Abstract

We are developing a bolometer based on a differential thermometer that senses temperature changes through changes in the kinetic inductance of a superconducting thin film. The temperature transducer is an inductance bridge patterned as an integrated circuit on a 1 cm$^2$ Si substrate. Two inductors from opposite arms of the bridge are patterned on a 2 mm$^2$ thermally isolated Si island which is supported by a 0.9 μm thick Si:B membrane. The bridge is excited with audio frequency current and the bridge imbalance is detected with a commercial DC SQUID amplifier. The bridge is balanced by applying power to the thermally isolated island. This thermometer is the sensor for a prototype radiometer that will provide an absolute measure of IR power. The radiometer, which is designed for a NEP of about $10^{-11}$ W/√Hz, is intended to measure the spectrally dispersed power of a 300 K black body. This absolute radiometer is being developed for use at the Low Background Infrared (LBIR) Facility at NIST, Gaithersburg. The noise floor of the temperature transducer for the radiometer has been measured to be 0.7 pW for a 1 s integration time. This is approximately 150 times lower noise than that of the commercial absolute radiometer currently used at the LBIR Facility in Gaithersburg.

Introduction

The National Institute of Standards and Technology (NIST) is developing a calibration system for black body IR sources. The heart of the Low Background Infrared (LBIR) Facility, located at NIST, Gaithersburg, Maryland, is a cryogenic chamber enclosing the black body to be tested and an absolute cryogenic radiometer for measuring the total radiated power. The radiometer is surrounded by an enclosure at 15 K except for a small aperture, at 4 K, through which the black body is viewed.

A radiometer can be described in a generically as shown schematically in Figure 1. This shows an absorber coating the inside of the cone. Radiation incident upon the cone is absorbed and reflected several times within the cone ensuring a high absorbance over a large bandwidth of the infrared radiation. A heater on the cone is used to bring the cone to a temperature $T$ above the fixed reference temperature $T_0$. The temperature of the cone is measured by the thermometer which also is thermally fixed to the cone. The entire cone and thermometer are thermally linked to the stable temperature bath through the thermal conductance $G(T)$.

For a 300 K black body, the radiometer must accurately measure radiation from 5 to 30 μm. To assure a uniform response across this broad bandwidth, a Cu cone, blackened with a commercial black paint, is used as the radiation absorber. This cone has a 3 cm diameter entrance aperture and an apex angle of 45°. The power absorbed by the cone is determined by electrical substitution. Electrical substitution is done by heating the cone to a prescribed temperature ($2 K$ in the present system) by direct current in heaters on the cone, with no applied radiation. When radiation is applied, the absorbed power is directly measured by the decrease in electrical power required to maintain the cone at constant temperature, with small corrections for substitution errors.

The noise of the absolute radiometer currently used at the LBIR Facility is 150 pW for a 3 min integration time. In the context of IR measurements, this is not a high sensitivity, but that is not the main consideration, the goal being high accuracy for a broad bandwidth measurement. Devices such as IR bolometers and photon detectors can have very fast response times and high sensitivities. This is usually not the case for radiometric detection of infrared radiation. A radiometer will typically have a response time limited by its thermal mass (usually set by the cone) and is designed to respond to the power of the radiating object (typically black bodies) with enough sensitivity to provide an accurate determination of the radiation absorbed from the source. The purpose of our work is to develop a more sensitive absolute radiometer which will ultimately be used for spectrally resolving the black body radiation with a Δ$\lambda$ of 1 part in 50 and accurate to at least 1%.

Basic Concepts

We have developed a temperature transducer for our radiometer based on the temperature dependence of the kinetic inductance of a superconducting microstrip. Our experimental circuit design, shown in Figure 2, was originally proposed by McDonald and a proof-of-principle experiment using a bridge device based on the kinetic inductance concept was discussed in an earlier publication. The bridge device is sensitive to temperature differences between the inductors comprising the bridge. In the present inductive bridge design, two identical microstrip inductors are on a silicon island which is weakly linked thermally to the remainder of the bridge. Each of the other inductors of the bridge (off the Si island) are designed to have a 2% larger inductance than those on the island, thus ensuring an intrinsic bridge imbalance in the correct direction. This means that a direct current applied to a heater on the island will raise the island temperature above that of the remaining chip. The inductance of the microstrip lines on the island will increase, due to the temperature dependence of the kinetic inductance, hence allowing bridge balance with the application of power to the heater. As the power to the island heater is varied, the commercial DC SQUID hallmeter, shown schematically in the figure, senses the current imbalance of the bridge.

