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Kinetic Inductance Phonon Sensors for the Cryogenic Dark Matter Search Experiment

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Abstract An important challenge faced by phonon-mediated detectors for the next generation of dark matter detectors (>100 kg) is to instrument large target mass at low cost, while maintaining the large background suppression offered by the combination of phonons and ionization (or scintillation) measurement. Kinetic inductance phonon sensors, operating far below the superconducting transition temperature, offer an interesting solution to this scaling problem. They do not critically depend on the uniformity of T_c and their resonant-cavity readout is easy to multiplex. We are studying a microstrip (two parallel planes) transmission line architecture that may offer the additional advantage of a separation of functions: the main detector is just covered by an unpatterned aluminum film and the number of quasi-particles created in it by athermal phonons are sensed by a second film, which has been independently patterned and is mounted a few microns away from the detector. We present current results on the responsivity and noise of large area ($\sim$33 mm^2) microstrip kinetic inductance phonon sensors.

Keywords Dark matter · Kinetic inductance sensors · Phonon mediated · Superconducting detectors · Semiconductor detector

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1 Introduction

The Cryogenic Dark Matter Search (CDMS) Experiment currently uses phonon-mediated detectors operating at 50 mK to search for weakly interacting particle dark

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matter. These detectors are composed of a 1 cm thick by 7.5 cm diameter semiconductor (germanium or silicon) crystal absorber with an array of transition-edge sensors coupled to aluminum phonon absorber fins lithographed on one of the crystal faces. Particle interactions occurring within the crystal produce athermal phonons, which reach the crystal surface and create quasi-particles in the aluminum fins if their energy is greater than 340 μeV. The quasi-particles then diffuse to the tungsten transition-edge sensors with a transition temperature adjusted to ≈80 mK and are detected as changes in resistance.

These detectors work well and their performance has established CDMS as a leading experiment in the field. Thirty detectors are deployed in the current phase of the experiment constituting a fiducial mass of 4 kg of germanium and 1 kg of silicon. The excellent background rejection we obtain should allow us to reach a cross section of 2×10^{-44} cm^2/nucleon. The next generation, Super CDMS 25 kg currently under review, promises to gain another factor of ten in sensitivity, with similar technology and improved background levels and rejection. Our long term goal is a background-free ton scale experiment. While the high signal to noise of the CDMS simultaneous measurement of phonons and ionization is attractive, the challenge is to substantially simplify the detector fabrication and test procedures.

Kinetic inductance (KI) phonon sensors represent an attractive technology for such a goal. In this approach, the energy incident on a superconducting metal film breaks Cooper pairs changing the surface impedance of the film. Such changes can be read-out by fashioning the superconductor into a high quality factor (Q) microwave transmission line resonator [1]. Consider a long microstrip transmission line with many microstrip stub resonators capacitively coupled to it along its length. Each stub acts as a microwave cavity with a unique resonant frequency determined by its length—slightly different from any of the other stubs. The idea is to excite this array of resonators with a comb of microwave probe signals tuned to each resonant frequency. Frequency domain multiplexing will be a natural consequence of the uniqueness of each resonance frequency. The transmitted amplitude is then measured down stream of the resonator. The decrease in the number of Cooper pairs and the accompanying change in the surface impedance of the superconducting transmission line resonator lead to a decrease of both the resonant frequency and Q. Precise measurements of these changes are easily and accurately made by comparing the phase and magnitude of the probe signal amplitude to the transmitted signal amplitude with an in phase-quadrature (IQ) mixer, for example.

We believe a KI phonon sensor would allow us to meet the scientific need for a larger scale experiment because of the following reasons:

- It allows multiple detectors, each comprised of multiple independent resonators, to share a common signal source, a common pre-amplifier and common single wiring. This reduces the complexity of readout.
- We believe a microstrip configuration, where quasi-particles are sensed in a featureless "ground plane" deposited on the absorber by a sensor wafer affixed above the ground plane allows us to separate the absorber function from the phonon sensor function (Fig. 1). The probe wafer is simply pressed against the absorber by a uniform pressure device.

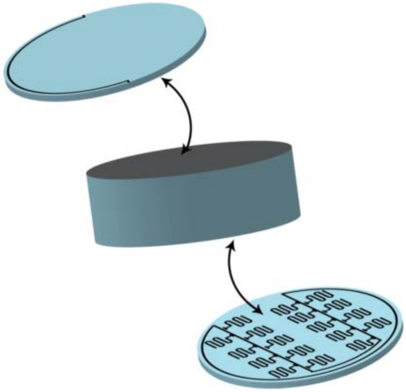


Fig. 1 (Color online.) Separation of function: resonators are patterned onto a standard sized wafer, which is then affixed to the thick absorber substrate. The absorber receives minimal processing

– The KI sensors we envision are more robust to fabrication variations because they are not operated at a sharp transition, but rather a temperature much lower than the critical temperature (a tenth). Also, this structure avoids the necessity of doing lithography on the thick absorber substrate.

