500 microkelvin nanoelectronics

Matthew Sarsby, 1,∗ Nikolai Yurttagül, 1,∗ and Attila Geresdi 1

1 QuTech and Kavl Institute of Nanoscience, Delft University of Technology, 2600 GA Delft, The Netherlands

Fragile quantum effects such as single electron charging in quantum dots or macroscopic coherent tunneling in superconducting junctions are the basis of modern quantum technologies. These phenomena can only be observed in devices where the characteristic spacing between energy levels exceeds the thermal energy, $k_B T$, demanding effective refrigeration techniques for nanoscale electronic devices. Commercially available dilution refrigerators have enabled typical electron temperatures in the $10 \ldots 100 \text{mK}$ regime, however indirect cooling of nanodevices becomes inefficient due to stray radiofrequency heating and weak thermal coupling of electrons to the device substrate.

Here we report on passing the millikelvin barrier for a nanoelectronic device. Using a combination of on-chip and off-chip nuclear refrigeration, we reach an ultimate electron temperature of $T_e = 421 \pm 35 \text{µK}$ measured by a Coulomb-blockade thermometer. With a hold time exceeding 85 hours below 700 µK, we provide a landmark demonstration of nanoelectronics in the microkelvin regime.

Accessing the microkelvin regime 1 holds the potential of enabling the observation of novel electronic states, such as topological ordering 2, electron-nuclear ferromagnets 3–4, p-wave superconductivity 5 or non-Abelian anyons 6 in the fractional quantum Hall regime 7. In addition, the error rate of various quantum devices, including single electron charge pumps 8 and superconducting quantum circuits 9 could improve by more effective thermalization of the charge carriers.

The conventional means of cooling nanoelectronic devices relies on the thermal coupling between the refrigerator and the conduction electrons, mediated by phonon-phonon coupling in the insulating substrate, $Q_{p-p} \propto T_{p1}^4 - T_{p2}^4$ and electron-phonon coupling in the device $Q_{e-p} \propto T_e^5 - T_p^5$ 10–11, both rapidly diminishing at low temperatures. In a typical dilution refrigerator, $T_p > 5 \text{mK}$, and specially built systems reach 1.8 mK 12, which limits $T_e > T_p$ to the millikelvin regime. The lowest static electron temperature reached with this technique was $T_e = 3.9 \text{mK}$ 13 in an all-metallic nanostructure, and other experiments reached similar values 14–16 in semiconductor heterostructures.

This technological limitation can be bypassed by adiabatic magnetic refrigeration, which relies on the constant occupation probability of the energy levels of a spin system, $\sim \exp(-g \mu_B m B T)$ in the absence of heat exchange with the environment 17. Here, $k_B T$ is the thermal energy at a temperature of $T$, $g \mu_B B$ is the energy split between adjacent levels at a magnetic field of $B$ and $m$ is the spin index. Thus, the constant ratio $B/T$ allows for controlling the temperature of the spin system by changing the magnetic field. Exploiting the spin of the nuclei 18–19, this technique has been utilized to cool bulk metals down to the temperature range of $T \sim 100 \text{pK}$ 20. If only Zeeman splitting is present, which is linear in $B$, the ultimate temperature is limited by the decreasing molar heat capacity, $C_n = \alpha B^2/T^3$ in the presence of finite heat leaks, $Q_{\text{leak}}$. Here, the prefactor $\alpha = N_0 I(I+1) \mu_B^2 g^2 n_s^2 / 3 k_B$ contains $I$, the size of the spin, $g_n$, the $g$-factor, $N_0$, the Avogadro number and $\mu_s$, the nuclear magneton.

