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Demonstration of a Meissner-effect transition edge sensor

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We have built and tested a transition edge sensor which monitors temperature change by measuring magnetic flux expulsion from a superconducting element. Flux change is sensed by a dc superconducting quantum interference device coupled to the element using a flux transformer in a gradiometer arrangement. The operating temperature of the sensor can be varied by application of moderate magnetic fields to the superconducting core, using an integrated solenoid. With a Sn core at 3.58 K, the thermometer has demonstrated a noise level of 2.25 $\mathrm{nK/Hz^{1/2}}$. We estimate that such a sensor will allow femtowatt sensitivity of an absolute cryogenic radiometer presently under development. [doi:10.1063/1.3456539]

I. INTRODUCTION

High resolution thermometry at liquid helium temperatures has improved significantly over the last three decades with the development of paramagnetic salt thermometers and transition edge sensors (TESs). these devices can achieve subnanokelvin resolution below 10 K, and the TES in particular has also been used for ultrasensitive measurements of incident photon energies.[1–5] Thin film TES devices can be miniaturized and fabricated in arrays in a straightforward way, and when operated in a bolometric mode with weak thermal coupling to the environment such arrays can be used for imaging with energy sensitivities down to 0.15 eV.[6] One drawback of both standard paramagnetic salt and TES devices is that they operate with highest sensitivity only over very small temperatures ranges, usually less than 100 mK.

We have been developing a new type of TES-based thermometer for use in a high sensitivity absolute cryogenic radiometer (ACR) to be used as a calibration standard for low power infrared signals. Radiometers of this type are electrical substitution devices where a physical equivalence between incident photon power and the electrical heater power required to maintain the radiometer cavity at a constant temperature can be used to define the optical power unit of the watt.[7–10] The power sensitivity of the ACR depends on the resolution of the thermometer used to measure radiometer temperature but unlike standard TES bolometers, the ACR must be designed to absorb virtually all optical radiation incident upon its receiver.

The new thermometer design uses elements from both standard TES and paramagnetic salt thermometers, and can be simply tuned for high sensitivity over a multikelvin range by application of moderate magnetic fields. The thermometer operates like a standard TES by monitoring a superconducting element as temperature changes within the width of its transition. For the ACR application, the thermometer will naturally be operated in a negative feedback mode where the thermometer will be part of a control loop with a heater used to maintain constant temperature of the ACR receiver. Closed loop operation is an ideal mode for a TES because it avoids problems arising from transition nonlinearity and narrow range of operation.

Unlike a standard TES, the superconducting transition is not monitored resistively but instead the new TES senses flux expulsion from the superconductor using a superconducting quantum interference device (SQUID), much as is done in paramagnetic salt thermometers. For an ACR, it is important to be able to measure a wide range of incident photon powers, which can require the receiver to operate over a multikelvin range of temperatures. To accommodate a wide range of receiver temperatures, the thermometer is integrated with a solenoid which can tune the transition temperature of the superconductor for operation at different temperatures. One limitation of the new thermometer is that it exhibits hysteresis in its response, so its use must be limited to applications where the temperature is ramped slowly or held constant, as it will be for our ACR. This new "Meissner-TES" thermometer tracks temperature change through flux expulsion associated with the Meissner effect.

II. EXPERIMENTAL DETAILS

A. Meissner-TES design

As with the standard TES,[4–6] the Meissner-TES achieves high sensitivity by using a superconducting element with a sharp transition and by sensing the transition with a SQUID. The SQUID gives a high gain response, with typical flux-to-voltage gain near 10^{15} $\mathrm{V/(T\,m^2)}$. By measuring the magnetic rather than resistive transition of the superconducting element, it is possible for the element to be monitored in a completely noncontact manner. This measurement mode, which requires no leads to be attached to the sensing element, allows for improved isolation of the thermometer from some common types of noise (Johnson, current, and thermal noise sources).

