Detection of single x-ray photons by an annular superconducting tunnel junction

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We present an experiment that detects photons by use of an annular Nb-based superconducting tunnel junction (STJ). In one magnetic field configuration, we stably trapped a single magnetic fluxon in the STJ barrier during a transition to the superconducting state. This is an innovative configuration which avoids the use of an externally applied field during detector operation. It offers potential benefits for STJs used in imaging arrays. In this configuration, and also in the conventional one with an externally applied parallel magnetic field, we observed current pulses produced by single 6 keV x-ray photons. The pulses were the same for the two configurations. [DOI: 10.1063/1.1405425]

Superconducting tunnel junctions (STJs) were proposed as photon and particle detectors with good energy resolution[1] and, since then, interest in this subject has expanded.[2] In operation, a photon absorbed by the STJ detector breaks Cooper pairs and creates excess quasiparticles. The number of excess quasiparticles is proportional to the photon energy. The quasiparticles are collected and counted by tunneling through the STJ barrier. In this way, the photon energy is measured with good intrinsic energy resolution that is allowed by the small superconducting energy gap, Δ ($\approx$1.5 meV for Nb). To minimize electronic noise, the STJ is biased in the subgap region of the current–voltage ($I-V$) characteristic where the dynamic resistance is large. To allow stable biasing, the Josephson critical current, I_c, must be suppressed from its zero-field value I_{c_0}. Typically, I_{c_0} is many orders of magnitude larger than the subgap current at the bias point, I_{qp}. The conventional method to suppress I_c consists of applying a magnetic field parallel $H_\parallel$ to the STJ barrier. This field has to be large enough to suppress I_c in a stable way, but should be much less than the critical field of the superconductor. Much effort has been devoted to finding the optimal STJ geometry to suppress I_c by a weak parallel field.[3–7]

The use of externally applied $H_\parallel$ has some drawbacks for detector application. First, the need for a continuously applied, stable field during detector operation could be problematic in some applications, for instance, in a satellite. Moreover, electromagnetic self-resonances occur at finite voltages on the $I-V$ curve of the STJ. These resonances are field dependent and can disturb the stability of the bias point even if they are small in amplitude.[8] Usually this problem has been solved by applying a large field to completely suppress any residual resonances, and by voltage biasing the detector far enough from the resonances that the degrading effect on the energy resolution is reduced. However, this is challenging when multiple STJs are employed. It is difficult to find a field value which fully suppresses I_c in every junction, due to small variations between junctions. For example, while good suppression was achieved in a 36-STJ array using a large field,[9] the suppression was not ideal in every junction.

An annular STJ provides an alternative route for achieving reproducible suppression of I_c. Here, fluxons are trapped in a ring-shaped junction, shown schematically in Fig. 1. Ideally, the flux should be trapped only between the two electrodes, in quantized units of $\Phi_0 = 2\times10^{-15}\,\mathrm{T\,m}^2$. Because of the quantization, it is anticipated that even with some variation of the geometry of different STJs in an array, each STJ would trap just an integral number of quanta. An applied $H_\parallel$ would then not be required during detector opera-

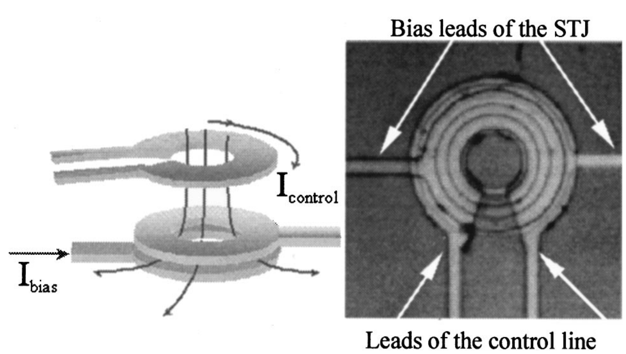

FIG. 1. Schematic "exploded view" of the annular STJ with a single trapped fluxon. The film thicknesses are not to scale. The control line coil is on top of the STJ. The magnetic field lines threading the electrode are shown. Also shown is a photograph of the Nb-based annular STJ detector which detected x-ray photons.

