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Shot noise thermometry down to 10 mK

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The authors report measurements of the shot noise thermometer (SNT), a primary thermometer based on the electronic noise from a tunnel junction, in the range from 10 to 200 mK. They demonstrate operation of the SNT down to 10 mK with 10% accuracy at the lowest measured temperature. At 10 mK, where for a measurement frequency of $f=450$ MHz, $hf=2.5k_BT$, the authors demonstrate that provided that quantum corrections are taken into account, the SNT continues to be a practical thermometer. They also show that self-heating is not a measurable problem and demonstrate a simplified readout of the SNT. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2382736]

Measurements at dilution refrigerator temperatures are complicated by the lack of easy to use and accurate thermometers which cover the whole relevant temperature range. A variety of thermometers have been developed for this range, including the Coulomb blockade thermometer,[1] the ^{3}He melting pressure thermometer, and a variety of noise thermometers. A serious problem in low temperature thermometry is the lack of practical thermometry in the range from 10 to 50 mK. We describe improvements in the shot noise thermometer[2] (SNT) that improve its applicability at temperatures below 100 mK, thus demonstrating the practicality of the SNT in this critical range just above 10 mK.

Determining the temperature from the electrical (Johnson-Nyquist) noise power of a resistor is a technique that dates back to the 1920s,[3] and that has measured temperatures from hundreds of kelvin to below 1 mK.[4] Due to the extremely small signals involved, very high gain amplifiers must be used to generate a measurable noise signal. The accuracy of the temperature measurement is limited by the accuracy with which the gain is known, placing restrictions on the type of amplifier that can be used. In order for gain to be known to acceptable levels of accuracy great care is required, and amplifiers cannot have more than a few hundreds of kilohertz of bandwidth, leading to often unacceptably slow speed. Several innovations have been devised over the years[5] to overcome this basic difficulty of noise thermometry, one of which is the SNT.[2]

The SNT is a primary thermometer in which the electrical noise from a tunnel junction is measured as a fucntion of dc bias voltage across the junction and the temperature is determined by the voltage dependence of this noise. The noise from a linear tunnel junction at frequencies such that $f \ll k_BT/h$ is described by the expression $S_I(V,T)=(2eV/R)\coth(eV/2k_BT)$.[6] In the limit as voltage goes to zero, this expression is reduced to the Johnson-Nyquist result, $4k_BT/R$,[3] and in the limit of $eV \gg k_BT$ it is reduced to the shot noise limit of $2eI$. By measuring noise at at least two bias points in the shot noise regime and at zero bias, it is possible to determine temperature, amplifier gain, and amplifier noise, circumventing the need for additional calibrations.

We previously demonstrated this thermometer from room temperature to ~30 mK. By improving the fabrication process, the sample mounting, and taking full account of the finite frequency nature of the shot noise, we now demonstrate accurate measurement with the SNT down to less than 10 mK, with an estimated accuracy of better than 10%.

For maximum cooling, the tunnel junctions used in these experiments were fabricated with large trapezoidal current leads and narrow voltage taps (see Fig. 1) using an optical double angle evaporation[7,8] of aluminum with a thermal oxidation. Each aluminum film was approximately 50 nm thick, and a 500 nm thick layer of copper was deposited onto the substrate with zero tilt angle to increase the electrical and thermal conductivities of the leads. The junctions were made close to 50 Ω in order to match the impedance of the rf transmission lines used for the noise measurement. As in previous measurements, surface mount capacitors and inductors allowed a four wire dc measurement to be carried out, while noise was measured in the band from roughly 350 to 550 MHz (see Fig. 1). A magnetic field was applied to drive the aluminum normal, although it will be possible to use manganese doped aluminum in the future, eliminating the need for a field.[9]

The shot noise thermometer sample holder was mounted at the end of an oxygen-free high conductivity copper rod at the base of a dilution refrigerator. The set temperature of the dilution refrigerator was varied while the temperature was simultaneously monitored using the SNT and a ruthenium oxide thermometer thick film resistor[10] calibrated in the range from 9 to 30 mK using a nuclear orientation thermometry and in the range from 50 to 4.2 mK against another resistive secondary thermometer.[11] The fractional calibration uncertainty of the ruthenium oxide thermometer was approximately 10% in the range where data were taken.