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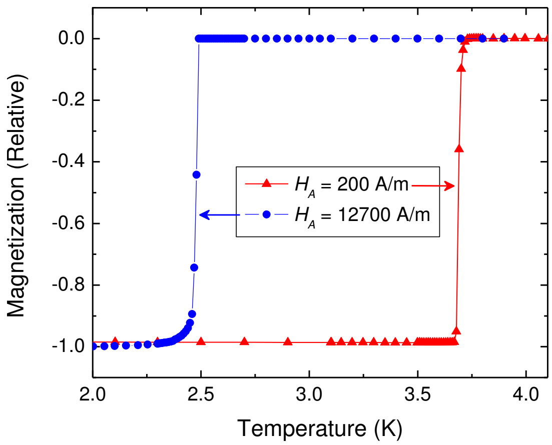

FIG. 1. (Color online) Magnetic superconducting transition for tin wire at two magnetic fields. For an applied field (H_A) of 1.3×10^4 A/m (160 Oe) applied parallel to the wire axis, the T_c is reduced from 3.7 to 2.5 K and the width of the transition remains below 30 mK.

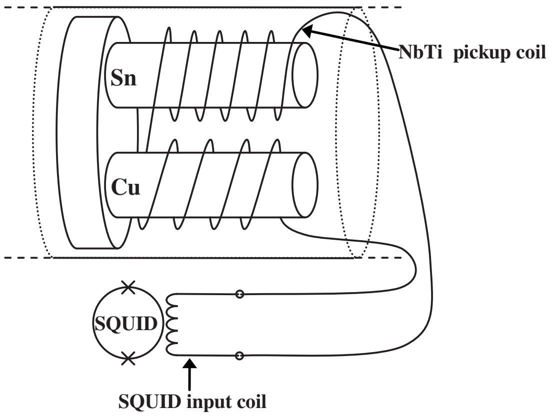

FIG. 2. Schematic of the gradiometer geometry used for the Meissner-TES pickup coil. The pickup coil is made of superconducting NbTi wire and is attached to the input coil of the SQUID.

The superconducting element we used for constructing a Meissner-TES was a tin wire (99.99% pure) with diameter 0.5 mm and length 8.7 mm. Our thermometer is designed for use in a pumped helium cryostat, so the tin transition temperature (T_c) of 3.7 K is ideal for the application. Tin is a type I superconductor with a moderate critical field, so it only requires about 2.4×10^4 A/m (300 Oe) of field to lower the transition temperature from its maximum value down to 0 K. The high aspect ratio cylindrical geometry of the TES simplifies the potential problem of demagnetization effects, allowing sharp superconducting transitions to be maintained in axial magnetic fields. Figure 1 shows magnetization data on the tin wire used for the TES: at small fields the wire has $T_c\approx3.7$ K with a transition width (10%–90%) of 27 mK; at an applied field of 1.3×10^4 A/m (160 Oe) the $T_c\approx2.5$ K, and the transition width remains less than 30 mK. Maintaining a sharp transition while lowering the transition temperature means that a thermometer made using this wire can achieve high sensitivity over a range of temperatures by applying magnetic field.

In addition to the extended temperature range of the Meissner-TES, another important design element is reduction in environmental noise pickup by using a gradiometer geometry for the superconducting sensing circuit. As with paramagnetic salt thermometers, the Meissner-TES flux couples the sensing element to the SQUID by winding a superconducting wire (NbTi) around the sensor (Sn) and attaching this coil to the input coil of the SQUID. For our thermometer, the superconducting wire is also counterwound about a nearby nonmagnetic element (Cu) as shown in Fig. 2. In this way, remote sources, which generate relatively uniform magnetic fields at the Meissner-TES, will generate canceling currents in the pickup coil. It is important to note that the quality of this gradiometer is not determined by precisely matching the areas of the counterwound coils but that the gradiometer can be actively zeroed by operating at a particular user-determined temperature and field. The effective flux-containing area of the coil around the tin changes significantly within the tin transition, so by fixing the temperature at a value within the transition and changing the field on the gradiometer, one can probe the relative pickup of the two counterwound coils. For fixed temperature, the gradiometer best cancels uniform sources at a value of applied field where the SQUID output reaches an extremum (at which value the slope of SQUID output with respect to field is zero).

