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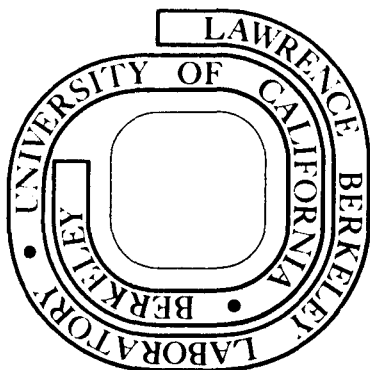
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Superconducting Tunnel Junction Bolometers

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ABSTRACT

Two new types of superconducting infrared bolometer are described. In one, the temperature dependent Josephson current in an SNS junction is measured with a SQUID galvanometer. In the other, the temperature-dependent quasiparticle tunneling current in an SIN junction is measured with a conventional fet amplifier. Either type of junction is deposited on a low heat capacity sapphire substrate covered on the reverse side with a thin Bi film to absorb infrared radiation. The best performance achieved thus far is for the SNS bolometer which has an electrical NEP $\approx 5 \times 10^{-15} \text{ W}/\sqrt{\text{Hz}}$ and $D^* \approx 10^{14} \text{ cm W}^{-1} \text{ Hz}^{1/2}$. Some improvement in these values is anticipated.

I. INTRODUCTION

Cryogenic bolometers, especially those made from doped germanium, are widely used as sensitive broadband infrared detectors. Superconducting bolometers operated at the resistive transition, though not presently in wide use, have been extensively studied.¹ In this paper we describe preliminary experiments to evaluate the performance of two new types of superconducting bolometer. In both of them the thermal signal is observed by measuring temperature-dependent tunneling currents. In the first we measure the maximum value of the Josephson (pair) tunneling current in a superconductor-normal metal-superconductor (SNS) junction.² The superconducting quantum interference device (SLUG or SQUID)³ can serve as a low noise amplifier for this bolometer because of the very low impedance of the SNS junctions ($\sim 10^{-6} \Omega$). The second type of bolometer makes use of the temperature-dependent quasiparticle tunneling current through a superconductor-insulator-normal metal (SIN) junction⁴ which is biased at a voltage below the superconducting energy gap. The differential resistance of such bolometers is typically $10^2 - 10^3 \Omega$ so they are best used with a cooled transformer and an fet amplifier.

Both types of bolometer are made from thin films vacuum deposited onto a sapphire substrate. Mechanical support is achieved with nylon threads which are coated with a superconductor such as In or Pb and attached to the substrate as is shown in Fig. 1 for the SNS case. The superconductor makes electrical contact with the tunnel junction which occupies a small fraction of the bolometer area. The thermal conductance of the sapphire is adequate to assure essentially isothermal operation for modulation frequencies below $\approx 10^4$ Hz. The design shown in

Fig. 1 includes a normal metal heater which is used to make electrical measurements of the bolometer sensitivity.

For our measurements of the performance of the SNS bolometer reported below, the nylon threads were glued to the substrate with General Electric 7031 varnish. The heat capacity of the varnish was about a factor of 30 larger than that of the sapphire plus the metal films. Subsequently, a method has been developed for soldering the leads to the substrate without this excess heat capacity.

For efficient bolometer performance it is necessary to absorb a large fraction of the incident infrared energy in the desired frequency range. We propose to use a thin Bi film with a surface resistance of $Z_0/n+1 \approx 100\Omega/\square$ (where Z_0 is the impedance of free space, and n is the dielectric constant of sapphire) evaporated on the reverse side of the substrate as a broadband absorber. Preliminary measurements suggest that the absorption of such films is close to the theoretical maximum of $n/n+1 \approx 3/4$ in the frequency range from 1 to 50 cm^{-1} . Alternatively, multilayer films can be used if sensitivity is required in a narrow frequency range.

