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M. Nahum, P.L. Richards, and C.A. Mears

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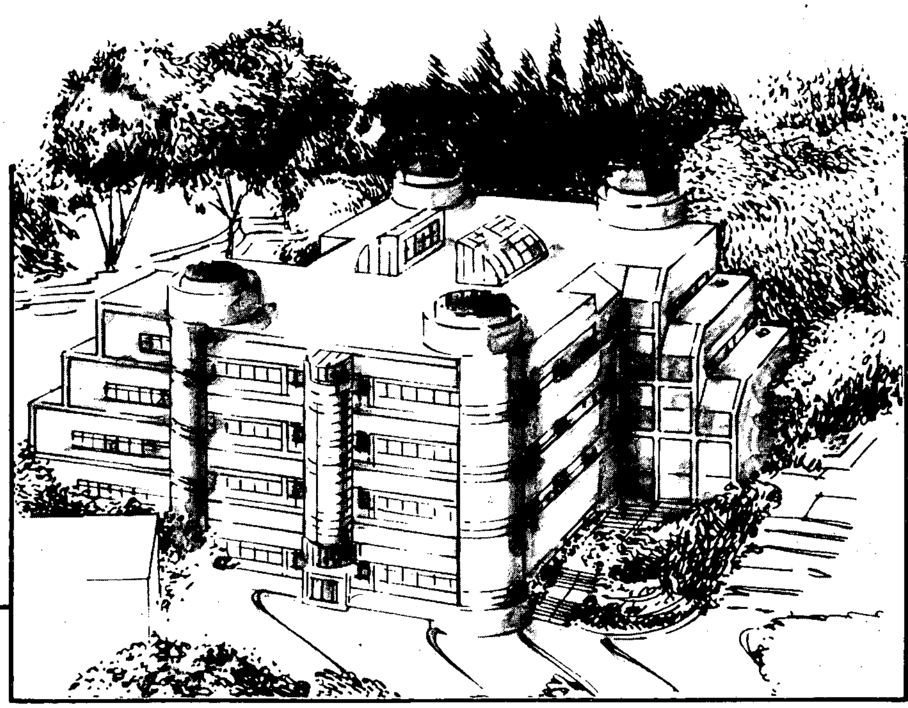

Materials and Chemical Sciences Division
Lawrence Berkeley Laboratory • University of California
ONE CYCLOTRON ROAD, BERKELEY, CA 94720 • (415) 486-4755

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DESIGN ANALYSIS OF A NOVEL HOT-ELECTRON MICROBOLOMETER

M. Nahum and P. L. Richards
Department of Physics, University of California, and Materials Sciences Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720

C. A. Mears
Laboratory for Experimental Astrophysics, Lawrence Livermore National Laboratory L-401, P. O. Box 808, Livermore, CA 94550

Abstract-[1] We propose a novel antenna coupled microbolometer which makes use of the weak coupling between electrons and phonons in a metal at low temperatures. The radiation is collected by a planar lithographed antenna and thermalized in a thin metal strip. The resulting temperature rise of the electrons is detected by a tunnel junction, where part of the metal strip forms the normal electrode. All components are deposited directly on a substrate so that arrays can be conveniently produced by conventional lihographic techniques. The active area of the bolometer is thermally decoupled by its small volume, by the thermal resistance between the electrons an phonons in the strip, and by the reflection of quasiparticles at the interface between the strip and the superconducting antenna. Design calculations based on a metal volume of 2x6x0.05 μm^3 at an operating temperature of T=100 mK give an NEP$\approx 3\times10^{-19}$ $WHz^{-1/2}$, time constant $\approx$10 μs, and responsivity $\approx 10^9$ V/W. The calculated sensitivity is almost two orders of magnitude higher than that of the best available direct detectors of millimeter and submillimeter radiation operated at the same temperature.

