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Inductive superconducting transition-edge detector for single-photon and macro-molecule detection

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Abstract
We present a new type of transition-edge sensor for single-photon and macro-molecule detection. In our detector the absorber element is an isolated, passive absorber of extremely low thermal mass, maintained close to, but below, its superconducting–normal transition, and strongly inductively coupled to a SQUID sensor. Incoming particles or photons are sensed in terms of a transient change in the inductive coupling, rather than a change in resistance. The detector's energy sensitivity and response time can be defined by the thermal mass of the absorber and its thermal contact with a substrate, independently of any electrical connections. We have modelled the energy sensitivity of our inductive superconducting transition-edge sensor using a sub-micron SQUID as an inductive read-out device. An ultimate energy resolution of order 10^{-25} J Hz^{-1} is theoretically estimated based on the properties of the read-out SQUID and the dimensions of the absorber. We also report our initial work on fabrication of the Nb nanoscale SQUID where we have used the same material deposited on top of the SQUID as a thin-film absorber.

1. Introduction

To measure the energy associated with a single particle, an extremely sensitive detector is required. A number of detectors with suitable sensitivity have been reported in recent years, all of which operate at low temperatures $T \sim 0.1$ K. For example, cryogenic detectors of keV energy x-rays have demonstrated 0.1% energy resolution, orders of magnitude better than conventional semiconductor performance. The capability of a detector to offer enhanced energy resolution, allows more detailed spectroscopic information on the detected particles to be acquired. The superconducting transition-edge bolometer has undergone extensive development as an ultra-sensitive detector of electromagnetic radiation extending in wavelength from x-rays [1] to the far-infrared [2, 3]. Recent devices have achieved single-photon detection combined with rapid (sub-ps) response times [4]. In general, the sensitive element is a current- or voltage-biased microbridge, which inevitably introduces a dissipative heat load, causing degradation of energy sensitivity and noise. Moreover, the thermal characteristics of the microbridge are often compromised by contiguous structures associated with the electrical bias and read-out leads.

In this paper, we describe the principle and advantages of our new type of bolometer: inductive superconducting transition-edge detector (ISTED). Our proposed detector technology employs non-dissipative readout unlike other superconducting transition-edge sensors. The detector element is a thin-film patch of superconducting material, deposited within the SQUID loop, and maintained just below its transition temperature. We have modelled the energy sensitivity of our sensor using the SQUID as an inductive read-out device. Both the sensitivity of the bolometer and the sensitivity of the read-out SQUID are improved by reducing the size of each to nanoscale. An ultimate energy resolution of order 10^{-25} J Hz^{-1} is theoretically estimated based on the

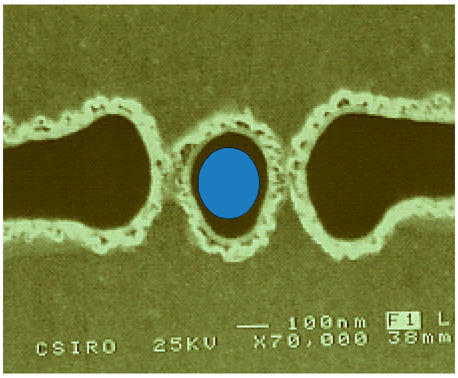

Figure 1. SEM picture of a sub-micron SQUID loop with schematic indication of a sub-micron thin-film absorber deposited in the centre.

properties of the read-out SQUID and the dimensions of the absorber. We also report our initial work on fabrication of the Nb nanoscale SQUID with an absorber of the same material deposited on top. By controlling the thickness of the Nb absorber its transition temperature can be reduced relative to that of the SQUID.

2. Inductive superconducting transition-edge detector

The principle of our ISTED is illustrated in figure 1: a proposed sub-micron thin-film absorber is deposited in the centre of a sub-micron SQUID loop. The sensitive element is an isolated, passive absorber of extremely low thermal mass, maintained close to, but below, its superconducting–normal transition temperature, and strongly inductively coupled to a read-out SQUID sensor which has higher transition temperature than the absorber. Incoming particles or photons and macro molecules produce a temperature rise in the absorber which may be sensed by the transient change in inductive coupling, rather than a change in resistance. The detector's energy sensitivity and response time can be defined by the thermal mass of the absorber and its thermal contact with a substrate, independently of any electrical connections. Both the sensitivity of the bolometer and the sensitivity of the read-out SQUID are improved by reducing the size of each to nanoscale.

