Aalto University
School of Science
Low Temperature Laboratory

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European Metrology Research Programme
Programme of EURAMET

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Coulomb Blockade Thermometer: a primary device for sub-kelvin measurements

M. Meschke[1], O.M. Hahtela[2], A.V. Feshchenko[1], A. Kemppinen[2], D. Gunnarsson[3], M. Prunnila[3], A. Manninen[2], M. Heinonen[2], J.P. Pekola[1]

1 Aalto University, Low Temperature Laboratory, (OVLL), Finland
2 Centre for Metrology and Accreditation (MIKES), Finland
3 VTT Technical Research Centre, Finland

- CBT: the operation principle
- Challanges: E_C; background; homogeneity
- Fabrication for high T > 4K > low T sensor
- Sensor performance

Centre for Quantum Engineering

$$T_{\mathrm{CBT}} = \frac{eV_{1/2}}{5.439 N k_{\mathrm{B}}}$$

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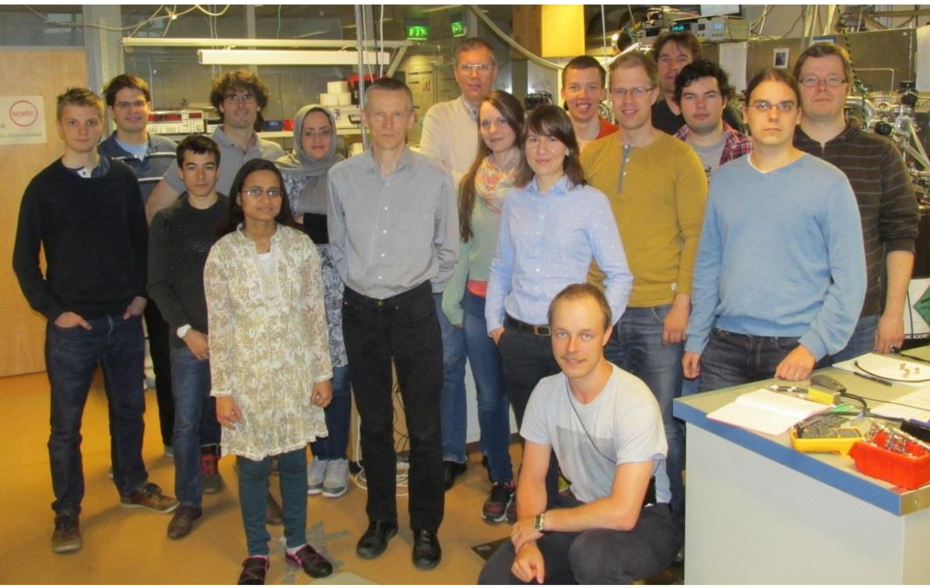
School of Electrical
Engineering

OtaNano

Low Temperature Laboratory

Pico group



MICRONOVA
Centre for Micro and Nanotechnology

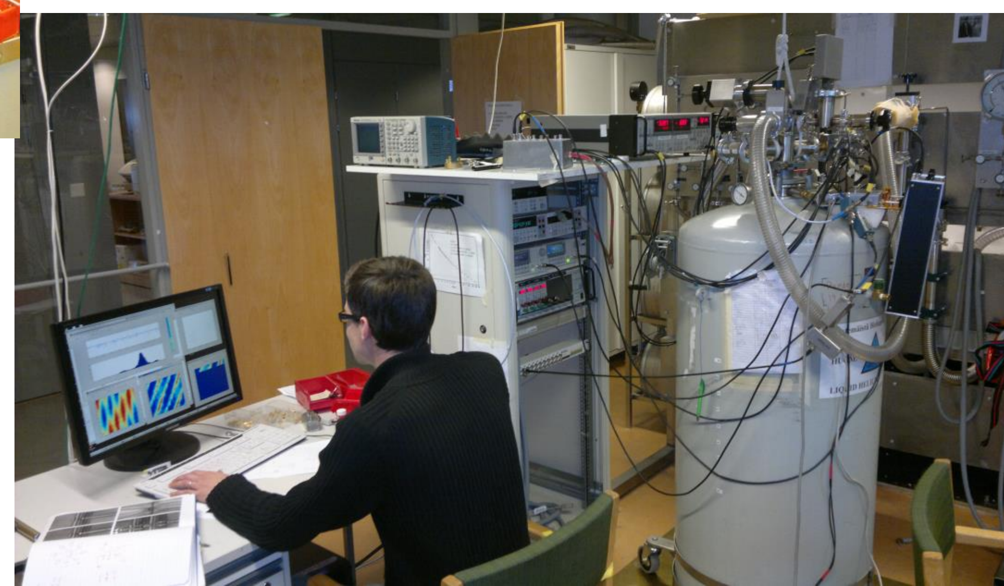
http://ltl.tkk.fi/PICO

- Laboratory

➧ wire bonder etc..

➧ 4 small dilution refrigerators T~30mK

➧ one „dry“ cryostate
for high frequency measurements,



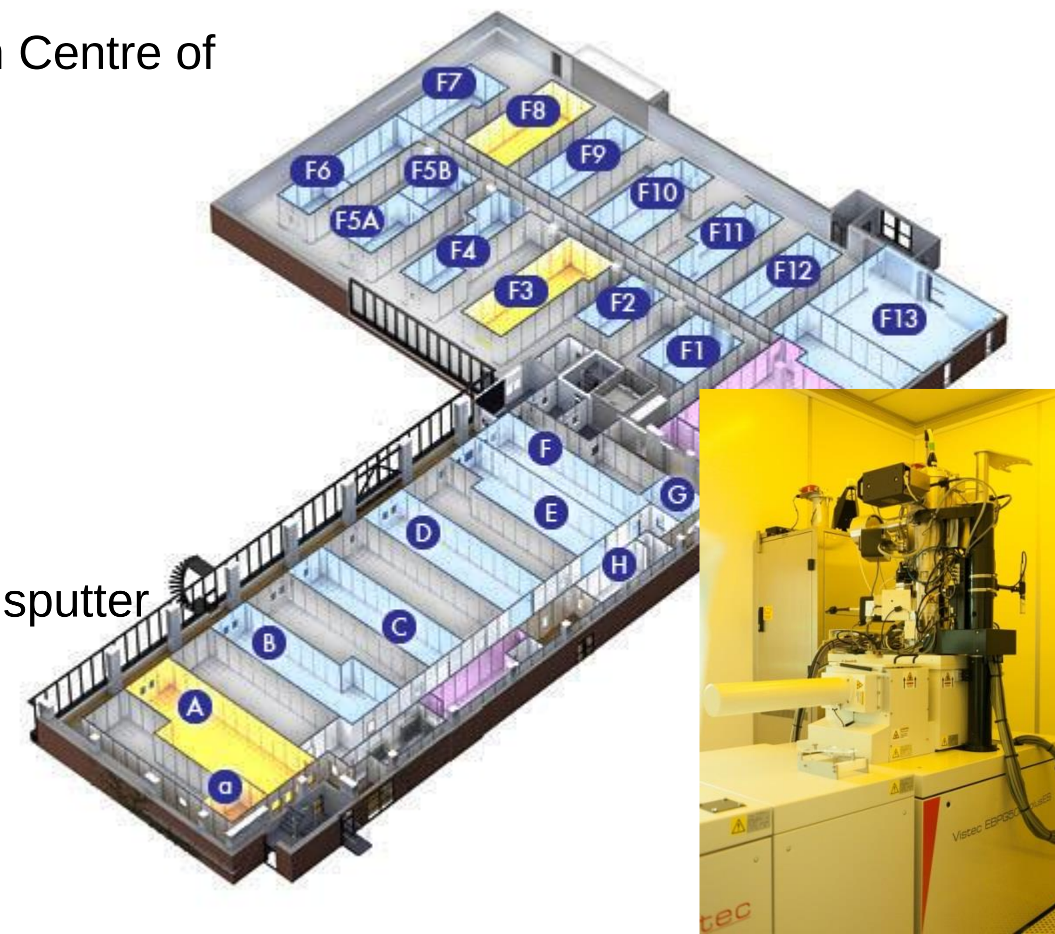
Research environment

Aalto University
School of Electrical Engineering

OtaNano

Low Temperature Laboratory

- 2600 m^2 cleanroom (ISO 4 to ISO 6)
- jointly run by VTT Technical Research Centre of Finland and Aalto University
- **open access facility**
- Electron beam lithographie Vistec EPGS 5000+ (2014)
- RIEOxfordPlasmaLab80Plus
- ALD reactors (Beneq, Picosun)
- Thin film deposition e-beam, thermal, sputter
- Mask aligner, Laserwriter
- sputter, FIB, SEM, ...



