Proximity effect thermometer for local temperature measurements on mesoscopic samples

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Using the strong temperature dependent resistance of a normal metal wire in proximity to a superconductor, we have been able to measure the local temperature of electrons heated by flowing a dc current in a metallic wire to within a few tens of millikelvin at low temperatures. By placing two such thermometers at different parts of a sample, we have been able to measure the temperature difference induced by a dc current flowing in the sample. This technique may provide a flexible means of making quantitative thermal and thermoelectric measurements on mesoscopic metallic samples.

74.80.Fp, 74.25.Fy, 74.80.-g, 74.80.Dm

For many experiments on mesoscopic metallic samples, the issue of determining the effective temperature \( T_e \) of the electrons at low temperature is of critical importance. This is because it is \( T_e \) which determines the electronic properties of the system, and not the temperature \( T_b \) of the thermal bath in which the sample is placed. With an energy input into the electron gas, the difference between \( T_e \) and \( T_b \) can be large, particularly at low temperatures, where the rapid decrease in the electron-phonon interaction means that the electron gas is out of equilibrium with the phonon bath. Hence it is not possible to determine the electron temperature by conventional low temperature thermometers (which are typically well coupled only to the phonon bath), and the need arises for thermometers which directly measure the electron temperature.

In samples whose dimensions are much shorter than the electron-electron scattering length \( L_{ee} \), the electron system itself may not be in equilibrium, so that the question of the effective electron temperature is not a valid one. This was elegantly demonstrated in a recent experiment by Pothier et al., who measured the nonequilibrium electron distribution function in a short metal wire using mesoscopic superconductor-insulator-normal metal (SIN) junctions. For samples whose dimensions are longer than \( L_{ee} \) but shorter than the electron-phonon scattering length \( L_{ep} \), however, one can think about a position dependent electronic temperature \( T_e \) which can be substantially different from \( T_b \). Previous techniques to measure \( T_e \) have included correlating the temperature with the Johnson noise measured across a sample, utilizing the temperature dependence of the weak localization contribution to the magnetoresistance, or measuring the current voltage characteristics of a metallic system weakly coupled to a superconductor.

In this Letter, we describe a thermometer which makes use of the large temperature dependent resistance of the superconducting proximity effect to measure the temperature at different points of a complex mesoscopic sample. In contrast to techniques utilizing noise measurements or weak localization, which only measure the average temperature over relatively long samples, this thermometer can measure the electron temperature over size scales as small as \( \sim 100 \) nm. Consequently, one can determine the gradient of the electron temperature in a mesoscopic sample, which may prove useful in making quantitative thermal and thermoelectric measurements on mesoscopic samples.

FIG. 1. SEM images of device structure. (a) Large area layout. Al structures are outlined with dashed lines for clarity. The wide V-shaped wire with contacts marked \( I_{dc}\pm \) which runs left to right at the top is the heater. (b) Closeup view of top thermometer. (c) Closeup view of bottom thermometer.

The samples for this experiment were fabricated using standard multi-level electron beam lithography techniques. Figure 1 shows a scanning electron micrograph of one of our samples. The design of the samples was driven by our ongoing experiments on the width depen-
dence of the thermopower in mesoscopic Kondo wires, which will be described in detail elsewhere. The bright regions in the micrograph of Fig. 1(a) correspond to a 51 nm thick Au film which was deposited in the first layer of lithography. After implantation of this entire layer with Fe ions to a concentration of ~100 ppm, a 75 nm thick Al film was deposited to form the proximity effect thermometers (the Al film is outlined by dashed white lines for clarity). The sample consists of a number of wires which meet at a central node. The 0.36 µm wide V-shaped wire at the top of Fig. 1(a) is the heater wire through which a dc current can be driven to raise the effective temperature \(T_e\) of the electrons at the node above the bath temperature \(T_b\). From the node, six wires of different widths radiate downward, each terminating in a large circular pad. These are the samples for the width-dependent Kondo thermopower experiment, and they include a 0.35 µm wide control wire which runs vertically from the node to a circular pad at the bottom of the micrograph.

In this sample, there are two proximity effect thermometers which are shown in greater detail in Figs. 1(b) and 1(c). The first, which we will denote the top thermometer (Fig. 1(b)), is attached to the top of the node. It consists of a ~0.5 µm long AuFe wire with five terminals. One terminal is connected to an Al film which provides the superconducting reservoir for the proximity effect. The remaining contacts are used for making four terminal resistance measurements on the wire. These contacts are connected to the wire bonding pads by superconducting Al lines. Since the superconductor has negligible thermal conductivity below its transition temperature, this ensures that heat loss through these contacts is minimized, and consequently, the thermal gradient across the length of the thermometer is small. The normal metal part of the thermometer, which is evaporated at the same time as the heater, is well coupled thermally to the node.