I. INTRODUCTION

Bolometers are known to be the most sensitive direct detectors of infrared and millimeter waves and are widely used in ground and space-based astronomical observations. Although excellent performance has been available with bolometers operated at ^{3}He temperatures [1] and at 100 mK [2], there is a need in the community for improved sensitivities at millimeter and submillimeter wavelengths. The key is to reduce both the heat capacity of the material which responds thermally to the input power and the thermal conductance to the surroundings. The work of Nahum et al. on antenna coupled superconducting microbolometers for use at 90 K [3] and at T<4.2 K [4,5] suggests a way in which this can be done. Following this approach, we propose to make ultra sensitive hot-electron microbolometers at LHe and lower temperatures. A thin strip of metal with micron dimensions serves as a resistive load to thermalize the infrared currents. The temperature rise of the electrons in the metal absorber is measured from the temperature dependence of the current-voltage (I-V) characteristics of a superconductor-insulator-normal metal (SIN) junction, where part of the metal strip forms the normal electrode. The thermally active volume of this bolometer is ≈ 1 μm^3 compared with $\approx 10^8$ μm^3 for more conventional millimeter wave bolometers. Thermal isolation is provided by the weak electron-phonon interactions at low temperatures and by the reflection of electrons at the interface between the metal absorber and the superconducting antenna. Efficient radiation coupling can be achieved by means of a planar lithographed antenna. A schematic of the proposed configuration is shown in Fig. 1. All of the components are deposited directly on the substrate and can be produced in arrays using standard photolithographic techniques.

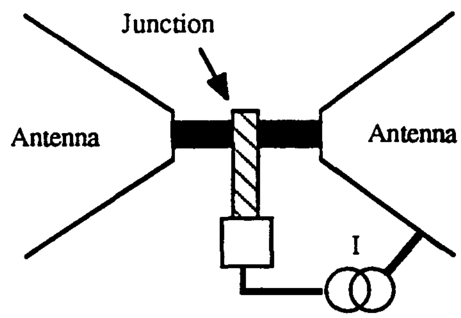

Fig. 1. Schematic of the radiation coupling and temperature readout configuration. The rf current from the superconducting antenna is dissipated in the resistive metal strip (black strip), the resulting temperature rise of the electrons in the strip are measured as a change in the voltage across the junction which is biased at a constant current I. The contact to the superconducting electrode is made of a superconductor whose T_c is much higher than that of the electrode.

II. FIGURES OF MERIT

The figures of merit that are commonly used to characterize the sensitivity of bolometers are the noise equivalent power (NEP), the time constant τ, and the voltage responsivity S. If we model the thermal circuit as a heat capacity C coupled to a heat bath through a conductance G then τ=C/G and $S=(dV/dT)G^{-1}(1+\omega_0^2\tau^2)^{-1/2}$, where $\omega_0=2\pi f$ is the modulation frequency, and V(T) is the voltage across a thermometer which measures the temperature rise of the thermally active region. The optical NEP is computed by summing the squares of statistically independent contributions, and represents the minimum detectable power in a one Hz noise bandwidth,

$$(NEP) = 1/\eta\ [4kT^2G+V_n^2/S^2]^{1/2}, \qquad (1)$$

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where η is the optical efficiency. The first term is due to energy fluctuations, commonly referred to as phonon noise, in the thermally active region and represents the intrinsic limit imposed by thermodynamics. The second term is due to the voltage noise V_n of the junction. It should be noted that the Johnson noise arising from the resistance of the metal strip does not contribute to the NEP in this configuration. For the device described in this paper $1/\tau > 10^6$ Hz, so that for most applications, we can assume that $\omega_0\tau << 1$, in which case the responsivity S is proportional to 1/G. The contribution to the NEP from the temperature readout can then be made negligible by reducing G until the second term of Eq. 1 is sufficiently small. Consequently, the NEP will be limited by the energy fluctuations in the active region and additional improvements in the sensitivity can only be attained by further reduction of G. To that end, it is necessary to understand the various mechanisms through which energy can be removed from the active region.

