Nanokelvin DC and AC Meissner-Transition-Edge Temperature Detectors

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Abstract: Based upon a superconducting transition edge sensor (TES), the Meissner-TES is a relatively new type of high resolution cryogenic thermometer which employs the magnetic transition of a superconductor to measure temperature. We have improved the signal-to-noise for DC sensing by a factor of 30 compared to our prior effort, and developed a new AC mode which uses an oscillating magnetic field and lock-in technique with much lower magnetic noise than the DC mode. The thermometer was tuned *in situ* over a range of operating temperatures 10 to 50 times larger than the transition width of the superconductor, using an applied persistent magnetic field. The DC mode can have sensitivity better than 1 nK for 100 s averaging, and the AC mode has sensitivity better than 120 nK for very small applied magnetic fields near 14 nT and 100 s averaging. The Meissner-TES can be applied to high resolution temperature control, high sensitivity infrared sensing, optical power scale realization, and the study of temperature-dependent phase transitions.

I. INTRODUCTION

Temperature detectors with nanokelvin sensitivity at low temperatures have been realized using the sharp changes in temperature associated with the magnetic or superconducting transitions of appropriate material systems. High resolution thermometry (HRT) exploits the Curie point of paramagnetic salts [1,2] and transition edge sensors (TES) provide high sensitivity within a superconducting transition [3-6]. Other superconducting devices such as kinetic inductance detectors [7,8] have also been developed for photon detection, but have not yet been as widely applied to thermal measurement and control. The ability of these sensors, particularly TESs, to measure extraordinarily small amounts of dissipated heat (~ 10^{-20} W) can be used to discriminate single photons [3], single electron-hole pairs [4], and potentially dark matter [5]. Transition edge sensors have also been used for fundamental tests of quantum mechanics [6], and can be coupled with separate optical absorbers to enable high sensitivity photodetection over an ultra-broad spectral range from the UV to the THz [9,10].

A significant limitation of TESs is that they only exhibit high sensitivity within the very narrow temperature range of the superconducting transition, which can be 10 mK in width or less. What this means is that for every temperature of interest a different TES must be developed, made using different materials or fabrication parameters. The transition of a TES is typically measured resistively, but we have recently demonstrated a prototype Meissner-TES device, where the transition is monitored magnetically [11]. In that earlier work, we suggested that the Meissner-TES could be tuned for operation over a range of temperatures using magnetic field, and in this work we present results from the first practical implementation of this type of TES, successfully operating the newly designed detector over a range much larger than the superconducting transition width. The Meissner-TES also has the advantage that the superconducting sensing element is electrically and thermally isolated from the bias and readout circuits, allowing for better mitigation of several common noise sources. Compared to a resistive TES measurement, Johnson noise associated with the TES electrical resistance, Joule heating from current across the TES, and direct thermal conduction from bias wires are reduced.

Here we provide data on Meissner-TES devices with greatly expanded functionality, in both DC mode and a newly-realized AC measurement mode. Responsivity and noise data show that this tin-based thermometer achieves nanokelvin sensitivity in DC mode from 2.76 K to 3.71 K, a temperature range 50 times larger than the zero-field transition width of tin, by tuning the transition with applied DC field. The data exhibit the lowest temperature noise floor for the DC measurements, but the AC mode can provide high temperature sensitivity using a magnetic drive field more than 100 times smaller than that used in DC mode. The applicability of the Meissner-TES extends beyond temperature sensing or control at a fixed temperature: its tunable temperature range of operation and noise tolerance in DC and AC modes make it attractive for adjustable temperature control at different setpoints, high resolution measurement of optical power over a wide range of powers, and potentially quantitative thermometry.

