Cooling electrons in nanoelectronic devices

Yuri Pashkin

Lancaster University, UK

24 April 2019

Physics | Lancaster University

International collaboration

Lancaster (UK)

Ian Bradley, Richard George, Tony Guénault, Rich Haley, Stephen Holt, Alex Jones, Yuri Pashkin, Jon Prance, Matthew Sarsby†

Aivon Oy (Finland)

Jari Penttila, Leif Roschier*

VTT (Finland)

David Gunnarsson*, Hannele Heikkinen, Leif Grönberg, Kestutis Grigoras, Mika Prunnila

(* Now at Bluefors Cryogenics)
(† Now at TU Delft)

Bradley et al., Nat. Commun. **7**, 10455 (2016)
Bradley et al., Sci. Rep. **7**, 45566 (2017)

Timeline of low- temperature technology

Physics | Lancaster University

The Joule–Thomson effect (1850s) = gas temperature decreases when the gas expands in vacuum

1870s: nitrogen is liquefied

1892: James Dewar invented the vacuum-insulated, silver-plated glass Dewar flask

1898: James Dewar liquefies hydrogen

1908: Kamerlingh Onnes liquefied He4, and discovered superconductivity in 1911

1913 

1933: adiabatic demagnetization refrigeration

1937: He4 seen flowing without resistance – the first superfluid

1978 

1951: dilution refrigerator invented, the main tool in reaching low-temperatures

1972: superfluidity discovered in He3

1996 

Benefits of low temperatures

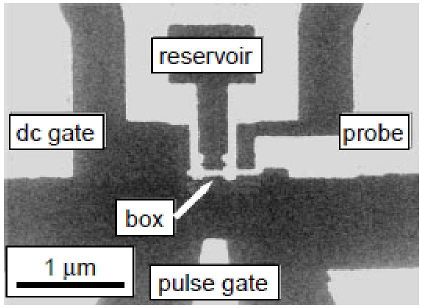
Reducing thermal fluctuations leads to the observation of new phenomena.

- Collective behaviours emerge (e.g. superconductivity and superfluidity in some materials) as thermal fluctuations are reduced
- Statistical occupation of states can become different (e.g. Bose-Einstein condensation)
- Quantum coherence in solid-state devices (qubits)
- And more…

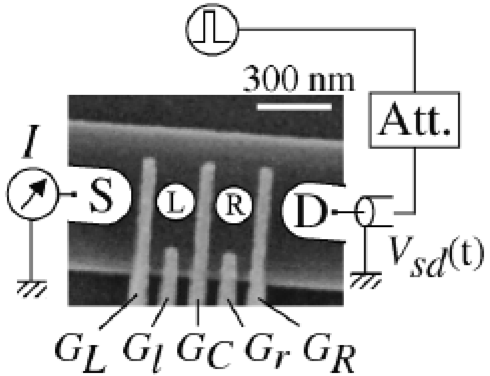
Applications of cold nanoelectronics

(a few examples)

Superconducting and semiconductor qubits



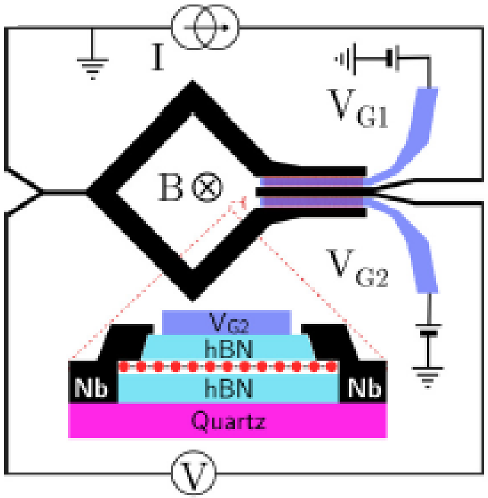
Y. Nakamura, Yu.A. Pashkin, J.S. Tsai, Nature **398**, 786 (1999)



T. Hayashi et al., PRL **91**, 226804 (2003)

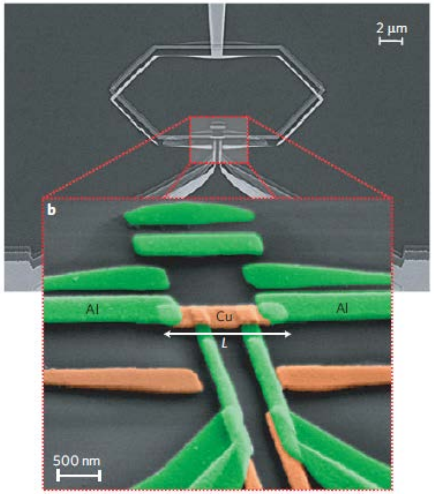
New SQUID-like magnetometers based on the superconducting proximity effect

SQUID with graphene junctions



Thompson et al., APL **110**, 162602 (2017)

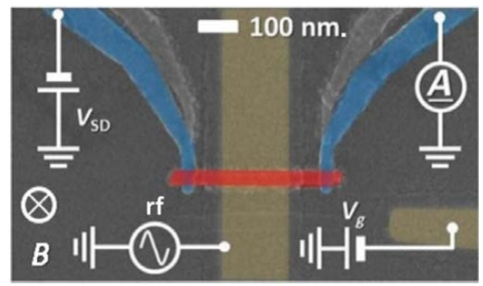
"SQUIPT" with copper junctions



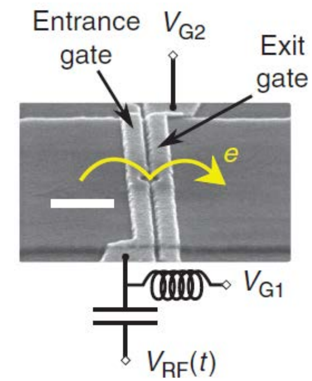
Giazotto et al., Nature Physics **6**, 254 (2010)
Ronzani et al., Phys. Rev. Appl. **2**, 024005 (2014)

Applications of cold nanoelectronics

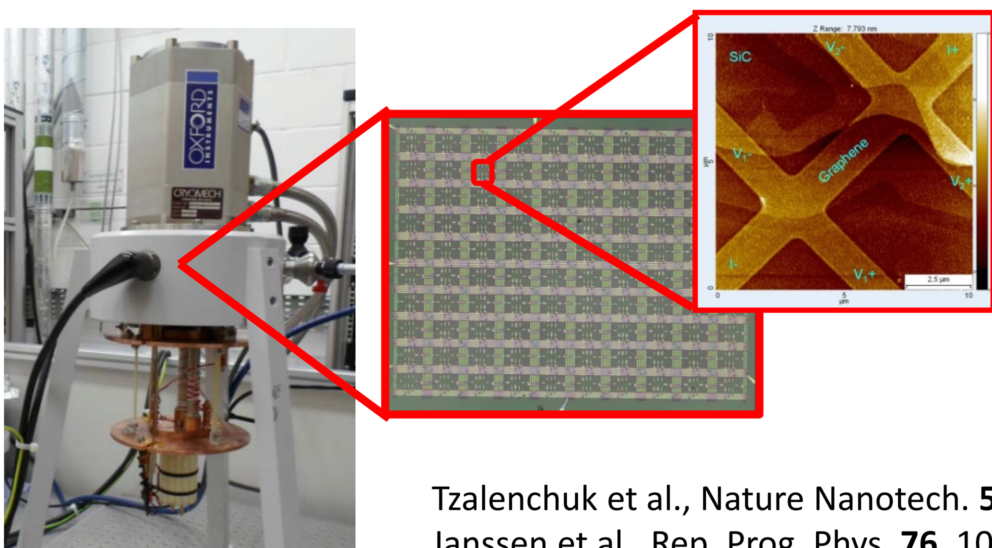
Single-electron charge pumps for new metrological definition of the Ampere



S. Nakamura et al.
Phys. Rev. Appl. **7**, 054021 (2017)



S.P. Giblin et al.
Nat. Commun. (2012)



Resistance standards based on the quantum Hall effect in graphene

Tzalenchuk et al., Nature Nanotech. **5**, 186 (2010)
Janssen et al., Rep. Prog. Phys. **76**, 104501 (2013)

How cold do we need to go?

