Hot-Electron Microcalorimeters for X-Ray and Phonon Detection

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We propose a novel hot-electron microcalorimeter for measurements of x-rays or phonons produced by the interaction of a high energy particle with the underlying substrate. This type of detector uses a normal metal film to absorb the incoming excitation which subsequently heats the electrons above the lattice temperature. The temperature of the electrons is measured from the current - voltage characteristics of a superconductor-insulator-normal metal tunnel junction, where part of the absorber forms the normal electrode. We present simple calculations of the energy sensitivity of the junction and of the ultimate performance of x-ray and phonon detectors. We also present preliminary measurements of prototype devices which were used to test the basic detector physics.

1. INTRODUCTION

Many important issues in particle and astrophysics will be addressed when sensitive low-threshold particle detectors and high resolution x-ray detectors are developed. Although significant progress has been made by many groups, there remains a need in the community for improved detector performance.

In this paper we explain the basic physics of a new type of device, the hot-electron microcalorimeter, which can be used as an ultra-sensitive detector of x-rays or phonons produced by the interaction of a high energy particle with the underlying substrate. This detector is based on a normal metal film to absorb the incoming excitation and a superconductor-insulator-normal metal (SIN) junction to measure the temperature of the electrons in the absorber (Fig. 1). At low temperatures $T << 1$ K and for small absorber volumes, the electrons are sufficiently decoupled from the phonons so that even small amounts of deposited energy can be detected by measuring the rise in the electron temperature. Our estimates indicate that this novel detection scheme may be much more sensitive than current state of the art detectors of x-rays and phonons.

In what follows we present simple calculations of the energy sensitivity of the SIN junction and of the ultimate performance of x-ray and phonon detectors. We also present preliminary measurements of non-optimized devices which were used to test the basic detector physics.

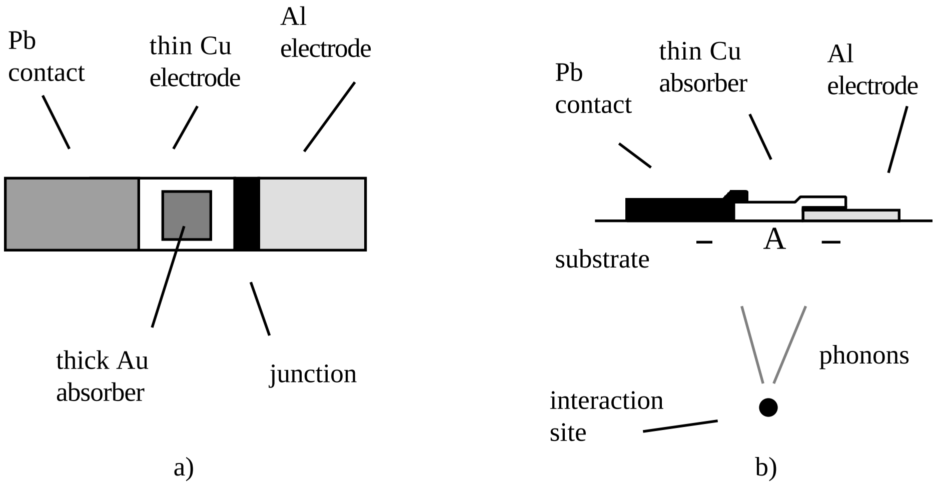

Fig. 1. Schematic of the SIN based detectors. a) Top view of the x-ray detector. X-rays are absorbed in the thick Au film, and subsequently heat the electrons in the normal metal electrode. The temperature rise of the electrons is measured from the I - V characteristics of the SIN junction. The Pb contact confines the thermal energy within the normal metal island, but allows electrical contact to the island.[1,2] In this configuration the absorber is not deposited directly on top of the junction. b) Side view of the phonon detector. A high energy particle interacts with the dielectric crystal and emits high energy ballistic phonons. Approximately one half of the phonons which are incident on the area A of the absorber interact with the electrons in the normal metal. The resultant temperature rise of the electrons is measured from the I - V characteristics of the SIN junction. The Pb contact serves the same purpose as in a) above.

2. ENERGY RESOLUTION OF SIN JUNCTION

In order to estimate the energy sensitivity of the junction, it is first necessary to understand the temperature evolution of the electrons upon absorption of an excitation with energy E. To a good approximation, the electrons thermalize instantaneously and then relax to their environment with a characteristic time τ. For a small temperature rise, the change in the electron temperature evolves in time as $\delta T(t) = (E/C)\exp(-t/\tau)$, where $C = \gamma VT$ is the electronic heat capacity, $\gamma \approx 440$ eVK^{-2}μm^{-3}, and V is the volume of the metal absorber. Here $\tau = C/G$ is the thermal relaxation time and G is the total thermal conductance between the electrons and the environment.