II. EXPERIMENTAL PROCEDURE

The magnetically-sensed TES is composed of a tin-wire transition element wrapped in one coil of a NbTi gradiometer pickup coil pair, which is attached to the input coil of a Superconducting Quantum Interference Device (SQUID). The tin wire provides a large magnetic response as temperature changes within the superconducting transition of the tin, the gradiometer reduces the effects of external electromagnetic signals on the thermometer, and the SQUID provides high gain amplification of the sensed field to voltage. In low fields around the superconducting transition temperature (T_c) near 3.71 K, the tin wire has a magnetic transition width of 18 mK, where transition width is defined to extend from 10 % to 90 % of the total signal change. The gradiometer pickup coils, separated by about 1 mm, register zero net signal for magnetic fields which vary on spatial scales significantly greater than 1 mm, effectively minimizing pickup of background noise sources from outside the cryostat. The voltage signal from the SQUID can be related to the magnetic flux passing through it; the relationship for our experimental configuration was approximately 2.85 V/Φ_0, where Φ_0 is a fluxoid (or flux quantum) equal to $\frac{h}{2e} \approx 2.07 \times 10^{-15}\ \mathrm{T \cdot m^2}$. The flux-to-volts relationship was determined by measuring the average flux jump size when the SQUID control circuit was reset.

A schematic of the experimental apparatus is provided in Figure 1. The new experimental apparatus starts from a base configuration similar to that described earlier for the Meissner-TES [11] with a number of improvements to expand functionality and increase sensitivity. First, an extra electromagnetic drive coil has been added around the thermometer to enable an AC, or susceptibility, mode of measurement. Second, components near the sensing element which were made of copper in the original design have been replaced with sapphire or G-10, in order to reduce eddy current noise. Third, signal has been boosted by increasing the number of gradiometer coil turns around the tin element. In addition, a number of practical improvements were made: the diameter of the DC drive coil has been increased to provide a more uniform magnetic field at the Meissner-TES, the superconducting circuit for the drive coil has been made more modular with Nb pad junctions, and the reference thermometers on the primary thermometry platform and the heat sink have both been fully calibrated over the temperature range of interest.

In the DC mode of measurement, a large uniform DC magnetic field is applied to the tin TES core using a surrounding NbTi solenoid. The solenoid is connected to a persistent current switch, which can be heated and subsequently cooled to induce a low-noise persistent current in the coil. A SQUID reset circuit employing feedback with two digital acquisition boards allows recording of large multi-fluxoid response with slew rates as high as 10^4 fluxoids/s [12]. Improved responsivity of this mode has resulted in 30-fold higher temperature sensitivity at DC than previous work. In the AC mode of measurement, a spatially uniform AC magnetic field is applied to the TES core using a second NbTi solenoid, driven by an oscillating current source with frequency in the 10 Hz to 1 kHz range. The AC mode senses a change of susceptibility as the tin sweeps in temperature within its superconducting transition. The AC mode provides a noise advantage over the DC mode because the SQUID noise floor is at least two orders of magnitude smaller than at DC for all frequencies above 10 Hz, and lock-in techniques can be used to select operation frequencies which have the smallest external noise. Measurements of thermal response and magnetic noise were made to quantify thermal sensitivity for both DC and AC modes. For quantifying thermal response, the SQUID signal was measured throughout the superconducting transition while a nearby calibrated resistance thermometer recorded temperature. The DC noise was determined from the standard deviation of repeated voltage measurements; lock-in amplifier and spectrum analyzer measurements were used to quantify AC noise. All data were gathered with the experimental apparatus attached to the cold plate of a pumped liquid helium cryostat. Measurements were made in a typical laboratory space, not in an electromagnetic screen room.

Figure 2 shows schematics for the magnetization of a Type I superconductor (e.g., Sn, Pb, Ta, In, Al) as a function of temperature (with applied magnetic field fixed) and applied field (with temperature fixed). A sharp transition in temperature, as flux is expelled from the superconductor near the transition temperature T_c, provides high sensitivity to temperature changes (as shown in "part a" of the figure). Below the transition region the response is perfectly diamagnetic in the ideal case, and above the transition response is nearly zero. Within the transition the magnetization has a negative slope with respect to field (as shown in "part b" of the figure), is nearly linear for small fields, and falls to zero above a critical field H_c. In the DC mode, magnetization is measured at a large fixed applied field, and the difference in this magnetization at different temperatures provides a relative temperature scale. In the AC mode, a small field oscillation with amplitude ΔH is applied and the response $2 \cdot \Delta H \cdot \chi(H,T)$ is measured, where $\chi(H,T)$ is the magnetic susceptibility of the superconductor. Measurements at different temperatures in AC mode probe the temperature-dependent susceptibility of the Sn core.