It depends…

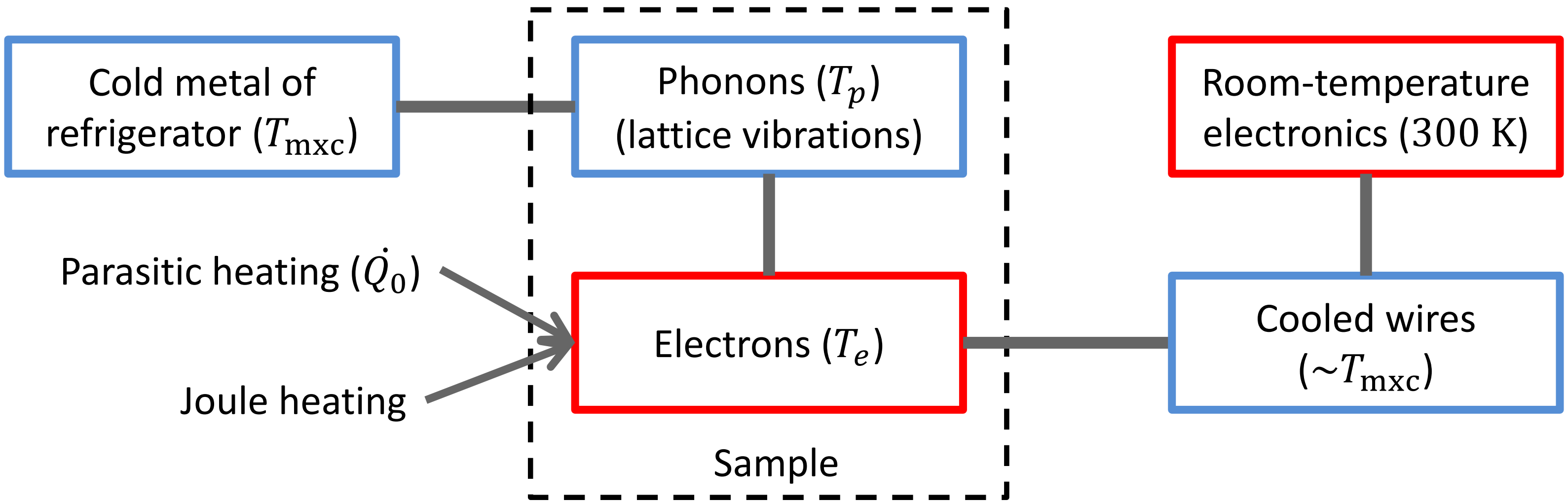
$300\ \mathrm{K}$	Quantum Hall effect in graphene.
$< 130\ \mathrm{K}$	High-temperature superconductivity, HTS SQUIDs, filters, etc.
$\sim 4\ \mathrm{K}$	Quantum Hall effect in high-mobility semiconductors (e.g. GaAs). Metrology-level resistance quantisation in graphene QHE. Nb-based SQUIDs, RSFQ circuits.
$10 - 100\ \mathrm{mK}$	Solid-state qubits, Coulomb blockade devices, etc.
$\sim 10\ \mathrm{mK}$	Fractional quantum Hall effect, engineered topological states, manipulation of single microwave phonons.
$\ll 10\ \mathrm{mK}$…. ?	

A few physical systems have been studied extensively at lower temperatures (e.g. superfluid ^{3}He), but nanoelectronic structures have not yet been explored.

Cooling a nanoelectronic sample

Physics | Lancaster University

Normal method: attach your sample to the coldest point of the refrigerator.



Problem: electron-phonon coupling is very weak in small structures at low temperatures.

Heat flow from the electrons to the phonons:

$$\dot{Q} = \Sigma\Omega\left(T_e^5 - T_p^5\right)$$

F.C. Wellstood et al., PRB **49**, 5942 (1994)

Electrons in the sample are often at a different temperature to the phonons

= **hot-electron effect**

The scale of the effect

Take a Cu cube of size 100nm x 100nm x 100nm

$\Sigma \approx 10^9$ W/(m^{3}K^5)

Set $T_p = 0$

$$T_e = (\dot{Q}/\Sigma\Omega)^{1/5}$$

Dissipated power $\dot{Q}$	**1 pW**	**1 fW**	**1 aW**
Effective electron *T*	**1 K**	**250 mK**	**63 mK**

Very weak dependence of T_e due to 1/5 power

Physics | Lancaster University

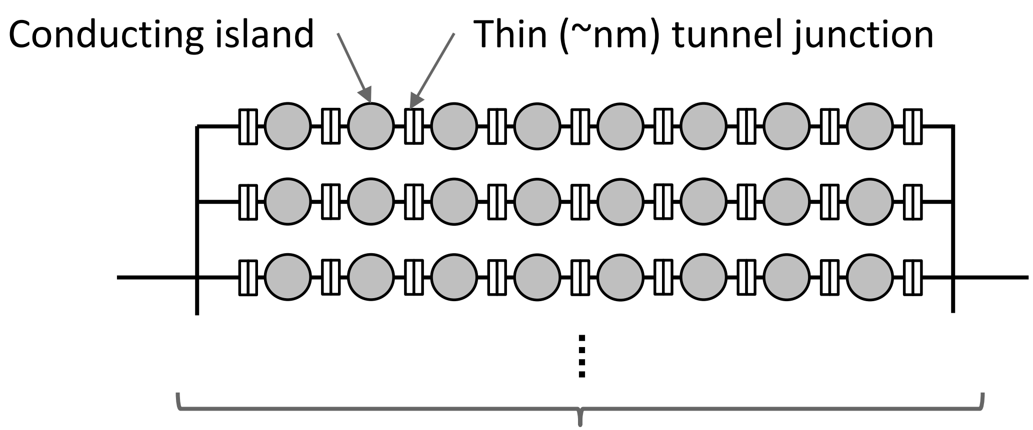
Primary electron thermometry: Coulomb Blockade Thermometer

VOLUME 73, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 1994

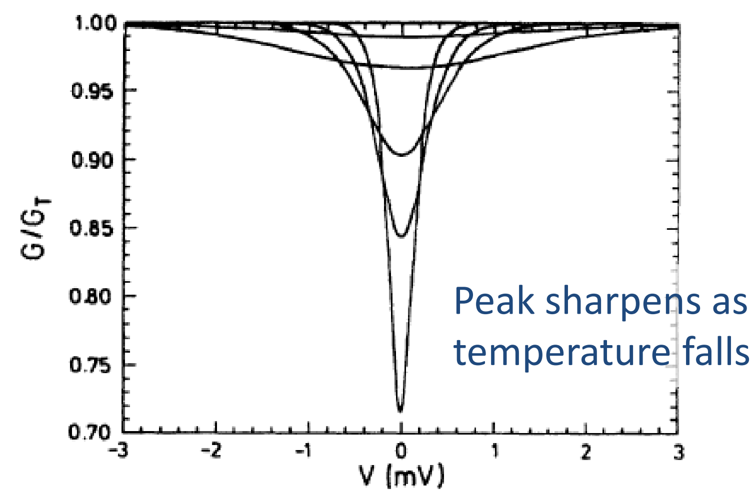
Thermometry by Arrays of Tunnel Junctions

J. P. Pekola, K. P. Hirvi, J. P. Kauppinen, and M. A. Paalanen
Laboratory of Applied Physics, Department of Physics, University of Jyväskylä, P. O. Box 35, 40351 Jyväskylä, Finland
(Received 13 July 1994)

We show that arrays of tunnel junctions between normal metal electrodes exhibit features suitable for primary thermometry in an experimentally adjustable temperature range where thermal and charging effects compete. I-V and dI/dV vs V have been calculated for two junctions including a universal analytic high temperature result. Experimentally the width of the conductance minimum in this regime scales with T and N, the number of junctions, and its value (per junction) agrees with the calculated one to within 3% for large N. The height of this feature is inversely proportional to T.



Measure total conductance G of array as a function of bias voltage V



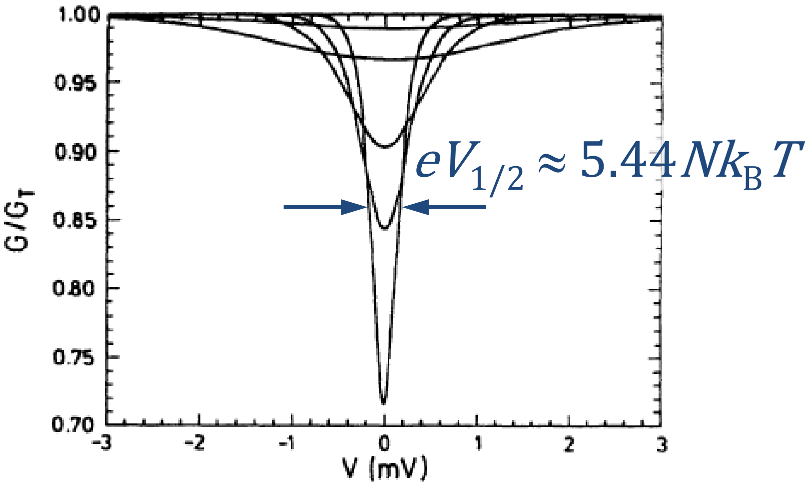
Primary electron thermometry: Coulomb Blockade Thermometer

$$k_B T \gg E_C = {e^2}/{2C_\Sigma}$$

seemed to be absolutely useless regime, but appeared to be extremely useful.

Primary thermometer:
$V_{1/2} \approx 5.439 N k_B T/e$

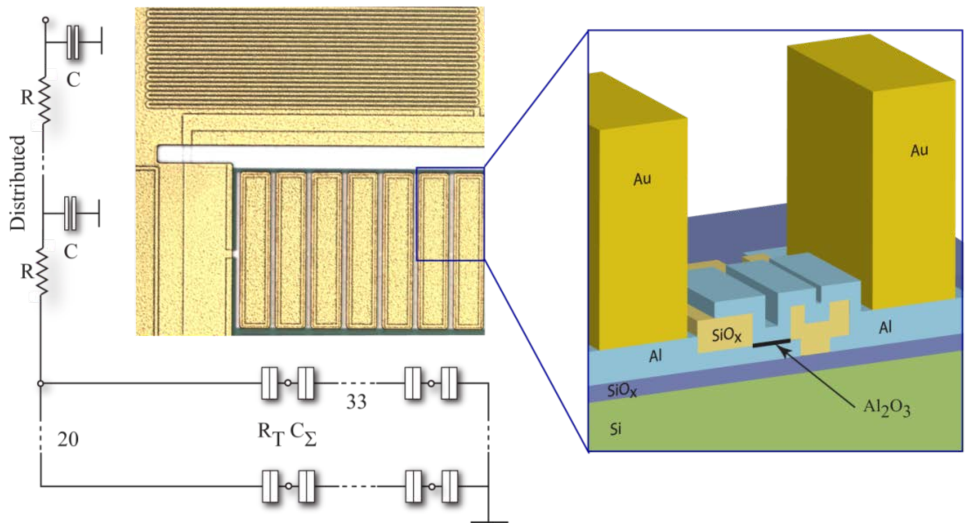
Secondary mode:
$G(0) = G_T(1 - u/6 + \dots)$
$u = (e^2/C_\Sigma)/k_B T$