Bulk nuclear cooling stages have predominantly been built of copper 19, owing to its high thermal conductivity, beneficial metallurgic properties and weakly coupled nuclear spins, which allows for magnetic refrigeration of the nuclear spins down to 50 nK 21, however the weak hyperfine interaction results in a decoupling of the electron system at much higher temperatures, $\sim 100 \mu \text{K}$. Another material, a Van Vleck paramagnet, PrNi5, has been used as a bulk nuclear refrigerant exploiting its interaction-enhanced heat capacity in a temperature range of $T > 200 \mu \text{K}$ 22 even in dry dilution refrigerators 23.

Integrating the nuclear refrigerant with the nanoelectronic device yields a direct heat transfer between the electrons and nuclei $Q_{e-n} = \alpha \kappa^{-1} B^2 (T_e/T_n - 1)$ per mole. Here, $\kappa$ is the Köringa constant, and $T_e$, $T_n$ are the electron and nuclear spin temperatures, respectively. Owing to an $\alpha/\kappa$ ratio 60 times better than that of copper, indium has recently been demonstrated as a viable on-chip nuclear refrigerant 24. In addition, indium allows for on-chip integration of patterned thick films by electrodeposition and has been demonstrated as a versatile interconnect material for superconducting quantum circuits 25.

However, on-chip nuclear refrigeration is limited by the large molar heat leaks, which thus far limited the attainable electron temperatures above 3 mK both for copper 26 and indium 24 as on-chip refrigerant. Furthermore, only very short hold times were attained, limiting the practical applications of these devices. In contrast, encapsulating the chip in a microkelvin environment has led to superior cooling performance using copper, yielding $T_e = 2.8 \text{mK}$ with a hold time of approximately 1 hour.

* These authors contributed equally to this work.
FIG. 1. The experimental setup. (A) The cross-sectional sketch of the setup integrated into a dilution refrigerator with the characteristic temperatures listed on the left. The device, a Coulomb-blockade thermometer (CBT) with the integrated indium refrigerant, is shown as a cyan box, encircled in red. (B) The thermal path between the mixing chamber of the dilution refrigerator and the CBT (highlighted in cyan, the grey blocks denote In cooling fins). The electrical signal lines pass through the indium blocks. The effective molar amount of the refrigerant material is listed in each block, respectively. (C) Photograph of the CBT chip with the press-welded connections to the off-chip indium stages consisting of 1 mm diameter indium wires are visible on the left. (D) Photograph of the indium refrigerant mounted on the copper block with an electrically insulating membrane in between. The picture was taken during the assembly of the stage. The slots of the copper block contain the copper powder filters of the electrical lines to reduce radiofrequency heating, see also the cross-sectional image in panel (E). (F) False-coloured scanning electron micrograph of an island of the CBT, with a cross-sectional schematics shown in panel (G) along with the legend of colours. The encircled Al/AlO
x tunnel junction is shown in higher magnification in panel (H).

We attach the copper frame (1.7 mol total, 0.32 mol effective amount) to the mixing chamber via an aluminium-foil heat switch [29], which is activated by a small solenoid at \( \approx 10 \text{ mT} \). Crucially for our design, the electrical measurement lines are not connected to the copper stage, rather to the parallel network of nuclear cooled indium wires with a 23 mmol total and 17 mmol effective amount per line. These wires are attached to the copper frame by an epoxy resin membrane (Fig. 1B) which provides an additional layer of thermal isolation during nuclear cooling. The electrical and thermal contact to the device is made by press welding the indium wires onto electroplated indium bonding pads on the chip (Fig. 1C).