As previously discussed, the temperature rise of the electrons is measured by a SIN junction, where part or all of the metal absorber forms the normal electrode. The junction is a very sensitive thermometer of the electrons and is particularly useful for measuring the temperature of electrons in very small metal volumes. To first order, the current I through the junction depends only on the temperature T of the electrons in the normal electrode and is independent of the temperature of the superconducting electrode. If the junction is biased below the energy gap such that $kT \ll eU$ and $kT \ll \Delta$, then

$$I = [(2\pi kT\Delta)^{1/2}/2eR_n] \exp[-(\Delta - eU)/kT], \tag{1}$$

where Δ is the energy gap of the superconducting electrode, R_n is the normal state resistance of the junction, and U is the bias voltage across the junction.[3] The temperature responsivity of the junction is $dI/dT = (I/T)[1/2 + T_b/T]$, where we define $T_b = (\Delta - eU)/k$ which is typically about 2T. In general, it is advantageous to use a junction with a low R_n which results in a large current and hence a large responsivity.

It is necessary to use a low noise amplifier to measure the junction current. This amplifier should have a bandwidth of about 1 MHz and have a current noise less that 1 $pAHz^{-1/2}$. An ideal candidate which achieves this performance is a 2-stage integrated dc SQUID amplifier which uses a series array of 100 SQUIDs as the readout for a low noise single SQUID.[4]

In our configuration, the electrons can cool via two possible mechanisms. The first is by radiating energy to the phonons at a rate given by $P_{e-p} = \Sigma V(T^5 - T_p^5)$, where $\Sigma \approx 1.3\text{x}10^{10}$ $eVs^{-1}K^{-5}\mu m^{-3}$ and T_p is the phonon temperature.[5] The thermal conductance coupling the electrons to the lattice is computed from $G_{e-p} = dP_{e-p}/dT = 5\Sigma VT^4$. The second channel for energy dissipation arises from the temperature measurement. Since $eU < \Delta$, the tunneling process preferentially removes electrons from the normal metal whose energy is higher then the Fermi energy and consequently cools the electrons in the absorber. If we assume that all the electrons tunnel to the gap energy, then the cooling power is given by $P_{sin} = kT_b(I/e)$ which is simply the product of the energy kT_b of the tunneling electrons and the tunneling rate (I/e). The thermal conductance of the SIN junction is then computed from $G_{sin} = dP_{sin}/dT = (kI/e)(T_b/T)(1/2 + T_b/T)$. The remaining power $IU(1 + kT_b/eU)$ is dissipated in the superconducting electrode and thus does not heat the electrons in the normal metal. The electrons relax to the environment by dissipating energy through both conduction paths and cool with a characteristic time $\tau = C/(G_{e-p} + G_{sin})$. A practical constraint is that $1/\tau$ should be smaller than the bandwidth of the amplifier, which is the case for the devices discussed below. The SIN junction is a novel temperature sensor in that the measurement of the electrons in the normal metal also provides cooling.

Energy fluctuations arise from both the thermal and electrical circuits. The thermal circuit has two noise contributions. The first is due to the thermodynamic fluctuations in the coupling of electrons to phonons, which gives a power spectral density $(4kT^2G_{e-p})$.[6] Fluctuations in the cooling power of the junction are an additional source of noise. These fluctuations arise from the shot noise characteristics of the tunneling current and have a spectral density $(kT_b)^2(2I/e) = 4kT^2G_{sin}/(2 + T/T_b)$, where we have used the approximation discussed above. Apart from the denominator, this result indicates that the spectral density of the power fluctuations depends on the thermal conductance of the junction through the usual thermodynamic relation. Thus, both the thermal circuit and its noise can be described as an electronic heat capacity C coupled to a heat bath through a total thermal conductance $G = G_{e-p} + G_{sin}$. The spectral density at a frequency $\omega/2\pi$ of the output current arising from this thermal circuit is $(dI/dT)^2(4kT^2/G)(1 + \omega^2\tau^2)^{-1}$.

The electrical circuit contributes two additional sources of noise which can be treated in an identical manner. The shot noise of the junction current has a spectral density $S_i(sin) = 2eI$, and the noise of the SQUID amplifier can be approximated as a source of current noise with spectral density $S_i(amp)$. The spectral density of the current fluctuations including both sources of noise is simply $[S_i(sin) + S_i(amp)]$.

