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Published in:
Communications Physics

DOI:
10.1038/s42005-018-0066-8

Publication date:
2018

Document version
Publisher's PDF, also known as Version of record

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Citation for published version (APA):
Primary thermometry of a single reservoir using cyclic electron tunneling to a quantum dot

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At the nanoscale, local and accurate measurements of temperature are of particular relevance when testing quantum thermodynamical concepts or investigating novel thermal nanoelectronic devices. Here, we present a primary electron thermometer that allows probing the local temperature of a single-electron reservoir in single-electron devices. The thermometer is based on cyclic electron tunneling between a system with discrete energy levels and the reservoir. When driven at a finite rate, close to a charge degeneracy point, the system behaves like a variable capacitor whose full width at half maximum depends linearly with temperature. We demonstrate this type of thermometer using a quantum dot in a silicon nanowire transistor. We drive cyclic electron tunneling by embedding the device in a radio-frequency resonator which in turn allows reading the thermometer dispersively. Overall, the thermometer shows potential for local probing of fast heat dynamics in nanoelectronic devices and for seamless integration with silicon-based quantum circuits.
An essential element in low temperature experimental physics is the thermometer. Sensors that link temperature to another physical quantity in an accurate, fast, stable, and compact manner are desired. If the link is done via a well-known physical law, the sensor is called a primary thermometer because it removes the need of calibration to a second thermometer.

Several primary thermometers have been developed for low temperature applications. A common technique is based on the Johnson-Nyquist noise of a resistor which can be used in combination with superconducting quantum interference devices to perform current-sensing noise thermometry (CSNT). Shot-noise thermometry (SNT) uses the temperature-dependent voltage scaling of the noise power of a biased tunnel junction. Coulomb blockade thermometry (CBT) makes use of charging effects in two-terminal devices with multiple tunnel junctions. A common technique is based on the thermal diode or thermal energy harvesters. In these systems, determining the local temperature in nanoelectronic devices, with a focus on adiabatic and ballistic transport, is capacitively coupled to a gate electrode. However, in all these cases, the sensors require a continuous flow of electrons from source to drain in two-terminal devices which, for particular experiments such as in single-molecule junctions and single-nanoparticle devices, might not be possible or even desirable.

Moreover, recent advances in device nanoengineering have led to a focused interest in using concepts from quantum thermodynamics to improve the efficiency of technologies such as the thermal diode or thermal energy harvesters. In these nanoelectronic devices, determining the local temperature in different reservoirs of the device is of particular relevance but challenging from an experimental perspective.

Here, we demonstrate a type of primary thermometer that uses cyclic electron tunneling to measure the temperature of a single electron reservoir without the need of electrical transport. The tunneling occurs between a system with a zero-dimensional (0D) density of states (DOS) in this case a quantum dot (QD)—and a single electron reservoir of unknown temperature. Our thermometer relates temperature and capacitance changes with a well-known physical law by using the ratio of electronic charge, which might be possible or even desirable.

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and this is depicted as a function of detuning in Fig. 1d. At large negative detuning the QD remains unoccupied \((P^0_1 = 0)\), at large positive detuning the QD is occupied \((P^0_1 = 1)\), and at \(\varepsilon = -k_B T \ln 2, P^1_1 = 1/2\). We calculate the tunneling capacitance of the system and obtain

\[
C_t = \frac{(ea)^2}{4k_B T \cosh^2 \left(\frac{e\varepsilon}{2k_B T}\right)}.
\]

where we have redefined the detuning \(\varepsilon\) to account for the peak-center shift induced by temperature \((\varepsilon \rightarrow \varepsilon + k_B T \ln 2)\). Thus the tunneling capacitance \(C_t\) has a full width at half maximum (FWHM) with respect to \(\varepsilon\) of

\[
\varepsilon_{1/2} = 4 \ln \left(\sqrt{2} + 1\right) k_B T,
\]

as plotted in Fig. 1e. Since \(\varepsilon_{1/2} = eaV_{1/2}\), the analysis shows it is possible to obtain the temperature of the electron reservoir from the FWHM of the \(C_t\) vs \(V_{1/2}\) curve once the gate lever arm \(a\) is known. The quantity \(V_{1/2}\) is the FWHM with respect to gate voltage. Furthermore, from Eq. (4) we see that the peak amplitude \(C_t^0\) of the tunneling capacitance \(C_t\) is inversely proportional to the reservoir temperature \(T\),

\[
C_t^0 \propto \frac{1}{T}.
\]

