter of 5–10 μm originated from synchrotron radiation. Quasiparallel intense synchrotron radiation enables one to obtain the full two-dimensional images of junctions with dimensions of 200×200 μm² in about 1 h. The LTSSM results indicate that the standard quasiparticle diffusion and edge loss model for the spatial distribution of the junction response to x rays is evidently inadequate for intermediate or large junctions (with respect to a Josephson penetration depth). On this basis, it is argued that the models proposed for the signal creation and loss mechanism should be reconsidered. © 2000 American Institute of Physics.

Superconducting x-ray detectors, which use a superconducting energy gap (2Δ) as a scale for measuring the energy of an incident photon and a superconducting tunnel junction (STJ) as a readout device, have a theoretical energy resolution better than 0.1%, a moderate x-ray detection efficiency of an incident photon and a superconducting tunnel junction insulation barrier. The actual energy resolution is further degraded by eventual nonuniformities in the spatial distribution of the detector response. In the soft x-ray range between 200 and 1 keV, it was reported that the intrinsic energy resolution of a Nb-based STJ detector reached the sum of the statistical fluctuations, first, in the number of excited carriers that are broken Cooper pairs called quasiparticles, and second, in the number of quasiparticles that tunnel through the insulation barrier. The actual energy resolution is further degraded by eventual nonuniformities in the spatial distribution of the detector response. In the soft x-ray range between 200 and 1 keV, it was reported that the intrinsic energy resolution of a Nb-based STJ detector reached the sum of the statistical fluctuations, first, in the number of excited carriers that are broken Cooper pairs called quasiparticles, and second, in the number of quasiparticles that tunnel through the insulation barrier. The actual energy resolution is further degraded by eventual nonuniformities in the spatial distribution of the detector response. In the soft x-ray range between 200 and 1 keV, it was reported that the intrinsic energy resolution of a Nb-based STJ detector reached the sum of the statistical fluctuations, first, in the number of excited carriers that are broken Cooper pairs called quasiparticles, and second, in the number of quasiparticles that tunnel through the insulation barrier.

Imaging of the junction response is performed by scanning the pinpoint collimation experiments. This is because the pinpoint collimation experiments are explained by a quasiparticle diffusion and edge loss model (QD model) and found to be consistent with actual x-ray energy spectra. A straightforward way for imaging diagnosis is to scan STJ detectors with an x-ray microbeam. There are no reports on x-ray microbeam imaging experiments except for the pinpoint collimation experiments. This is because the faint intensity of standard Fe x-ray sources prohibits from scanning whole STJ area at a necessary spatial accuracy of ~μm within a realistic measurement time.

In this letter, we report on the x-ray imaging diagnosis by a LTSEM, which uses an x-ray microbeam with a diameter of 5–10 μm from synchrotron radiation. Quasiparallel intense monochromatic synchrotron radiation enables to use a pinhole collimator just in front of a He cryostat with x-ray windows. The imaging of the junction response is performed by scanning the pinhole collimator at step intervals of 3–10.
μm in two dimensions. Junction response to x-ray photons was read by a charge-sensitive preamplifier and amplified by a shaping amplifier. The pulse height spectra were recorded together with the x-ray microbeam coordinates, which are referred to as pixels, by a data acquisition system. The measurement time for a 200×200 μm² junction is about 1 h. The detail of the LTSSM system will be published elsewhere. The STJ detectors analyzed in this study have a square shape of 50–200 μm, a layer structure of Nb(200)/Al(30)/AlOₓ/Al(30)/Nb(200)/SiO₂(600)/Si (thickness is indicated in nanometers), a normal resistance of 12 Ω cm², and a quality factor (dynamic resistance divided by normal resistance) of more than 10⁵–10⁶ at 0.4 K. In this letter, we focus on a 200×200 μm² junction. The junctions were cooled in a magnetic shield to avoid Abrikosov vortex trapping, which induces a considerable charge-output reduction and were kept at 0.4 K. A magnetic field of 12 mT was applied in the plane parallel to the insulation barrier and along the diagonal direction to suppress the dc Josephson current and minimize the Fiske resonance modes. The junction was biased below Δ/e by a current source.

Figure 1 shows a full illumination spectrum at 6 keV. The spectrum is a reconstruction from all spectra measured with a 10 μm microbeam at scanning step intervals of 10 μm and a bias current of 300 nA. This bias point is in the beginning of the sharp current increase, which may be related to multiparticle tunneling or multiple Andreev reflection, at about Δ/e in the IVC. An identical spectrum was recorded in a full illumination experiment with a ⁵⁵Fe radiation source. The spectrum of Fig. 1 shows very poor energy resolution, with no clear distinction between the events in the counter and base electrodes. The LTSSM images have revealed that the poor spectrum reflects a pronounced spatial nonuniformity in the junction response. The three-dimensional plots in Fig. 2 display the spatial distribution profiles of the charge output values with the contour lines. The charge output values representing the centroids of the total absorption peaks for the events in the counter and base electrodes are shown in Fig. 2.