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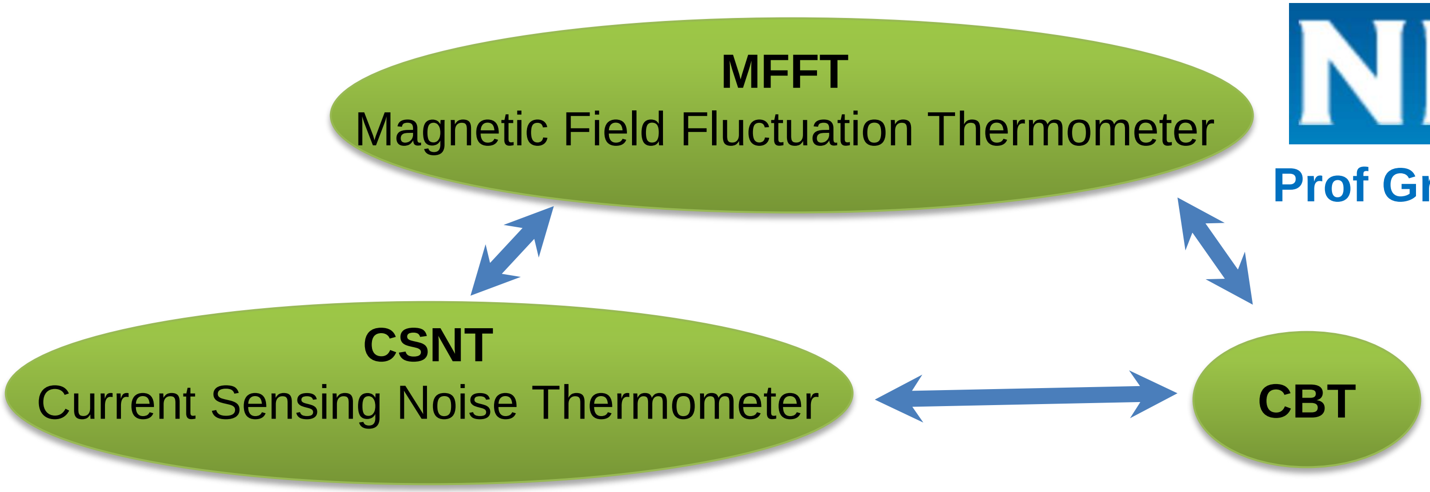
UNCERTAINTY COMPONENTS AND TRACEABILITY OF COULOMB BLOCKADE THERMOMETRY

- below 1 K: Provisional Low Temperature Scale of 2000, PLTS-2000
- proposed kelvin redefinition in terms of the Boltzmann constant (k_B)
  Fellmuth, B., Gaiser, C., and Fischer, J., *Meas. Sci. Technol.* **17**, R145-R159 (2006).
- **Implementing the new kelvin InK (2) => need for primary thermometry methods**



NPL
Prof Graham Machin

results with different methods, check of consistency

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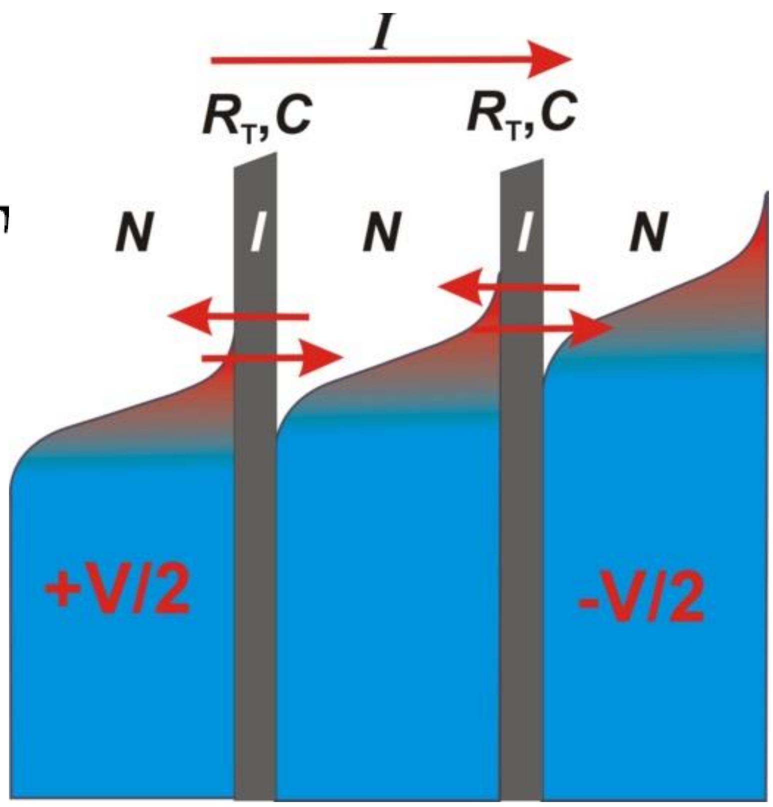
CBT: Coulomb Blockade Thermometer

VOLUME 73, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 1994
Phys. Rev. Lett. **73**, 2903

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)

$$E_C \ll k_B T$$



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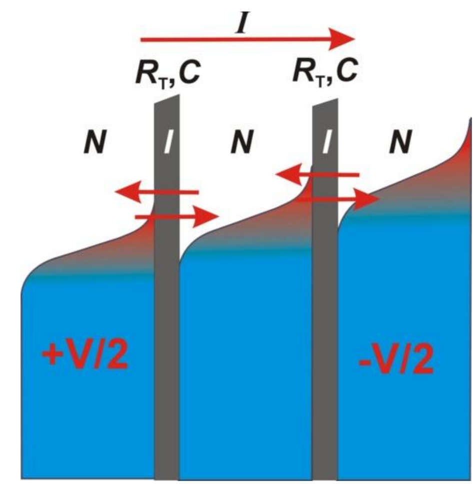

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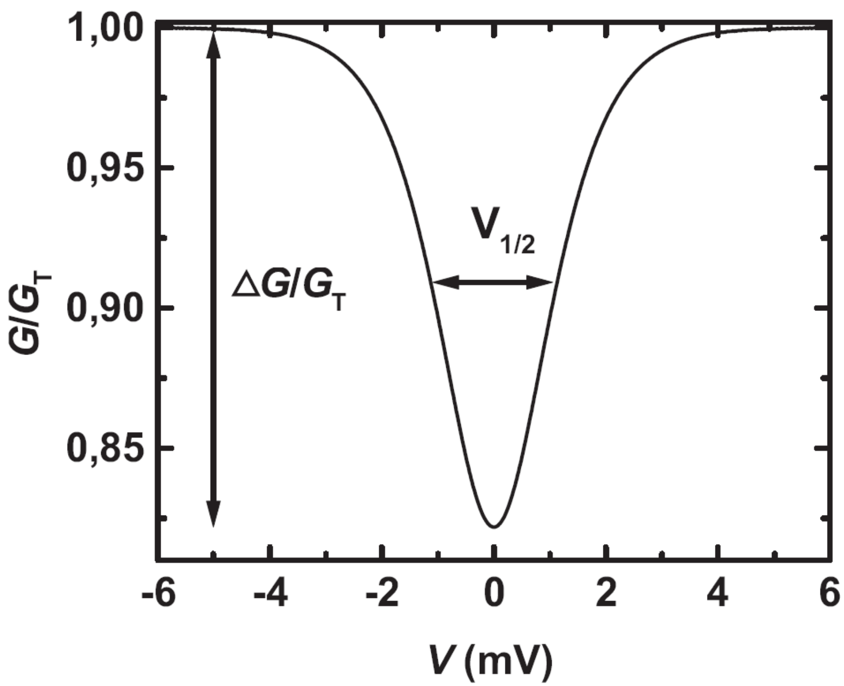

$$T_{CBT} = \frac{eV_{1/2}}{5.439 N k_B}$$

$$\Delta G / G_T = \frac{1}{6} \frac{E_C}{k_B T}$$

CBT: Coulomb Blockade Thermometer

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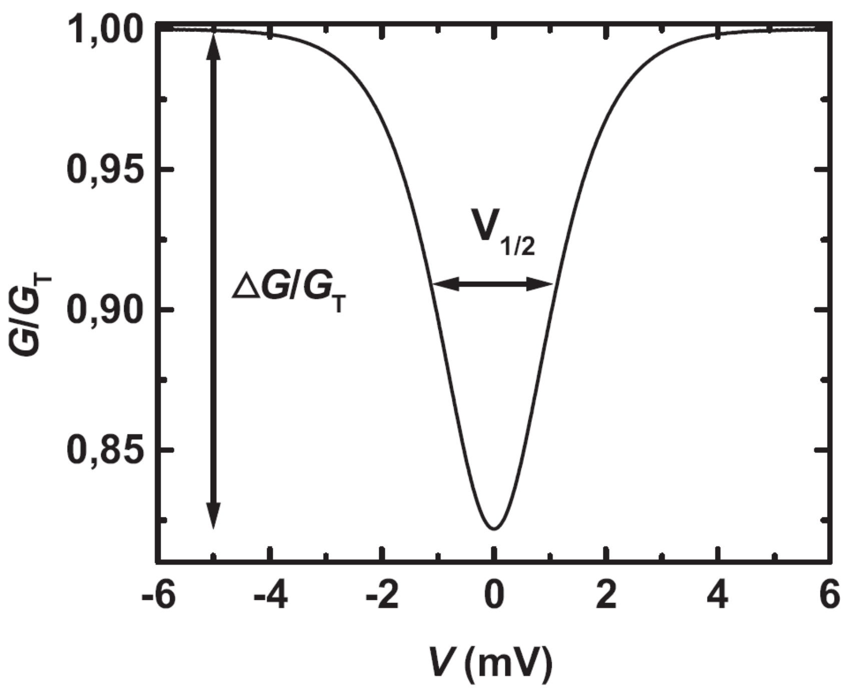
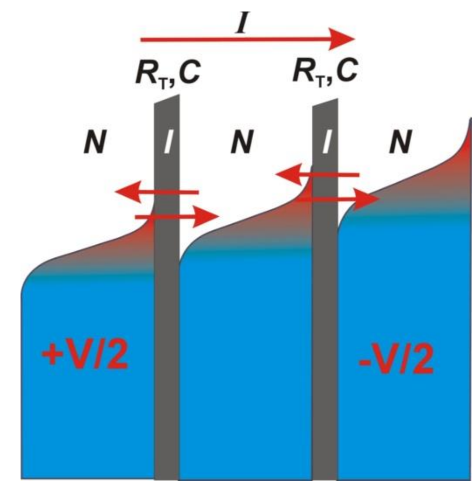