Unique features of this novel technique include: an isolated nanoscale passive absorber, of extremely low thermal mass; non-contacting operation and non-dissipative inductive readout. Its main advantage over the conventional method of detecting the transition is that in the latter method, the absorber is in contact with electrical current-carrying leads, which add to the heat capacity of the absorber, and the sensor itself represents a dissipative heat load.

3. Energy sensitivity

We can calculate the ISTED detector ultimate energy sensitivity. Consider a small SQUID loop containing a thin-film patch of superconductor maintained at a temperature a little below its transition temperature T_c (as shown in figure 1). When the temperature of the thin-film patch changes, for example if a particle (photon or macro molecule) with energy E is absorbed by it, its London penetration depth will change slightly as a result. The SQUID loop inductance will thus change and the SQUID's altered response to an applied magnetic field will produce a voltage change which may be read out.

We can break down this calculation into three separate terms: the variation of the voltage (V) with inductance (L) of the read-out SQUID loop, the variation of the inductance of the loop with the superconducting absorber penetration depth (λ) and the variation of λ with temperature (T). It follows that

$$\frac{\mathrm{d}V}{\mathrm{d}T} = \frac{\mathrm{d}V}{\mathrm{d}L}\frac{\mathrm{d}L}{\mathrm{d}\lambda}\frac{\mathrm{d}\lambda}{\mathrm{d}T}. \tag{1}$$

The first term on the right may be simply estimated since for most dc SQUIDs the optimum slope for the flux to voltage conversion is

$$\frac{\mathrm{d}V}{\mathrm{d}\Phi} \approx \frac{R_{\mathrm{dyn}}}{L} \tag{2}$$

where R_{dyn} is the dynamic resistance of the read-out SQUID at the bias point. Then it is easy to estimate that

$$\frac{\mathrm{d}V}{\mathrm{d}L} = \frac{-R_{\mathrm{dyn}} i_c}{L} \tag{3}$$

where i_c is the critical current of the SQUID.

Consider the self-inductance of a superconducting thin-film SQUID loop of radius a, where the centre of the SQUID loop is filled out to a radius ka by a superconducting thin-film absorber. Assume for simplicity that, both the SQUID washer and absorber have the same thickness t. A modelling of the variation of the SQUID loop inductance L with penetration depth $\lambda(T)$ for the absorber film involves a numerical calculation, which will be presented elsewhere. An analytical expression which closely approximates to the numerical result is given by

$$L \approx \mu_0 a \left[6\pi \left(1 - k - \frac{\lambda(T)}{a} \right) \right]^{1/2}. \tag{4}$$

From equation (4), it can be shown that

$$\frac{\mathrm{d}L}{\mathrm{d}\lambda} \approx \frac{-3\pi \mu_0^2 a}{L}. \tag{5}$$

For a conventional superconductor the London theory provides a phenomenological expression which describes the temperature dependence of the penetration depth $\lambda(T)$. This is usually rather accurate, especially closed to T_c where our proposed bolometer would operate. The form of the London expression is described by a two-fluid model:

$$\lambda(T) = \frac{\lambda(0)}{\left(1 - \left(\frac{T}{T_c}\right)^4\right)^{1/2}}. \tag{6}$$

Where T_c is superconducting to normal transition temperature of absorber, $\lambda(0)$ is absorber penetration depth at $T = 0$ K. Thus the final term in the right in equation (1) becomes

$$\frac{\mathrm{d}\lambda}{\mathrm{d}T} = \frac{2\lambda(0)T^3}{\left(1 - \left(\frac{T}{T_c}\right)^4\right)^{3/2} T_c^4}. \tag{7}$$

Using the above equations, the dependence of L on the absorber filling fraction, k, and on temperature can be derived, and examples for three values of normalized temperature are shown in figure 2.

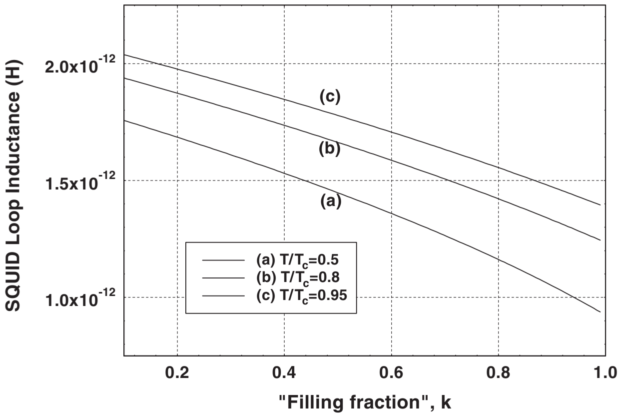

Figure 2. Calculated SQUID inductance versus patch absorber filling fraction, *k*, for three values of absorber normalized temperature T/T_c.

