Kinetic Inductance Photodetectors Based on Nonequilibrium Response in Superconducting Thin-Film Structures

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Abstract – **While experimental studies of kinetic-inductance sensors have been limited so far by the temperature range near the superconducting transition, these detectors can be very sensitivity 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, which can be measured by a sensitive SQUID readout. We modeled the kinetic inductance response of detectors made from disordered superconducting Nb, NbC, and MoRe films. Low phonon transparency of the interface between the superconductor and the substrate causes substantial re-trapping 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 ~10^{-19} W/√Hz at He4 temperatures.**

Bolometric sensors are currently the detector 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 the noise equivalent power (*NEP*) of the order of 10^{-17} - 10^{-18} W/√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 the bolometers based on Si_3N_4 membranes. An alternative approach to the problem of increasing sensitivity relies on the electron heating in superconducting structures. The corresponding detectors do not require thermal mechanical insulation and can be fabricated on bulk substrates. For example, recently proposed hot-electron resistive microbolometer with disorder-controlled electron-phonon coupling [3] promises the *NEP* ~ 10^{-19} W/√Hz and the time constant, $\tau \sim 10^{-5}$ s at 0.3 K, and *NEP* ~ 10^{-20} W/√Hz and $\tau \sim 10^{-4}$ s [4] at 0.1 K. Another way to make a hot-electron sensor is to use a kinetic inductance of a superconducting film. In this case, the detector will be able to operate at temperatures above 1 K with very high sensitivity.

There has been significant interest to the kinetic-inductance detectors (KID) operating near the superconducting transition [5,6,7,8,9,10]. Near T_c, the kinetic inductance has strong temperature dependence and can be used as superconducting thermometer. Both bolometric [5-7] and hot-electron [8-10] 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 6. 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, the kinetic-inductance detectors offer approximately the same *NEP* and the response time as corresponding 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. To our knowledge, the non-equilibrium (hot-electron) mode of operation of the KID at $T << T_c$ has not been considered yet. Meanwhile, this regime is advantageous for the detector operation since the number of quasiparticles is exponentially small and the corresponding generation-recombination noise is small as well.

In the current paper, we consider a hot-electron KID operating in the superconducting state far below the superconducting transition but still at temperatures accessible with sorption He3 or He4 cryostats. Such a detector made from a superconductor with $T_c \sim$ 6-10 K allows for the *NEP* $\sim 10^{-19}$ W/√Hz determined by the quasiparticle generation-recombination noise. The background radiation is effectively cut off below the superconducting gap frequency, $f_c = 2\Delta/h$ (Δ is the superconducting gap). As well as the resistive hot-electron detector [3], the kinetic-inductance one has a number of attractive features for submillimeter and far-infrared operation: 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 has a large array scalability.

The schematic circuit of the KID with a SQUID readout is shown in Fig. 1. The 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 second branch, L_2, is significantly larger than that in the first branch, the magnetic flux generated by radiation is given by

$$\delta\Phi = \delta I\, L_2 = \delta L_k I_1 . \qquad (1)$$

Under the radiation, the kinetic inductance is determined by the nonequilibrium distribution function of quasiparticles, $f(\varepsilon)$, and by the value of Δ, which is function of $f(\varepsilon)$ [11],

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

Far below the superconducting transition, the nonequilibrium distribution function under the radiation is described by the Boltzmann function, $f(\varepsilon)=\exp[(\mu-\varepsilon)/k_BT]$, with a non-vanishing chemical potential [12]:

$$\mu = \frac{k_BT}{2}\ln\left(1+\frac{2rP_0\tau_{qp}}{\hbar\Omega n_0}\right). \quad (3)$$

Here P_0 is the power of electromagnetic radiation absorbed in a unit volume of the superconducting microbridge, Ω is the radiation frequency, 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:

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

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

The quasiparticle lifetime is determined by the recombination time, τ_R, enhanced by phonon re-trapping. 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 $T_c \geq 5$K, the mean free path of such phonons, $\lambda_{ph} = \hbar v_F/\pi\Delta$ (v_F is the Fermi velocity), is smaller than the effective film thickness d/K (K~0.01-0.1 is the acoustic transparency of the film/substrate interface [13]). As a result of the phonon re-trapping, the quasiparticle lifetime, τ_{qp}, is substantially longer than the recombination time:

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

where $\tau_{e-ph}(T_c)$ 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 the phonon transparency, the characteristic time can be varied in a broad range 10^{-5}-10^{-3} sec at 1 K.