III. RESULTS AND DISCUSSION

A. DC mode results

The results of DC mode measurements, exhibiting high thermal sensitivity tunable with magnetic field, are shown in Figure 3. The y-axis parameter in the plot is the net flux Φ threading the pickup coils of the SQUID, given in units of fluxoids Φ_0, the natural unit for SQUID magnetometry. The x-axis parameter is the temperature measured by the calibrated reference thermometer concurrently with the SQUID measurement. As the current in the DC solenoid coil is increased from 1 mA to approximately 150 mA, the center of the tin superconducting transition was depressed from about 3.71 K to about 2.76 K. The field within the solenoid coil scales with current as 0.114 mT/mA, so the field range tested was approximately 0.114 mT to 17.14 mT. The temperature sensitivity depends directly upon the transition width of the transition, and inversely with the total signal change over the transition. Over the field range tested, the transition width rose with increasing field from a minimum of about 18 mK to a maximum of 105 mK (inset, Figure 3), where the transition is defined to extend from 10 % to 90 % of the total signal change. The signal change depended directly upon applied current and was about 14 times larger at 150 mA than at 10 mA.

An analysis of the magnetic transition curves in Figure 3 shows that the dependence of the signal flux Φ on the temperature T for each curve is linear (correlation coefficient > 0.99) over significant fractions of the superconducting transition (33 % to 59 % of the transition width). This suggests that over these linear regions, the Meissner-TES could potentially serve as a high resolution secondary standard thermometer if calibrated at relatively sparse (approximately every 1 mK) points against a reference thermometer for the International Temperature Scale of 1990 (ITS-90). In order to establish this capability, further experiments would be required to show that the Meissner-TES response is reproducible from cooldown to cooldown and behaves predictably despite its magnetic history. Furthermore, the slope of the linear region of the Φ-T transfer function depends on applied magnetic field, so this slope must be determined at each temperature range of operation.

B. AC mode results

The noise in a temperature measurement is a combination of the SQUID detector noise and other internal and environmental noise sources, including stray electromagnetic fields, microphonic noise, change in optical load, and temperature fluctuations. The detector and environmental noise can be two orders of magnitude larger near DC than at higher frequencies, and the effect of thermal noise is much stronger within the superconducting transition than away from the transition because the magnetization-temperature gain is much higher within the transition. Although the noise at DC can be much higher than for AC, the signal-to-noise ratio (SNR) at DC can still be superior because much larger fields can be sourced. Complete details on the noise and SNR analysis are include in Section C immediately below.

The AC mode results also display a very sharp change in the magnetic signal near the transition temperature of tin, and the output noise spectrum from the SQUID displays a baseline more than 100 times better than DC for frequencies greater than 10 Hz. Figure 4 exhibits the differential susceptibility in a sinusoidal oscillating field with peak-to-peak amplitude of 14 nT at 105.5 Hz, with zero applied DC field. The transition center is 3.74 K and the transition width is approximately 18 mK. The onset of the superconducting transition is often at slightly higher temperatures in magnetic measurements than in resistance measurements because the magnetic signal is volume-dependent rather than dependent upon a complete path between electrodes.