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tion. This was proposed in previous work.[10] Since then electromagnetic characterization of annular STJs was performed and many elements of the theory confirmed,[11,12] but no photon detection studies were undertaken.

To demonstrate the feasibility of using annular STJs as detectors a number of issues have to be addressed. One must develop a procedure by which to trap magnetic fluxons and one must determine (i) if trapped fluxons change I_{qp} in the STJ; (ii) if the detector performance deteriorates in the presence of trapped fluxons; and (iii) if trapped fluxons remain stably trapped in the STJ ring-shaped barrier under x-ray irradiation. Indeed, detrapping of fluxons was observed for STJ electrodes in conventional geometry under γ-ray and α-particle irradiation.[13] In this letter we present experimental results of x-ray photon detection by an annular STJ detector and we address most of the above issues.

In our experiments we employed two different field configurations. In the first, an annular STJ detector was voltage biased after suppressing its I_c with an externally applied $H_\parallel$. The bias point obtained was stable and allowed us to detect x-ray photons. The field remained during photon detection. This is the usual configuration used by STJ detectors. In the second configuration,[14] we cooled the annular STJ detector through its critical temperature, T_c, in a magnetic field perpendicular to the plane of the STJ tunnel barrier. A control line integrated on a chip above the STJ generated a perpendicular magnetic field. We trapped a single fluxon in the annular STJ barrier during transition to the superconducting state, as shown schematically in Fig. 1. Ideally, the fluxon in the tunnel barrier causes the superconducting phase difference, φ, to increase by exactly 2π as one moves around the loop of the STJ. Thus, I_c is zero because the critical current density is $J_c \sin\varphi$, which integrates to zero around the loop. This effect of the fluxon can be verified by measuring the $I-V$ curve and I_c vs $H_\parallel$ of the STJ. The perpendicular magnetic field that was initially applied can be turned off after the fluxon is trapped. The trapped fluxon suppresses I_c, allowing stable voltage biasing of the detector and photon detection. This is an innovative configuration which avoids the use of an externally applied $H_\parallel$ during detector operation.

The experiments were performed on a Nb/Al–AlO_x/Nb annular STJ with $J_c = 100\ A/cm^2$, shown in Fig. 1, fabricated on an oxidized Si wafer at HYPRES Inc.[15] The detector geometry is of ''island'' type, which has 3.5 μm wide leads connecting the electrodes to the read-out electronics. All the layers were patterned in the annular geometry. The STJ normal resistance is 3.5 Ω. A Nb control line in the form of a single turn coil was deposited coaxially on top of the STJ ring, as shown in Fig. 1. This control line was used either to supply a perpendicular magnetic field to the device during cooling through T_c, or to heat the device above T_c. A SiO_2 layer insulates the control line from the detector. Integration of the control line on the chip is intended to avoid using external coils to generate the perpendicular magnetic field required to trap fluxons.

Measurements of I_c vs $H_\parallel$ and of the $I-V$ curve were performed at 4.2 K and at 0.21–0.24 K in a two stage ^{3}He cryostat. The results at lower temperature were obtained in a rf-shielded box in order to reduce electromagnetic noise. Two superconducting NbTi coils were used to produce $H_\parallel$. The experimental dependence of I_c vs $H_\parallel$ at $T = 210$ mK is in quite good agreement to the theoretical[10] in spite of the fact that the experiment was performed with no dc magnetic shielding. The estimated Josephson penetration depth is $\lambda_J = 37\ \mu$m and the radius ratio is $\delta = R_{int}/R_{ext} = 0.5$ with $R_{ext} = 16\ \mu$m. In the theory we treated the STJ as ''small,'' that is, we neglected self-fields. In an annular STJ, the necessary condition is $R_{ext} < \lambda_J$ for an externally applied $H_\parallel$ or $R_{ext} < n\lambda_J[(\ln\delta)/(\delta^2-1)]^{1/2}$ in the case of n trapped magnetic fluxons.[6,16] Both conditions were satisfied in our device.

