MULTIPLEXABLE KINETIC INDUCTANCE DETECTORS

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ABSTRACT

This paper describes a new superconducting photon detector concept which is applicable from millimeter waves to X–rays. Photons are absorbed in a superconductor, producing quasiparticle excitations, which change the surface reactance (kinetic inductance) of the superconductor. The changes in the kinetic inductance are monitored using microwave high–Q thin–film superconducting resonators. A particularly intriguing aspect our concept is that the detector is amenable to frequency–domain multiplexing, with likely detector multiplexing factors of $\sim 10^3$ or more per microwave HEMT amplifier. We are now investigating the practical aspects of this concept, and have already demonstrated energy–resolved detection for 6 keV X–rays.

PHOTOCONDUCTOR ANALOGY

Semiconductor photoconductive detectors, which are discussed in detail elsewhere in these proceedings, operate by absorbing photons to produce free electrons or holes which carry current. Their sensitivity is controlled by the fluctuations of the dark current, which theoretically decreases exponentially as the temperature is reduced. This is the key reason that photoconductors operate at higher temperatures than bolometers. A major difficulty in pushing (extrinsic) photoconductors to longer wavelengths is the development of a high-quality materials system which has impurity states with sufficiently low binding energy.

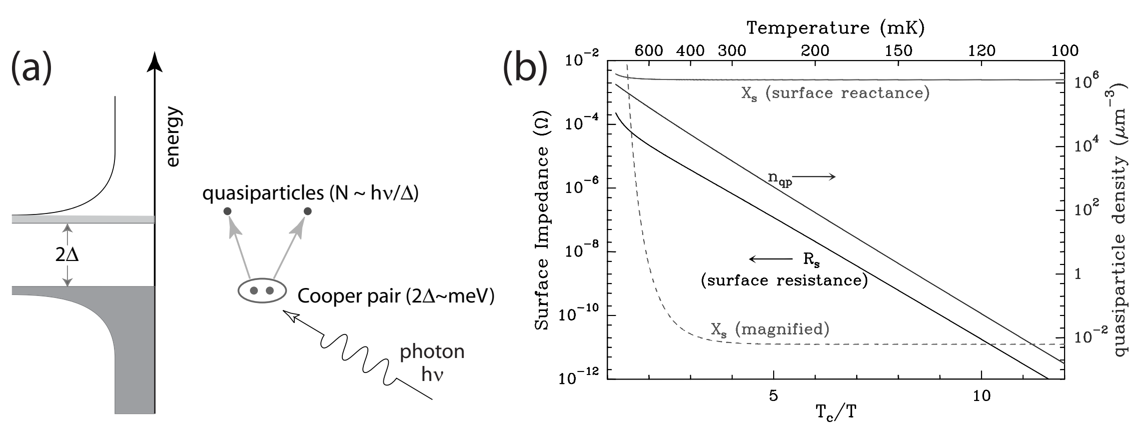

Figure 1: (a; left): Basic concept for superconducting pair–breaking detectors. (b; right): Variation of surface impedance (at 5 GHz) and quasiparticle density n_{qp} with temperature for aluminum.

Superconducting pair–breaking detectors are in many ways analogous to photoconductors. Superconductors have a finite gap in their electronic density of states, as shown on in Fig. 1(a). The energy gap scales with T_c; the BCS result is $2\Delta \approx 3.5kT_c$. States below the gap represent Cooper pairs, or bound electron pairs; states above the gap represent "single–electron" quasiparticle excitations. As shown in Fig. 1(a), photons with energy $h\nu > 2\Delta$ can break Cooper pairs, each producing of order $\sim h\nu/\Delta$ quasiparticles. In contrast to photoconductors, the long–wavelength cutoff $\lambda_c = hc/2\Delta$ can easily be tuned, simply by choosing a metal with the appropriate T_c, or by combining metals in a bilayer or alloy. For example, high quality aluminum ($T_c \sim 1.2$ K) films can readily be made, which have a cutoff wavelength of $\lambda_c \sim 3$ mm.