To model the detector performance, we fist find the inductive response to radiation. Under condition of strong phonon re-trapping, the quasiparticle multiplication factor $r = \hbar\Omega/\Delta$ [14]. According to Eqs. 1 and 2, the shift of the kinetic inductance at $T \ll T_c$ is given by the change of the non-equilibrium distribution function,

$$\frac{\delta L_k}{L_k} = \frac{2\delta f(\Delta)}{1-2f_0(\Delta)} = \frac{2P_0\tau_{qp}}{\hbar\Delta n_0}\exp(-\Delta/k_BT) \propto \exp(\Delta/k_BT). \qquad (6)$$

The basic noise mechanism of the inductive detector is intrinsic fluctuations of the number of quasiparticles (generation-recombination noise). Exponentially small number of equilibrium quasiparticles (N_{eq}) well below the superconducting transition in micron size film structures may provide unparallel performance of the KID at $T \approx 1$ K. The NEP_{GR} conditioned by the generation-recombination noise is given by [14]:

$$NEP_{GR} = 2\Delta\sqrt{N_{eq}/\tau_{qp}} \propto \exp(-\Delta/k_BT) \qquad (7)$$

Here τ_{qp} is the quasiparticle lifetime, Δ is the superconducting gap.

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, $N_{eq}=n_0V \approx 100$, the noise equivalent power is $NEP_{GR} \approx 600\Delta\sqrt{\text{Hz}} \approx 10^3 k_BT_c\sqrt{\text{Hz}} \approx 10^{-19}$ W/$\sqrt{\text{Hz}}$.

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

$$NEP_{SQUID} = \frac{\delta\Phi}{2L_kI_1}\frac{N_{eq}V\Delta}{\tau_{qp}}\exp(\Delta/k_BT). \qquad (8)$$

As an example, we calculated performance of a Nb sensor operating at 1 K. We considered a 4.0×1.0 μm^2 Nb microbridge made from a 10 nm thick film. The transition temperature of such a film is 6.5 K, the sheet resistance $R_{sq} \approx 20\ \Omega$ [15,16], and the electron-phonon relaxation time is 0.6 ns at 6.5 K [16]. According to Eq. 5, the recombination time at 1 K is 1.4×10^{-5} sec. 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 sapphire substrate [13] which suggest the parameter τ_{qp}/τ_R to be equal 4.4 d/nm. Thus, we expect the quasiparticle lifetime in a 10 nm Nb film to be 0.62 ms. Such a response time is short enough for most of applications. Note, that substrates with rigid lattice and large acoustic impedance (e.g, diamond) would provide strong acoustic mismatch to the superconducting films, and, therefore, increase the quasiparticle lifetime.

The results of modeling of the noise characteristics are shown in Fig. 2 (the kinetic inductance of the Nb microbridge was 18 pH and the electric current was chosen be 1 mA). The NEP_{SQUID} is significantly smaller than the NEP_{GR}, and $NEP_{GR} \approx 0.6\times10^{-19}$ W/$\sqrt{\text{Hz}}$ is achievable at $T = 1$ K. The reduction of volume might produce additional decrease of the NEP but at the same time the number of quasiparticle would become too small to obtain reasonable dynamic range. A thin-film inductive sensor is naturally well matched to a planar antenna impedance (Z =40-100 Ω) at wavelengths $\lambda < \lambda_c = hc/2\Delta \approx$ 0.4 mm, whereas the background radiation with $\lambda > \lambda_c$ is not absorbed by the sensor. Note, that since the device length is much smaller than $(D\tau_{qp})^{1/2}$ = 200-400 μm (D is the electron diffusion constant) the Andreev contacts with the 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 for contact material.

In Table 1 we summarize characteristics of the Nb detector and also present film parameters and characteristics of NbC and MoRe KIDs with the $NEP \approx 10^{-19}$ W/√Hz at 1-1.6 K. We used parameters of available films (NbC [17] and MoRe [18]) and optimized the characteristics in the following way. The operating temperature was chosen to provide the response time of ~1 ms (Eq. 5 with the trapping factor τ_{qp}/τ_R = 4.4 d/nm). The volume of the sensor was taken sufficiently large to accommodate ~100 equilibrium quasiparticles. The number of squares was adjusted to match the sensor rf impedance to that of a planar antenna impedance.

Note, that despite NbN thin films have been also well characterized and can have large T_c, they are not useful for sensitive KIDs since its electron-phonon relaxation time in this material is too short [13]. Our analysis is not applicable to high-temperature cuprates, which are d-wave superconductors with large number of quasiparticles in nodal regions. New 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 of the lifetime and the sensitivity.

In conclusion, we have analyzed the kinetic inductance detector in the hot-electron mode well below the superconducting transition. The detector noise equivalent power of the order of 10^{-19} W/√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 possibility to fabricated sensors on bulk dielectric substrates are attractive for making a submillimeter monolithic array of antenna-coupled detectors.

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Table 1. Parameters of kinetic inductance detectors made from different superconductors.