VTT/Aivon CBT design

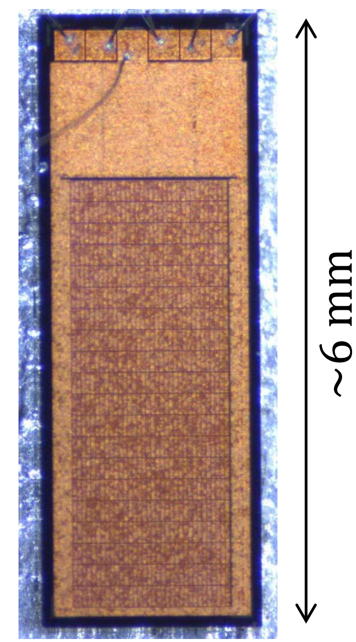
Optimised for sub-10mK operation:

- **On-chip, distributed RC filters.**
- **Large cooling fins (≈ 205 x 40 x 5 µm^3) provide electron-phonon coupling**
- **32 × 20 arrays of Al islands**

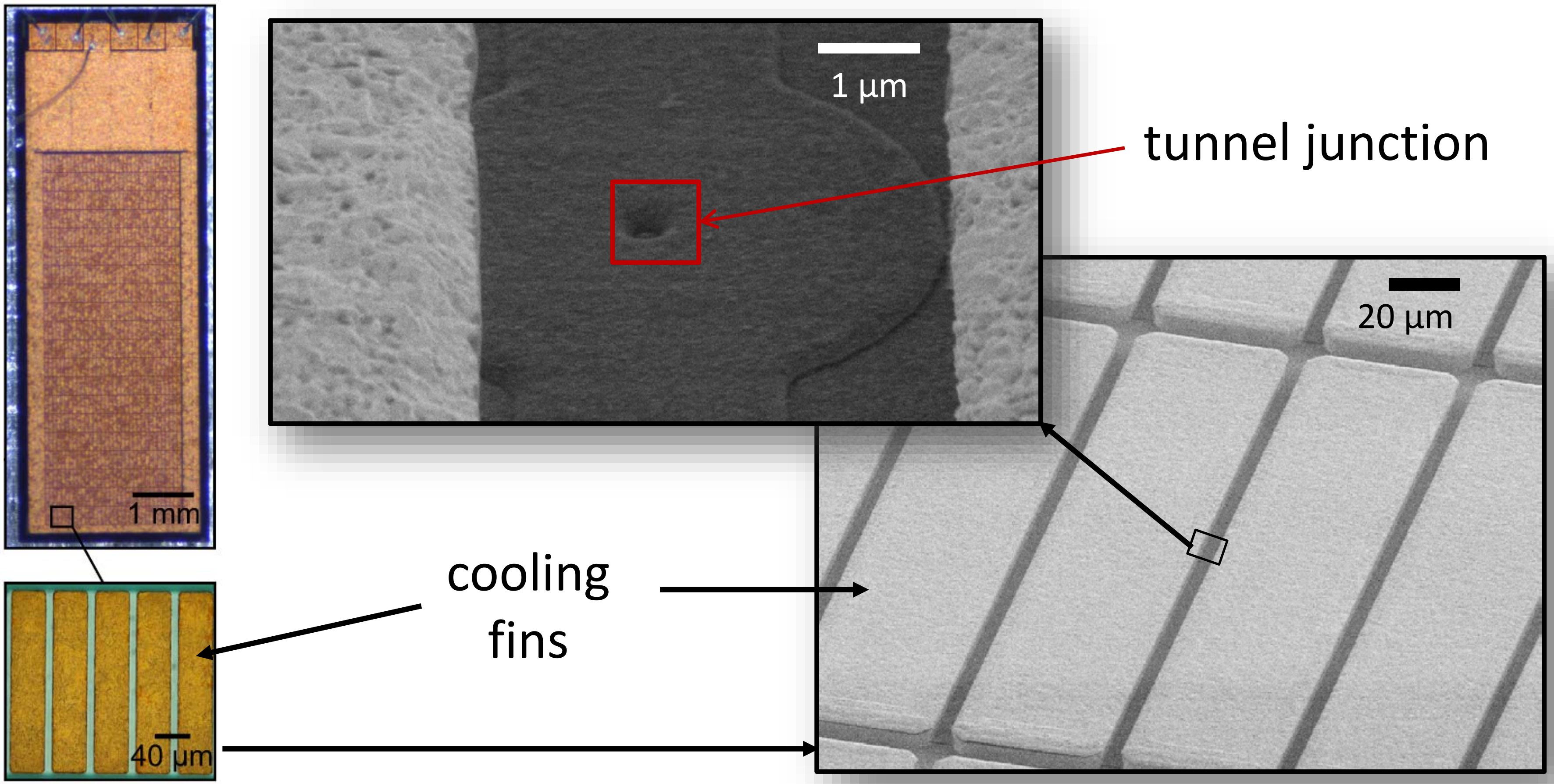


Some measurements were made with products from Aivon (Finland)

- PA-10 current source and voltage preamplifier
- Low-temperature RC filters

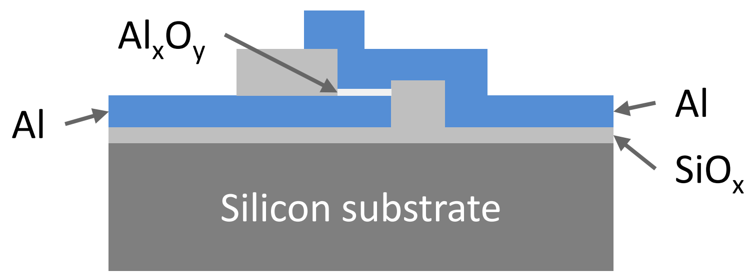


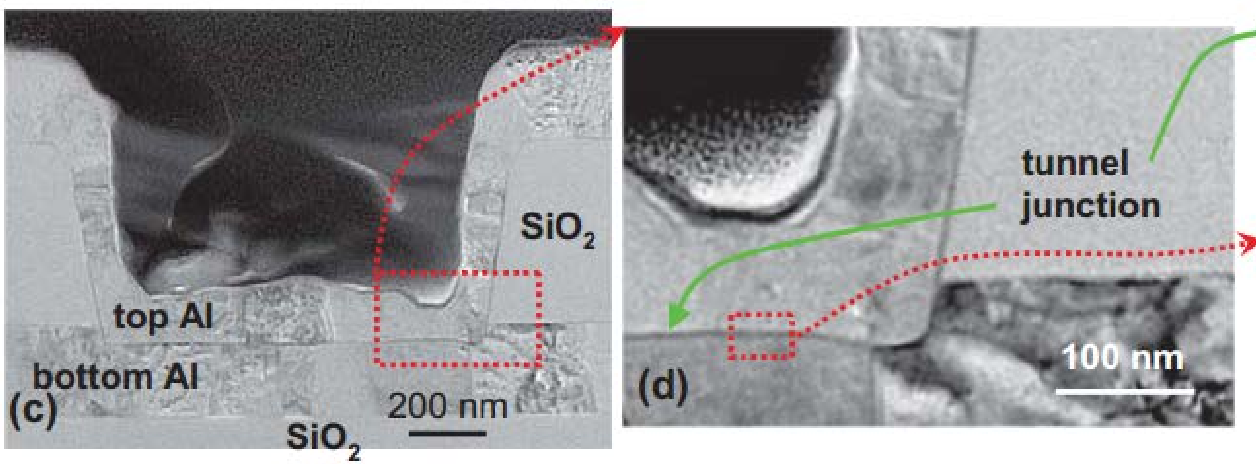
CBT fabrication

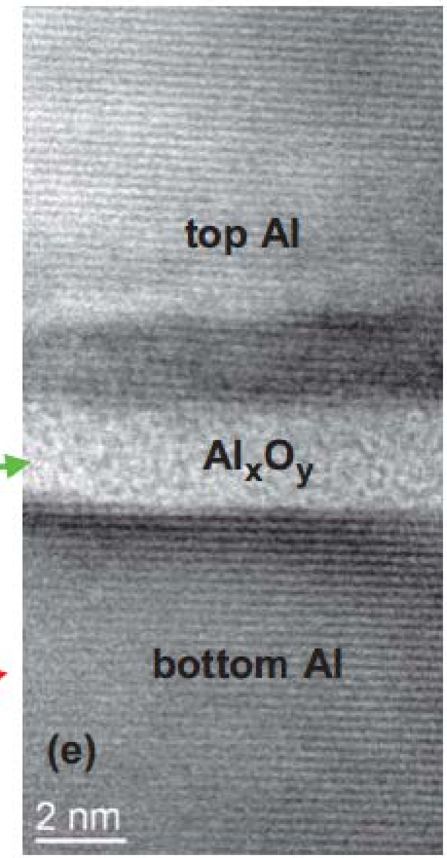


CBT fabrication

Instead of the commonly used angle deposition, a multi-layer ex-situ process was used







