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Development of an Inductive NIS Thermometer

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Abstract. We have studied an inductive readout for normal metal-insulator-superconductor (NIS) tunnel junctions by using on-chip planar inductors and a DC SQUID (superconducting quantum interference device) to develop a sensitive and fast thermometer for studies of nanoscale heat conduction and bolometry. Our initial results show the feasibility of the concept, with a good sensitivity for temperatures below 1 K for aluminum as the superconductor when voltage biased close to the superconductor energy gap.

1. Introduction

The desire for sensitive bolometers has encouraged people to develop fast response, low temperature and nanoscale normal metal-insulator-superconductor (NIS) tunnel junction thermometers which can easily be integrated into antenna and absorber structures to form the bolometer structure [1–3]. Such a device has strong temperature-dependent current-voltage characteristics, submicron size, low self heating and natural bandwidth up to few MHz[4], and has been used extensively in studies of low-temperature thermal transport [5–7]. It is also an attractive candidate for far-infrared bolometry applications [8].

However, in all previous applications the NIS thermometer is working under constant current bias with a measurement of the temperature dependence of the voltage (or resistance) across the tunnel junction $V(T)$ [9]. In contrast, in this study we have fabricated a novel on-chip sub-Kelvin symmetric SINIS thermometer, which is biased with DC voltage and read out using four on-chip planar inductors to amplify and inductively couple the current signal to a DC SQUID mounted on the 1 K stage of the refrigerator. By using this method, we can measure the conductance bias and the temperature dependence of the conductance of the NIS tunnel junctions above audio frequency range and pre-amplify the signal before the SQUID.

2. SINIS thermometer

The basic principle of a NIS thermometer is based on the existence of the energy gap Δ of the superconducting electrode. Ideally, at $T \to 0$, for low bias voltage $|eV| < \Delta$, electrons cannot tunnel from the occupied states of the normal metal to the superconductor because of the energy cost of creating quasiparticle excitations. However, when $eV = \Delta$, quasiparticle injection becomes possible and tunneling current will first sharply increase and then becomes linear as a function of V. For $T > 0$, the presence of thermally excited electrons in the normal metal allows some electrons to tunnel at a lower voltage, giving an exponential tail of the current in the region below $eV = \Delta$. This tail can be used in sensitive thermometry.

In practice, typically two NIS junctions are used in series symmetrically (SINIS) in order to double the signal responsivity, and thus the tunneling current can be written as [10]:

$$I(V,T) = \frac{1}{2eR_T}\int_{-\infty}^{\infty} n_S(E)[f_N(E - eV/2, T_N) - f_N(E + eV/2, T_N)]dE \tag{1}$$

where $n_S(E)$ is the superconducting density of states (DOS) given by BCS theory, $f_N(E)$ is the Fermi-Dirac distribution of the normal metal island, T_N is the temperature of normal metal, V is the voltage bias across both junctions and R_T is the tunneling resistance of a junction, independent of V and T.

From the equation we can see that the $I-V$ characteristics, and therefore also the conductance $G(T)$ of the tunnel junction, are related to the temperature of the normal metal. This dependence is normally measured under a constant current bias by measuring the voltage response with a differential voltage amplifier at room temperature [6]. In this experiment, we instead bias the SINIS tunnel junction with constant voltage, and then apply an 26 kHz frequency excitation signal across the tunnel junction, and measure the conductance directly using a lock-in amplifier, with an inductively coupled SQUID amplifier at the 1 K stage as a preamplifier stage, as shown in Fig.1. The potential benefits of the SQUID readout are: (i) increased sensitivity due to the low-temperature preamplifier stage (ii) increased read-out bandwidth, as capacitive loading of the wiring is reduced, and (iii) reduced external noise heating radiated down from the read-out circuit. This last issue is typically limiting the operational range of SINIS thermometers to > 100 mK if no strong measures are taken to filter the high-frequency noise.

