Nanoelectronic primary thermometry below 4 mK

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Cooling nanoelectronic structures to millikelvin temperatures presents extreme challenges in maintaining thermal contact between the electrons in the device and an external cold bath. It is typically found that when nanoscale devices are cooled to ~10 mK the electrons are significantly overheated. Here we report the cooling of electrons in nanoelectronic Coulomb blockade thermometers below 4 mK. The low operating temperature is attributed to an optimized design that incorporates cooling fins with a high electron-phonon coupling and on-chip electronic filters, combined with low-noise electronic measurements. By immersing a Coulomb blockade thermometer in the 3He/4He refrigerant of a dilution refrigerator, we measure a lowest electron temperature of 3.7 mK and a trend to a saturated electron temperature approaching 3 mK. This work demonstrates how nanoelectronic samples can be cooled further into the low-millikelvin range.
Understanding how to obtain and measure electron temperatures approaching 1 mK has the potential to open a new regime for studying nanoelectronics and pave the way towards pioneering sub-millikelvin techniques. This would benefit numerous areas of activity; for example, investigations of the fractional quantum Hall effect in two-dimensional electron gases and solid-state quantum technologies including superconducting and semiconducting qubits. To access these superconducting qubits (see Methods for details). Efficient sandwiched between large-area grounded metal films, separated by 250 nm SiO2, CBTs typically function over a thermal excitations and an electrostatic barrier to single electron of the array is temperature dependent, due to the balance between metallic islands connected by tunnel junctions. The conductance below 4 mK. A CBT consists of an array of Coulomb-blockaded tunnel junction uniformity, and has also been used to fabricate CBTs studied here is shown in Fig. 1. Devices are fabricated using an ex situ tunnel junction process, which provides excellent tunnel junction uniformity, and has also been used to fabricate superconducting qubits (see Methods for details). Efficient thermal coupling between electrons and phonons in the metallic islands of the CBT is critical for reaching low electron temperatures. The electron–phonon heat flow \( P_{ep} \) is described by the material-dependent electron–phonon coupling constant \( \Sigma \) and the volume of the metallic island \( \Omega \),

\[
P_{ep} = \Sigma \Omega \left( T_e^3 - T_p^3 \right),
\]

where \( T_e \) is the electron temperature and \( T_p \) is the phonon temperature. To minimize \( T_e \), the island volume should be large and the material chosen to maximize \( \Sigma \). We use electroplated Au on top of the CBT islands to increase their volume to nominal 5 \( \times \) 205 \( \times \) 38.5 \( \mu \)m3 (see Methods for details). The effective electron–phonon coupling in these islands, with relatively large volume and a high coupling constant in Au \( \Sigma = 2.4 \times 10^9 \) W K\(^{-5}\) m\(^{-3}\), is estimated to be more than two orders of magnitude larger than in previous CBTs fabricated using the ex situ junction process.

In addition to efficient thermalization of the CBT itself, it is important to cool the incoming leads through robust thermal anchoring and heavy electromagnetic filtering. We improve the chain of thermalization and filtering by including on-chip resistive meander structures in line with all electrical contacts. These form a distributed resistive-capacitive chain with a cutoff frequency \( \approx 40 \) MHz. Similar filters based on a large-area capacitor and tunnel junctions in series have previously been incorporated in a CBT.

CBT characteristics above 7 mK. Figure 2 shows the behaviour of a CBT fabricated using the process described above, focusing on temperatures between 7 and 80 mK. The sensor is measured in both a commercial cryogen-free dilution refrigerator (Bluefors Cryogenics LD250) with a base temperature \( \approx 7 \) mK and in a custom dilution refrigerator manufactured at Lancaster University with a base temperature \( \approx 2.5 \) mK. The conductance of the CBT is measured in a current-driven four-wire configuration, with the drive current and voltage amplification provided by an Aivon PA10 amplifier. A small AC excitation (typically \( 5 \) pA \( \leq \) \( I_{AC} \leq 100 \) pA) is added to the DC bias \( I_{DC} \), allowing the differential conductance \( G \) to be measured with a lock-in amplifier.

In both refrigerators, the CBT is in a vacuum and housed in a gold-plated copper package (Aivon SH-1) that is attached to the mixing chamber plate. The package includes RC filters with a cutoff frequency \( \approx 300 \) kHz. Electrical contacts to the CBT are thermalized in additional cold RC filters potted in Eccosorb CR.
To determine temperature, the CBT is used to fit conductance dips measured in the cryogen-free refrigerator (circles) and the custom refrigerator (triangles). This suggests that the thermal contact between the CBT and the refrigerator is relatively strong, and that its slow cooling is probably due to heat leak from an external warm object.

