Development of High Throughput X-ray detectors using Superconducting Tunnel Junctions with a large area size

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Abstract. We have developed 100-pixel Nb/Al based superconducting tunnel junction (STJ) array detectors which was enlarged the pixel size to improve X-rays detection throughput. The two different sizes of 100 µm × 100 µm and 160 µm × 160 µm STJs which consisting of Nb (100 nm)/Al (70 nm)-AlOₓ (70 nm)/Al (70 nm)/Nb (300 nm) were fabricated to determine the effective size of a single STJ. The leakage current, the fabrication yield and the energy resolution for Al-Kα of 100 µm-square and 160 µm-square STJs were 9.3 ± 4.6 nA and 12.3 ± 9.7 nA, 85 % and 84 %, 23.6 ± 4.6 eV and 27.5 ± 3.8 eV, respectively. Since these exhibited almost equal performance, it is found that STJs with a size of 160 µm × 160 µm can be used as a high throughput X-ray detector.

1. Introduction

Materials analysis using X-rays, particularly fluorescence analysis is utilized in various research fields. In conventional X-rays analytical instruments, semiconductor detectors are used to detect X-rays. However, by using the conventional ones, it is difficult to perform the analysis of light trace elements in advanced functional materials, which are important for realizing the low-carbon society. Because semiconductor X-ray detectors can’t distinguish clearly the characteristic X-ray peaks of light elements due to the limitation of its energy resolution. On the other hand, a superconducting tunnel junction (STJ) X-ray detector can exhibit theoretically several tens of times higher energy resolution than that of semiconductor detectors. Therefore, to realize advance X-ray analytical instruments with a quite high energy resolution, we have developed an STJ array detector. Our fabricated STJ arrays consisting of 100 pixels have already been applied for an X-ray absorption fine structure measurement of nitrogen dopants in n-SiCs [1]. However, the analysis throughput of our STJ array detectors is currently less than one-hundredth of semiconductor detectors one. To overcome the above drawback, there are two methods as follows. One is to increase the pixel number in the array. In fact, we had already developed a 400-pixel STJ array detector [2]. The other is to enlarge the pixel size. In the first
place the energy resolution of the total detection system using STJs, $\Delta E_{\text{total}}$, is assumed to be

$$\Delta E_{\text{total}}^2 = \Delta E_{\text{int}}^2 + \Delta E_{\text{ele}}^2.$$  

Here, $\Delta E_{\text{int}}$ is the intrinsic detector energy resolution of the STJ and $\Delta E_{\text{ele}}$ is the electronic noise. Generally, the larger the area size of STJ becomes, the bigger the $\Delta E_{\text{ele}}$ becomes due to an enlargement of the capacitance of the STJs, which leads to the degradation of the $\Delta E_{\text{total}}$. However, if $\Delta E_{\text{ele}}$ is sufficiently smaller than $\Delta E_{\text{int}}$, degradation of $\Delta E_{\text{total}}$ can be fairly small [3]. At this moment, the $\Delta E_{\text{ele}}$ of our measurement system has already been small, then it is possible to determine an appropriate STJ size to satisfy the energy resolution required for individual applications by evaluating the performance of the different size of the STJs. In addition, the fabrication yield is very important to realize the large detection area for array detector. This means the ratio of the number of STJs with the low subgap leakage current to the number of STJs in the whole array.

In this paper, we fabricated two types of Nb/Al STJs with different areas to determine the effective limit of the size of a single STJ. The fabricated STJs were evaluated by the current-voltage ($I$-$V$) characteristics, fabrication yield, $\Delta E_{\text{total}}$ and $\Delta E_{\text{ele}}$ on each STJ area size.

2. Fabrication and Experiment

Two types of STJs with different areas of 100 µm × 100 µm (100 µm-square) and 160 µm × 160 µm (160 µm-square) were designed. 100-pixel STJ array detectors of each size were fabricated in the Clean Room for Analog & digital superconductivity (CRAVITY) [4]. All STJs have a same multilayer structure with Nb (100 nm)/Al (70 nm)- AlO$_x$ /Al (70 nm)/Nb (300 nm). The STJs were fabricated using photolithography, DC magnetron sputtering, lift-off technique, reactive ion etching, and wet etching. These processes are explained by reference [5] in detail. The multilayer was fabricated by only DC sputtering equipment without breaking vacuum and tunneling barrier was formed by oxidation with O$_2$ gas. The Josephson current density ($J_c$) of the STJ was designed to be 200 A/cm$^2$. The STJ chips were fabricated on a 3-inch Si wafer. Each chip has an area of 10 mm × 10 mm. The 100-pixel STJ array was on the chip. Figure 1 (a) and (b) show a 100 µm-square and a 160 µm-square STJ in a 100-pixel array. The bias current is fed through the contact on the top electrode, which indicated with “A” in the figure 1. The almost area of the top electrode aren’t covered by the SiO$_2$ layer except for the area underneath top electrode (Nb) of the STJ. This structure can realize a high detection efficiency for low energy X-ray photons.

