Terahertz Detector using a Nb-based Superconducting Tunnel Junction

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Abstract

We have developed a terahertz (THz) radiation detector using a Nb-based superconducting tunnel junction (STJ). The STJ was fabricated on a stoichiometric $LiNbO_3$ substrate. The incident THz photons absorbed by the substrate generate THz phonons, and a substantial amount of the phonons are detected by the STJ. The detector is expected to be sensitive to a wide-band THz/far-infrared radiation above the energy gap of the Nb superconductor. We radiated monochromatic nanosecond THz pulses with the repetition rate of 49 Hz, and detected the corresponding periodic signals for the 1.1-1.9 THz radiation.

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). The STJ was fabricated on a stoichiometric $LiNbO_3$ substrate which abosorbs THz photons. Fig. 1 shows the schematic cross section of the detector. When a THz photon is absorbed by the crystal and generates phonon(s) of frequency within the THz range, the phonon(s) propagating in the substrate reaches to the superconductor electrode, breaks a Cooper pair, and generates quasiparticles. Then, the emergent quasiparticles passing through the tunnel barrier will be observed by measuring the excess of the tunneling current. This kind of phonon-mediated detector was proposed by Kurakado et al. for the detection of X-rays and high-energy particles [5]. The sensitive frequency is above the energy gap of the superconductor used in the base electrode. For niobium, the frequency corresponds to above 0.75 THz.

Fabrication and experimental setup

A STJ consists of three kinds of layers: a top superconductor, an insulator, and a bottom superconductor layer. The real STJ devices used in our detectors have the layer structure Nb/Al/AlOx/Al/Nb (See Fig.1). Niobium and aluminum are superconductors whose critical temperature is 9 K and 1 K, respectively. The aluminum-oxide (AlOx) insulator works as a tunneling barrier. The thickness of each layer is as follows: 200 nm bottom niobium, 50 nm bottom aluminum, thin (~nm) aluminum-oxide, 50 nm top aluminum, and 200 nm top niobium. The substrate used was a stoichiometric $LiNbO_3$ mono-crystal with the thickness of 0.5 mm produced by Oxide Corporation. We expect that the mean free path of phonons is longer in the stoichiometric one than others because of its low defect density. The STJs of sizes of 50μm x 50μm, 100μm x 100μm and 200μm x 200μm were fabricated on the +Z surface of the substrate using a fabrication facility of RIKEN. The critical current density of the STJ was about 150 A cm^{-2}. The leakage current for a 50μm x 50μm junction is about 15 nA at 0.2 mV bias voltage at 0.35 K. This value was about five orders smaller than that at 4.2 K. Detailed fabrication process of the device will be found in [6].

The fabricated detector was mounted on a Silicon hyper-hemisphere lens at 0.3 K stage of a ^{3}He depressurized cryostat. The stray radiation of 300 K blackbody through the window increased the DC current to 2 μA at 0.2 mV for the STJ with the size of 200μm x 200 μm. The transmission efficiency of the thermal filters of the cryostat was about 10 % at 1.5 THz. The transmittance of the Silicon lens is estimated to be 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.

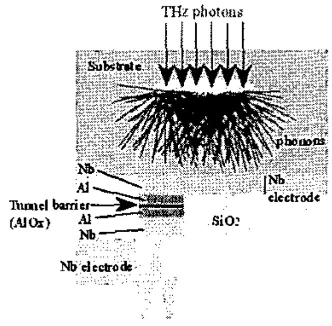

Fig. 1: Schematic cross section of tbe detector.

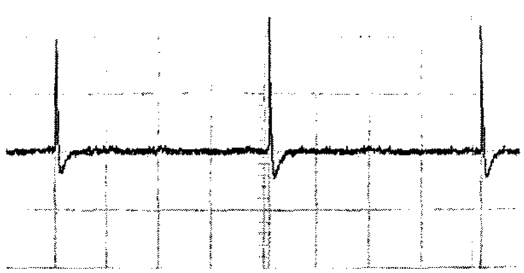

Fig. 2: Output of a preamplifier. The horizontal axis is 5ms/div and the verical axis shows 2 V/div, respectively. The frequency of input THz radiation was 1.5 THz.

