Ultrasensitive superconducting terahertz detectors: novel approaches and emerging materials

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Abstract. Novel approaches to THz sensing based superconductor detectors and emerging superconducting nanomaterials have a strong potential to boost development of advanced optoelectronic devices, such as THz detectors, THz mixers, single photon counters and quantum calorimeters with outstanding sensitivity. Such devices have a number of applications in THZ environmental and industrial monitoring, astrophysics, homeland security, and medicine. Single photon counters have potential as key elements for optical communication and networking, quantum imaging and metrology, quantum optical computing and bio-photonics, and single-molecule spectroscopy.

1. Introduction and background

The bolometer was invented 125 years ago by S.P.Langley. In preliminaries to his original publication he pointed out: "I found … that science possessed no instrument that could deal successfully with quantity of radiant heat so minute… I have entered into these preliminary remarks as an explanation of the necessity of such an instrument as that which I have called the Bolometer or Actinic Balance." Originally, bolometers were designed for measuring incident electromagnetic radiation. However, these devices are sensitive not only to the electromagnetic but to every form of energy. For example, bolometers may be used to measure phonon fluxes and have a potential to measure separate phonons. Bolometric devices are used for search for unknown forms of energy, like dark matter. Currently, superconducting bolometers are the most sensitive detectors in the THz range.

Superconducting bolometer was suggested just before the World War II. These devices combine small heat capacity with large intrinsic responsivity, which is determined by the strong temperature dependence of resistance at the superconducting transition. Currently, superconducting microbolometers are widely used in submillimeter astrophysics, high-energy physics, quantum calorimetry, etc. Various applications of bolometers require a wide range of device operating times. Moreover, the sensitivity and operating time are interrelated. Improving one of this characteristics results in deterioration of another. For these reasons, it is extremely desirable to have possibility to adjust the operating time to values required by specific applications. However, in "classical" bolometers on solid substrates the thermal coupling between a superconductor (thermometer) and substrate (heat sink) is determined by the Kapitza conductance or, in other words, by the phonon transparencies at the film-substrate interface. At low temperatures, the phonon transparency is given

by the acoustic mismatch between film and substrate, and this parameter cannot be verified substantially.

Proposed three decades ago [1], superconducting hot-electron bolometers (HEBs) combine robustness and reliability with small electron heat capacity and controllable thermal conductance. In HEBs, radiation overheats only electrons, while film phonons play the role of a heat sink for electrons. This regime is achieved by decreasing the film thickness, so that the phonon escape from the film to substrate dominates over the phonon-electron relaxation in the film.

2. Superconducting nanohebs

We investigate capabilities of a a submicron size superconducting transition edge sensor made from thin disordered *Ti* film, which has a critical temperature, $T_C \approx 350$ mK [2]. The *Ti* bridge is fabricated on silicon or sapphire substrate between *Nb* contacts which block the diffusion of hot electrons out of the bridge due to Andreev reflection (see figure 1). A planar antenna provides coupling to THz radiation. The *Ti* nanobridge will operate in the voltage-biased TES mode; that is, its operating temperature T will be somewhat lower than the critical temperature, T_c, and the resistance at the operating point, R, will be much smaller than the normal resistance R_n. This situation is convenient for the simultaneous antenna impedance match and the SQUID noise match. Indeed, the dc resistance in the operating point is < 1 Ohm that is the device Johnson noise is greater than the noise of a typical dc SQUID. At the same time, the radiation "sees" the device normal resistance that is 40-50 Ohm, which can be well matched using planar antennas. The radiation causes an increase of the electron temperature, which relaxes due to the electron-phonon interaction with the time constant $\tau_{\text{e-ph}}$. Depending on the bias conditions, the response time can decrease, that is, $\tau = \tau_{\text{e-ph}}/(1+L)$, where $L \sim 10\text{-}100$ is the electro-thermal feedback (ETF) loop gain. The expected Noise Equivalent Power, $NEP = T(2k_B G_{\text{e-ph}})^{1/2}$, based on the experimentally measured electron-phonon thermal conductance $G_{\text{e-ph}} = C_e/\tau_{\text{e-ph}}$ and on the dimensions of available *Ti* nanosensors is shown in Fig. 2. The electron-phonon time is greatly enhanced in disordered thin films. This circumstance helps to achieve high sensitivity. One can see that in this *photon integration mode* the device intrinsic *NEP* reaches 10^{-19} W/Hz$^{1/2}$ [2].
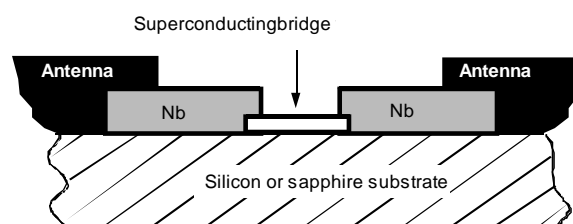

