Ultrasensitive Superconducting Transition Edge Sensors Based On Electron-Phonon Decoupling

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Abstract—We have successfully fabricated the superconducting transition edge sensor (TES), bolometer technology that centers on the use of electron-phonon decoupling (EPD) to thermally isolate the bolometer. Along with material characterization for large format antenna coupled bolometer arrays, we present the initial test results of bolometer based on EPD designed for THz detection. We have selected a design approach that separates the two functions of photon absorption and temperature measurement, allowing separate optimization of the performance of each element. We have integrated Molybdenum/Gold (Mo/Au) bilayer TES and Ion assisted thermally evaporated (IAE) Bismuth (Bi) films as radiation absorber coupled to a low-loss microstrip line from Niobium (Nb) ground plane to a twin-slot antenna structure. The thermal conductance and the time constant of these devices have been measured, and are consistent with our calculations. The device exhibits a single time constant at 0.1 K of ~160 μs, which is compatible with readout by a high-bandwidth single SQUID or a time domain SQUID multiplexer. The effects of thermal conductance and electrothermal feedback are major determinants of the time constant, but the electronic heat capacity also plays a major role. The NEP achieved in the device described above is 2.5 x 10^-17 W/√Hz. Our plan is to demonstrate a reduction of the volume in the superconducting element to 5 μm x 5 μm in films of half the thickness at Tc = 60 mK. By calculation, this new geometry corresponds to an NEP reduction of two orders of magnitude to 2.5 x 10^-19 W/√Hz, with a time constant of ~130 μs.

I. INTRODUCTION

A TES bolometer has a higher sensitivity-response time product than a semiconducting bolometer with the same geometry due to the strong negative electrothermal feedback intrinsic in typical a voltage-biased TES [1,2,3]. TES bolometers are inherently low impedance devices, so they are well matched to being read out by DC SQUID amplifiers. SQUID amplifiers are mature and have been used extensively for TES bolometer arrays in formats of up to ~1000 pixels. Because SQUIDs operate at the base temperature of the bolometer, they can be coupled very closely, removing the complex interfaces necessary with semiconducting bolometers and FET amplifiers. Most TES employ fragile mechanical isolation in order to decouple the detector temperature from a cold stage temperature in order to achieve high sensitivity. Since, the electronic and phononic temperatures of the sensor can be significantly different, one can eliminate the need for mechanical isolation if T<<1K and sensors volume is small (~10s μm^3). The weak interaction (thermal coupling) between the electrons and the phonons in metals allows a large temperature rise of the electrons for small input power. The main advantage of using this effect for thermal isolation rather than fragile mechanical isolation is that the bolometer does not require micromachining or assembly. Instead, the radiative power is coupled directly into the electrons in the metal, and the temperature of these electrons is measured directly.

Detectors that achieve the required NEP will be designed taking into account this effect, called Electron-Phonon Decoupling (EPD). This method can produce low NEPs at achievable temperatures while enabling large-format arrays with reasonable fill factor and rapid thermal response time.

II. DETECTOR DESIGN AND FABRICATION

We have integrated a small volume resistor, a similarly small volume TES, and a low-loss microstrip line to an antenna structure to fabricate EPD TES receiver. We have chosen to implement a twin-slot antenna because of its symmetric beam pattern, high efficiency at short wavelengths, good rejection of out-of-band radiation, and the convenient ground plane that can be used to shield DC wiring. Short sections of microstrip with low loss at THz frequencies (high quality Au, which modeling shows will have ~0.1dB loss) will allow manipulation of the placement of circuit components for optical coupling purposes. Nb bias line chokes allow on-chip filtering of the TES bias lines and improved shielding. Figure 1 shows the schematic layout of complete EPD detector.
Niobium (Nb) will be employed as both the ground plane and stripline material in the lower frequency range of interest (300 - 500 GHz) because of its superconductivity. However, at frequency above its energy gap Nb acts like a normal metal with relatively high impedance. Consequently, gold, which is a low impedance normal metal film will be used, and retains low radiation loss properties over a wide frequency range. In order to minimize both radiation loss and high reactance, we aimed to maximize the gold microstrip sheet conductance so as to permit a variety of microstrip geometries. We have fabricated these devices and plans for are underway [10].

We use ion assisted thermally evaporated (IAE) Bismuth (Bi) as radiation absorber [10]. It is found that the residual resistance ratio of the IAE Bi is an order of magnitude higher than that of evaporated (TE) Bi. IAE Bi can be useful for antenna-coupled sub-millimeter bolometers, because it is resistive (i.e., it has a low reactance) to high frequencies. This contrasts with TE Bi, which is reactive at frequencies as low as 1 THz. The improved performance of IAE Bi over that of TE Bi might be attributed to its smaller grain structure and/or lower impurity concentration. Because the IAE Bi resistivity \( \rho \) is a thickness-independent quantity, we can easily estimate the noise power \( P \) of a termination resistor fabricated with this material [10].