2 Experimental

We have constructed devices which tests the concept (Fig. 2). Half-wave resonators are patterned on one side of a silicon or sapphire wafer (∼500 μm thick). A microstrip "through line" is pattered on the other side of the wafer. A second wafer, serving as the ground plane, receives a blanket metal coating. The width of the through line is calculated so that, when the sensor wafer is suspended over the ground plane at the desired separation, the through line is 50 Ω to match our readout circuitry. The resonators are simply metalized strips with both ends open. One end is positioned under the through line to capacitively couple the resonator to the through line. We characterize the strength of the coupling with a coupling quality factor parameter, Q_c. By tuning Q_c, we can obtain a desired total Q and signal bandwidth. For the dark matter search, we would need our resonances to have a bandwidth of ∼150 kHz.

For the test devices, the separation between the ground plane and resonators is maintained by pieces of metallic foil (Fig. 2), which are carefully placed far from the resonators. (The foil is about 6 μm thick). The actual separation is consistent with 7 μm based on the observed resonant frequencies. Since a smaller separation would be preferable, future devices will have 1 to 3 μm tall metal pillars fabricated on to them.

Our films are made of either niobium or aluminum with 2% silicon. These materials are sputter deposited at $<5 \times 10^{-7}$ torr with argon process gas and their measured transition temperatures are consistent with high purity material. We use aluminum for the ground plane because of its low gap and niobium is used for the through line and the resonators (Fig. 2). At very low temperature, and in the absence of excess noise [2], the signal to noise of a kinetic inductance sensor is proportional to the current in the resonator structure. (This leads us to use niobium, which has relatively high critical current and T_c, to define the resonators and the through line.)

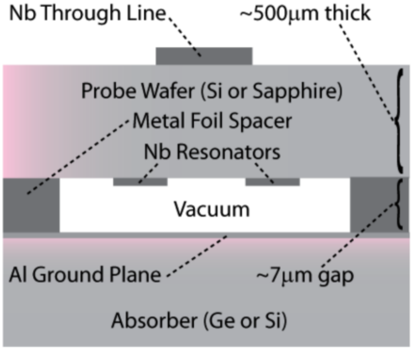


Fig. 2 (Color online.) Cross section view of kinetic inductance phonon sensor test device. The probe wafer, containing the resonators, is suspended above the absorber using metal foil spacers

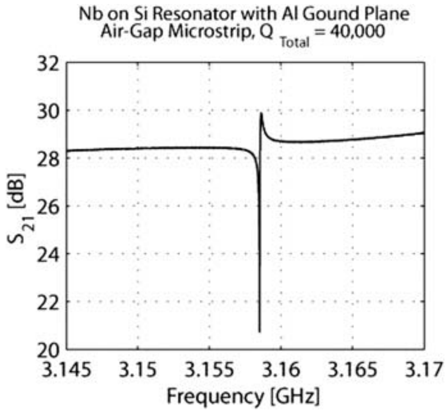


Fig. 3 Resonance measured from vacuum microstrip test device at ∼50 mK

3 Results and Discussion

As a proof of principle for the vacuum microstrip sensor design, we report that devices faithfully display resonances (Fig. 3). These resonances have resonant frequencies that typically come within 5% of the designed resonant frequency. Although we have yet to obtain close agreement between the measured Q and the designed Q, we have demonstrated much lower and much higher than what is needed for our signal bandwidth in the range of resonant frequencies we have explored, 0.5 GHz to 4 GHz. We also report that these devices have been made to work within the existing (test) apparatus of the CDMS experiment, which only increases their attractiveness and applicability.

