Experimental Study of Superconducting Hot-Electron Sensors for SubMM Astronomy

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Abstract—The superconducting and noise properties of micron-size hot-electron sensors made from thin Ti film are studied. The sensors can be used for both hot-electron direct detectors (HEDD) and hot-electron photon-counter (HEPC) depending whether a weak electron-phonon coupling or an electron diffusion is a dominating cooling mechanism. The HEDD with a potential NEP = 10^{-28} W/Hz at 0.1 K and the time constant ~0.1 ms will meet the needs for future background-limited arrays on space telescopes. Current effort is aimed at the demonstration of the feasibility of such a detector at 0.3 K where the NEP ≈ 10^{-18} W/Hz and the time constant ~1 μs are expected. The fabrication technology for a few-μm-long HEDD devices using thin Ti films has been developed and the first output noise measurements data are presented. The results indicate good agreement with the hot-electron model. The radiation frequency response of a prototype antenna-coupled Nb device has been measured and proved to be flat over the range 250-900 GHz. The HEPC would be able to operate between 300 GHz and 40 THz with the photon counting rate in the GHz range.

Index Terms—bolometers, electron-phonon coupling, photon counters, superconducting devices.

I. MOTIVATION AND BACKGROUND

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 applications (NEP ≤ 10^{-19} W/Hz) and can be used for background-limited detector arrays on future submillimeter space telescopes. The detector is based on a microbridge transition edge sensor (TES) fabricated from an ultra-thin film of a superconductor with the critical temperature T_c = 0.1-0.3 K. The sensor is a radiation absorber at the same time. Since it is made from a thin disordered film its normal resistance is large (~50 Ω) and is suitable for matching to a planar microantenna. A very strong temperature dependence and the electron-mean-free-path dependence of the electron-phonon coupling allow for adjustment of the electron-phonon scattering time, τ_e-ph, in Hf and Ti films to the desired value ~1 ms at T = 0.1 K [2]. The microbridge contacts need to be 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 [3]. 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^{-29} W/Hz at T = 0.1 K and ~10^{-18} W/Hz at T = 0.3 K, which is correspondingly 100 and 10 times better than that of state-of-the-art bolometers. By exploiting the negative electron-thermal feedback [4], the detector time constant can be made much shorter than bare τ_e-ph, i.e. ~0.1 ms at 0.1 K and ~1 μs at 0.3 K without sacrificing sensitivity. As well as for the other TES’s, a dc SQUID is the most suitable readout amplifier for the HEDD. A typical noise of the state-of-the-art SQUIDs (~1 pA/√Hz) will be smaller than that of the HEDD itself [1].

Another application of hot-electron microsensors can be a photon-counting device. There has been recently an increasing interest to photon-counting devices for submillimeter waves. Direct registration of single submillimeter photons has been reported using single quantum dots in magnetic filed [5] and coupled quantum dots [6]. Other ideas for photon counting include a device integrating a superconducting absorber and a single-electron transistor for reading individual charges [7] and a hot-electron type device using a hot-spot formation mechanism in a superconducting current carrying strip [8]. The use of superconducting bolometers for counting high-energy photons has become a common practice. For applications at submillimeter waves, a very small heat capacity of a bolometer is needed since it sets the energy resolution limit for the counter. The antenna-coupled hot-electron sensor is the best choice since its heat capacity is given by electrons only and the size can be submicron. In this case, there is no need to pursue a relatively long relaxation time as in the case of bolometric direct detectors. The cosmic microwave background photon rate is rather higher and slow bolometers can be useful for photon counting only in very high resolution instruments. Fortunately, beside the electron-phonon interaction there is another mode of cooling in hot-electron sensors, namely diffusion cooling. This mechanism [9] has been successfully used in Nb hot-electron mixers at
THz frequencies [10]. For submillimeter photon counting, same small Ti microbridges can be use but without Andreev contacts.

Our current experimental effort is aimed at the demonstration of the feasibility of the HEDD at submillimeter waves. We have addressed the issue of the spectral response in HEDD, have developed fabrication technique for short Ti devices, have performed first dc and noise tests of subkelvin HEDDs and are currently working towards fabrication of a fully functional antenna-coupled HEDD operating at 0.3 K. The estimates of the potential performance of HEPC have been made demonstrating good potential of this device for variety of applications.

II. FABRICATION AND CHARACTERIZATION OF Ti MICROBRIDGES

A. DC measurements.

Titanium has been previously identified as a good candidate material for an HEDD operated at 0.3 K [2]. We fabricated simple Ti microbridges to test the quality of the material and the operability of our dilution refrigerator test system with a SQUID. The devices were fabricated at Rutgers University with a final removal of the protection gold layer done at JPL. 20 nm thick films grown by magnetron sputtering on sapphire substrate were used. The films were patterned into 1-μm-wide, 0.5-to-3-μm-long microbridges with normal Au contacts. Most of bridges exhibited sharp superconducting transition \( T_c \) \( \approx 10 \) mK wide. The critical temperature was in the range 0.3-0.36 K and the normal state resistance was 40-50 Ohm for longest bridges.

