2nd Quantum Thermodynamics Conference

Experimental realization of a Coulomb blockade refrigerator

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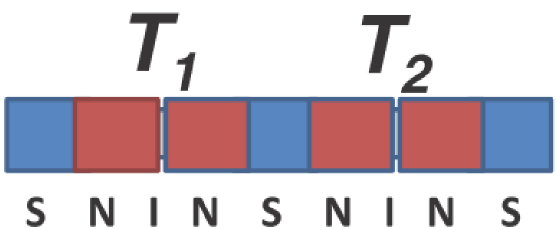

- *J. P. Pekola, J. V. Koski and D. V. Averin*, **Refrigerator based on the Coulomb barrier for single-electron tunneling**, Phys. Rev. B **89**, 081309**(R)** (2014)

- *A. V. Feshchenko, J. V. Koski, and J. P. Pekola*, **Experimental realization of a Coulomb blockade refrigerator**, Phys. Rev. B **90**, 201407(R) (2014)

Outline of the talk

Theoretical proposal

- How does the device work?
- What parameters should it have?
- What is needed to realize cooling?

Experimental realization

- Fabrication of the device
- Characterization of the device parameters
- Final measurement setup and results
- What limits cooling and what can be improved?

- *J. P. Pekola, J. V. Koski and D. V. Averin*, **Refrigerator based on the Coulomb barrier for single-electron tunneling**, Phys. Rev. B **89**, 081309**(R)** (2014)
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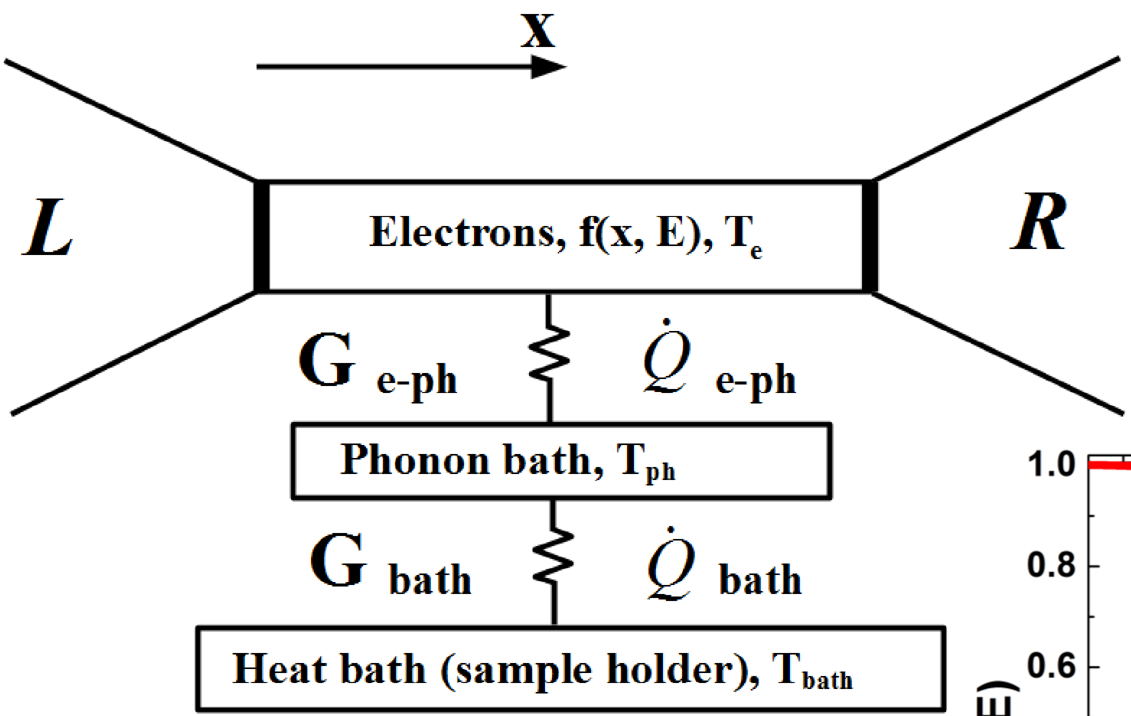
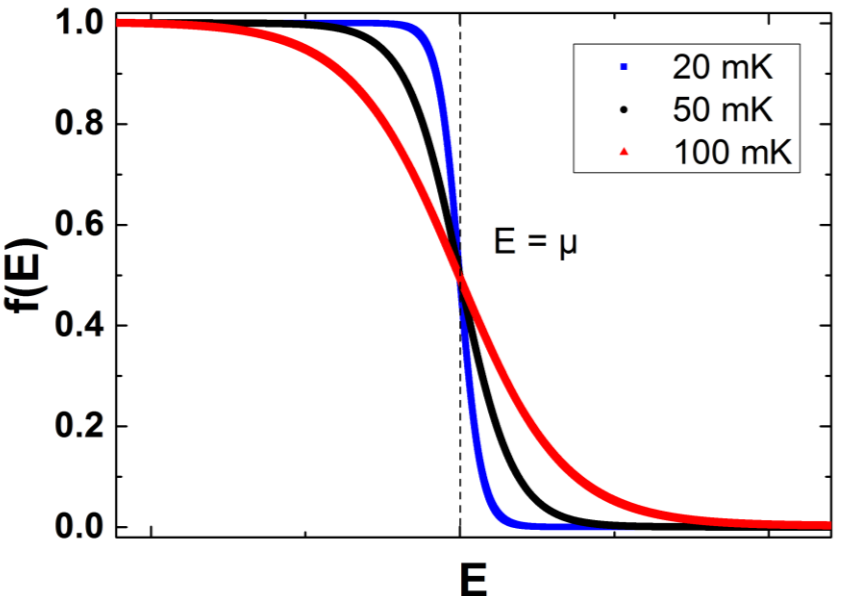
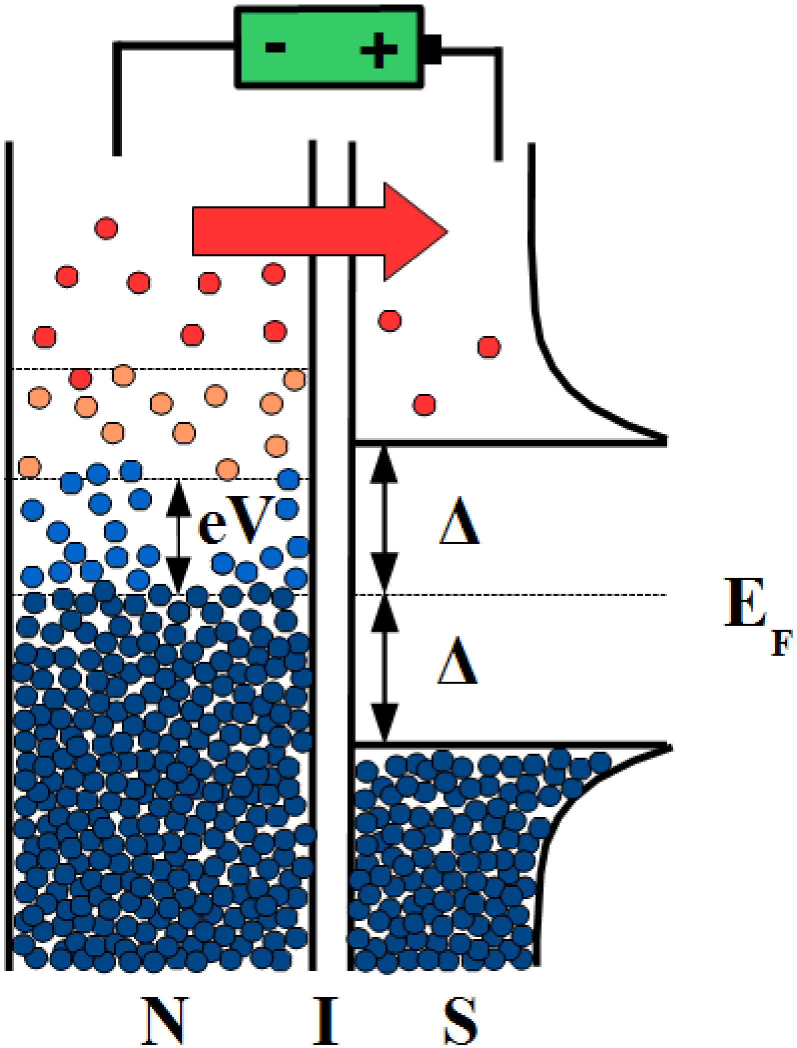
Temperature in a metallic structure