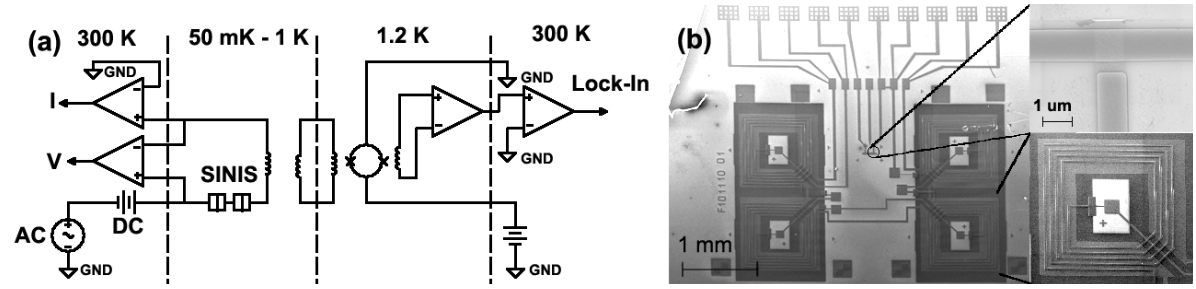

Figure 1. (a) Measurement setup for this experiment. AC and DC voltage signals are applied to the SINIS tunnel junction. Two read outs are used, (i) direct DC read out with one current pre-amplifier and one voltage pre-amplifier to measure the DC IV characteristics of tunnel junction (standard way), (ii) DC SQUID read out in combination with a on-chip transformer to measure the conductance of the junction using lock-in detection. (b) SEM micrograph of the sample. The upper inset shows one NIS junction, the lower inset shows the Niobium washer and coil.

3. Experiment

The SINIS tunnel junction is fabricated with conventional electron beam lithography (EBL) and shadow evaporation techniques in an ultra high vacuum (UHV) chamber into $Al - AlO_x - Cu - AlO_x - Al$ structure, with film thicknesses of 60 nm for Al and 80 nm for Cu. The junction size was 1 μm^2 and the AlO_x was formed by thermal oxidation in pure oxygen atmosphere. Four pairs of niobium input washers (thickness 60 nm) and output coils (thickness 120 nm) are fabricated on the same chip with EBL and UHV evaporation, separated by a 200 nm HV deposited AlO_x insulator layer (Fig. 1) . A thin gold layer (6 nm) is used on the niobium layer to prevent oxidization and to allow electronic connection to the SINIS tunnel junctions and bonding pads. The sample we studied has a total tunneling resistance of $R_T = 800\Omega$, with 27.4

nH output coils, 400 pH input washers and a measured coupling constant of $K = 0.83$ between them.

The sample was measured in a compact dilution refrigerator with a base temperature of about 50 mK. A two stage DC SQUID amplifier fabricated at NIST Boulder is also mounted on the 1 K stage of the refrigerator and connect to the sample stage with superconducting Nb-Ti wires and superconducting Al bonding wires on the chip [11]. A calibrated RuO thermometer is mounted on the sample stage to monitor the stage temperature, and a metallic resistor is used as a heater on the stage, so that a PID controller can stablize the stage temperature.

