CAPACITIVELY COUPLED HOT-ELECTRON MICROBOLOMETER AS A PERSPECTIVE IR AND SUB-MM WAVE SENSOR

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ABSTRACT

A novel concept of the normal-metal hot-electron bolometer using capacitive coupling of the absorber to antenna (NHEB-CC) has been proposed. The concept is based on the normal metal hot-electron microbolometer with Andreev mirrors (NHEB-A) using a SIN junction as a temperature sensor [1-3]. The NHEB-A technology brings a possibility to fabricate the sub-mm wave receiver for space applications with a noise equivalent power NEP about $3x10^{-18}$ W/Hz$^{1/2}$ at 100 mK. However, the Andreev mirrors could give certain frequency limitations for using this bolometer for higher frequencies with the energy quantum hf higher than the energy of a superconducting gap Δ. The NHEB-CC technology with capacitive coupling of the absorber to antenna avoids these problems. The effective high frequency coupling of the external signal in NHEB-CC is achieved by a low impedance of the coupling capacitances. At the same time, the capacitance gives reliable protection against escaping the hot electrons from the absorber. Usual tunnel junctions with proper thickness of the barrier can be used as capacitors. In such realization, we keep the main advantage of the NHEB technology - very small thermal conductance between electrons and phonons due to small volume of an absorber (typical value of G is $2x10^{-13}$ W/K for T=100 mK) in combination with frequency independent protection of the absorber against thermal leak to the antenna.

I. INTRODUCTION

Ultra low noise bolometers are required for space - based astronomical observations. The most sensitive and fast bolometer for infrared and millimeter wave region is a normal metal hot-electron microbolometer (NHEB-A) with Andreev mirrors and an SIN junction as a temperature sensor [1,2]. A schematic of the NHEB-A is shown in Fig. 1a.

The NHEB-A technology is based on a weak coupling between electrons and phonons in normal metal strip at low temperatures (so called "hot electron effect") to produce a large temperature rise of electrons T_e for small absorbed power P

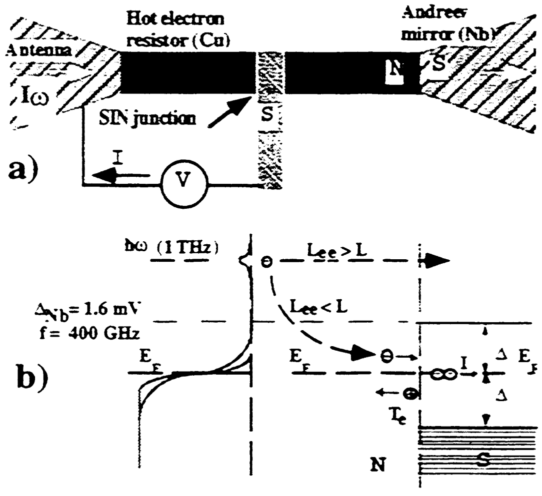

Fig. 1. A schematic of the normal metal hot-electron microbolometer (NHEB-A) with Andreev mirrors (a) and illustration of possible problems with escaping the high-energy electrons through SN interface for higher frequencies (b).

$$T_e = \left(T_{ph}^5 + \frac{P}{\Sigma V}\right)^{1/5},$$

where V is volume of the strip, Σ is material constant and T_{ph} is the phonon temperature. A very elegant approach is using the Andreev reflection for *thermal insulation* at SN interface between a metal absorber and a superconducting antenna. Simultaneously, the SN interface provides a perfect *electrical contact* to the superconducting antenna (Fig. 1b).

The NHEB-A technology brings possibility to fabricate the sub-mm wave receiver for space applications with a noise equivalent power NEP about $3x10^{-18}$ W/Hz$^{1/2}$ at 100 mK and $3x10^{-17}$ W/Hz$^{1/2}$ at 300 mK with a time constant better than 20 µs [2]. However, the Andreev mirrors could give certain frequency limitation for using this bolometer. The problem can arise for higher frequencies when the photon energy hf becomes higher than the energy of a superconducting gap Δ [5] as it is demonstrated in Fig. 1b . For example, the Nb gap Δ=1.6 meV corresponds to the frequency 400 GHz. Really, the probability of photon absorption can be considerable only at at energy level corresponding to interband transitions [6]. For copper, for example, this level of energy corresponds to 2 eV. Thus the photon absorption process should be really important only at frequencies considerably higher than 1 THz. Thermalization of the excited electrons depends on relation between an electron-electron inelastic scattering length L_{ee} and length of the absorber L. In the case of $L_{ee} > L$, there is no effective thermalization at the length of absorber and electrons can come to SN interface roughly with the same energy as after excitation. In this case, the Andreev SN interface would not be an effective mirror for these hot electrons and thermal conductance can be increased.

