ANTENNA – COUPLED SUPERCONDUCTING ELECTRON-HEATING BOLOMETER

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Abstract.

We propose a novel antenna-coupled superconducting bolometer based on electron-heating in the resistive state. A short narrow ultrathin superconducting film strip (sized approximately 4x1x0.01 μm^3), which is in good thermal contact with the thermostat, serves as a resistive load for infrared or submillimeter current. In contrast to conventional isothermal superconducting bolometers, electron-heating ones can have a higher sensitivity which grows when film thickness is reduced. Response time of electron-heating bolometer does not depend on heat transfer from the film to the enviroment. To calculate the sensitivity (NEP), we have used experimental data on wideband Al, Nb and NbN bolometers which have the same underlying physical mechanism. The bolometers have been made in the form of a structure composed of a number of long narrow strips. The values of NEP have been found to be $1.5 \cdot 10^{-16}$, $1 \cdot 10^{-15}$, and $2 \cdot 10^{-14} W \cdot Hz^{-1/2}$ for Al, Nb and NbN respectively. In the paper, the prospects are also discussed of improving the picosecond YBaCuO detector, developed recently. NEP value of the detector, if combined with a microantenna, can reach the order of 10^{-10}–10^{-11} $W \cdot Hz^{-1/2}$.

Introduction.

Over the last decade, a substantial progress has been made in the creation of high-sensitive superconducting devices intended to receive electromagnetic radiation in the spectral range of 20 - 1000 μm. Due to frequency-independent response, bolometers have certain advantages over other superconducting detector types, such as Josephson junction or superconductor-insulator-superconductor structure. Further improvement in bolometer parameters can be primarily achieved by reducing the size of the bolometer, which in its turn entails the use of small antenna coupled with the sensitive unit of the bolometer [1]. This approach seems very promising for the development of radiation detectors with very low NEP values. Very recently we have proposed to utilize the electron-heating effect in thin and narrow superconducting films for radiation detection. A fundamental property of the effect is a small value of time constant as compared to the traditional bolometric effect.

The present paper views the characteristics of an antenna-coupled microbolometer whose operation is based on the electron-heating effect. It is shown that the sensitivity of the electron bolometer is enhanced both by reducing film area and by getting the film thinner. Moreover, NEP value can be diminished in comparision to conventional bolometers, to achieve an extremely rapid action, as well as to ensure a much better matching between the bolometer and the antenna.

Results and Discussion.

Our previous papers [2-4] have demonstrated that the electron-heating effect is manifested at liquid helium temperatures in thin (thickness d $\simeq$ 100$\mathring{A}$) and narrow (width w $\simeq$ 1 μm) films of Al, Nb and NbN, deposited onto the substrates having good heat conductivity. Under these conditions one can obtain a unique combination of rapid action and high sensitivity inherent in the material. The electron heating has been most thoroughly studied in Nb films. As demonstrated in [2], a small mean free path of electrons (5-10 $\mathring{A}$) in thin disordered films leads to the enhancement of electron-electron interaction and to the weakening of electron-phonon one. As a result, unlike in pure metals, the inequality $\tau_{ee} \ll \tau_{eph}$ (τ_{ee} is the electron-electron interaction time, τ_{eph} is the electron-phonon interaction time) holds at temperatures $T \leq 10K$. Under such circumstances the Fermi-type distribution function of excited electrons with the temperature $\Theta > T$ is established during electron-electron relaxation time after radiation absorption. The next phase of relaxation is controlled by the electron temperature decay that is characterized by the time constant τ. Another peculiarity of ultrathin films is fast ballistic escape of nonequilibrium phonons from the film during the time τ_{es} smaller than the time of the back energy transfer from phonons to electrons τ_{phe}. In this case τ is defined by τ_{eph} only. For rather thick films, when the conventional bolometric effect is observed, τ coincides with the bolometric time constant $\tau_b = \tau_{es}C_e/C_p$ (C_e and C_p are specific heat capacities of electrons and phonons, respectively, and $C_e \gg C_p$ at low temperatures). Taking into account the result of [5] concerning the theoretical study of the superconducting film response to radiation as a function of the modulation frequency, one can show that if $\tau_{eph} \gg \tau_{phe}, \tau_{es}$, the bolometric response may be described by a single time constant $\tau = \tau_{eph} + \tau_b$.