For an event which deposits an energy E in the normal metal, the output current decays exponentially with a time constant τ and has a spectral density $(dI/dT)^2(E/C)^2 4\tau(1 + \omega^2\tau^2)^{-1}$. In practice, the measurement frequency is such that $\omega\tau << 1$, so that the total energy resolution of the detector is

$$(\Delta E) = (kT^2C)^{1/2}\ [1 + a(1 + G_{e-p}/G_{sin})(1 + S_i(amp)/S_i(sin))]^{1/2}, \qquad (2)$$

where a = $(2 + T/T_b)^{-1} \approx 0.4$. The minimum attainable resolution is the thermodynamic limit $(kT^2C)^{1/2}$, and is approached when $G_{e\text{-}p} << G_{sin}$ and $S_i(amp) << S_i(sin)$. The former criterion implies that the energy of the electrons is dissipated through the junction by the measurement process and is not lost to phonons, whereas the latter states that the noise of the amplifier is lower than the noise of the junction. These conditions imply that it is advantageous to use as large a current as possible. In practice the current is limited by the Joule heating in the normal metal electrode. We think that the thermodynamic limit for the energy resolution should be accessible with reasonable experimental parameters.

3. PERFORMANCE OF AN SIN-BASED X-RAY DETECTOR

In this section we estimate the ultimate energy resolution of the SIN-based x-ray detector. We first discuss the properties of a normal metal film as an absorber of x-rays and then estimate the energy resolution of an optimized detector.

An x-ray photon interacts with a metal by ejecting a high energy inner core electron from an atom which then forms a local hot spot by interacting with other free electrons and emitting high energy phonons. To a good approximation the electrons remain in thermal equilibrium with the phonons as the hot spot expands. The two systems thermally decouple when the leading edge of the hot spot reaches the substrate, since then the phonons can be transmitted to the substrate whereas the electrons are confined to the metal. The usefulness of the metal as a high-resolution x-ray absorber is determined by the fluctuations in the energy which couples to the phonons, with a rough estimate of this effect obtained by considering the fluctuation in the number of phonons produced. The typical phonon energy can be estimated by calculating the temperature of the hot spot before the electrons have decoupled from the phonons. As discussed above, the volume of this hot spot corresponds to a sphere whose radius equals half the thickness of the film; its temperature is then found from the heat capacity of this volume and the deposited energy. For a 6 keV x-ray and a radius of 0.5 µm, we calculate a hot-spot temperature of 3 K, which corresponds to a phonon energy of 0.25 meV. From the ratios of the electron and phonon heat capacities at 3 K, approximately four fifths of the x-ray energy is stored in the lattice so the total number of phonons produced is approximately 10^7. The corresponding fluctuation in the phonon energy is then $(10^7)^{1/2}$ (0.25 meV) ≈ 1 eV. Although this is a rough calculation, the high resolution obtained with superconducting absorbers,[7] whose underlying physics is more complex than for our case, seems to substantiate these estimates. Our planned experiments will measure this effect directly. If the energy resolution of the absorber becomes important, then it may be possible to deposit the absorber on a thin membrane. The majority of the phonons will eventually deposit their energy to the electrons, hence eliminating the fluctuations in the phonon energy. We thus ignore this effect in our estimates.

As a specific example of a device that we plan to fabricate, we consider an SIN junction with an area of 100x100 μm^2 and a normal state junction resistance of 0.1 Ω. The normal electrode is a 1 µm thick gold film so that approximately 50% of 6 keV x-rays will be absorbed in the gold. The superconducting electrode is an Al film with Δ = 235 µV. The voltage bias is adjusted so that the current through the junction is about 6 µA for which $G_{sin} = 4G_{e\text{-}p}$. The resulting shot noise is 1 $pAHz^{-1/2}$ and is higher than the SQUID noise. We calculate that at 50 mK the energy resolution is 0.3 eV which is only slightly higher than the thermodynamic limit $(kT^2C)^{1/2}$ = 0.2 eV. In practice other phenomena may limit the energy resolution. Their presence will be determined in our planned experiments.