III. THERMAL ISOLATION

In our geometry the absorbed power can be dissipated via three paths. The first is direct heat flow from the electrons in the strip to the substrate via electron phonon coupling and phonon transport. At temperatures above ≈10 K the thermal conductance is dominated by the spreading resistance arising from the thermal conductivity of the substrate, as is the case for the high-T_c microbolometer [3]. At the lower temperatures of interest here, the thermal boundary resistance can contribute significantly to the thermal isolation. This property has been used to construct sensitive low-T_c microbolometers [4,5]. At very low temperatures however, an additional mechanism for thermal isolation has to be considered. For temperatures less than ≈1 K, the inelastic collision processes (energy loss processes) for electrons in a metal are very infrequent. As a result, the electrons become thermally decoupled from the lattice and heat up as they absorb power. The theory of hot-electrons is relatively well understood and in reasonable agreement with experiment. The simplest treatment assumes that the electrons and phonons are each in internal thermal equilibrium and are in weak contact with one another. The deformation potential approximation and Fermi's Golden rule are then used to calculate the inelastic scattering time $\tau_{e\text{-}p}$. Typical experiments on hot-electrons usually measure the temperature difference between the electrons and the phonons and thus the thermal conductance G between the two systems. The inelastic relaxation time is then obtained from $\tau_{e\text{-}p}=C/G$, where C is the heat capacity of the electron system. Copper is one of the more widely studied metals and has a measured electron-phonon conductance of $G \approx 2\times10^3 VT^4$ W/K, where V is the volume in cm^3 and T is the temperature in Kelvin [6]. The calculated inelastic scattering rate $\tau_{e\text{-}p} \approx 10.6/T^3$ ns. The measurements of Wellstood et al. on CuAu thin films give $G \approx 2\times10^3 VT^4$ W/K [7]. For a typical active bolometer volume of 1 μm^3 at an operating temperature of T = 100 mK the thermal conductance can be as low as $G \approx 10^{-13}$ W/K, this is several orders of magnitude smaller than typical values for conventional bolometers operated at the same temperature. In order to fully utilize this effect it is thus necessary to insure that the contribution of all other energy relaxation processes to the thermal conductance are also small.

The contact area between the metal absorber and the antenna terminals provides an alternate path for heat dissipation. In addition to the phonon relaxation mechanism discussed above, there exists the possibility that electrons could also transfer energy across this interface. However, if the antenna is made from a superconductor whose T_c is higher than the operating temperature of the device, then the Andreev reflection [8] of electrons at the interface between the metal absorber and the superconducting antenna traps the hot-electrons and hence the absorbed energy in the active region. The transmission probability for quasiparticles in the metal absorber to cross the interface is proportional to $\exp(-\Delta/kT)$. For a superconductor whose energy gap Δ is much larger than the thermal energy of the electrons in the metal strip, the predicted transfer of energy will be negligible. A convenient choice is Nb with a transition temperature of ≈9.2 K.

An additional mechanism for energy dissipation is due to the presence of the SIN junction. Electrons which tunnel through the insulating barrier remove energy from the active region and thus provide an additional mechanism for heat dissipation. If the contact to the superconducting electrode is made with another superconductor whose energy gap much is larger than that of the electrode then the Andreev reflection of quasiparticles at this interface will also trap the energy in the active region. The contribution of the superconducting electrode to the volume of the active region would have a negligible effect on the sensitivity if it can be made small in comparison with the volume of the metal strip.

IV. TEMPERATURE READOUT

As previously discussed, the temperature rise of the electrons is detected by a SIN junction, where part of the metal absorber forms the normal electrode. The usefulness of the junction as a thermometer for the electron temperature stems from the exponential dependence of the tunneling current on the temperature. It is possible to show that to first order, the quasiparticle current through a SIN junction, whose electrodes are at different temperatures, depends only on the temperature T of the electrons in the normal electrode and is identical to the case where both electrodes have the same temperatures [9]. If the junction is biased such that $eV<\Delta$ and $kT<<\Delta$ then the quasiparticle current is given by

$$I=(kT/eR)\sinh(eV/kT), \qquad (2)$$

where $R=R_N(kT/2\pi\Delta)^{1/2}\exp(\Delta/kT)$ is the dynamic resistance of the junction at low bias, R_N is the normal resistance of the junction, and Δ is the energy gap of the superconducting electrode [13]. If the junction is biased with a constant current then the voltage responsivity at $\omega_0=0$ is

$$S_0=(1/G)dV/dT=-(1/G)(k/e)[(\Delta/kT+1/2)\tanh(eV/kT) - (eV/kT)]. \qquad (3)$$

For a given choice of Δ and kT it can be shown that the responsivity is maximized when $\cosh^2(eV/kT)=(\Delta/kT+1/2)$.

In order to estimate the contribution of the temperature readout to the NEP it is necessary to understand the noise mechanisms in the junction. The voltage fluctuations of a biased SIN junction can be derived using standard many-body techniques and in general, are related to the quasiparticle current-voltage characteristics and the frequency [10]. For most applications, the frequencies of interest are such that $h\omega_0 << eV$. In this low frequency limit the voltage noise across the junction is independent of frequency and is given by $V_n^2 = (dV/dI)^2 2eI\coth(eV/2kT)$, or

$$V_n^2 = 2kTR\tanh(eV/kT)\coth(eV/2kT)/\cosh(eV/kT). \quad (4)$$

When $eV << kT$, Eq. 4 reduces to Johnson noise arising from the dynamic resistance of the junction, when $eV >> kT$ the noise is due to the shot noise arising from the discrete nature of the charge carriers. The contribution of the temperature readout to the NEP is given by the ratio of the voltage noise and the responsivity $(NEP)_{SIN} = V_n/S_0$. In general, the bias current which minimizes $(NEP)_{SIN}$ does not simultaneously maximize the voltage responsivity.