Electron-phonon decoupled TES were fabricated on 4” Si(001) wafers. One notable aspect of our sensor design is the absence of membranes, which greatly simplifies the fabrication process. An Nb ground plane was DC magnetron sputter deposited and etched, via a CF\(_4\)O\(_2\) plasma, in regions designated for the slot antennas. A silicon dioxide dielectric was next applied via electron cyclotron resonance enhanced chemical vapor deposition. This was a low temperature process, in which the wafer temperature never exceeded 180 C, and enabled a conformal dielectric coating. Niobium microstrip lines were then deposited and etched in a manner similar to that used to fabricate the ground plane. The TES consisted of a Mo/Au bilayer film and was deposited on top of the silicon dioxide using electron beam deposition and DC magnetron sputtering for the Mo and Au, respectively. The Mo/Au deposition was conducted inside a custom set of vacuum chambers, which are connected via a common
loadlock. This configuration allowed for a high degree of Tc uniformity and reproducibility of the TES bilayer film across the wafer, because the Mo surface was never exposed to atmosphere. The TES were delineated using a positive photoresist mask, and ion milling and reactive ion etching, with a CF4/O2 plasma, were used to etch the Au and Mo, respectively. Niobium bias leads were then deposited and etched in a manner similar to that used to fabricate the ground plane and were aligned so as to overlap the TES by 0.5 µm and 1.0 µm for 25, 50 µm and 100, 300, 1225 µm devices, respectively (see Figure 1). Aluminum pads were deposited through a lift-off mask and made contact to the bias leads. The final step in the fabrication process involved deposition of a bismuth termination resistor. Bismuth is a highly reactive material, which makes it susceptible to subsequent fabrication processes, e.g., photore sist application and developing. Consequently, we first patterned a PMGI lift-off mask prior to IAE deposition of 99.999% bismuth. The bismuth was then lift-offed in acetone. Fabrication of the TES diagnostic devices, whose purpose was to solely characterize the TES, was a much more simple process. This process only consisted of TES deposition on a SiO2-coated Si(001) wafer and deposition of the Nb bias leads and Al pads.

III. EXPERIMENTAL RESULTS

We have fabricated devices in different geometries. Table 1 presents details of these devices and their characteristic parameters. We used Resistance-Temperature curves: \( G(T) = \frac{1}{R_n} \frac{d}{dT}(VT) \) (Figure 4) to determine the thermal conductance for each device [6,8,9]. Here, \( G(T) \) is the thermal conductance at the temperature \( T \), \( R_n \) is the normal state resistance of sensor, and \( VT \) is the hysteresis in the Resistance-Temperature curve while increasing and decreasing the fridge temperature.

<table>
<thead>
<tr>
<th>Device</th>
<th>Surface area (µm²)</th>
<th>On Nb Ground plane</th>
<th>Rn (Ω/°C)</th>
<th>Tc (mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>25</td>
<td>No</td>
<td>0.28</td>
<td>410</td>
</tr>
<tr>
<td>B</td>
<td>50</td>
<td>No</td>
<td>0.45</td>
<td>559</td>
</tr>
<tr>
<td>C</td>
<td>300</td>
<td>Yes</td>
<td>0.36</td>
<td>232</td>
</tr>
<tr>
<td>D</td>
<td>1225</td>
<td>Yes</td>
<td>0.36</td>
<td>341</td>
</tr>
</tbody>
</table>

The proposed EPD approach will employ a thermal diagram (Figure 1) and electrical connection (Figure 3). An antenna couples power into an absorbing resistor, which thermalizes the power into the electron bath in a time given by its internal thermal conductance, \( G_{WF} \). This power is communicated through \( G_{\text{electron-electron}} \) (\( G_{ee} \)) to the TES. The power then dissipates into the lattice phonons through a weak thermal link \( G_{\text{electrophonon}} \) (\( G_{ep} \)). Provided that \( G_{ep} \ll G_{WF} \) and \( G_{ep} \ll G_{ee} \), which we calculate to be true for temperatures below ~ 400mK, the sensitivity and time constant of the detector are then dominated by \( G_{ep} \). This approach is very similar to that used by other research groups [8,9], who have tested EPD devices fabricated by our group, yielding accurate knowledge of materials parameters related to our processes.
The power conducted between electrons at a temperature $T_e$ and phonons at a temperature of $T_p$ is given by:

$$P_{ep} = \Sigma V (T_e^4 - T_p^4).$$  

where $V$ is the volume of the metal and $\Sigma$ is a material-dependent constant. A typical value of $\Sigma$ for gold [9] at modest cryogenic temperatures ($< 1K$) is thought to be around $5 \times 10^8$ W/m$^2$K.$^4$.

Differentiating Eq. (1) provides the thermal conductance:

$$G_{ep} = 5 \Sigma V T_e^4.$$  

As the film thickness is much smaller than the thermal acoustic wavelength as is certainly the case in these experiments, the Kapitza conductance is underestimated by acoustic mismatch arguments. As has been determined experiment by many other groups [6,7,8,9], the principal impedance for heat flow is the electron phonon coupling. The electron phonon conductance depends on $T_e$. Figure 5 plots the measured $G$ values for all the devices at different base temperature, and $T'$ fit to the data. Using Eq. 2, we calculated the $\Sigma$ for Mo/Au bi-layer to be $1.75 \times 10^{12} (\cong 0.25 \times 10^{13})$ W/m$^2$K.$^4$.