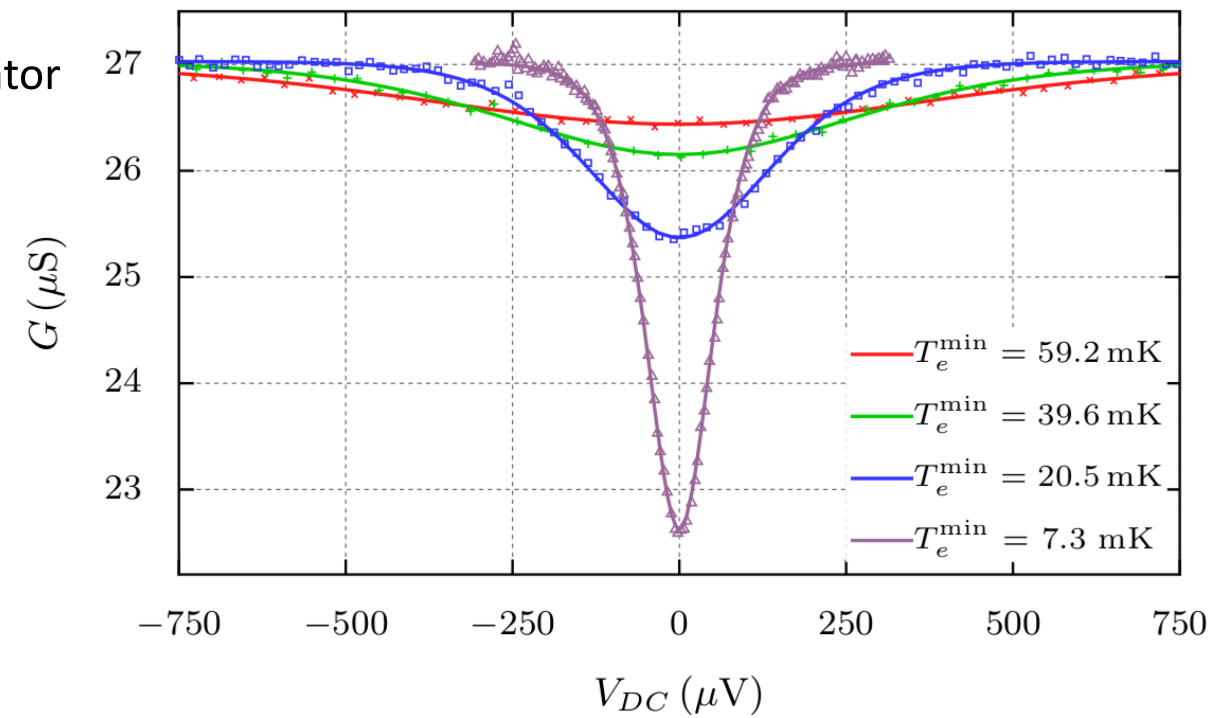
Prunnila et al., J. Vac. Sci. Tech. B **5**, 1026 (2010)

CBT performance down to 7 mK

Physics | Lancaster University

Bradley et al., Nat. Commun. **7**, 10455 (2016)

Measured in a commercial, cryogen-free dilution refrigerator (BlueFors Cryogenics LD250)



Warmest three isotherms are fitted (simultaneously) to calibrate the CBT. The fit gives $C_\Sigma = 236.6$ fF and $R_T = 22.42$ kΩ

The actual temperature of the measurements does not need to be known because the CBT is a primary thermometer.

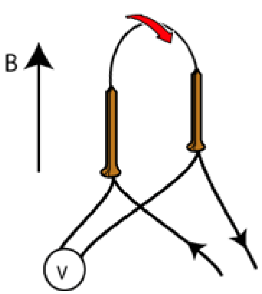
The fitted C_Σ and R_T are used to relate peak height to electron temperature.

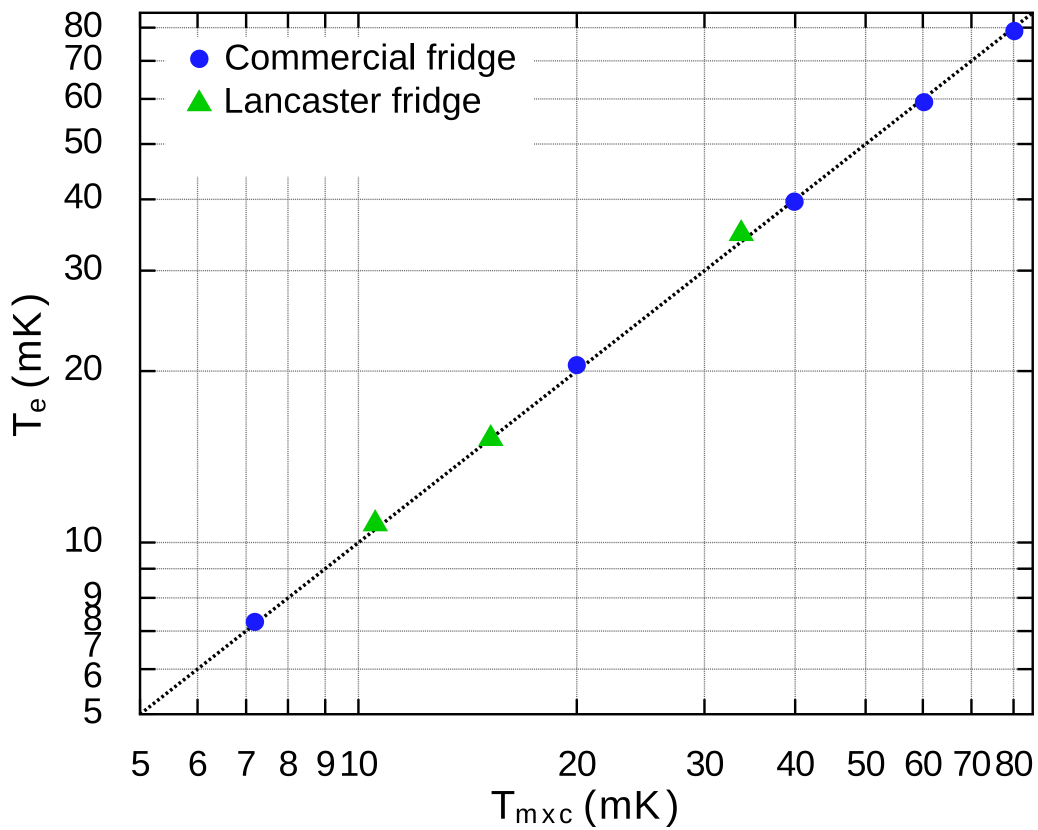
CBT performance down to 7 mK

The same CBT was also measured in a custom dilution refrigerator (Lancaster design)

In the commercial fridge, base temperature (T_{mxc}) is measured using a calibrated RuO_2 resistor.

In the custom fridge, T_{mxc} is determined from viscosity of the refrigerant, measured using a vibrating wire loop.





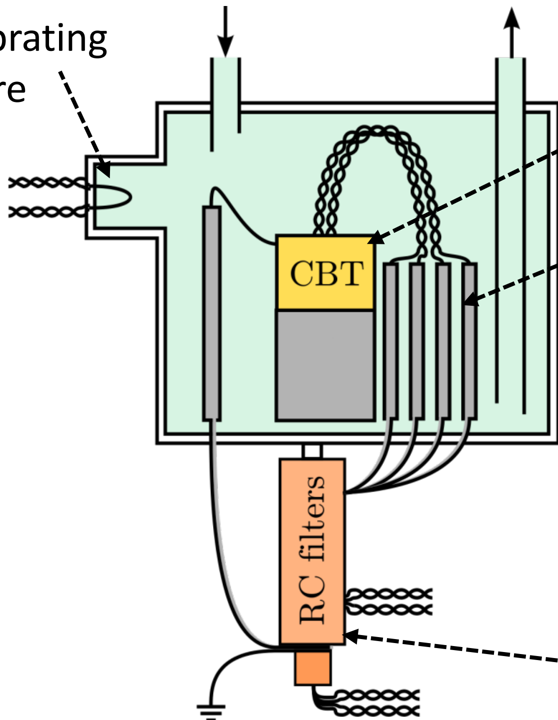
The CBT temperature T_e matches the refrigerator temperature T_{mxc} down to ≈ 7 mK

CBT immersed in $^3He/^4He$ mixture

Physics | Lancaster University

A cell was built to immerse a CBT in the mixing chamber of a dilution fridge

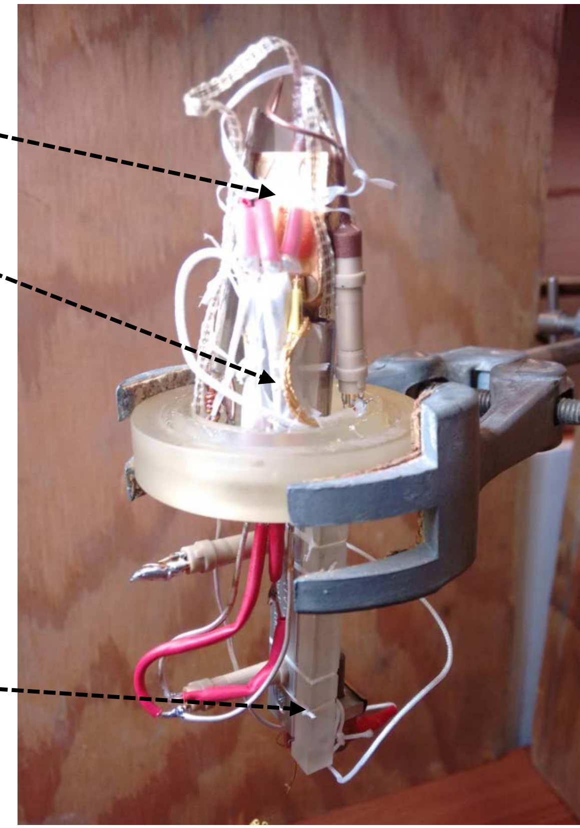
Vibrating wire



CBT package

Sintered silver heat-sink (x 6)

RC filters, connected to sinter pad inside mixing chamber.