B. Experimental arrangement

We tested the Meissner-TES in a prototype arrangement where the basic function of an ACR using this thermometer could be evaluated. For this test, optical inputs were not used; instead, the heater on the receiver was used to apply electrical load and the response of the thermometer was monitored. The prototype arrangement is shown in Fig. 3. The heat sink on the bottom of the assembly was bolted with standoffs onto the cold plate of a superinsulated liquid helium cryostat. The receiver is a copper block attached by a thermal link (consisting of G10 legs and a copper wire) to the heat sink, and the TES is located on a copper arm extending from the receiver. There is a superconducting solenoid surrounding the TES, shown by the smaller semitransparent cylinder on the right of Fig. 3. There is a persistent current switch attached to the solenoid which allows a stable magnetic field to be maintained for tuning the transition temperature of the tin element. The larger cylinder around the solenoid is a niobium shield to protect the TES from external magnetic fields. The TES is mounted on a copper button and

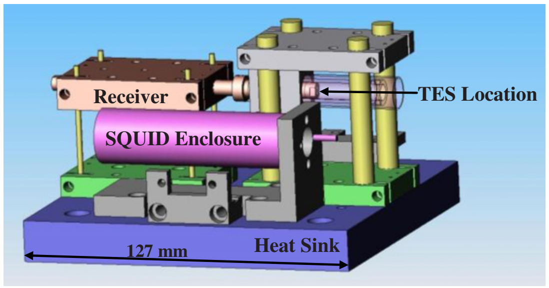

FIG. 3. (Color online) Schematic of the measurement arrangement for the Meissner-TES. Heat is applied to the receiver block, and resulting changes in temperature at the TES are monitored by the SQUID.

is comprised of NbTi superconducting wire counterwound around a tin wire and a copper wire in a gradiometer arrangement.

The NbTi leads, protected along their length from external magnetic fields by a Pb/Sn capillary, are fed to the input coil of a remote SQUID housed in a Nb tube, as shown in the foreground of Fig. 3. The SQUID is controlled in a current-locked loop using a STARCryo PC-1000 controller,[11] and tracks the flux difference through the two gradiometer coils. A fluxoid reset circuit makes it possible to run the SQUID at high gain and keep track of signals much larger than a flux quantum.

C. Estimated thermometer performance

As the temperature of the tin element changes within its superconducting transition, the susceptibility of the tin can range from 0 to −1, becoming a near-perfect diamagnet below the transition. With decreasing temperature, an increasing amount of flux is expelled from the tin by the Meissner effect. If the NbTi pickup coil is tightly wound about the tin, a significant fraction of this flux will also be expelled from the coil, leading to a change in the external flux through the coil. As the total flux through the superconducting pickup coil is conserved by flux quantization, a countercurrent must be generated in the pickup coil to exactly cancel the change in external flux. The signal sensed by the SQUID is proportional to the generated countercurrent, so the SQUID output will register any change in the flux expulsion from the tin core. A simple estimate for thermometer response can be made by considering how flux within the tin changes with temperature, and how SQUID voltage varies with change in external flux through the pickup coil.

An approximate upper limit on the Meissner-TES response can be made by considering the expected external flux difference through the pickup coil above and below the tin superconducting transition. At the upper end of the transition, the applied magnetic field can pass freely through the tin and the external flux through the NbTi pickup loop is therefore maximal, given by the area-field product of the pickup loop. At the low-temperature end of the tin transition, practically all applied flux is expelled, and if the pickup loop were in intimate contact with the superconductor, the external flux through the pickup loop would fall to zero. The maximal possible value for the external flux change through the Meissner-TES pickup coil is therefore:

$$\Delta\Phi_{\max} = (\Phi_{T_c+\Delta T_c/2} - \Phi_{T_c-\Delta T_c/2}) = H_A \mathrm{x} N \mathrm{x} A, \tag{1}$$

where ΔT_c is the superconducting transition width, H_A is the applied field, N is the number of turns in the tin pickup coil, and A is the area of a loop for the tin pickup coil. This change in external flux occurs over the width of the transition, which is approximately 30 mK. The response of the SQUID to a change in external flux through the NbTi pickup coil is:

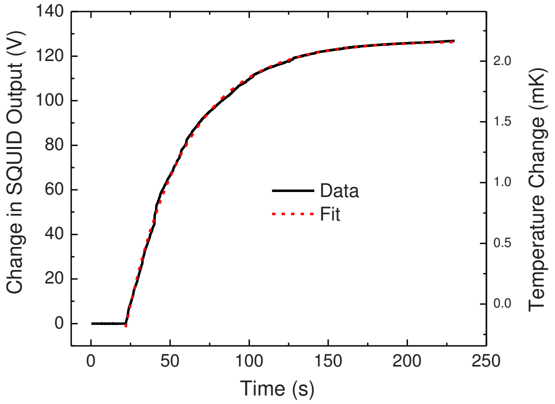

FIG. 4. (Color online) SQUID response as a function of time as the receiver was heated with 1 μW of power. The data is well fit by $\Delta V = V_{\max}(1 - \exp[(t-t_o)/\tau])$, where $V_{\max} = 127$ V and $\tau = 37.9$ s. Total change in temperature was approximately 2.15 mK, as measured by a reference thermometer on the receiver.

$$\Delta V = \left(\frac{\partial V}{\partial \Phi}\right)(\Delta\Phi_{\mathrm{input}})\left(\frac{\Delta\Phi_{\mathrm{SQUID}}}{\Delta\Phi_{\mathrm{input}}}\right), \tag{2}$$

where $\partial V/\partial\phi$ is the flux-to-volts transfer function for the SQUID, $\Delta\Phi_{\mathrm{input}}$ is the change in external flux through the pickup coil, and $(\Delta\Phi_{\mathrm{SQUID}}/\Delta\Phi_{\mathrm{input}})$ is flux produced at the SQUID per flux through the pickup coil. Assuming linear change in flux with temperature across the transition, full exclusion of field from the pickup loop below the transition, and using measured values for $\partial V/\partial\phi$ and $(\Delta\Phi_{\mathrm{SQUID}}/\Delta\Phi_{\mathrm{input}})$, one finds a maximum possible response of 6.77×10^5 V/K, using Eqs. (1) and (2) and a transition width of 30 mK. Using the maximal response value, one can calculate a minimum temperature noise for this thermometer configuration to be around 400 pK/Hz$^{1/2}$ for a SQUID with noise floor $\sim 10^{-4}$ $\phi_o/\mathrm{Hz}^{1/2}$.

Numerous factors will lower the actual thermometer responsivity below the calculated upper limit. First, not all the flux expelled from the tin will be sensed by the gradiometer. There is a nonzero distance between the tin and the coil wound about it, so it is possible for flux expelled from the tin to remain within the coil and thus not be sensed as a change by the SQUID. Second, in the compact geometry of the experiment, it is difficult to deliver a spatially uniform, axially-directed magnetic field to the TES gradiometer area. Any reduction from the peak field at the tin or misalignment with the tin wire axis will lower thermometer sensitivity. Third, if the thermometer is not tuned at the steepest part of the Sn transition, responsivity can be significantly degraded. Fourth, if care is not taken in how temperature of the thermometer is ramped, the magnetization state of the tin wire core can be caught in a minor hysteresis loop, leading to lower temperature-dependent responsivity.

III. RESULTS AND DISCUSSION

We operated the Meissner-TES with a tin core at a temperature of about 3.58 K in an open loop mode. Figure 4 shows a time trace of the SQUID response when 1 μW of power was applied to the receiver heater, a power which generated a temperature increase of approximately 2.15 mK

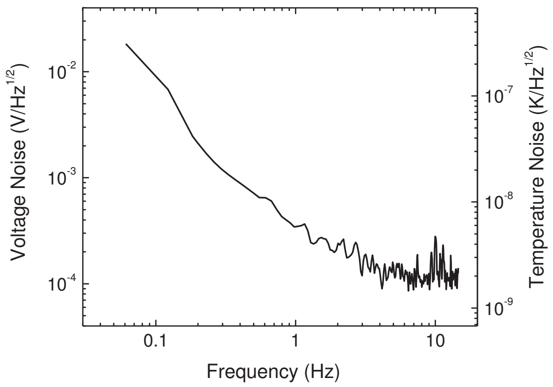

FIG. 5. Low frequency voltage noise spectrum for the SQUID as operated in the Meissner-TES. The approximate temperature noise spectrum is shown on the right axis, using the measured thermometer responsivity.