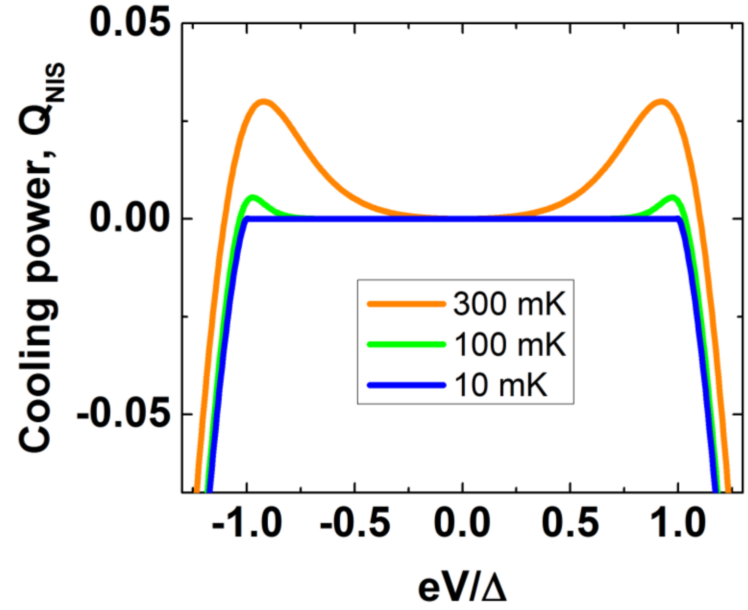


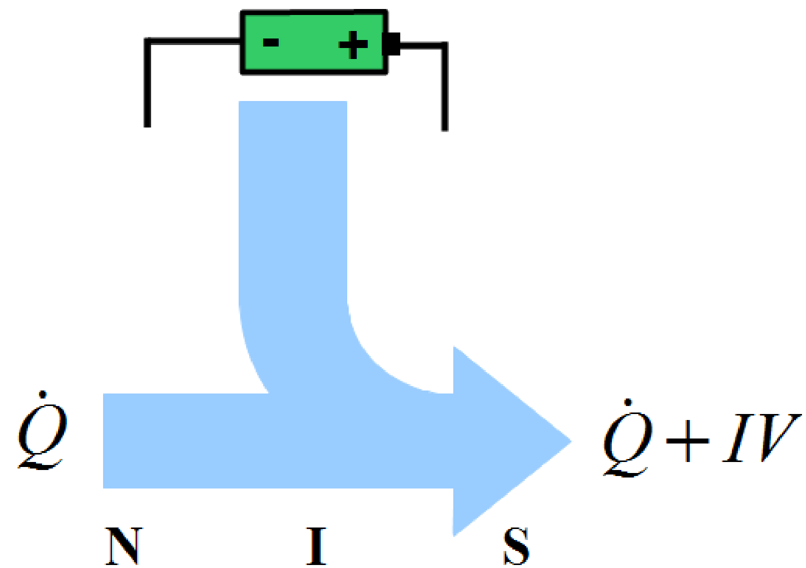
$$f(E) = \frac{1}{1 + e^{(E-\mu)/k_B T}}$$



NIS cooler

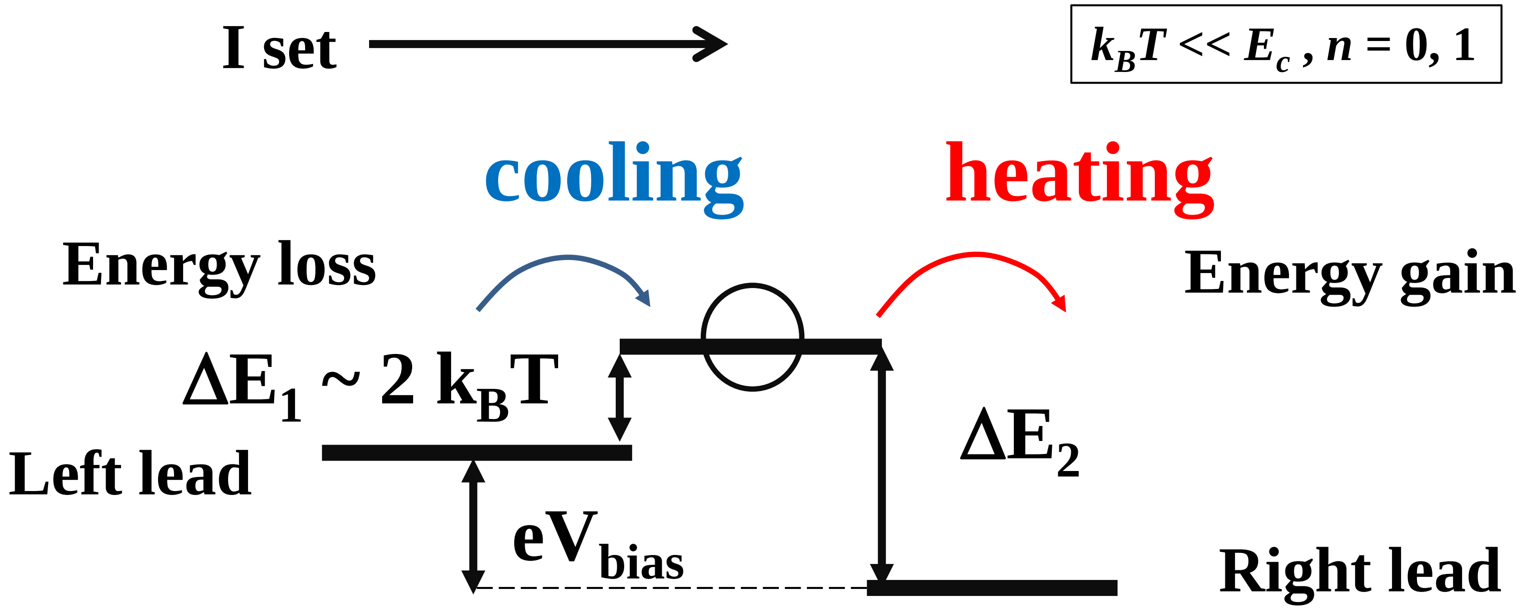






H. Q. Nguyen, T. Aref, V. J. Kauppila, M. Meschke,C. B. Winkelmann, H. Courtois and J. P. Pekola, **Trapping hot quasi-particles in a high-power superconducting electronic cooler**, New J. of Phys. **15**, 085013 (2013)