Figure 1. Cross-sectional view of the HEDD design. The energy gap in the HEDD is suppressed due to operation at the superconducting transition edge.
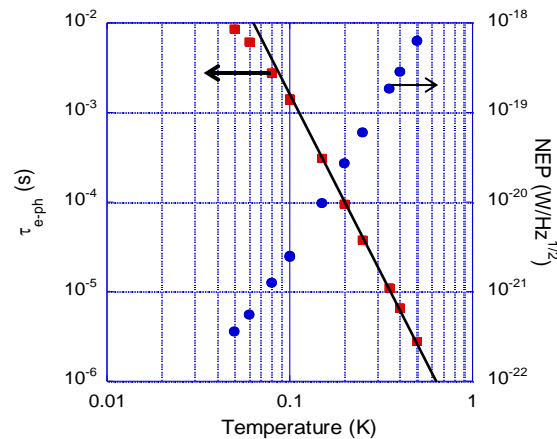
Figure 2. The experimentally measured electron-phonon relaxation time in disordered *Ti* film and the expected *NEP* for a submicron device.

3. Superconducting counters of terahertz photons

The *photon counting mode* for THz spectroscopy has been considered before rather as an option than the actual practical requirement for spectrometer on SAFIR-like platforms [3],[4]. It is becoming clear that it will be crucial for achieving the highest sensitivity needed above 1 THz. The ability of the bolometric device to detect a single photon depends on the magnitude of the intrinsic thermal fluctuations. The equivalent energy fluctuation is $\delta E = 2T((2n)^{1/2}C_e/\alpha)^{1/2}$, where $\alpha = d\ln R/d\ln T$ and $n = 5$-6 is the exponent in the electron-phonon thermal conductance, which depends on the purity of material. In order to detect low energy photons, the temperature must be low and the volume of the device must be small. For the photon counter, the frequency $v_R = \delta E/h$ can be treated as the "red boundary" or lower frequency limit for the detection mechanism. Our estimates show that $v_R < 1$ THz can be achieved for a *Ti* device of practical submicron size at 0.3 K. In other words, the equivalent *NEP* is 10^{-20} W/Hz$^{1/2}$ at 0.3 K. The best integrating detector alternatives with comparable sensitivity would require cooling down to at least 0.1 K.

The value of $N_{max.} = 1/(2\tau)$ determining the maximum count rate, is about 5×10^5 sec^{-1}. This would provide a large dynamic range for the counter. In order to achieve the background limited performance, the dark count rate in the device itself, N_d, must be lower than photon arrival rate. The fundamental dark counts are due to the fact that the device phonon noise produces spikes which can be mistaken for the signal. To avoid that, a corresponding level of the discrimination threshold, $E_T < hv$, must be chosen in the photon counter or/and in the readout electronics. Then the counts are caused only by the energy fluctuations that exceed the discriminator threshold. The corresponding dark count rate is given by

$$N_d = \frac{1/(2\tau)}{\sqrt{2\pi}} \cdot \int_{E_T/\delta E}^{\infty} \exp\left(-x^2/2\right) \, dx$$

With the above parameters, setting $E_T = 0.7hv$ brings N_d to ~ 0.1 count per sec. At the same time, the probability to detect a real photon (= quantum efficiency) remains high. N_d is very sensitive to the ratio ET/dE. If, for example, the device length is chosen to be 0.4 μm instead of 0.5 μm, Nd becomes less than 0.01.

The upper limit for the spectral range of the counter depends on the superconducting transition

width, δT_c. For example, for $\delta T_c \approx 15$ mK, a 2-THz photon would drive the counter into the normal state. Photons of higher energy will still be detectable, but the amplitude of the output pulses will be truncated at the level corresponding 2 THz.

A dc SQUID can be the readout amplifier for the HEDD. Even with a feedback loop, the SQUID bandwidth can be easily made ~ 100 kHz, which is very close to the HEDD bandwidth. An array SQUID with the bandwidth ~ 1 MHz is even better choice. A typical SQUID has a spectral noise density ~ 1 pA/Hz$^{1/2}$ so the total current noise is a fraction of a nA. This is much smaller than the expected amplitude of the response.

4. Emerging superconducting materials for THz sensing

Impressive recent progress [5],[6] in the MBE growth of superconducting heterojunctions of *LaCuO/LaSrCuO* oxides provides new intriguing possibilities for novel superconducting hot-electron sensors. The transition temperature in these low-dimensional superconductors is considerably higher than in bulk crystals of *La$_{2-x}$Sr$_x$CuO$_4$*, reaching as high as 51K. Remarkably, superconductivity may persist even in a single atomic layer at the atomically sharp interface between two non-superconducting materials, namely, the Mott insulator *La$_2$CuO$_4$* and the strongly over-doped metallic oxide *La$_{2-x}$Sr$_x$CuO$_4$*.

