Direct temporal measurement of hot-electron relaxation in a phonon-cooled metal island

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We report temporal measurements of the electronic temperature and the electron-phonon thermal relaxation rate in a micron-scale metal island, with a heat capacity of order 1 J/K ($C \sim 10^7 k_B$). We employed a superconductor-insulator-normal metal tunnel junction, embedded in a radio-frequency resonator, as a fast ($\sim 20$ MHz) thermometer. A resistive heater coupled to the island allowed us to drive the electronic temperature well above the phonon temperature. Using this device, we have directly measured the thermal relaxation of the hot electron population, with a measured rate consistent with the theory for dynamic electron-phonon cooling.

Measurement of the heat capacity $C$ of a thermodynamic system, in contact with a thermal reservoir through a thermal conductance $G$, necessitates the measurement of temperature over time scales shorter than the characteristic thermal relaxation time $\tau = C/G$. For mesoscopic devices, this time scale becomes exceedingly short, as both the electron and phonon heat capacities scale with device volume $V$. Furthermore, it is difficult to thermally isolate a phonon system from its environment, as even a very weak mechanical suspension is limited at low temperatures by the scale-independent quantum of phonon thermal conductance $G_{e-p} \propto V T^4$. The electron heat capacity scales as $C_e \propto V T$, the electron-phonon thermal relaxation time $\tau_{e-p} = C_e/G_{e-p}$ is independent of volume, and scales as $T^{-3}$. At 1 K, $\tau_{e-p}$ is on the order of $10$ nanoseconds, a time scale that is accessible using a radio-frequency superconductor-insulator-normal metal (rf-SIN) tunnel junction thermometer [5].

In this letter, we present large-bandwidth measurements of the electronic temperature of a micron-scale metal island. Our measurement has ample bandwidth with which to directly measure $\tau_{e-p}$ at temperatures up to 1 K. This system therefore allows us to probe the thermodynamic behavior of electrons in very small metal volumes, potentially with heat capacities as small as 10 $k_B$. Such small metal volumes are prime candidates for energy absorbers in far-infrared photon-counting bolometers [6], and would allow unprecedented calorimetric sensitivity in the mesoscopic regime. Measurements over time scales shorter than $\tau_{e-p}$ are also critical for developing a complete understanding of the thermodynamics of mesoscopic systems.

The thermal decoupling of electrons and phonons at low temperatures was first described theoretically by Little [4], with a more general discussion provided by Gantmakher [7]. For a bulk metal with volume $V$, the power flow $P_{e-p}$ from the electron gas at temperature $T_e$ to the phonon gas at $T_p$ is given by

$$P_{e-p} = \Sigma V (T_e^n - T_p^n), \tag{1}$$

where $\Sigma$ is a material-dependent parameter. For a spherical Fermi surface and a Debye phonon gas, $n = 5$.

A number of researchers have verified that Eq. (1) applies to the static heating of thin-film metals, albeit with $n$ slightly lower than 5 (fit values for $n$ fall in the range from 4.5 to 4.9, with values for $\Sigma$ in the range $1 - 2 \times 10^9$ W/m$^3$.K$^{-5}$ [8, 9]). These measurements were made using a dc superconducting quantum interference device (dc-SQUID) to measure the Johnson-Nyquist noise in the metal film, and thus extract the electronic temperature.

A second approach to measuring the electron temperature in thin metal films was presented by Nahum et al. [10]: using a SIN tunnel junction as an electronic thermometer. These authors suggested that such a structure could form the heart of a bolometric detector. Measurements of the static energy distribution of electrons in a normal metal under voltage bias were made by Pothier et al. using a similar SIN-based thermometer [11]. Yung et al. [3] also demonstrated a SIN thermometer in contact with a normal metal island, the whole fabricated on a micron-scale suspended GaAs substrate.