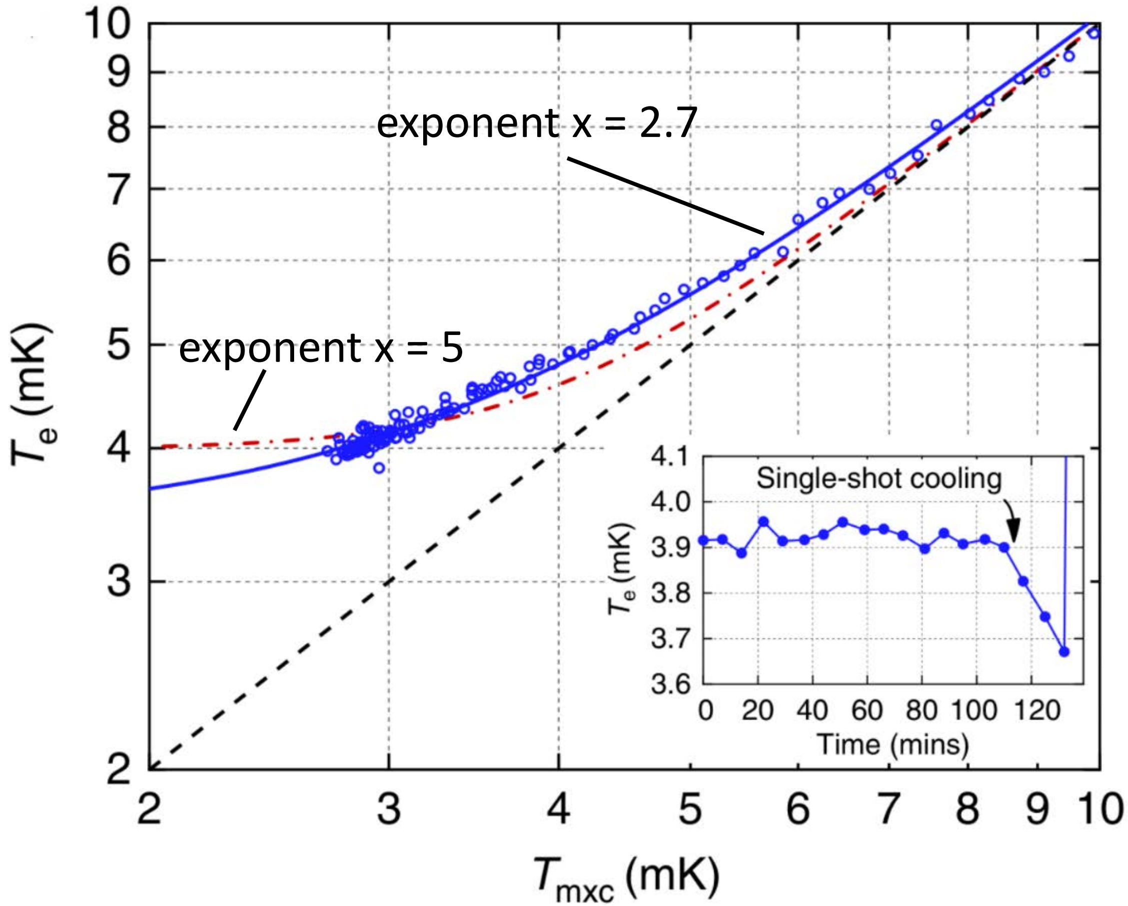


Blocks of sintered silver powder make excellent thermal contact with the refrigerant due to their high porosity and immense service area.

CBT immersed in $^3He/^4He$ mixture

Physics | Lancaster University

Bradley et al., Nat. Commun. **7**, 10455 (2016)

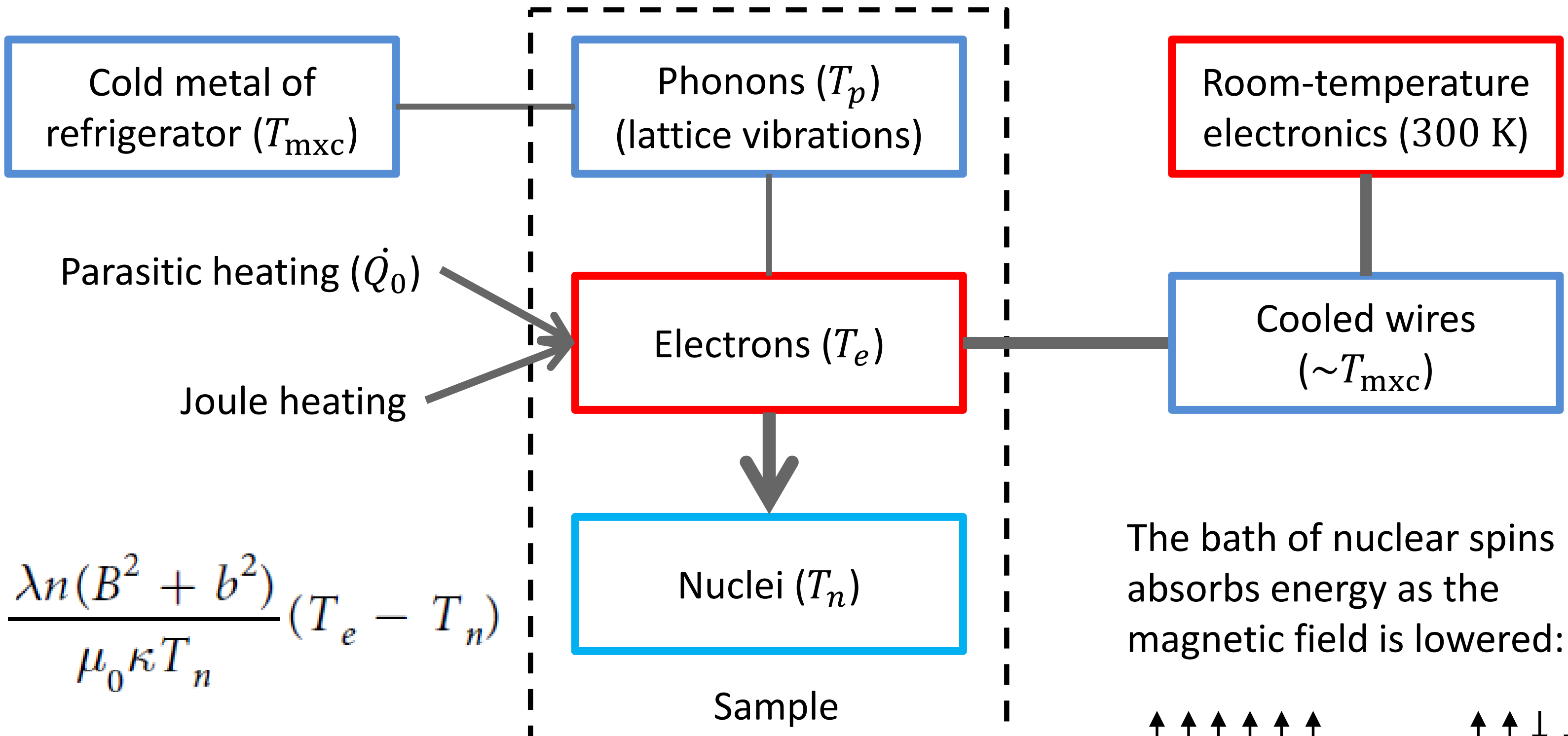


Below $7\ \mathrm{mK}$, the electron temperature reported by the CBT no longer agrees with the temperature of the refrigerator (as measured by a vibrating wire viscometer)

$\Rightarrow$ Electrons and phonons not in thermal equilibrium.
Cooling through direct contact is insufficient.

