

Improving the spatial resolution of superconducting tunnel junction THz wave detectors using a modified LiNbO₃ absorber

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Abstract. We proposed a superconducting tunnel junction (STJ) detector for terahertz (THz) waves with a modified substrate absorber. The absorber of each STJ was isolated by trenches in order to restrict the diffusion of phonons generated by THz waves, which are made with a dicing process. We evaluated the diffusion characteristics of phonons in the LiNbO₃ substrate by detecting THz photons. We found that the phonon diffusion length in a 500- μ m-thick LiNbO₃ substrate was over 1 mm. No degradation of the current – voltage (*I*–*V*) characteristics of the STJ after performing the dicing process.

1. Introduction

Terahertz (THz) waves are categorized between millimeter radio waves and infrared radiation. Since soft materials exhibit a high transmittance and many materials show specific absorption spectra in the THz range, THz waves have a great potential for use in a nondestructive imaging tool [1-3]. In fact, the detection of illegal drugs within envelopes has been done by THz waves [2]. To perform THz imaging and measurement of an absorption spectrum, a THz detector equipped with a fast response time, a broad band, and a large detection area is required. A superconducting tunnel junction (STJ) is one of the candidates for the THz detector. The STJ is attractive as a detector because of its high speed, high sensitivity, and wide band. We previously developed a STJ with a substrate absorber for THz photons [4]. The STJ detects phonons generated in the substrate when THz waves are illuminated from the back. These phonons are isotropically diffused in the substrate. Therefore, the spatial resolution of its detector is poor.

In this study, we fabricated a new STJ with a modified substrate absorber for the THz detector. The absorber size of each STJ was isolated by trenches in order to restrict the diffusion of phonons generated by THz waves, which are made with a dicing process. The trenches with a mesh pattern are formed from the back. Each STJ is fabricated on the front of the absorber and set in the center of each absorber divided by trenches. The absorber size can be modified by changing the trench pitch and affects the spatial resolution. The fabrication method and the evaluated results are reported.

2. Improvement of spatial resolution

The STJ consists of three layers, the top superconducting layer, thin insulation layer, and base superconducting layer. Usually, the STJ absorbs photons by the top layer. On the other hand, when a



substrate is used as the photon absorber, STJs detect phonons by the base layer. Our STJ, of which the fabrication process was described previously, was on an LiNbO_3 (LN) substrate [4]. The LN is the best material for detecting the THz waves.

Figure 1(a) shows a cross-sectional view of the STJs with a conventional LN absorber. The THz waves are illuminated from the back. The phonons diffuse isotropically in the substrate. The STJ detects phonons generated at different positions of the LN, the STJ cannot identify the illuminated positions of individual THz waves. Therefore, we proposed the modification of the absorber to improve the spatial resolution, as shown in Figure 1(b). Trenches formed on the opposite side of the STJs restrict the diffusion of phonons in the substrate. The THz waves were also absorbed at the bottom of the trenches. In order to eliminate generated phonon at the bottom of the trenches, the THz waves must be reflected at those areas. Therefore, an Al layer is deposited in the trenches. In order to decide the appropriate trench pitch, the evaluation of the phonon diffusion length in the substrate is required.

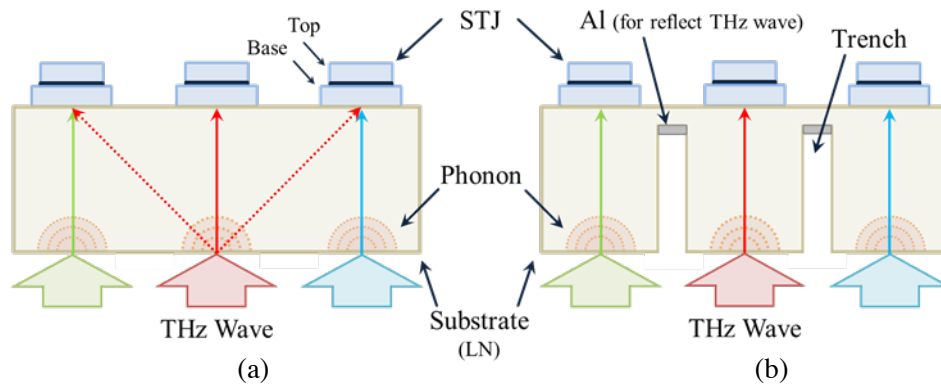


Figure 1. (a) STJ with a conventional substrate absorber (b) STJ with a modified substrate absorber.