Here we study the dynamic temperature response of a small metal island using a SIN tunnel junction thermometer. Well below the superconducting transition temperature $T_C$, the tunnel junction’s small-signal resistance at zero bias, $R_0 \equiv dV/dI(0)$, is exponentially dependent on the ratio of temperature $T$ to the superconducting energy gap $\Delta$, $R_0 \propto e^{\Delta/k_B T}$. A sub-micron scale SIN tunnel junction therefore has a low-temperature resistance that can easily exceed $10^6 \Omega$, limiting conventional time-domain measurements to bandwidths of order 1 kHz. In order to monitor changes in this resistance at sub-microsecond time scales, we circumvent the unavoidable stray capacitance in the measurement circuit by embedding the junction in a LC resonant circuit, as shown in Fig. 1 [12]. We then measure the resistance of the SIN junction, and thus the normal metal electron temperature, by measuring the power reflected from the circuit at the LC resonance frequency. A change of the junction resistance $R_0$, induced by heating the electrons, in turn changes the amplitude of the reflected radio frequency signal. In this technique, the stray cable capacitance $C$ is in resonance with the inductor $L$, the resonator also serving to impedance-match the resistance of the tunnel junction to the measurement system. This readout scheme is analogous to that employed in the radio-frequency...
FIG. 1: (Color Online) (a) Optical micrograph of the electron calorimeter. The center Au island is contacted on the left by a rf-SIN thermometer, and on the right by a NiCr resistor. The outer ground leads and the contact right of the resistor are superconducting Al. inset: Detail drawing of the SIN junction, Al shown in gray, Cu in white, and overlap junction area in black. The dotted outlines are fabrication artifacts. (b) Electrical circuit. The SIN thermometer is embedded in an LC resonator formed by a discrete inductor and the stray lead capacitance. The junction resistance is monitored using the power reflected from the LC resonator at its resonance frequency. (c) Thermal schematic. The calorimeter electron gas $C_e$ is thermally isolated by the superconducting Al contacts ($G_{Al}$); the dominant thermal link is thus through the substrate phonons ($G_{e-p}$). The NiCr resistor directly heats the electron gas. (d) Timing diagram. The voltage pulse applied to the heater causes the temperature to rise, saturate, and then decay. The envelope of the reflected power from the LC resonator is directly related to the temperature.

Our device is fabricated on a $4 \times 4 \times 0.5$ mm$^3$ single-crystal GaAs chip using four lithography steps. A 85 nm thick Au center island and wire-bond pads were first deposited on the GaAs substrate; an intermediate Au pad was also deposited in this layer. We then deposited a 100 nm thick NiCr film, designed to have a 50 $\Omega$ resistance, matching the characteristic cable impedance $Z_0$. The ground leads and heater contact were evaporated in the third layer, using superconducting Al to ensure thermal isolation below 1 K [14]. The NiCr contacts the Al via the intermediate Au pad, to ensure low interfacial resistivity. The tunnel junction thermometer was deposited in the fourth lithography step. We used a standard suspended resist bridge, double-angule evaporation method to define the tunnel junction [13]: A 90 nm thick Al electrode was evaporated, and the Al then oxidized in 200 mTorr of pure O$_2$ for 90 s. The junction was completed by evaporating a 90 nm thick Cu counterelectrode, which also contacted the center Au island.

The device is shown in Fig. 1(a). Note that the Au center island is electrically grounded, so that heating signals applied to the NiCr resistor do not couple directly to the SIN junction, but instead affect it by changing the temperature of the Au island. The heating signals are in principle therefore limited by diffusion time from the NiCr through the Au island and then along the Cu electrode to the SIN tunnel junction; we estimate this time to be less than 10 ns.

We mounted the chip containing the device on a printed circuit board, which was enclosed in a brass box. Gold wire bonds (25 $\mu$m diameter) were made between the Au bond pads on the chip and Cu coplanar striplines on the circuit board. A chip inductor with $L = 390$ nH was placed between the Au bond pads on the chip and Cu coplanar stripes on the circuit board. A chip inductor with $L = 390$ nH was placed in series with the SIN junction. The resonance capacitance $C$ was from the geometric capacitance of the stripline and Au bond pads, with $C = 0.5$ pF. The expected LC resonance frequency is $f_{res} = 1/2\pi(LC)^{1/2} \approx 350$ MHz, the tuned circuit quality factor is $Q = \sqrt{L/CZ_0'^2} \approx 20$, and the measurement bandwidth is $\Delta f = f_{res}/Q \approx 20$ MHz. The measurement circuit is shown in Fig. 1(b). The tunnel junction is configured for simultaneous dc and rf measurements via a bias tee, not shown in Fig. 1.

