Development of embedded STJ for large format array X-ray detector

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Abstract. We have been developing an embedded superconducting tunnel junction (e-STJ) for a large-format array X-ray detector. Compared with the conventional STJ array, the e-STJ array is suitable for enlarging the detection area effectively because the e-STJ detector utilizes a three-dimensional packaging technology. To investigate the relationship between the fabrication method and the electric characteristics of the e-STJ, we designed and fabricated three types of simplified e-STJ and measured their subgap leakage current in the temperature range from 4.2 K to 0.3 K. We found that the roughness of the embedding hole on the Si substrate and the contact part between the embedded STJ and the side of the embedding hole affected the subgap leakage current.

1. Introduction

Recently, X-ray detectors have been used in the material analysis field such as fluorescence analysis, and semiconductor detectors have been mainly used for material analysis; however, their energy resolution is limited by their energy gap [1]. On the other hand, X-ray detectors based on a superconducting tunnel junction (STJ) can be expected to theoretically have several tens of times higher energy resolution than semiconductor detectors [2]. Therefore, the STJ as an X-ray detector enables the measurement of light-element materials. However, conventional STJ detectors fabricated on a Si substrate are unsatisfactory for practical use owing to spectral artifacts and their small detection area. Spectral artifact events are generated in the Nb base electrode, wiring and SiO₂ of the STJ [3]. Here, we focus on SiO₂, which is generally used as the insulation and passivation layers of conventional STJs. It causes low-energy artifact events in the spectrum, which means that conventional STJs cannot clearly distinguish dilute specimens and detect weak light elements. To overcome this problem, another research group has proposed and demonstrated a new STJ design, which has a minimum junction edge coverage of SiO₂ [4]. Regarding the latter problem, the detection area of a single STJ is quite small (100 μm x 100 μm). When using a detector with a small detection area, it takes much times to obtain a spectrum. There are two methods of enlarging the detection area. One is by enlarging the detection area of a single STJ. We have been attempting to increase the detection area of a single STJ [5]. It is possible to operate an STJ detector with a 2.5 times larger detection area. The other is to increase the number of STJs, the so-called array detector. An STJ array detector with more than a hundred pixels has already been developed and applied to X-ray measurement using three-dimensional STJs, which embedded the
wiring layers under a SiO$_2$ insulation layer underneath the STJ array by introducing a chemical mechanical polishing process [6, 7].

In this paper, we propose and present a new STJ to further improve the artifact phonon events and detection area of the STJ. We focus on the construction of new STJs; three types of simplified STJ were fabricated to investigate the relationship between their fabrication method and electric characteristics.

2. Embedded STJ (e-STJ) array detector

Our proposed STJ is an embedded STJ (e-STJ) with a 3D packaging technology as a new array detector. Figure 1 shows the (a) cross-sectional and (b) top views of the e-STJ detector. The proposed array detector consists of three components described as follows. (1) The e-STJ has a structure in which the STJ is embedded in the Si substrate. The e-STJ array detector is fabricated utilizing a 3D packaging technology such as (2) that using through Si vias (TSVs) and (3) the flip chip bonding (FCB) method. The detector chip and the wiring chip are fabricated individually. The detector chip consists of the e-STJs embedded in the Si substrate, an absorption and common ground layer deposited on the whole chip, and TSVs. The thickness of the absorption and common ground layer can be adjusted with the irradiating photon energy. The wiring chip consists of superconducting bumps and wiring layers. These chips are mechanically and electrically connected through TSVs and superconducting bumps by the FCB method. We have been developing superconducting bumps [7] and superconducting TSVs. In Ref. 7, the Pb-In alloy is utilized as the superconducting bump. Its concentration ratio affects the electrical connection, surface morphology, roughness, and hardness of superconducting bumps. The results of the superconducting TSVs are as follows. The side wall of the proposed TSVs is tapered by deep reactive ion etching and grayscale lithography. The taper angle of TSVs can be controlled by modifying its mask design. The tapered TSVs enable the deposition of a thin film as its electrode. As a result, we have succeeded in electrically connecting through the superconducting TSVs using a Nb film deposited by dc magnetron sputtering instead of the conventional copper electroplating.