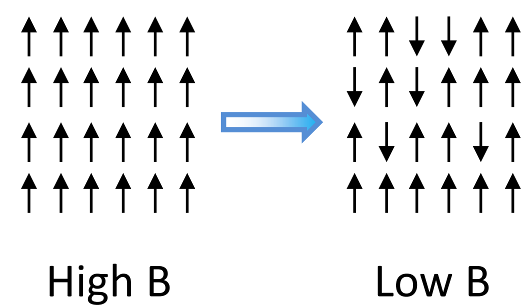
On-chip magnetic cooling

New method: cool on-chip electrons directly through the magnetocaloric effect



$$\dot{Q}_{en} = \frac{\lambda n (B^2 + b^2)}{\mu_0 \kappa T_n}(T_e - T_n)$$

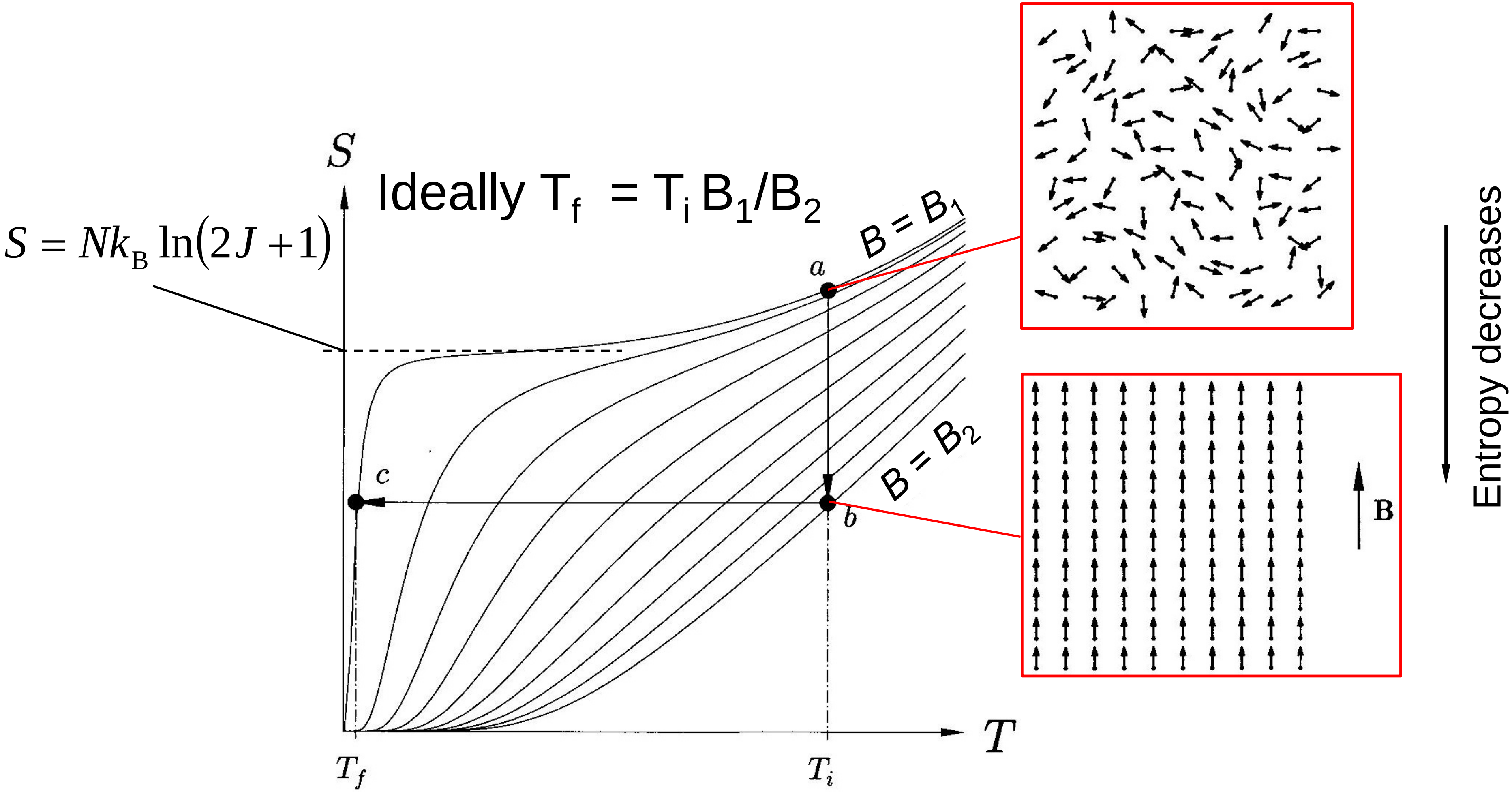
The bath of nuclear spins absorbs energy as the magnetic field is lowered:



Weak electron-phonon becomes an advantage: electrons are isolated from their host lattice.