The low thermal conductance that couples the electrons to their environment places an additional restriction on the bias current. The issue is that the IV power which is dissipated in the vicinity of the junction could significantly raise the temperature of the electrons, and consequently reduce the sensitivity of the device. An optimum value for this temperature rise can be calculated if the background infrared power dissipated in the detector is known. For purposes of this discussion we require that bias power not raise the temperature of the electrons by a fraction α of the operating temperature, where $\alpha \approx 0.1$. If we assume that all of the dissipated power gets re-absorbed in the electron system then this requirement reduces to $IV < G\alpha T$. In reality, some of the power will be transferred to the phonons and will subsequently be removed through the substrate. This requirement thus represents an upper limit on the bias current.

V. DESIGN CALCULATIONS

Due to the large number of parameters, the optimization of the hot electron microbolometer is somewhat complicated. In general, it is advantageous to pick the smallest possible volume for the metal absorber so as to reduce the thermal conductance. Once the operating temperature has been determined, it then becomes possible to estimate the thermal conductance between the electrons and the phonons. One then proceeds by finding the bias current which minimizes the contribution of the temperature readout to the NEP. It is then necessary to ensure that the bias heating will not raise the temperature of the electrons by a significant factor. An important feature of the hot electron microbolometer is that the time constant τ, which equals the electron-phonon relaxation time τ_{e-p}, is much smaller than is required for most applications. Thus, the tradeoff between speed of response and sensitivity which is inherent to the optimization of conventional composite bolometers, is avoided. As a specific example of a device whose performance would be very beneficial to the astrophysics community, we assume an active volume of $2\text{x}6\text{x}0.05\ \mu m^3$ at operating temperatures of 100 mK and 300 mK. The ratio of the energy gap of the superconducting electrode to the operating temperature is assumed to be $\Delta/kT \approx 6.5$, and the normal state resistance of the junction is assumed to be $R_N = 100\ \Omega$. For an operating temperature of T=100 mK the superconducting electrode could be made of Ti, whereas at T=300 mK a useful choice would be aluminum. Although other metals may be more appropriate, we use the value of G which was measured for Cu films [6] for the purpose of the present analysis. In Table 1 we list the figures of merit of the hot-electron microbolometer as well as the bias current, the output voltage, and the total voltage noise V_n^{out} resulting from the contributions of energy fluctuations in the active region and the fluctuations in the junction. For an operating temperature of 100 mK the sensitivity of this device is almost two orders of magnitude higher than the best available conventional composite bolometer. The total voltage noise at the output of the detector is $V_n^{out} \approx 1\ nVHz^{-1/2}$, which is comparable with the input voltage noise of $\approx$1-2 $nVHz^{-1/2}$ of commercially available low noise JFET amplifiers at frequencies above any 1/f noise knee.

Table 1. Operating parameters for a device operated at 100 mK and 300 mK. The normal electrode is assumed to be 500 Å thick and have an area of $2\text{x}6\ \mu m^2$. The junction is assumed to have a normal state resistance $R_N = 100\ \Omega$.

T (mK)	100	300
G (W/K)	$1.2\text{x}10^{-13}$	$9.7\text{x}10^{-12}$
τ_{e-p} (μs)	10.6	0.4
S (V/W)	$3.4\text{x}10^{9}$	$4.2\text{x}10^{7}$
I (nA)	1.9	5.7
V (μV)	14.0	42.1
$(NEP)_{SIN}$ ($WHz^{-1/2}$)	$3.7\text{x}10^{-20}$	$5.2\text{x}10^{-18}$
$(4kT^2G)^{1/2}$ ($WHz^{-1/2}$)	$2.6\text{x}10^{-19}$	$7.0\text{x}10^{-18}$
(NEP) ($WHz^{-1/2}$)	$2.6\text{x}10^{-19}$	$1.0\text{x}10^{-17}$
V_n^{out} ($nVHz^{-1/2}$)	0.5	0.8