We apply both electronic filtering and microwave shielding in order to reach sub-1 mK electron temperatures. We thermalize all electrical lines by custom-made copper-powder filters [30] at each stage of the dilution refrigerator and a fifth order RC filter with a cutoff frequency of 50 kHz at the mixing chamber. To decouple the cold chip below 1 mK from the thermal noise of the mixing chamber [31], we install an additional set of copper-
FIG. 2. Calibration and primary operation of the CBT. (A) The voltage-dependent differential conductance, \( G \) of the device at different temperatures. The conductance is normalized with the conductance at large bias, \( G_t \) and fitted against the single electron tunneling model to determine the electron temperature for each curve and the total capacitance per island, \( C_S = 669.8 \pm 2.2 \, \text{fF} \). The inset shows \( G_t \) as a function of the magnetic field, at two distinct temperatures. (B) The electron temperature, \( T_e \) at \( B = 100 \, \text{mT} \) with the heat switch closed as a function of the mixing chamber temperature of the dilution refrigerator, measured by a calibrated cerium magnesium nitrate (CMN) mutual inductance thermometer. The temperature errors are shown as horizontal and vertical lines, respectively. (C) The zero bias calibration curve based \( C_S \) with the \( k_B T_e \) as the horizontal line, see text. The theoretical maximum of \( T_e(G/G_t) \) with all CBT islands in full Coulomb blockade is denoted by the orange line. The average \( T_e \) and the \( 3\sigma \) confidence interval are shown as the blue solid line and the blue shaded region, respectively, based on the Markov chain Monte Carlo (MCMC) method, see text.

 powder filters within the copper stage which is demagnetized together with the indium lines (Fig. 1D,E). Further details on the measurement circuit are listed in the Supplementary Information.

To directly measure the electron temperature, we utilize a Coulomb-blockade thermometer (CBT) [33]. CBTs rely on the universal suppression of charge fluctuations in small metallic islands enclosed between tunnel barriers at low electron temperatures. With a total capacitance of each island, \( C_S \), we define the charging energy for a tunnel junction array of length \( N \) to be \( E_C = e^2/C_S \times (N - 1)/N \) with \( e \) being the charge of a single electron. In the weak charging regime, \( k_B T_e \approx E_c \), the full width at half maximum of the charging curve is \( eV_{1/2} = 5.439 N k_B T_e \), providing the possibility of primary thermometry independent of \( E_C \) defined by the device geometry [34]. Crucially for temperature measurements during demagnetization cooling, CBTs exhibit no sensitivity to the applied magnetic field [35].

We fabricated a \( 36 \times 15 \) array with an ex-situ Al/AlOx/Al tunnel junction process [24, 36] to create junctions of \( 780 \times 780 \, \text{nm}^2 \) in size (Fig. 1H). Since the highly resistive tunnel junctions with \( R_j = 35 \, \text{k\Omega} \) correspond to a high thermal barrier, we electrodeposited indium cooling fins (\( 50 \times 140 \times 25.4 \, \mu\text{m}^3 \) corresponding to 11.4 nmol, see Fig. 1F,G) on each island for local nuclear cooling. We note that the current device has only 5 conducting lines, resulting in an \( N \times M = 36 \times 5 \) CBT array. The details of the device fabrication are previously described in [24].

In Fig. 2A, we show the normalised differential conductance \( G(V)/G_t \) of the CBT at different temperatures obtained by conventional low frequency lock-in technique at 19.3 Hz. We use the master equation of single electron tunneling [33, 34] to find the electron temperature of each curve and the charging energy as a global fit parameter, \( E_C = 232.6 \pm 0.8 \, \text{neV} \), yielding \( C_S = 670 \pm 2 \, \text{fF} \). Remarkably, at a small magnetic field of \( B = 45 \, \text{mT} \) required to suppress superconductivity, we achieve an electron temperature \( T_e = 7.07 \pm 0.09 \, \text{mK} \) by phonon cooling, attesting to the well-shielded environment of the device. We note that at this low temperature, we had to account for the Joule heating of the CBT chip [37], see the Supplementary Information. Upon calibration, we numerically invert \( G(T_e, E_C, N, G_t) \) to use for continuous thermometry, see the Supplementary Information. We note that we observe a temperature-independent \( \Delta G_t/G_t \approx 0.03 \) magnetoresistance between zero and 12 T (inset of Fig. 2A), which we account for during the magnetic field ramps. To demonstrate the limitations of phonon cooling, we evaluate \( T_e \) as a function of the mixing chamber temperature and observe a saturation behavior below 10 mK (Fig. 2B).