It is useful to trace the transition from the electron-heating mode to the bolometric mode when film thickness is varied. As is known, the escape time of phonons is presentable by the formula $\tau_{es} = 4d/(v\eta)$, where v is the velocity of sound and η is the coefficient of transmission of a phonon through the film-substrate interface. In this way the following expression for τ can be obtained:

$$\tau = \tau_{eph} + \frac{4dC_e}{v\eta C_{ph}}. \qquad (1)$$

Such a dependence is confirmed by the experiment. The experimental data for Nb films shown in Fig.1, have been taken from [2]. The experimental curves follow the dependence given by Eq.1. Since for Nb $\tau_{eph} \sim T^{-2}$, the transition to the electron-heating regime is shifted towards the smaller values of thickness when the temperature rises. It can be seen that the minimum response time corresponds to the electron-heating mode. In this case the time constant at the transition temperature for Al, Nb and NbN is of the order of 10^{-8} s, 10^{-9} s, and 10^{-11} s respectively.

We shall further analyze the superconducting bolometer sensitivity and determine its change while the transition to the electron heating occurs. It is well known that a minimum detectable power may be represented in the following form:

$$NEP^2 = \frac{4kT^2G}{\alpha^2} + \frac{4kTR}{S_u^2} + \frac{8\sigma kT_\phi^5 S\Omega}{\alpha} + \frac{(U_{exc})^2}{S_u^2}. \qquad (2)$$

The first term in the right-hand side of the formula describes temperature fluctuations (G is the effective thermal conductance). The second describes the Johnson noise , the third describes fluctuations of the background radiation with the effective temperature T_ϕ (S is the area and Ω is the viewing angle of the device), and the fourth describes excess noise of various sources. In the formula R is the film resistance, α is the absorptivity, S_u is the responsivity. A good bolometer is characterized by a narrow superconducting transition. The typical transition widths are less than 0.01 K for Al and approximately 0.1 K for Nb and NbN. The responsivity S_u of such films is extremely high, therefore the second and the forth terms in equation (2) become negligible. So, the first term will be dominating in the absence of background radiation.

The value of effective thermal conductance at low temperatures ($C_e \gg C_p$) can be written as

$$G = \frac{C_e L w d}{\tau}, \qquad (3)$$

where L is the film length. Substitutions of Eq.1 and Eq.3 into Eq.2 yield

$$NEP = \alpha^{-1}\sqrt{\frac{4kT^2 C_e w L d}{\tau}}. \qquad (4)$$

This is a well khown expression for NEP. For an isothermal bolometer the value of τ is defined by the thermal boundary resistance between the film and the substrate, i.e. $\tau \sim d$, and NEP does not depend on the film thickness. However, for ultrathin films this is not correct. For films having thicknesses $\leq 100\mathring{A}$ the electron heating mode is prevalent and τ reaches its minimum value τ_{eph}. In this case Eq. 4 should be re-written in the following form (Eq. 1 for τ is used):

$$NEP = \alpha^{-1}\sqrt{\frac{4kT^2 C_e w L d}{\tau_{eph} + 4C_e d/(v\eta C_{ph})}}. \qquad (5)$$

This formula shows that the reduction of the film thickness causes smooth transition from the conventional bolometric effect to the electron-heating effect. In the latter case τ does not depend on heat conductivity and is only controlled by τ_{eph}. In its turn the sensitivity rises with the decrease of the thickness.

