Research of Micro-stripline STJ Detector for Terahertz Band

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***Abstract*—We have proposed and demonstrated a new broadband and high efficiency THz wave detector using a superconducting tunnel junction (STJ). The detector consists of an impedance transformer and a long (micro-stripline) STJs, which are both located on a wing of a log-periodic antenna in the mirror-symmetrical arrangement. The detector utilizes the excess tunneling current caused by the Cooper pair breaking due to the radiation whose photon energy is greater than the energy gap of the used superconductor (around 0.7 THz for niobium). If the length of STJ is long enough compared with the mean free path of the emergent quasiparticles (~10 μm for niobium), the energy of THz waves is absorbed and we detect it.**

We have fabricated the device and performed the experiments for confirming the principle of this detector. We have succeeded the detection for the first time and the detector has sensitivity from 0.35 THz by the CPB process and some peaks by the PAT process.

***Index Terms*—THz wave, Detector, STJ, Transmission-line**

I. Introduction

Terahertz (THz) waves are electromagnetic waves with frequencies between high-frequency edge of the microwave band and the long-wavelength edge of far-infrared light. Although THz waves has been remained largely undeveloped due to the difficulty of generation and detection at these frequencies, a study of THz band has been significantly advanced in late years and THz waves are attracting a lot of attention in the field of not only basic research but also industrial applications [1].

For example, it is the shortest wavelength band having high permeability for various materials (particularly soft materials). By making use of the high permeability and moderate space resolving power, it is expected as a new non destructive inspection technology with minimizing the risk of radiation exposure. Furthermore, the THz wave may be used for powerful probe for early space exploration, since it is expected

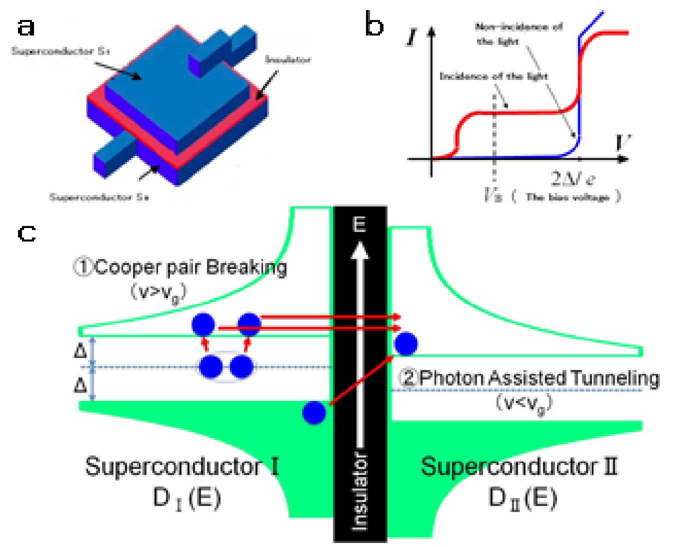

Figure1. Superconducting Tunnel Junction
a:Materials shown in blue are superconductors. Material in red is an insulator. b:Blue and red lines are I-V curves without and with radiation, respectively. c:Blue particles are represent electrons.

basically to have enough sensitivity to detect radiation at THz frequency, which is red-shifted light coming from the distant space. Our detector is a super high sensitive detector and we expect that it is used in the fields of basic research needing ultimate sensitivity.

II. Superconducting Tunnel Junction

THz detector using superconductor is more sensitive than any other room temperature detectors. The noise equivalent power (NEP) of a superconducting tunnel junction (STJ) to express minimum detection performance is

$$\mathrm{NEP} = \frac{N}{\eta GS} = \frac{2\Delta}{\eta G}\sqrt{\frac{I_0}{2e}}, \qquad (1)$$

where N is the current noise, η is the coupling efficiency, G

corresponds to the gain related to the back-tunneling effect, S is the current responsivity, Δ is gap energy of superconductor, and I_0 is leakage current. The STJ is three levels of structure of Superconductor-Insulator-Superconductor (SIS) (Fig.1a) and it shows strong non-linear current-voltage characteristics. We detect the light by using the characteristic current-voltage. There are two detection processes in the STJ detector. One way is the Cooper-pair Braking (CPB) and the other is the Photon Assisted Tunneling (PAT) process. They are separate by the gap frequency of the superconductor (Fig.1c). Gap frequency is found from the next expression.

$$h\nu_g = 2\Delta(0) = 3.528 k_B T_C. \quad (2)$$

Where h, ν_g, and k_B are Planck's constant, signal frequency, and Boltzmann's constant, respectively, and $\Delta(0)$ and T_C are the gap energy at zero temperature and transition temperature, respectively.

If superconductor is niobium, the gap frequency is approximately 0.7 THz. When the STJ is irradiated by THz radiation with a frequency greater than 0.7 THz, Cooper-pairs are broken by the incident radiation into quasiparticles which can tunnel across the barrier and a measurable increase of current can be observed if the bias voltage is applied to the STJ. Thus, we can detect the radiation by observing increase of quasiparticle tunneling current. The other process is that electrons below Fermi level are excited with the help of bias voltage and energy of the radiation less than the gap energy. It is our main purpose to make a broadband detector based on the CBP process.