3. Formation of trenches and Al deposition

There are two alternative processes to form the trenches on the LN substrate. One is the dry etching method, the other is the dicing method. It is difficult to etch the substrate by the dry etching method because of its large thickness of 500 μm . Although an etching yield of 10 μm was realized by using a nickel mask exhibiting a high selectivity ratio for the dry etching process [5], the nickel mask cannot be used in the process of STJs because of its magnetism. Therefore, we adopted the dicing method to form the trenches. It is important to determine the optimal conditions to prevent chipping at the edge of the trench. We succeeded in forming the trenches under the following conditions: speed of blade movement of 1 mm/s and rotation speed of 20000 rpm. The time of the making one trench was 25 second. Figure 2 shows a side view and an oblique view of the trenches. The trenches showed no chipping and the depth of the trenches was 320 μm , which is about 10% larger than the design value. The fabrication process to deposit the Al layer on the bottom of the trenches is as follows. First, the photoresist was coated on the substrate. Then the substrate with the photoresist was cut for forming the trenches. Without removing the photoresist on the LN, the Al was deposited by the sputtering from the back. After deposition of the Al layer on the substrate, the Al layer on the photoresist was removed using a lift-off process.

4. Phonon diffusion in the substrate

First of all, we fabricated the STJ with a substrate absorber for the THz photons. The STJ array with 25 (5×5) pixels was fabricated on the LN substrate of 500 μm thickness. The structure of the STJ was Nb (150 nm)/Al (20 nm)/ AlO_x /Al (20 nm)/Nb (150 nm) with the Josephson current density of about

100 A/cm². The size of each STJ was 100 μ m square. STJs were arranged with a pitch of 360 μ m on the LN substrate of 500 μ m thickness.

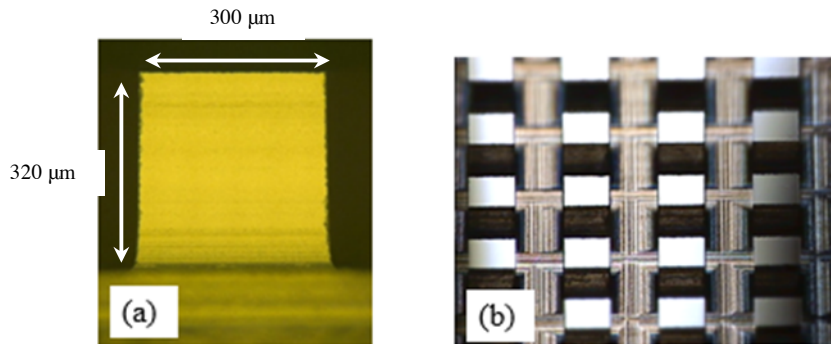


Figure 2. (a) A side view and (b) the oblique view of the trenches.

It is important, for our proposed THz detector, to evaluate the phonon diffusion in the substrate when THz waves are illuminated to the LN substrate, in order to reveal the optimal parameters of the trench pattern. To confirm the phonon diffusion, we used STJs without trenches. THz waves were illuminated to the LN substrate through a Si lens. The THz waves were generated by a ring terahertz parametric oscillator (R-TPO) as the THz pulse source [6]. Figure 3 shows the output pulse signal corresponding to THz pulse input from one STJ in the array. Then the output pulse signals were observed using the other 11 STJs. Figure 4 shows the dependence of the pulse height of the output signal on the STJ position. In this figure, the STJ situated with a distance more than 1 mm from the irradiated STJ can detect the generated phonons. When the intensity decay of the maximum output signal is 1/e, the phonon diffusion length of the LN substrate is estimated to be 1 mm. Therefore, if the device needs the spatial resolution of less than 1 mm, the LN has to cut into the desired size. Moreover, this result is the first demonstration of detection by the STJ array with a substrate absorber in the THz range.

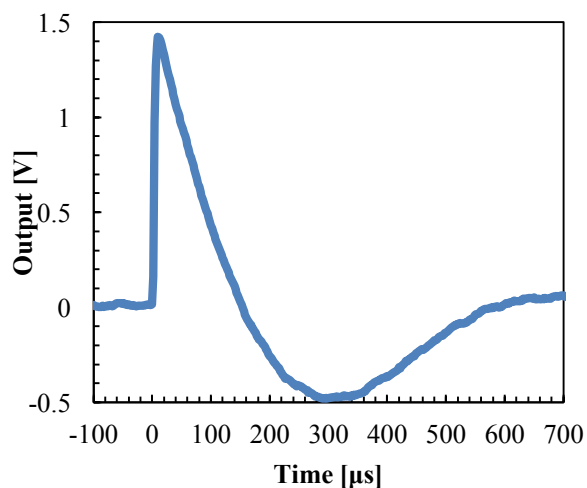


Figure 3. The output pulse from one STJ in the array.