We have described the technical aspects of rf-SIN thermometry elsewhere [5]. Here we will describe the salient aspects as they pertain to these measurements. We determined the resonance frequency of the LC circuit to be 345 MHz. A carrier signal source was connected through a directional coupler to a coaxial line, which was in turn connected to the LC resonant circuit. The carrier frequency was set close to the LC resonant frequency [14]. The signal reflected from the LC resonator was high-pass filtered and amplified using...
then adjusted to achieve maximum differential response sufficient to get a clipped response. The junction resistance is temperature-independent above the Al superconducting transition temperature: $T_{\text{NiCr}} = 1100 \text{ mK}$. The electron temperature inferred from the change in reflected signal is the mixer if voltage, and the labels on the right axis indicate the electron temperature nears the phonon temperature.

FIG. 3: Composite response to pulsed heating signals, with pulses 3.0 $\mu$s long with peak power 0.1, 0.3, 0.8, 2.2, 6.2, 17.6, 49.0, and 140 nW. The resulting electronic temperature for each pulse is used to determine the relation $P(T_e, T_p)$. Inset: The solid line is a fit to $P(T_e, T_p) = V \Sigma(T_e^n - T_p^n)$, with $T_p = 300$ mK, $n = 4.7$, $V = 10 \mu$m, and $\Sigma = 2.1 \times 10^9$ W/m$^3$K$^{3.7}$.

![Graph showing composite response to pulsed heating signals](image)

In order to characterize the response of the system, we first heated the NiCr resistor using a $f_0 = 25$ kHz sinusoidal drive signal. Figure 3 shows the response for various drive powers. The if signal was low-pass filtered ($f < 2$ MHz), and each curve is the result of averaging 256 drive periods. The left axis is the mixer if voltage, and the labels on the right axis indicate the electron temperature inferred from the change in reflected signal. The instantaneous power dissipated in the resistor is proportional to the square of the voltage applied to the heater ($P(t) = V^2(t)/R_{\text{NiCr}}$); this causes the reflected signal to be modulated at twice the heater signal, $2f_0 = 50$ kHz. At low powers $P$, contributions at 25 kHz were also present, due to a small dc offset on the heater voltage $V(t) = V_{\text{dc}} + V_0 \sin 2\pi f_0 t$. At the highest powers, the reflected signal is clipped near the Al superconducting transition temperature: $T_{\text{Al}}$.

The measured signal depends on the proper adjustment of the detection mixer’s local oscillator (lo) phase. In order to correctly adjust this phase, we first applied a heater signal sufficient to get a clipped response. The phase of the lo was then adjusted to achieve maximum differential response between the lowest ($\approx 300$ mK) and highest ($\approx 1400$ mK) electron temperatures. The SIN junction ranges from 105 $\Omega$ to 6 $\Omega$ over this temperature range, and passes through the value of $R_0$, where optimal matching with the cable impedance occurs [17]. In the parlance of radio-frequency electronics, the carrier signal is over-modulated, so the absolute value of the reflected power is a non-monotonic function of temperature. However, as we are sensitive to the phase of the carrier, the proper quadrature of the mixer if voltage does have a monotonic response. Finally, the reflected if signal as a function of cryostat temperature, for no heater voltage applied, was used to construct the temperature calibration, $V_{\text{if}}(T)$.

