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Superconducting nanosensors with mesoscopic number of quasiparticles

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Abstract

Novel approach to detection of low-energy (submillimeter and infrared) photons is based on implementation of the electron heating in superconducting nanostructures with small number of quasiparticles. In a hot-electron sensor, the incoming quanta generate nonequilibrium quasiparticles, which affect either the resistivity (transition-edge sensor) or the inductance (kinetic-inductance sensor operating in the superconducting state). The sensitivity of this sensor is limited by equilibrium fluctuations of the number of quasiparticle excitations, and a small number of quasiparticles is the key issue for high performance. The relaxation time in superconducting structures can be controlled over the range from 10 ps (outdiffusion of quasiparticles) to 0.1 s (phonon cooling). Therefore, hot-electron sensors can be employed as relatively slow ultra-sensitive detectors or fast photon counters, depending on a dominant cooling mechanism. The counter can resolve photons of submillimeter and terahertz ranges with the counting rate of 10^{11} count/s. Hot-electron nanosensors are expected to deliver the unique performance: the noise equivalent power of 10^{-20} W/$\sqrt{\text{Hz}}$ and the energy resolution of 10^{-21}–10^{-23} J.

Keywords: Sensor; Detector; Counter; Single-photon; Andreev mirrors; Terahertz

1. Introduction

The detection of submillimeter and far infrared (FIR) 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 molecule spectroscopy, submillimeter astronomy, nanoscale solid-state physics and thermophysics. Although photon detectors in the visible range were developed decades ago, it is difficult to extend the existing mechanisms of single-photon detection to lower energies. In general, quantum detectors work as photomultipliers. An incoming photon generates a photoelectron, which initiates an avalanche of electron multiplication. Finally, a cascade of electrons leads to a measurable current pulse. Straightforward implementation of this method for IR and submillimeter ranges is hindered because these photons are a thousand times less energetic than the optical ones, and the number of generated electrons is insufficient to overpower the detector noise. Only recently the first successful measurement of single low-energy quanta has been reported [1]. Suspended nano-patterned bolometers [2], quantum dots [1,3] and superconducting tunnel junctions integrated with

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single-electron transistors (SET) [4] are considered to be candidates for ultra-sensitive detectors. All these detectors require milli-Kelvin temperatures and have complicated design. Here we show that comparable characteristics may be obtained in relatively simple sensors based on electron heating in superconducting bridges. Moreover, the operating time of these sensors can be varied over a huge range, from 10 ps to 0.1 s, and they can be used as ultra-sensitive detectors and fast photon counters.

The operation of the hot-electron sensors is based on the generation of nonequilibrium quasiparticles in a superconducting bridge and on detection of these excess quasiparticles [5]. In transition-edge sensors the excess quasiparticles affect the resistance of a superconducting sensor driven by the temperature and/or magnetic field in the resistive state. In kinetic-inductance sensors, the excess quasiparticles affect the kinetic inductance of a sensor in the superconducting state [5]. The sensitivity and energy resolution of hot-electron sensors as well as SET integrated detectors are limited by the equilibrium fluctuations of the number of quasiparticles in the device, $\sqrt{N_{eq}}$. Regardless of the complexity of the sensor design, a small ("mesoscopic") number of quasiparticles is required for record performance: the low-energy quanta should excite more quasiparticles than $\sqrt{N_{eq}}$. Thus, decrease in the equilibrium quasiparticle population is the key issue in realization of single-quantum sensitivity and high-energy resolution.

In the transition-edge sensor, the equilibrium number of electronic excitations is of the order of $n_e(T/\varepsilon_F)$, where n_e is the total number of electrons, ε_F is the Fermi energy. A nanosensor with dimensions of $10 \times 100 \times 100\ \mathrm{nm}^3$ will comprise $\sim$100 quasiparticles at sub-Kelvin temperatures. In the kinetic-inductance sensor well below the superconducting transition temperature, T_c, the number of quasiparticles is exponentially small, and a $10 \times 100 \times 100\ \mathrm{nm}^3$ niobium sensor ($T_c \sim 9$ K) with 30–100 quasiparticles can be realized at much higher, liquid helium, temperatures. Currently we carry out experiments with sensors comprising $\sim 10^4$ quasiparticles [6]. Here we evaluate limiting sensor parameters, when N_{eq} decreases to mesoscopic number.