Material	d	R_{sq}	T_c	$\tau_{e\text{-}ph}(T_c)$	$\nu(0)$	$W{\times}L$	T	τ_{qp}	NEP_{GR}
	nm	Ω	K	ns	10^{22} eV^{-1}cm^{-3}	μm×μm	K	ms	10^{-19} W/√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	0.60

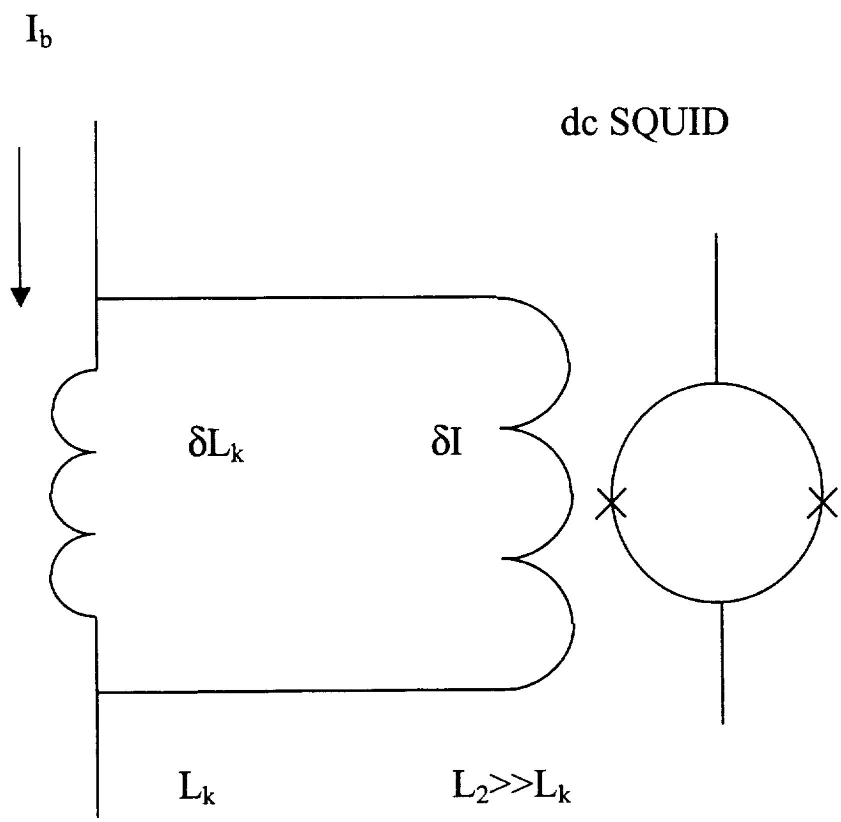

Fig. 1. The schematic circuit demonstrating redistribution of the signal current in a KID/SQUID loop. An increase of the kinetic inductance caused by radiation decreases the current flowing through a SQUID coil producing detectable magnetic field.

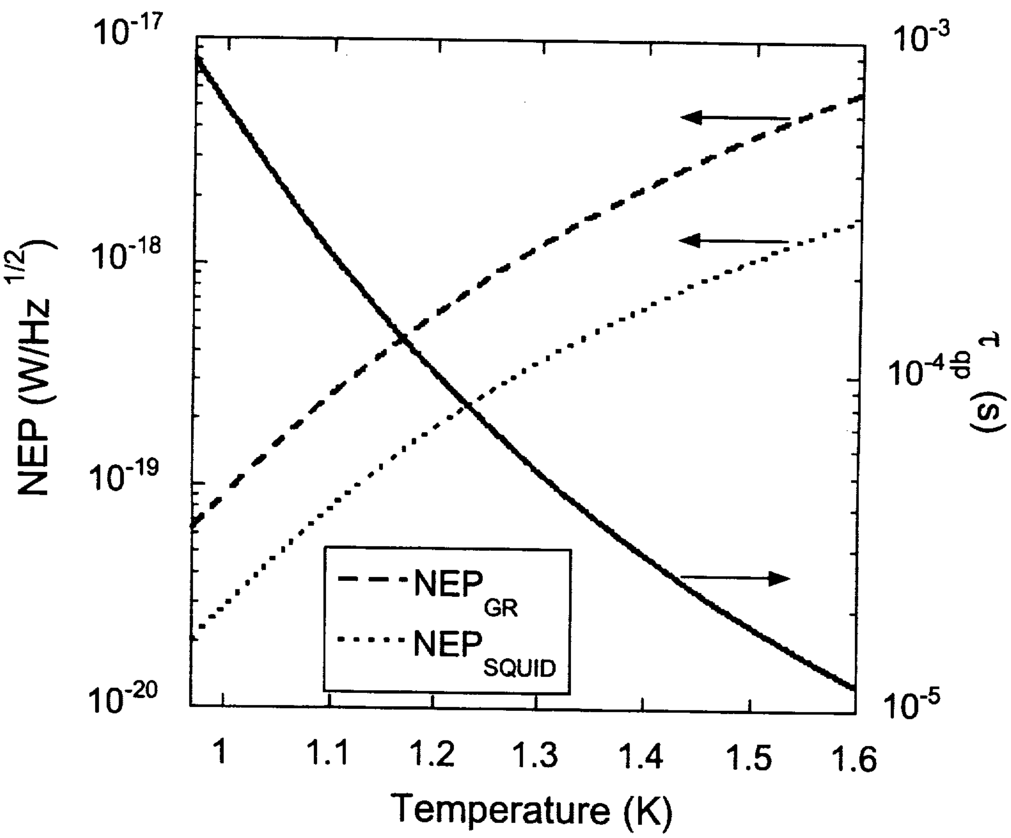

Fig. 2. Temperature dependencies of the NEP and the quasiparticle lifetime in the Nb KID.