In the case of a finite magnetic field (see Supplementary Note 1), the expressions for \(\varepsilon_{1/2}\) and \(C_t^0\) remain as in Eqs. (5) and (6), respectively. We note that the \(C_t\) peak center shifts to lower detuning values as the magnetic field \(B\) is increased, see Supplementary Fig. 1a, b. The shift tends to \(\varepsilon(B) = \varepsilon(0) - g_B|\mu_B|B|/2\) for \(\mu_B|B| > k_B T\), where \(g\) is the electron g-factor and \(\mu_B\) is the Bohr magneton. This demonstrates our proposed method of determining the reservoir temperature \(T\) from capacitance \(C_t\) measurements is independent of magnetic field. We note that our analysis is valid as long as \(k_B T\) remains smaller than the discrete energy spacing in the QD (\(\Delta E\)) and larger than the QD level broadening \((\hbar \gamma)\). These two conditions set the temperature range in which thermometry by cyclic electron tunneling is accurate. In the latter case \((k_B T < \hbar \gamma)\), \(C_t\) takes a Lorentzian form given by

\[
C_t = \frac{(ea)^2}{\pi \hbar y} \frac{\hbar y}{(\hbar y)^2 + e^2}.
\]

and \(\varepsilon_{1/2}\) is given by \(2\hbar y\)\(^{30}\), and is thus no longer temperature dependent. The relaxation rate \(y\) is directly linked to the shape of the tunnel barrier between the QD and the reservoir which can be tuned electrically by, for example, a gate electrode. The tunneling capacitance \(C_t\) can be probed with high-frequency techniques such as gate-based reflectometry\(^{31,32}\) and can be used to measure temperature. We refer to this sensor as the gate-based electron thermometer (GET).

**Device and high-frequency resonator.** The device used here is a silicon nanowire field-effect transistor (NWFET)\(^{33}\) fabricated in fully-depleted silicon-on-insulator (SOI) following CMOS fabrication processes. At low temperatures, gate-defined QDs form in the channel of the NWFET\(^ {34,35}\), see Fig. 2a. The transistor has a channel length \(l = 44\) nm and width \(w = 42\) nm. The 8 nm thick NW channel was patterned on SOI above the 145 nm buried oxide (BOX). The gate oxide consists of 0.8 nm SiO\(_2\) and 1.9 nm HfSiON resulting in an equivalent gate oxide thickness of 1.3 nm. The top-gate (tg) is formed using 5 nm TiN and 50 nm polycrystalline silicon. The NW channel is separated from the highly doped source and drain reservoirs by 20 nm long Si\(_3\)N\(_4\) spacers. The silicon wafer under the BOX can be used as a global back-gate (bg).

To probe the device tunneling capacitance, we embed the transistor in a resonator formed by a 470 nH inductor—connected to the top-gate (tg) of the device—and the device parasitic capacitance \(C_{\text{par}}\) which appears in parallel with the differential capacitance of the device, as can be seen in Fig. 2a. We couple the resonator to a high-frequency line via a coupling capacitor \(C_c = 130\) fF. In order to characterize the resonator, we
measure the reflection coefficient \( \Gamma \). In Fig. 2b, we plot the magnitude \(|\Gamma|\) (data in blue and a fit in red) as a function of frequency \( f \) at a fixed back-gate voltage \( V_{bg} = 3 \) V. We extract the resonator’s natural frequency of oscillation, \( f_0 = \frac{1}{2\pi} \sqrt{\frac{L}{C_g + C_p}} \), which is 408 MHz, the bandwidth \( BW = 2.9 \) MHz, and the loaded quality factor \( Q_l = 141 \) and \( C_p = 194 \) fF. We find that the resonator is overcoupled but the depth of resonance, \( |\Gamma|_{min} = 0.18 \) indicates that the resonator is close to being matched to the line.

**The nature of cyclic electron tunneling.** A system with discrete energy levels \( E_0 \) and \( E_1 \) as described in the Sec. Theory, can be found in a 0D QDs where the DOS consists of a series of delta functions at discrete energies\(^36\). In this section, we demonstrate the discrete nature of the QD in NWFET using electrical transport measurements.

