Direct and Indirect Detection of Terahertz Waves using a Nb-based Superconducting Tunnel Junction

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Abstract. We are developing a broadband THz detectors using Nb-based superconducting tunnel junctions. We found two components in a current signal for 1-2 THz pulse input. From the comparison of results obtained for the signals, the frequency response for the different size of STJs and the STJs fabricated on different substrate materials, we demonstrate that they correspond to photons absorbed with the superconductor electrode (referred as ‘direct’ component) and phonons generated by photons absorbed with the substrate (referred as ‘phonon-mediated’ component).

1. Introduction

Diagnosis using terahertz (THz) waves holds a great potential for various applications in fields such as medicine, biology, industry and agriculture because of its transmittance to soft matters as well as the good spatial resolution [1-3]. One of the important characteristics in the range is the specific spectral absorption feature. This feature is different from material to material and is applicable for identifying materials inside packages that are opaque to visible light. One of the most impressive examples of such applications is the detection of illicit drugs inside an envelope [4]. To utilize the specific spectral feature, a sensitive and wide-band detector is required.

We have developed a wide-band detector using a Nb-based superconducting tunnel junction (STJ). Previously, we reported the first detection of THz pulses from a THz pulse source, Terahertz Parametric Oscillator (TPO), by Nb-based superconducting tunnel junctions (STJs) fabricated on LiNbO\textsubscript{3} and LiTaO\textsubscript{3} substrates, when the THz waves illuminated the substrates [5]. In this detection, we expected that the THz photons were absorbed and generated THz phonons in the substrate (Fig.1). However, there remains a possibility of the contribution of the direct detection through the break of Cooper pairs in the superconductor electrode. In this paper, we report the first detection of the direct component and the phonon-mediated component simultaneously.

2. Experimental setup

A STJ consists of three kinds of layers: a top superconductor layer, a thin insulation layer, and a base superconductor layer. The real STJ devices used in the detection have the layer structure Nb/Al/AlO\textsubscript{x}/Al/Nb/substrate. The aluminum-oxide (AlO\textsubscript{x}) insulator works as a tunneling barrier. The thickness of each layer is as follows: 200 nm top niobium, 60 nm top aluminum, ~1.5-nm-thick aluminum-oxide, 60 nm bottom aluminum, and 200 nm base niobium. The substrates used were stoichiometric LiNbO\textsubscript{3} and LiTaO\textsubscript{3} mono-crystals with the thickness of 0.5 mm produced by Oxide Corporation. In addition, we also fabricated the similar STJs on a sapphire substrate with the thickness...
of 0.4 mm. The junctions of sizes of 20 µm x 20 µm, 50 µm x 50 µm and 100 µm x 100 µm were fabricated on the +Z surface of the substrate using a fabrication facility of RIKEN [6]. The size of the base electrodes of these junctions were slightly greater than the junction sizes, and were 40 µm x 40 µm, 70 µm x 70 µm and 120 µm x 120 µm for the 20 µm x 20 µm, 50 µm x 50 µm and 100 µm x 100 µm junctions, respectively (Fig. 2). The critical current density of the STJ was about 150 A/cm². The leakage current for a 50 µm x 50 µm junction was 13 nA at 0.2 mV bias voltage at 0.4 K. This value was about five orders smaller than that at 4.2 K.

The substrate on which the STJs were fabricated was directly mounted on a Silicon hyper-hemisphere lens at the cold stage of a 3He depressurized cryostat operated at 0.4 K. The stray radiation of 300 K blackbody through the window increased the DC current to 100 nA at 0.2 mV for the 50 µm x 50 µm STJ. The transmission efficiency of the thermal filters of the cryostat was about 10% at 1.5 THz. The transmittance of the Silicon lens was calculated to be about 70% due to the surface reflection. A magnetic field of 1.5-4.5 mT was applied during operation to suppress the superconducting tunneling current. The emergent tunnel current was fed to and amplified by an AC-coupled charge-sensitive preamplifier with the feedback capacitance of $C_{FB} = 1$ pF. THz pulses were generated using a frequency-tunable THz source (TPO), which can generate mono-chromatic pulses in the frequency range of 1-2 THz with the pulse repetition rate of 49 Hz [7, 8]. The typical pulse width is about 10 ns and is much shorter than the typical tunneling time of quasiparticles of an STJ. The laser pulses emitted with THz pulses were shut by a black-polyethylene film which was placed before the window of the cryostat. The beam size at the location of the STJ was estimated to be about 2 mm in diameter and was much greater than the size of the base electrode of the STJ. Detail of the setup is also found in [5].