4. Results

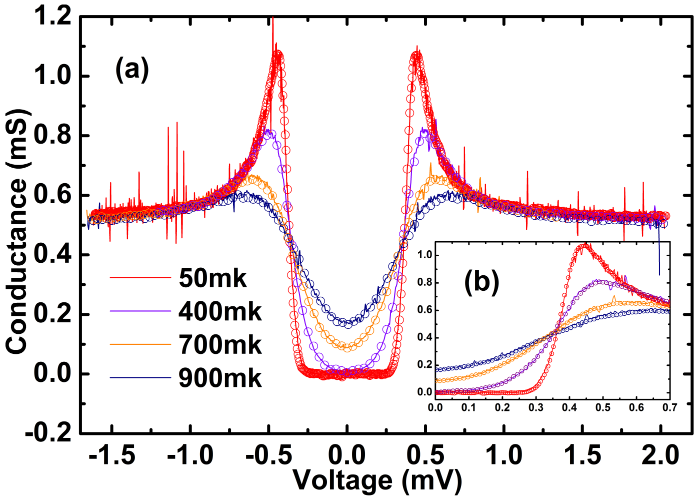

Figure 2. The temperature dependence of SINIS tunnel junction conductance $G(T)$ with varying bath temperature from 50 mK to 1 K from the SQUID and DC measurements. Different curves correspond to different bath temperatures. Open circles: SQUID measurement, lines DC measurement. Inset: Zoom-in at the useful range of V.

Figure 2 shows the results of $G(V)$ for both the standard DC measurements and SQUID measurements at four different bath temperatures between 50 mK and 1 K. The solid lines in Figure 2 are the calculated conductance curves from DC measurement (numerical differentiation) and the open circles are the SQUID measurement results. The SQUID measurement results follow extremely well the DC results for all temperatures, showing that our measurement scheme works. The inset (b) shows the same conductance data from 0.1 mV to 0.6 mV, which is the functional regime for our thermometry.

Figure 3 gives the temperature dependence of the SINIS tunnel junction conductance $G(T)$ from 50 mK to 1 K with different voltage biases from the SQUID measurement. An interesting observation is that there is a strongly temperature-dependent regime below $T < 0.2$ K with opposite responsivity (G increasing with T rather than decreasing as observed at $T > 0.2$ K) when the bias voltage is near the superconductor energy gap Δ. This part can be used as a very sensitive thermometer at temperatures lower than ~ 0.2 K. We stress that this responsivity is still good at our base temperature 50 mK, especially considering that no filters were used in the measurement wires. In contrast, in the higher temperature regime (from 200 mK to 1 K), a lower bias voltage will give a higher $G(T)$ sensitivity to the temperature, and thus one can choose it accordingly.

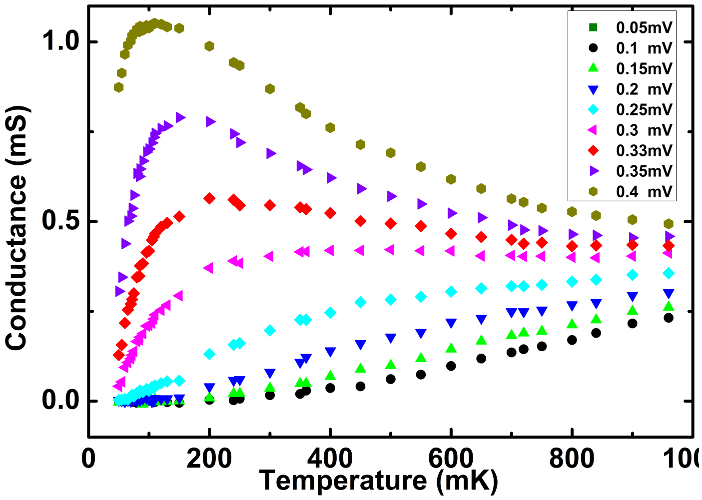

Figure 3. $G(T)$ for the SQUID measurement. Different colors corresponds to different bias voltages between 0.05 mV to 0.4 mV. 2Δ is approximately 0.45 mV.

5. Conclusions

In conclusion, we have fabricated a SINIS tunnel junction thermometer with an integrated on-chip inductive readout coupled with a sensitive SQUID amplifier. Our data indicates that it is feasible to use this scheme to directly measure the conductance of SINIS tunnel junction at audio frequencies. The frequency of operation of this type of device is not limited to audio frequency range, but could possibly be extended to RF (up to few MHz), where limitations of SQUID amplifier and SINIS internal thermal time constants are met.

Acknowledgments

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