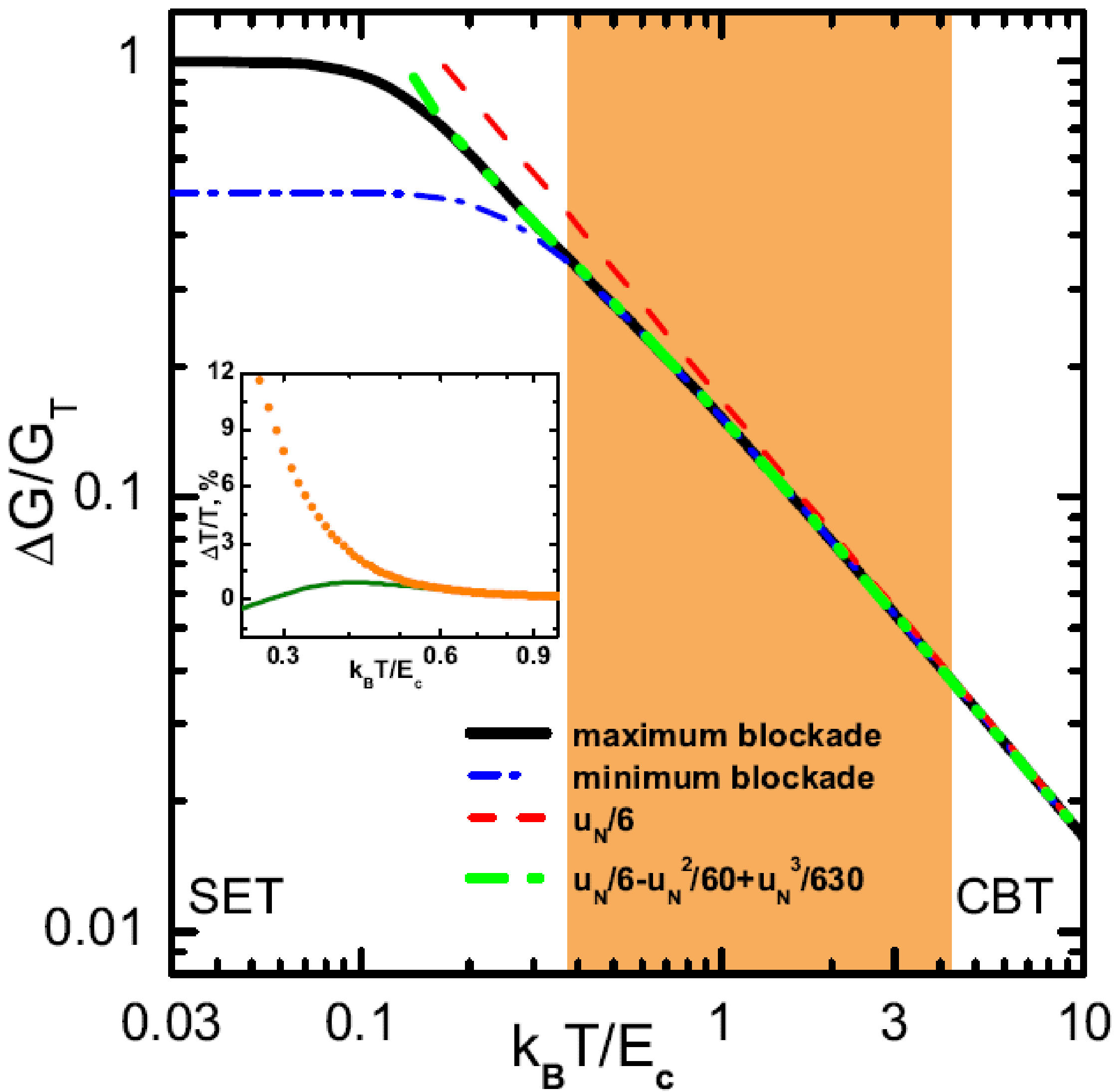
$$T_{CBT} = \frac{eV_{1/2}}{5.439 N k_B}$$

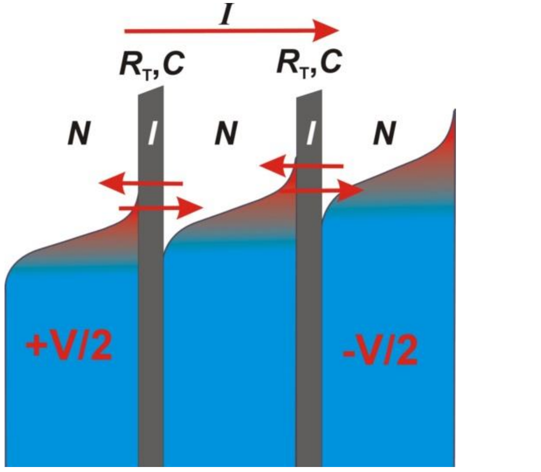
$$\Delta G/G_T = \frac{1}{6}\frac{E_C}{k_B T}$$

Challanges: Ec, high T (homogenity, background)

low T, (thermalisation)

Coulomb Blockade: charging energy E_C





$$E_C \ll k_B T$$

T Ec/kB	size	Fabrication
100 K	1 nm	?
10 K	10 nm	EBL
1 K	100 nm	Optical/EBL
100 mK	1 µm	Optical mask
10 mK	10 µm	Optical mask

A. V. Feshchenko, M. Meschke, D. Gunnarsson, M. Prunnila, L. Roschier, J. S. Penttilä and J. P. Pekola
Primary thermometry in the intermediate Coulomb blockade regime
Journal of Low Temperature Physics 173, 36 (2013).

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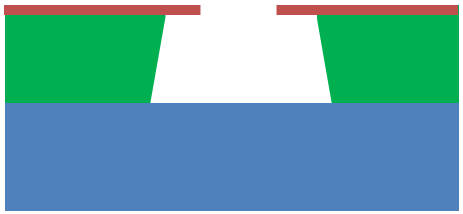
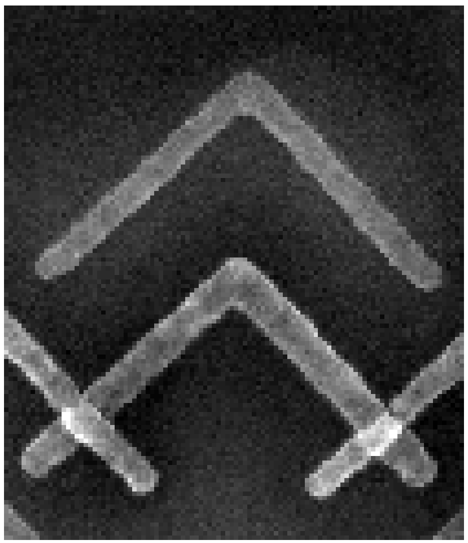
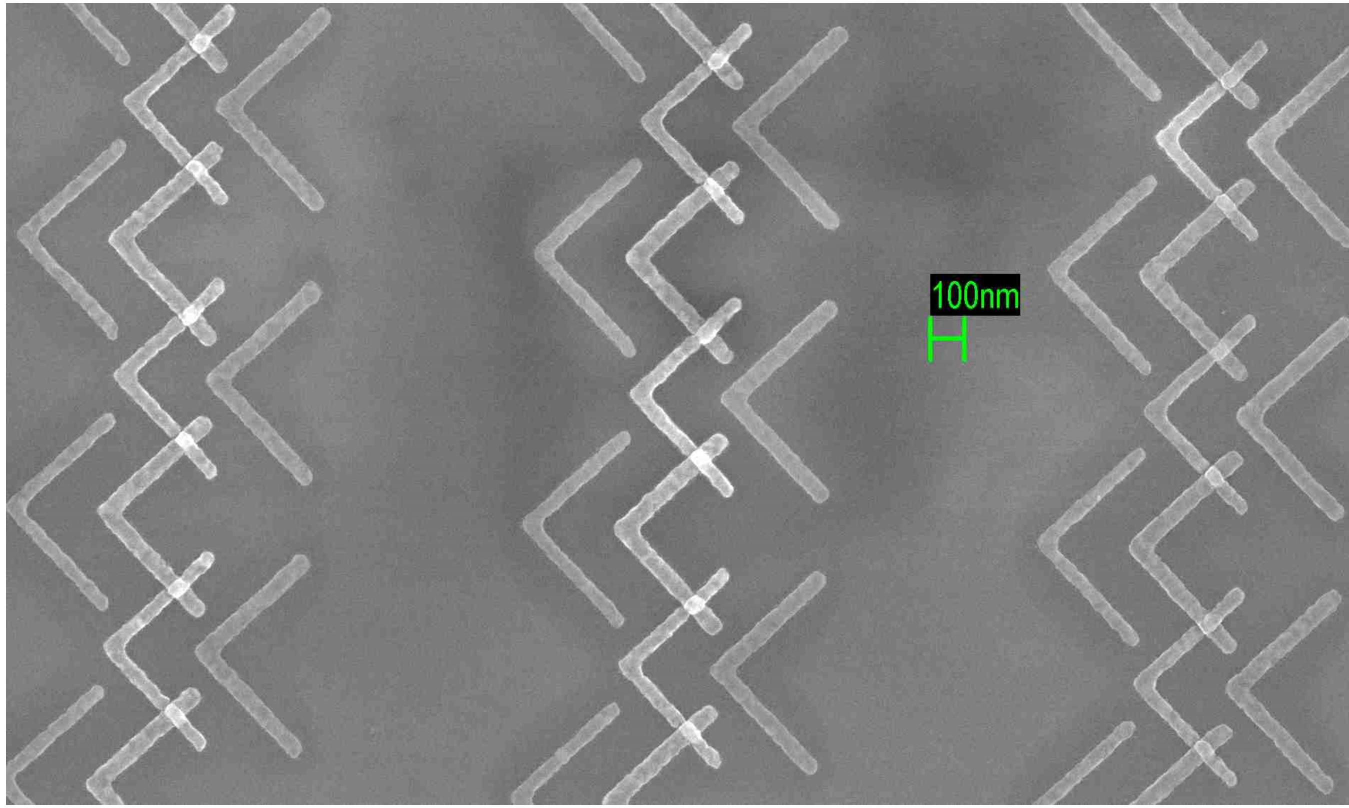
Fabrication with tri layer resist scheme