at the receiver. The receiver follows a simple negative exponential heating curve, and the data in Fig. 4 allows a responsivity for the thermometer as well as a time constant for the prototype setup to be determined. A temperature change of 2.15 mK generated a voltage change of about 127 V from the SQUID, yielding a thermometer responsivity of 5.91×10^4 V/K. The time constant for the thermal link in the prototype is about 37.9 s, made comparable to the time constants of the ACRs operated in our laboratory by design.[9]

To estimate the capability for thermal sensitivity of the Meissner-TES, a spectrum analyzer was used to measure the voltage noise of the SQUID as operated within the device. Figure 5 shows a low frequency noise spectrum for the SQUID in units of voltage on the left axis and in units of temperature on the right axis, employing the calculated thermometer responsivity. At around 10 Hz, the thermometer has a noise level of about 2.25 nK/Hz$^{1/2}$ at a temperature of 3.58 K. In our present experimental setup, overall performance is dominated at higher frequencies (20 to 1000 Hz) than those shown in the figure by vibrational noise associated with pumps and cryogen boiling, issues that will be improved in future designs.

The responsivity of the Meissner-TES is only 8.7% of the estimated upper limit, implying that considerable amounts of flux expelled from the tin core are not being sensed by the TES gradiometer or that nonideal applied field or operating point are impacting the sharpness of superconducting transition. The thermometer could be further optimized by wrapping the gradiometer coil more tightly about the tin core and testing responsivity at different points along the tin superconducting transition. Operating at lower temperatures (which are accessed using larger background fields) and increasing the number of gradiometer turns can also be used to increase responsivity and lower the thermometer noise level.

As already mentioned, the temperature-dependent magnetization curve of the Meissner-TES in the presence of an applied field exhibits hysteresis. The existence of hysteresis will affect the optimal procedure to use for changing temperature or for locating a previous temperature setpoint again after a change in temperature. One has to ensure that each time a measurement is made that the same branch of the tin core magnetization is sampled. For instance, to sample the temperature dependence of the magnetization along the limiting ascending branch of the hysteresis curve, one could lower the temperature until the Meissner-TES core is well below its superconducting transition and then slowly heat up the Meissner-TES until the desired magnetization is reached. The heating rate and control PID parameters must be chosen such that the magnetization is reached without significant oscillation.

IV. CONCLUSIONS

We have demonstrated a noise level capability in the nanokelvin range in the first experiments with a Meissner-TES. This thermometer is intended for use in a high sensitivity ACR, for which we have already demonstrated a practical thermal link with thermal conductance of approximately 2×10^{-7} W/K. We estimate that when operated in closed loop mode with such a thermal link, the Meissner-TES will be able to yield an ACR with power noise level less than a femtowatt. This level of sensitivity should be achievable for all temperatures below 3.6 K using a Sn-based thermometer. Operated at fixed temperature in a closed loop, the Meissner-TES can be fully operated within the tin superconducting transition. By fixing the transition at different temperatures with an applied magnetic field, the ACR will be able to operate over a wide range of incident photon power.

Further measurements can optimize the signal-to-noise ratio for the Meissner-TES. Using the thermometer at lower temperatures with more gradiometer turns can increase the thermometer signal. Better vibration isolation, optimized gradiometer zeroing and ac measurements can be used to further decrease the noise. For ac operation, the dc field would still be applied to set the temperature of operation (the tin transition temperature) but an ac component would also be introduced through an applied field or through oscillation of the SQUID modulation signal or bias current. It should be noted that the conditions for minimizing the temperature noise of the Meissner-TES and those for minimizing the power noise of an ACR using this thermometer have opposite ideal operating regimes with respect to thermal isolation. Temperature noise (S_T) is minimized when coupling to the bath is high because $S_T \approx \sqrt{4k_BT^2/G}$, where G is the thermal conductivity of the heat link between the thermometer and bath. Power noise (S_{ACR}) from the thermal link of the ACR is minimized when coupling to the bath is low because $S_{\mathrm{ACR}} \approx \sqrt{4k_BGT^2}$. Given these different ideal regimes, optimizing the Meissner-TES for temperature or power measurements will require different experimental configurations.

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[11] Reference is made to commercially available products to adequately specify the experimental procedures involved. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that these products are the best for the purpose specified.