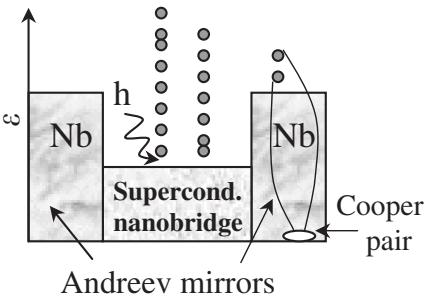

Fig. 1. The energy diagram of a hot-electron detector. The sensor is flanked by superconducting leads ("Andreev mirrors"), which prevent outdiffusion of nonequilibrium quasiparticles.

2. Transition-edge hot-electron sensor

In the hot-electron regime, radiation overheats the electrons in a superconducting film, while phonons in the film play the role of a heat sink for electrons [5]. This regime is achieved by decreasing the sensor dimensions and increasing the Kapitza conductance of the film-substrate interface. In a transition-edge sensor, an incoming photon generates the photoelectron, and electron–electron interaction leads to a fast multiplication of nonequilibrium quasiparticles, which suppresses superconductivity. In the linear regime, the voltage variation in the resistive state is proportional to the number of excess quasiparticles created in the multiplication processes. The nonequilibrium quasiparticles leave the sensor either by escaping into the conducting leads or by relaxing due to electron–phonon coupling. In order to increase the sensor sensitivity, it is necessary to block the former mechanism, the outdiffusion of hot electrons. This can be achieved by a special design of the current leads. The leads are fabricated from a superconductor with a superconducting energy gap Δ much larger than that of the sensor (Fig. 1). The DC bias and RF currents will flow freely through the structure, whereas outdiffusion of hot electrons with energies $\varepsilon < \Delta$ will be blocked by Andreev reflection.

In the hot-electron transition-edge nanosensor, the effective electron temperature, T_e, is established because of a strong electron–electron scattering. The noise equivalent power is limited by fluctuations of T_e

(see Ref. [5]): NEP$=\sqrt{4k_B T_e^3 \gamma V/\tau_{e-ph}}$, where γ is the Sommerfeld constant ($C_e = \gamma V T_e$ is the electron specific heat), and V is the nanosensors volume. In fact, the combination $\gamma T_e V/k_B$ represents the number of equilibrium quasiparticles in the sensor, N_{eq}. Thus, the noise equivalent power (NEP) of the transition-edge detector can be expressed as

$$\mathrm{NEP} = 2k_B T\sqrt{N_{eq}/\tau_{e-ph}}. \quad (1)$$

At ultra low temperatures, the electron–phonon relaxation rate has been measured in disordered (the electron diffusivity $D = 1$–2 cm^2/s) superconducting films of Hf and Ti [7]. The films were patterned in a shape of a long and narrow (10 cm $\times$ 5 μm) meander stripe to avoid the leak of thermal energy via outdiffusion of "hot" electrons into the current leads. We found that the electron–phonon coupling in these films is significantly suppressed by disorder. The electron cooling time τ_ε follows the T^4-dependence, which is consistent with predictions of the theory of electron–phonon interaction (EPI) in disordered metals when the electron scatterers vibrate the same way as the host atoms [8]. For both Hf and Ti films, an excellent agreement between the experimental data and the theory was obtained with no fitting parameters. A record-long value of $\tau_\varepsilon = 25$ ms was observed at $T = 0.04$ K [7].

