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Ultrasensitive hot-electron kinetic-inductance detectors operating well below the superconducting transition

A. V. Sergeev[a] and V. V. Mitin
Department of Electrical and Computer Engineering, Wayne State University, Detroit, Michigan 48202

B. S. Karasik
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

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While most experimental studies of kinetic-inductance sensors have been limited so far by the temperature range near the superconducting transition, kinetic-inductance detectors can be very sensitive at temperatures well below the transition, where the number of equilibrium quasiparticles is exponentially small. In this regime, a shift of the quasiparticle chemical potential under radiation results in the change of the kinetic inductance. We modeled the noise characteristics of the kinetic-inductance detectors made from disordered superconducting Nb, NbC, and MoRe films. Low-phonon transparency of the interface between the superconductor and the substrate causes substantial retrapping of phonons providing high quantum efficiency and the operating time of ~ 1 ms at ≈ 1 K. Due to the small number of quasiparticles, the noise equivalent power of the detector determined by the quasiparticle generation–recombination noise can be as small as $\sim 10^{-19}$ W/$\sqrt{\mathrm{Hz}}$ at He_4 temperatures. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1445462]

Bolometric sensors are currently the detectors of choice for space astrophysics missions in a broad range from millimeter waves to x rays. In the submillimeter-wave range, bolometers are the only option having currently demonstrated noise equivalent power (NEP) of the order of 10^{-17}–10^{-18} W/$\sqrt{\mathrm{Hz}}$ at ~ 0.1 K.[1] Future space radio telescopes will require two orders of magnitude greater sensitivity,[2] which may be difficult to achieve with a conventional mechanical design of bolometers based on Si_3N_4 membranes. An alternative approach to the problem of increasing sensitivity relies on electron heating in superconducting structures. The corresponding detectors do not require thermal mechanical insulation and can be fabricated on bulk substrates. For example, a recently proposed hot-electron resistive microbolometer with disorder-controlled electron–phonon coupling[3] promises NEP$\sim 10^{-19}$ W/$\sqrt{\mathrm{Hz}}$ and time constant $\tau \sim 10^{-5}$ s at 0.3 K, and NEP $\sim 10^{-20}$ W/$\sqrt{\mathrm{Hz}}$ and $\tau \sim 10^{-4}$ s (Ref. 4) at 0.1 K. Another way to make a hot-electron sensor is to use the kinetic inductance of a superconducting film. In this case, the detector may be able to operate at temperatures above 1 K with very high sensitivity.

Kinetic inductance detectors (KIDs) have been proposed by Grossman, McDonald, and Sauvageau[5] and by Bluzer and co-workers.[6,7] Some characteristics of the inductive response and parameters of KIDs have been experimentally investigated in Refs. 5 and 7–12. Near T_c, the kinetic inductance has a strong temperature dependence and can be used as a superconducting thermometer. Both bolometric[5,8] and nonequilibrium (hot-electron)[6,9–12] components have been observed in the response of superconducting microbridges to electromagnetic radiation. Infrared bolometers using kinetic inductance thermometers have been developed in Refs. 5 and 8. In the superconducting state near T_c, the electron and phonon heat capacities and characteristic relaxation rates are close to those in the resistive state. Therefore, kinetic-inductance detectors offer approximately the same NEP and response time as resistive bolometers and hot-electron detectors. The main advantage of the inductive detectors operating near T_c, in comparison to the resistive counterpart, is the absence of Johnson noise. The noise characteristics of the nonequilibrium kinetic-inductance detector operating at $T \ll T_c$ have not been considered yet. Meanwhile, this regime is advantageous for detector operation since the number of quasiparticles is exponentially small and the corresponding generation–recombination noise is small as well.

In the current letter, we consider a hot-electron KID operating in a superconducting state far below the superconducting transition but still at temperatures accessible with sorption He_3 or He_4 cryostats. Such a detector made from a superconductor with $T_c \sim 6-10$ K allows for NEP $\sim 10^{-19}$ W/$\sqrt{\mathrm{Hz}}$ determined by the quasiparticle generation–recombination noise. The background radiation is effectively cut off below the superconducting gap frequency, $\Omega_c = 2\Delta/h$ (Δ is the superconducting gap). As in the resistive hot-electron detector,[3] the kinetic-inductance detector has a number of attractive features: the devices can be fabricated on Si or sapphire substrates, the rf impedance can be easily matched to that of a planar antenna, and the detectors have a large array scalability.