We measure the source-drain current \( I_{sd} \) as function of \( V_{sd} \) and source-drain voltage \( V_{sd} \). The source-drain current \( I_{sd} \) shows characteristic Coulomb blockade diamonds when measured as a function of \( V_{bg} \) and \( V_{sd} \), see Fig. 2c. Coulomb blockade diamonds are a signature of sequential single-electron transport through the QD from the source (s) to drain (d) reservoir. From the height of the Coulomb diamond in the charge stable configuration, we extract the QD first addition energy, \( E_{add} = 6 \) meV, and 3.75 meV for subsequent additions. Such a variable \( E_{add} \) is characteristic of the few-electron regime where transport occurs through single-particle (0D) energy levels.

When the QD has a 0D DOS and the source(s)d) reservoirs have a 3D DOS, then Fermi’s golden rule yields for the source (drain) tunnel rate

\[
y_{s(d)} = \frac{y_{0,s(d)}}{1 + \exp\left(-\frac{-\epsilon_{s(d)}}{k_BT}\right)},
\]

where \( \epsilon_{s(d)} \) is the level detuning between the QD and s(d) reservoirs and \( y_{0,s(d)} \) is the tunnel rate at \( \epsilon_{s(d)} = 0 \).\(^32\) Note that these tunnel rates are significantly different from metallic (3D DOS) QDs tunnel coupled to 3D reservoirs\(^37\). Assuming that a single discrete energy level of the QD is within the energy window \( \epsilon_{V_{sd}} \), the source drain current \( I_{sd} \) can be written in terms of tunneling rates \( \gamma_{V_{sd}} \) and \( \gamma_{sd} \) by the relation \( I_{sd} = e \gamma_{s} \gamma_{d}(\gamma_{s} + \gamma_{d}) \)\(^38\) and is fitted to the data measured at fixed \( V_{sd} = -1.5 \) mV in Fig. 2d. The agreement between the data and the fit demonstrates the QD nature of the QD, showing it is suitable for the electron thermometry method introduced in the Sec. Theory. Moreover, the top hat shape shows that there are no excited states within 1.5 meV of the ground state. Excited states at an energy comparable or lower than \( 2 \times 3.53k_BT \) could interfere with the method but the fit reveals they could only become an issue at temperatures \( T > 2.5 \) K.

**Gate coupling and optimal power.** In order to get an accurate reading of the temperature \( T \) from Eq. (5), the gate lever arm \( \alpha \) needs to be obtained. We use gate-based reflectometry techniques to probe the charge stability map of the QD in the voltage region of interest, see Fig. 2e taken at 50 mK. We excite the resonator at resonant frequency \( f_0 \) and monitor the reflected signal. We used standard homodyne detection techniques\(^32\) to measure the demodulated phase response \( \varphi \) of the resonator as a function of \( V_{sd} \) and \( V_{bg} \). The phase of the resonators changes (dark blue lines I and II in Fig. 2e) at the charge degeneracy points due to a tunneling capacitance contribution. The separation in \( V_{tg} \) between I and II, \( \Delta V_{tg} \), at a given \( V_{sd} \) gives a measurement of \( \alpha = \frac{V_{sd}}{\Delta V_{tg}} \). We repeat these measurements for several \( V_{sd} \) and obtain \( \Delta V_{tg} \) as a function of \( V_{sd} \) providing a measure of \( \alpha \) from the slope and of the \( V_{td} \) offset from the intercept. We obtain \( \alpha = 0.9 \pm 0.01 \), and this large value — close to 1 — is consistent with the multi-gate geometry and the small equivalent gate oxide thickness of 1.3 nm of NWFETs\(^32\). We consider a temperature-independent\(^5,39\) because the capacitances that define \( \alpha \) are determined by the geometry of the device and the voltage bias applied to the electrodes which we keep constant throughout the range of temperatures measured.

Finally, we calibrate the optimal power on the resonator using transition II at \( V_{sd} = -1.5 \) mV, which we will subsequently use to perform thermometry. In Fig. 2f, we plot \( \epsilon_{s(d)} \) as a function of the carrier power \( P_c \) at the input of the resonator. At high carrier power, \( P_c > 93 \) dBm, \( \epsilon_{s(d)} \) increases with \( P_c \) indicating the transition is power broadened. For \( P_c < -93 \) dBm, \( \epsilon_{s(d)} \) remains independent of \( P_c \) and hence, we observe the intrinsic linewidth of the transition. We select \( P_c = -95 \) dBm hereinafter.

