Terahertz imaging with a direct detector based on superconducting tunnel junctions

S. Ariyoshi,a1 C. Otani, A. Dobroiu, H. Sato, K. Kawase, and H. M. Shimizu
RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

T. Taino
Saitama University, 255 Shimo-Ohkubo, Saitama, Saitama 338-8570, Japan

H. Matsuo
National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

(Received 26 January 2006; accepted 3 April 2006; published online 17 May 2006)

We demonstrated terahertz imaging using a direct detector based on niobium superconducting tunnel junctions (STJs). The detector is composed of linearly distributed junctions placed on a superconducting microstrip line and is integrated on two wings of a log-periodic antenna. We succeeded nondestructive imaging for an integrated-circuit card and dry material using the detector around its sensitivity peak (≈0.66 THz). The dynamic range was measured to be higher than 4 × 107 (76 dB). Thus, the STJ detector is applicable to high-sensitivity and high-speed terahertz imaging for various nondestructive inspection applications. © 2006 American Institute of Physics. [DOI: 10.1063/1.2204842]

Terahertz waves, located at the gap between microwaves and infrared, have been recognized as a potential tool in a wide range of applications. Terahertz waves have the ability to penetrate various materials such as plastics, paper, wood, bone, semiconductors, and many others that are visually opaque. This ability is applicable to the nondestructive inspection of numerous materials in industry and the early diagnosis of cancer in medicine. Terahertz waves also opened the possibility in astronomical research to survey primordial galaxies, which unveil galaxy formation and evolution in the early universe.

Terahertz imaging devices with high sensitivity, wide frequency coverage, and large format arrays are required in these applications. Semiconductor bolometers have been widely used as high sensitivity cryogenic detectors of terahertz waves. However, bolometers are sensitive to temperature fluctuation, mechanical vibration, and electrical interference. Superconducting tunnel junctions (STJs) provide an excellent alternative. STJ direct detectors, based on the photon-assisted tunneling process, have a responsivity approaching the quantum-limited value e/hv at a bias voltage below the superconductor gap.1,2 For example, superconducting niobium is sensitive at radiation frequencies below 0.72 THz.

We have proposed and developed a terahertz-wave direct detector, with linearly distributed niobium STJs integrated on two wings of a log-periodic antenna (Fig. 1).3 The distributed junction array,3,5 which consists of two series of six parallel STJs placed on a superconducting microstrip line, achieves a broadband coupling of input radiation. Prototype detectors were designed to have the maximum sensitivity at 0.66 THz with a fractional bandwidth of 10%, which fits one of the essential atmospheric transmission windows at the astronomical observation site in Atacama Desert.6–8

STJ devices were fabricated using a conventional sputtering process, reactive ion etching, photolithography, and anodization for junction edges. They have the layer structure Nb/Al–AlOx/Al/Nb with 200 nm thickness for the Nb layers and 10 nm for Al. Each STJ has extremely low leakage current density of less than 1 pA/μm2 at 0.3 K, which is six orders of magnitude less than that at 4.2 K.3 The resulting noise equivalent power (NEP) of the detector is of the order of 10−10 W/√Hz. This value is dominated by the shot noise in the STJ leakage current, that is much higher than thermally excited leakage.3 Thus, significantly lower values of NEP can be achieved by reducing the leakage current. Table I summarizes the performance comparison of the STJ direct detectors, semiconductor bolometers, and superconductor bolometers generally called transition edge sensors (TESs). The comparison shows clear advantages of the STJ detectors in terms of imaging capability, cryogenics, sensitivity, dynamic range, and frequency response.

FIG. 1. Microscope photograph of a STJ direct detector. Linearly distributed junctions are integrated on two wings of a log-periodic antenna, whose radius is about 140 μm. The spectral response of the STJ detector is determined by a resonance circuit in the distributed junctions, while that of the log-periodic antenna is relatively broad, from 0.3 to 1.2 THz, so as not to disturb the detector spectral response.

aElectronic mail: ariyoshi@riken.jp

© 2006 American Institute of Physics.
As a demonstration of terahertz imaging with the STJ direct detector, we employed an imaging system using a backward-wave oscillator (BWO) as a terahertz source.\textsuperscript{10} The BWO source shows high output power and frequency tunability from 0.52 to 0.71 THz, which includes the sensitivity peak of the STJ detectors (0.66 THz). Figure 2 shows the BWO imaging system with the STJ detector. Continuous terahertz waves emitted by the BWO source are collimated and then focused onto the sample by two off-axis parabolic mirrors. The sample is moved in a plane perpendicular to the beam axis using an XY linear motor stage. The beam transmitted through the sample is refocused onto the STJ detector in a cryostat by an off-axis parabolic mirror, a convex terahertz lens, and a hyperhemispherical lens. The signal from the STJ detector is fed to a lock-in amplifier synchronized with an optical chopper in front of the BWO source, followed by a personal computer for image data acquisition. The optical system achieves nearly the diffraction limit and its spatial resolution is about 550 millimeters. We also used a deuterated L-Alanine triglycine sulfate (DLATGS) sensor as a reference detector.