The schematic circuit of the KID with a superconducting quantum interference device (SQUID) readout is shown in Fig. 1.[5,6] Constant bias current I_b splits between two branches of a superconducting loop. The change of the kinetic inductance, δL_k, of the detector results in a signal electric current, δI, circulating in the superconducting loop and producing a magnetic flux, which is detected by a sensitive dc SQUID. If the inductance in the SQUID coil, L_s, is significantly larger than the kinetic inductance of the detector,

[a]Electronic mail: sergeev@ciao.eng.wayne.edu

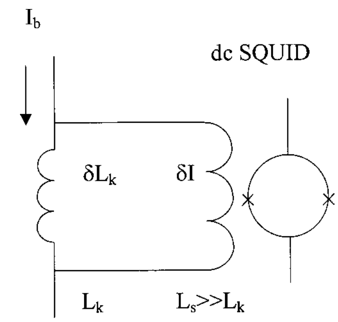

FIG. 1. Schematic circuit demonstrating the redistribution of the signal current in a KID/SQUID loop. An increase of the kinetic inductance caused by radiation increases the current flowing through a SQUID coil, producing a detectable magnetic field.

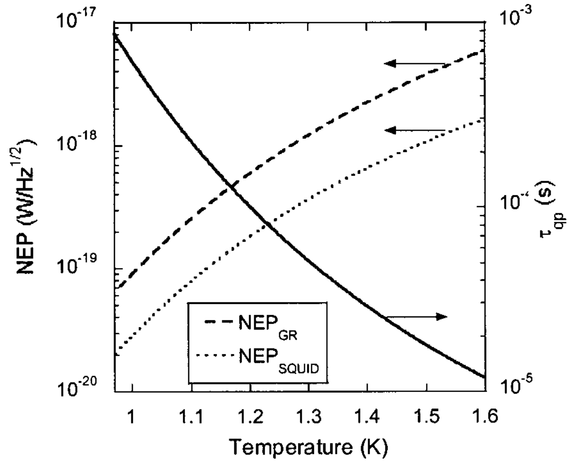

FIG. 2. Temperature dependencies of NEP and of the quasiparticle lifetime in a Nb KID.

L_k, the magnetic flux generated by radiation is given by

$$\delta\Phi=\delta I L_s \cong \delta L_k I_b . \tag{1}$$

Under the radiation, the kinetic inductance of the cubic superconducting sample is determined by the nonequilibrium distribution function of quasiparticles, $f(\epsilon)$, and by the value of Δ, which is a function of $f(\epsilon)$,[13]

$$\frac{1}{L(\Omega,T)}=\frac{\sigma_n}{\hbar}\int_{\Delta-\hbar\Omega}^{\Delta} d\epsilon[1-2f(\epsilon-\hbar\Omega)] \times\frac{\epsilon(\epsilon+\hbar\Omega)+\Delta^2}{(\Delta^2-\epsilon^2)^{1/2}[(\epsilon+\hbar\Omega)^2-\Delta^2]^{1/2}} . \tag{2}$$

Here, σ_n is the normal-state conductivity.

Far below the superconducting transition, the nonequilibrium distribution function under the radiation is described by the Boltzmann function, $f(\epsilon)=\exp[(\mu-\epsilon)/k_B T]$, with a nonvanishing chemical potential (μ model[14]):

$$\mu=\frac{k_B T}{2}\ln\left(1+\frac{2rP_0\tau_{\mathrm{qp}}}{\hbar\Omega n_0}\right). \tag{3}$$

Here, P_0 is the power of electromagnetic radiation absorbed in a unit volume of the microbridge, $\Omega>\Omega_c$ is the radiation frequency,[15] r is the coefficient of quasiparticle multiplication due to electron–electron and electron–phonon interactions, τ_{qp} is the quasiparticle lifetime, and n_0 is the concentration of equilibrium quasiparticles:

$$n_0=\nu(0)(\pi k_B T\Delta/2)^{1/2}\exp(-\Delta/k_B T), \tag{4}$$

where $\nu(0)$ is the electron density of states at the Fermi surface.