New low-dimensional superconducting materials have the following physical characteristics that make them especially attractive for use in detectors, THz heterodyne receivers, and IR single photon counters: (i) High superconducting transition temperature, adjustable by doping in a wide range from sub-Kelvin to 50 K; (ii) Ultra-small electron heat capacity, C_e. due to the quasi-two-dimensional nature of the electron gas in oxide heterostructures; (iii) Strong coupling to the radiation, expected due to the Drude absorption (short momentum relaxation time); (iv) Strong photoresponse due to strong temperature dependence of the resistivity at the transition; (v) Strong electron heating by THz radiation, due to strong absorption of the radiation, small electron heat capacity, and significant temperature dependence of the resistivity; (vi) Ideal phonon heat sink for hot electrons, because nonequilbrium phonons immediately escape from the superconducting layer (there is no Kapitza resistance for phonons); (vii) Weak electron coupling to thermal phonons (see below). New materials provide exciting possibilities for superconducting hot electron nanobolometers that may lead to potential breakthroughs in modern THz sensing technologies.

To evaluate performance of hot electron bolometers based on superconducting MBE-grown quasi-two dimensional LaSrCuO structures, we investigate electric and thermal characteristics of the resistive states in structures with several (3-10) superconducting Cu-O layers covered by top and bottom overdoped metallic layers. The resistive states in these S-M sandwiches are observed over a wide temperature range (8-25 K), which shifts to lower temperatures in a magnetic field. At low currents the *V-I* characteristic demonstrate a strong nonlinearity, $V = \gamma I^2$, where the coefficient γ is mainly determined by the resistance, $R(T,H)$, and weakly depends on T and H directly.
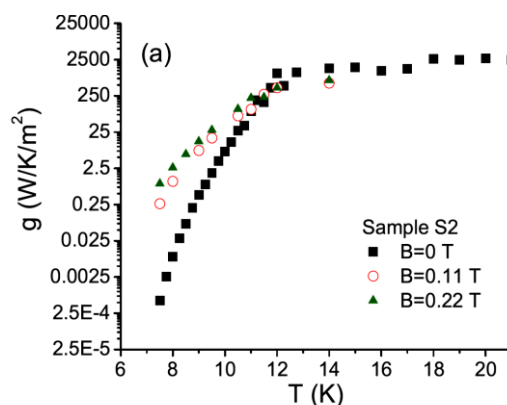
Figure 3. Electron-phonon thermal conductance of superconducting LaSrCuO
nanostructure calculated from the nonlinearity of V-J characteristic.

Figure 3 presents the temperature dependence of the electron-phonon thermal conductance per unit area at different magnetic fields. Let us note that the resistance of the superconducting layer is shunted by top and bottom metallic sheets. In result, a characteristic temperature T*, at which the resistance of the superconducting layer reaches a half of its normal resistance, corresponds to a significant total resistance of the sandwich. For the sample S2 the value of T* is approximately 13K. Figure3 demonstrates that above T* the thermal conductance slowly increases with the temperature indicating a small temperature variation of the heat capacity C_e and electron-phonon relaxation time τ_{e-ph}, which is consistent with the heating model. Below T* the electron-phonon conductance strongly decreases with the temperature decrease.

Above T* the conductance is expected to be close to the conductance in the normal state. For the sample S2 the conductance is ~2000 W/Km^2 at 14 K. Other samples show approximately the same values of the thermal conductance.

Let us first highlight that these values are three orders in magnitude smaller than that in NbN or MgB ultrathin films. Such strong difference may be explained by the small carrier density in LaSrCuO, which leads to a small electron heat capacity and weak electron-phonon coupling via the deformation potential. Let us highlight that in the metallic state the electron-phonon relaxation rate is proportional to the carrier density [7]. Weak coupling of hot electrons to the thermal phonons strongly increases the responsivity and sensitivity of HEBs based on MBE-grown LaSrCuO structures.

In summary, the detection of single THz photons is vital for many branches of basic science, as well as for a variety of engineering applications. Sensors of these quanta are of great interest for molecular spectroscopy, nanoscale solid-state physic and thermophysics. Research in this area is of fundamental importance for the broad field of mesoscopic solid-state physics and, in particular, for numerous quantum nanodevices operating at low temperatures. Superconducting single photon THz detectors are expected to be a valuable tool for NASA, European, and Russian missions addressed to investigations of structure and evolution of the Universe.

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