Data taken from a niobium on silicon device with aluminum ground plane, resonant frequency 3.16 GHz, and $Q \sim 40{,}000$ gives insight into the noise of our vacuum microstrip design. It has been found by our colleagues at Caltech/JPL that coplanar waveguide (CPW) resonators with high-Q (several hundred thousand) and small features (center strip to gap ratio 3 µm:2 µm) exhibit excess phase noise, probably from two-level systems on the surface of the device [2]. They find the phase noise to be more than a factor of 100 higher in noise power than the magnitude noise. As shown in (Fig. 4), our vacuum microstrip devices do not show such a large separation between phase and magnitude noise; the noise in both signals is close to the HEMT

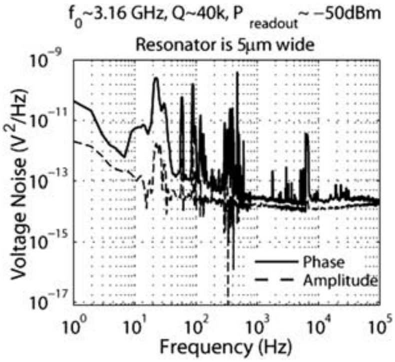
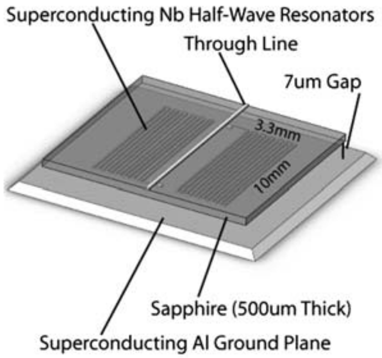


Fig. 4 Phase and Amplitude noise from resonance depicted in Fig. 3. The spectrum is consistent with no excess phase noise



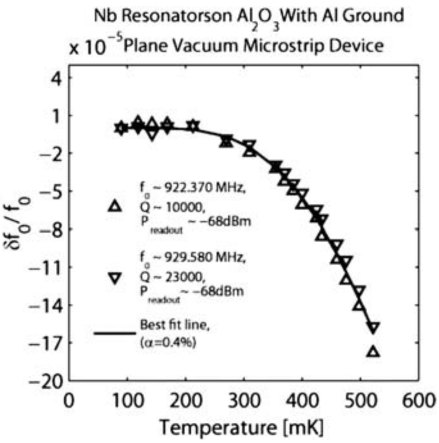


Fig. 5 *Left*, schematic of device from which data is taken. *Right*, fractional frequency shift of resonance as a function of temperature for two different resonators

noise floor. (We attribute the small separation in noise levels in (Fig. 4) to the HEMT.) Since our devices are much larger in geometry and have a lower Q than these CPW devices, both lower responsivity and lower noise in comparison to CPW devices are expected. For this reason, the data in (Fig. 4) is not sufficient to tell if there are two-level systems in our microstrip devices. We speculate, however, that our devices have little sensitivity to two-level systems existing on the exposed surface or in the bulk of the probe wafer, but would be susceptible to two-level systems in the oxide layer on the metals. This is because in the vacuum microstrip architecture, the electric field is mostly confined in the vacuum between the resonators and the ground plane, rather than spread into the probe wafer substrate. In the future, we plan to explore the noise character of our devices by looking at small geometries and higher Qs.

We tested a device with niobium resonators on sapphire substrate using an aluminum ground plane, which displayed resonant frequencies around 925 MHz. To estimate the responsively, we graph the decrease in resonance frequency as the temperature is increased (Fig. 5). The curve determines the kinetic inductance fraction [3], α, which we use to calculate responsivity, expressed as the change in transmitted voltage amplitude *phase* (in radians) per quasi-particle using (1) [4]. The change in the transmitted voltage amplitude *magnitude* change per quasi-particle, which we would also measure, is significantly less than the phase change. The fitting of the data in (Fig. 4) leads to

$$\frac{d\theta}{dN_{qp}} = 4 \times 10^{-7} \frac{\alpha Q}{V} \approx 5.3 \times 10^{-12}. \quad (1)$$

For a given amplifier noise, the ultimate resolution of this resonator depends on three factors: (i) the maximum biasing current that it can handle before non-linear behavior emerges; (ii) the presence of excess noise such as the two-level systems (quasi-particle generation-recombination noise should be negligible at our temperature); (iii) the quasi-particle lifetime. We have not yet systematically investigated these parameters. We can, however, provide the following estimate. We assume, conservatively, a lifetime of 100 μs. It is reasonable to assume that, like the first resonator described, there is no discernable excess noise with the 4 K noise amplifier that we are using. At the input power of −68 dBm used to take the measurement shown in (Fig. 5), this 33 mm^2 device would have a r.m.s energy resolution of 3 keV. We have not seen significant distortion of the resonance at an input power of −40 dBm. If no additional noise were created by this larger bias, the energy resolution would be ∼100 eV, in comparison to the ∼80 eV per quadrant resolution achieved by the current CDMS detector. This begins to be in the region of interesting sensitivity for a dark matter detector and it gives us strong incentive to pursue this approach and explore its limits.

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