The quasiparticle lifetime is determined by the recombination time, τ_R, enhanced by phonon retrapping. Every time two quasiparticles with energy Δ recombine, a phonon with energy 2Δ is emitted. Even in thin films (thickness $d \sim 10$ nm) with $T_c \geqslant 5$ K, the mean-free path of such phonons, $\ell_{\mathrm{ph}}=\hbar\nu_F/\pi\Delta$ (ν_F is the Fermi velocity), is smaller than the effective film thickness d/K ($K\sim 0.01$–0.1 is the acoustic transparency of the film/substrate interface[16]). As a result of the phonon retrapping, the quasiparticle lifetime, τ_{qp}, is substantially longer than the recombination time:

$$\tau_{\mathrm{qp}}=\tau_R\frac{4d}{K\ell_{\mathrm{ph}}}=0.8\tau_{e-\mathrm{ph}}(T_c)\frac{d}{d\ell_{\mathrm{ph}}}\left(\frac{T_c}{T}\right)^{1/2}\exp\left(\frac{\Delta}{k_B T}\right), \tag{5}$$

where $\tau_{e-\mathrm{ph}}(T_c)$ is the electron–phonon relaxation time in the normal state. The quasiparticle lifetime is the characteristic response time of the hot-electron KID. Due to exponential temperature dependence and strong dependence on phonon transparency, the characteristic time can vary in a broad range of 10^{-5}–10^{-3} s at 1 K.

To model the detector performance, we first find the inductive response to radiation. Under the condition of strong phonon retrapping, the quasiparticle multiplication factor $r=\hbar\Omega/\Delta$.[17] According to Eqs. (1) and (2), the shift of the kinetic inductance at $T\ll T_c$ is given by the change of the nonequilibrium distribution function:

$$\frac{\delta L_k}{L_k}=\frac{2\delta f(\Delta)}{1-2f_0(\Delta)}=\frac{2P_0\tau_{\mathrm{qp}}}{\hbar\Delta n_0}\exp(-\Delta/k_B T). \tag{6}$$

The basic noise mechanism of the inductive detector is intrinsic fluctuations of the number of quasiparticles (generation–recombination noise). The exponentially small number of equilibrium quasiparticles (N_{eq}) well below the superconducting transition in a micron-size film structure may provide unparallel performance of the KID at $T\approx 1$ K. The $\mathrm{NEP_{GR}}$ conditioned by the generation–recombination noise is given by[17]

$$\mathrm{NEP_{GR}}=2\Delta\sqrt{N_{\mathrm{eq}}/\tau_{\mathrm{qp}}}\propto\exp(-\Delta/k_B T). \tag{7}$$

Assuming that τ_{qp} is adjusted to 1 ms and the total number of equilibrium quasiparticles in the inductive sensor of volume V is statistically sufficiently large, $N_{\mathrm{eq}}=n_0 V\approx 100$, the noise equivalent power can be estimated as $\mathrm{NEP_{GR}} \approx 600\Delta\sqrt{\mathrm{Hz}}\approx 10^3 k_B T_c\sqrt{\mathrm{Hz}}\approx 10^{-19}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$.

The total NEP includes the contribution of the SQUID readout. A typical flux sensitivity of modern SQUIDs, $\delta\Phi\approx 1\ \mu\Phi_0/\sqrt{\mathrm{Hz}}$ (Φ_0 is the quantum of magnetic flux). The corresponding $\mathrm{NEP_{SQUID}}$ can be calculated as

$$\mathrm{NEP_{SQUID}}=\frac{\delta\Phi}{2L_k I_b}\frac{L_s}{M}\frac{N_{\mathrm{eq}}\Delta}{\tau_{\mathrm{qp}}}\exp(\Delta/k_B T), \tag{8}$$

where M is the mutual inductance between the SQUID coil and the Josephson junction loop.