III. Micro-Stripline STJ Detector

Since a long-length STJ can be considered as a micro-strip transmission line (Fig.2) [2], the energy of the electromagnetic wave coupled to the STJ is absorbed during propagation in the STJ transmission line. We can calculate a decay constant α for the electromagnetic wave in the STJ transmission line by the following equation,

$$A = \exp(-\alpha L_j) \approx exp\left\{-\left(\frac{R_S}{Z_j} + \frac{Z_j}{R_n}\right)/2\right\}, \quad (3)$$

where A is amplitude of THz wave in the STJ, L_j is length of the STJ, Z_j is a characteristic impedance of the STJ transmission line, R_s is the surface resistance of niobium, R_n is normal resistance of STJ. Since the longer length of the STJ, the higher absorption of energy, we have made STJs with four kinds of lengths to determine the optimum length. On the other hand, since the coupling efficiency of the radiation between the antenna and STJ depends on the width of STJ keeping the width of the impedance transformer constant, we have made STJs with three kinds of widths to find an optimum one.

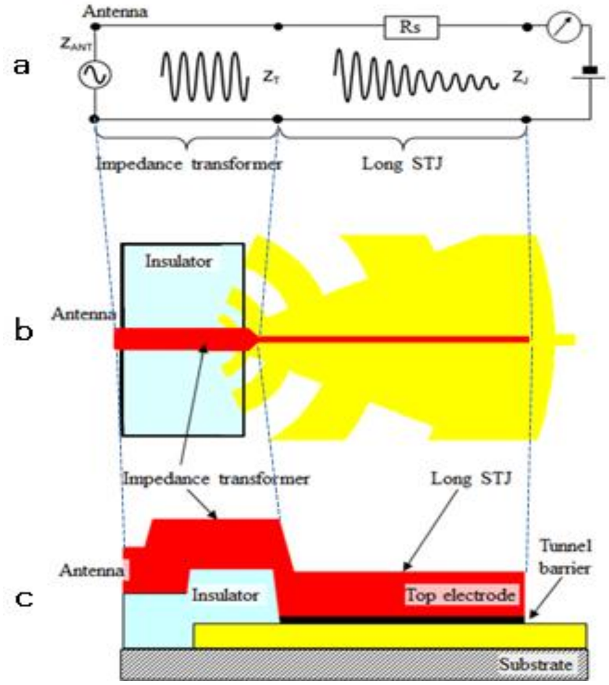

Figure2. Structures of micro-stripline STJ [3]
a:Circuit diagram, b:Top view, c:cross section

IV. Fabrication And Measurement

We fabricated these STJs in the RIKEN west clean room. Substrate is sapphire (Fig.3). STJ structure is five level of Nb/Al/AlO$_x$/Al/Nb=200/10/1/10/200nm. Oxidation is done at the condition of pressure-time product of 10 [Torr·hour].At first, dc I-V curve is measured at 1.5 K and it is found that leakage current I_0 at 1mV is 25nA and that 2Δ is 2.2meV. If we suppose η and G to be 1, then NEP in the dark is expected to be 1×10^{-16}[W/√Hz]. This NEP is low enough to be used for some applications such as the observation of cosmic radiation from the ground. In the next step, we measured optical properties of the STJ detector at 0.3K by a Fourier transform infrared spectrometer (FT-IR). We successfully detected THz wave above the gap frequency and found that STJ showed different optical properties which are strongly dependent on the bias voltage applied to the STJ (Fig.4).

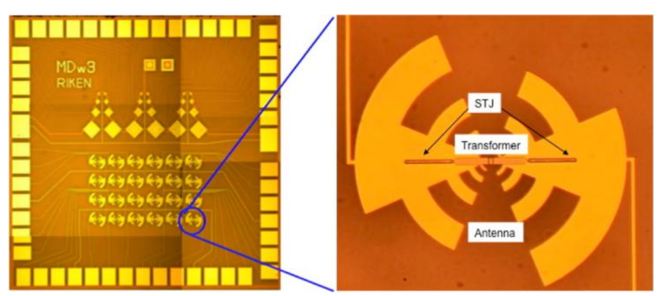

Figure3. Picture of a micro-stripline STJ
Left picture shows a picture of a chip with a dimension of 5×5 mm^2. 12 kinds of STJ devices with different combinations of length and width are located on the chip. Right picture is a magnified image of a STJ device

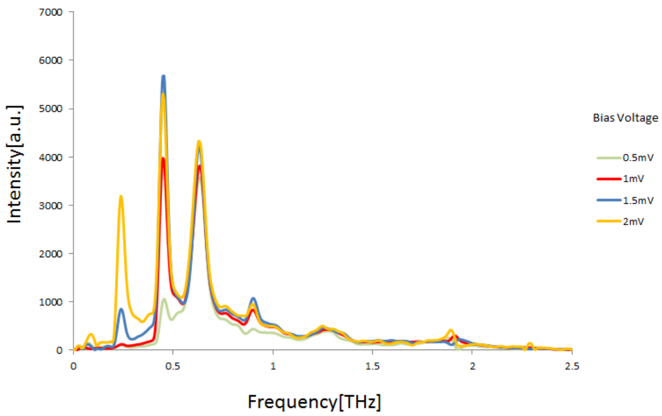

Figure4. Optical measurements (FT-IR)
Peaks located between 0.25 and 0.6THz may be attributed to the absorption by the PAT process, while those between 0.6 and 2.4THz may be attributed to the absorption by the CPB process.

V. CONCLUSION

We successfully detected radiation with frequency at 0.6THz, which is thought to be lowered from gap frequency of niobium by an effect of aluminum, or higher by CPB process. We found several sensitivity peaks below the gap frequency of 0.6 THz in the FTS response. Those peaks are attributed to the absorption of radiation by the PAT process, because the frequencies and height of the peaks decrease and increase, respectively, asincreasing the bias voltage. It is shown that our detector has sensitivity from 0.6THz to 2.4THz by the CPB process and from 0.25THz to 0.6 THz bythe PAT process. In the next step we are going to move on the detailed analysis on some peaks observed in the FTS response, and at the same time, to make an actual THz detector based on the present technology.

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