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Hot-electron direct detectors: feasibility of NEP ≈ 10^{-20} W/√Hz at submillimeter waves

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Recently, we have presented a concept for a hot-electron direct detector (HEDD) capable of counting single millimeter-wave photons [1]. Such a detector meets the needs of future space far-infrared missions (NEP ≤ 10^{-19} W/√Hz) and can be used for background-limited detector arrays on the Space InfraRed Interferometric Telesope, the 10-meter space telescope and Submillimeter Probe of the Evolution of Cosmic Structure [2]. The detector is based on a microbridge (1-μm-long) transition edge sensor fabricated from an ultra-thin film of a superconductor with the critical temperature T_c = 0.1-0.3 K. A very strong temperature dependence of the electron-phonon coupling allows adjustment the electron-phonon scattering time, $\tau_{e\text{-}ph}$, to the desired time constant of the detector ($\tau = 10^{-4}$-10^{-3} s) at T = 0.1 K. Further adjustment of $\tau_{e\text{-}ph}$ is possible due to the electron-mean-free-path dependence of $\tau_{e\text{-}ph}$. The microbridge contacts are made from a superconductor with a higher critical temperature (Nb); these contacts will block the thermal diffusion of hot carriers into the contacts because of the Andreev reflection (see Fig. 1). The low electron-phonon heat conductance, high thermal resistance of the contacts, and small heat capacity of electrons in a micron-size bridge determine the noise equivalent power of ~ 10^{-20} – 10^{-21} W/√Hz at T = 0.1 K, which is 10^2 to 10^3 times better than that of state-of-the-art bolometers. By exploiting the negative electro-thermal feedback, the detector time constant can be made as short as 10^{-5}-10^{-4} s without sacrificing sensitivity.

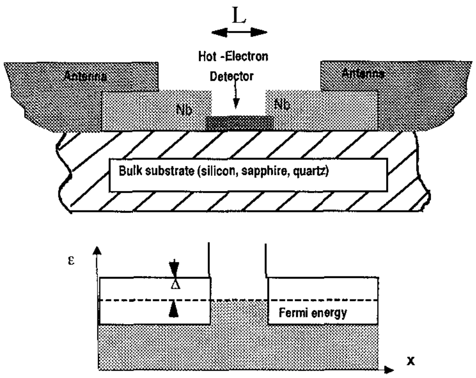

Fig. 1. Schematic diagram of the HEDD design. The low-T_c microbridge is surrounded by superconducting "Andreev mirrors" which prevent leakage of the thermal energy into the contacts. The energy gap in the microbridge is suppressed while in the contacts it is fully open. The size of superconducting contacts is small to avoid undesirable rf loss at high frequencies.

Our recent measurements [3] addressed the attainability of the low NEP in realistic low-T_c materials. For an optimized bolometer one would expect the intrinsic noise to be dominated by the "phonon" noise (temperature fluctuations). In the case of hot-electron bolometer, the noise equivalent power is given by

$$NEP = \sqrt{4k_B T_e^3 \gamma V / \tau_{e-ph}} \qquad (1)$$

where γ is the Sommerfeld constant, V is the microbridge volume, $\tau_{e\text{-}ph}$ is the electron-phonon relaxation time, and T_e is the electron temperature.

Reducing the temperature greatly improves the sensitivity. For practical reasons, $T_e \approx 0.1$ K is the limit. The minimum volume will be determined by the bolometer's lateral size L which will ensure i). a small influence of the large superconducting gap in the Nb contacts on the bolometer properties (proximity effect), and ii). sufficient thermalization of the quasiparticles excited by radiation at energies above the superconducting gap in the contacts. Both negative effects should be negligible at $L \sim 1$ μm [1]. The electron-phonon time is a material dependant parameter. In clean film, its temperature dependence is $\tau_{e\text{-}ph} \sim T^3$. In dirty materials, however, this time can be increased by a factor of $(q_t l)^{-1} \sim$ 10-100 ($q_t \sim T$ is the transverse phonon wavevector, l is the electron mean free path).