Another problem at higher frequencies can arise due to increasing resistance of the superconducting antenna for frequencies higher than 2Δ. Resistance increase can lead to heating the antenna and decreasing the effective superconducting gap at SN interface. For example, the Nb double gap corresponds to the frequency 800GHz. To avoid this problem, the main part of antenna can be covered by normal metal with good conductivity except a part near the SN interface to keep Andreev reflection for hot electrons of an absorber. Thus, discussed problems are complicated and can lead to suppression of the device parameters at higher frequencies. This situation has stimulated search for new configurations of the microbolometer where these problems will not limit the operation of the device.

A novel concept of the normal-metal hot-electron bolometer using capacitive coupling of the absorber to the antenna (NHEB-CC) has been proposed to avoid the frequency limitation of the NHEB-A and for technological improvements.

II. HOT ELECTRON BOLOMETER WITH CAPACITIVE COUPLING

The idea of this device is to use the capacitance for thermal isolation of the normal-metal absorber instead of the Andreev SN mirrors (Fig. 2a).

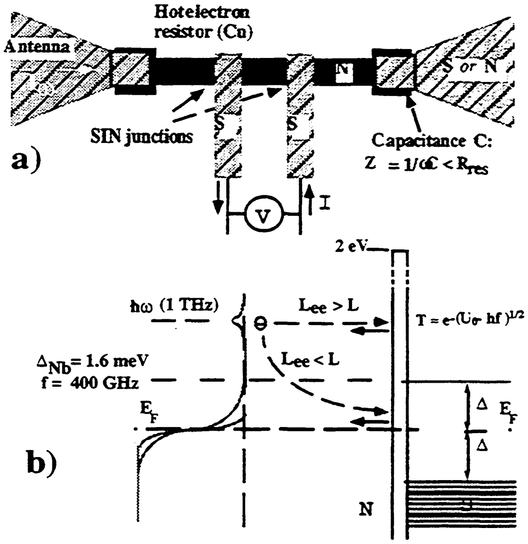

Fig. 2. (a) A schematic of the normal metal hot-electron microbolometer with capacitive coupling to the antenna (NHEB-CC) and (b) energy diagram for illustration of protection of an absorber against escaping the high-energy electrons for higher frequencies by high potential barrier.

In this case, the effective high frequency coupling of the external signal in the NHEB-CC can be achieved by the low impedance of coupling capacitances between the absorber and the antenna. For an absorber resistance R_{abs} = 100 Ohm and a frequency 1 THz it is enough to have C = 15 fF to get the impedance of the capacitance equal to 10 Ohm that would provide good coupling. Such capacitance can be easy realized by overlap 0.5x0.5 μm^2. The antenna can be made of both superconducting or normal metal.

The insulation barrier of the capacitors gives perfect thermal protection of absorber in the NHEB-CC configuration. A more universal and effective approach for this device is to use the tunnel junctions as capacitors. More than that, it is possible to use tunnel junctions made in the same vacuum circle as tunnel junctions for temperature measurements but of different area. The transparancy of a barrier is exponentially dependent on the thickness of the barrier d

$$\mathbf{T} \approx e^{-(U_0 - hf)^{1/2} d}$$

and for typical d=12 Å and $U_0 = 2$ eV, T ≈ 4×10^{-8}. For all frequencies with energy hf well below the height of the potential barrier U_0 (corresponding to 5×10^{14} Hz) the transparency will be negligibly small.

In such realization, we keep the main advantage of the NHEB technology - very small thermal conductance between electrons and phonons due to the small volume of the absorber (typical value of G is 2×10^{-13} W/K for T=100 mK) in combination with reliable protection of the absorber against thermal leak to the antenna.

Impedance matching. The NHEB-CC configuration uses the dimensions of the absorber much smaller than the wavelength of a signal and a planar antenna structure can be used to provide efficient coupling in this case [1]. To our experience the optimal choice is a very broad-band (over a decade) log-periodic complementary antenna having a frequency independent real impedance

$$Z_{ant} = 377[2(1+\varepsilon)]^{1/2}$$

where ε is dielectric constant of the substrate [7]. For Si substrate $Z_{ant} \approx 80\ \Omega$.
For high frequency coupling of the bolometer to the antenna, we have to match the impedances of these parts. The impedance of the bolometer has three components

$$\mathbf{Z}_{bol} = \mathbf{Z}_C + \mathbf{Z}_L + \mathbf{Z}_{abs},$$

where $\mathbf{Z}_C$ is the impedance of two coupling capacitances

$$Z_C = (2/j\omega C),$$

Z_L is the impedance due to geometrical inductance of the absorber [6]

$$Z_L = 2\times10^{-7} j\omega l \left[\ln\frac{l}{(w+t)} + 1.19 + 0.22\frac{(w+t)}{l}\right]$$

where l - length, w - width, and t - thickness of the absorber. For typical parameters of the absorber [2,3]: l = 6 µm, w = 3 µm, and t = 0.05 µm,- one can get for inductance component:

$$Z_L = 8\times10^{-13} j\omega l,$$

with a length of the absorber l in µm.

