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Terahertz direct detection in $YBa_2Cu_3O_7$ microbolometers

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***Abstract*— A high sensitivity broadband terahertz direct detector based on $YBa_2Cu_3O_7$ high-Tc superconductor microbolometers is presented. At 77 K, the responsivity of the spiral antenna-integrated microbolometers (1.5 μm x 1.5 μm) is 190 V/W, referenced to the input of the silicon substrate lens, across the frequency range of 330 GHz to 1.63 THz in a single device. The response time is approximately 300 ps. Using a room temperature readout, we measure an optical noise equivalent power (NEP) of 20 pW/Hz$^{1/2}$ (readout noise limited) for modulation frequencies ranging from 500 Hz to 100 kHz.**

***Index Terms*—Terahertz (THz) detectors, microbolometers, spiral antenna, superconductor, YBCO.**

I. Introduction

Antenna integrated superconducting microbolometers have been used both for heterodyne and direct detection at terahertz frequencies (100 GHz to 10 THz), although mainly for radio astronomy [1], [2]. Necessity of LHe cooling prevented bolometers from being used in other applications, like THz imaging, and spectroscopy [3]. After the discovery of high-temperature superconductors, significant attention has been paid to the implementation of superconducting bolometers that are capable of operating at temperatures as high as 90 K [4], [5]. Now, very compact cryocoolers are available, with a cooling capacity down to 77 K [6], which makes high-Tc bololometers potentially attractive for a wide use.

Another type of THz detectors, which utilize high-Tc superconductors are Josephson junction detectors. At temperatures close to LHe an NEP ~20pW/ Hz$^{0.5}$ was reported in [7] at 600 GHz. As the temperature approaches the Tc, the sensitivity of Josephson junction detectors at THz frequencies decreases [7]. Recently, junctions with higher characteristic voltages were reported [8], demonstrating en electrical NEP (excluding optical losses) of 5 pW/Hz$^{0.5}$ at 600 GHz and 80 K.

As direct detectors, $YBa_2Cu_3O_7$ (YBCO) bolometers have been theoretically predicted to reach a phonon noise-limited NEP of 3 pW/Hz$^{0.5}$ [9]. This is much lower than for other wideband THz detectors, like Golay cells or pyroelectric detectors [10], [11]. In [12], an NEP of ~9 pW/Hz$^{0.5}$ was reported for an YBCO bolometer with a log-periodic antenna. Such sensitivity was achieved by thermally isolating the bolometer using an air-bridge approach. The resulting response time was τ ~10 μs. In [13], an YBCO bolometer on a bulk YSZ substrate was discussed with an electrical NEP of ~4.5 pW/Hz$^{0.5}$; however, the optical efficiency was only 5%. This bolometer had a time constant of ~20 μs. In both cases, the THz optical responsivity was measured using broadband black body sources. Therefore, spectral information on the YBCO bolometer responsivity across the THz range was not accessible. Furthermore, many applications require detectors with even higher response rate, e.g. observations of short electromagnetic pulses, fast scan spectroscopy, active imaging [14], [15].

In general, bolometers on bulk substrates are more attractive from a practical point of view. This device structure makes them more robust, and the fabrication process is more reproducible. For YBCO thin films on bulk substrates, a bolometric response on the order of ~ns can be achieved [16].

In this paper, we present antenna integrated YBCO microbolometers, where we combine both a high sensitivity (comparable to Schottky diode detectors) and a nanosecond response time in a single device. We performed optical characterization of bolometers over a wide frequency range, ranging from 330 GHz to 1.63 THz. Both the responsivity and the noise were optimized versus the bolometer operation temperature.

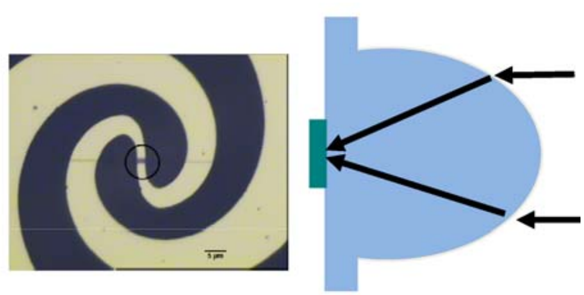

Fig. 1. A photograph of a spiral antenna-integrated YBCO microbolometer. The bright area is gold. The bolometer is at the center (in the circle). (left) The bolometer chip is mounted on an elliptical silicon lens. (right)