This e-STJ photon detector has the potential to further improve the artifact phonon events and detection area of the STJ. The conventional STJ as the photon detector is mostly covered with SiO$_2$. Therefore, the artifact phonon events appear in the spectrum. To solve this problem, a new design of the STJ, which has a minimum SiO$_2$ coverage, has been proposed and demonstrated in Ref. 3. On the other hand, the e-STJ has no SiO$_2$ insulation layer, as shown in Figure 1. This structure can be expected to provide a spectrum without the low-energy artifact events compared with other STJs. Concerning the detection area of the photon, the integration density of the conventional STJ array is limited by the wiring area. With the e-STJ, we can ignore the limitation due to the wiring area because the e-STJ array can ideally increase the number of wiring chips according to the number of arrays by the chip stacking technique, as shown in Figure 1(c) [8]. Each e-STJ is connected to a TSV and a superconducting bump.

![Figure 1](attachment:image.png)

**Figure 1.** (a) Cross-sectional, (b) top views of e-STJ array detector and (c) cross-sectional view of the e-STJ detector by the chip stacking.

Therefore, the e-STJ array is suitable for enlarging the detection area effectively. Figure 2 shows the effective detection area ratio with respect to the number of arrays of the conventional STJ and e-STJ.
Here, we define the STJ fabricated on the Si substrate as the conventional STJ. The effective detection area ratio denotes the ratio of the area of the STJ array to the required area to fabricate the STJ array. The design rules of this calculation are as follows. The junctions are squarely arranged, the width of the wiring is 10 µm, the space between the wires is 5 µm, and the area of the e-STJs is 100 µm × 100 µm. From this figure, the pixel number of the e-STJ can be increased effectively in comparison with that of the conventional STJ array.

![Image](image.png)

**Figure 2.** Detection area ratios of conventional STJ and e-STJ.

### 3. Fabrication of e-STJ

To utilize the e-STJ as an X-ray detector, the e-STJ with low subgap leakage current is required. The e-STJ is embedded in the embedding hole on the Si substrate. Therefore, there are two factors, that affect the subgap leakage current of the e-STJ. One is the roughness of the embedding hole. The thickness of the tunnel barrier of the e-STJ is about 1-2 nm. It is important to determine the etching condition of the embedding hole with high flatness. The other is the contact part between the embedded STJ and the side of the embedding hole, as shown in Figure 1.

#### 3.1. Formation of the embedding hole

The embedding hole on the Si substrate is formed by reactive ion etching (RIE). The flatness of the embedding hole is essential to the e-STJ with a low subgap leakage current. To investigate the suitable condition for the formation of the embedding hole, the surface of the embedding hole is analyzed by atomic force microscopy (AFM). The Si substrate is etched as a function of Ar gas pressure. Here, the etching depth is 200 nm. Figure 3 shows the dependence of the roughness of the embedding hole on the etching gas pressure. The measured roughness is the average of 3 points on the embedding hole. Results show that the Ar gas pressure of 0.5 Pa is suitable for obtaining a flat surface after Si etching.

#### 3.2. Fabrication of three types of simplified e-STJ

To investigate the effect of the contact part between the side of the embedding hole and the e-STJ, we designed and fabricated three types of simplified e-STJ with different embedding hole structures as follows. Type 1 is shown in figure 4(a) and (b). The top and base electrodes of the e-STJ are in contact with the side of the embedding hole. Type 2 has no contact part between the side of the embedding hole...
and the e-STJ, as shown in Figure 4(c), (d). The base electrode of the e-STJ shown in Figure 4(e), (f) is in contact with the side of the embedding hole (Type 3).