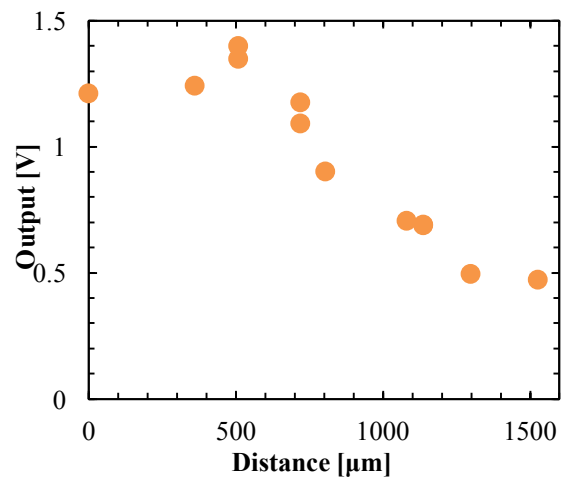


Figure 4. The dependence of the pulse height of the output signal on the STJ position.

5. *I-V* characteristics of STJ with trenches

To evaluate the effect of the dicing process on the STJ performance, the electric characteristics of the STJ were measured. The *I-V* characteristic of the STJ on the LN without trenches and with trenches at

4.2 K is shown in Figure 5(a) and (b), respectively. Each STJ of 100 μm square was fabricated on the front of the absorber and set in the center of each absorber divided by the trenches.

Figure 5(c) shows the temperature dependence of the subgap leakage current of the STJs without the trenches and with trenches. In these figures, similar results were observed in the temperature range from 4.2 to 0.3 K. Therefore, the formation of the trenches and the deposition of the Al layer do not affect the quality of the STJ.

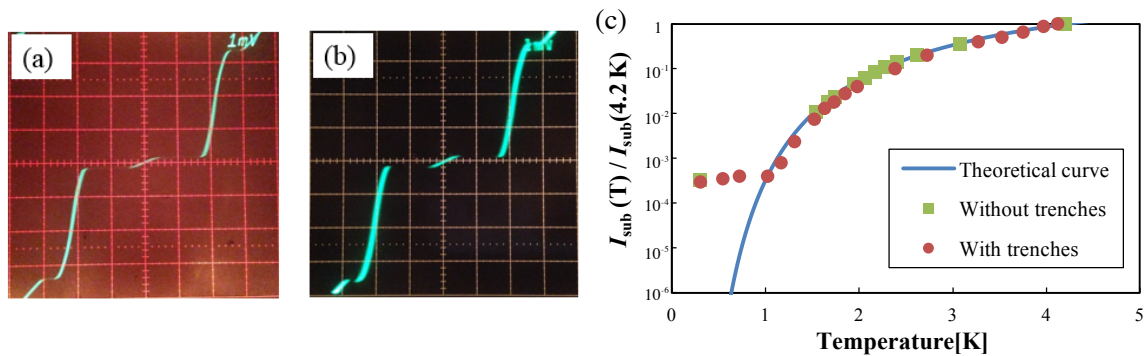


Figure 5. Current–voltage characteristics of the STJ (a) before the formation of trenches, (b) after the formation of trenches and (c) the temperature dependence of the subgap leakage current at the temperature range from 4.2 to 0.3 K.

6. Summary

We proposed and fabricated a STJ with a modified substrate absorber for THz photons. Our proposed STJ has trenches to restrict the diffusion of phonons. We obtained the diffusion of phonons in the THz range using the STJ array without trenches. The effect of phonon diffusion ranged over 1 mm with a 500 μm thickness of the LN substrate. Then, we succeeded in forming trenches on the LN substrate by the dicing method and the Al deposition for the reflect of the THz wave in the trenches. STJs on the LN without trenches and with trenches showed the same I – V characteristics at the temperature range from 4.2 to 0.3 K. Our future aim is to demonstrate for detecting performance of the STJ with trenches.

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