

SUPERCONDUCTING KINETIC INDUCTANCE BOLOMETER*

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Abstract

We are developing a bolometer with a temperature sensor based on the temperature dependence of the inductance of a superconducting microstrip line. As a first step in exploring this idea experimentally, we have designed experiments to test only the temperature sensor. The experimental devices are all-niobium inductance thermometers fabricated on silicon substrates which have been deeply etched to provide areas of relative thermal isolation. The ground plane superconductor is thin enough that its kinetic inductance dominates the audio frequency impedance of the stripline near its critical temperature, at $0.9T_c$. This differential thermometer uses a commercial SQUID as the preamplifier. Our preliminary results demonstrate a proof-of-principle for our thermometer design.

Motivation

Conventional bolometers are limited in performance by their intrinsic Johnson noise, phonon noise, amplifier noise, and self heating. We are developing a new type of bolometer, which, in its idealized form, should have no Johnson noise, unusually low amplifier noise, and minimal self heating. Bolometers are described in a generic way by Fig. 1, which shows a radiation absorber and temperature transducer affixed to some mass with composite heat capacity $C(T)$. This mass is thermally linked to a stable temperature bath through thermal conductance $G(T)$. Initially, the entire device is in equilibrium with the bath at a temperature T_b . If radiation is now absorbed by the bolometer, it will cause an increase of its temperature to T , which is detected by the thermometer. The absorbed power is given by $P_{\text{absorbed}} = G(T)[T - T_b]$. Usually the temperature sensor is a resistive material that has a large temperature coefficient of resistance, but any mechanism which yields a measurable quantity that is sensitive to changes in temperature may be used as the temperature transducer in the bolometer.

Recently, a novel superconducting thermometer for bolometric applications was proposed,¹ based on the temperature dependence of the kinetic inductance of a superconducting microstrip line. Previous superconducting bolometers used the resistive transition of a superconductor² as a temperature sensor. These devices produced Johnson noise and could use only very limited bias current because of self heating. In contrast, the superconducting stripline device is operated below its transition temperature, so it has no Johnson noise, and it can accommodate very large sensing currents without self heating. Also, its very low impedance means that it is ideal as a signal source for a very low-noise SQUID (Superconducting Quantum Interference Device) amplifier. A theoretical analysis of this device suggested that a bolometer incorporating this temperature transducer can be very sensitive. This analysis demonstrated that the Johnson noise and the preamplifier noise for this type of bolometer can be reduced to about 7×10^{-20} W/ $\sqrt{\text{Hz}}$, if an ideal device could be made. Here we explore the practical limitations of a device designed for only modest sensitivity.

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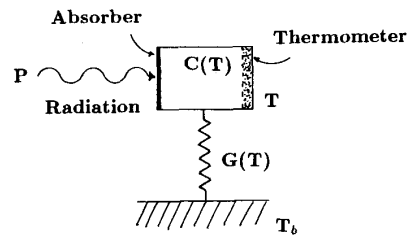


Fig. 1 Thermal equivalent circuit for a bolometer.

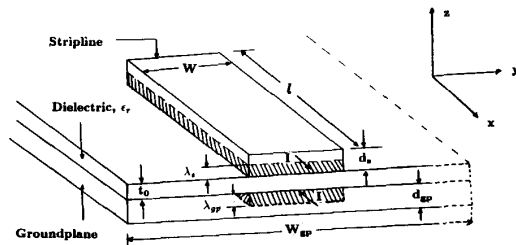


Fig. 2 Schematic section of a superconducting microstrip line.

Basic Concepts

Figure 2 depicts a superconducting stripline of width W , length l and thickness d_s , over a superconducting groundplane of width W_{gp} and thickness d_{gp} . The two films are separated by dielectric of thickness t_0 . Analysis reveals, for $W \gg t_0$, that any low-frequency current in the microstrip line is essentially confined within a penetration depth λ in each of the superconducting films.³ This current confinement is due to the Meissner effect, which implies that a magnetic field will exponentially decay to zero in the interior of a superconductor. The currents and magnetic fields are negligible at distances greater than λ from the film surface.

The inductance of the microstrip line shown in the figure³ is

$$L = \mu_0 \frac{l}{W} \left[t_0 + \lambda_s \coth \left(\frac{d_s}{\lambda_s} \right) + \lambda_{gp} \coth \left(\frac{d_{gp}}{\lambda_{gp}} \right) \right]. \quad (1)$$

The first term is due to the magnetic field in the dielectric while the second and third terms are contributions from the two superconducting films. The important thing to notice here is that the inductance has a functional dependence on the penetration depths, λ_s and λ_{gp} , of the two films. While the penetration depth of a superconductor is analogous to the skin depth in normal metals, at audio frequencies the penetration depth is frequency independent. The penetration depth has only a very slight, and therefore usually negligible, dependence on an applied magnetic field. However, it has a strong dependence on temperature, for temperatures just less than T_c where

$$\lambda(T) = \frac{\lambda_0}{\sqrt{1 - (T/T_c)^4}}. \quad (2)$$

Since the inductance of a superconducting microstrip line depends on the penetration depth, and hence upon temperature, we can construct a thermometer based upon this temperature dependence.