Cooling by adiabatic demagnetization

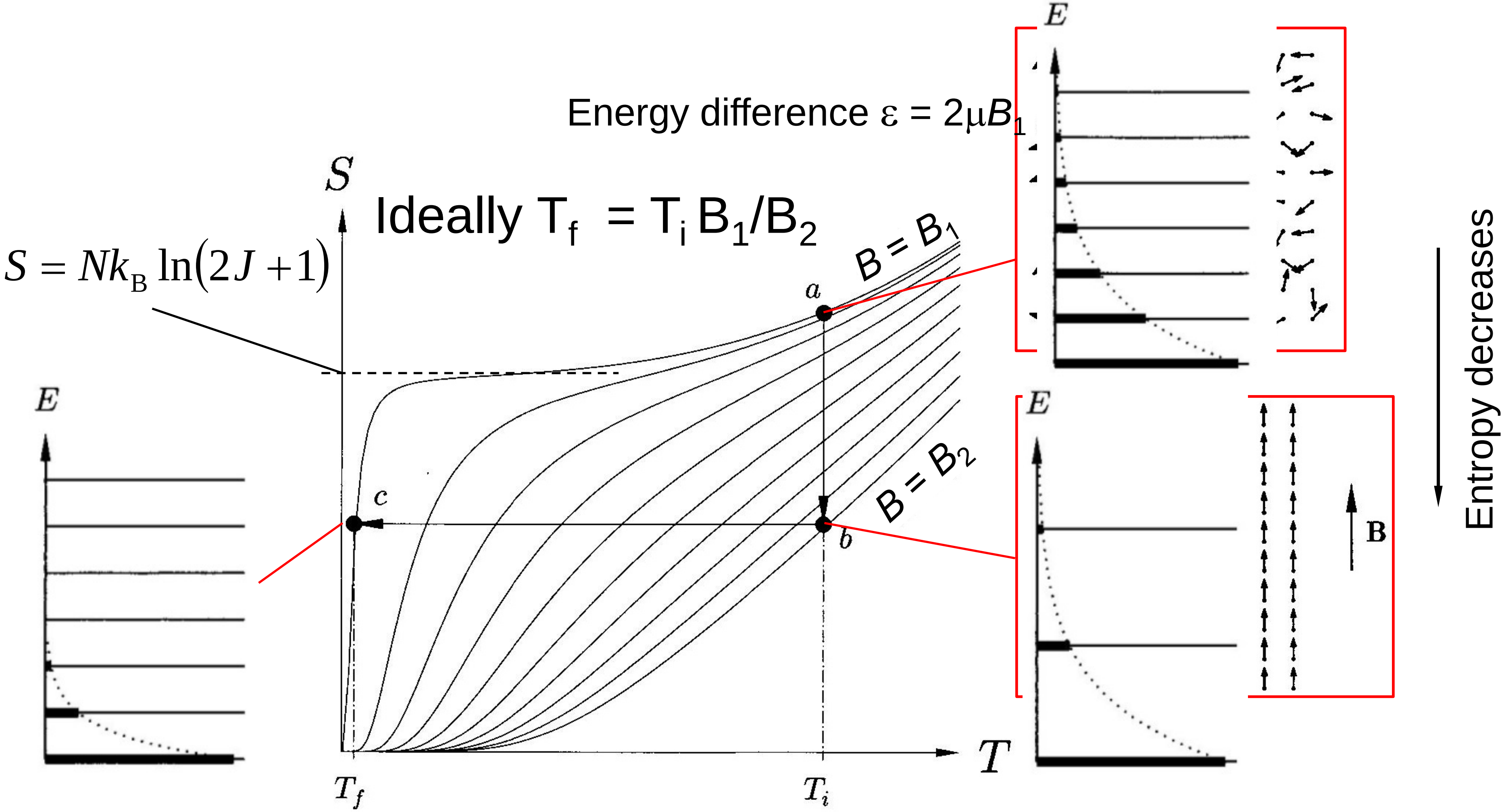
spin system in a magnetic field



For isentropic process: B/T = const

Cooling by adiabatic demagnetization

spin system in a magnetic field



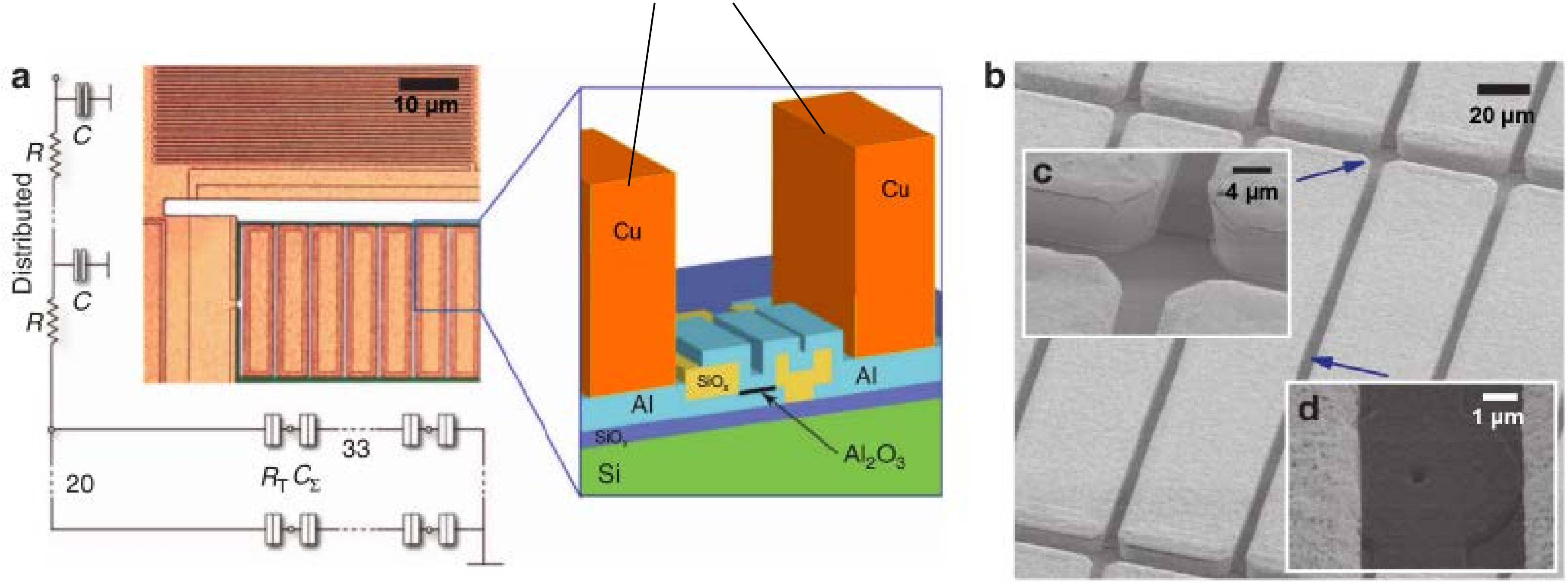
For isentropic process: B/T = const

CBT design for on-chip cooling

Physics | Lancaster University

Same an ex-situ tunnel junction process used

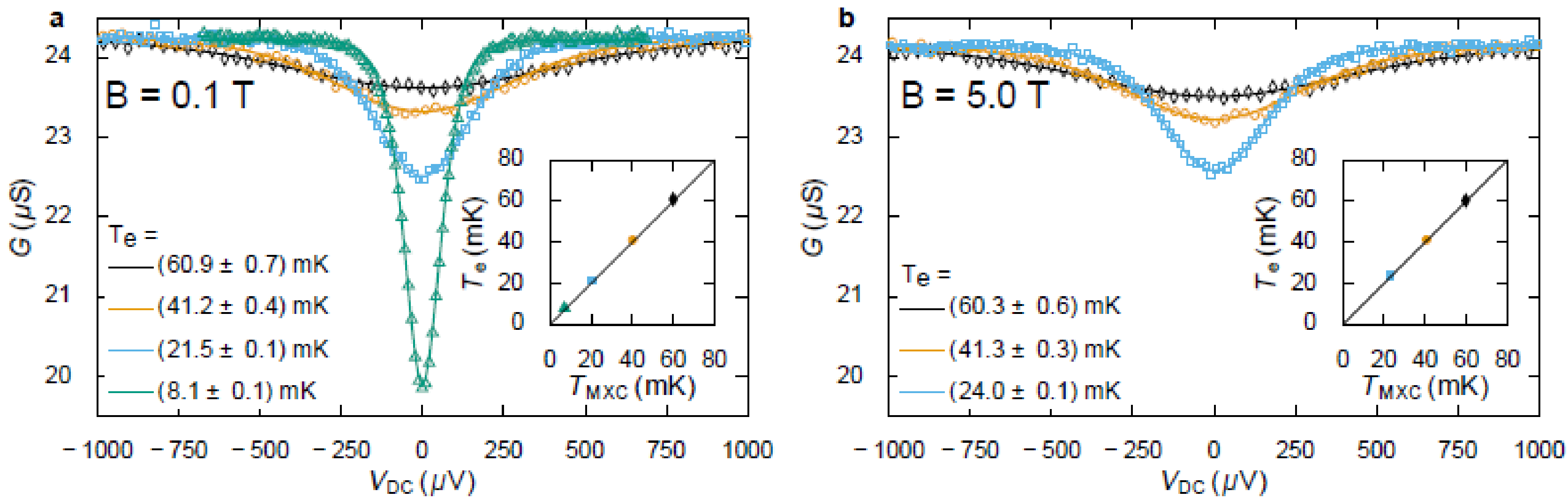
Cu nuclei used as refrigerant for electrons



Prunnila et al., J. Vac. Sci. Tech. B **5**, 1026 (2010)

Sample calibration with and w/o magnetic field

Physics | Lancaster University

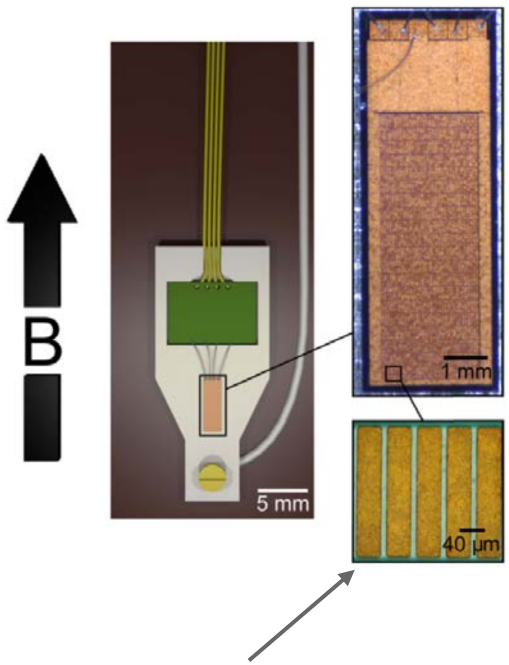


Field (T)	C_Σ (fF)	R_T (kΩ)
0.1	192.4 ± 0.9	24.99 ± 0.06
5.0	191.9 ± 0.8	25.10 ± 0.06

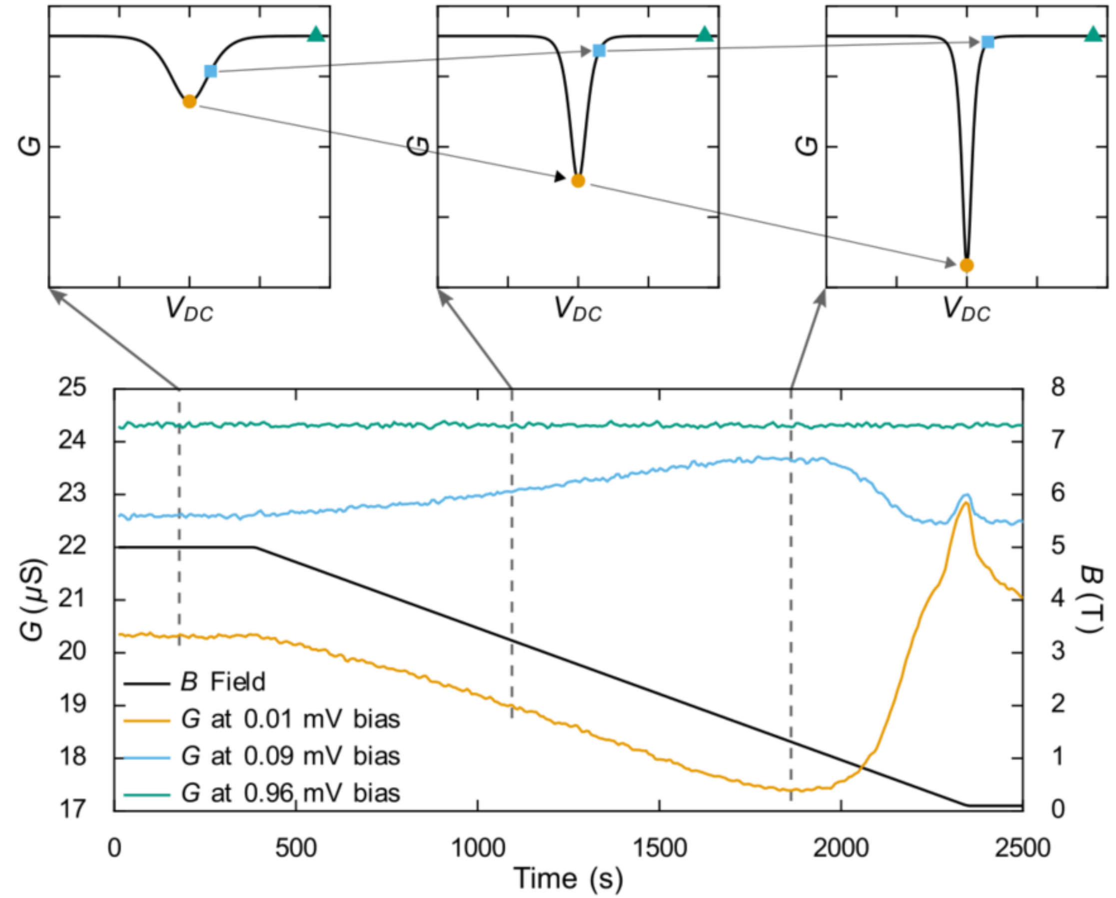
Magnetic cooling of a CBT

Bradley et al., Sci. Rep. **7**, 45566 (2017)

Demagnetisation of a CBT in a commercial, cryogen-free dilution refrigerator:



CBT islands are electroplated with copper (refrigerant)