**Primary thermometry.** In this section, we explore experimentally gate-based primary thermometry using transition II (see Fig. 2e). As we have seen in the Sec. Theory, when \( \hbar \omega_0/2 \gamma > f_0 \), electron tunneling between QD and reservoir has an associated tunneling capacitance whose \( \epsilon_{s(d)} \) gives a reading of the reservoir temperature (see Eq. (5)). In this experiment, we probe \( T \) as a function of \( \varphi \), by \( \varphi = -2\epsilon_{s(d)}C_p/C_T \) when the resonator is overcoupled to the line. We drive the resonator at frequency \( f_0 \) and monitor \( \varphi \) as we sweep \( T \) across the charge degeneracy for different temperatures of the mixing chamber \( T_{mc} \) in Fig. 3a. We measure \( T_{mc} \) with a 2200 Q RuO\(_2\) resistive thermometer. As the temperature is increased, \( \epsilon_{s(d)} \) increases and the maximum phase shift decreases. We fit the data to Eq. (4) (red dotted lines), extract \( \epsilon_{s(d)} \) for several \( T_{mc} \) and plot it in Fig. 3b (black dots). Two clear temperature regimes become apparent:

At low temperatures, for \( T_{mc} < 200 \) mK, we see that \( \epsilon_{s(d)} \) is independent of \( T_{mc} \) and equal to 160 \( \mu \)eV (blue dotted line). In this regime, as we shall demonstrate later, the thermal energy is smaller than the QD level broadening (\( k_BT < h\varphi \)). As a result, the temperature reading of the GET, \( T_{GET} \), deviates from the mixing chamber thermometer. On the other hand, at high temperatures, \( T_{mc} > 1 \) K, we observe that \( \epsilon_{s(d)} \) presents a linear dependence with \( T_{mc} \) as predicted by Eq. (5). For comparison, we plot the theoretical prediction (red dashed line) and observe that both follow a similar trend. In this regime, since \( h\varphi < k_BT \), the GET can be used to obtain an accurate reading of the temperature of the electron reservoir. We quantify the precision of the thermometer by measuring the fractional uncertainty in the temperature reading of the gate-based thermometer, \( \Delta T_{GET}/T_{GET} \) (see Fig. 3c).

At low temperatures, the precision of the thermometer is primarily determined by the uncertainty in the lever arm, \( \delta\alpha/\alpha = 1.1\% \). As we raise the temperature, the phase response of the resonator becomes smaller leading to an increase in the uncertainty of \( \epsilon_{s(d)} \), which, at the highest temperatures, becomes comparable to that of \( \alpha \). We find \( \delta T_{GET}/T_{GET} \) increases up to 1.6%. Additionally, in Fig. 3d, we determine the fractional accuracy of the GET thermometer, \( \Delta T/T_{mc} \) by comparing its reading with that of the RuO\(_2\) thermometer (\( \Delta T = T_{GET} - T_{mc} \)). We see that the discrepancy between thermometers is less than \( 8\% \) for temperatures higher than 1 K and this goes down to an average of 3.5% above 1.5 K. The error in the accuracy is primarily determined by the uncertainty in the reading of the RuO\(_2\) thermometer, which varies from 1% at the lowest temperatures to 6% at 2.4 K, rather than by the precision of the GET.

We note that, although not applicable for primary thermometry purposes, the whole temperature range can be described by a single expression that combines both regimes, level-broadening...
and thermal broadening, in to a single expression $\epsilon_{1/2} = \sqrt{(3.53 k_B T)^2 + (2 h y)^2}$ (see magenta dashed line in Fig. 3b). This formula fits well the data and we find that the difference is <6% for all temperatures.

Lastly, in Fig. 3c, we plot the maximum phase shift $\phi^0$ extracted from the fit, as a function of $T_{mc}$. Again, the two regimes are apparent. At low temperatures $\phi^0$ remains constant and only at temperatures $T_{mc} > 1 K$, $\phi^0$ shows an inverse proportionality with $T_{mc}$ as predicted by Eq. (6) (dashed red line).

Low temperature limit. In Fig. 3b, e, we have seen that at low temperatures both $\epsilon_{1/2}$ and $\phi^0$ deviate from the prediction in Sec. Theory. In this regime, the gate-sensor cannot be used as an accurate thermometer. Two mechanisms may be responsible for this discrepancy: Electron-phonon decoupling, due to the weaker interaction at low $T$, or lifetime broadening, when the QD energy levels are broadened beyond the thermal broadening of the reservoir, which occurs when $h y > k_B T$. In the latter case, $\epsilon_{1/2}$ is given by $2 h y$ (see Eq. (7)) whereas for the former, it is given by $3.53 k_B T_{dec}$, where $T_{dec}$ is the decoupling temperature.