The fundamental limiting noise mechanism is the random generation and recombination of thermal quasiparticles,[1–3] which causes $\sqrt{2N}$ fluctuations in the mean number N of quasiparticles in a detector. The resulting sensitivity limit[3] is NEP$= (2\Delta/\eta)\sqrt{N/\tau_{\rm qp}}$, where $\tau_{\rm qp} \sim 10^{-3} - 10^{-4}$ s is the quasiparticle lifetime, and η is the quantum efficiency. As shown in Fig. 1(b), at low temperatures $T << T_c$ the quasiparticle density is very low due to the Boltzmann factor $\exp(-\Delta/kT)$. Thus, it should be possible to make a very sensitive detector if it is operated at $T << T_c$, if the photons can be absorbed efficiently by the superconductor ($\eta \sim 1$), and if the quasiparticles produced by the photons can be measured. Efficient absorption is not actually much of a problem; measuring the quasiparticles is the key difficulty, due to the presence of the Cooper pairs. The Cooper pairs are responsible for the zero DC resistance; thus, we cannot simply measure the DC current as is done for photoconductors. Superconducting tunnel junctions, or "STJs", are one solution: they can "filter" out the quasiparticles from the Cooper pairs. However, this approach has many complications: (1) STJs are nontrivial to fabricate; (2) suitable fabrication recipes exist only for a limited selection of materials; (3) STJs require a very uniform magnetic field across the detector array, and (4) STJs are difficult to multiplex.

DETECTOR CONCEPT

We are investigating a simple, easily multiplexable method for detecting quasiparticles. Quasiparticles block Cooper pairs from occupying some of the electron states (through the exclusion principle). Quasiparticles therefore affect the complex (a.c.) electrical conductivity, and thus the surface impedance Z_s. The surface impedance of superconductors is primarily inductive (see Fig. 1(b)); this is the "kinetic inductance". Most previous kinetic inductance detector concepts[4–7] used the rapid variation of the kinetic inductance with temperature near T_c to read out a bolometer. As shown in Fig. 1(b), the kinetic inductance ($X_s(T) = {\rm Im}\, Z_s(T)$) does not vary much for $T << T_c$. However, as shown in Fig. 2(a), it is actually not constant: the difference $\delta X_s = X_s(T) - X_s(0)$ follows the same exponential variation with temperature as the quasiparticle density $n_{\rm qp}$. Note that the *response per quasiparticle* $\delta X_s/n_{\rm qp}$ is nearly independent of temperature.

Extremely small changes in the kinetic inductance can be measured by monitoring the (microwave) resonance frequency of a superconducting thin–film resonator. A change in the quasiparticle density $\delta n_{\rm qp}$ leads to a change in the resonance frequency $\delta\nu$, which produces a change in the resonator transmission phase of order $\delta\phi \sim \delta\nu/\Delta\nu$, where $\Delta\nu = \nu_0/Q$ is the resonance width. With low–noise microwave sources and amplifiers, very small changes ($\sigma_\phi << 1$ degree) in the transmission phase can readily be measured, which correspond to extremely small changes in the resonance frequency, of order $\sigma_\phi Q^{-1}$. Thus, Q is a key parameter for determining the sensitivity of the detector. It is clearly important to minimize the parasitic losses (e.g. due to radiation, dielectrics, etc.), so that the superconductor loss becomes the limiting factor. Fortunately, the AC ohmic loss of the superconductor (due to quasiparticles) falls exponentially with temperature, as shown in Fig. 2. This again pushes us to operate at $T << T_c$; furthermore, the exponentially increasing responsivity (Q) offsets the exponentially falling generation–recombination noise, yielding the result that the required microwave amplifier noise performance is actually constant with operating temperature.