Each shot noise thermometer temperature reading was extracted from a fit of noise data as a function of voltage. Typical normalized plots of these data are shown in Fig 2. These data demonstrate the agreement of the SNT at finite

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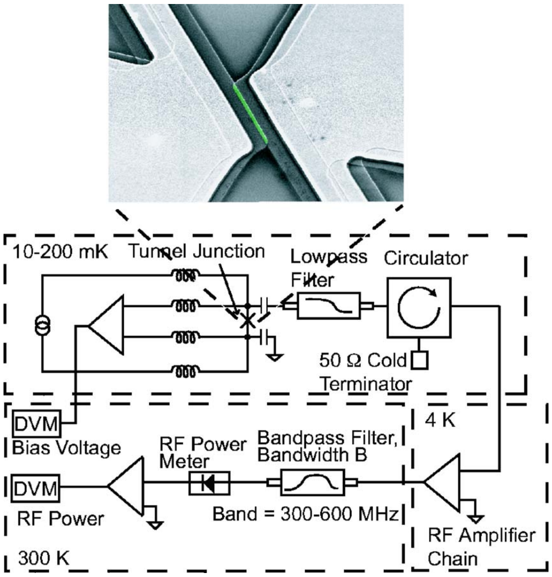

FIG. 1. (Color online) Experiment layout and schematic of zero dimensional heating model. The circulator and lowpass RF filter keep the amplifier noise from heating the junction. The inset at top shows scanning electron microscope of junction, with junction highlighted in green false color.

frequency with theory. The fit temperatures were then compared to the ruthenium oxide thermometers, as shown in Fig 3. This comparison demonstrates an agreement between the SNT and the reference thermometer, as indicated by the straight line in Fig. 3, proving the operation of the SNT down to 10 mK.

At the lowest temperatures, it is necessary to take into account that the photon energy at the measurement frequency (hf/k_B=22 mK at 450 MHz) is comparable to or larger than the thermal energy, so that quantum corrections must be taken into account to get an accurate temperature determination. The current spectral density of the noise from a tunnel junction at frequency f takes the form

$$S_I(f,V,T) = 2k_BT/R\left\{\frac{eV+hf}{2k_BT}\coth\left(\frac{eV+hf}{2k_BT}\right) + \frac{eV-hf}{2k_BT}\coth\left(\frac{eV-hf}{2k_BT}\right)\right\}, \tag{1}$$

where R is the resistance of the junction, V is the voltage across the junction, T is temperature, e is the charge on the electron, h is Planck's constant, and k_B is Boltzmann's constant. Note that in the limit of zero frequency we retain the standard form for junction noise described above, and that in the limit of zero voltage, we retain the fluctuation dissipation result of $(2hf/R)\coth(hf/2k_BT)$.[12] This frequency dependence of shot noise has been demonstrated on mesoscopic wires up to 20 GHz.[13]

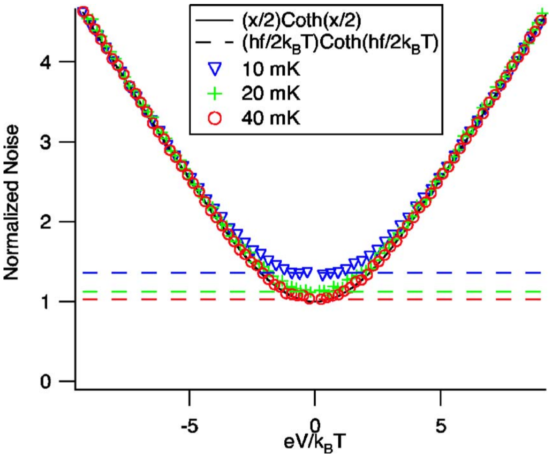

FIG. 2. (Color online) Normalized noise plots. The vertical axis is normalized to zero frequency equilibrium noise and the horizontal axis is normalized to k_BT. The rise is the zero-bias noise as temperature gets lower comes from the finite frequency of the measurement.