Fig. 2 demonstrates a current-voltage (IV) characteristic of a typical bridge at 100 mK. The critical current is rather large and a strong hysteresis due to self-heating is observed. The position of the drop-back point on the IV-curve did not depend on the temperature and allowed us to estimate the effective thermal conductance of the bridge using a simple heat balance equation:

\[ P = \gamma V(T_c^2 - T^2)/(2\tau_{\text{diff}}) \]  

(1)

Here \( \gamma \) is the Sommerfeld constant, \( V \) is the bridge volume, \( P \) is the Joule power. This equation assumes that the heat is removed from the bridge via a diffusion of hot electrons to the normal metal contacts. The diffusion time derived from this expression \( \tau_{\text{diff}} \approx 30 \) ns agrees well with the theoretical value calculated as \( \tau_{\text{diff}} = L^2/(12D) \) [11] with \( D = 2.4 \) cm/s. If the contacts were made from Nb the heating would be defined by the electron-phonon relaxation which is much slower process for given conditions (\( \tau_{\text{e-ph}} = 20 \) μs at 0.3 K [2]).

B. Noise measurements.

The output noise of a microbridge was measured when the device was voltage biased at a temperature somewhat below \( T_c \). The IV characteristic of a 3-μm-long Ti bridge at 100 mK.

where a negative differential resistance was seen. A Quantum Design dc SQUID amplifier connected in series with the bridge was used for the measurements. A 1-Ω resistor in parallel to the device+SQUID chain provided sufficient voltage bias. An example of the data set taken at 338 mK is shown in Fig. 3. Solid dots is experimentally measured noise for different bias voltages. The noise was highest when the bias point was right on the top of the IV characteristic. The noise of the circuit loop with the device in the normal state was 2 pA/Hz\(^{1/2}\). The variation of the noise vs bias agrees with what might be expected from a hot-electron mechanism with diffusion cooling. Assuming that the shape of the IV characteristic is defined by self-heating only, the thermal

Fig. 3. Output noise data at 338 mK. Circles— experimental points, dashes and dots — hot-electron model calculations.
energy fluctuation (TEF) noise (dotted line) and the Johnson noise (dashes) were calculated. The experimental points are within a factor of 2 from the theoretical curve and demonstrate the same trend with the bias. Another indication of the diffusion cooling is a very large noise bandwidth. Actually, no difference in the shape of the noise spectra was seen up to the instrumentation limit of 100 kHz. The TEF noise cuts off at the frequency roughly corresponding to the inverse temperature relaxation time (with some modification due to self-heating effects). In our case, the bare temperature relaxation time is already just a few nanoseconds, so the corresponding bandwidth would be several tens of MHz.

III. SPECTRAL RESPONSE IN HEDD

Spectral response of a bolometer is usually determined by the spectral behavior of the absorber and by the input circuit (antenna, filters etc.). For a normal metal absorber the spectral characteristic shows weak variations with frequency. The same is true for a superconducting absorber if the radiation frequency is larger than 2Δ (Δ is the superconducting gap in the bolometer material). In HEDD, the small sensor size is the key to the high sensitivity. At low temperature, however, the diffusion length of quasiparticles at 0.1 K is much longer than the device length, so Andreev contacts should be used to prevent the escape of thermal quasiparticles [3]. All nonequilibrium quasiparticles excited up to the frequency \( v_e = \Delta_e / h \) (\( \Delta_e \) is the gap in the Andreev contacts) are confined within the sensor area. For higher frequencies, the quasiparticles with energy greater than \( \Delta_e \) may, in principle, diffuse out before they relax to the gap \( (\Delta_e) \) energy, and recombine in the contacts. In this case, a part of the signal energy may be lost via recombination and emission of 2\( \Delta_e \)-phonons and will not contribute to the change of the bolometer resistance. The effect would have a spectral threshold at \( v_e \). This effect is only important if quasiparticles have time to reach the contacts before they scatter via electron-electron interaction and reduce their energy to the value below \( \Delta_e \). A fraction of the device length affected by this process is \( L_c = [D \tau_c(\Delta_e)]^{1/2} \) where \( D \) is the electron diffusion length, \( \tau_c(\Delta_e) \) is the effective energy relaxation length at the edge of the energy gap in the Nb contacts (\( T_e \sim 9K \)). Since \( \tau_e \sim e^{-m} \) (\( m \geq 2 \)) at high energies, the quasiparticles excited above \( \Delta_e \) will have the diffusion length shorter than \( L_c \). The estimates [1] done under an assumption that \( \tau_e \) is determined by the electron-electron scattering only show that \( L_c = 100 \) nm in dirty films. Thus, in principle, a 1-\( \mu m \)-long device can be long enough to make the above process ineffective. This is, however, a situation that has never been studied experimentally, so we performed direct measurements of the spectral response.