The STJs were cooled at ~0.34 K in $^3$He cryostat. To evaluate fabrication yield of two types of 100-pixel STJ array, we measured the subgap leakage current (I$_{\text{leak}}$) of all the STJ. The I$_{\text{leak}}$ was defined around energy gap ($\Delta/e$). The magnetic field was applied to suppress the Josephson current along the diagonal direction of STJ. Two kinds of 100-pixel STJ array were irradiated Al-K$_\alpha$ (1487 eV) X-ray to evaluate the detection performance. The fluorescent X-ray was generated using an Al

![Figure 1](image-url)
target and carbon nanostructure electron emitter. The output signals of STJs were amplified by 16-channel charge-sensitive amplifier and processed by 16-channel FPGA DSP based pulse height analyzer.

3. Results

Figure 2 shows typical I-V characteristics of two types of the STJs. In these figures, the $I_{\text{leak}}$ of 100 µm and 160 µm-square STJ were about 5.3 and 6.8 nA, respectively. The fabrication yields of the 100-pixel array of 100 µm and 160 µm-square STJ were 85 and 84 %. This means the total sensitive areas of the STJ array, which is the summation of the all STJ area size with the low $I_{\text{leak}}$, are $0.85 \times 2 \text{ mm}^2$ with 100 µm-STJ and $2.15 \times 2 \text{ mm}^2$ with 160 µm-STJ. The average and standard deviations of the $I_{\text{leak}}$ of 100 µm and 160 µm-square STJ were $9.3 \pm 4.6$ and $12.3 \pm 9.7$ nA, respectively. This uniformity of the fabricated STJ is considered to be obtained due to the high reproducibility of CRAVITY.

In the preliminary X-ray detection experiment, the constant bias current was fed to the array STJs because of excellent uniformity of the $I_{\text{leak}}$. Figure 3 (a) shows typical spectra obtained by two different sizes of the STJ irradiated by Al- K$_\alpha$. Peaks around 1300 and 1500 eV are generated in the bottom and top electrode of the STJ by X-rays absorption, respectively. These spectra of Al- K$_\alpha$ (top) are normalized by the number of these peak counts. Two peaks about 1800 eV correspond to the pulser. The $\Delta E_{\text{total}}$ of 100 µm and 160 µm-square STJ were 22.4 and 28.5 eV, respectively. These results show that both types of STJs exhibit better energy resolution than that of silicon drift detector (SDD) [6]. The $\Delta E_{\text{total}}$ of 160 µm-square STJ was slight inferior to 100 µm-square STJ.

Figure 3 (b) shows the distribution of $\Delta E_{\text{total}}$ about two different sizes of STJ in the 100-pixel arrays. The best $\Delta E_{\text{total}}$ of 100 µm and 160 µm-square STJ are 17.6 eV and 20.6 eV. The average and standard deviations of $\Delta E_{\text{total}}$ of 100 µm and 160 µm-square STJ were $23.6 \pm 4.6$ and $27.5 \pm 3.8$ eV, respectively. The $\Delta E_{\text{elec}}$ of the pulser was measured to be 7.5 eV with 100 µm-square STJ and 13.0 eV with 160 µm-square STJ. By using equation 1, the average of $\Delta E_{\text{int}}$ of 100 µm and 160 µm-square STJ were calculated to be 21.5 and 23.4 eV. Since $\Delta E_{\text{int}}$ of 160 µm-square is 1.1 times larger than that of 100 µm-square, these are almost equal. Thus, this degradation of $\Delta E_{\text{total}}$ was caused by increasing of the $\Delta E_{\text{elec}}$ for enlargement STJ size. Anyway, $\Delta E_{\text{total}}$ of 160 µm-square is sufficient to distinguish K-lines of various elements.

We succeeded in the enlargement of detection area of an STJ and good energy resolution.
Figure 3. (a) Energy spectrum measured by STJ for Al-Kα line. (b) Histogram of ΔE_{\text{total}} measured by 100 array STJ.

4. Conclusion
The 100-pixel array of 160 µm-square Nb/Al STJs was fabricated to improve throughput of detector. The fabrication yield of the 100-pixel array was 84%. The average and standard deviations of I_{\text{leak}} was 12.3 ± 9.7 nA. The average and standard deviations of ΔE_{\text{total}} was 27.5 ± 3.8 eV. This result shows that it is possible to operate STJ array detectors with 2.5 times larger detection area than that of the conventional STJ array consisting of 100 µm-square STJs, indicating that throughput of STJ can be improved with keeping enough high energy resolution.

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