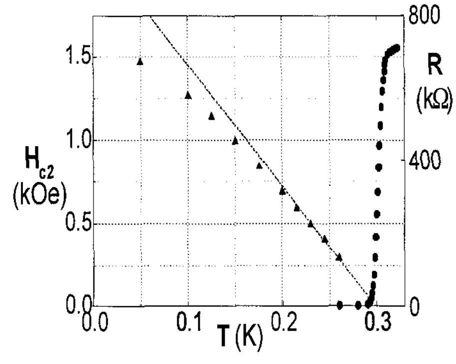

Fig. 2. The superconducting transition $R(T)$ at $H = 0$ with $\Delta T_c = 7$mK (dots) and the temperature dependence of the upper critical field H_{c2} (triangles) for a Hf meander structure with d = 250 Å and $R_\square$=38 Ω.

We have measured $\tau_{e\text{-}ph}$ in thin films of hafnium deposited on sapphire substrates. Hafnium (Hf) is a promising material for ultra-low-temperature HEDDs (T_c = 0.13K for bulk Hf). In these preliminary experiments, instead of using superconducting leads to block the outdiffusion of hot electrons, we fabricated a very long meander-type structure with total length $L >> \sqrt{D\tau_{e-ph}}$ (D is the electron diffusion constant). The critical temperature and resistivity of the magnetron-sputtered Hf films depend strongly on the argon pressure and deposition rate. By varying the deposition parameters, we were able to increase T_c up to 0.5 K. The R vs T and the temperature dependence of the critical magnetic field H_{c2} for one of the samples is shown in Fig. 2. The thickness of the Hf films was varied between 250 Å and 850 Å to keep the sheet resistance $R_\square$ in the 30-50 Ω range (for better impedance matching of the antenna-coupled HEDDs).

In the heating experiments, the resistance of a sample is measured at a small ac current I_{ac} by a resistance bridge as a function of the temperature and the heating dc current I_{dc}. The temperature dependence of quantum corrections to the resistance has been used as an electron "thermometer" in the temperature range $T > T_c$. Below T_c, the sample was driven into the resistive state by applying the magnetic field. The resistive state is very sensitive to electron overheating; this allows measurement of the thermal conductance between electrons and phonons $G_{e\text{-}ph}$ with unparalleled accuracy. The electron-phonon relaxation time is then consequently calculated as $\tau_{e\text{-}ph} = \gamma VT/G_{e\text{-}ph}$.

The temperature dependencies $G_{e\text{-}ph}$(T) measured for samples with different T_c are shown in Fig. 3. By assuming that the electron heat capacity in Hf films is the same as that in bulk Hf [γ = 160 W/(m^{3}K^2)], we can estimate the temperature dependence of the electron cooling time $\tau_{e\text{-}ph}$ in these films (Fig. 4).

We compare the experimental data with the theoretical estimate of the electron cooling time in the "dirty" limit $q_T l << 1$:

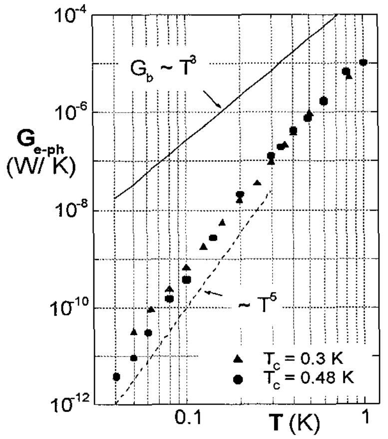

Fig. 3. Temperature dependencies of the thermal conductivity $G_{e\text{-}ph} \sim T^5$ for 250 Å-thick Hf meanders with the total area 0.5 mm^2, deposited on sapphire substrates. The solid line is the theoretical estimate for the thermal conductivity $G_b \sim T^3$ of the metal-sapphire interface.

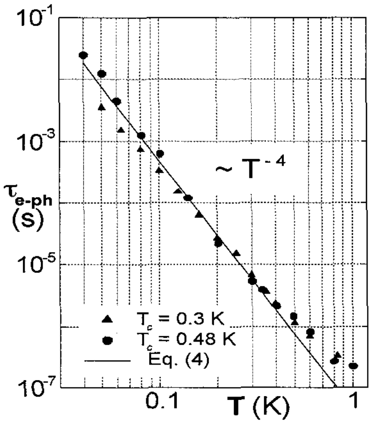

Fig. 4. The electron cooling time $\tau_{e\text{-}ph}(T)$ for 250 Å-thick Hf films with resistivity ρ = 0.1 mΩ·cm. For the other three Hf films with similar ρ, $\tau_{e\text{-}ph}$ was in the range 4 – 9 ms at T = 40 mK. The solid line is the dependence $\tau_{e\text{-}ph}(T)$ (Eq. 2) calculated for Hf with ρ = 0.1 mΩ·cm.