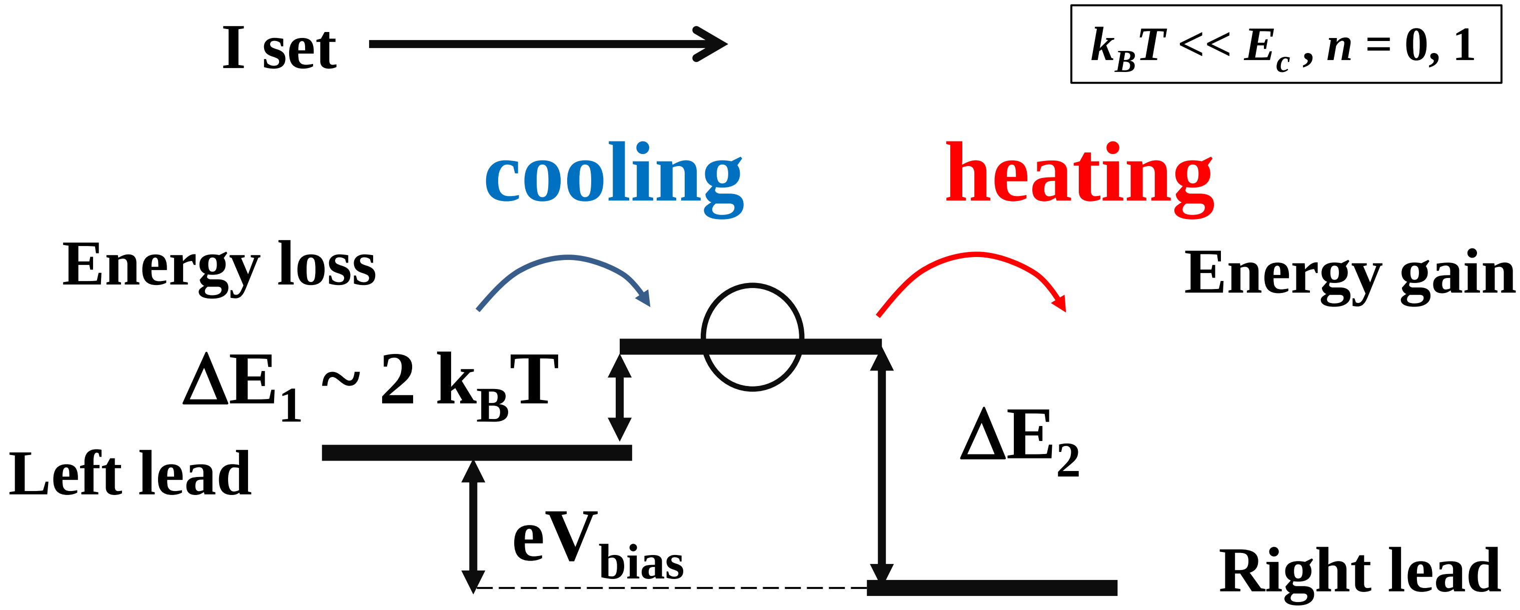
Coulomb blockade refrigerator (CBR)



Electrostatic energy $$\Delta E^{\pm} = -\frac{eV}{2} \pm 2E_c(\tfrac{1}{2} - n_g)$$

Gate position $$n_g \equiv -C_g V_g / e$$

Principle of operation



Cooling power

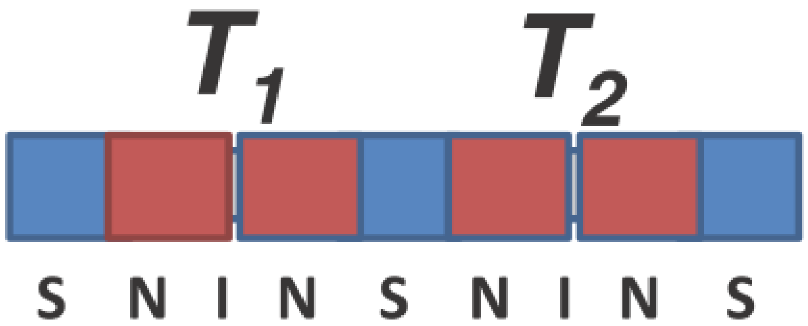
$$\dot{Q}_k^{\pm}(n) = \frac{1}{2e^2 R_T} \frac{[\Delta E_k^{\pm}(n)]^2}{e^{\beta \Delta E_k^{\pm}(n)} - 1}$$

Maximum cooling power,
when $\Delta E_1 \sim 2\ k_B T$

$$\dot{Q}_{opt} \simeq 0.31 \frac{(k_B T_1)^2}{e^2 R_{T,1}}$$

k = 1, 2 – number of the junction; n – number of electrons on the island.

What is needed to achieve and observe cooling?



