Multiplexable Kinetic Inductance Detectors

B. A. Mazin*, P. K. Day†, J. Zmuidzinas* and H. G. Leduc†

*California Institute of Technology, Pasadena, CA
†Jet Propulsion Lab, Pasadena, CA

Abstract.
We are starting to investigate a novel multiplexable readout method that can be applied to a large class of superconducting pair-breaking detectors. This readout method is completely different from those currently used with STJ and TES detectors, and in principle could deliver large pixel counts, high sensitivity, and Fano-limited spectral resolution. The readout is based on the fact that the kinetic surface inductance L_s of a superconductor is a function of the density of quasiparticles n, even at temperatures far below T_c. An efficient way to measure changes in the kinetic inductance is to monitor the transmission phase of a resonant circuit. By working at microwave frequencies and using thin films, the kinetic inductance can be a significant part of the total inductance L, and the volume of the inductor can be made quite small, on the order of $1\,\mu\mathrm{m}^3$. As is done with other superconducting detectors, trapping could be used to concentrate the quasiparticles into the small volume of the inductor. However, the most intriguing aspect of the concept is that passive frequency multiplexing could be used to read out $\sim 10^3$ detectors with a single HEMT amplifier.

DETECTOR CONCEPT

Kinetic inductance detectors operate on the principle that a change in the number of quasiparticles in a superconductor will produce a change in the kinetic inductance. This occurs because the quasiparticles block Cooper pairs from occupying some of the electron states. Photons (or particles) are absorbed in the superconductor, producing quasiparticles, and the resulting change in the inductance is measured to produce the detector output.

Bolometric detectors using kinetic inductance *thermometers* have been previously suggested [1, 2, 3, 4, 5, 6]. However, such thermometers must be operated close to T_c, since the variation of the kinetic inductance with temperature is most rapid near T_c, and vanishes exponentially at low temperatures. Although it has been discussed previously [7], it is not widely appreciated that the the variation of the kinetic inductance with *energy* or *quasiparticle number* is actually fairly constant down to very low temperatures. The idea, then, is to use the kinetic inductance effect to read out *changes in the quasiparticle population produced by the direct absorbtion of pair-breaking photons* rather than changes in the temperature of the phonons in a bolometric absorber.

How can one measure the change in the kinetic inductance of a superconductor? One way is to make the superconductor act as an inductive element in a resonant circuit. A change in the quasiparticle population will change the inductance of the superconductor, and therefore the resonance frequency of the circuit, which can be monitored by measuring the transmission phase of a constant-frequency microwave probe signal transmitted through (or reflected from) the resonator. This method is extremely attractive, due both to

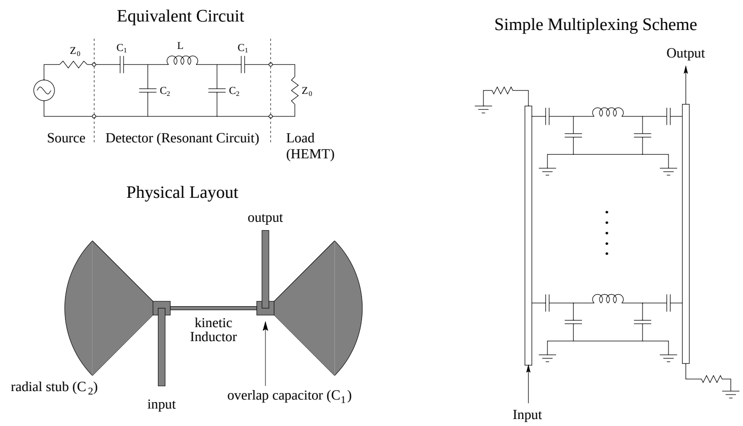

FIGURE 1. Our detector readout concept. Top left: the equivalent circuit representation of a readout. Quasiparticles (generated by photons) are trapped in the inductor L, causing a change in the inductance and resonance frequency, which is sensed by a microwave readout. Bottom left: a possible physical layout for 30 GHz readout using a thin-film aluminum microstrip. The inductor dimensions are $50\,\mu$m x $1\,\mu$m x $.05\,\mu$m. Right: a simple frequency multiplexing arrangement using one input and one output transmission line to read out multiple detectors. The maximum number of detectors that can be read out through one amplifier is determined by the amplifier bandwidth (typically around 10 GHz) and the spacing of resonant frequencies of each device, ultimately set by Q.

its simplicity (no tunnel junctions), as well as the possibility of a frequency-multiplexed readout.