II. THE SNS BOLOMETER

For this device we use a Pb/CuAl/Pb SNS junction, which we have found to be very stable with respect to both aging and thermal cycling. Since the normal metal is a CuAl alloy in the dirty limit the critical supercurrent I_c of the junction is of the form

$$I_c = I_0 \exp -(T/T_0)^{1/2}. \quad (1)$$

Here T is the temperature and $T_0 \approx 0.1K$. The rate of change of I_c with temperature is

$$\frac{\partial I_c}{\partial T} = - \frac{I_c}{2\sqrt{TT_0}}. \quad (2)$$

If the junction is biased at a finite voltage by a constant current just greater than I_c , the voltage is a function of I_c . We can approximate $\partial V / \partial I_c$ by the differential resistance R_D at the bias point. The minimum temperature change which can be measured in the presence of the rms noise voltage V_N can be written

$$\delta T = \frac{\partial T}{\partial I_c} \delta I = \frac{2\sqrt{TT_0}}{R_D I_c} V_N. \quad (3)$$

If we assume that the noise generated in the SNS junction is close to Johnson noise, as seems to be the case in practice, then $V_N = (4k TR_D)^{1/2}$. For typical operating parameters, $T = 1.5K$, $T_0 = 0.1K$, $R_D = 3 \times 10^{-6}\Omega$ and $I_c = 20$ mA, we find $\delta T \approx 2 \times 10^{-7} K/\sqrt{Hz}$. The junction is used as a bolometer by fabricating it on a substrate of heat capacity C , which is connected to a heat sink via a thermal conductance G . Our design values were $C \approx 10^{-9}$ J/K and $G \approx 10^{-8}$ W/K from which we expected to obtain a noise equivalent power $NEP = G\delta T \approx 2 \times 10^{-15}$ W/ $\sqrt{Hz}$ and a time constant $\tau = C/G \approx 0.1$ sec. The best experimental results obtained give an electrical $NEP = 5 \times 10^{-15}$ W/ $\sqrt{Hz}$ and $\tau = 3$ sec. The long time constant was due to the excess heat capacity of the varnish.

III. SIN BOLOMETER

For preliminary tests of this device, we have used a $\text{Pb}/\text{Al}_2\text{O}_3/\text{Al}$ junction. The quasiparticle current through an SIN junction, for $\Delta/kT \gg 1$ and $eV < \Delta$, is given by⁵

$$I = \sqrt{\frac{2\pi kT}{\Delta}} \frac{\Delta}{eR_N} e^{-\Delta/kT} \sinh \frac{eV}{kT} \quad (4)$$

where R_N is the normal state resistance of the junction, and 2Δ is the superconducting energy gap and is equal to 2.7 meV in Pb. Solving Eq. (5) for V and taking the derivative with respect to T at constant I , we obtain

$$\left(\frac{\partial V}{\partial T}\right)_I = \frac{V}{T} - \frac{k}{e} \left(\frac{\Delta}{kT} + \frac{1}{2}\right) \tanh \frac{eV}{kT} \quad (5)$$

At $T = 1.5\text{K}$, $\left(\frac{\partial V}{\partial T}\right)_I$ reaches a maximum at $V = 0.2 \Delta/e$, and under these conditions (i.e., $\Delta/kT \gg 1$ and $eV/kT \gg 1$) Eq. (5) reduces to

$$\left(\frac{\partial V}{\partial T}\right)_I = \frac{V - \Delta/e}{T} = - \frac{0.8\Delta/e}{T} \quad (6)$$

Thus, the minimum detectable temperature change is

$$\delta T = \frac{TV_N}{0.8\Delta/e} \quad (7)$$

If we again assume that $V_N = (4kTR_D)^{1/2}$ and that $R_D = 100\Omega$, then $\delta T \approx 10^{-7} \text{K}/\sqrt{\text{Hz}}$.

Thus, the estimated performance of the SIN bolometer is about the same as that of the SNS bolometer. In our first experimental work on the SIN bolometer we have obtained $\delta T = 10^{-5} \text{K}$. The performance of the bolometer

was limited by amplifier noise, and the use of a cooled transformer will be required in order to approach ideal performance.