The thermometer responsivity $R$ can be derived from an analysis of the bridge circuit in Figure 2. It can be shown that

$$
R = \frac{\Delta P_{SQ}}{dP} = \left( \frac{\Delta V_{SQ}}{dI} \right) \left( \frac{dL_1}{dI} \right) \left( \frac{dL_1}{dT} \right) / G(T)
$$

(1)
in Figure 3 (labeled 1 and 3 in Figure 2), are thermally isolated from the remaining circuit by a 9 μm thick membrane of silicon which has been boron doped to a concentration of \(5 \times 10^{19}\) cm\(^{-3}\). The island geometry is achieved through an anisotropic etch done from the back side of the wafer, before circuit fabrication. This process leaves a silicon island suspended by a 400 μm wide boron-doped silicon membrane. A measurement of the thermal conductance of this geometry yielded a value of approximately \(1.3 \times 10^{-4}\) W/K at 6.6 K. The thermal conductance \(G(T)\) for the boron-doped membrane is empirically given by

\[
G(T) = G_o T^2
\]

where \(G_o\) is approximately 3 μW/K\(^2\). From our geometry we have calculated the effective thermal conductivity \(\kappa(6.6\ K)\) of the boron-doped Si to be approximately \(6.7 \times 10^{-3}\) W/K cm.

The thermally isolated silicon island also contains a 10 μm wide, 11.34 mm long thin film resistive heater, consisting of 5 nm thick Cr and 30 nm thick Au. This film has a sheet resistance of approximately 103 Ω/sq and is used for controlling the temperature of the thermally isolated inductors.

**Experimental Results**

**Thermal Coupling Experiments**

Figure 4 schematically depicts the coupling between the cone and kinetic inductance thermometer. The thermal conductances of the various components were measured in a series of experiments using a Cu block, containing a Ge thermometer and heater, instead of the cone as shown in the figure. These experiments were conducted with a bare Si substrate (no circuitry on chip). The 1 cm\(^2\) silicon substrate, on which the bridge circuit is fabricated, is epoxy mounted on a molybdenum mess, which in turn is mounted to a copper block. The Mo mesa is necessary to accommodate the different thermal expansions of Si and Cu during the cool down. To ensure good coupling between the Si chip and the Mo mesa, an array of square pits (12×12 μm\(^2\), 48 μm periodicity) is etched into the back side of the Si substrate and island during the moat etching which defines the island. These etched pits effectively increase the surface area of the chip and promote a strong and cyclable bond between the chip and Mo mesa. The measured
thermal conductance for this bond was approximately 241 mW/K and independent of temperature between 4 K and 9 K. This thermal conductance is over three orders of magnitude higher than that of the boron-doped silicon membrane which thermally isolates the island from the chip. This implies that the difference in temperature between the chip and the thermal platform is negligible. The cone will be connected to the thermometer using a 1.3 mm diameter, fine Cu "pigtail" braid. The Cu pigtail, shown in the figure, is bonded to the back side of the Si island with a silver-filled epoxy. The measured thermal conductances of the 1 cm long Cu pigtail and Si island-Cu pigtail joint, at 4.0 K, are $3.7 \times 10^{-3}$ W/K and $1 \times 10^{-3}$ W/K respectively. These thermal conductances, both being over an order of magnitude higher than the that of boron-doped membrane, appear to be satisfactory for the cone-thermometer coupling.

Kinetic Inductance Thermometer Experiments

The Mo mesa-copper block (shown in Figure 4) on which the kinetic inductance thermometer is mounted, is coupled to a temperature controlled copper platform. The copper platform, shown in Figure 5, contains a resistive heater and a commercial Ge resistance thermometer. This platform sits on stainless steel rods which thermally link it to the base plate of the dewar, which is at liquid helium temperature. This platform also contains the wiring for the chip mount. The platform can be temperature stabilized through the use of the Ge thermometer and heater. The commercial DC SQUID amplifier and Cu platform assembly are mounted on the base plate of the dewar (4.0 K) and the entire assembly is under vacuum.

One of the most important problems that we addressed in our experiments concerned the coupling of the DC SQUID to the thermometer chip. A 0.6 μm thick Nb film was sputter deposited on a Cu-Be foil. Then a 30 nm Au film was deposited on the niobium to protect the surface from further oxidation. A printed circuit board was made from the foil and patterned. This contains the "fingers" which connect the pads on the chip to the external electrical environment. We initially used small pieces of 0.05 mm thick In foil between the DC SQUID input fingers and the on-chip pads. The DC SQUID noise was about 12 dB higher than expected and we found that this noise could be accounted for by a 1 mΩ contact resistance between the SQUID fingers and the on-chip pads. This problem was solved by using 0.05 mm thick Nb foil instead of indium. These
for a lock-in amplifier integration time of

to stabilize the silicon island temperature on the chip. The rms standard deviation of the noise is approximately \( \sigma = 0.7 \text{ pW} \), for a lock-in amplifier integration time of 100 s.