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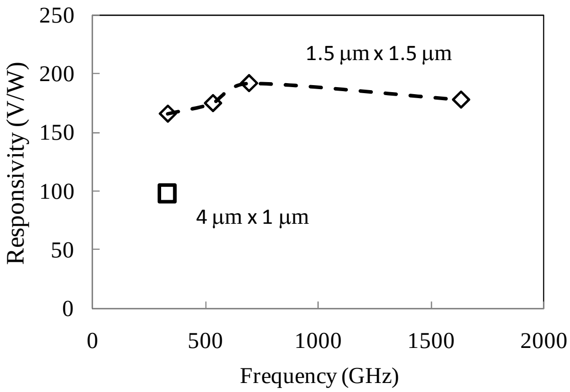

Fig. 2. Responsivity versus signal frequency at 77 K for the 1.5 μm × 1.5 μm (diamonds) and 4 μm ×1 μm (square) sized bolometers.

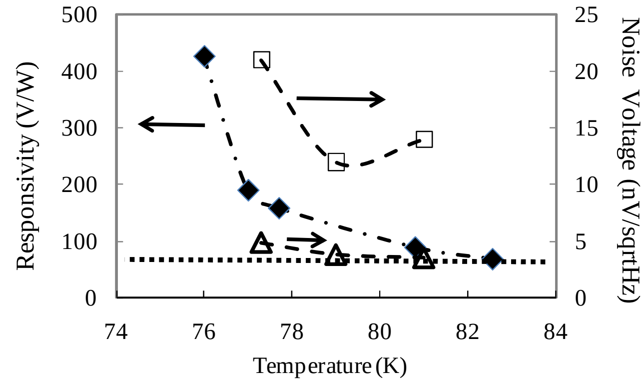

Fig. 3. Responsivity as a function of temperature for a 2 μm × 1 μm in size bolometer at 330 GHz is shown with filled diamonds. The total system noise (bolometer + readout) is shown with open squares (18 Hz) and triangles (1 kHz). The lock-in amplifier noise (1 kHz) is shown with a dotted line.

II. Device fabrication

Bolometers were fabricated using 50-nm-thick YBCO films on sapphire substrates with a CeO_2 buffer layer using pulsed laser deposition. The critical temperature was 88 K in continuous film. The YBCO film was patterned as a microbridge so as to overlap the antenna (made of 350 nm thick gold film) via UV photolithography (see Fig. 1). The bolometer area between the antenna pads was (the width, *w*, times the length, *l*) 1.5 μm x 1.5 μm, 2 μm × 1 μm, and 4 μm × 1 μm. The choice of a logarithmic spiral antenna was motivated by its real impedance of 90 Ω in a wide frequency range [17]. The substrate with the antenna-integrated bolometer was then clamped to the backside of a 12-mm elliptical silicon lens. The fabricated microbolometers exhibited a normal state resistivity of ρ_n = 270 μΩ×cm and a critical current density of j_c = 4 MA/cm^2 at 77 K, indicating that the high quality of the film was preserved through the fabrication process.

III. Measurement technique

The responsivity (the ratio of the output voltage to the incident RF power) was measured at 330 GHz and 530 GHz using a backward wave oscillator (BWO) and at 0.69 THz and 1.63 THz using a FIR gas laser as signal sources. The sources were amplitude modulated by a chopper wheel at 18 Hz, which provided a 100% modulation depth. The incoming THz beam was matched to the bolometer (on the silicon lens) using a Teflon lens. The beam power at the cryostat window was calibrated with two types of THz power meters: a Thomas Keating and an Erickson PM4. Spiral antennas are generally elliptically polarized with an axial ratio that varies from zero (linearly polarized at the edges of its frequency band) to 1 (circularly polarized in the middle of the band) [17]. Because the polarization of the THz sources was linear, we assumed a polarization coupling factor to our antenna of 0.5. A transmission coefficient through the cryostat window of 0.7 was another factor, which we included in the beam power calibration. We have not corrected for Si lens reflection losses. The correction factors (for the polarization and the window loss) were verified during the bolometer tests. For this purpose, the bolometer was heated to a temperature that was above Tc. In this case, the effects of both the RF power and the dc power on the bolometer were entirely thermal and were, hence, the same. Therefore, the isothermal technique for computation of the RF power absorbed in the bolometer is valid [18]. In this way, we identified that the ratio of the THz power that was incident on the cryostat to the power absorbed by the bolometer was approximately 4:1. This ratio agrees with our estimates presented above (including Si lens reflection losses).