Germanium mask







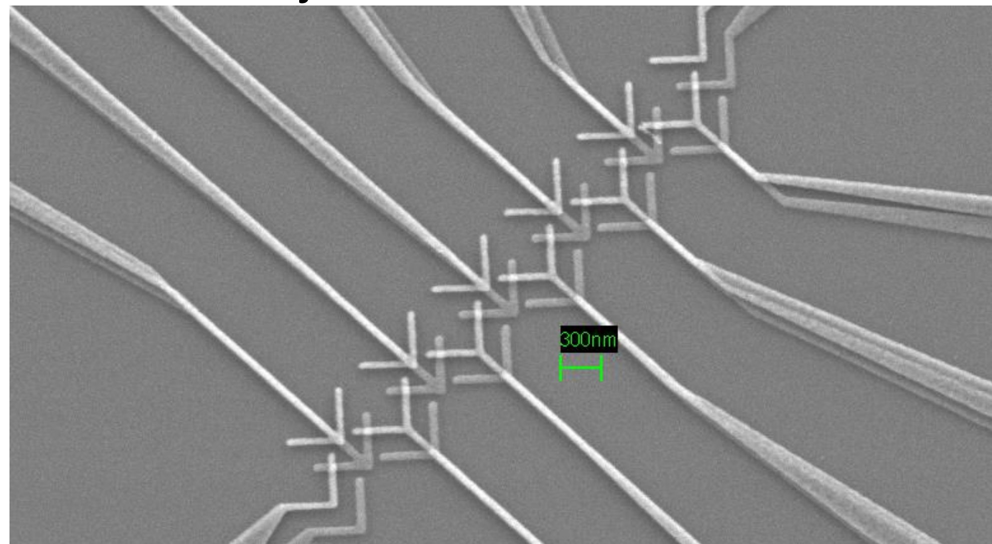
45 nm x 32 nm

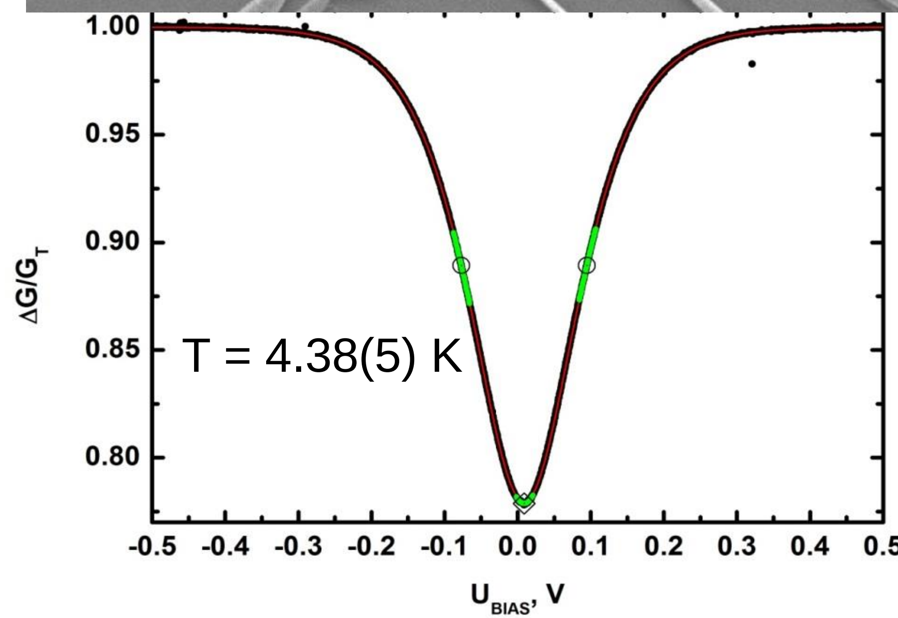
77 x 30 junction array; Evaporation rate > 1nm/s

Fabrication with tri layer resist scheme

Germanium mask, 45 nm x 32 nm junction size

Junction	Array 1 kΩ	Array 2 kΩ	Array 3 kΩ
1	78	93	74.0
2	71	92.5	69.5
3	80	85	64
4	72	89.5	68.9
5	74	--	70.9
6	89	92	70.2
7	94	92	68
8	99	103	72
9	76	107	68
10	87	96	68
11	78	88	75.6
Mean, kΩ	81.6	93.8	70
standard deviation, kΩ	9.3	6.7	3.3
relative deviation,	11.4 %	7.2 %	4.7 %
Resulting temperature deviation	-0.7 %	-0.25 %	-0.07 %





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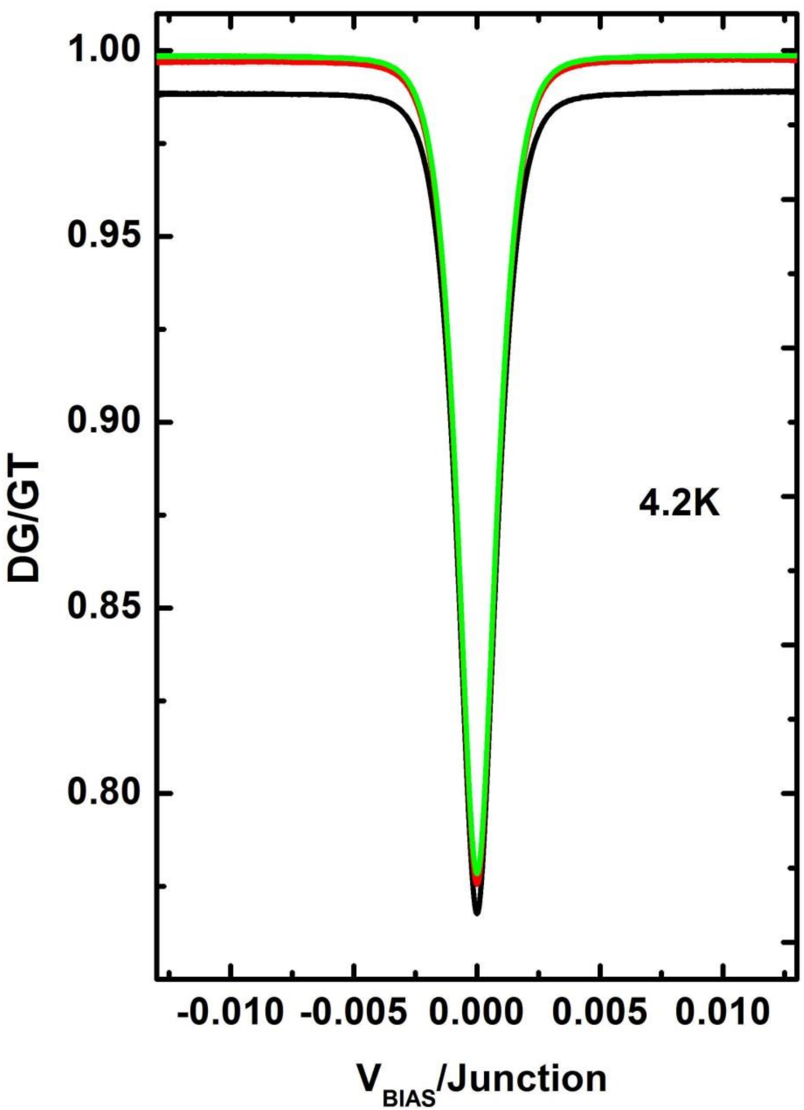
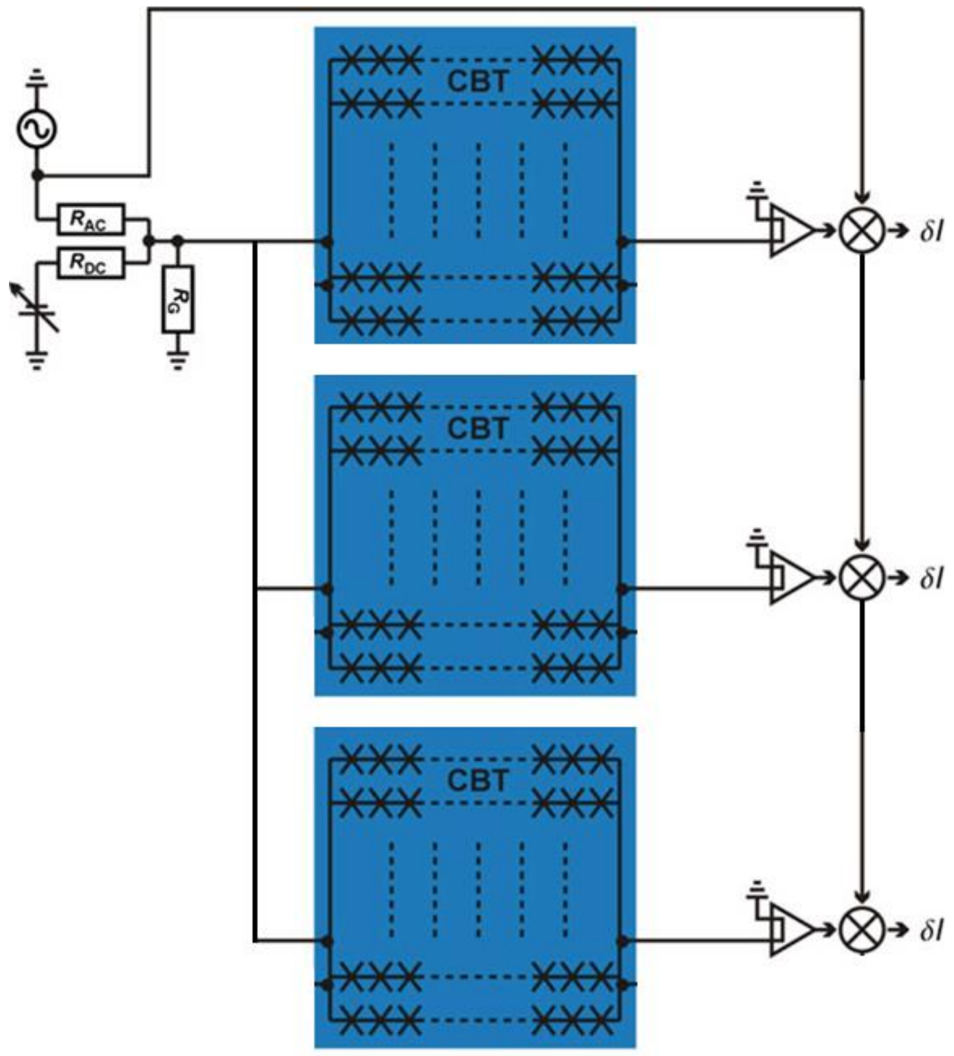
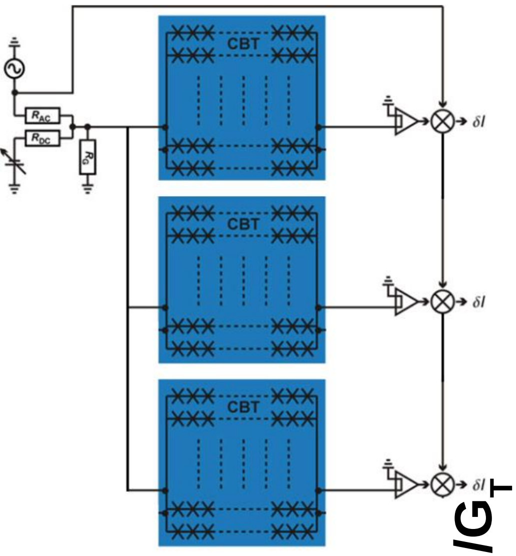
CBT setup: compare 3 sensors