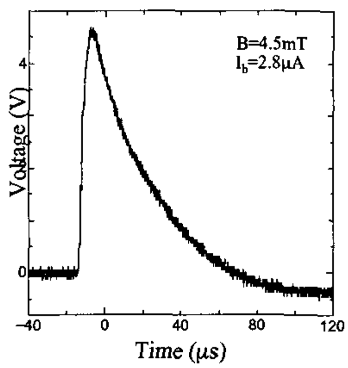

Fig. 3 Close-up of an output pulse of a preamplifier. The peak height corresponds to the integration of the output charges. The rise time corresponds to the duration of current output and the decay time is determined by the timescale of the preamplifier's feedback circuit.

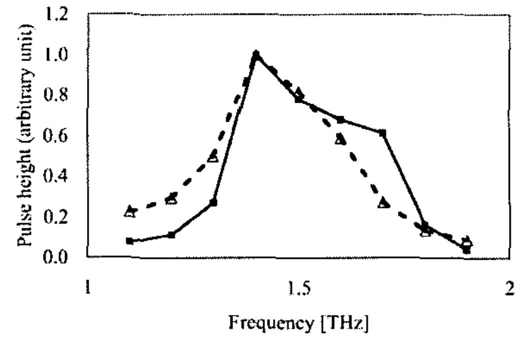

Fig. 4 Frequency distribution of TPO intensity measured by a STJ detector (solid line) and a DLATGS detector (dashed line). The pulse height was normalized by the intensity at 1.4 THz for each detector. Note that these data were obtained in independent measurements

THz pulses were generated using Terahertz Parametric Oscillator (TPO), which can generate monochromatic pulses in the frequency range of 1-2 THz with the repetition 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.

Detection of THz pulses

Fig.2 shows the output signal of the preamplifier connected to the 200μm x 200 μm STJ when we input pulses of 1.5 THz from the TPO source. The input power is about 10 pJ per pulse, which corresponds to about 7×10^8 photons per pulse after being corrected for the surface reflection on the Silicon lens and the filter transmission of the cryostat. The output pulses disappeared when we inserted a glass plate in the ray path. This shows that we detected the THz radiation by this kind of detector for the first time. The output pulse height was V_{out} = 6 V for a feedback capacitor of C_{FB} = 1 pF of the preamplifier. This means that the emergent current corresponds to charges of $Q = C_{FB} V_{out}$ = 6 pC = 4 x 10^7 electrons. The risetime (about 10 μs) of an output pulse of the preamplifier gives the duration of the tunneling current when a THz pulse illuminates the detector (Fig.3). This timescale corresponds to the detector response, and it shows that this detector can be used above 10 kHz repetition rate when a current preamplifier is used. The value is much greater than the typical risetime (about 1μs) of the direct detection of radiation by a similar STJ. This is a typical characteristic of phonon-mediated STJ detectors.

We compared the frequency response of the detector with that obtained in advance by a DLATGS detector (Fig. 4). Though they were independently measured in different conditions in different days, their trends are very similar. The difference in 1.1-1.3 THz and around 1.7 THz is probably due to the difference of the condition of the TPO source in these measurements.

The absolute efficiency is mainly dominated by the absorption efficiency of the substrate and the collection efficiency of photons by the STJ. The absorption efficiency of the 0.5 mm-thick $LiNbO_3$ substrate at 0.3 K is expected to be 5-10 %, and is much lower than that at room. The collection efficiency of phonons is unknown, but is expected to be higher than that estimated from the solid angle seen from the location of the absorption of photons. We expect that the reflection of phonons on the $LiNbO_3$-Nb interface is very small because of the good matching of acoustic impedance between $LiNbO_3$ and Nb. Assuming the amplification factor of the multi-tunneling process of our STJ to be about 3-7 [9, 10], the collection efficiency is roughly estimated to be about 5-10 % for a 200μm x 200μm STJ. The value is surprisingly high, and the reason has not been understood yet. The strong anisotropy of phonon propagation along the *Z*-axis direction of the substrate may play an important role for the high collection efficiency.

The absorption efficiency can be increased if we adopt a thicker substrate. In that case, the thickness should be determined by considering the mean free path of phonons in the substrate. The collection efficiency will increase by covering the surface of the substrate with many STJs. A series-array STJ detector invented by Kurakado *et al.* [5] is very attractive for the purpose, and it will increase the collection efficiency of phonons up to more than 50 %.

In summary, we have succeeded the detection of THz radiation by this type of detector for the first time. We demonstrated that the detector works as a broadband detector. The modification of the detector design will improve its performance significantly.

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