As seen from the Figure 5, Device D does not fit very well to $T'$ fit. The higher order $T$ term ($T^2$) could fit Device D data more precisely. In the cases in which electron scattering mechanisms are governed by impurities, defects, or boundaries of the film, the shortened mean free path of the electrons should affect the electron-phonon coupling in the disordered metals. In a disordered film, the electron mean free path $l_e$ is very short compared to the wavelength of phonons: $qL_e < l$ with $q$ as the phonon wave vector. In this **dirty limit**, M. Yu. Reizer and A. V. Sergeev [11] suggested that the thermal conductivity should be proportional to $T^5$, not $T^4$. Since, Device D has larger sensors area, the distortions in the film can produce imperfections in the film, which can lead to higher $G$ values.

The Noise Equivalent Power (NEP) derived from phonon fluctuations is straightforward:

$$NEP = \sqrt{4k_bT^2G} = \sqrt{20k_b\Sigma VT_e^5}.$$  

Assuming Device A geometry, and corresponding $G$ value, Figure 6 presents the calculated NEP for the detector. At 60 mK, the achieved NEP is $1.65 \times 10^{18}$W/ /Hz.

The time constant of an EPD detector is given by:

$$\tau_{ep} = \frac{C_e}{G_{ep}} = \frac{\gamma T_e^4}{5 \Sigma V T_e^4} = \frac{\gamma}{5 \Sigma T_e^3}.$$  

where $\gamma$ is the Sommerfeld constant for electronic specific heat. $\gamma_Au \sim 71 J/K^2 m^3$. We estimate the time constant, $\tau_{ep} \approx 5 \mu s$, which is compatible with a typical SQUID amplifier or time division SQUID multiplexer. The effects of thermal conductance and electrothermal feedback are major determinants of the time constant, but the electronic heat capacity also plays a major role.

<table>
<thead>
<tr>
<th>Material</th>
<th>$V$ (m$^3$)</th>
<th>$\Sigma$ (W/m$^3$K.$^4$)</th>
<th>$\gamma$ (J/K$^2$ m$^3$)</th>
<th>$C_e$ (J/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi</td>
<td>$1.68 \times 10^{-6}$</td>
<td>$0.24 \times 10^8$</td>
<td>$0.39$</td>
<td>$2.09 \times 10^{-17}$</td>
</tr>
<tr>
<td>Au (TES)</td>
<td>$5 \times 10^{-14}$</td>
<td>$5 \times 10^9$</td>
<td>$71$</td>
<td>$1.11 \times 10^{-16}$</td>
</tr>
<tr>
<td>Mo/Au (TES)</td>
<td>$1.75 \times 10^{-17}$</td>
<td>$1.75 \times 10^{12} (\cong 0.25 \times 10^{13})$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

As an aside, we did not observe a correlation between superconducting transition temperature, $T_c$, and the lead-to-lead distance in our measurements. The lead-to-lead distance for Device A and Device B is 4 mil, and for Device C and Device D is it 12 mil and 36 mil, respectively.

**IV. CONCLUSION AND FUTURE WORK**

We have successfully fabricated TES with various geometries, which exhibit thermal isolation that is dictated by electron-phonon coupling phenomena based upon the relationship between thermal conductance and temperature. The measured values of $G$ are consistent with our initial calculations and published values [8,9]. With a 25 $\mu$m$^2$ sensor area, we estimate NEP to be $\sim 1.65 \times 10^{18}$W/ /Hz and time constant of $\sim 5 \mu s$. The material-dependent constant, $\Sigma$, for Mo/Au bi-layer was calculated to be $1.75 \times 10^{12} (\cong 0.25 \times 10^{13})$ W/m$^2$K.$^4$. We plan on fabricating devices with lower superconducting transition temperature and simultaneously testing different...
6. Measured G and calculated NEP for TES with Device A geometry. We aim to operate our detector at 100 mK transition temperature.

TES geometries e.g., the zebra normal metal stripes, superconducting imbedded structures in TES devices. The improvement in the TES designs and geometry will increase the sensitivity of detector by 30% to 50%, and hence, estimated NEP is $\sim 2.5 \times 10^{-19}$ W/\sqrt{Hz}, which is in the ZeptoWatts/\sqrt{Hz} sensitivity range. The antennas have been designed, simulated and produced for frequencies of 300 GHz, 1 THz, and 3 THz. We plan on testing the antenna with optical input power and integrate them onto TES device. Recently, we have fabricated device with copper (Cu) ground plane, and testing is planned in near future. We are in the process of characterizing superconducting proximity effect for Mo/Au films, and optimistic about achieving required transition temperature. Such devices operating at lower temperature, e.g., 60 mK will be ideal for low background measurements of millimeter and submillimeter wave astrophysics.

REFERENCES


