Quasiparticles Injection Effects for Nb/Al/AlO_x/Al/Nb Tunnel Junctions at 0.4K using Stacked Josephson Junctions

Hiroaki Myoren, Akiko Shigihara, Tohru Taino, and Susumu Takada
Department of Electrical and Electric Systems, Faculty of Engineering, Saitama University, 255 Shimo-okubo, Sakura-ku, Saitama 338-8570, Japan
E-mail: myoren@super.ees.saitama-u.ac.jp

Abstract. We have studied on the quasiparticles (QPs) injection effects for Nb/Al/AlO_x/Al/Nb tunnel junctions at 0.4 K. A device structure was a stack of an injector Josephson junction (JJ) and a detector JJ. At a low temperature, there is small number of thermally excited QPs and we expected to observe easily the QPs injection effect of the detector JJ using the injector JJ. In this study, the structure of the Nb/Al/AlO_x/Al/Nb tunnel junctions was the same for X-ray detectors using superconducting tunnel junctions. For constant-QPs current injection, we expected a small-signal current gain exceed the unity. We used pulsed-QPs current with changing pulse duration. For long duration, I-V curves for the detection junctions were sum of original current and QP current. On the other hands, for short duration time, the I-V curves showed different shapes from those for the long duration time.

1. Introduction
To realize current amplification in superconducting electric circuits, quasiparticles (QPs) trapping effects have been investigated.[1, 2] To obtain a large current gain, superconductor-normal phase change induced by QPs injections would be one of main roles.

Since photon detectors using superconducting tunnel junctions (STJs) generate QPs of order of 10^3 or less for infrared to visible lights, current amplifiers working at detector temperature close to detectors would be very useful. To simplifying the fabrication process, it would be convenient if the the amplifier consists of the same materials as the STJ structure.

In this study, we investigated QP injection effects of proximized Al trapping layers at 0.4 K, the STJ’s operating temperature.

2. Device Fabrication
Figure 1 shows a cross sectional schematic view of the device structure. QP injector-junction’s structure was Nb/Al/AlO_x/Nb and QP detector-junction’s structure was Nb/Al/AlO_x/Al/Nb and the detector-junction was stacked on the injector-junction. The detector-junction’s structure was the same as the STJ photon-detector’s structure that we used. Figure 2 shows a microscope image of a stacked JJ device. The 2-dimensional shape of the stacked JJ was normal-distribution-function-shape (NDF-shape) in order to reduce the applied magnetic field used for suppressing Josephson current.[3] We fabricated two different sizes of the stacked JJs: 1,600μm^2-d detector JJ
Stacked JJs were fabricated using RIKEN STJ fabrication line. To avoid the leakage current at sub-gap voltage regions, side walls of tunnel barriers were oxidized by oxygen plasma. Critical currents of stacked JJs were 200 A/cm² for the injector JJs and 50 A/cm² for the detector JJs. The observed gap voltage was around 3 mV for the injector JJs and 1.2 mV for the detector JJs. The Al(S') layers were proximized by superconductivity of Nb layers and showed enhanced gap voltage of 1.2 mV. The observed sub-gap leakage currents of a 1,600 μm²-detector JJ and 2,500 μm²-detector JJ were 2.7 μA at 1 mV and 6.0 μA at 2 mV, respectively, at 0.4 K.

3. Quasiparticles injection to detector JJs

3.1. Constant QPs injection effects

We measured I-V curves of the detector-JJs using triangle wave oscillated at 20 Hz, as changing the injection current at 0.4 K. Figure 3 shows I-V curves of a 6,400 μm²-detector JJ under applying constant QPs injections. The detector excess current, \( I_{\text{Det}}(I_{\text{Inj}}) - I_{\text{Det}}(0) \), at sub-gap voltage region was increased with increasing \( I_{\text{Inj}} \) but the gap voltage of the detector JJ didn’t change at all. It also should be noted that the excess current of the detector JJs did not depend on the polarity of the injection current. Figure 4 shows the detector excess current, \( I_{\text{Det}}(I_{\text{Inj}}) - I_{\text{Det}}(0) \), as a function of the injector current \( I_{\text{Inj}} \), extracted at \( V_{\text{Det}} = 0.5 \text{ V} \). The excess current for the
negative $I_{Inj}$ are also plotted as $I_{Inj} = |I_{Inj}|$. Apparently a threshold current $I_{Inj_{th}}$ exists and the excess current increased as $\sqrt{I_{Inj} - I_{Inj_{th}}}$. The excess current didn’t exceed $I_{Inj}$ but $I_{Det}(20 \mu A) - I_{Det}(0)$ increased proportional to the square root of the detector junction area $A$, as shown in Fig. 5. It seemed that a small fraction of $I_{Inj}$ contributed to excess current and the probability that $I_{Inj}$ contributes to the excess current, would be increased by increasing the junction area and 25,600$\mu m^2$-detector JJ would show unity gain as shown in Fig. 5. In Fig. 4, the expected small-signal current gain $\Delta I_{Det}/\Delta I_{Inj}$ is shown as a solid line. The gain exceed the unity was expected just above the threshold current of $I_{Inj_{th}}$.

![Figure 3](image1.png)

**Figure 3.** I-V curves of a 6,400$\mu m^2$-detector JJ under applying constant QPs injections with different current levels.

![Figure 4](image2.png)

**Figure 4.** QPs injection-induced excess current as a function of the injection current of the injector-JJ extracted at $V_{DET}=0.5mV$.

![Figure 5](image3.png)

**Figure 5.** QPs injection-induced excess current as a function of the square root of the junction area $A$. 
3.2. Pulsed-QPs injection effects

Instead of the constant current injection of QPs, pulsed-QPs with duration time $\tau$ were injected to the detector-JJs.

Figure 6 shows I-V curves of a 6,400$\mu$m$^2$-detector JJ subjected to pulsed QPs injections with $\tau=1.25\mu$s. The excess current $\Delta I_{\text{Det}}^-$ in the negative voltage region was larger than the excess current $\Delta I_{\text{Det}}^+$ in the positive voltage region. The asymmetric response ratio $\Delta I_{\text{Det}}^-/\Delta I_{\text{Det}}^+$ are plotted as a function of the inverse of the duration time $1/\tau$ in Fig. 7. $\Delta I_{\text{Det}}^-/\Delta I_{\text{Det}}^+$ was increased with increasing $1/\tau$. Since the duration time of X-ray photon-induced QPs current is less than 1$\mu$s for the STJ X-ray detectors, we expect larger asymmetric response using the stacked JJs for photon detector. This would lead us to get a large small-signal current gain for the X-ray detectors.

4. Conclusions

We have studied on the QPs injection effects for Nb/Al/AlO$_x$/Al/Nb tunnel junctions at 0.4 K. The detector excess current at sub-gap voltage region was increased with increasing the injection current but the sub-gap voltage of the detector JJ didn’t change at all. There was the threshold injection current and the small-signal current gain exceed the unity was expected just above the threshold current. We injected pulsed-QPs current with changing pulse duration to the detector JJ. For a short duration time, the I-V curves showed asymmetrical response, in contrast to those for a long duration time. This would lead us to a large small-signal current gain for the X-ray detectors.

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