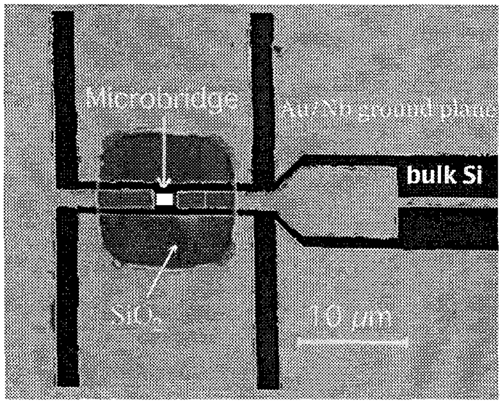

Fig. 5. SEM image of a twin-slot planar antenna. The actual antenna size implies a central frequency of 2. 5 THz. The white block in the center indicates the area which will be occupied by an HEDD sensor. The structure on the right is a low pass filter preventing leakage of the RF power into the dc line.

$$\tau_{e-ph} = 7.6\times10^{-4}\frac{M}{N_A}\frac{\rho}{R_Q}\frac{p_F^3 u_t^5}{(k_B T)^4 v_F}, \qquad (2)$$

Here $R_Q = \hbar/e^2 = 4.1$ kΩ is the quantum resistance, u_t is the transverse sound velocity, M is the molar mass, and p_F and v_F are the Fermi momentum and velocity, respectively. Equation (2) has been derived from the expression $\tau_{e\text{-}ph}(T)$ for electron scattering from transverse phonons [4]. The transverse phonons strongly dominate in electron-phonon interactions in the dirty limit. The condition of the dirty limit, $q_T l << 1$, is satisfied for our highly disordered Hf films at $T \leq 50$ K. It has been also assumed in Eq. (2) that the electron scatterers (impurities, defects, etc.) are completely dragged by phonons [5]. Finally, we took into account the energy averaging of $\tau_{e\text{-ph}}$ over the Fermi distribution of electrons (see, e.g., [6]).

Using the material parameters of bulk Hf ($M = 178.5$ g/mol, $u_t = 1.97\cdot10^5$cm/s, $p_F = 1.2\cdot10^{-19}$ g·cm/s, $v_F = 1.6\cdot10^8$cm/s), and the resistivity of the films studied ($\rho = 0.1$ mΩ·cm), we find $\tau_{e\text{-}ph}(T) = 4.8\cdot10^{-8}$ s·[1K/T]^4 (the solid line in Fig. 4). Below $T \sim 0.5$ K, the agreement between the experimental data and Eq. 2 is very impressive (note that this comparison does not involve *any* fitting parameters). At higher temperatures, the dependence $\tau_{e\text{-}ph}(T)$ becomes weaker than that predicted by Eq. 2.

Two important conclusions can be drawn from these experiments. First, the experimental values of $\tau_{e\text{-ph}}$ are sufficiently large to ensure record sensitivity of HEDDs at temperatures $T < 0.3$ K. A 1-μm-size bolometer made from such Hf film would have a NEP ≈ 3×10^{-20} W/√Hz at 0.1 K and 1×10^{-18} W/√Hz at 0.3 K. This is much better than the NEP of state-of-the-art bolometers. Second, the time constant of the detector at 0.1 K is about 1 ms. By using a negative thermo-electrical feedback this value can be reduced by at least an order of magnitude. This makes the output bandwidth of the HEDD at least 1.5 kHz at 0.1 K and ~ 300 kHz at 0.3 K. The energy resolution of the detector at 0.1 K would allow for counting of ~100 GHz photons.