Contrary to the EPI, the electron–electron scattering is substantially enhanced in disordered conductors. The electron–electron scattering rate (τ_{ee}^{-1}) is proportional to the sheet resistance of a film, as well as to the quasiparticle energy and the temperature. Strong electron–electron scattering is very important for implementation of the hot-electron regime. Even if outdiffusion of low-energy particles is blocked by the Andreev mirrors, the quasiparticles with energies $\varepsilon > \Delta$(Δ is the gap in the superconducting leads) can escape from the sensor (see Fig. 1). To prevent the outdiffusion of quasiparticles with energies $\varepsilon > \Delta$ into the superconducting leads, the outdiffusion time should be larger than the thermalization time, $\tau_{e-e}(\Delta)$. In other words, the sensor length L should be greater than the diffusion length of electrons with energies $\varepsilon \sim \Delta$, $L_{e-e} = [D\tau_{e-e}(\Delta)]^{1/2}$. By assuming $\tau_{e-e}(\Delta) \sim 10$ ps [5], we find $L_{e-e} \cong 30$ nm. Thus, if $L \geqslant 30$ nm, the energy of the incoming photon is trapped in the electron subsystem of the sensor. In this case the intrinsic quantum efficiency reaches its maximum value of $\sim h\nu/k_B T$. Another limitation on the sensor length is imposed by the proximity effect. The length should be larger than the coherence length in a normal metal, $L_T = \sqrt{\hbar D/2\pi k_B T}$, otherwise the resistive state of the sensor will be suppressed by the superconducting leads. For a disordered film with the diffusion constant $D \sim 1$ cm^2/s, L should be larger than $L_T \sim 20$ nm at $T = 0.3$ K. Therefore, reduction of the sensor size to ~ 100 nm is possible and will allow realization of the hot-electron transition-edge nanosensors with record parameters.

In Table 1 , we present the expected parameters for two transition-edge nanosensors, fabricated from the Hf and Ti films. The value of the electro-thermal feedback (ETF) loop gain that affects the energy resolution (ER) was assumed to be 40.

In a short sensor without Andreev mirrors, the excess nonequilibrium quasiparticles can leave superconducting bridge due to outdiffusion. The corresponding relaxation time is given by

$$\tau_{diff} = L^2/(\pi^2 D). \quad (2)$$

In nanobridges with $L \sim 100$ nm the relaxation time is as short as 10 ps, and such nanosensors can be used as fast single-quantum counters [6]. Thus, the counting rate of a hot-electron photon nano-counter, limited by the outdiffusion cooling, can be estimated as $1/\tau_{diff} \approx 10^{11}$ count/s. The sensitivity, determined by an extremely small heat capacity of a mesoscopic number of quasiparticle, is expected to be record-high. An estimate of the "red boundary" frequency for a $20 \times 100 \times 100$ nm^3 Ti sensor gives $\nu_1 \approx 100$ GHz. The upper frequency limit is set by the energy needed to heat the nanosensor above T_c, $\nu_2 \approx \gamma V T_c^2/2h = 20$ THz. Fundamental limitation on the energy resolution, imposed by the generation-recombination noise, can be expressed in terms of N_{eq} as [9]:

$$\Delta E \approx 8.6 k_B T\sqrt{N_{eq}/C}, \quad (3)$$

where $C = (V_b/R)^2(\mathrm{d}R/\mathrm{d}T)\tau_{e-ph/\gamma}T$ is the ETF loop gain. As seen from Table 1, a small number of electron quasiparticles in the sensors (which is equivalent to an ultra-small electron heat capacity) results in the record values of the noise equivalent power and energy resolution.

Table 1
Parameters of the Hf and Ti transition-edge nanosensors with a small number of quasiparticles

	d (nm)	T_c (K)	R_{sq} (Ω)	$W \times L$ (nm^2)	τ_{e-ph} (μs)	$\nu(0)$ (10^{22}/eV cm^3)	N_{eq}	NEP (10^{-20} W/$\sqrt{\text{Hz}}$)	ER (10^{-22} J)
Hf	25	0.3	38	100 × 100	5	4.1	26	0.3	0.3
Ti	20	0.4	15	100 × 100	7	7.9	54	0.5	1.7

Table 2
Parameters of the kinetic-inductance sensors with a small number of quasiparticles (N_{eq}), fabricated from Nb films

T (K)	W (nm)	L (nm)	N_{eq}	L_k pH	τ_{qp} (μs)	NEP$_{GR}$ (10^{-19} W/$\sqrt{\text{Hz}}$)	ΔE (10^{-21} J)
1.0	1000	4000	60	20	600	0.9	2.2
1.3	100	1500	36	100	50	2	1.7
1.4	70	1000	32	100	30	3	1.6
1.5	70	500	29	50	20	3.5	1.4
1.6	40	500	28	70	12	4	1.4
2.0	20	100	26	70	5	7	1.3

3. Kinetic-inductance sensor

There has been significant interest to the kinetic-inductance sensors (KIS) operating near the superconducting transition. Meanwhile, the nonequilibrium (hot-electron) mode of operation of the KIS at $T \ll T_c$ is advantageous for the detector operation since the number of quasiparticles is exponentially small and the generation-recombination noise is also small. It is expected that even at liquid *He* temperatures, the sensor fabricated from a superconductor with $T_c \sim 6$–10 K will have the NEP$\sim 10^{-19}$ W/$\sqrt{\text{Hz}}$ limited by the quasiparticle generation-recombination noise [10].