Fig.2 demonstrates the dependence of NEP on thickness which follows that of Eq. (5). The dependence was calculated using experimentally measured values of τ (Fig.1) and the dimensions $w = 1$ μm and $L = 4$ μm (α is supposed to be $\sim$1). The triangle corresponds to the NEP value measured in [6] and reduced to 4 μm^2 area. The solid line corresponding to the isothermal antenna coupled bolometer with the same area from Ref. 7 is also given for the sake of comparision. One can conclude that the experimental data are consistent with those expected. The re-calculsation of the experimental data for Al at 1.6 K [6] and NbN at 10 K [8] to 4 μm^2 area gives respectively $1.5 \cdot 10^{-16}$ and $2 \cdot 10^{-14}$ W$\cdot$Hz$^{-1/2}$. Due to its small heat capacity and low critical temperature, Al can be used as a high-sensitive electron-heating bolometer with the time constant of 10 ns, whereas NbN can be used as a high-speed receiver with a response time of 20 ps.

An important problem which should be solved in developing a microbolometer is its matching with an antenna. For conventional superconducting bolometers the film impedance is complex. It has a small real part and a large imaginary part mostly defined by kinetic inductance [7]. For ultrathin films the real part of surface resistance becomes rather large. Moreover, the suppression of the energy gap in a current carrying resistive state near T_c leads to an almost frequency independent absorptivity at submillimeter and far-infrared wavelengths [3]. It means that the afore-mentioned superconducting strips in the resistive state may be treated as a pure resistive load to an antenna. The surface resistance inherent in the films (40-80 Ohms) is well suitable to be matched to antennas with an impedance of 100 - 200 Ohms.

Currently the high-T_c superconductors are very promising for the development of radiation detectors. For YBaCuO thin films, recent works [9–11] have demonstrated the presence of a fast mechanism of photoresponse in submillimeter and far-infrared as well as in optical spectral regions. The most probable nature of this phenomenon is relaxation of nonequilibrium carriers excited by radiation. The order of magnitude of the time constant of the process ($\sim$ 1–2 ps) coincides with that of the electron-phonon interaction time. Due to the reverse (compared to conventional superconductors) relationship between electron and phonon specific heats ($C_e \ll C_{ph}$), phonons serve as a heat sink for electrons during the first phase of relaxation. It is manifested as a biexponential response in pulse experiments. In [12] we have studied the sensitivity of the fast component of YBaCuO detector photoresponse and found it to be about 10^{-7} W$\cdot$Hz$^{-1/2}$. Considering the fact that the readout system used was far from perfect, and a possibility exists to significantly reduce the dimensions of detector when the antenna is applied, we would claim the availability of an YBaCuO picosecond detector with $NEP \simeq 10^{-10} - 10^{-11}$W·Hz$^{-1/2}$.

Conclusion.

In summary, basing on experimental results we calculate the characteristics of the electron-heating microbolometer and show its availability as a high-speed antenna-coupled detector. Such a bolometer is more sensitive, rapid and easier to matching with an antenna than the isothermal bolometer. For conventional superconductors it is possible to attain the value of NEP less than 10^{-16} W·Hz$^{-1/2}$. Radiometers based on the electron-heating microbolometer are likely to have a sensitivity comparable to that of heterodyne receivers in the terahertz frequency range. Furthermore, such a bolometer will make it easier to produce matrix devices. Hot electron microbolometers based on superconductors with $T_c > 10$ K can be useful as mixers in space research applications [13].