FIG. 1. Reconstructed full illumination x-ray spectrum of the 200×200 μm² junction for 6 keV synchrotron radiation at a bias current of 300 nA. The corresponding spatial distributions are shown in Fig. 2.

The events between the 6×10⁶ and 9×10⁶ electrons correspond to the mountains. The spatial distribution profiles of the counter and base electrodes are slightly different, but the shapes are similar. It is demonstrated that the LTSSM can visualize a small difference of electrode property, which may be present even in the symmetric junction structure.

It is interesting to examine the bias dependence of one-dimensional diagonal line scans shown in Fig. 3. The scanning interval was 10 μm. The bias currents correspond to voltages between ~0.3 and ~0.7 mV. At bias currents substantially lower than 60 nA, line scan curves had a shape of plateau, and the counter- and base-electrode events were hardly distinguished. They clearly split into two curves at 60 nA. A full two-dimensional (2D) scan at 60 nA showed that the plateau had a concave profile with knolls at the four corners as expected from Fig. 3. As the bias current increases, the center mountain seems to superimpose the plateau. Two curves at 300 nA are equivalent to Figs. 2(a) and 2(b). There are the intersections between the counter and base curves. A preliminary pulse shape analysis of the charge-sensitive preamplifier output indicated that the average rise times of the counter- and base-electrode events were meaningfully different in the plateau region and in the mountain region. This observation suggests that the signal creation
which was expected from the trapped Abrikosov vortices, \cite{12} trial magnetic field exhibited a charge output reduction, results. In addition, although the junction cooled in a terrestrial magnetic field, the \textit{y} axis and the charge output values. Two curves at 300 nA are equivalent to Fig. 2.

The earlier mentioned results were reproducible in several measurement runs. We have also measured a 200 \mu m square junction on the different chip and obtained the same results. In addition, although the junction cooled in a terrestrial magnetic field exhibited a charge output reduction, which was expected from the trapped Abrikosov vortices, \cite{12} the spatial distribution profiles were essentially the same. Therefore, the trapped vortices have a negligible influence on the present argument. On the other hand, in the junctions of 100 \times 100 \mu m$^2$ or smaller on the same chip, spatial distribution at any bias points had smooth convex profiles, which may be explained by the QD model. Consequently, it is concluded that the QD model is evidently inadequate for the large junction of 200 \times 200 \mu m$^2$.

The best energy resolution of 38 eV at 6 keV was obtained with a 5 \mu m microbeam illuminating the center of a 146 \times 146 \mu m$^2$ junction, with an electronic noise of 20 eV. The intrinsic resolution of 32 eV is larger than 12 eV predicted by the Fano noise and the tunneling noise, which is expected from the average number of quasiparticle tunneling times of 2.2 within the framework of the standard model.

At this moment, there is no detailed model that explains the spatial distribution profiles and the bias dependence. An hypothesis is that the spatial distributions are related to such Josephson junction dynamics as oscillations, resonant modes, or flux flows. An important dimensional scale with respect to the junction size $L$ is the Josephson penetration depth $\lambda_J \equiv (\Phi_0/2\pi\mu_0dJ_c)^{1/2}$, where $\Phi_0 = 2.067 \times 10^{-15}$ Wb) is the magnetic flux quantum, $d = 2\lambda_J + t$ is the magnetic thickness, and $J_c$ is the maximum Josephson current density. When we take a London penetration depth of aluminum for $\lambda_J = 16$ nm, a barrier thickness $t = 1$ nm, and a $J_c$ value of 200 A/cm$^2$, the $\lambda_J$ value is estimated to be 60 \mu m. For the 200 \mu m square junction the $L/\lambda_J$ value is 3.3, which signifies that the junction is of an intermediate size or larger. Therefore, the junction can be subject to nonlinear Josephson dynamic behavior. The present junction has 30-nm-thick aluminum quasiparticle trapping layers and quasiparticles are confined in such layers during the forward and back tunneling. The quasiparticles trapped in the aluminum layers have a high probability of interacting with magnetic fields within $\lambda_J$, thus increasing the chance to be subject to junction dynamic effects compared to junctions with no effective trapping layers or thicker aluminum layers. This preliminary hypothesis requires further theoretical analysis.

In summary, we have performed the full 2D imaging diagnosis of the STJ detectors with an x-ray microbeam. It has been shown that large junctions exhibit a pronounced spatial nonuniformity, which is also strongly depending on bias point. The spatial distribution profiles are inconsistent with the quasiparticle diffusion and edge loss model. Such results imply that two different signal creation mechanisms take place, responsible for the plateau and the mountain structures made visible by the LTSSM scans. To understand the observed phenomena, further experimental and theoretical studies are necessary.

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