To perform the x-ray irradiation experiment in the first field configuration, we applied $H_\parallel$ to suppress I_c. The $I-V$ curve of our device is shown (dashed line) in Fig. 3 at $T = 210$ mK and $H_\parallel = 6.06$ mT. We biased our device at $V_b = 680\ \mu$V with $I_{qp} = 1.25$ nA. We acquired current pulses produced by single x-ray photons from a shutterable 6.56 mCi ^{55}Fe source with Mn K lines at 5.9 and 6.5 keV. The maximum collected charge from the STJ is $Q_{max} = 1.1\times10^5$ electrons with no pulse shaping. This is only about 4% of the predicted quasiparticle charge. Similar charge losses have been seen for other Nb-based STJs[17] which used a thin Al layer.

To trap a magnetic fluxon in the STJ barrier we employed the second field configuration. We followed one of three different procedures. In the first, we applied at $T = 4.2$ K a large current to the control line to drive it into the normal state and then used it as a local heater to drive the STJ normal. Then, quickly reducing the control line bias to a smaller, finite current, we allowed the annular STJ to become superconducting in the presence of the perpendicular magnetic field produced by this coil, of the order of 0.02 mT. This field would have been enough to produce two fluxons in the area of the STJ hole if the field threaded only through the barrier. The second procedure used the first one, but also included some bias current flowing at the same time through the STJ. The third procedure consisted of heating the cold finger on which the annular STJ detector is located and then cooling it while a small current was applied to the control line. We succeeded in trapping a fluxon only with the first procedure. Even this procedure was not fully repeatable. To obtain more repeatable results, efforts are in progress to fabricate STJs whose base electrode has no hole, is larger, and with T_c different from the top electrode.[18]

To check that a single fluxon was trapped, we measured both I_c vs $H_\parallel$ and the $I-V$ curve. The signatures of a single trapped fluxon in the annular STJ barrier are:[11] an almost completely suppressed I_c and the presence of only the first self-resonance on the $I-V$ curve at $H_\parallel = 0$. Once we observed these signatures, we cooled the device to $T = 240$ mK. No flux detrapping occurred. Figure 2 presents the I_c vs $H_\parallel$ observed (dots) together with the theoretical prediction (solid line).[10] I_c has been reduced to 2.5% of I_{c_0}, but does not achieve the ideal value, $I_c = 0$. Also the maxima are lower than expected. These minor disagreements can be attributed to the presence of some Abrikosov vortices trapped in the electrodes.[11] Because I_c was finite at $H_\parallel = 0$, we had to use an externally applied $H_\parallel$ to initially voltage bias the annular STJ. The $I-V$ curve of the device is shown (solid line) in Fig. 3 at $T = 240$ mK and $H_\parallel = 6.34$ mT, together with the curve (dotted line) we expected with no $H_\parallel$.

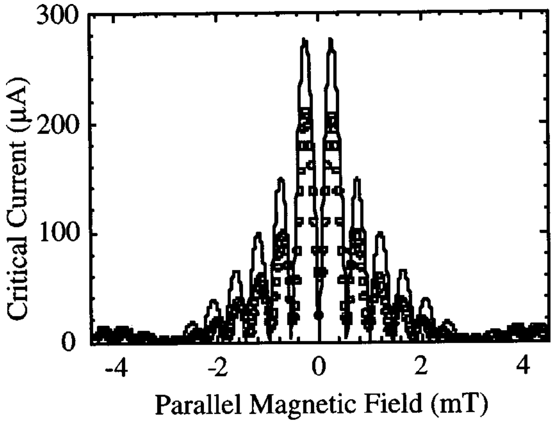

FIG. 2. I_c vs $H_{\parallel}$ of the sample. The dots represent the experimental results and the solid line the theoretical prediction: at $T=240$ mK with a single fluxon trapped in the STJ barrier.