The bolometer response was measured using a lock-in amplifier, which had a noise level of approximately 10 and 3 nV/Hz$^{0.5}$ at 18 Hz and 1 kHz, respectively. For the noise measurements, the same lock-in amplifier was used with an internal reference source from 18 Hz to 100 kHz. The bolometer response time was measured by mixing two sources (at 100 GHz: Gunn diode oscillators; and at 530 GHz: BWOs), and recording the roll-off of the bolometer response versus the beating frequency from 50 MHz to 1.5 GHz. The superior frequency stability of the Gunn oscillators permitted lower beating frequencies to be reached. During all of the measurements, the bolometers were constant current biased to the resistive state, i.e. exceeding the critical current value. At each temperature, responsivity maxima were observed at approximately 40 mV for the 1.5-μm- and 2-μm-wide bolometers and at approximately 30 mV for the 4-μm-wide bolometers. The dc resistance at this point was ~1/3 of the normal state value.

IV. Experimental Results

Fig. 2 summarizes the results of the responsivity measurements at 77 K. The responsivity variation from 330 GHz to 1.63 THz appears to be small. For the larger size bolometer, the responsivity is reduced, scaling approximately as the inverse of the bolometer area. The responsivity degrades as the bolometer temperature approaches T_c (Fig. 3).

The measured system noise, *Vn*, is strongly dominated by the noise that is coming from the readout. At low modulation frequencies (e.g., at 18 Hz in Fig. 3) up to approximately 200 Hz, the bolometer noise exceeds the lock-in amplifier noise. This low frequency noise decreases as the temperature approaches Tc. On the contrary, at modulation frequencies above 500 Hz (at 1 kHz in Fig. 3), the lock-in amplifier noise was dominating. The temperature dependence in this case was negligible. From 1 kHz and up to 100 kHz (the higher frequency limit of the lock-in amplifier), the noise stayed constant at approximately 3 nV/Hz$^{0.5}$.

Using the responsivity, S_V, and the noise voltage, the NEP was calculated as $NEP = V_n/S_V$. The presently achieved NEP is 110 pW/Hz$^{0.5}$ at 18 Hz and 20 pW/Hz$^{0.5}$ at modulation frequencies of 500 Hz and higher.

The roll-off of the bolometer response to the mixing signal from two THz sources was measured for both the 2-μm- and the 4-μm wide devices and fitted with a single-pole Lorentzian $S(f_{IF}) = S(0)/[1+(2\pi\times f_0\tau)^2]$, where f_0 is the beating frequency, $S(0)$ is the response at f_0=0, and τ is the bolometer time constant. The resulting time constants were approximately the same for both devices, 300 ps±100 ps. Considering the volume of the device, *V*, and the YBCO specific heat, *C* [19], at 90 K, we observed that the thermal conductivity from the bolometer to the heat sink ($G = C{\cdot}V/\tau$) was approximately 50 μW/K and 100 μW/K for the 2-μm- and the 4-μm-wide devices. Another method of measuring the thermal conductivity from the bolometer is as discussed in [13]. The bolometer was heated just above the Tc, and the resistance change versus the dissipated dc power was measured, $\partial P_{dc}/\partial R$. Using the $\partial R/\partial T$ from the *R(T)* curve, the heat conductivity was calculated as

$$G = \partial P_{dc}/\partial R \times \partial R/\partial T \quad (1).$$

We performed such computations for the 2-μm- and the 4-μm-wide devices. The obtained values for *G* were 70 μW/K and 180 μW/K for the given sizes, respectively. Although these values are somewhat higher than those we obtained from the time constant measurements, the general trend remains: the thermal conductance, *G* is proportional to the device in-plane area, $w \times l$, i.e. $G \propto w \times l$.

V. DISCUSSION

There are two major noise sources which contribute to the NEP of a bolometer: the Johnson noise and the thermal fluctuation noise [20].

$$NEP^2 = 4 \times R \times k \times T / S_V^2 + 4 \times k \times T^2 \times G \quad (2)$$

where *k* is the Boltzmann constant. For a bolometer with a high responsivity, the Johnson noise term will be much smaller compared to the thermal fluctuation term. Therefore, the thermal conductance will determine the ultimate bolometer sensitivity.