The sensitivity of a kinetic inductance detector depends on how well phase shifts at microwave frequencies can be measured and the responsivity of the detector (which is defined as the change in the transmission phase per quasiparticle injected into the inductor). The noise in the phase measurement is ultimately governed by the noise of the microwave amplifier following the detector. Meanwhile, the responsivity of the detector depends on the Q of the resonator, and on the fraction of the total inductance that is contributed by the kinetic inductance effect. In theory, the Q is limited only by the quasiparticle losses and can increase exponentially as the temperature is decreased, which leads to an exponential improvement in the responsivity and sensitivity. Ultimately, the Q will be limited by non–ideal effects, such as radiation losses, dielectric losses, or excess surface resistance. In addition, one cannot avoid the intrinsic noise of the detector, which is set by the random generation and recombination of quasiparticles by thermal phonons, or by the randomness in the number of quasiparticles produced by a photon (for an optical/UV or X–ray detector).

Space precludes us from giving a thorough quantitative discussion of the expected sensitivity of a microwave kinetic inductance detector. The basic results are as follows:

- For a mm/submm detector, the ultimate sensitivity is limited by the largest achievable surface impedance quality factor $Q_s = X_s/R_s$ of the superconducting films, or the minimum loss tangent $\tan\delta$ of the dielectric films. For the reference design shown in Fig. 1, we calculate that NEP $\approx 6\times10^{-15}\,Q_s^{-1}$ W/$\sqrt{\text{Hz}}$. This gives 3×10^{-18} W/$\sqrt{\text{Hz}}$ at 300 mK, and a factor of 4 better at 250 mK. The sensitivities at these temperatures could be improved substantially simply by increasing the

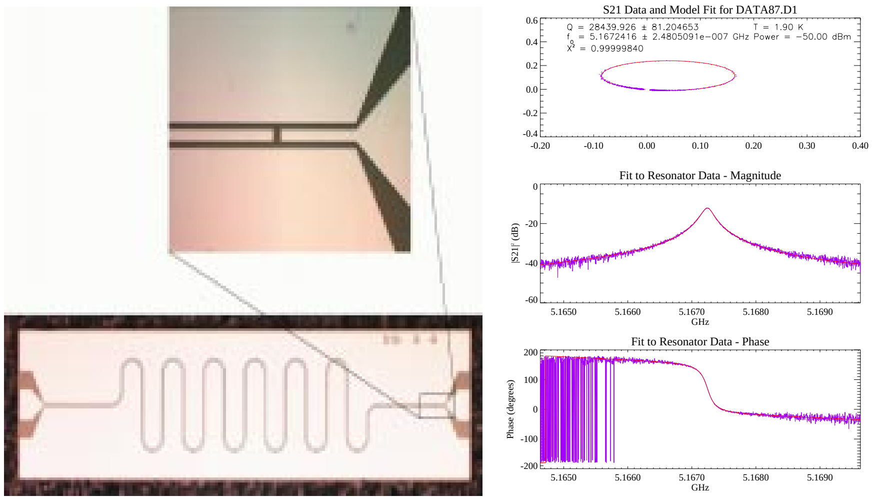

FIGURE 2. Left: A coplanar wave guide (CPW) resonator with gap capacitors fabricated to measure the properties of our thin superconducting films at microwave frequencies. Right: A sample fit to the complex S_{21} data from a CPW resonator.

superconducting gap energy somewhat. Our measurements on thin–film test resonators (see Fig. 3) indicate that $Q_s > 10^4$ and $\tan\delta < 3 \times 10^{-5}$ are readily achievable, so NEP values in the mid 10^{-19} range can be expected. It is very likely that even better sensitivities are possible.