VI. RADIATION COUPLING

Because the dimensions of the thermally active region are much smaller than the wavelength to be detected, a planar lithographed antenna can be used to provide efficient coupling. Self-complementary log-periodic or log-spiral antennas are very broadband and have a frequency independent real antenna impedance $Z_{ant} = 377[2(1+\varepsilon)]^{-1/2}\ \Omega$ that depends only on the dielectric constant ε of the substrate [11]. When deposited on quartz, $Z_{ant} \approx 120\ \Omega$. Since a planar antenna located on a dielectric surface radiates primarily into the dielectric, the signals are introduced through the back surface of the dielectric which is often placed on the back side of a dielectric lens. The optical efficiency of this quasi-optical coupling scheme is being explored in a number of laboratories. A recent report by Grossman et al. suggests an antenna efficiency of ≈50 % for a broad band blackbody radiation centered at 19 μm [12]. The measurements of Nahum et al. indicate comparable efficiencies at 1000 μm [13]. Other antenna structures have been proposed in which the radiation does not radiate through the substrate [14], thus eliminating absorption losses in the dielectric. An alternative approach is to place the bolometer in a waveguide and to couple it with thin film elements similar to those used for superconducting-insulating-superconducting (SIS) mixers. The impedance of these various coupling structures can vary from 1-100 Ω. A common characteristic of all antennas is that they couple to a single spatial radiation mode and one polarization, whereas a conventional composite bolometer can couple to a number of radiation modes equal to $A\Omega/\lambda^2$ and two polarizations, where the throughput $A\Omega$ is the product of the area A of the beam at a focus times the angle Ω of divergence from the focus, and λ is the wavelength. The throughput $A\Omega$ of the antenna thus decreases with frequency. This in helps to reduce the detrimental effects of background radiation loading in comparison with conventional absorbers.

A major advantage of using the metal strip as an absorber is that the rf properties of such a strip are relatively easy to understand and can be varied by changing its dimensions. As a consequence, it becomes possible to integrate the strip in a wide variety of coupling configurations. The most straightforward design is a simple thin strip of length l, width w and thickness t, located directly between the terminals of an antenna. As discussed in Ref. [5], the impedance of such a strip can be written as

$$Z_{bolo} = Z_L + Z_S l/w, \qquad (5)$$

where Z_L is the impedance due to the geometrical inductance of a rectangular thin strip over a dielectric half plane and is approximately $Z_L=5\times10^{-13}i\omega l$, with l in μm, and in Z_L ohms. The surface impedance is given by the usual expression $Z_S=i\omega\mu_0[(1+i)/\delta]^{-1}\coth[(1+i)t/\delta]$, where $\delta = (2/\mu_0\sigma\omega)^{1/2}$ is the classical skin depth, σ is the conductivity of the metal, and ω is the rf frequency. For most practical applications, the film thickness $t \ll \delta$ so that the surface impedance is just the dc resistance per square of the strip $Z_S=(t\sigma)^{-1}$. Because most types of coupling structures have real impedances, it is necessary to reduce the inductive component of Z_{bolo} as much as possible. For the simple configuration discussed here, this is achieved by minimizing the length of the strip. In addition, to match the impedance of a typical antenna it is necessary to choose metal with a relatively low electrical conductivity. A more powerful and elegant approach is to integrate the absorber in a superconducting microstrip line and to use efficient matching networks such as quarter wave transformers and filter elements [6]. With this technique, the geometrical inductance of the strip and its optimal resistance are controlled by the properties of the microstrip line, rather than the length of the metal strip and the impedance of the antenna.

VII. CONCLUSIONS

Potential applications of these devices can be understood by considering applications of conventional composite bolometers. They are used in ground and space-based telescopes as sensitive broadband detectors for measurements of thermal emission from interstellar gas and dust from point sources such as quasars, from planetary atmospheres, and for measurements of the anisotropy of the cosmic microwave background. The estimated sensitivity of the hot-electron microbolometer can exceed that of the best available conventional bolometers by two orders of magnitude, with a time constant which is three orders of magnitude smaller. Also, it is possible to construct multiplexed systems by designing on-chip networks with different bandpass filters fed from a single antenna. Using well developed reproducible lithographic techniques it should be possible to make powerful array receivers with multiple spectral bands. It thus appears that the hot-electron microbolometer could be the detector of choice in applications requiring very high sensitivities and array compatibility.

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LAWRENCE BERKELEY LABORATORY
CENTER FOR ADVANCED MATERIALS
1 CYCLOTRON ROAD
BERKELEY, CALIFORNIA 94720