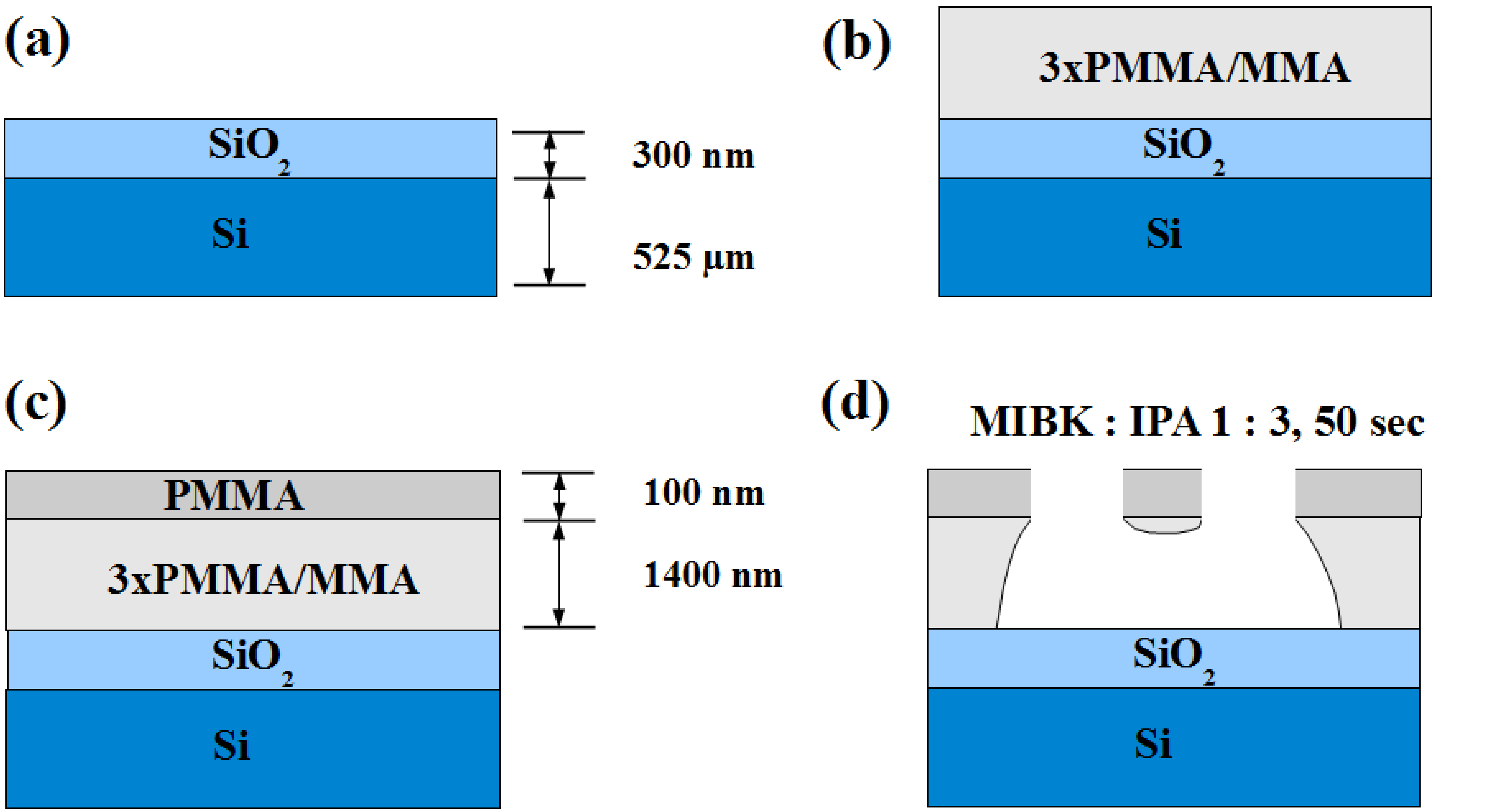
- $E_c / k_B \sim 1 - 3$ K **(SET island few μm long)**
- $R_T \sim 1$ **Mohm**

- **Normal tunnel junctions**
- **Low temperature:** $k_B T \ll E_c$, $n = 0, 1$
- **Thermal insulation**
- **On-chip thermometer**

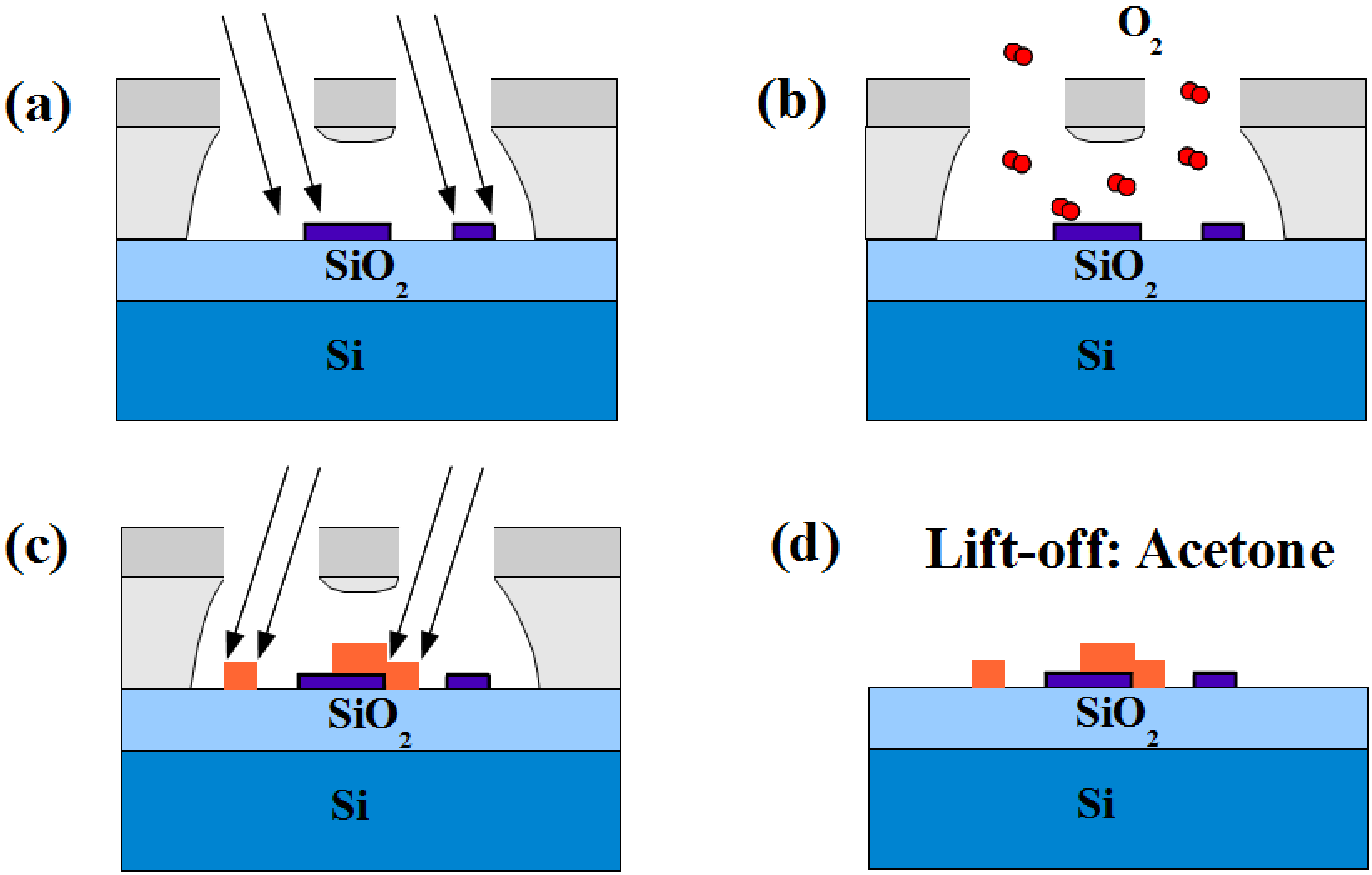
$$\dot{Q}_{\rm opt} \simeq 0.31 \frac{(k_B T)^2}{e^2 R_T}$$