- These results assume standard materials parameters (e.g. T_c, λ) for aluminum as found in the literature. The major uncertainties are in the limiting values of the quasiparticle lifetimes and Q_s.
- For a UV/optical detector, the parameters are quite similar to the STJ case. The basic requirement is that the mean number of thermal quasiparticles $\langle N \rangle$ is low enough so that the $\sqrt{\langle N \rangle}$ generation–recombination fluctuations do not hurt the energy resolution.
- Microwave cryogenic HEMT amplifiers now have sufficiently low noise temperatures that the detectors should be limited by intrinsic (generation–recombination) detector noise or background (photon) noise.

MICROWAVE PROPERTIES OF SUPERCONDUCTING FILMS

The first step towards a sensitive detector is to understand the properties of thin superconducting films at microwave frequencies. The most critical parameters are the surface resistance and reactance, the "surface quality factor" $Q_s = X_s/R_s$, and the effects of microwave power. We have therefore fabricated and tested a variety of resonators (such as those shown in Fig. 2) with different geometries and materials (Al, Ta, and Nb superconductors) over a wide range of temperatures and frequencies.

The resonators are fabricated at JPL's Microdevices Laboratory (MDL) using conventional contact lithography. The devices are cooled in either a helium dewar or a dilu-

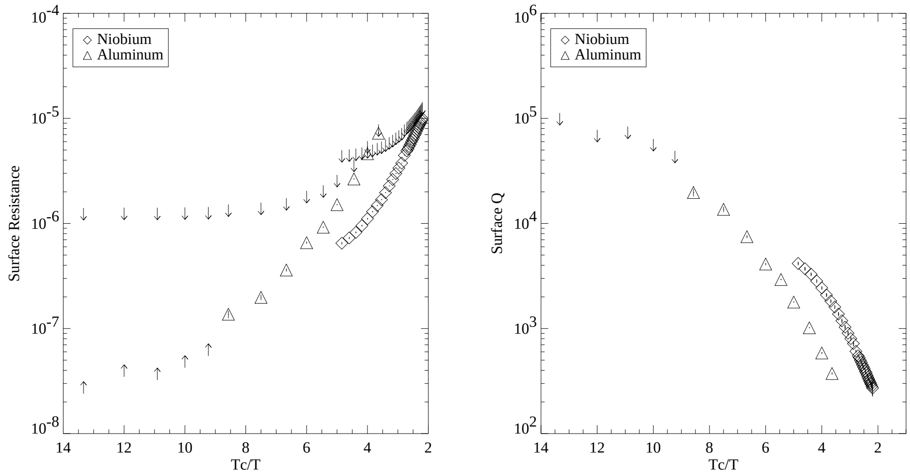

FIGURE 3. Left: Surface resistance as a function of temperature. Right: Measured surface quality factor $Q_s = X_s/R_s$.

tion refrigerator, then probed with a vector network analyzer. We measure the complex transmission amplitude, S_{21}, near the resonant frequency. The complex S_{21} data from the network analyzer are directly fit to an analytic resonance model using a Levenberg–Marquardt minimization routine. This directly gives us Q, the resonance frequency f_0, and their associated uncertainties. Using appropriate geometrical factors, the values of Q and f_0 can then be translated to provide information on the surface resistance and reactance, or penetration depth. Example results are shown in Fig. 3. The results so far indicate that very high values of Q_s are readily achievable, in excess of 10^4. In fact, we believe that the maximum Q values we have observed to date are not limited by the losses of the superconductors, but by other loss mechanisms, such as radiation, which are not fundamental and can be reduced by modifying the resonator design.

ACKNOWLEDGMENTS

This work has been supported by NASA Grant NAG5-10358, the JPL Director's Discretionary Fund, and the Caltech President's Fund.

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