We measured the quasi-static relation between the electron-phonon power flow $P_{e-p}$ and the electron and phonon temperatures, $T_e$ and $T_p$, as given by Eq. (1). We applied a series of 3 $\mu$s pulses while varying the peak heating power, and monitored the resulting time-dependent electron temperature. The substrate temperature was kept at 300 mK. The signal was filtered with a 2 MHz low-pass filter, and the result of 256 averages is shown in Fig. 2. This is equivalent to a dc heating measurement with a key difference, namely that as the heating pulses were delivered to the device at a 1 kHz repetition rate, the duty cycle was only 0.3%, so that the substrate phonons did not have sufficient time to heat. The equivalent measurement in a dc heating experiment requires 300 times as much power, with significant phonon heating a likely outcome. We find a fit relation matching that of Eq. (1), with $n = 4.7$ and $\Sigma = 2.1 \times 10^9$ W/m$^3$K$^{4.7}$, in good agreement with previously measured values [18].

We finally performed measurements of dynamic electron-phonon cooling, by monitoring the detailed time-dependent behavior of the electron temperature at the end of a heating pulse. Figure 4 shows the measured response to a heater pulse (2560 averages, using a 50 MHz low-pass filter). The heating pulse was configured to have 1.6 ns leading and trailing edges, and it has a width of 2 $\mu$s. The initial temperature rise is at least as fast as the time resolution of the measurement, with an expected rate $\dot{T} = P/C_e \approx 140$ mK/nsec, as we are directly heating the electron population. The rapid onset also indicates that electron diffusion in the composite metal structure is not a rate-limiting factor. At the end of the pulse, the heating power drops to zero, leaving a non-equilibrium hot electron population that relaxes by phonon emission. Initially this relaxation is seen to be quite rapid, but it slows markedly as the electron temperature nears the phonon temperature.

The shape of the relaxation curve shown in Fig. 4 can be understood by examining the dynamics of the electron temperature. The electron heat capacity is $C_e = \gamma V T_e$, where $\gamma$ is the Sommerfeld constant. The power flow to the phonons is given by Eq. (1). The time rate of change of the electron temperature $T_e$ is then

$$T_e = \frac{\Sigma}{\gamma} (T_e^{n-1} - \frac{T_p^n}{T_e}).$$

(2)
Using the normalized temperature \( \theta \equiv T_n/T_p \), this is

\[
\dot{\theta} = -\frac{1}{n} \frac{1}{\tau_{e-p}(T_p)} (\theta^{n-1} - 1/\theta),
\]

in terms of the small signal thermal relaxation rate \( \tau_{e-p}^{-1} = n \Sigma T_p^{n-2}/\gamma \) for electrons near the phonon temperature \( T_p \).

We fit our measured response to Eq. (3) using this rate as the only adjustable parameter, finding the value \( \tau_{e-p} = 1.6 \mu s \). This is in agreement with the measured value of \( \Sigma \), and a composite \( \gamma \) which takes into account the relative metal volumes in the device. We can thus determine the the heat capacity of the metal island, \( C \sim 1 \text{fJ/K} \equiv 10^7 \text{K} \) at 300 mK.

There are some extremely interesting opportunities for electronic calorimetry in this temperature and size regime. Intriguing theoretical results have been presented for the thermodynamic response of mesoscopic superconducting disks [21] and giant moment electronic paramagnets such as PdMn [22] and PdFe [23] offer a means of probing the thermodynamics of a mesoscopic phonon-electron-spin-coupled system.

We are far from the ultimate calorimetric limits for this technique. Devices with active metal volumes that are smaller by a factor of \( 10^3 - 10^4 \) can be fabricated, yielding a total heat capacity of order \( 10 - 100 \text{ K} \) at 30 mK. Changes in the heat capacity of less than 10% are easily detected, yielding a sensitivity of order 1 K, i.e. that associated with a single degree of freedom.

In summary, we have performed sub-\( \mu \)s timescale measurements of the electron temperature of a micron scale metal island, cooled dynamically by phonon emission. The ability to apply and measure the response to fast heat pulses has permitted us to directly measure the electron-phonon thermal relaxation, and thus extract the heat capacity of the metal island. This, to our knowledge, is the smallest measured heat capacity to date. The device that we have fabricated is a major step forward for mesoscopic thermodynamics, provides a platform for sub-\( \text{aJ/K} \) calorimetry, and can potentially play an important role in future single photon and phonon bolometers.

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