In the low temperature regime, where \( E_C \gg k_B T_e \), random island charge offsets influence the conductance of the CBT [32]. Here, \( G/G_t \) can be calculated by a Markov chain electron counting model with a random set of offset charges for each island. Using the Markov chain Monte Carlo (MCMC) approach, we evaluate the conductances of the tunnel junction chain for 1000 gate charge configurations at a given \( T_e \), and build a histogram of the total CBT conductance, which is the sum of \( M = 5 \) randomly selected line conductances. We plot the average of the inverse function \( T_e(G/G_t) \) with a \( 3\sigma \) confidence interval in Fig. 2C (blue solid line and blue shade, respectively). In comparison, we display the \( T_e = 0.4E_C/k_B = 1.1 \, \text{mK} \) limit of the universal behaviour [32]. In addition, we plot the theoretical maximum of \( T_e(G/G_t) \), which occurs when all islands are in full Coulomb blockade. The details of our numerical simulations can be found in the Supplementary Information.
FIG. 3. Nuclear demagnetization of the CBT to the microkelvin regime. (A) A nuclear demagnetization run starting from $T_e = 13 \, \text{mK}$ and $B_i = 12 \, \text{T}$ ramping down to $B_f = 0.1 \, \text{T}$ with a ramp rate of $\dot{B} = \left[ -2 \times 10^{-7} \, \text{s}^{-1} \right] \cdot B$. The inset shows a closer view of the minimum electron temperature reaching well below $T_e = 500 \, \text{µK}$ for all numerical models, see text. (B) The inverse temperature $1/T_e$ as a function of time, which is used to estimate the heat leak, see text. (C) and (D) display finite bias voltage data in demonstration of the primary CBT operation in the µK regime. (E) Finite voltage bias data of the CBT in a broad temperature range. In panels (C), (D) and (E), the experimental data is shown as circles and the fits yielding $T_e$ listed in the legend are denoted by dashed lines, see text.

Supplementary Information.

We initialize a nuclear demagnetization experiment by precooing the device with a closed heat switch at $B_i = 12 \, \text{T}$ and reach $T_{e,i} = 13 \, \text{mK}$ after precooling for 164 hours. After opening the heat switch, we remove the magnetic field with a decreasing rate of $\dot{B} = \left[ -2 \times 10^{-7} \, \text{s}^{-1} \right] \cdot B$ to $B_f = 0.1 \, \text{T}$, which results in a decreasing $T_e$ (Fig. 3A). After finishing the ramp, we find the lowest electron temperature $T_e = 421 \pm 35 \, \text{µK}$ calculated using our MCMC model, averaged over a period of one hour (see inset of Fig. 3A). We note that the full blockade limit of the CBT also yields $T_{e,\text{min}} < 500 \, \text{µK}$.

After reaching the minimum temperature, the device gradually warms up. We find a warm-up rate of $\dot{T} = 1.7 \, \text{µK/h}$, and a hold time of 85 hours with $T_e < 700 \, \text{µK}$. This duration is limited by the cryogenic liquid transfer to the host cryostat, which induced mechanical vibrations and consequently a rapid warmup of the device.

As a proof of concept quantum transport experiment in the microkelvin regime, we measure the finite bias charging curve of the CBT at two different temperatures below 1 mK (circles in Fig. 3C.D). Remarkably, we find an excellent agreement with the calculated curves, using $T_e$ as the single fit parameter (dashed lines). In addition, we observe no distortion of the lineshape due to Joule heating at finite voltage biases, further demonstrating the role of strong electron-nucleus coupling in indium. To demonstrate the wide range of primary thermometry in our regime of interest, we display a set of experimental data taken between $T_e = 480 \, \text{µK}$ and 23.2 mK (Fig. 3E) together with the fitted theoretical curves on a logarithmic scale (circles and dashed lines, respectively).