The characteristic response time of the hot-electron KIS coincides with the lifetime of nonequilibrium quasiparticles, τ_{qp}. The latter time exceeds the quasiparticle recombination time, τ_R, because of re-absorption of nonequilibrium phonons:

$$\tau_{qp} = 0.8\tau_{e-ph}(T_c)(d/K\ell_{ph})(T_c/T)^{1/2} \times \exp(\Delta/k_B T), \quad (4)$$

where $\tau_{e-ph}(T_c)$ is the electron–phonon relaxation time in the normal state, in thin films (thickness $d \sim 10$ nm) with $T_c \geqslant 5$ K, the mean free path of such phonons, $\ell_{ph} = \hbar v_F/\pi\Delta$ is the mean free path of phonons with the energy of 2Δ, $K \sim 0.01$–0.1 is the acoustic transparency of the film/substrate interface. Because of the exponential temperature dependence and strong dependence on the phonon transparency, the characteristic time can be varied over a wide range ($\sim 10^{-5}$–10^{-3} s at 1 K).

The dominant noise mechanism of the KIS is the intrinsic fluctuations of the number of quasiparticles (generation-recombination noise). Due to the superconducting gap, the number of equilibrium quasiparticles (N_{eq}) well below T_c is exponentially small

$$N_{eq} = \nu(0)V(\pi k_B T\Delta/2)^{1/2}\exp(-\Delta/k_B T), \quad (5)$$

where $\nu(0)$ is the electron density of states at the Fermi surface. The *NEP* limited by the generation-recombination noise is

$$\text{NEP}_{GR} = 2\Delta\sqrt{N_{eq}/\tau_{qp}} \propto \exp(-\Delta/k_B T). \quad (6)$$

The energy resolution of the KIS can be estimated as $\Delta E \approx \text{NEP}\sqrt{\tau_{qp}} \propto \sqrt{N_{eq}}$ (this conservative estimate does not take into account the ETF effects).

In Table 2 we calculate the performance of a Nb-based KIS operating at 1 K. We considered nanobridges fabricated from a Nb film with d = 10 nm, $T_c = 6.5$ K, the sheet resistance $R_\square \approx 20\ \Omega$, and the electron–phonon relaxation time $\tau_{e-ph}(T = T_c) = 0.6$ ns. According to Eq. (4), the

recombination time at 1 K is 1.4×10^{-5} s. The film-substrate acoustic transparency for 2Δ-phonons, K, is not well known. In our modeling, we have taken $\tau_{qp}/\tau_R \sim 4.4d/1$ nm. Thus, we expect $\tau_{qp}(1\,\mathrm{K})$ to be 0.62 ms for a 10-nm-thick Nb film. This response time is short enough for most of applications. Table 2 shows that well below T_c the energy resolution depends only on the number of quasiparticles in the sensor. Decrease of the sensor volume allows for a corresponding increase of the operating temperature T.

4. Conclusions

The hot-electron superconducting sensors combine the controllable electron kinetics of SET integrated detectors with the strong dependence of superconducting parameters on the radiation power and low intrinsic fluctuations of superconducting bolometric sensors. Due to the small number of quasiparticles, record values of the noise equivalent power ($\mathrm{NEP} \sim 10^{-20}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$) and the energy resolution ($\mathrm{ER} \sim 10^{-21}$–$10^{-22}$ J) are expected at sub-Kelvin and liquid helium temperatures. Simple design of these sensors eliminates noise contributions from multiple signal transducers common in complex systems. An important advantage of superconducting nanosensors, in comparison with their semiconductor counterparts (quantum dot sensors), is a large total number of electrons, which provides a strong coupling of the sensor to incoming quanta. The hot-electron nanosensors can be fabricated on bulk substrates. In contrast to conventional bolometric sensors, they do not require mechanical isolation from the environment. For this reason, these sensors offer excellent scalability for multi-sensor applications.

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