IV. CONCLUSION

The preliminary results described here suggest that superconducting tunnel junction bolometers with areas as large as $A = 0.3 \text{ cm}^2$ can be constructed with $\text{NEP} \approx 10^{-15} \text{ W}/\sqrt{\text{Hz}}$ and $\tau \approx 0.1 \text{ sec}$. These values of NEP and τ are comparable to the performance of the best Ge bolometers with much smaller $A \approx .005 \text{ cm}^2$. As long as the heat capacity C scales with area and G can be chosen to give a convenient value of τ , then the figure of merit $D^* = \sqrt{A}/\text{NEP}$ is an appropriate way to compare bolometers with different areas. We therefore anticipate about an order of magnitude improvement over the Ge bolometer.

In order to use this small NEP , room temperature blackbody radiation, which introduces noise as well as heat, must be rigorously avoided. This can be conveniently be done with low-pass cooled filters in the far infrared, but very narrow-band cooled filters would be required for near infrared systems which have room temperature background.

Cooled astronomical systems above the earth's atmosphere are an obvious application of these high sensitivity detectors. For small astronomical sources, A should be reduced to the image size in order to minimize the NEP . There will, of course, be a practical limit to how small such a bolometer can be made without degrading its D^* .

The large area detector shown in Fig. 1 performs substantially better than the best Ge bolometers with comparable area. Such detectors are useful for experiments which involve many electromagnetic modes. If our present SNS detector is filled at $f/1$ with radiation from a blackbody in the Rayleigh Jeans limit, then the smallest blackbody temperature interval which can be detected at a frequency $\nu = 10 \text{ cm}^{-1}$,

for a predetection bandwidth of 1 cm^{-1} , and a postdetection bandwidth of 1 Hz, is $\Delta T \approx 2 \times 10^{-4} \text{ K}$. If a single mode microwave heterodyne radiometer⁶ is used for the same measurement, the system noise temperature required for equivalent performance is $\Delta T(v)^{1/2} \approx 30 \text{ K}$.

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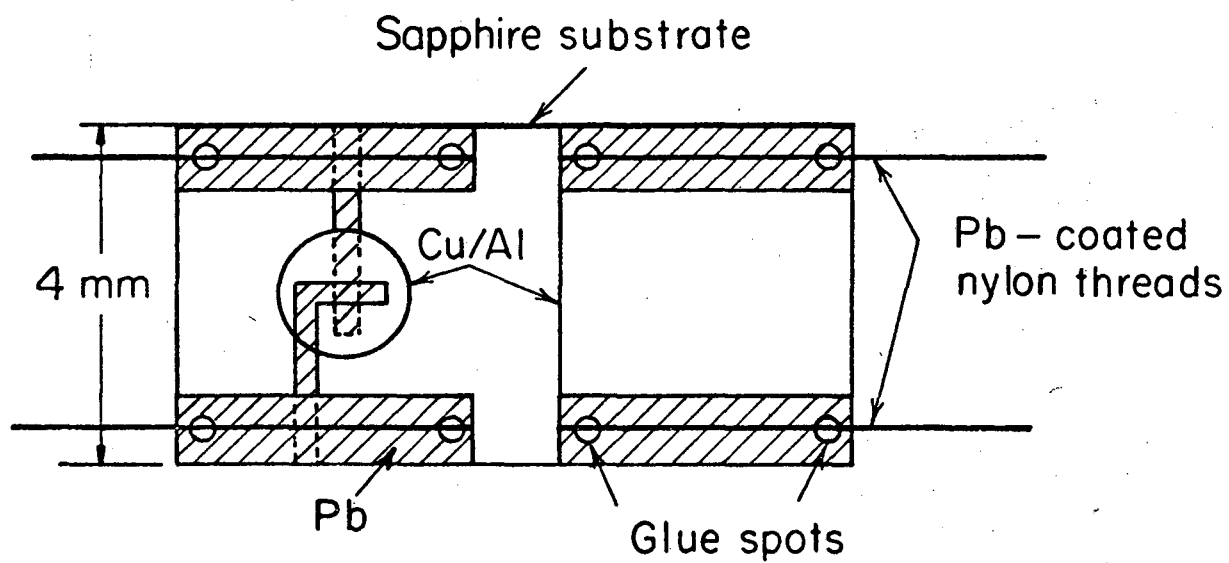
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FIGURE CAPTION

Fig. 1. Configuration of superconductor-normal metal-superconductor (SNS) junction bolometer.



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