**Figure 7a. Responsivity measurement at \( T_1 = 5.09 \) K; \( P_{\text{brt}} = 66.5 \mu\text{W} \); \( \Delta P = 14 \text{ nW} \); \( \tau_{\text{rel}} = 0.1 \text{ s} \); \( R = 0.76 \times 10^{4} \text{ V/W} \).**

**Figure 7b. Measured responsivity versus island temperature.**

**Figure 8. Thermometer noise floor.** The servo system was used to stabilize the silicon island temperature on the chip. The rms standard deviation of the noise is approximately \( \sigma = 0.7 \text{ pW} \), for a lock-in amplifier integration time of 100 s.

**Bridge Responsivity**

Figure 6 schematically represents the experimental arrangement used for measuring the thermometer responsivity and SQUID output noise at bridge balance. An audio frequency oscillator at 3.363 kHz delivered a rms bias current \( I_{\text{bias}} \) of 6.04 mA to the bridge circuit. The imbalance current of the superconducting bridge was amplified by the DC SQUID, whose output was fed to a lock-in amplifier. The bridge was manually nulled through the application of direct current to the island heater. The response of the bridge to a series of power pulses is shown in Figure 7a. This was done by applying current pulses to the island heater when the bridge was nulled and measuring the response to each pulse using the lock-in amplifier and a time base plotter. Using the measured island heater resistance of 1118.5 \( \Omega \), we can calculate the power delivered by a single pulse to the heater. A calibration of the lock-in amplifier allows a measurement of the voltage response of the DC SQUID which senses the bridge response. From these measurements, the voltage responsivity \( \frac{R}{4} \) in rms volts per watt (referred to the output of the SQUID) was calculated and is shown in Figure 7b for a range of island temperatures. As expected, the bridge response increases as the critical temperature of the groundplane is approached. The curve through the data represents the theoretical responsivity calculated from Eqn.(1) using the measured film parameters. The theoretical curve is in reasonable agreement with the measured responsivity.

**Bridge Noise Measurements**

The spectral density of the DC SQUID output voltage was measured using a spectrum analyzer over a range of bridge drive currents. The most significant result of this investigation is that the SQUID noise floor (around the 3.363 kHz excitation frequency) does not change with bridge current-bias amplitude. These measurements were made from 4.0 K to 7.4 K (0.48 \( \leq T/T_c \leq 0.89 \)). For each platform temperature, there is a critical (maximum) rms bridge drive current that can be used before the film is driven normal, and this decreased with increasing temperature. This behavior was as expected although the actual value of this critical rms current was lower than the dc critical current of the thin film groundplane at each temperature. This may be due to some lower current density contacts on the chip. The measured SQUID voltage noise, \( \Delta V_{\text{s}} \), is about 121.6 \( \mu\text{V/}\sqrt{\text{Hz}} \). This corresponds to a SQUID current noise (referred to the input) of approximately 2.7 \( \text{pA/}\sqrt{\text{Hz}} \) and this is a factor of 1.77 times larger than the current noise measured when the SQUID is shorted at its input terminals (in its housing). Assuming the noise in both quadratures is equal and that only the component in quadrature is relevant, then the noise equivalent electrical power, \( \text{NEP}_{\text{e}} = 8V_{\text{e}}^2/\sqrt{2R} \), is about 44 \( \text{pW/}\sqrt{\text{Hz}} \) using the measured \( R = 1.9 \times 10^{7} \text{ V/W} \) at 6.01 K (0.8 \( T_c \)).

Finally, to cancel out drifts caused by the island heater supply, the island heater was controlled by a commercial servo loop in such a way as to hold the bridge balanced. The imbalance signal was then recorded over a long time period to obtain a measure of the overall system noise. This noise measurement, presented in Figure 8, was made with a 100 s integration time and is approximately 0.7 pW. Presently, the lowest noise obtained using the absolute cryogenic radiometer at the LBIR Facility is about 150 pW for a 180 s integration time. Assuming a radiometer based on the kinetic inductance thermometer and no additional noise (due to coupling to the cone), one would expect a noise floor that is more than two orders of magnitude lower than the absolute radiometer used at the LBIR facility.

**Conclusions**

We have measured the responsivity and noise of a thermometer which will serve as the thermal sensor for an absolute cryogenic radiometer. This radiometer is being developed for spectrally dispersed measurements of 300 K black bodies at the LBIR Facility at NIST, Gaithersburg, Maryland. The thermometer responsivity was measured and is in reasonable agreement with the theoretical analysis of the device. Present measurements yield a noise of approximately 0.7 \( \text{pW} \) for a 100 s integration time. These results imply two orders of magnitude improvement over the existing radiometer noise measured at the LBIR Facility. Noise measurements will soon be made with the sensor connected to the cone to see whether there are any changes in the thermometer sensitivity due to other noise sources such as microphonics.

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**References**