The strongest dependence of the inductance on temperature is obtained if the superconducting films have thicknesses smaller than their penetration depths, the so called kinetic inductance limit. (In this limit the inductance is directly related to the kinetic energy of the charge carriers in the conductor.⁴) To illustrate this point we consider the groundplane term in Eq. 1. The groundplane contribution to the total microstrip line inductance is given, for thick and thin films respectively, by

$$L = \mu_0 \left(\frac{l}{W} \right) [\lambda_{gp}] \quad (d_{gp} \gg \lambda_{gp}), \quad (3a)$$

$$L = \mu_0 \left(\frac{l}{W} \right) \left[\frac{\lambda_{gp}^2}{d_{gp}} \right] \quad (d_{gp} \ll \lambda_{gp}). \quad (3b)$$

Equation 3a shows that for a thick film geometry one has a linear dependence of the inductance on the penetration depth. In the case of Eq. 3b, we find a stronger dependence on the penetration depth by a factor λ_{gp}/d_{gp} , where $\lambda_{gp}/d_{gp} \gg 1$. It is this second case which we refer to as the kinetic inductance limit.

Figure 3 shows the contributions of each term in Eq. 1 to the total inductance of a stripline for a range of temperatures. The film thicknesses and parameters used for these graphs are those of our experiments. We have assumed a zero-temperature penetration depth $\lambda(0)$ of 83 nm for our Nb films. The strong temperature dependence of the inductance near the operating temperature of $0.9T_{cgp}$ is due to the kinetic inductance of the groundplane film as described by Eq. 3b, above.

Our experimental design, shown in Fig. 4, was originally proposed by McDonald.¹ If the four inductors of the figure are structurally identical, their inductances will be equal when they are all at the same temperature. In that case the bridge as a whole is not sensitive to temperature changes. However, the bridge is sensitive to temperature differences between the inductors. To make a practical differential thermometer, two of the inductors are on silicon islands which are weakly thermally coupled to the remainder of the bridge. Having two such elements ensures that the bridge can be balanced even with the inevitable fabrication variations among the inductors. As the power to the island heaters is varied, the SQUID galvanometer in the figure senses the current imbalance of the bridge.

A SQUID is used as the null detector because of its low noise. The commercial device that we are presently using has an input inductance of $2 \mu\text{H}$, which is about 50 times larger than desired for best signal-to-noise ratio.

Thermometer Chip Fabrication

Our present chip design has four meander line structures over a groundplane, each structure forming one arm of a superconducting bridge. Each microstrip line or meander line consists of a thin film of sputter-deposited Nb, $3.1 \mu\text{m}$ wide, $0.57 \mu\text{m}$ thick, and 10 cm long, and fills a 1 mm^2 area. The Nb meander line is separated from the Nb groundplane, which is approximately $0.078 \mu\text{m}$ thick, by two insulating layers. These layers are $0.13 \mu\text{m}$ of Nb_2O_5 and $0.22 \mu\text{m}$ of thermally deposited SiO dielectric.

Figure 5a shows the integrated circuit bridge fabricated on a silicon substrate. Each chip contains two test structures which allow independent measurements of the critical temperatures of the Nb groundplane and meander line thin films. The measured

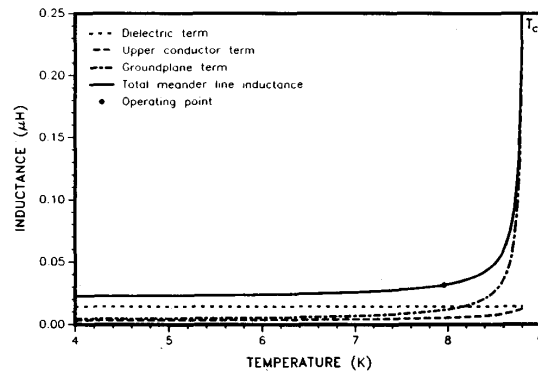


Fig. 3 Inductance vs. Temperature for superconducting microstrip line.