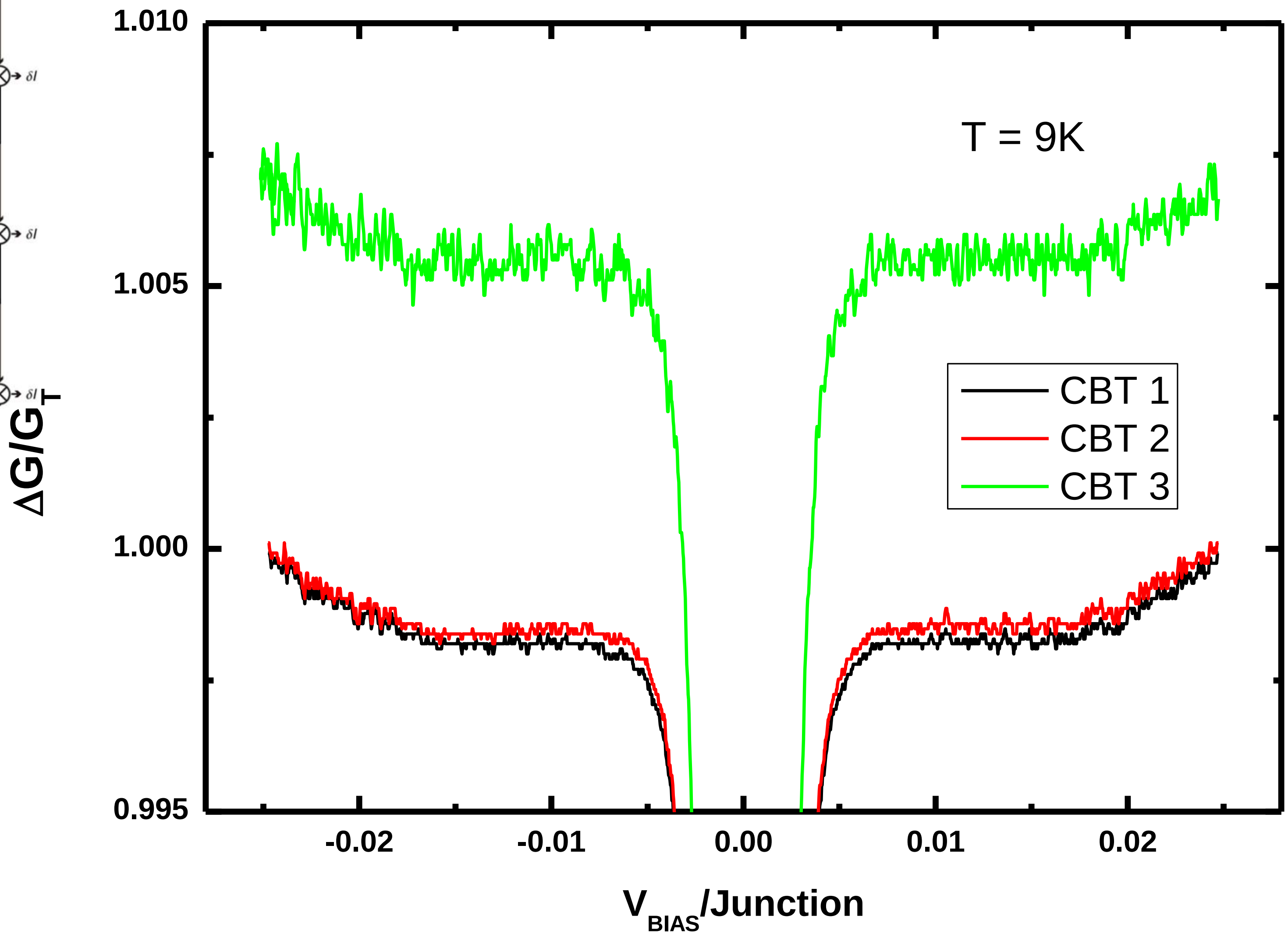




Ec/kB = 11 K

CBT & background correction





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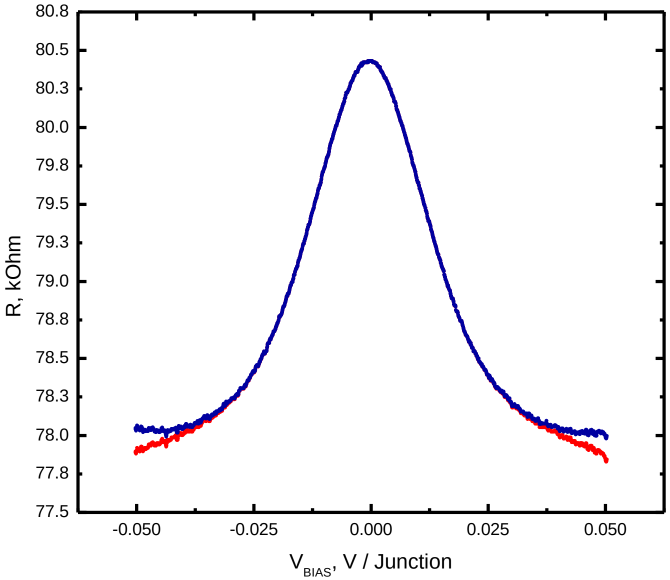
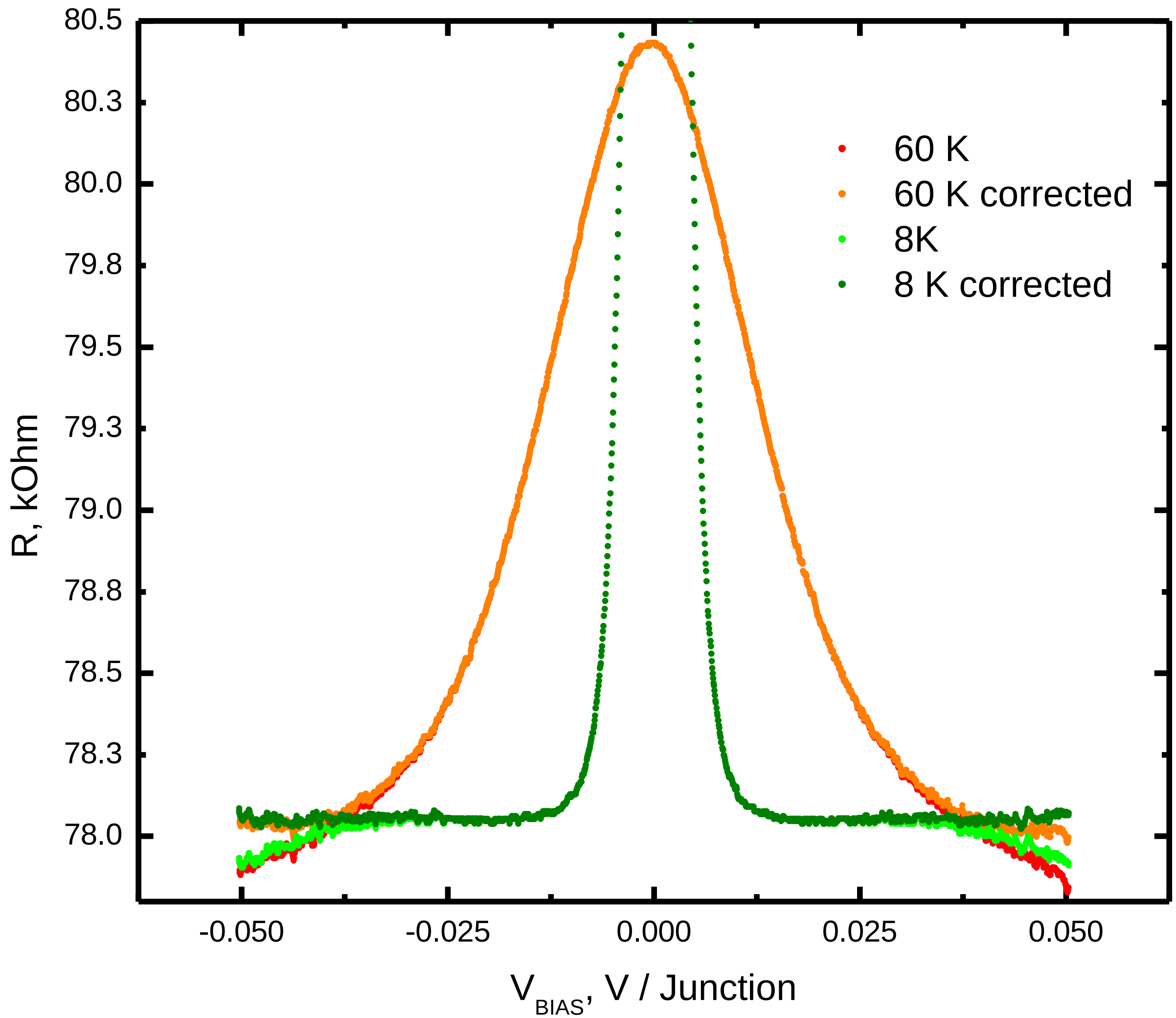