There has been much debate over the physics of the heat transfer at the YBCO/substrate interface. A number of papers have reported the response time of YBCO films on optical pulses to be proportional to the film thickness [16], [21]. It indicates that the thermal boundary resistance plays the determining role in the YBCO/substrate heat transfer. It has also been shown that the YBCO/substrate thermal boundary resistance is most likely to be determined by the acoustical mismatch between the film and the substrate for temperatures up to 90 K [22]. As deduced from pulsed measurements, as well as from direct measurements [23], [24], the thermal boundary resistance from a YBCO film to a sapphire substrate was approximately 10-15 μW/K per each 1 μm x 1 μm of the film area. For a 2 μm x 1 μm YBCO bolometer it results in *G*~20-30 μW/K. It is within a factor of 2 from the values which were obtained in our experiments.

In our devices, YBCO films on sapphire substrates are made with a CeO_2 buffer layer, which provides good lattice match and chemical isolation from YBCO to Al_2O_3 [25]. From experimental data in [24] it was suggested that variation of buffer layers (though CeO_2 was not used) under YBCO films on sapphire had a minor effect on the thermal boundary resistance. However, to the best of our knowledge no detailed investigation of the CeO2 thickness effect on the YBCO film cooling rate has been performed.

As the second figure of merit, the bolometer responsivity is a function of the temperature coefficient of resistance $\alpha \equiv \partial R/\partial T \times 1/R$, the bias current i, and the thermal conductance to the heat sink *G* [4]:

$$S_V = i \times \alpha \times R/(G - i^2 \times \alpha \times R) \quad (3).$$

Under the discussed bias conditions, the second term in the denominator (the self-heating coefficient) is much smaller than *G*, and it can be neglected. As we have mentioned, the bias current is just above the critical current. The dc resistance is $R = 1/3 \times \rho_n \times l/(w \times d)$. Therefore, the expression for the responsivity can be rewritten as: $S_V = \frac{1}{3} \times (j_c \times \alpha \times \rho_n \times R_b)/w$. As it can be seen, the responsivity is expected to scale linearly with 1/*w*, as we have experimentally observed (Fig. 2).

In order to be able to calculate the responsivity, the temperature coefficient of resistance has to be known. Because we discuss bolometers which operate at temperatures much below Tc with a large bias current, the temperature distribution along the bolometer is not uniform [26]. Therefore, α is not the same as obtained from $R(T)$ measurements, which are done with a small bias current under quasi-equilibrium conditions. Instead, we deduce α from (1), where $\partial P_{dc}/\partial R$ was calculated from bolometer IV-curves (maximum responsivity bias). For the 2-μm-wide bolometer, the calculated responsivity is 338 V/W. The discrepancy with the experimental value (Fig. 2) is most probably due to unaccounted optical coupling losses.

Because all device parameters are known now, the NEP can be calculated using (2). The calculated NEP is 5.6 pW/Hz$^{0.5}$, where the thermal fluctuation noise stands for the most of the total value. It means that for present devices the measured NEP is close to the theoretical one. Because *G* is proportional to the bolometer area, a lower NEP can be obtained by reducing the bolometer size. E.g. a factor of 20 lower NEP (~0.25 pW/Hz$^{0.5}$) is expected for 100 nm×100 nm bolometers, which is quite realistic to fabricate via e-beam lithography.

It is important to note that nearly all of the YBCO bolometer direct detectors presented in the literature operate at temperatures that are close to the middle of the superconducting transition. Our measurements demonstrate that a higher responsivity can be achieved at lower temperatures; however, the output noise (at least at low frequencies) also increases (Fig. 3).

VI. Conclusion

We demonstrate that an NEP of ~20 pW/Hz$^{0.5}$ can presently be achieved with an YBCO microbolometer in the terahertz range from 330 GHz to 1.63 THz at a 77 K operation temperature and with a room-temperature readout. The response time is ~1 ns. This NEP is comparable to Schottky diode detectors for frequencies below 1 THz [27]. However, YBCO bolometers have a real RF impedance, and are therefore easy to integrate with broadband antennas to extend to several THz. Further sensitivity improvement (~0.25 pW/Hz$^{0.5}$) is feasible by making smaller bolometers. Fabrication of such detectors in large arrays is also quite straightforward.

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