To assess the origin of the discrepancy, we modify the tunnel barrier potential by varying the vertical electric field across the device (Fig. 4a) which effectivly changes $y$. We do so by changing the potential on the back-gate electrode $V_{bg}$ while compensating with $V_{lg}$. In Fig. 4b, we plot $\epsilon_{1/2}$ as a function of $V_{bg}$. We see that as we lower $V_{bg}$, $\epsilon_{1/2}$ decreases, indicating that the tunnel rate $\gamma$ across the potential barrier is lower due to the increasing height of the potential barrier at lower $V_{bg}$. This trend indicates that at low temperature, our primary thermometer is limited by level broadening and not by electron-phonon decoupling. Moreover, it demonstrates it is possible to tune electrically the low temperature range of the primary thermometer, as long as $\gamma$ remains larger than the excitation frequency $f_0$.

Discussion

We have described and demonstrated a novel primary electron thermometer based on cyclic electron tunneling that allows measuring the temperature of a single electron reservoir without the need of electrical transport. The GET requires of a system with discrete energy levels tunnel-coupled to the reservoir to be measured, a scenario that can be found in a broad range of nanoelectronics devices such as single-molecule junctions and/or in single-electron devices. Here, we have implemented the thermometer with a QD using CMOS technology which makes it ideal for large-scale production. Driving and readout of the thermometer can be performed simultaneously using reflectometry techniques which have recently demonstrated high-sensitivity with MHz bandwidth. Since the driving must be...
done in the adiabatic limit, the GET is likely to show low shelf heating. Moreover, the technique is not affected by external magnetic fields. We have shown accurate primary thermometry down to 1 K and have proven that the low temperature range can be electrically tuned in situ. For sub-10 mK operation, low transparency barriers and driving resonators with sub-200 MHz resonant frequencies should be used to ensure the thermometer is operated in the adiabatic limit and other materials such as GaAs could be used to improve the electron-phonon coupling.

When compared with other low-temperature primary electron thermometers, the GET presents some advantages and disadvantages. The GET requires a single tunnel barrier, similar to the SNT, but only a single reservoir. Both sensors must be probed by high-frequency techniques which provides an enhanced bandwidth over quasi-static measurements. However, the GET is unlikely to have the large dynamic range of the SNT since high temperature limit in the GET is set by quantum confinement. When compared to the CBT, which requires multiple tunnel barriers, the GET fabrication process is simpler with the trade-off that a low-temperature high-frequency amplification set-up is required but with the added benefit of the larger bandwidth. All three methods are independent of magnetic field as long as normal metals are used.

Overall, our thermometer shows potential for local probing of fast heat dynamics in nanoelectronic devices and it may have applications in the better study of thermal single-electron devices such as rectifiers and energy harvesters. Moreover, since the device is made using silicon technology it could naturally be integrated with silicon-based quantum circuits.

Methods

Device fabrication. The device used in this manuscript is fabricated on SOI substrate above the 145 nm buried oxide (BOX)13. The 8 nm thick NW channel pattern is channel is patterned using deep ultraviolet lithography (193 nm) followed by resist trimming process. For the gate stack, 1.9-nm HfSiON capped by 5 nm TiN and 50 nm polycrystalline silicon were deposited. The Si thickness under the HfSiON/TiN gate is 11 nm. After gate etching, a Si layer (thickness 10 nm) was deposited and etched to form a first spacer on the sidewalls of the gate. 18-nm-thick Si raised source and drain contacts were selectively grown before the source/drain extension implantation and activation annealing. Then a second spacer was made from 0.8-mm-thick Rogers RO4003C laminate with an immersion silver finish. The re...

Acknowledgements
We thank Jonathan Prance for providing useful comments. This research has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under grant agreement No 688539 (http://mos-quito.eu), No 732894 (FET Proactive HOT) and the Winton Programme of the Physics of Sustainability. I.A. is supported by the Cambridge Trust and the Islamic Development Bank. A.C. acknowledges support from the EPSRC Doctoral Prize Fellowship.

Author contributions
M.F.G.Z. devised the experiment. I.A., A.C., and M.F.G.Z. performed the experiment. S.B. fabricated the sample. I.A., J.A.H., J.J.L.M., and M.F.G.Z. analyzed the data. All authors contributed in the writing of the manuscript.

Additional information
Supplementary Information accompanies this paper at https://doi.org/10.1038/s42005-018-0066-8.

Competing interests: The authors declare no competing interests.

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