We used prototype antenna-coupled HEDD devices fabricated at JPL. 1-\( \mu m \)-long bridges were made from a 12 nm thick Nb film with \( T_e = 6.5 \) K. The contacts were made from a 100 nm thick Nb film with \( T_e = 8.6 \) K. The devices were fabricated on a Si substrate with a planar spiral antenna whose operating range was between 100 GHz and 3 THz. The

![Fig. 1. Submillimeter spectra of a Nb HEDD measured at two temperatures: dots—4.2K, solid—8.4K.](image)
that would indicate a potential problem with the loss of quasiparticles. Fig. 1 shows the two spectra in a broad frequency range. The bandgap in Nb contacts $v_e = 330$ GHz lies within this range. As one can see, there is no noticeable difference between two spectra. This result indicates that it is unlikely that outdiffusion of hot quasiparticles is important in micron-size HEDD sensors made from dirty superconductors. This conclusion applies to subkelvin HEDDs: the gap in the contacts would be the same in any case and diffusivities of dirty Ti, Hf and Nb films are all of the order of $1 \text{ cm}^2/\text{s}$.

IV. CONCEPT OF THE HOT-ELECTRON PHOTON COUNTER

Currently, superconducting transition edge calorimeters are broadly used for X-ray, UV and optical photon detection. The energy resolution of a bolometric calorimeter is given by:

$$\delta E = 2.355 \cdot \sqrt{\frac{4\pi k_B T_c}{n - 1} C_e} \alpha$$  \hspace{1cm} (2)

where $\alpha = \frac{d \ln R}{d \ln T}$, $C_e = \gamma VT_c$.

The maximum counting rate is $N = 1/2$ where $t$ is the bolometer response time modified by the negative electrothermal feedback (by a factor $\alpha/n + 1 \approx 100$ shorter than the bare relaxation time).

In conventional transition-edge sensors, both the energy resolution and the maximum counting rate depend on the heat capacity. The latter is set by the design of the absorber and the thermometer. In an antenna-coupled hot-electron sensor, $C_e$ can be extremely small. If one uses a diffusion cooling of electrons as in our current experiment, $\tau$ will be determined by $\tau_{diff}$ which is very short. For a $0.5 \mu m \times 0.2 \mu m \times 0.02 \mu m$ (readily achievable size) Ti photon-counting sensor the "red boundary" $v_1 = \delta E / h \approx 300$ GHz. The upper frequency limit is set by the energy needed to heat the bolometer above $T_c$ (see Eq. 1), that is $v_2 = \gamma V T_c^2 / 2h = 40$ THz. The $v_1-v_2$ range covers essentially all submillimeter wavelengths.

The maximum counting rate of the hot-electron photon counter can be found as $\alpha \cdot 2 \pi T \approx 3 \times 10^{11}$ count/s. The counting rate which can be realized in an instrument would likely be smaller. However, even for a low resolution photometry in space ($R \approx 2$), the 3-Kelvin photons from the microwave background would arrive at a rate $< 2 \times 10^8$ count/s at 300 GHz, so there is a large margin in the dynamic range. The situation gets even better for higher frequencies or/and higher spectral resolution.

V. CONCLUSION

Hot-electron microsensors set a base for a variety of ultrasensitive detector for submillimeter space applications. The use of planar antennas for coupling of micron-size bolometers to submillimeter radiation and bulk (Si, sapphire) substrates would allow for a small size imaging array chip. Indeed, one detector element would occupy as little as $\sim 100 \mu m \times 100 \mu m$ area on Si. So, a 100x100 array chip would have a $1 \times 1 \text{ cm}^2$ size. Since the illumination of the monolithic detector array has to be done from the back of the chip the array can be integrated with a multiplexer chip using a well established indium bump bonding technique routinely used at wavelengths between 1 and 30 $\mu m$. HEDDs are compatible with the SQUID readout and would be able to be integrated in any of readout schemes that are being developed for conventional TES. The readout technique for the HEPC would rather be RSFQ electronics [12]. This topic is still at a very early stage.

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REFERENCES

[11] Since the diffusion cooling is not exactly "exponential" process there is a difference in definition of the time constant depending on how it is measured. We used the "static" value, whereas for dynamic measurements $\tau_{diff} = L^2 / (\pi D)$ is a more suitable definition. For detail, see P.J. Burke, "High frequency electron dynamics in thin film superconductors and applications to fast, sensitive THz detectors," Ph.D. dissertation, Dept. Appl. Phys, Yale Univ., New Haven, CT, 1997.