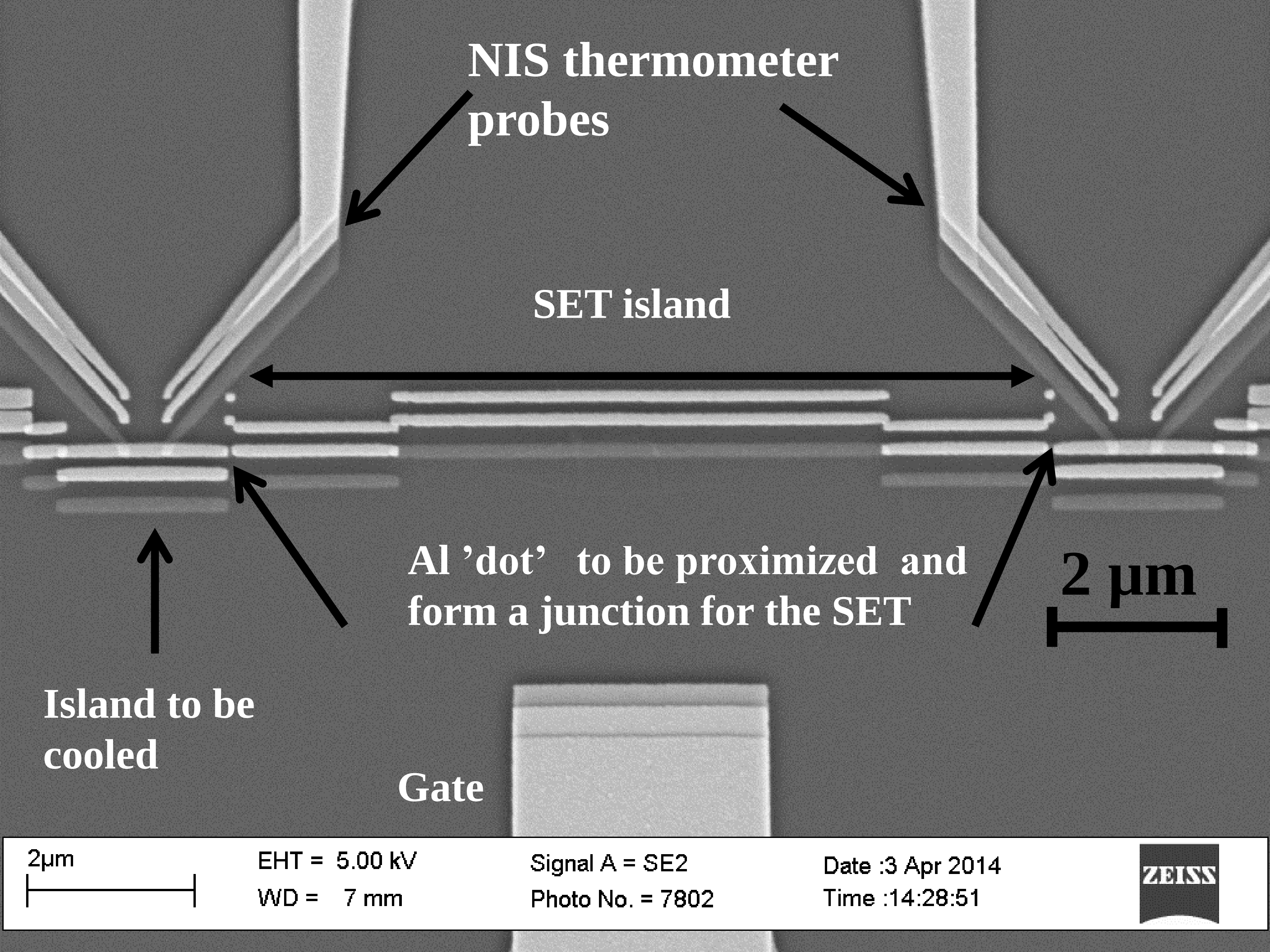
J. P. Pekola, J. V. Koski and D. V. Averin,
Refrigerator based on the Coulomb barrier for single-electron tunneling,
Phys. Rev. B **89**, 081309**(R)** (2014)

Fabrication process scheme

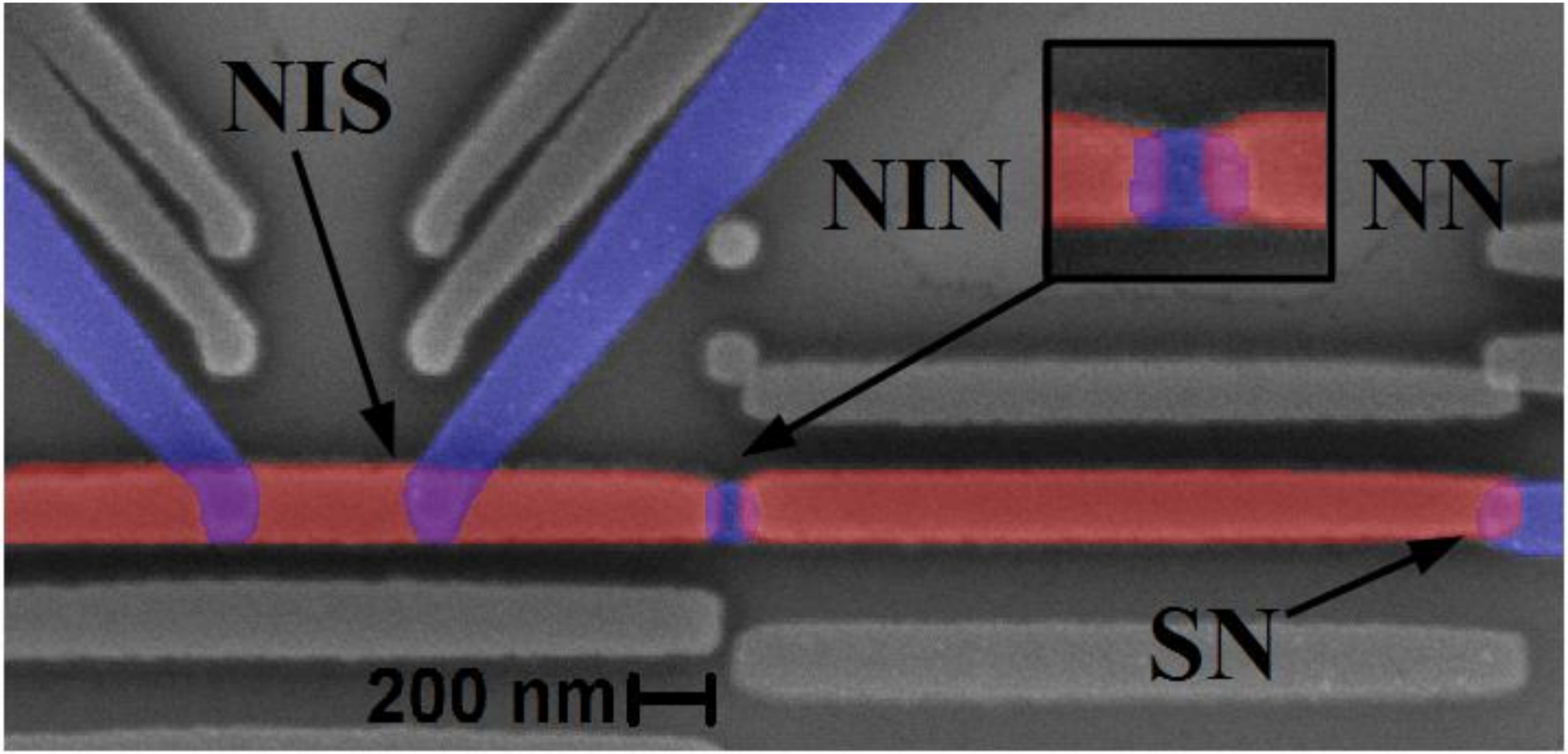


Fabrication process scheme: shadow evaporation, thermal oxidation




NIS thermometer probes
SET island
Al 'dot' to be proximized and form a junction for the SET
2 µm
Island to be cooled
Gate
2µm
EHT = 5.00 kV
WD = 7 mm
Signal A = SE2
Photo No. = 7802
Date :3 Apr 2014
Time :14:28:51
ZEISS