A second CBT was immersed in the ⁴He/³He refrigerator of the custom dilution refrigerator to improve thermal coupling and better isolate external sources of heating. A schematic of the immersion cell is shown in the Fig. 3c. Sintered silver blocks increase the thermal contact between the refrigerant and the incoming contact wires. Several sinters are attached to the sensor package, to each of the four measurement wires and to a grounding wire for the package and the RC filters. The immersed CBT is found to equilibrate much faster, as shown in Fig. 3a,
The dot-dashed curve shows a best fit of $R_f$ faster. (single-shot mode to 2.2 mK, reaching a lowest as measured by the vibrating wire resonator (VWR) thermometer: 29.4, 19.0 and 10.5 mK, respectively. (note that even when $C_B T$ in the $^3$He/$^4$He mixture of a dilution refrigerator. Temperatures agree with $C_B T$ in vacuum is extremely slow to thermalize. By comparison, the CBT immersed in $^3$He/$^4$He thermalizes significantly faster. (b) Cooling of the immersed CBT after it has been heated by a large DC drive current (50, 40 and 30 nA for run 1, 2 and 3, respectively). Fitting to an exponential decay (solid line) yields a time constant of 570 s and a saturation temperature of 3.8 mK. (c) Schematic of the immersion cell used to cool a CBT in the $^3$He/$^4$He mixture of a dilution refrigerator.

Figure 3 | Thermalization of two CBTs at a refrigerator temperature $\leq 2.8$ mK. (a) Cooling of one CBT in vacuum (circles) and one immersed in the $^3$He/$^4$He refrigerant of the dilution refrigerator (triangles). In both cases, the CBTs are cooling after being warmed above 10 mK by temporarily increasing the refrigerator temperature. The CBT in vacuum is extremely slow to thermalize. By comparison, the CBT immersed in $^3$He/$^4$He thermalizes significantly faster. (b) Cooling of the immersed CBT after it has been heated by a large DC drive current (50, 40 and 30 nA for run 1, 2 and 3, respectively). Fitting to an exponential decay (solid line) yields a time constant of 570 s and a saturation temperature of 3.8 mK. (c) Schematic of the immersion cell used to cool a CBT in the $^3$He/$^4$He mixture of a dilution refrigerator.

reaching $T_e \approx 3.8$ mK at $T_{\text{max}} \approx 2.7$ mK. It is important to note that even when $T_e$ is elevated above $T_0$ and $T_{\text{max}}$ the CBT remains a primary thermometer of its internal electron temperature.

To study the CBT at $|V_{\text{DC}}| > 0$, the time needed for the sensor to reach thermal equilibrium after a change of Joule heating needs to be known. Figure 3b shows the relaxation of $T_e$ after the CBT has been heated by a large drive current for long enough to reach thermal equilibrium ($> 30$ min). The subsequent value of $T_e$ is measured by scanning close to $V_{\text{DC}} = 0$, where Joule heating should be negligible. The relaxation of $T_e$ is found to have a time constant of 570 s.

Figure 4a shows the calibration of the immersed sensor. The three warmest measurements are fitted simultaneously to determine $C_Z = 209.5$ fF and $R_I = 23.21 k\Omega$. The fitted temperatures agree with $T_{\text{max}}$ to within 6%. Given the agreement between the fitted $T_e$ and $T_{\text{max}}$, we can assume that parasitic heating is still negligible down to 10 mK.

The coldest measurement in Fig. 4a is fitted using the above values, yielding a minimum electron temperature of 3.86 ± 0.01 mK. This measurement was made over a period of 7 h, to ensure that the CBT was in thermal equilibrium at each value of $V_{\text{DC}}$. At these temperatures, the parasitic heating of the CBT is now significant and $T_e$ does not match the refrigerator temperature of $T_{\text{max}} = 2.7$ mK. To fit this conductance dip, the thermal model, equation 3, is used with $T_e = T_{\text{max}}$ and with the parasitic heating $P_0$ and the electron–phonon coupling $\Sigma\Omega$ as free parameters.

Figure 4b shows how the CBT electron temperature diverges from the refrigerator temperature below $\approx 7$ mK. Here the value of $T_e$ is found by measuring $G_0$ close to $V_{\text{DC}} = 0$ and so Joule heating can be neglected. The lowest temperature reported by the
CBT is below 3.7 mK when operating the fridge in single-shot mode (see Fig. 4c).