C. Temperature sensitivity analysis

Frequency-dependent noise, measured two ways, is presented in Figure 5. Data from a spectrum analyzer from 4 Hz to 1560 Hz shows a gently falling noise baseline superposed by noise spikes from electromagnetic and vibrational sources. The cold experimental components are shielded by niobium and PbSn, but the experimental cryostat is operated in an unshielded environment. To achieve temperatures below 4.2 K, the helium reservoir of the cryostat is constantly pumped-on using a mechanical pump. For the AC measurements, however, one is free to select operational frequencies with low overall noise. Three relatively low-noise frequencies, marked in Figure 5, were selected for lock-in amplifier noise measurements (37 Hz, 105.5 Hz and 969 Hz), and correlate well with the spectrum analyzer data. The larger frequency bins around each frequency value for the spectrum analyzer leads to somewhat larger noise amplitudes around these minima in comparison to the lock-in measurements. Accounting for the time taken for each DC measurement, the relative noise for DC and AC measurements is compared in Figure 5, with the DC result graphed at 1 Hz. For the measurement at 1.14 mT (10 mA) in the field coil, the DC noise was approximately 1.11 mV near 2 K for 100 s averaging. The base noise level here is determined from the SQUID voltage noise away from the superconducting transition (near 2 K); additional noise in the transition is presumed to be from real thermal fluctuations.

Compared to earlier measurements (Reference 11), the calculated temperature responsivity in DC mode was improved from 5.91×10^4 V/K to 1.73×10^6 V/K near 3.6 K. This responsivity is given by:

$$R = \left(\frac{\partial \Phi_{meas}}{\partial T_{meas}}\right) \cdot \left(\frac{\partial V}{\partial \Phi}\right) \tag{1}$$

where $(\partial\Phi_{meas}/\partial T_{meas})$ is the measured slope of flux change in the transition (from Figure 3), and $(\partial V/\partial\Phi)$ is the flux-to-volts transfer function for the SQUID. The voltage noise of the SQUID output was similar in both studies, which means that the effective temperature noise has been improved by approximately 30 times, as shown in Figure 6. Taking the ratio of total flux change across the superconducting transition (from Figure 3) to the flux expected from total expulsion of flux from the gradiometer coils surrounding the Sn core, one can define a coupling efficiency for the Meissner-TES. This coupling efficiency is given by:

$$E = \frac{\Phi_{meas}^{total}}{\Phi_{max}^{SQUID}} = \frac{\Phi_{meas}^{total}}{\Phi_{max}^{input} \cdot \left(\frac{\Delta\Phi_{SQUID}}{\Delta\Phi_{input}}\right)} \tag{2}$$

where $\Phi_{meas,total}$ is the total flux change measured across the superconducting transition, $\Phi_{max,SQUID}$ is the maximum flux which could be sensed at the SQUID based on the pickup loop geometry (assuming full flux expulsion by the tin core), $\Phi_{max,input}$ is the maximum flux change through the pickup coil (assuming full flux expulsion by the tin core), and ($\Delta\Phi_{SQUID}/\Delta\Phi_{input}$) is flux produced at the SQUID per flux through the pickup coil. The maximum flux change $\Phi_{max,input} = H_{app}NA$, where H_{app} is the applied magnetic field, N is the number of pickup coil turns wound around the tin core, and A is the area of each loop of the pickup coil. In the earlier Meissner-TES design (Reference 11), the coupling efficiency was estimated to be 8.7 %, and in the data reported here we found the coupling efficiency had improved to 58.6 %. Tighter and more uniform winding of the gradiometer coil around the Sn core, as well as a more uniform magnetic field from a redesigned superconducting solenoid have contributed to this improvement in coupling efficiency. The improvement in responsivity (by a factor of ~30) has resulted from a combination of the increased coupling efficiency (by a factor of 6.7) and by the use of more gradiometer turns about the Sn core (increased by a factor of 4).