As an example, we calculated the performance of a Nb sensor operating at 1 K. We considered a $4.0\times 1.0\ \mu\mathrm{m}^2$ Nb microbridge made from a 10-nm-thick film. The transition

TABLE I. Parameters of kinetic-inductance detectors made from different superconductors.

Material	d nm	R_{sq} Ω	T_c K	$\tau_{e-ph}(T_c)$ ns	$\nu(0)$ 10^{22} eV^{-1} cm^{-3}	$W\times L$ μm$\times\mu$m	T K	τ_{qp} ms	NEP$_{GR}$ 10^{-19} W/$\sqrt{\mathrm{Hz}}$
NbC	20	27	10	0.5	2.6	1.5×3.0	1.6	1.0	1.0
Nb	10	20	6.5	0.6	16	1.0×4.0	1.0	0.62	0.91
MoRe	30	150	6.1	0.7	8.7	1.3×0.8	1.0	1.0	0.6

temperature of such a film is 6.5 K, the sheet resistance $R_{sq}\approx 20\,\Omega$,[18,19] and the electron–phonon relaxation time is 0.6 ns at 6.5 K.[19] According to Eq. (5), 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 used experimental data for NbN thin films on a sapphire substrate,[16] which suggest that the parameter τ_{qp}/τ_R is equal to 4.4 d, where d is measured in nanometers. We expect the quasiparticle lifetime in a 10 nm Nb film to be 0.62 ms.

The results of modeling of the noise characteristics are shown in Fig. 2 (the kinetic inductance of the Nb microbridge was 18 pH, the electric current was chosen to be 1 mA, and, also, we assume $M\cong L_s$). NEP$_{SQUID}$ is significantly smaller than NEP$_{GR}$, and NEP$_{GR}\approx 0.6\times 10^{-19}$ W/$\sqrt{\mathrm{Hz}}$ is achievable at $T=1$ K. The reduction of volume might produce an additional decrease of NEP but, at the same time, the number of quasiparticles would become too small to obtain a reasonable dynamic range. A thin-film inductive sensor is naturally well matched to a planar antenna impedance ($Z=40-100\,\Omega$) at frequencies $\Omega>\Omega_c\approx 750$ GHz, whereas the background radiation with $\Omega<\Omega_c$ practically is not absorbed by the sensor. Note, that since the device length is much smaller than the quasipartical diffusion length $(D\tau_{qp})^{1/2}=200-400\,\mu$m ($D$ is the electron diffusion constant), Andreev contacts with a superconducting gap larger than Δ should be used to prevent the diffusion loss of quasiparticles from the sensor volume. In our example, thicker Nb films, or NbN and NbC films can be used as the contact material.

In Table I, we summarize characteristics of the Nb detector and also present film parameters and characteristics of NbC and MoRe KIDs with NEP$\approx 10^{-19}$ W/$\sqrt{\mathrm{Hz}}$ at 1–1.6 K. We used the parameters of available films [NbC (Ref. 20) and MoRe (Ref. 21)] and optimized the characteristics in the same manner as was done for the Nb KID.

Note that despite the NbN thin films having large T_c, they are not useful for sensitive KIDs since the electron–phonon relaxation time in this material is too short.[16] Our analysis is not applicable to high-temperature cuprates, which are d-wave superconductors with a large number of quasiparticles in the nodal regions. s-wave superconductor MgB_2 with $T_c=40$ K may be an interesting material for mid- and near-infrared KIDs offering a broad temperature range for adjusting the lifetime and sensitivity.

In conclusion, we have analyzed the kinetic inductance detector in a hot-electron mode well below the superconducting transition. Detector noise equivalent power of the order of 10^{-19} W/$\sqrt{\mathrm{Hz}}$ has been found to be possible at temperatures above 1 K. The detector output can be read out by a conventional dc SQUID amplifier. A high rf impedance and the possibility of fabricating sensors on bulk dielectric substrates are attractive for making a submillimeter monolithic array of antenna-coupled detectors.

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