Discussion

The overheating of the sensor at $V_{DC} = 0$ constrains the value of $P_0(\Delta) - 1$ in the fit to the coldest measurement in Fig. 4a. However, the parasitic heating is not large enough to reliably separate the values of $P_0$ and $\Sigma$ in the fitting. Qualitatively, the fits suggest that $P_0 \geq 300$ aW per island and $\Sigma$ is at least four times larger than expected from the nominal size of the thermalization blocks and the literature value of $\Sigma$ for Au$^{16,17}$. It is not possible to determine an upper bound on $P_0$ without constraining $\Sigma$. It is worth noting that the power required to measure the CBT conductance ($\sim 1$ aW per island due to Joule heating from $I_{AC}$) is much lower than our estimate of $P_0$. As such, we believe that CBTs of this type can be operated at still lower temperatures by further reducing the parasitic heating.

The functional form of $T_x$ versus $T_{mxc}$, as shown in Fig. 4b, should have the same temperature dependence as the dominant thermalization mechanism, that is, $T_x^{\alpha}$ for electron–phonon coupling. However, other power laws have been observed$^9$. Here we find that the best fit of $T_x = T_{mxc} + c$ gives $\alpha = 2.7$ and a saturated $T_x$ of $1.34$ mK. The fitted exponent $\alpha$ cannot be confirmed by fits to the conductance dips in Fig. 4a, because the overheating is still relatively weak, even at the lowest temperatures, and there is little effect on the shape of the dip. We find that a thermal model with a $T^3$ thermalization term fits the conductance dips equally well as a model using $T^2$.

The saturation of the measured CBT temperature below 7 mK could be caused by parasitic heating of the islands or excess voltage noise across the tunnel junctions. It is possible that the operating temperature could be lowered by reducing parasitic heating through better shielding and by lowering the voltage noise in the measurement circuit. To understand the cause of saturation in more detail, or to test an improved measurement environment, this sensor would need to be cooled closer to 1 mK.

In conclusion, the CBTs described here have been shown to operate as reliable primary thermometers of electron temperature down to 3.7 mK. The large thermalization blocks incorporated in the device and a relatively low level of parasitic heating ensure that the electron subsystem in the sensor is well coupled to the phonon subsystem down to $\sim 7$ mK. An immersion cell is shown in Fig. 4a; however, the parasitic heating is not large enough to cool the sensor further to fully characterize the thermalization mechanisms.

Methods

Device fabrication. The CBT devices are fabricated using an ex situ tunnel junction process$^{1,1}$. The Al films that define the CBT circuit have a thickness of 50 nm. Tunnel junctions between sections of Al are formed by an insulating layer of 250 nm SiO$_2$ deposited by plasma-enhanced chemical vapour deposition (PECVD). The junctions have a nominal diameter $0.6$ μm and a resistivity $\sim 10$ kΩ mm$^2$. The substrate is undoped Si with 300 mm thermal oxide on the surface. The island thickness achievable with the ex situ tunnel junction process or other deposition techniques used for tunnel junction devices is typically up to 1 μm. Thicker films suffer from stress build-up, causing poor adhesion between the film and the substrate. This is a severe problem at mK temperatures where poor adhesion can lead to poor thermalization and even mechanical failure due to thermal motion during cool down. We avoid these problems by using a combination of the ex situ process followed by masked electroplating of Au on top of the CBT island$^{1,2}$, which we refer to as thermalization blocks. Electroplating can produce $\sim 10$ μm-thick, low-stress films and here we choose a nominal thickness of 5 μm for the thermalization blocks.

Refrigerator thermometry. Two different dilution refrigerators are used in the experiments described above. In the commercial refrigerator, the mixing chamber temperature $T_{mxc}$ is measured by a calibrated RuO$_2$ resistor (Sensor model RU-1000-BF0.007 supplied and calibrated by Bluefors Cryogenics) in contact with the mixing chamber plate. In the custom refrigerator, $T_{mxc}$ is measured using a conventional vibrating wire resonator viscometer immersed in the saturated dilute phase of the $^3$He-$^4$He refrigerant in the mixing chamber$^{1,2,4}$. The vibrating wire resonator is validated by comparison with a calibrated RuO$_2$ resistor (calibrated to 20 mK and supplied by Lake Shore Cryogenics). This resistor is thermally connected to the refrigerator via an immunerid ried of painted sintered silver.

Data and software availability. All data used in this paper are available at http://dx.doi.org/10.17635/lancaster/researchdata/31, including descriptions of the data sets. The python-based pyCBT software library is freely available from Aivon Oy at https://github.com/AivonOy/pyCBT.

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Author contributions

D.G., H.H., J.P., M.P. and L.R. designed, fabricated and packaged the devices. J.P. and L.R. developed custom measurement instrumentation and methods. D.I.B., R.E.G., R.P.H., Yu.A.P., J.R.P., L.R. and M.S. performed measurements and calculations. J.R.P. drafted the manuscript. All authors discussed the results and implications, and commented on the manuscript at all stages.

Additional information

Competing financial interests: The authors declare no competing financial interests.

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Erratum: Nanoelectronic primary thermometry below 4 mK

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