Taking into account that the log-periodic antenna has a real impedance Z_{ant}, there is an optimal way to compensate the inductive component Z_L by the capacitive component Z_C. For typical length of absorber l= 6 µm [2,3], the estimated Z_L is 30 Ω. For compensation Z_L, the capacitive component $Z_C = Z_L$ gives at f= 0.8 THz the value of the capacitance C = 13 fF that can be easy realized by tunnel junctions with an area of 0.5x0.5 µm^2.

As a result, using the NHEB-CC configuration we have even improvement of coupling to the antenna due to compensation of the inductive impedance of an absorber by the capacitive impedance of coupling junctions.

Double-layer technology. One more advantage of the NHEB-CC is that the same type of SIN tunnel junctions as for a temperature sensor but of larger area can be used for capacitive coupling. In this case we can use double-layer technology with one vacuum circle that would considerably simplify fabrication of the bolometer in comparison with triple-layer technology [2,3].

The inconvenience of the NHEB-CC is absence of possibility to calibrate the bolometer using dc current measurements: such calibration can be made only using a high frequency signal.

Two SIN junctions for measurements. The NHEB-CC technology suggests using two SIN junctions for temperature measurement in comparison with one junction used in Refs. [1,2]. This necessary step should only improve the performance of the device due to increase of output signal by a factor of 2 (and noise of the junctions only by a factor of $2^{1/2}$) that is important for the amplifier-noise limited bolometer.

The optimal configuration. Taking into account that the same tunnel junctions are used for capacitive coupling to antenna as for temperature measurement, we can combine these two functions in one pair of junctions. The simplest configuration is shown in Fig. 3.

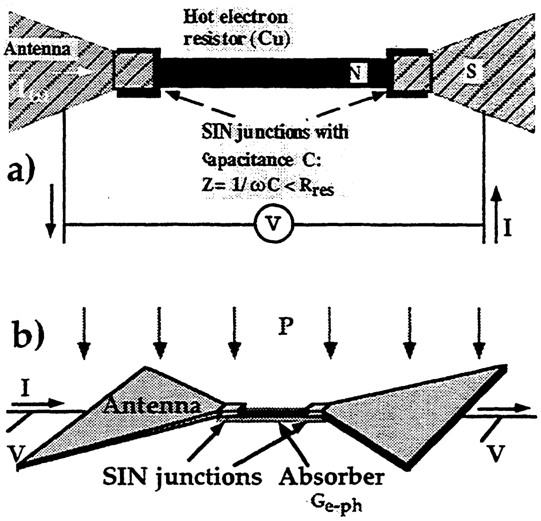

Fig. 3. a) The optimal simplest configuration of the NHEB-CC comprising an absorber and two tunnel junctions. The tunnel junctions carry out three functions: temperature measurements, capacitive coupling to antenna, and thermal isolation of the absorber. b) The high frequency coupling of the NHEB-CC.

The measuring junctions are placed in series with the absorber and bias electrical contacts are made to the antenna. Taking into account that typical resistance of the junctions (≈20 kΩ) is considerably higher than the resistance of the absorber (≈80 Ω) we would have still correct measurements of the junction voltage in this configuration.

Electronic microrefrigeration. The additional advantage of using tunnel junctions for capacitive coupling is a possibility to use these junctions for electronic microrefrigeration [9-11].

For electronic cooling, the tunnel junctions should be made of larger area that coincides with a purpose of capacitive coupling. The SIN junctions for temperature measurements are located in the center of the strip as in usual configration (Fig. 2a). The whole configuration becomes to be simpler than the NHEB-A configuration with possible cooling discussed in Ref. 9.

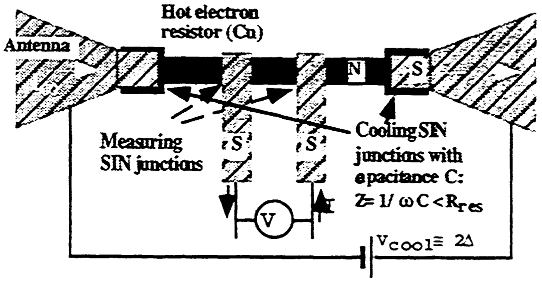

Fig. 4. A schematic of the NHEB-CC with possible electronic cooling through coupling SIN junctions.

III. CONCLUSIONS

Finally, the NHEB-CC technology seems very worthwhile and can help to overcome the possible frequency limitation of the NHEB technology with Andreev mirrors. Simplification of the fabrication technology using two layers (instead of three layers in NHEB-A configuration) is especially attractive. Due to compensation of the inductive impedance of an absorber by the capacitive impedance of coupling junctions, the NHEB-CC configuration gives improvement of coupling to the antenna.

The obligatory two SIN junctions for measurements (instead of one in the NHEB-A) can improve a noise figure by a factor of two for the case of the amplifier -noise-limited microbolometer. The simplest configuration consisting of an absorber and two junctions for coupling with antenna and temperature measurements looks optimal for applications requiring arrays of microbolometers .

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