Close up of the ”Al” dot



Al 20 nm / Cu 25 nm / 3mbar 3min Ox / Cu 25 nm

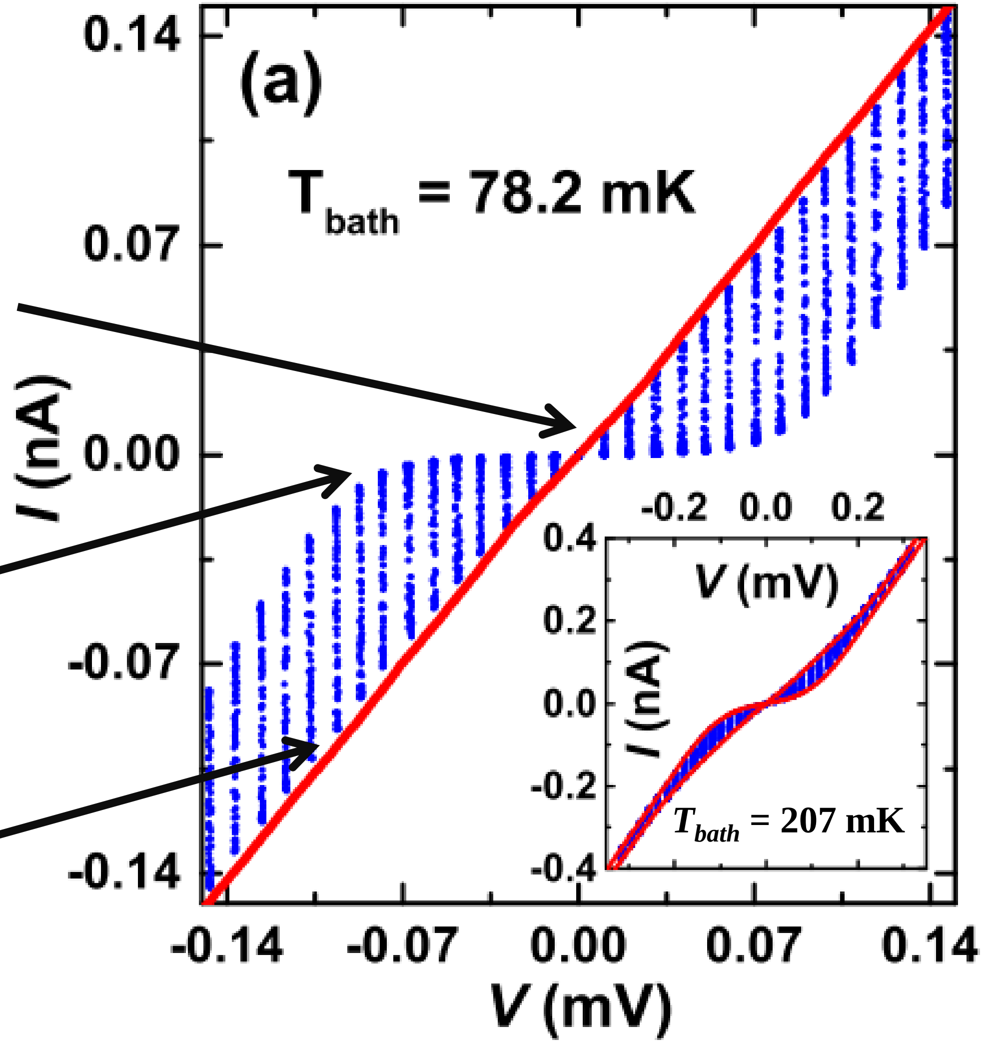
J. V. Koski, J. T. Peltonen, M. Meschke, and J. P. Pekola, **Laterally proximized aluminum tunnel junctions**, Applied Physics Letters **98**, 203501 (2011)