This concept takes advantage of the recent dramatic advances in the performance of cryogenic microwave HEMT (High Electron Mobility Transistor) amplifiers, which provide $T_n < 10$ K across multi-gigahertz bandwidths (see Gaier *et al.*, these proceedings). Our calculations indicate that $T_n < 4\Delta/k_B \sim 10$ K is required in order to reach the generation–recombination sensitivity limit. The idea of using the kinetic inductance effect for detectors at $T << T_c$ has been discussed previously.[3,8,9] These papers discuss the use of SQUID amplifier readouts. The microwave approach we advocate is simpler – no SQUIDS – and is very amenable to frequency–domain multiplexing.

Finally, we point out that the detectors are very simple to fabricate, and there is a great deal of flexibility in the choice of detector architecture. The simplest detectors involve a single patterned superconducting film on a dielectric substrate. These can be designed to be "bare pixel" detectors, which have the correct effective surface impedance for good absorption. Alternatively, one can use antenna coupling, as discussed by Goldin *et al.* and Lee *et al.* in these proceedings.

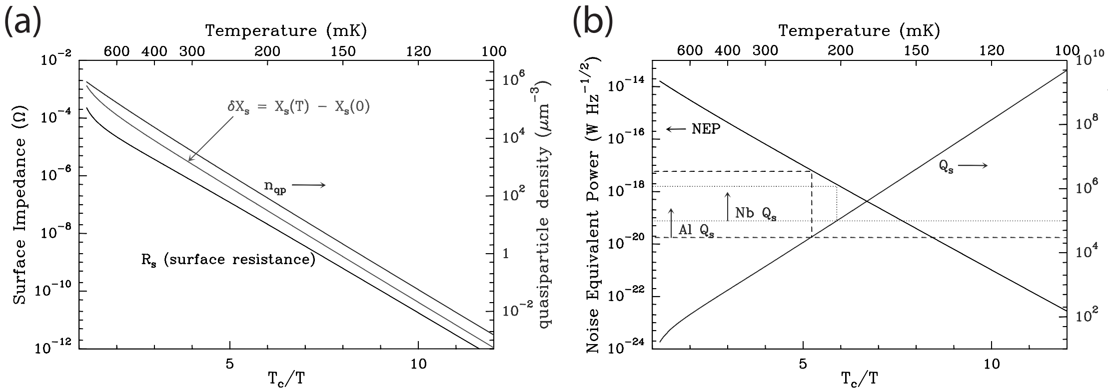

Figure 2: (a; left): The variation of $\delta X_s = X_s(T) - X_s(0)$ with temperature follows the same exponential behavior as R_s and $n_{\rm qp}$. (b; right): The surface impedance quality factor $Q_s = X_s/R_s$ and the generation–recombination limit for the noise equivalent power (NEP) for a detector volume $V = 10^4\,\mu{\rm m}^3$, appropriate for bare pixel detectors.