We obtained terahertz images of two samples using one-pixel STJ detector. Figure 3 shows a terahertz image of an integrated-circuit (IC) card, with a scanning step of 200 μm. The internal structures such as a large six-loop antenna and other elements of the circuitry were seen with reasonably good spatial resolution. Figure 4 shows an image of powder milk inside a nylon bag, in which three needles were placed. The reflection and diffraction of the terahertz waves on the metallic needles make them appear as dark in the terahertz image. The total acquisition time using the one-pixel STJ direct detector was about 60 min for Fig. 3 and 40 min for Fig. 4.

The long acquisition time is not due to the detector time response nor the limitation of the detector sensitivity, but due to the data acquisition and the mechanical movement of the stage. Improvement of the data acquisition system as well as multipixel STJ detectors are expected to shorten the total acquisition time considerably.

The imaging performance of the STJ detector was evaluated by scanning a thin piece of aluminum foil with a 1 mm diameter hole and by choosing different values for the time constant of the lock-in amplifier [Fig. 5(a)]. Each image of the aperture was used to estimate the signal-to-noise ratio (SNR), defined as the peak signal on the aperture divided by the rms signal of the opaque area. Figure 5(b) shows the SNR measured by the STJ detector, compared to a DLATGS sensor that has a NEP of 6 × 10\textsuperscript{−14} W/√Hz, as a function of the integration time from 3 up to 300 ms. At 10 ms integration time, for example, the STJ detector operated at 0.3 K had a SNR of over 60 dB, which was about 3.5 orders of magnitude higher than that of the DLATGS sensor in these measurements. Therefore, if we introduce a 0.3 K STJ detector array with 100 elements, the time to scan the area in Fig. 5(a) will be only 1 s at SNR of 1 000 000 at integration time of 10 ms per point. The relatively high SNR allows the detector to be applied in high-speed imaging for various kinds of inspection. We also evaluated the dynamic range of the 0.3 K STJ detector, defined as the maximum photocurrent divided by the dark noise that was observed when the 4 K cryostat window was blocked. The maximum photocurrent of 4 × 10\textsuperscript{−15} A was measured at the BWO frequency of 0.66 THz, and the dark noise was 1 × 10\textsuperscript{−14} A/√Hz, which

TABLE I. Comparison of STJ direct detectors and semiconductor/TES bolometers.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>STJ direct detectors</th>
<th>Semiconductor bolometers</th>
<th>TES bolometers</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEP limited by Leakage current</td>
<td>10\textsuperscript{−16}</td>
<td>10\textsuperscript{−16}, 10\textsuperscript{−17}</td>
<td>...</td>
<td>W/√Hz</td>
</tr>
<tr>
<td>Voltage response</td>
<td>≤0.8</td>
<td>≤0.3</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Time constant</td>
<td>≤10\textsuperscript{−3}</td>
<td>≤10\textsuperscript{−3}</td>
<td></td>
<td>V/W</td>
</tr>
<tr>
<td>Array size (expected)</td>
<td>≤1000</td>
<td>≥100</td>
<td></td>
<td>1000–10000 pixels</td>
</tr>
</tbody>
</table>

FIG. 2. Schematic of the BWO imaging system with the STJ detector. The numbers on the optical elements indicate their effective focal lengths in millimeters.

FIG. 3. Terahertz image of a railway payment IC card. This card is 50 × 85 mm\textsuperscript{2} in size and 1 mm thick. The scanning step is 200 μm.

FIG. 4. Left: A nylon bag containing dehydrated milk powder, about 3 mm in thickness, in which three needles were inserted. Right: The terahertz image of the central 50 × 50 mm\textsuperscript{2} area with the scanning step of 200 μm, revealing the needles.
was of the same order of magnitude with the shot noise in the dark leakage current of 100 pA. The resulting dynamic range was higher than $4 \times 10^7$ (76 dB).

In conclusion, we have demonstrated the possibility of terahertz imaging using an STJ-based direct detector, for the first time. The STJ detector at 0.3 K shows superior imaging performance compared with a room temperature DLATGS sensor. Highly sensitive terahertz imaging with the STJ detector will make it possible to achieve fast and nondestructive inspection of various industrial materials.

We expect that future advances will come from the following two directions. The first is the detector array development. The STJ detector has a good potential to be used in multispectral focal-plane array sensors because of its intrinsic bandpass filtering characteristic, which can be adjusted by tuning parameters in the distributed junctions. The detector array can be also used for real-time imaging. The second is a 0.3 K cooling system for the STJ detector. In recent years, pulse-tube refrigerators with qualities such as ease of use, low noise, long duration, and remote operation have become not only available but also affordable. Such mechanical refrigerators will replace the liquid helium cryostat and accelerate the practical application of the STJ detector.

The authors thank Dr. Takashi Noguchi for useful discussions. This work was supported by the Leading Project “Development of Superconducting Terahertz Detector Array” and partially supported by the Grants-in-Aid 17686010, both from the Ministry of Education, Culture, Sports, Science and Technology of the Japanese Government.