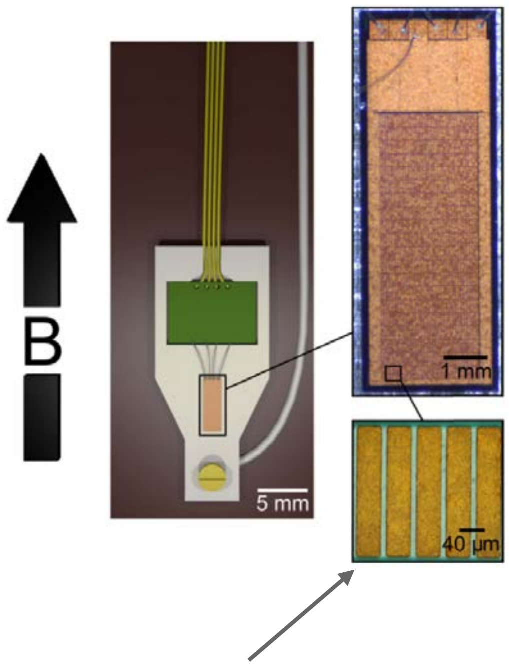


Magnetic cooling of a CBT

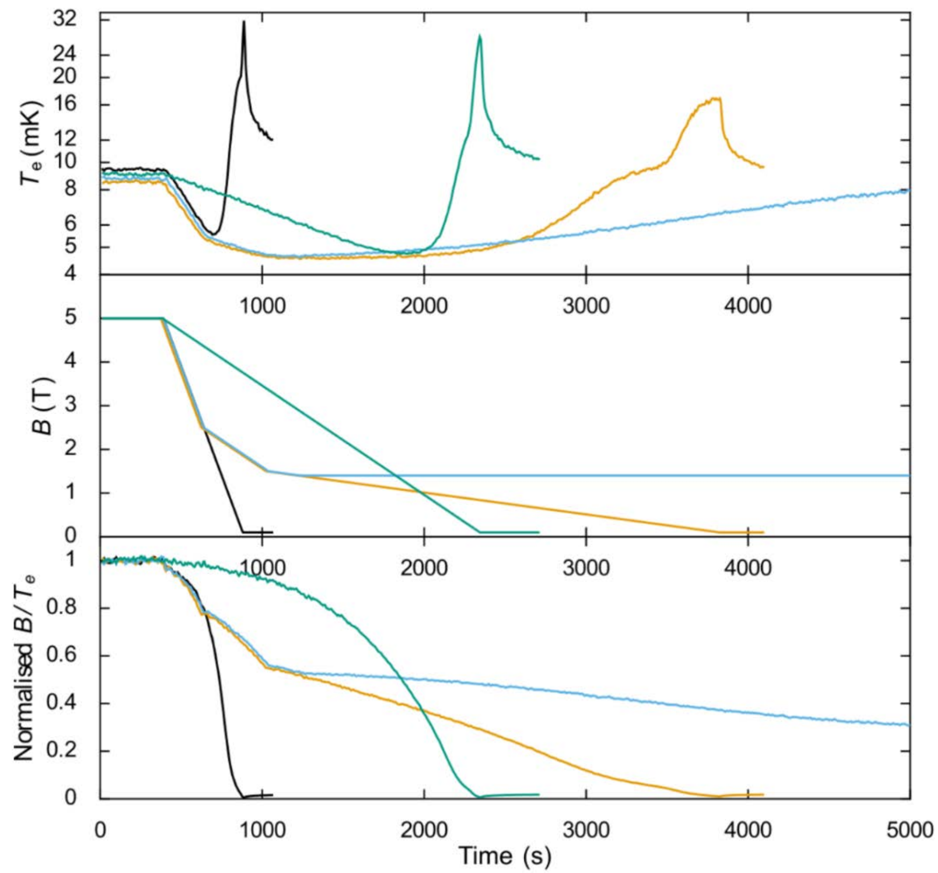
Physics | Lancaster University

Bradley et al., Sci. Rep. **7**, 45566 (2017)

Demagnetisation of a CBT in a commercial, cryogen-free dilution refrigerator:



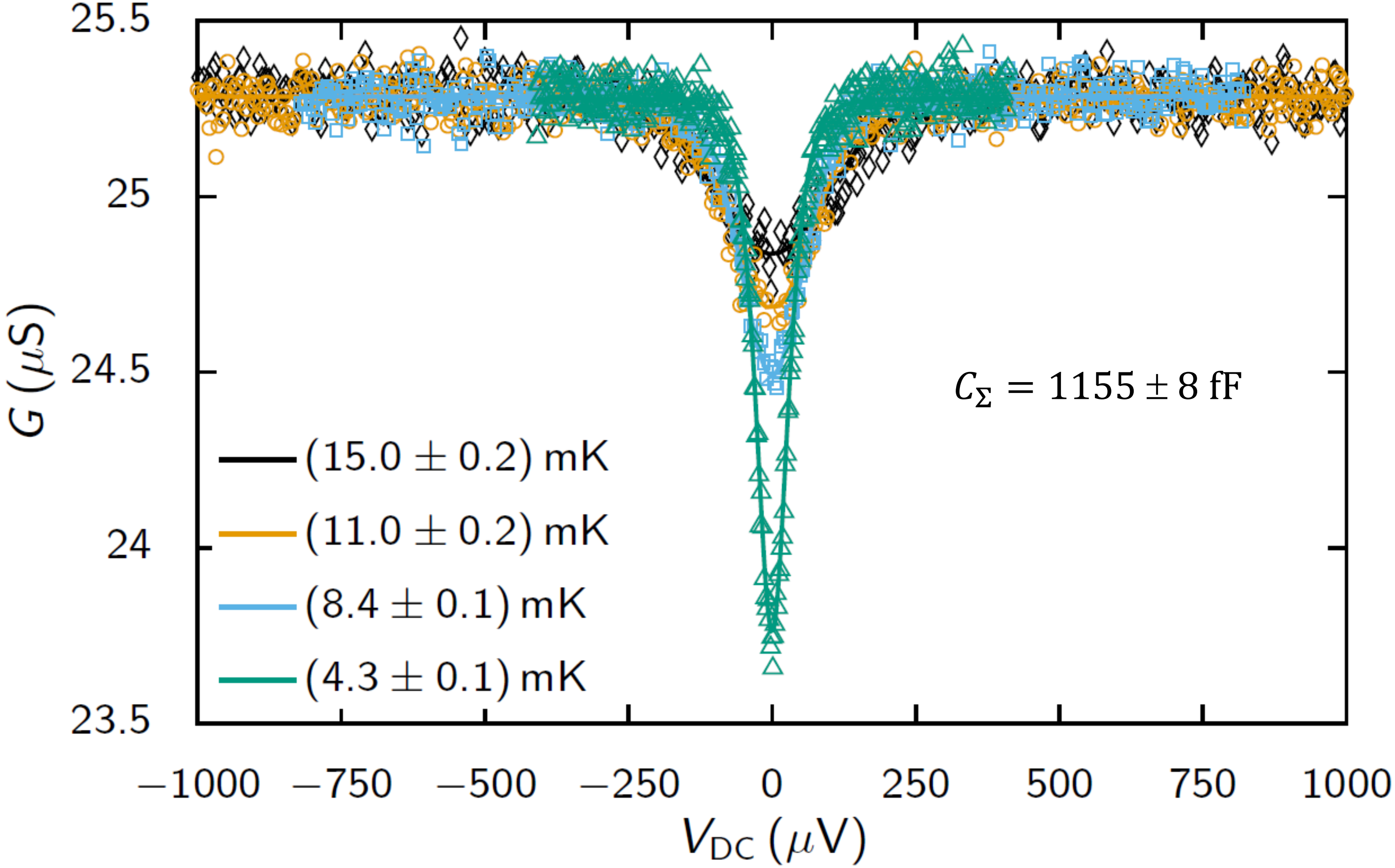
CBT islands are electroplated with copper (refrigerant)



Best result: CBT cooled from $9\ \mathrm{mK}$ to below $5\ \mathrm{mK}$ for over 1000 seconds.
Next step: target $< 1\ \mathrm{mK}$ by starting colder and in a larger magnetic field

Calibration with large *C*

taken in a home-made dilution refrigerator



Summary

Passive electron cooling down to 3.7 mK
fridge temperature 2.4 mK

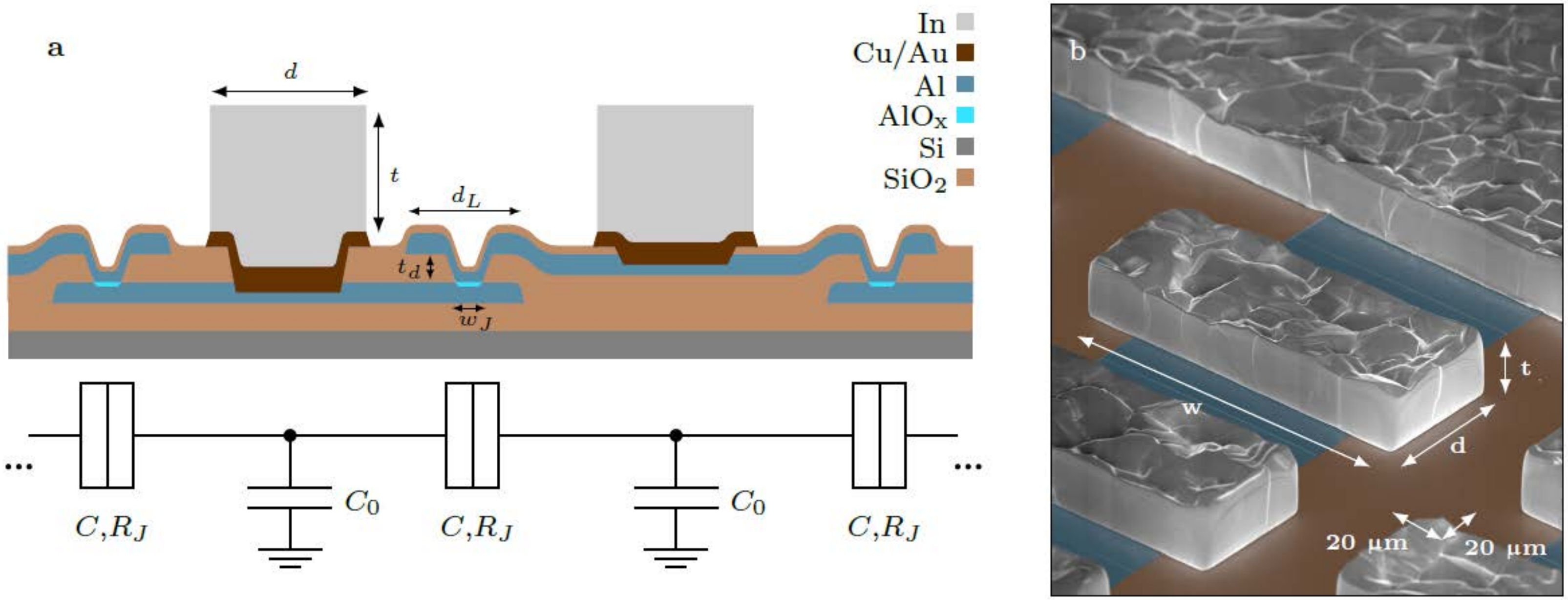
On-chip demag cooling down to 1.14 mK

Cooled below 2 mK for over 3000 s

CBT primary thermometry into sub-mK range

Related work

Yurttagül et al., arXiv:1811.03034



on-chip cooling of electrons with In refrigerant,
temperature of 3.2 mK reached
Claim 0.55 mK electron *T* with on-chip and wire demagnetisation cooling