High sensitivity was achieved for the DC measurements using a tin core over a temperature range from 2.76 K to 3.71 K. Figure 7 shows the temperature sensitivity, defined as the temperature-equivalent noise level, for a measurement time of 100 seconds. The transfer function from volts to temperature ($\delta T/\delta V$) was determined from the linear region of the superconducting transition, and the voltage noise level δV_{noise} was measured for each field condition. The temperature sensitivity was computed from the product $(\delta T/\delta V)\cdot\delta V_{noise}$. Over the entire temperature range, the sensitivity is smaller than 3.3 nK, with a minimum of 0.53 nK at a persistent field of 1.14 mT, when the transition temperature is 3.65 K. At low drive fields, the signal is weak because it scales approximately linearly with field. At fields above 1.14 mT, it is found empirically that noise increases super-linearly with field, so sensitivity worsens over the range from 1.14 mT to 17.14 mT (corresponding to transition temperatures of 3.65 K to 2.76 K). Sensitivity for the AC measurements in zero DC field was approximately 1.09×10^{-6} K·Hz$^{-1/2}$, or 109 nK for a 100 s measurement. Compared to the DC results at 1.14 mT drive field, the magnetic drive signal is about 10^5 times smaller in the AC case, but the magnetic noise for equal measurement times is about 500 times smaller, leading to a signal to noise ratio (SNR) about 200 times greater for the DC case. Although the AC mode has poorer temperature sensitivity, it could be advantageous for measurements which could be perturbed by the moderately strong magnetic fields required for the DC mode.

IV. CONCLUSIONS

The Meissner-TES magnetic thermometer provides nanokelvin sensitivity and tunability over a range of temperatures. The thermometer core can be made from any superconductor with a sharp thermal transition, using an applied magnetic field to tune operation over a broad range of temperatures below the zero-field transition temperature. Such a thermometer can be used for highly stable temperature control at multiple setpoints, and potentially for highly sensitive quantitative thermometry, by interpolating between calibration points shared with a primary temperature standard. Nanokelvin thermometry can enable high sensitivity radiometers for absolute measurement of optical power [13], accurate study of temperature-dependent phase transitions [14], and research on heat transfer and fluctuations [15]. Although the AC mode of the Meissner-TES, demonstrated here for the first time, is as yet less sensitive than the DC mode, it is more practical for systems which would be perturbed by moderate magnetic fields or which suffer from high DC noise. Noise rejection through lock-in methods and lower noise away from low frequency 1/f effects permit operation at much lower magnetic fields.

References

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[12] The SQUID controller allows external reset of the feedback integrator with a TTL signal within less than 5 µs. The digital acquisition boards trigger resets whenever the SQUID output signal changes by the voltage associated with a flux change of one fluxoid (i.e., when $V_{out} > V(\Phi_0)$ or $V_{out} < -V(\Phi_0)$). In this way the gain of the SQUID can be kept high, the total change in SQUID signal can range up to the equivalent of 10^5 V, and the SQUID output can always be kept from railing at its 10 V limit.

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Figure Captions

Figure 1: Thermal and magnetic schematic for the Meissner-TES operation. Thermal linkages between experimental components are shown in red, and the SQUID/gradiometer flux circuit is shown in green. The heat sink and thermometry platform are both equipped with heaters and calibrated resistance thermometers for temperature control. Materials used for components near the gradiometer are identified by color: sapphire (blue), G-10 (orange), tin (gray).

Figure 2: Schematics for magnetization of a Type I superconductor as a function of:
a) Temperature, at a fixed applied magnetic field H_{app} and b) Applied magnetic field, at a fixed temperature within the superconducting transition. The magnitude of the field oscillation applied in the AC mode is indicated in the figure by ΔH.

Figure 3: The operating temperature of the Meissner-TES (i.e., the transition temperature of the tin core) is tuned from 3.71 K down to 2.76 K by application of a magnetic field from 0.114 mT to 17.14 mT. These fields are generated by application of persistent currents between 1 mA and 150 mA. The inset shows the increase of superconducting transition width as operating temperature was reduced.

Figure 4: For the AC mode, a sharp change in the susceptibility is exhibited at the superconducting transition temperature. For this data, the measurement frequency is 105.5 Hz, and the peak-to-peak amplitude of the applied magnetic field is only 14 nT.