The fabrication of the three types of e-STJ is based on the Nb/Al fabrication technology. First, a Si substrate was processed by RIE to form an embedding hole of 160 nm depth. After the formation of the embedding hole, a multilayer film of Nb (100 nm) / Al (30 nm) / AlOₓ / Al (30 nm) / Nb (150 nm) was deposited by dc magnetron sputtering without breaking the vacuum. An AlOₓ tunnel barrier was formed by thermal oxidation in a 133 Pa O₂ atmosphere for 60 min. The e-STJ structure was patterned by photolithography and RIE. After forming the e-STJ, a SiO₂ film (450 nm) for insulation between the top and base electrodes of the STJ was deposited on the e-STJ. Then a Nb film (1000 nm) as a wiring layer was deposited. The area of the embedded STJ was 100 µm × 100 µm. The three types of e-STJ were fabricated on the same chip.

Figure 4. Top and cross-sectional views of three types of e-STJ.

Figure 3. Dependence of roughness of embedding hole on etching gas pressure.
4. Results of current-voltage characteristics

To confirm the quality of each e-STJ, the electrical characteristics of the e-STJs were measured in the temperature range from 4.2 K to 0.3 K. Figure 5 shows the $I$-$V$ characteristics at 4.2 K. Figure 5(a) shows the typical $I$-$V$ characteristics of the three types of e-STJ. As shown in this figure, the Josephson current density is 55 mA/cm$^2$. The Josephson current was suppressed by applying a magnetic field of about 10 mT. Figure 5(b) shows the $I$-$V$ characteristics of Types 2 and 3. The $I$-$V$ characteristics of Type 1 are shown in Figure 5(c). We found that Type 1 has a larger subgap leakage than the other types, which indicates that the contact part between the side of the embedding hole and the e-STJ increased the subgap leakage current, which deteriorated the characteristics. Figure 6 shows the temperature dependence of the subgap leakage current of the e-STJs. The vertical scale is normalized to the subgap leakage current at 4.2 K. The normalized leakage current of Type 3 is about five orders smaller than that at 4.2 K, and good characteristics were obtained. Figure 7 shows the $I$-$V$ characteristic at 0.3 K of the Type 3 e-STJ. As shown in Figure 7, its subgap leakage current is 30 nA at 0.3 K, and the e-STJ applicable for X-ray detection was successfully fabricated.

![Figure 5](image1.png)

Figure 5. (a) Typical $I$-$V$ characteristics of three types of e-STJ. Scale: x-axis 1 mV/div., y-axis 5 mA/div. (b) $I$-$V$ characteristics of Types 2 and 3. Scale: x-axis 500 μV/div., y-axis 200 μA/div. (c) $I$-$V$ characteristics of Type 1. Scale: x-axis 500 μV/div., y-axis 500 μA/div.

![Figure 6](image2.png)

Figure 6. Temperature dependence of subgap leakage current in temperature range from 4.2 K to 0.3 K.
5. Conclusions
We have proposed an e-STJ using fabricated by a 3D packaging technology such as that using TSVs and the FCB method. By using the e-STJ, we can increase the pixel number effectively to suppress the decrease in the ratio of the detection area to the number of arrays, which is an issue with the conventional STJ. The surface of the embedding hole was analyzed by AFM, and it was found that Ar gas pressure of 0.5 Pa is suitable for obtaining a flat surface. On the basis of the results, we designed and fabricated three types of e-STJ with different embedding hole structures. The I-V characteristics indicated that the contact part between the side of the embedding hole and the e-STJ increased the subgap leakage current, which deteriorated the characteristics. The e-STJ (Type 3), the base electrode of which is in contact with the side of the embedding hole, has a normalized leakage current about five orders smaller than that at 4.2 K, good characteristics were obtained.

In the future, to completely embed the STJ in the Si substrate, we will investigate an effective method of fabricating for the contact between the STJ side and the Si substrate.

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