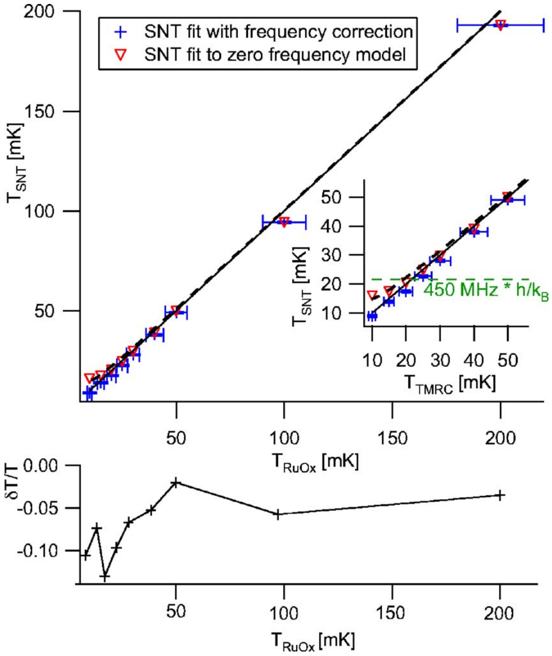

FIG. 3. (Color online) Comparison of SNT temperature to ruthenium oxide temperature. Deviation of zero frequency model shows the effect of finite measurement frequency. The horizontal error bars show calibration uncertainty of ruthenium oxide thermometer, the vertical error bars show statistical uncertainty in SNT measurement, and the dotted line shows theoretical estimate of deviation of naive zero frequency temperature fit from correct fit.

As the thermal energy falls relative to the measurement photon energy, Eq. (1) describes how the zero-point contribution to the low voltage noise is expected to become more important, causing the deviations in the voltage dependence of the noise seen in Fig. 2 and raising the apparent temperature inferred from a naive zero frequency fit. Using the correct finite frequency form [Eq. (1)] gives the correct temperature, however, as shown in the inset of Fig. 3. Even in the limit $hf \gg k_BT$, the noise from the junction could still be used to infer the correct temperature. In this limit[13] the noise from the junction will be totally independent of very low bias voltages, and will transition smoothly to the linear shot noise limit for $eV > hf$. This transition takes place at approximately $V=hf/e$, and its curvature contains information about the temperature. A fit of noise data for a large enough voltage range will still yield accurate temperature readings.

A common problem for many cryogenic electronic thermometers is self-heating. We have yet to observe measurable effects on SNT accuracy from heating, and have calculated the effects of heating, which is not measurable in the present experiment. The effect of self-heating is to cause distortions in the noise curve from the theory, which we have not observed (see Fig. 4).

In this experiment we also demonstrated a method of taking data where only two finite bias points were acquired and temperature was calculated from a lookup table. This

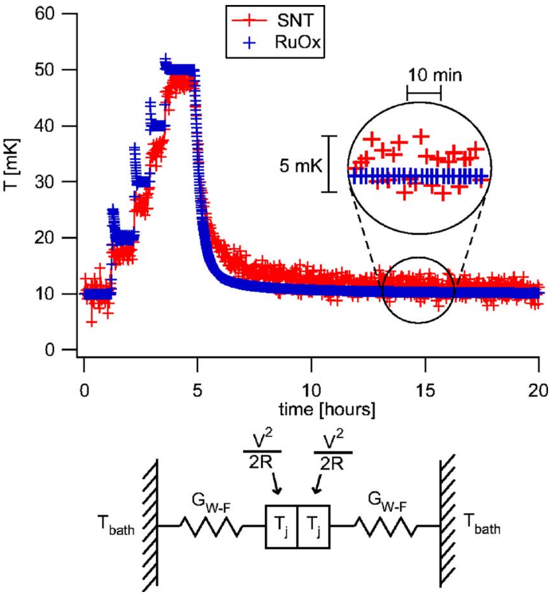

FIG. 4. (Color online) Comparison of thermometer time series. SNT temperature tracks the ruthenium oxide temperature, with different time constants because they are on different parts of the cryostat. Bottom illustration depicts our one-dimensional heating model. Wiedemann-Franz thermal conductance scales with temperature, as does the required bias voltage to make a temperature determination, and so the fractional temperature deviation remains constant. The lead resistance in SNT junctions is typically less than a part in a thousand of the junction resistances, making this a very small effect.

real-time temperature measurement gave a $7\ \mathrm{mK}/\sqrt{\mathrm{Hz}}$ statistical uncertainty, and could easily be incorporated into a microcontroller chip that would make a small and fast self-contained readout box for the SNT practical. A time series of temperature taken in this way is shown in Fig. 4.

In conclusion, we have extended the accurate range of the SNT down to 10 mK, have demonstrated that self-heating is not an observable problem at these levels of accuracy, and have developed a way of taking data that increases the usability of the SNT. Having demonstrated better than 1% accuracy in the range from 5 to 30 K,[14] we also believe that with comparison against higher accuracy standards the accuracy of the SNT could be improved without changing any other aspect of the experiment, and that presently observed deviations in the temperature are purely artifacts of the secondary thermometer calibration. We see no reason that the SNT should not continue to work at still lower temperatures. This work positions the SNT as a very practical thermometer for operation over the full range of dilution refrigerator temperatures.

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