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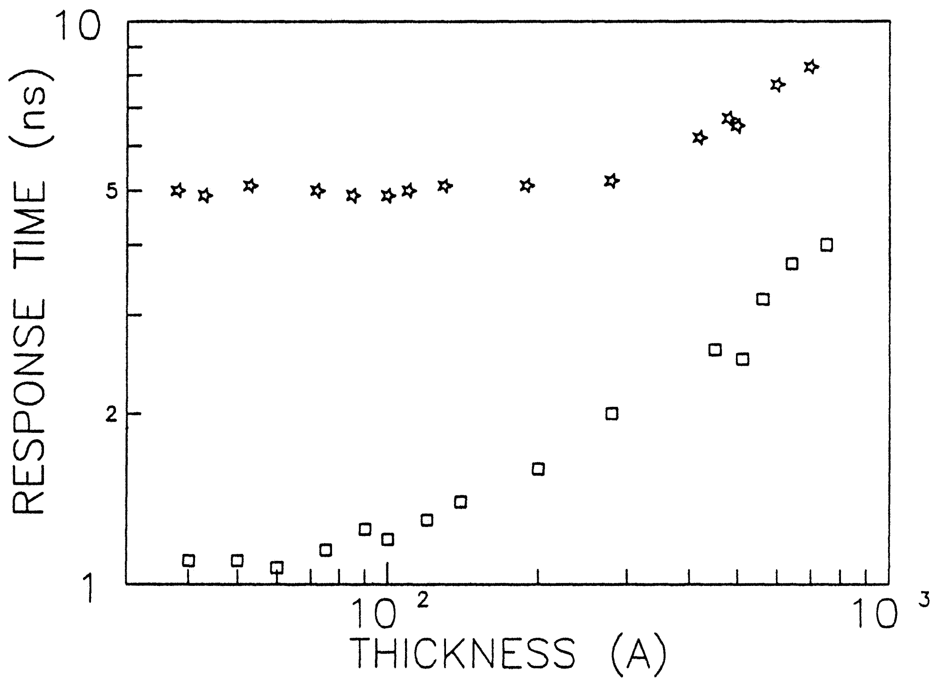

Fig. 1. The dependence of τ on d for Nb films at different temperatures. $\star$ – 1.6 K, ⊓ – 4.2 K.

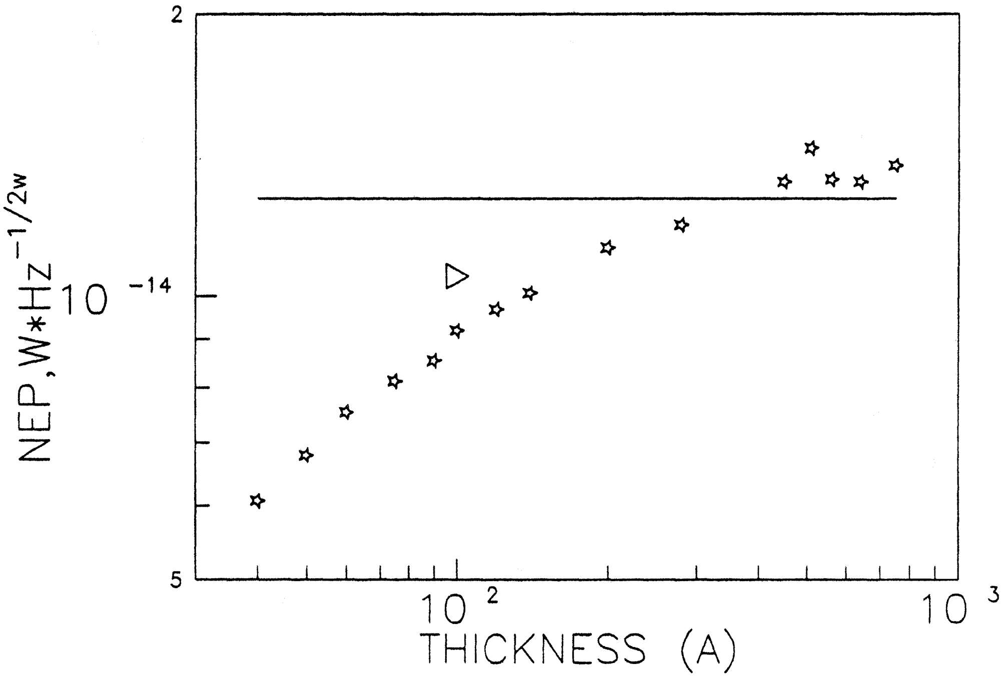

Fig. 2. The dependence of NEP on d ($\star$) at 4.2 K. $\triangle$ – recalculation of the experimental data from Ref.6, solid line – calculated value for isothermal bolometer from Ref.7.