3. Results and discussion

Fig. 3 shows the output signals of the preamplifier connected to the 20 µm x 20 µm, 50 µm x 50 µm and 100 µm x 100 µm STJs, when we input pulses of 1.5 THz from the TPO source [9]. The signal of the 20 µm x 20 µm STJ rose within about 1 µs, whereas that of 100 µm x 100 µm STJs rise with about 7 µs. The signal of the 50 µm x 50 µm STJ was just like a combination of these two. The risetime of an output pulse of the charge-sensitive preamplifier gives the duration of the tunneling current when a THz pulse illuminates the detector. To study the current variation more directly, we calculated the time derivative of the output signals of the preamplifier (Fig. 4) [9]. They clearly show that there are two different components: one is a fast one with the duration of about 1 µs and another is a slow one with the duration of about 7 µs. These timescales are comparable with those of the tunneling time observed for direct and phonon-mediated detection in X-ray detection, respectively. Therefore, it is natural to interpret that they also corresponds to the direct and phonon-mediated
components in THz detection, respectively. The reason why such a two timescales were not observed in [5] is that the pulse shape was obtained by the mean of several individual pulses and that the fast change of the output signal was smeared out. The difference of the pulse shapes for different size of STJs are explained by the size dependence of each component. The direct component is approximately proportional to the square of the size of the base electrode, whereas the phonon-mediated component is approximately proportional to the cubic dependence of the size.

Next, we compared the pulse heights of the output signals for different frequency in 1-2 THz. We used 20 μm x 20 μm, 50 μm x 50 μm and 100 μm x 100 μm STJs fabricated on a LiNbO₃ substrate. In the comparison, we used the pulse heights obtained with the broadband pyro-electric (deuterated L-alanine-doped triglycine sulfate (DLATGS)) detector as references reflecting the intrinsic source intensity during the measurements. The DLATGS detector itself has the flat frequency response in the frequency range. The 50 μm x 50 μm and 100 μm x 100 μm STJs showed the similar ones with the DLATGS detector. Since the phonon-mediated component does not show the strong frequency dependence, the main component in the 50 μm x 50 μm and 100 μm x 100 μm STJs is consistent with the phonon-mediated component. In fact, the integrated amount of this component was dominant in these STJs as seen in Fig. 3 and 4. On the other hand, the 20 μm x 20 μm STJ gave a very different features with the DLATGS detector. This means that the phonon-mediated component is not dominant in the STJ, and it is qualitatively consistent with that the almost all component detected with the STJ is faster one.

Furthermore, we compared the pulse heights for STJs (50 μm x 50 μm) fabricated on different substrate materials (sapphire, LiNbO₃ and LiTaO₃) as shown in Fig. 5. Because the absorption coefficient is the lowest for sapphire and the highest for LiTaO₃ in these three in this frequency range, the results mean that higher the absorption coefficient, more similar the shape with the frequency of DLATGS. This fact is consistent with that the phonon-mediated component corresponding to the slower current pulse shows the flat spectral response as DLATGS. This is also confirmed that we observed little faster current pulse for the STJ on a LiTaO₃ substrate and little slower pulse for the STJ on a sapphire substrate. From the whole results shown above, we conclude that the observed fast and slow components corresponds to the direct and phonon-mediated ones, and that the latter one shows the flat spectral response as DLATGS.
We are developing THz detectors using Nb-based superconducting tunnel junctions. We found two components in a current signal for 1-2 THz pulse input. From the comparison of the pulse shapes and the frequency response of the different size of STJs and those for STJs fabricated on different substrate materials, we demonstrate that they correspond to photons absorbed with the superconductor electrode (referred as direct component) and phonons generated by photons absorbed with the substrate (referred as phonon-mediated component).

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