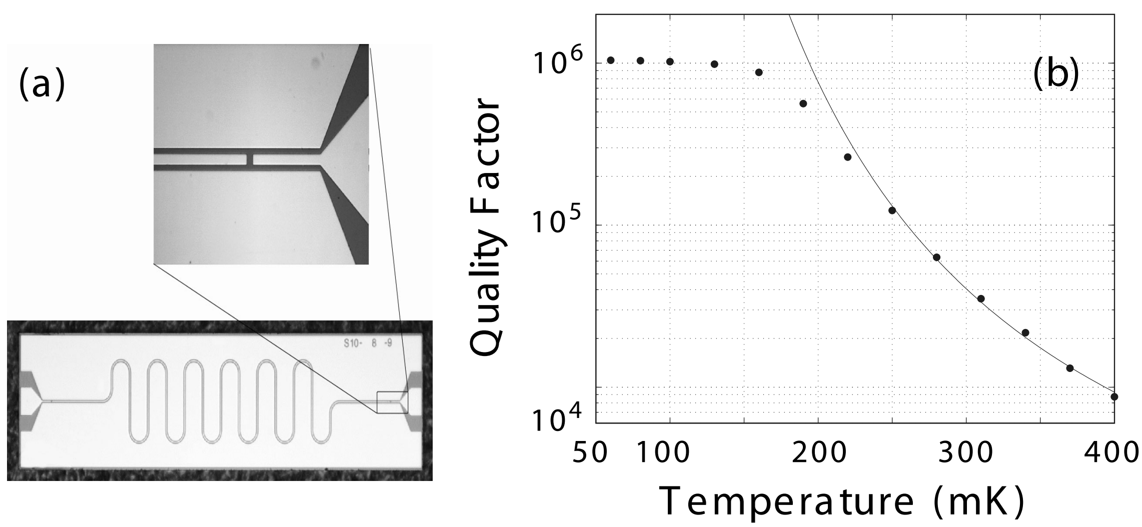

Figure 3: (a; left): Photograph of a CPW test resonator. (b; right): The measured quality factor $Q = \nu_0/\Delta\nu$ as a function of temperature for an aluminum CPW resonator on a sapphire substrate.

TEST RESONATORS

In order to examine the feasibility of this detector concept, we have begun testing superconducting resonators. Fig. 3(a) shows an example of a coplanar waveguide (CPW) test resonator, which has capacitive coupling gaps at each end. This device behaves much like a Fabry–Perot resonator. Fig. 3(b) shows an example of the measured quality factor vs. temperature at 5 GHz, $Q(T)$, which exceeds 10^6. From the dependence of Q with resonator geometry, and by comparing measurements with calculations, we deduce that so far our resonators are limited by radiation loss rather than ohmic losses at the lowest temperatures. By designing resonators with reduced radiation loss, we expect that Q can be substantially increased. Even with no improvements in Q, very interesting sensitivity levels are predicted. As shown in Fig. 2(b), our test resonator results already indicate that NEP's of order a few 10^{-18} W/$\sqrt{\text{Hz}}$ should be achievable. We have successfully demonstrated the detector concept by exposing our aluminum test resonators to 6 keV X–rays (see Fig. 4): we see $\sim$ 15 degree phase pulses with very high signal–to–noise ratios. The fall time of the pulse gives us an estimate of the quasiparticle lifetime, which is of order 50–100 μs.

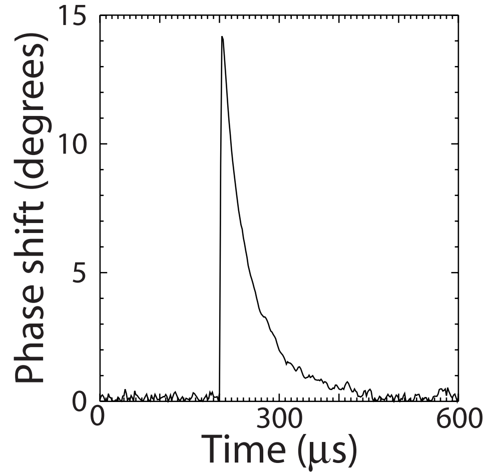

Figure 4: Measured response of a test resonator to 6 keV ^{55}Fe X–rays.

MULTIPLEXING

The multiplexing approach would use single microwave cable entering the cryostat, carrying multiple microwave frequencies. Each detector pixel would be designed to have a slightly different resonance frequency, and would therefore select the appropriate signal from the input. The separated frequencies would pass through the detectors, and then the phase-shifted signals would be recombined and sent to a single HEMT amplifier. Because Q is so large, and since HEMT amplifiers can easily have octave bandwidths, frequency crowding is not expected to be a serious limitation on the multiplexing factor. Rather, lithographic variations are expected to be important. A rough estimate is that $\sim 10^4$ detectors may be multiplexed through one amplifier. The idea of generating a large number of microwave frequencies, and measuring their phases, may seem daunting at first. However, a wide variety of integrated circuits are now available for these tasks, due to the rapid advances in wireless communication technology. Furthermore, the complex readout electronics are all outside the cryostat; the cryostat contains only the detector array, which is passive and is very straightforward to fabricate, the HEMT amplifier, and a pair of microwave cables.

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