Figure 5: Frequency-dependent noise for the AC mode and DC noise for the DC mode. Spectrum analyzer data from 4 Hz to 1560 Hz and three lock-in measurements are presented, demonstrating noise floor less than 10^{-4} V·Hz$^{-1/2}$ (3×10^{-5} Φ_0·Hz$^{-1/2}$) for frequencies above 10 Hz.

Figure 6: Comparison of thermal noise level in this study as compared to measurements reported in Reference 11. The thermal responsivity has been increased by approximately a factor of 30, and SQUID output voltage noise is similar, so the thermal noise floor is significantly improved, reaching values below 10^{-10} K·Hz$^{-1/2}$ near 10 Hz.

Figure 7: Thermal sensitivity (with error bars) for DC mode measurements as a function of operating temperature for 100 s averaging. For all temperatures, the sensitivity is better than 3.3 nK, with a minimum of 0.53 nK at a persistent field of 1.14 mT.

Figures

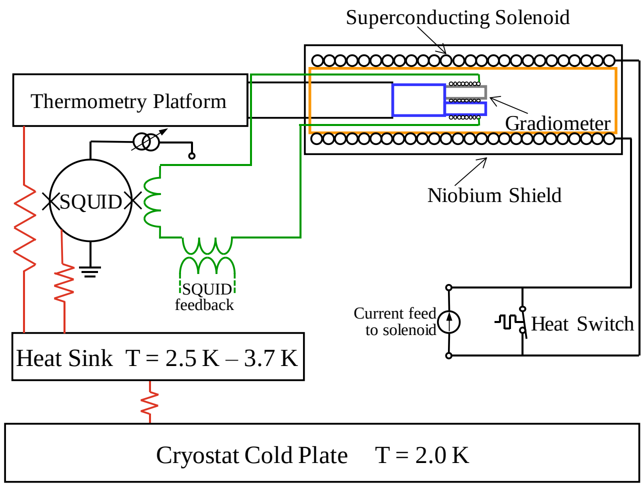


Figure 1

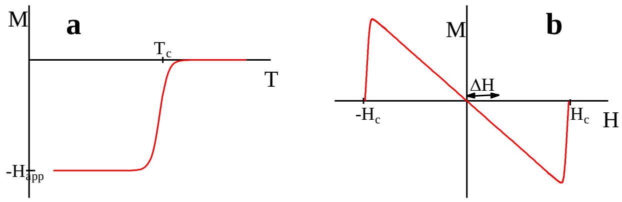
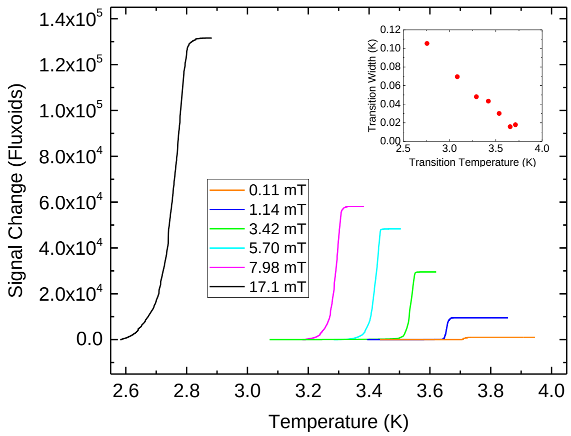


Figure 2



Signal Change (Fluxoids)
1.4x10^5
1.2x10^5
1.0x10^5
8.0x10^4
6.0x10^4
4.0x10^4
2.0x10^4
0.0
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0
Temperature (K)
0.11 mT
1.14 mT
3.42 mT
5.70 mT
7.98 mT
17.1 mT
Transition Width (K)
Transition Temperature (K)