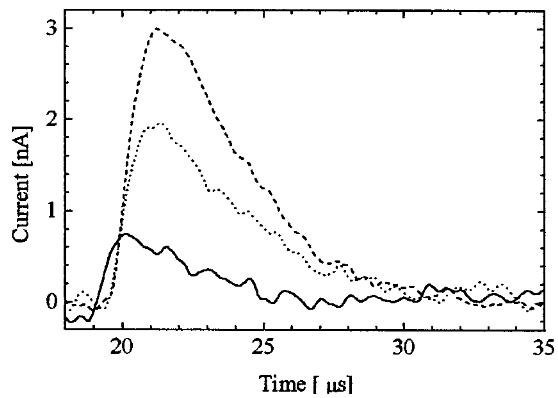

FIG. 4. Current pulses observed during the 6 keV x-ray irradiation in the presence of a trapped fluxon. The solid line is a pulse generated by an absorption event in the substrate or Nb control line. The dotted and dashed lines are pulses generated, respectively, in the top and base electrodes.

To detect photons with a trapped fluxon, we biased the detector at $V_b=725\,\mu$V with $I_{qp}=4$ nA, and then turned off the externally applied $H_{\parallel}$, without losing bias stability, as would happen in a STJ with nonannular geometry. We acquired x-ray current pulses and integrated these to determine the charge. Samples are shown in Fig. 4. These pulses appeared to be just like those observed with only $H_{\parallel}$. The fluxon stayed trapped during the x-ray irradiation. $Q_{\max}=1.7\times10^5$ electrons with no pulse shaping. This is a yield of about 6%. For both field configurations, the current pulses can be separated into three groups with different collected charge. The pulses with the smallest charge (solid line in Fig. 4) were generated by absorption events in the substrate or in the Nb control line, while the larger pulses were generated, respectively, in the top (dotted line) and base electrodes (dashed line, largest charge). The poor energy resolution obtained is mainly due to the loss mechanisms in the Nb. These included loss in the polycrystalline Nb electrodes, outdiffusion into the leads, self-recombination, and the presence of a background of small charge absorption events which can overlap over time with the x-ray current pulse due to absorption in the STJ electrodes. Use of an Al trap can reduce the losses in the polycrystalline Nb electrodes, while inserting a short section of higher gap superconductor into each of the leads can reduce outdiffusion. For future devices, the control line should be located outside the STJ area to reduce the background of absorption events in the Nb control line. This will also allow detection of less energetic photons (e.g., $E<3$ keV) which would otherwise be fully absorbed by the control line.

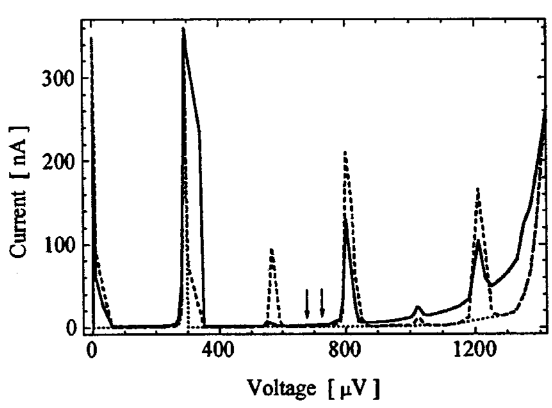

FIG. 3. $I-V$ characteristics of the sample. The dashed line is measured with no trapped fluxon at $T=210$ mK and $H_{\parallel}=6.06$ mT. The solid line is measured with a single trapped fluxon at $T=240$ mK and $H_{\parallel}=6.34$ mT and the dotted line is the curve expected without the parallel field. The two arrows represent the voltage bias points used in this work.

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