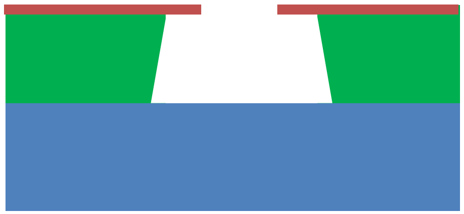
- Fit [-30 mV/J .. 30 mV/J]
- Background correction $R(1 + aV^b)\ b = 6$

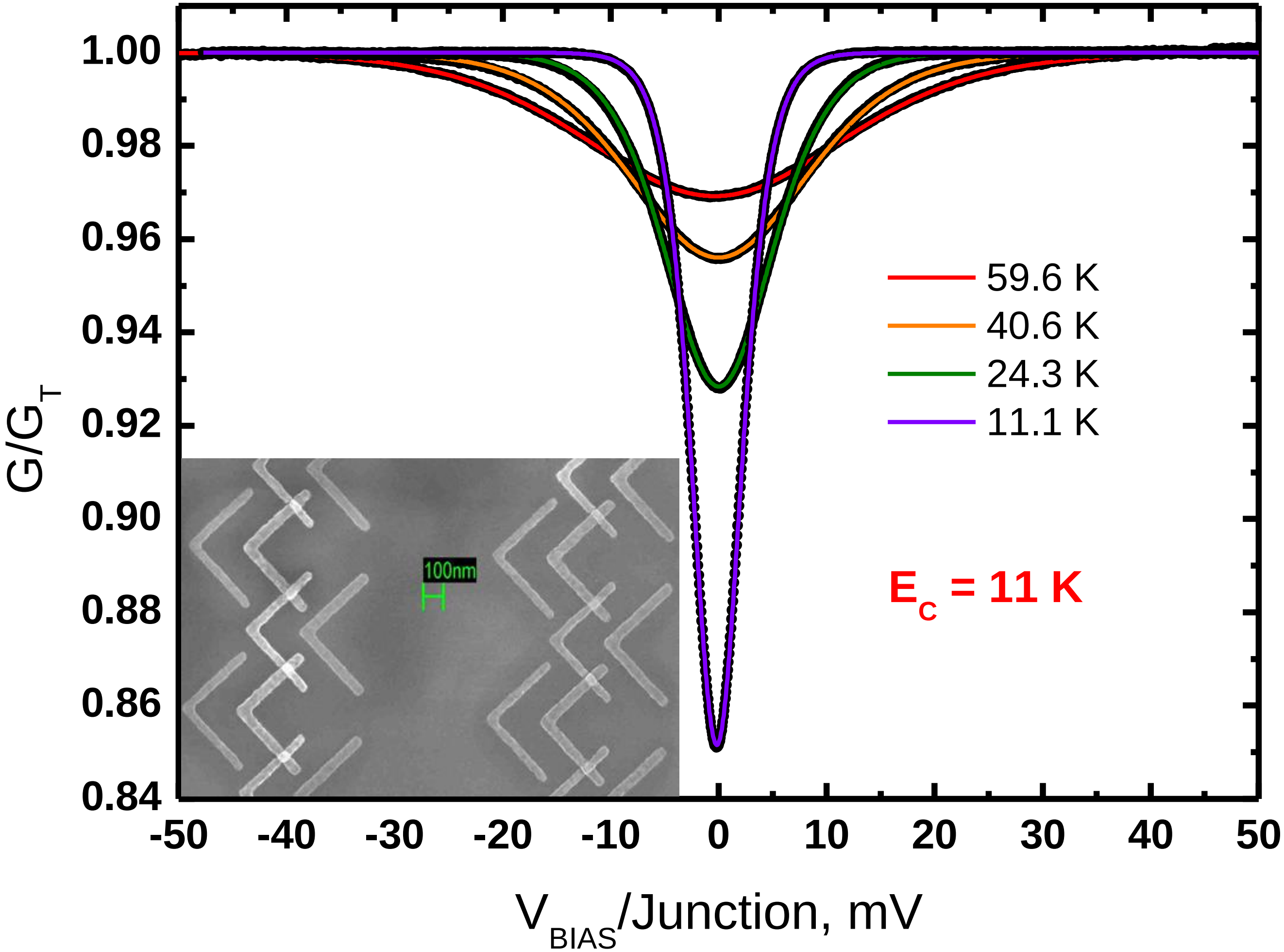
homogeneity of CBT for T>10 K

M. Meschke, O.M. Hahtela, A. Kemppinen, A. Manninen, M. Heinonen, J.P. Pekola

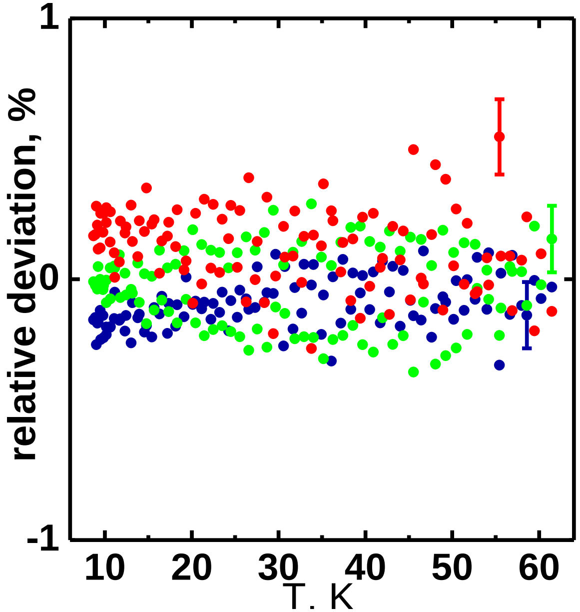
Fabrication with suspended germanium mask:

- Good resolution => high E_C (>10 K)
- Homogenity of R_T (~ 5%) for absolute T accuracy of ~ 0.5%





3 sensors agree within 0.2 % (relative deviation)
$\Rightarrow$ <10 % scatter in R_T



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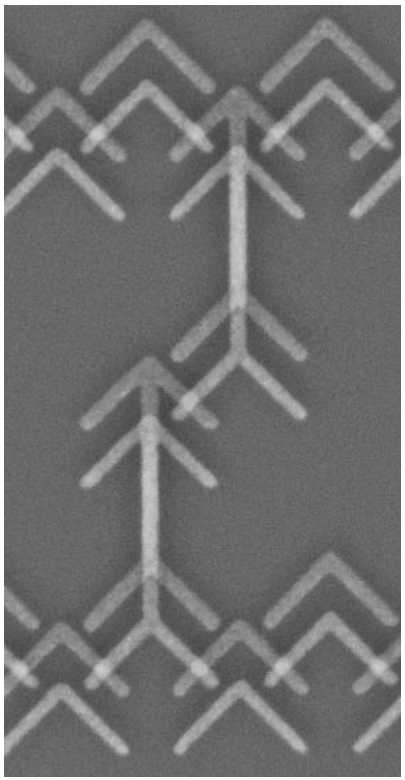
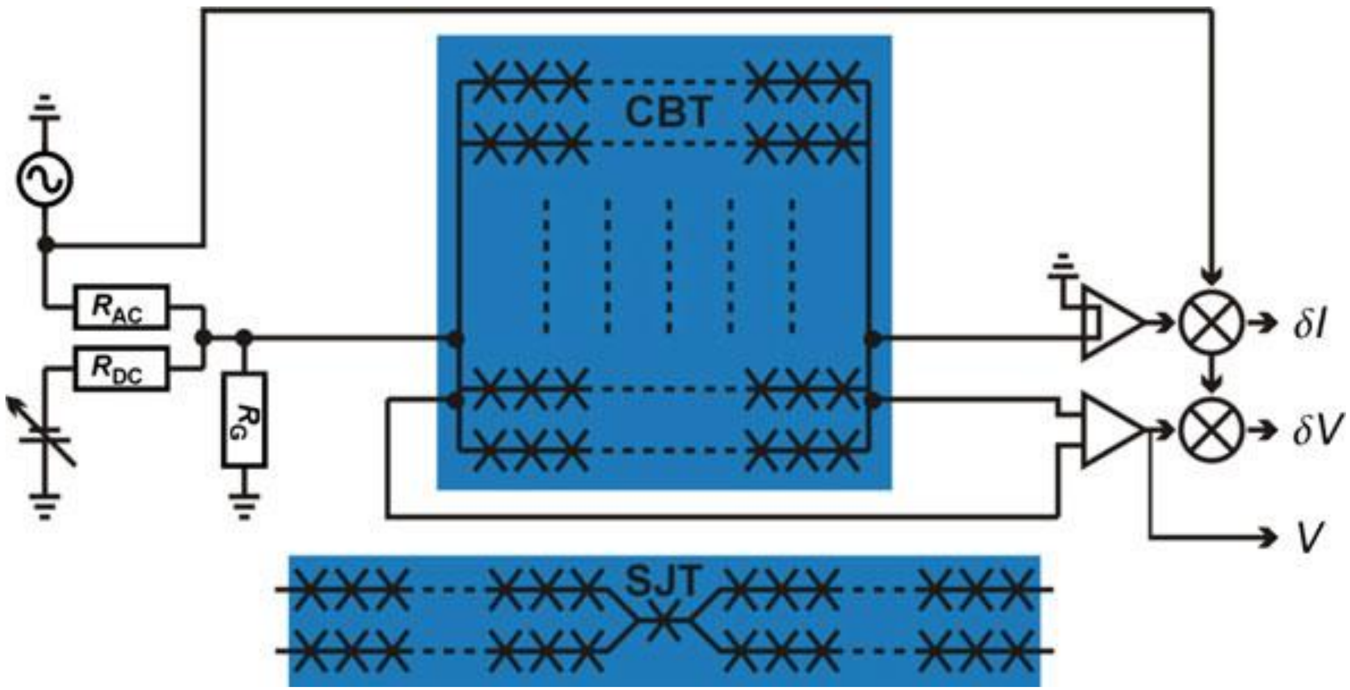
SJT vs. CBT for T>10 K





Voltage gain of 100 required for SJT!