Device characterization: SET

No superconducting
gap observed,
SET is fully normal

Gate closed

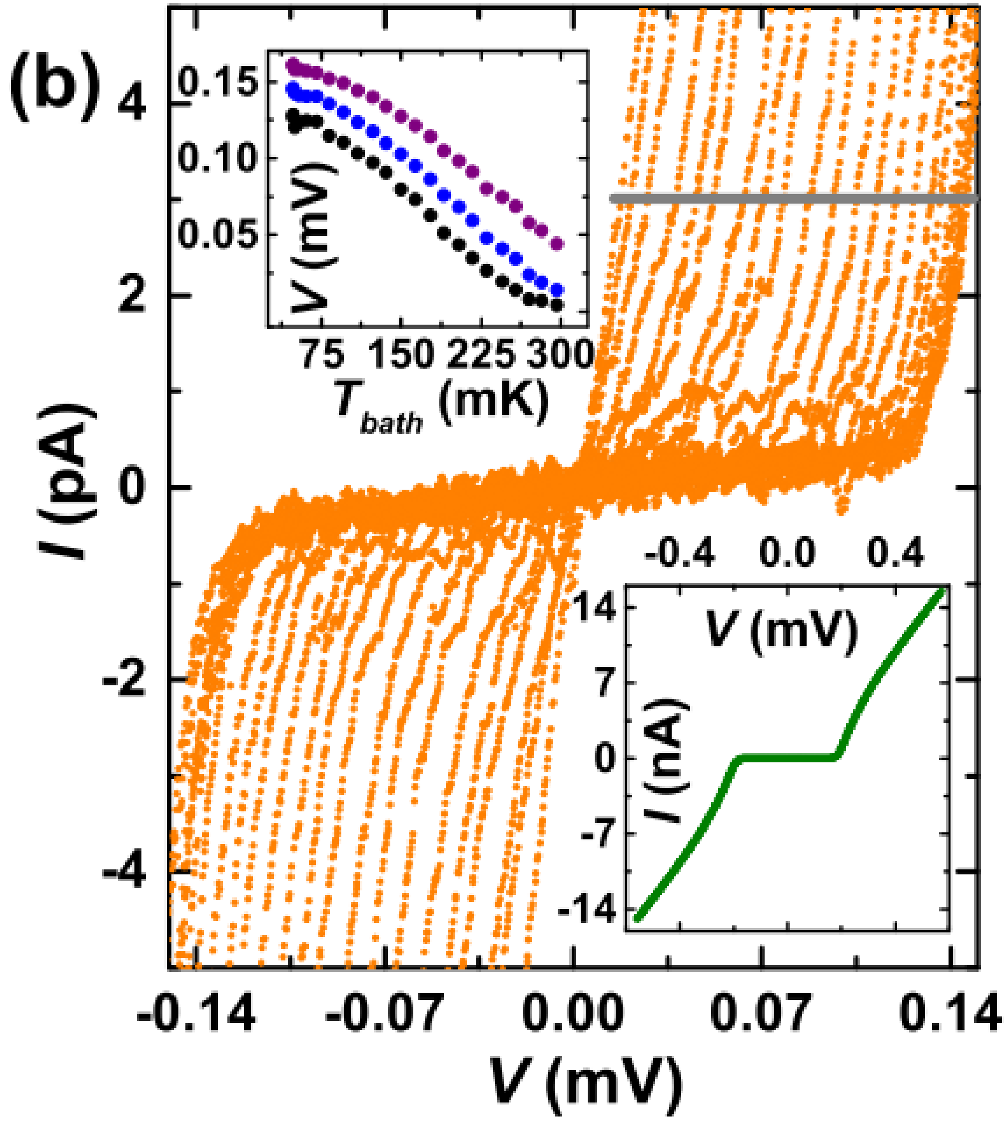
Gate open



From the fit

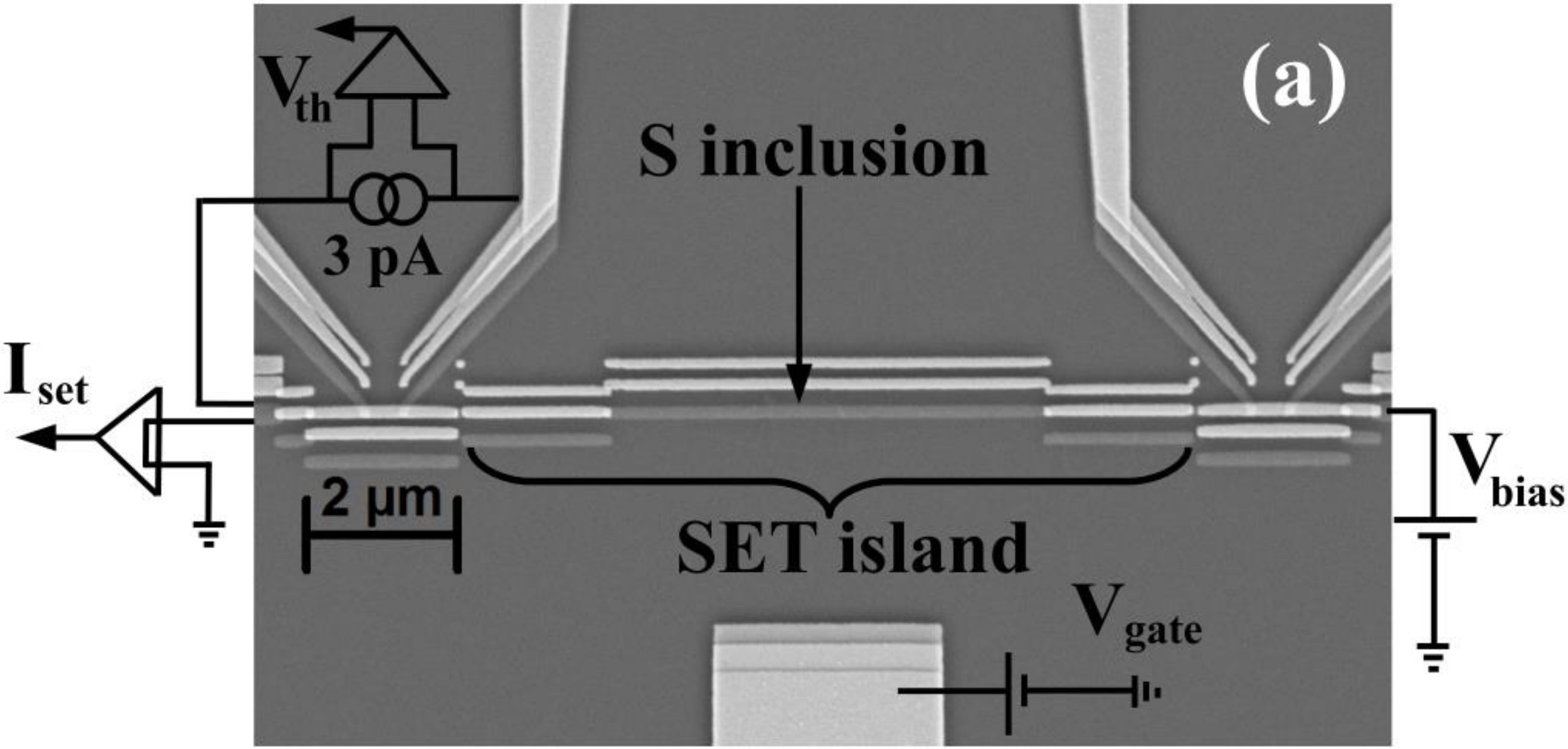
$\boldsymbol{E_c}$ = 78 µeV (0.9 K), $\boldsymbol{R_{T,1}}$ = 103 kOhm, $\boldsymbol{R_{T,2}}$ = 448 kOhm