Figure 3

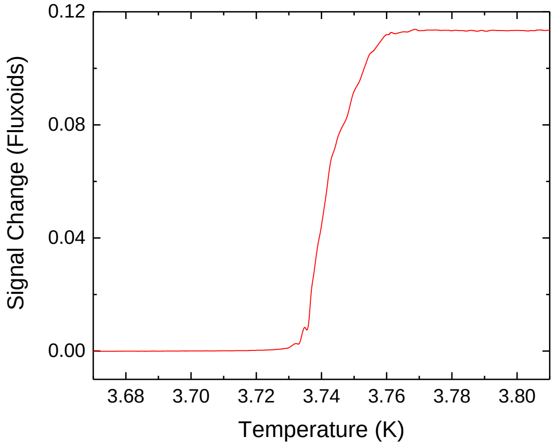
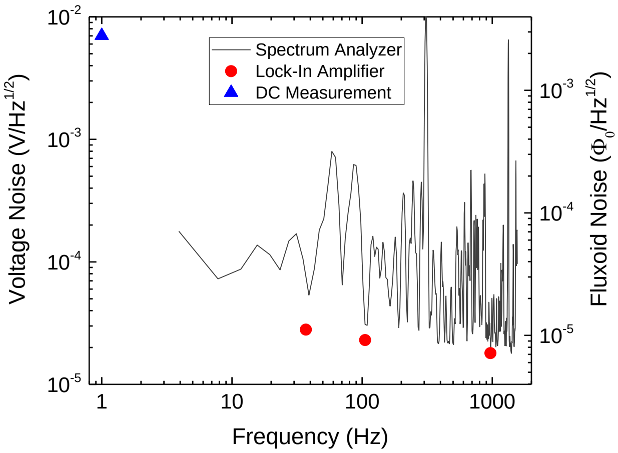

0.12
0.08
0.04
0.00
Signal Change (Fluxoids)
3.68
3.70
3.72
3.74
3.76
3.78
3.80
Temperature (K)

Figure 4



Spectrum Analyzer
Lock-In Amplifier
DC Measurement
Voltage Noise (V/Hz^1/2)
Fluxoid Noise (Φ0/Hz^1/2)
Frequency (Hz)

Figure 5

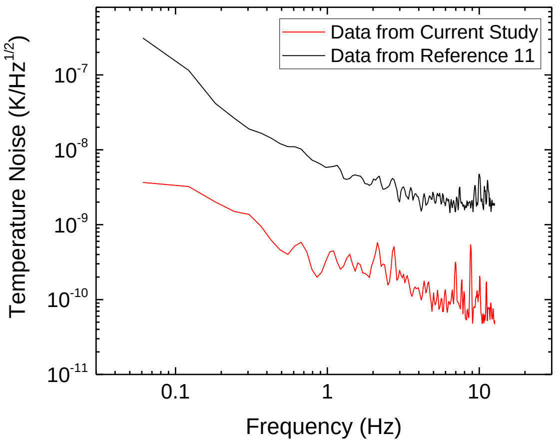

Data from Current Study
Data from Reference 11
Temperature Noise (K/Hz^1/2)
10^-7
10^-8
10^-9
10^-10
10^-11
0.1
1
10
Frequency (Hz)

Figure 6

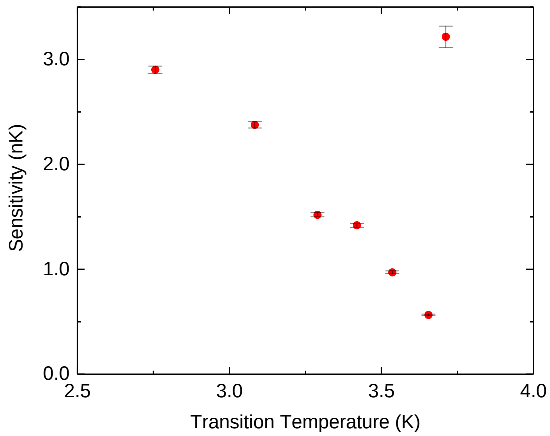

3.0
2.0
1.0
0.0
Sensitivity (nK)
2.5
3.0
3.5
4.0
Transition Temperature (K)

Figure 7