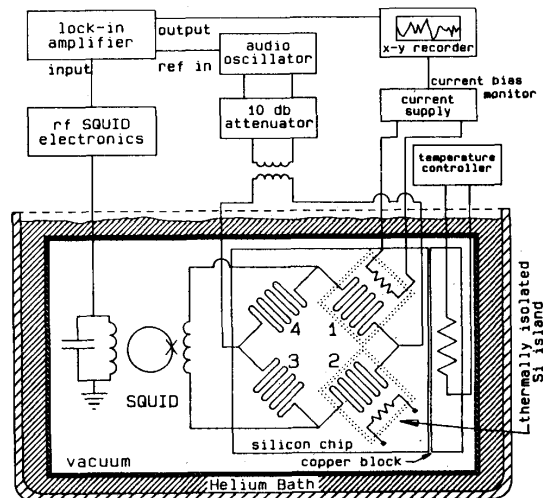


Fig. 4 Schematic of silicon chip and experimental setup. The heart of the experiment is the silicon chip on which the superconducting inductance bridge is fabricated. The 4 meander lines of the bridge are superconducting microstrip lines. Two of the meander lines are on thermally isolated sections of the chip so that their temperatures can be controlled by adjacent resistive heating elements. The silicon chip is itself mounted on a copper block with a heater and thermometer for controlling the temperature of the silicon chip as a whole.

critical temperatures of our Nb groundplane and meander line films are 8.83 K and 8.99 K, respectively. All external contacts to the on-chip Nb wires are made through 30 nm thick Au films which were deposited after sputter cleaning the Nb contact pads.

Two meander lines, labeled 1 and 2 in Fig. 4, are thermally isolated from the remaining circuit by a $15 \mu\text{m}$ thick membrane of Si which has been B doped to a concentration of $5 \times 10^{19} \text{ cm}^{-3}$.⁵ This geometry is achieved by first patterning a B doped frame around the meander line and then anisotropically etching the back side of the wafer, as shown in Fig. 6. This procedure leaves a silicon island suspended by a $71 \mu\text{m}$ wide boron doped silicon membrane. Figure 5b shows the silicon islands from the back side of the thermometer chip. A measurement

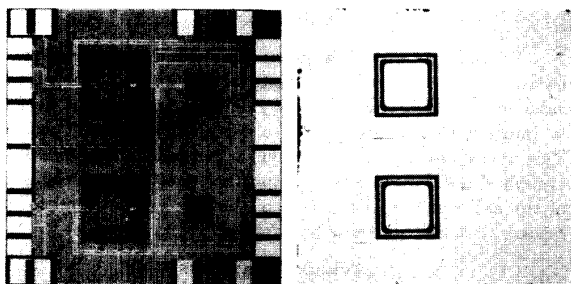


Fig. 5 (a) Front-side photograph of kinetic-inductance thermometer integrated circuit. (b) Back side photograph of silicon chip showing the "moats" etched in the silicon for thermal isolation.

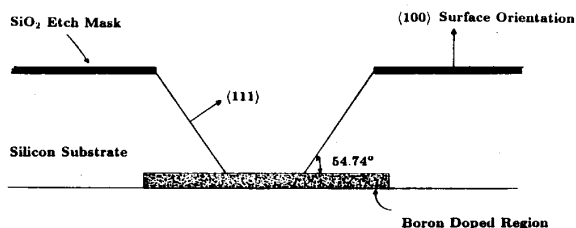


Fig. 6 Schematic of side profile of an etched silicon moat.

of the thermal conductance of this geometry yielded a value of approximately 8.5×10^{-4} W/K at 8.3 K. This is about an order of magnitude larger than our design value so the present device is much less temperature sensitive than desired. We were unable to find low temperature data on the thermal conductivity of such heavily boron doped silicon in the literature, so our design was based on theoretical extrapolations. The geometry can be adjusted for the higher thermal conductivity in the future.

The thermally isolated silicon islands of Fig. 4 have 11 μm wide, 9.14 mm long thin film resistive heaters, consisting of 5 nm thick Cr and 25 nm thick Au. These films have a sheet resistance of approximately 1.05 ohms per square and are used for controlling the temperature of the thermally isolated inductors.

Experimental Results

Bridge Balance and Sensitivity

The first experiments were concerned with obtaining bridge balance and measuring the bridge sensitivity at various temperatures, with the experimental setup of Fig. 4. The silicon substrate, on which the bridge circuit is fabricated, is mounted on a Cu platform using vacuum grease. This Cu platform contains a resistive heater and commercial Ge resistance thermometer. The SQUID amplifier and Cu platform are mounted in a vacuum can and immersed in a He bath. The Cu platform is thermally linked to the bath through a flange at the top of the probe vacuum can. An audio frequency oscillator at 100 Hz delivered a bias current $I_{b\omega}$ of 0.39 mA to the bridge circuit. The imbalance current of the superconducting bridge was amplified by the RF SQUID, whose output was fed to a lock-in amplifier.