As a critical experimental step to prove this concept, we are fabricating an antenna-coupled Hf HEDD based on our previous experience with hot-electron superconducting THz mixers. The bolometer will be integrated with a twin-slot antenna whose in-plane size defines the central frequency of the detector (see Fig. 5). The Si chip with the planar structure is mounted on the back of an elliptical or hyperhemispherical Si lens in such a way that the geometrical focal plane would be at the antenna plane. Direct measurements of the antenna spectral characteristic [7] have shown that the position of the central frequency can be predicted and the antenna bandwidth is about one octave. With the well defined one-octave antenna bandwidth the direct optical measurements of the NEP using a submillimeter black body source will be straightforward.

As a future development we consider integrating single bolometers into large arrays. There is a variety of planar antennas which might be potentially suitable for this. Besides a twin-slot antenna, other possibilities include a double-dipole antenna, an integrated horn antenna and others.

A crucial issue related to a focal plane array is a readout scheme capable of handling large numbers of sensing elements. Using a separate amplifier for each detector element is certainly a radical solution, however when the number of elements becomes of the order of hundreds the electrical layout for all amplifiers may become nearly impossible. Another important concern is about the large number of wires leading to a 0.1-0.3 K platform. In the case of a transition-edge bolometer a time-division multiplexing of read-out SQUID amplifiers has been proposed [8]. This allows for some reduction in the number of wires leading to the amplifiers but the number of amplifiers remains the same.

We are going to investigate a novel solution for the sensor read-out which is based on a combination of coded mask technique and detector bias multiplexing. Coded mask technique was used, for example, in some X-ray telescopes to record an image using a single detector and a set of masks with transparent and opaque segments. If the sequence of segments fulfills certain mathematical ordering the original image can be recovered after recording a number of detector responses to the radiation passed through different masks. An optimal set of mask is known to be represented by Walsh-Hadamard functions [9]. Many other applications of the Hadamard transform for imaging and spectroscopy are described in [10]. To the best of our knowledge it has never been used for submillimeter-wave imaging.

Instead of a set of physical masks placed against the sensing elements, we are going to use a manipulation of the electrical dc bias to generate the "masks". An example of the circuit which could be built for a 4-element bolometer/HEDD array is shown in Fig. 6. All elements are connected in parallel and voltage-biased individually. The sum of all ac current signals is recorded by a single SQUID amplifier via a transformer. The image is represented by signals S1-S4 across the elements. The multiplexing coding is given by the following Hadamard matrix:

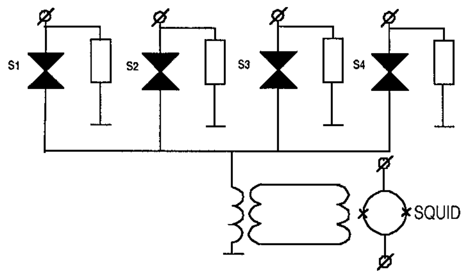

Fig. 6. The schematic of the 4-element array of bolometers with a single SQUID amplifier read-

$$\mathbf{H4} = \begin{vmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{vmatrix}, \qquad (3)$$

where 1's correspond to a positive dc bias and -1's to a negative bias of the same magnitude. Four bias "masks" corresponding to the rows in Eq. 3 are consequently applied and each time a reading R1-R4 is made. The following Hadamard transform relations are valid:

$$\mathbf{R} = \frac{1}{4}\mathbf{H4} \bullet \mathbf{S}\,,\ \mathbf{S} = \mathbf{H4} \bullet \mathbf{R}. \qquad (4)$$

Higher order Hadamard matrices exist for larger N's.

The advantage of this techniques is that just a single amplifier is needed to read the whole array. Also, if the system noise is dominated by the electronics, then the total signal-to-noise ratio can be improved in average by a factor of $N^{1/2}$ (N is the number of detectors). Since the detectors are connected in parallel, one damaged element will not affect the performance of the others. The proposed coding/multiplexing techniques can be applied to practically any type of detector element. In the case on the detectors with non-symmetrical current-voltage characteristic the multiplexing should be done turning element on and off rather than by changing polarity of the voltage. The relations of Eq. 4 can be easily modified in this case.

In conclusion, a novel hot-electron direct detector for submillimeter radioastronomy is being developed. The sensitivity is enhanced by supression of the electron-phonon interaction strength in a disordered superconducting film. The measurements of the thermal conductance in thin Hf films suggest that the NEP can be of the order of 10^{-20} W/√Hz at 0.1 K. A new multiplexing scheme for a detector array using Hadamard transform coding detector biasing is under study.

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