The second thermometer, which we denote the bottom thermometer (Fig. 1(c)), is attached to the circular terminal pad of the wide control wire. This thermometer is ~1.0 µm long, and can also be measured using four terminals, two of which are connected through the circular pad. One dangling lead connected to the thermometer terminates in an Al film, which provides the superconducting reservoir for the proximity effect for this thermometer. Unlike the top thermometer, connections to the wire bonding pads are not made by superconducting leads, since the lower thermometer is relatively far away from the heating source, and we initially expected the temperature gradients at the pad to be small. It should be noted that for both thermometers, the four-terminal resistance does not include the Al film, but only the proximity coupled normal metal.

The proximity effect thermometers were first calibrated against a RuO\(_2\) thermometer attached to the mixing chamber of a dilution refrigerator by measuring the resistance of the thermometers as a function of temperature with no dc current flowing through the sample.

![FIG. 2. (a) Resistance of top and bottom thermometers (normalized to the resistance \(R_N\) at \(T = 1.2\) K) as a function of temperature. Solid lines are fits to Eq. (\ref{eq:1}) over the range \(0.1\) to \(0.7\) K. (b) Normalized differential resistance of top and bottom thermometer as a function of dc current through heater wire. Solid lines are fits to Eq. (\ref{eq:2}) over the range \(I_{dc} = \pm 40\) µA, with the parameters \(a = 2.1458, b = 0.46022, c = 40.348\) for the top thermometer, and \(a = 4.3007, b = 2.5575, c = 62.362\) (with appropriate units) for the bottom thermometer. \(R_N = 2.1537\) Ω for the top thermometer, and 4.3185 Ω for the bottom thermometer.](image-url)
reduce the electron phase coherence length in the normal metal, and hence the amplitude of the proximity effect. Nevertheless, the magnitude of the resistance change is quite large. For example, the resistance contribution due to weak localization is typically on the order of $10^{-4}$ of the total resistance [11], two orders of magnitude smaller than the temperature dependent resistance shown in Fig. 2.

In order to demonstrate the use of these thermometers to measure the local temperature of the electrons in the AuFe film, we flow a dc current $I$ through the wide heater strip using the terminals marked $I_{dc}$± in Fig. 1(a), while simultaneously measuring the resistance of both the top and bottom thermometers with an ac resistance bridge. The dc current heats the electrons in the current path to a temperature above $T_b$. The electrons are cooled through interaction with phonons in the metal, and by electronic thermal conduction through the metallic parts of the sample itself, which is more efficient near the large contact pads of the sample. This leads to a nonuniform electron temperature profile in the heater wire, with the maximum electron temperature at the node [12]. Parts of the sample which are connected to the heater but do not have a dc current flowing through them (such as the control wire) will also develop a temperature gradient as a function of the dc current through the heater.

Figure 2(b) shows the four terminal ac resistance $R$ of the top and bottom thermometer as a function of $I$. During this measurement, the mixing chamber of the dilution refrigerator was maintained at $\sim 97.5$ mK. Both curves are symmetric with respect to $I$, as would be expected since the heating of the electron gas by the dc current should be independent of the direction of the current. By correlating $R(I)$ shown in Fig. 2(b) with $R(T)$ shown in Fig. 2(a) for each thermometer, one can determine the effective electronic temperature at the node and at the contact pad of the control wire as a function of $I$. In order to do this, we fit $R(T)$ for each thermometer to a fourth order polynomial of the form

$$R(T) = \sum_{j=0}^{4} a_j (\log T)^j$$

over the temperature range 0.07-0.625 K. The resulting fits are shown as the solid lines in Fig. 2(a). Similarly, $R(I)$ for both thermometers were fit by an equation of the form [13]

$$R(I) = a + \frac{b}{|I|^{3/2} + c}$$

as demonstrated by the solid lines in Fig. 2(b), which are fits to Eq. (2) over the range $I_{dc} = \pm 40$ $\mu$A. Finally, the effective electron temperature $T_e$ as a function of $I$ is obtained by cross interpolating between $R(T)$ and $R(I)$ obtained from the fits for each thermometer [14]. Figure 3 shows $T_e(I)$ obtained in this manner for both thermometers. This plot indicates that even relatively small dc currents can substantially raise the effective temperature $T_e$ over the bath temperature $T_b$.

![Figure 3. $T_e$ as a function of $I_{dc}$ obtained by cross interpolating the fits for $R(T)$ and $R(I)$ shown in Fig. 2 for the top and bottom thermometer.](image)

For example, at a dc current of $I \sim 5$ $\mu$A, $T_e$ at the node is $\sim 218$ mK, an increase of $\sim 120$ mK over the bath temperature of 97.5 mK. The surprising fact is that the electron temperature at the lower thermometer also increases substantially, to a value of 183 mK, giving a temperature differential of $\sim 35$ mK across the control wire. At lower temperatures, where cooling by phonons is less efficient, the heating effect would be expected to be even more drastic. These results underline the importance of using low excitation currents in low temperature transport measurements on mesoscopic samples in order to avoid self-heating of the electrons.

The use of Al as the superconductor in these thermometers restricts the temperature range of the thermometers to below 0.8 K, but this range can easily be increased by using a superconductor with a higher $T_c$ such as Pb or Nb. The ability to measure the spatial variation of the electron temperature that we have demonstrated here opens up the possibility of using these thermometers to make quantitative thermal and thermoelectric measurements on mesoscopic samples.

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