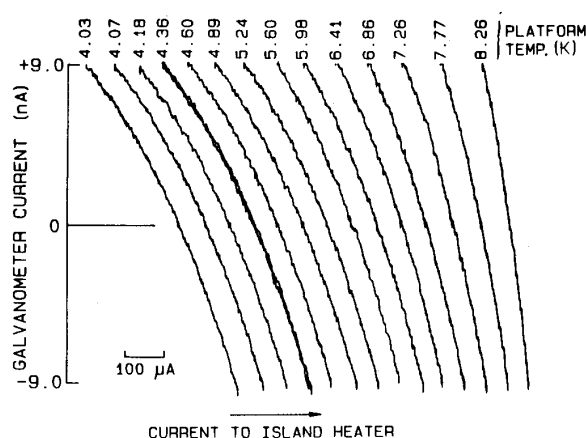


Fig. 7 Galvanometer current vs. island heater current for various Cu platform temperatures. The island heater currents for each of the nulls, from left to right, were: 0.723, 0.718, 0.706, 0.689, 0.671, 0.642, 0.610, 0.578, 0.532, 0.487, 0.431, 0.379, 0.306, and 0.224 mA. The fourth curve from the left was plotted twice to show the reproducibility of the data.

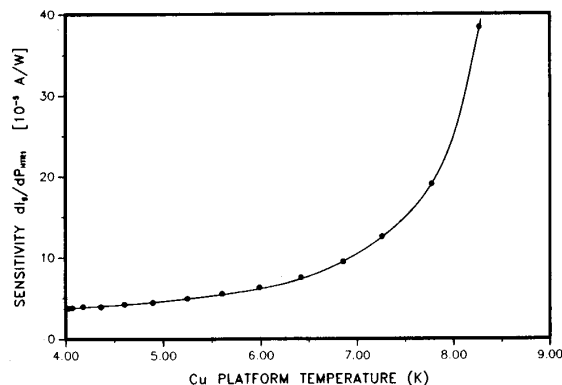


Fig. 8 Sensitivity vs. Cu platform temperature.

As the current to the island heater was manually adjusted the galvanometer current could be nulled as expected. Also, the phase detector showed the expected reversal of phase of the imbalance signal as it passed through null. A series of such results for various Cu platform temperatures are shown in Fig. 7. Using the measured island heater resistance of 890 Ω , we can calculate an effective galvanometer current sensitivity to the heat supplied to the island, P_{HTR1} . The quantity dI_g/dP_{HTR1} can be determined from the slopes of the curves of Fig. 7 at each null. These data are plotted in Fig. 8. This last result shows that the greatest sensitivity of the bridge comes as the critical temperature of the ground plane is approached, as expected.

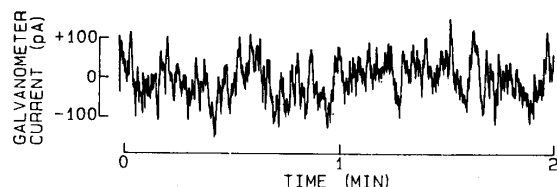


Fig. 9 Noise measured at bridge balance as a function of time with a 1 s integration time.

The noise amplitude at bridge balance was measured as a function of time at 4.02 K. This result is shown in Fig. 9. From this figure we estimated an rms noise at null of about 136 pA with a bridge excitation current of 0.39 mA. The ratio of these currents, which we call the depth of the null, is approximately 0.4×10^{-6} . Simple circuit analysis shows that the resolution of the bridge for observing changes in inductances is directly proportional to the depth of the null. For our bridge the implied sensitivity to changes in inductance is about 2.8 pH.

Another quantity of interest is the intrinsic imbalance of the bridge due to imperfect fabrication. The imbalance current from the bridge with no heater current applied was measured to be 15 nA with 0.39 mA of bridge excitation at 4.02 K. If all of this imbalance is attributed to a single inductor, an asymmetry in inductance of 1.3% is implied.

Finally, we also experimentally evaluated another sensitivity of the the superconducting thermometer, i.e. the sensitivity of the bridge galvanometer current, in the vicinity of null, to changes in the Cu platform temperature. This is a measure of how well this differential thermometer rejects changes in temperature of its thermal reservoir. We obtained a value 29 nA of galvanometer current per K change in Cu platform temperature. Considering the ultimate current resolution of this SQUID, about 10 pA, we can see that the requirements for temperature control of the Cu platform are in the 100 μ K range.

A more detailed analysis and comparison with an analytical model could not be completed in this first series of experiments due to the presence of He gas in the vacuum can, which substantially modified the thermal circuit. When this problem is remedied more complete results will be obtained.

Conclusion

Perhaps the most important quality factor for this type of measurement system is the depth of the null. We achieved a value of 0.4×10^{-6} , which is satisfying for a first try, but we want to improve that figure by one order of magnitude if possible. This means essentially that we will try to reduce the noise of the system at null. Another very important question is the behavior of the null signal as a function of the bias current level for the bridge; that has not been investigated yet.

Acknowledgments

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