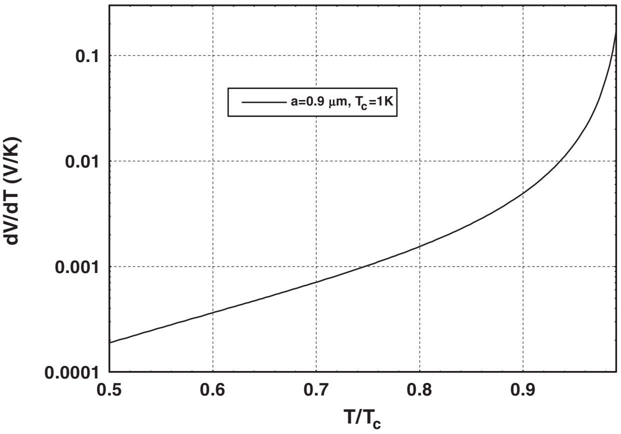

Figure 3. Calculated SQUID response dV/dT versus absorber normalized temperature T/T_c where T_c is the absorber's transition temperature. In this example, the SQUID loop radius is 0.9 μm, critical current 100 μA, dynamic resistance 10 Ω and absorber filling factor 0.9.

By substituting equations (3), (5) and (7) into equation (1), the read-out SQUID response to temperature changes in the superconducting thin-film absorber can be approximately given by the following equation:

$$\frac{dV}{dT} \approx \frac{6\pi R_{\rm dyn} i_c \mu_0^2 a}{L^2} \frac{\lambda(0) T^3}{\left(1-\left(\frac{T}{T_c}\right)^4\right)^{3/2} T_c^4}. \qquad (8)$$

The denominator of equation (8) indicates that the bolometer should be operated below, but as close as possible to, the absorber's transition temperature. In this way Nyquist noise can be ignored, while at the same time the temperature sensitivity dV/dT of the device, operating as a nano-thermometer, is greatly enhanced. The strong enhancement of dV/dT as the operating temperature approaches T_c is illustrated in figure 3. Stability of temperature will of course become a serious issue in the latter case. Realistic values for all parameters suggest that values of 10 mV K^{-1} can be achieved. A typical room temperature amplifier is capable of detecting a voltage change of ~1 nV Hz$^{-1/2}$ so that a temperature rise of only 0.1 μK in the absorber should then be detectable. Assuming an operating temperature of 0.1 K, an absorber of diameter 0.8 μm and thickness 50 nm, we estimate the minimum detectable energy to be ~10^{-25} J Hz^{-1}.

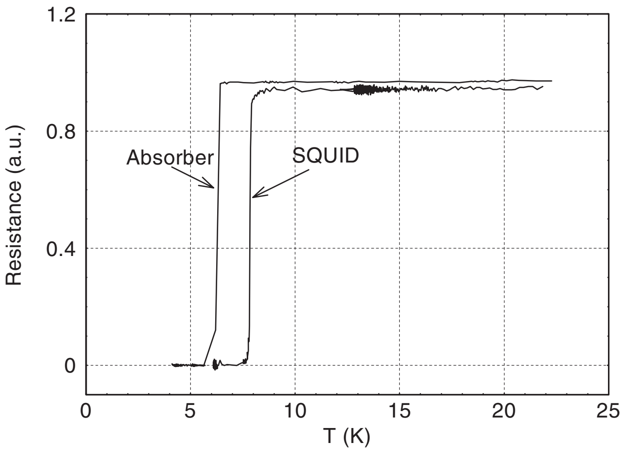

Figure 4. Superconducting to normal transition temperatures of nanoscale Nb SQUID film (20 nm thickness) and Nb absorber film (14 nm thickness). The transition temperature difference is about 1.6 K.

4. Experimental tests of nanoscale SQUIDs and absorber

We are using the fact that the sensitivities of both the bolometer and the read-out SQUID are improved by minimizing their dimensions to nanoscale. In the limit a nanoscale absorber deposited into the small SQUID loop would provide energy sensitivity to enable the detection of a single photon and particle. In addition the small thermal mass of the nanoscale absorber will allow intrinsic ns response time.