4. PERFORMANCE OF AN SIN-BASED PHONON DETECTOR

For the detection of particles such as dark matter candidates and of solar neutrinos, it is advantageous to detect the phonons that are produced by the interaction of the particle and the underlying substrate. Typically only a small fraction of the particle energy is transferred to the lattice,[8] which is converted into ballistic phonons with a characteristic energy of about 5 meV. For example, a 1 MeV neutrino will deposit an energy about 25 eV to the crystal in the form of approximately 5000 phonons. For simplicity, we assume that the phonons travel radially and isotropically away from the interaction site. The phonon absorber is a thin metal film which is deposited on the surface of the crystal. Approximately one half of the incident phonons will be reflected at the interface between the substrate and the absorber due to the mismatch in the acoustic impedance. The transmitted phonons will be absorbed by the electrons in the metal film, provided that its thickness is comparable with the phonon-electron mean free path $V_s\tau_{p\text{-}e} \approx 150$ nm. Here V_s is the mean phonon velocity and $\tau_{p\text{-}e}$ is the phonon-electron relaxation time.[9]

Ideally, a particle detector should have sufficient area coverage so as to interact with at least one ballistic phonon and sufficient sensitivity to detect that phonon. The figure of merit for such a detector is its energy threshold, or the minimum detectable energy deposited in the normal metal absorber. The energy threshold for the phonon detector is given by Eq. 2. We consider a 10x10 μm^2 normal metal absorber with a thickness of 50 nm at an operating temperature of 50 mK. A current I = 50 nA gives $G_{sin} = 70G_{e\text{-}p}$ and has a shot noise of 0.1 $pAHz^{-1/2}$ which is approximately equal to that of the SQUID amplifier operating at 50 mK. We calculate an energy threshold of $(kT^2C)^{1/2} = 5$ meV. At an operating temperature of 20 mK we calculate an energy threshold of 1.4 meV.

Although this design has sufficient sensitivity to detect a single ballistic phonon, the absorber has only a probability of 0.4% to interact with a single phonon, assuming that the particle/substrate interaction occurred a distance of 1 cm away from the detector and deposited a total energy of 25 eV to the lattice. In order to obtain a useful absorption area, it may be advantageous to use a large area superconducting absorber and a small area metal "trap".[10,11] Phonons which are incident on the superconductor will then break Cooper pairs, which will eventually diffuse into the normal metal and then dissipate their energy to the electrons. Here one obtains a large absorption area from the superconductor, but with no contribution to the electronic heat capacity. Although we are not able to estimate the efficiency of this "focusing" scheme, one might imagine several orders of magnitude improvement over the normal metal absorber estimates. If one could "focus" the phonon energy from an area of 1x1 mm^2 to the normal metal "trap" discussed above, then on average 4 ballistic phonons would be absorbed in the metal film for each particle absorbed in the substrate.

5. EXPERIMENTAL RESULTS

Having previously used electron beam lithography to fabricate submicrometer SIN junctions for infrared detectors,[2] it was easy for us to fabricate prototype x-ray and phonon detectors. We did not expect these devices to have a high energy sensitivity because of the high normal-state resistance of these small area junctions. We did however want to verify the basic detector physics and test the validity of several assumptions.

Our prototype x-ray detector consisted of a 1 μm thick gold absorber with an area of 10x10 μm^2. We chose this small absorber area in order to ensure an observable temperature rise. The junction was fabricated on one edge of the absorber and had a much smaller area of 0.2x1 μm^2 and a normal state resistance of 4 kΩ. The I-V characteristics of the junction agreed with Eq. 1 for $T > 100$ mK. It should be noted that in this configuration the absorber is not deposited directly on top of the junction, as is the case for most SIS based detectors.[8] The advantage of this configuration is that it becomes possible to independently vary the properties of the absorber and the SIN thermometer. The detector was cooled to 50 mK and irradiated with a 100 µCi ^{55}Fe source with a dominant x-ray energy of 5.89 keV. The distance between the source and the detector was 1 cm. For these first measurements the detector was biased at a constant current, and the voltage was measured with a room temperature JFET amplifier. The x-ray pulses were clearly observed, and had a characteristic decay time of about 100 µs, which is consistent with the electron-phonon relaxation time at 50 mK. It was difficult to estimate the energy resolution of this device, since the temperature rise of the electrons was sufficiently high ($\delta T(0) \approx 200$ mK) that the initial decay of the electron temperature was too fast (≤ 2 µs) to be measured with our electronics. Future experiments will use the 2-stage SQUID amplifier which has sufficient bandwidth to accurately measure the output pulse. From the device parameters and the amplifier noise we estimate an energy resolution of several hundred eV for this prototype detector.

The configuration of the phonon detector was identical to that of the x-ray detector, except that the thickness of the gold absorber was 50 nm. The x-rays were incident on the front side of the substrate, so the majority of phonons were produced within a depth of approximately 50 µm from the front surface. Pulses due to substrate events were clearly observed and had a characteristic decay time of about 100 µs. From the pulse rate we estimate that events were observed within a radius of ≈ 70 µm from the detector. Accurate estimates of the energy sensitivity were difficult to make for the same reasons as for the x-ray detector discussed above. A rough estimate suggests a minimum detectable phonon energy of about 5 eV deposited in the absorber.

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