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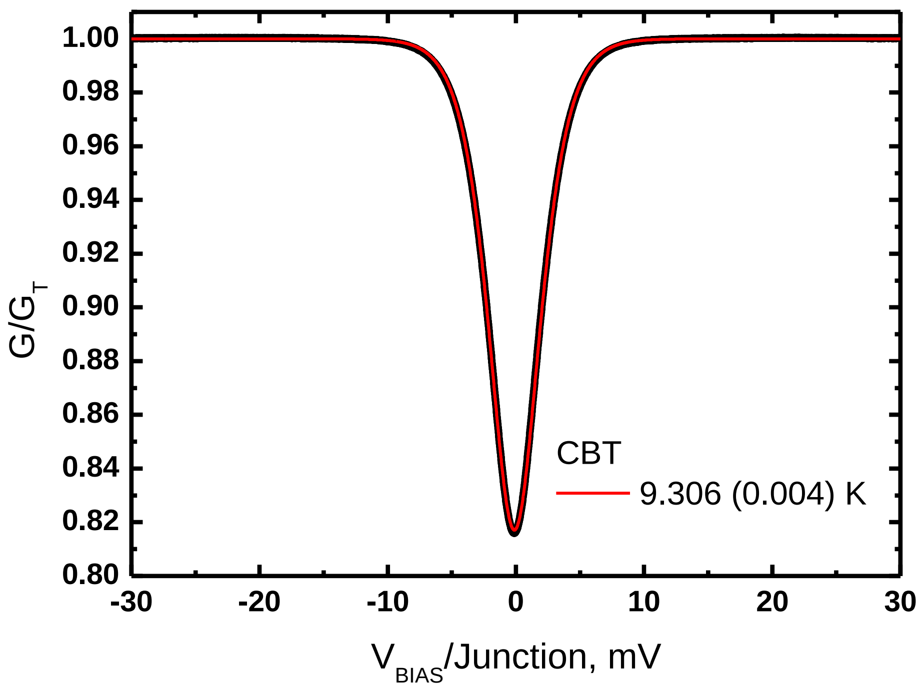
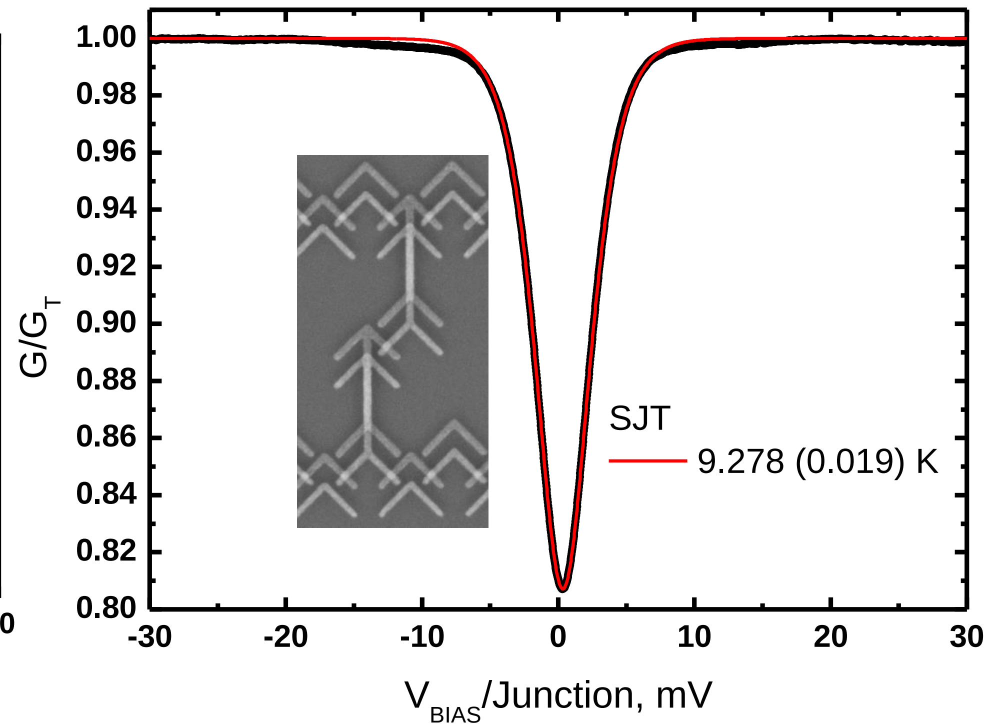
SJT vs. CBT at T optimum



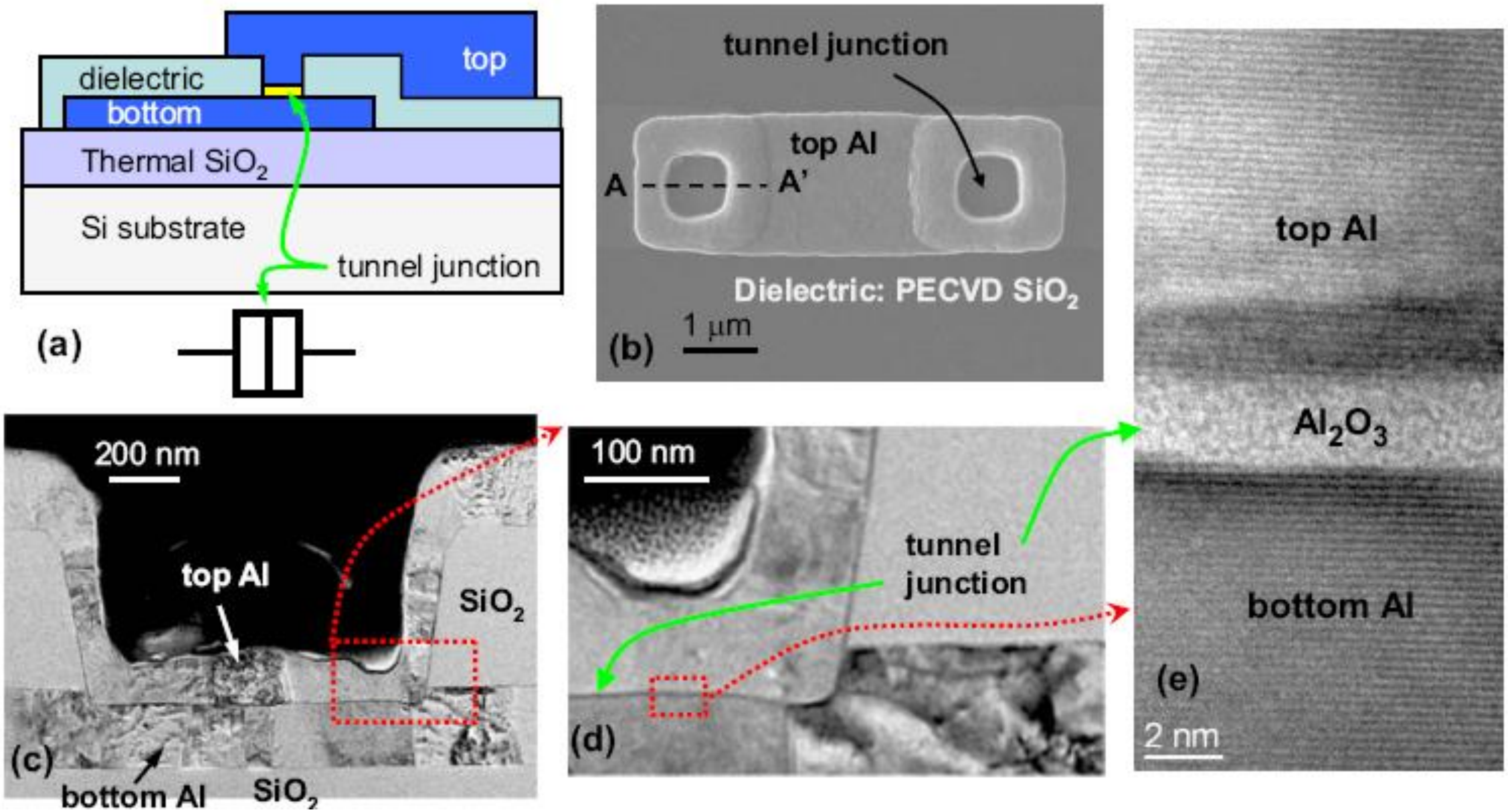


Direct voltage measurement,
No amplification needed
(77 Junctions)
⇒ 1e-4
⇒ Limit homogeneity < 1e-2

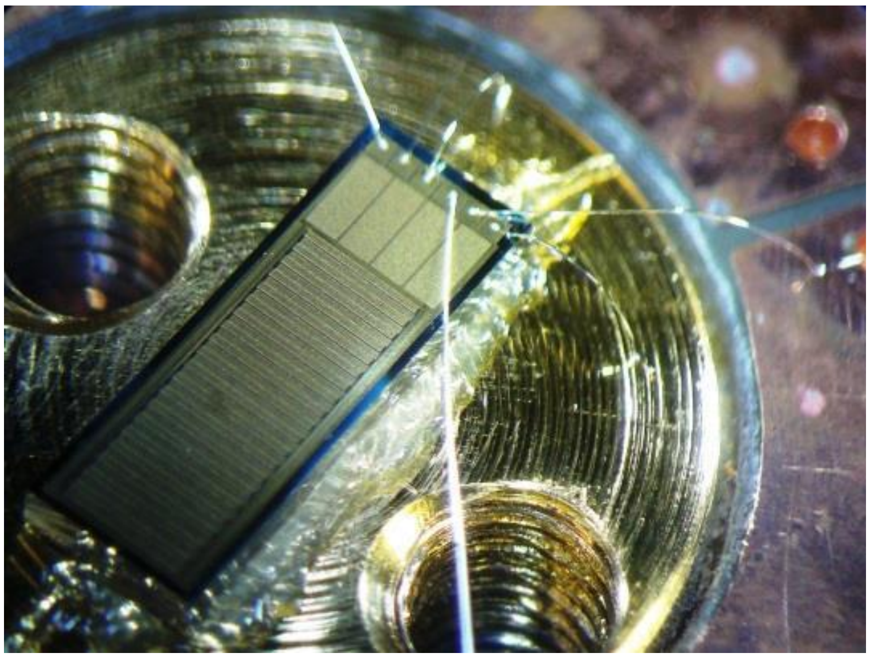
Voltage gain of 100 required for SJT!
=> 1e-2