Initial experiments have been carried out with Nb SQUIDs of various dimensions and characteristics. For our initial trials, we used commercially-available SQUIDs with loop areas ~3 × 3 μm^2, where the absorber was located either above the plane of the SQUID, or else was in the form of a thin-film coating on the end of an optical fibre [5]. Recent work at CSIRO has demonstrated the feasibility of fabricating sub-micrometre Nb SQUIDs by electron-beam lithography [6]. In the present work, which we report in this paper, we have used the same technique [6] to fabricate the Nb nano-SQUIDs and deposit a thin-film Nb absorber patch on top of the SQUID structure. The objective is firstly to characterize the nano-SQUID, then add the absorber film, and finally to observe the interaction between it and laser light incident on its surface via an optical fibre. Experience has shown that the T_c of Nb films (nominally 9 K) decreases for film thickness less than ~30 nm. To achieve an absorber transition temperature T_{ab} somewhat lower than the Nb SQUID transition temperature T_{sq}, the absorber material was chosen also to be Nb, but with a thickness less than that of the SQUID. In a particular case, the SQUID film of thickness 20 nm was found to have T_c of 7.9 K. During deposition of the absorber patch (10 μm × 20 μm area) of a thickness 14 nm, a test film was simultaneously deposited on an adjacent substrate, with which T_{ab} was later measured to be 6.3 K as shown in figure 4.

5. Conclusion and future work

We have described the principle and advantages of our new type of bolometer: inductive superconducting transition-edge detector. Calculations of the energy sensitivity of an idealized model of our bolometer using a SQUID as an inductive read-out device have been presented. The sensitivities of both the bolometer and the read-out SQUID are improved by reducing the size of each to nanoscale. An ultimate energy resolution of order 10^{-25} J Hz^{-1} ($\sim 10^{-6}$ eV Hz^{-1}) is theoretically estimated based on the properties of the read-out SQUID and the specified sub-micrometre dimensions of the absorber at an operating temperature of 0.1 K. In this ideal case, particles of energy 1 eV, for example, could be detected with a precision of order 0.1%, in a detector bandwidth of 1 kHz. In any practical situation, the sensitivity would undoubtedly be degraded by other factors such as the capture probability of a particular class of particles, the efficiency of energy transfer to the absorber and the achievable level of temperature stabilization. Similarly, operation at a higher temperature would be feasible, but with a loss of sensitivity due to the increasing thermal mass of the absorber and higher SQUID noise. If a particular application demands a larger capture area, for example to intercept a broader beam flux, the device dimensions can be scaled up proportionately, although the ultimate sensitivity and fast response time which we have calculated for single-particle detection may not then be achieved. We report our initial work on fabrication of the Nb nanoscale SQUIDs incorporating a patch of thin-film Nb absorber which is deposited on top of the SQUID loop. Experimental results achieved so far show that it is feasible to deposit a controlled thickness of the Nb absorber such that its transition temperature is about 1.6 K lower than that of the Nb SQUID.

In ongoing work, the response of the ISTED to illumination by laser light transmitted through an optical fibre is being investigated. In this way the achieved sensitivity and response time will be compared with the theoretical data described above. In addition, more experimental results will be obtained on new devices where the Nb thin-film patch absorber is deposited directly within the SQUID loop. This innovation will both enhance the coupling to the SQUID, and allow the thermal mass of the absorber to be reduced. The 4.2 K stage will be replaced with a sub-1 K cryostat so that the ultimate energy resolution of this technique can be explored.

A further outcome of the ISTED development can be foreseen in its possible application as an energy-resolving detector of massive (>200 amu) molecular or polymeric species. There is a perceived need, for instance in the biophysics and pharmaceuticals measurement community, for new approaches to this problem, as outlined below.

The detection of molecular species of molecular weight >200 amu by mass spectrometric techniques is increasingly of interest in the analysis of polymeric and biological macro molecules. Species such as fragments of DNA, for example, and bio-molecules such as immunoglobulin, have been the subject of recent studies [7, 8]. In conventional mass spectrometers, the ionizing detector sensitivity is determined by the number of electrons emitted when a fast-moving ion strikes a collector electrode. The electron emission is directly related to the velocity of the particle, which (for a given ion energy) falls off inversely with the mass of the impinging macro-molecular ion. The reason is linked to the diminishing efficiency of energy transfer of massive molecules to the electrons of the detector medium. The resolution and sensitivity of the spectrometer therefore become increasingly impaired as the macro-molecular mass increases. An entirely different situation arises, however, when a bolometric type of detector, which works on the calorimetric principle, is installed. In this case, the detected signal is directly related to the KINETIC ENERGY of the impinging ion, which, in contrast to the velocity, is mass-independent, for a given ion energy. This principle, combined with 'time-of-flight' measurements, has enabled unprecedented energy resolution and mass spectrographs of previously 'difficult' molecular species to be achieved. Although resistive-transition detectors have been used up to now, the application of our proposed ISTED technique would lead to enhanced sensitivity as described above.

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