Next, we turn to the refrigeration properties of indium,
and display a series of $T_e(B)$ curves in Fig. 4. Notably, $T_e^2(B^2)$ follows a linear proportionality, with a negative intercept, $-b = -(295±7 \text{mT})^2$ (Fig. 4A), which demonstrates that indium does not follow a constant $B/T$ ratio. We attribute our results to the strong quadrupolar splitting due to the inhomogenous electric field in the crystalline lattice [38]. A resulting effective magnetic field $b$ then adds to the applied magnetic field, $B_{\text{tot}}^2 = B^2 + b^2$ [39], which limits the lowest attainable temperature, even if $B \ll b$ (Fig. 4B). Our measurements yield similar $b$ values to earlier nuclear demagnetization experiments in bulk indium samples [39]. This correspondence directly confirms that the measured $T_e$ and the inferred nuclear spin temperature, $T_n$, are close to each other, which is the key requirement for nuclear demagnetization cooling of nanoelectronics.

Based on the obtained internal magnetic field, we estimate the heat leak of the CBT as $Q_{\text{leak}} = -n\alpha B_T \frac{d(1/T_e)}{dt}$, where $n$ is the molar amount of the refrigerant and $d(1/T_e)/dt$ is the inverse warmup rate (Fig. 3B). At $B = 100 \text{mT}$, we get $Q_{\text{leak}} = \pm 26.7 \text{mW/island}$, which is lower than the value obtained earlier using copper [27].

The small heat leak is further attested by the direct demonstration of the adiabaticity of the experiment. In the inset of Fig. 4B, we show a measurement run starting with $B_i = 1 \text{T}$ and $T_{e,i} = 1.57 \pm 0.01 \text{mK}$. After ramping up the magnetic field up to 8 T and back to $B_f = 1 \text{T}$, we acquire $T_{e,f} = 1.57 \pm 0.06 \text{mK}$. With $B_f = B_i$, the adiabatic efficiency $\eta = T_{e,i}/T_{e,f} = 1.00 \pm 0.04$, unity within error margin. This remarkable result demonstrates the outstanding control of $T_e$ by setting the magnetic field, which is unprecedented for nuclear magnetic cooling stages built for nanoelectronics.

In conclusion, we demonstrated nuclear magnetic cooling of electrons in a nanostructure down to an ultimate temperature of $T_e = 421 \pm 35 \mu\text{K}$. Integrating on- and off-chip refrigeration utilizing the strong electron-nucleus coupling of indium, we achieve 85 hours of hold time in the microkelvin range, which opens up this, so far unexplored, temperature regime for nanoelectronic devices and quantum transport experiments in pursuit of novel topological and interacting electron systems. In addition, we extend the range of primary nanoelectronic thermometry below 1 mK, opening new avenues for metrological applications and quantum sensing in the ultra-low electron temperature regime. Cooling down electrons to the microkelvin regime also paves the way towards investigating the limits of quantum coherence in solid state devices on the macroscopic scale [40].

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**AUTHOR CONTRIBUTIONS**

A. G. designed and supervised the experiments. N. Y. designed and fabricated the CBT devices with integrated indium fins. M. S. designed and fabricated the off-chip nuclear cooling stages and filters. M. S. and N. Y. performed the experiments. N. Y. implemented the numerical CBT array simulation. All authors analyzed the data. The manuscript has been prepared with contributions from all the authors.

**DATA AVAILABILITY**

Raw datasets measured and analysed for this publication are available at the 4TU.ResearchData repository, DOI: 10.4121/uuid:ffaeb9fc-9baf-428e-8a33-7e4b451d89e (Ref. [11]).

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**CORRESPONDING AUTHOR**

Correspondence and request of materials should be addressed to Attila Geresdi.

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