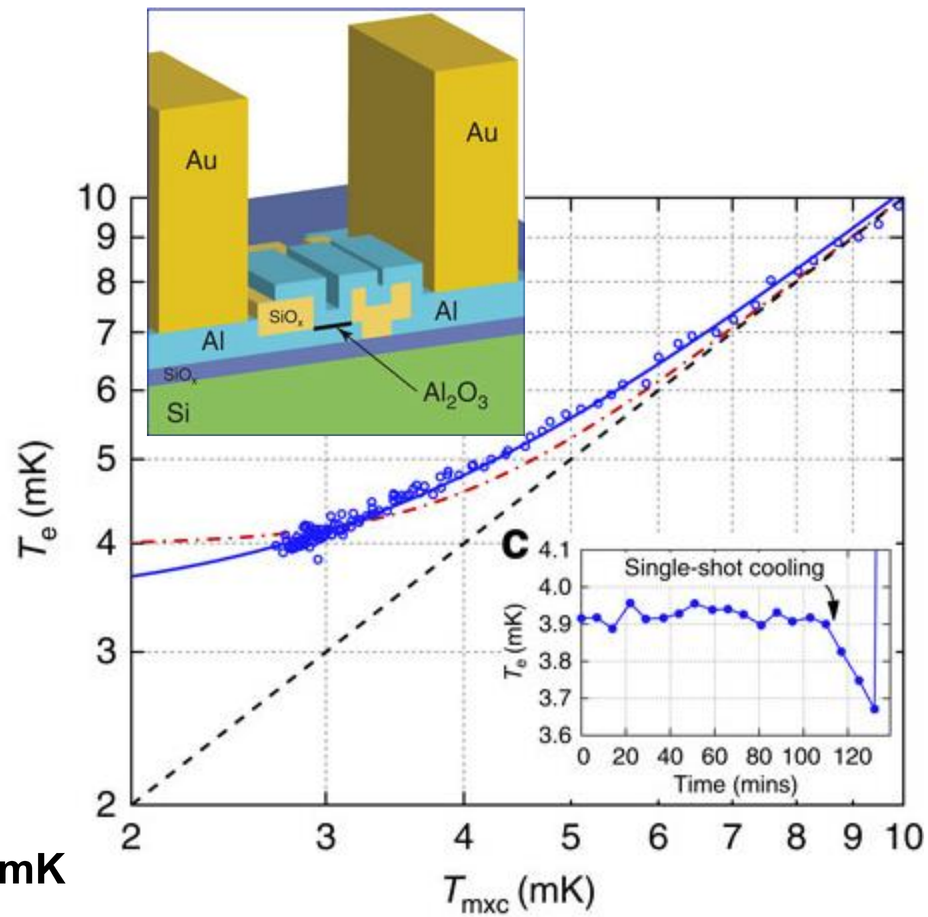
Tunnel junction process for CBTs

M. Prunnila, M. Meschke, D. Gunnarsson, S. Enouz-Vedrenne, J. M. Kivioja, and J.P. Pekola
Ex situ Tunnel Junction Process Technique Characterized by Coulomb Blockade Thermometry,
Journal of Vacuum Science and Technology **28**, 1026 (2010).



Fabrication of Low Temperature CBTs

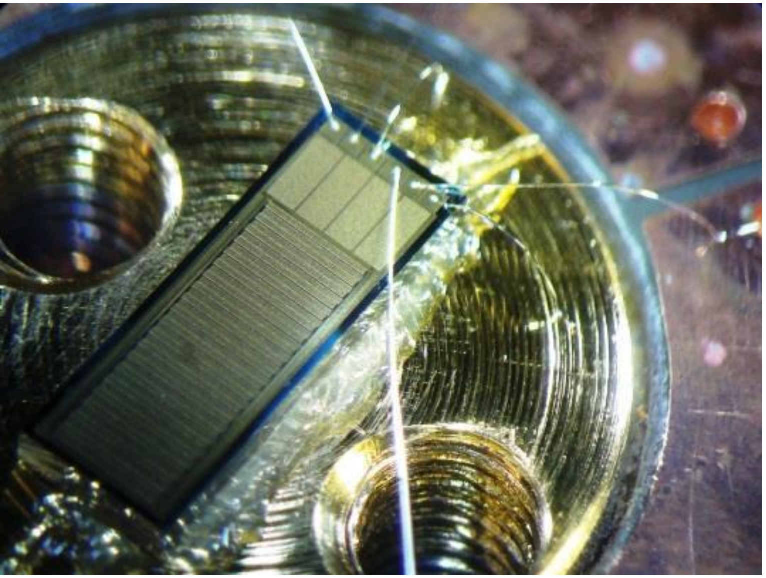


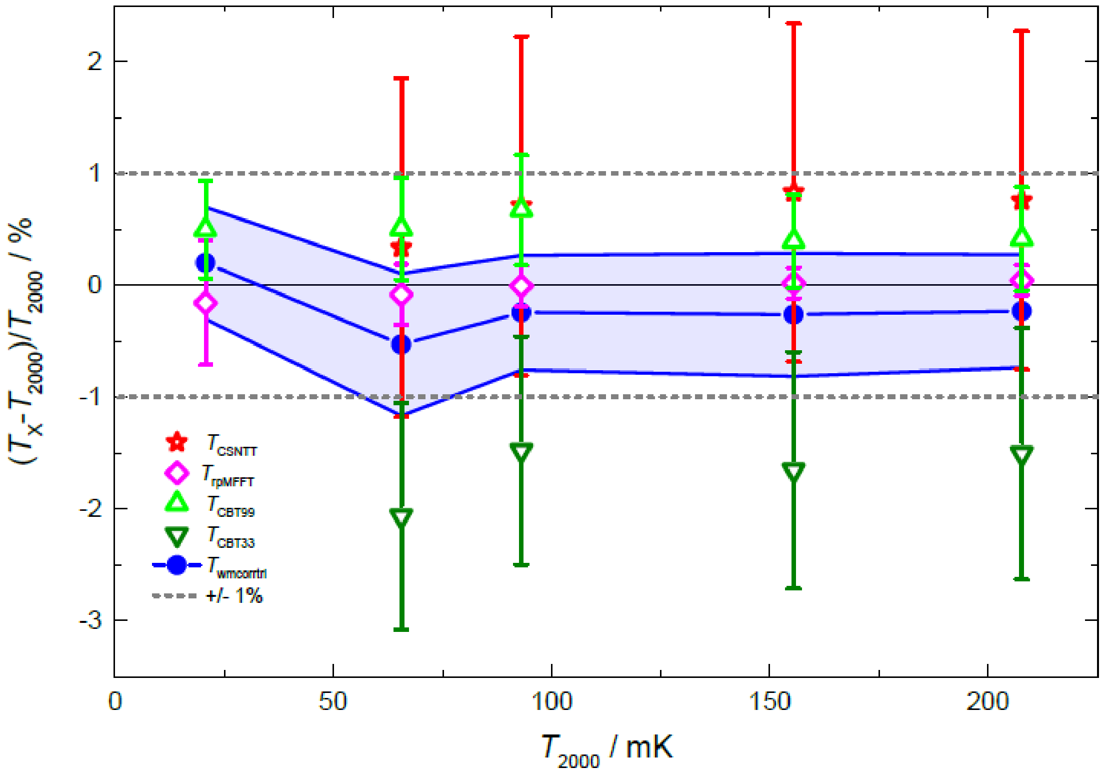


Nanoelectronic primary thermometry below 4 mK

D.I. Bradley, R.E. George,D. Gunnarsson,R.P. Haley,H. Heikkinen,Yu. A. Pashkin,J. Penttilä,
J.R. Prance, M. Prunnila,L. Roschier& M. Sarsby
Nature Communications 7, 10455 (2016)

Characterisation of Low Temperature CBTs





New evaluation of $T - T_{2000}$ from 0.02 K to 1 K by independent thermodynamic methods

J. Engert, et al. proceedings of Tempmekko 2016 (InK)

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InK - Implementing the new kelvin

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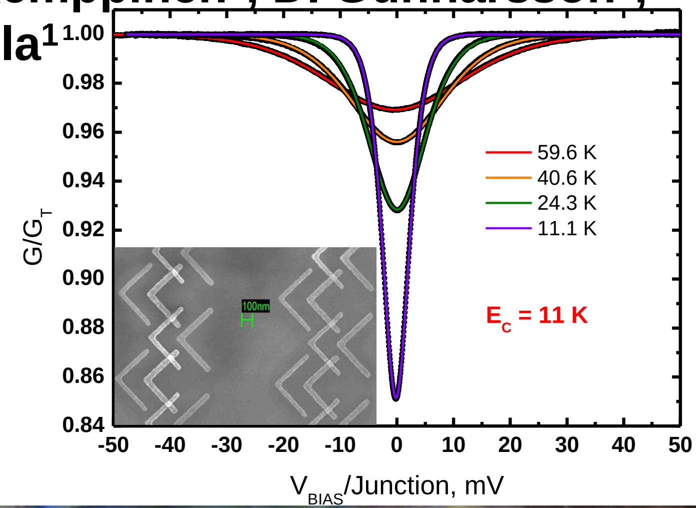

- Robust temperature range 10 mK .. 10 K
- Primary + self diagnostic
- Accurate (1% total accuracy)
- Simple voltage measurement
- Robust (ESD, radiation, magnet field (20 Tesla)