Device characterization: NIS

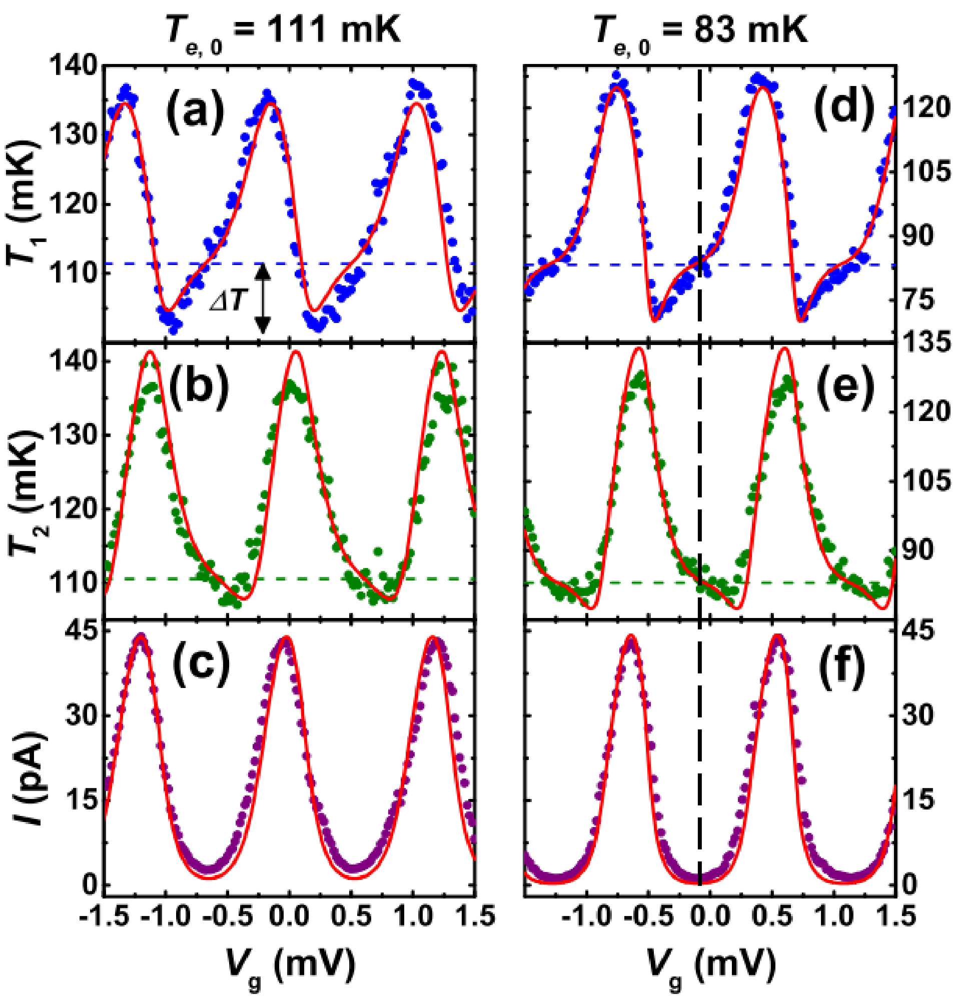


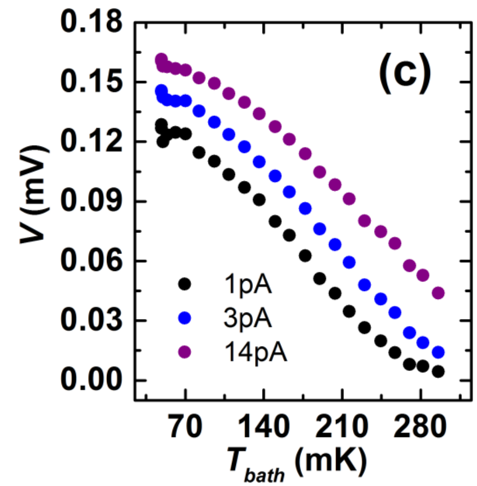
3 pA

Full measurement setup

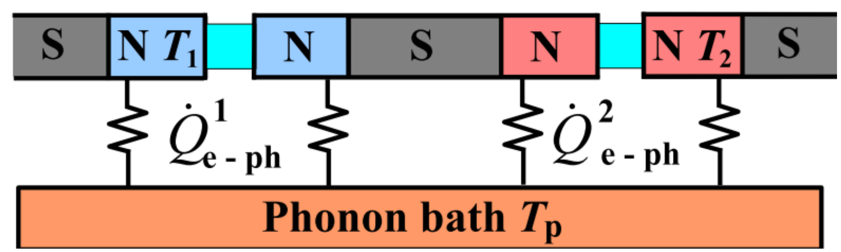


Temperature traces





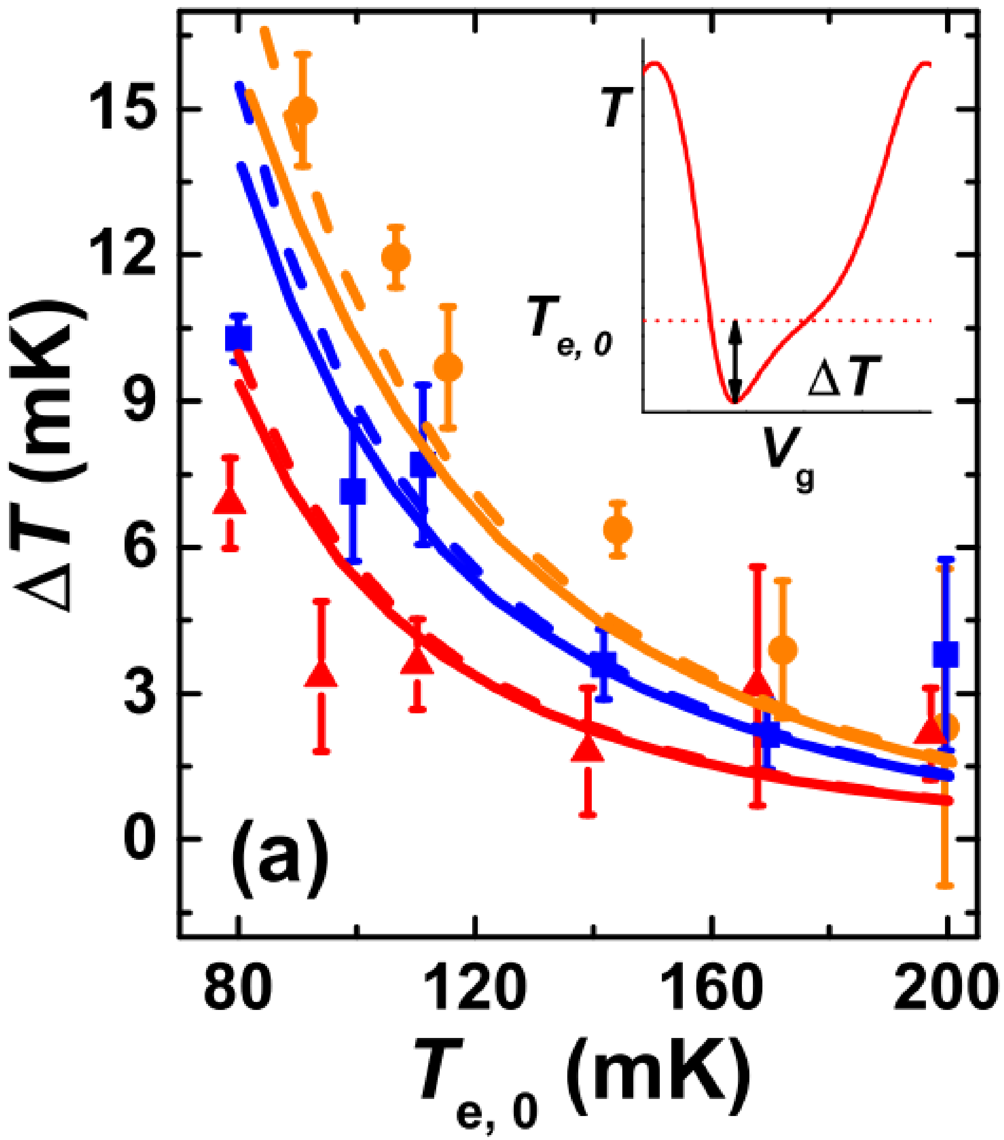
Thermal scheme



$$\dot{Q}^k_{e-ph} = \Sigma\Omega_k(T_k^5 - T_p^5)$$

Heat balance eq. $\dot{Q}_{SET,k} + \dot{Q}^k_{e-ph} = 0$

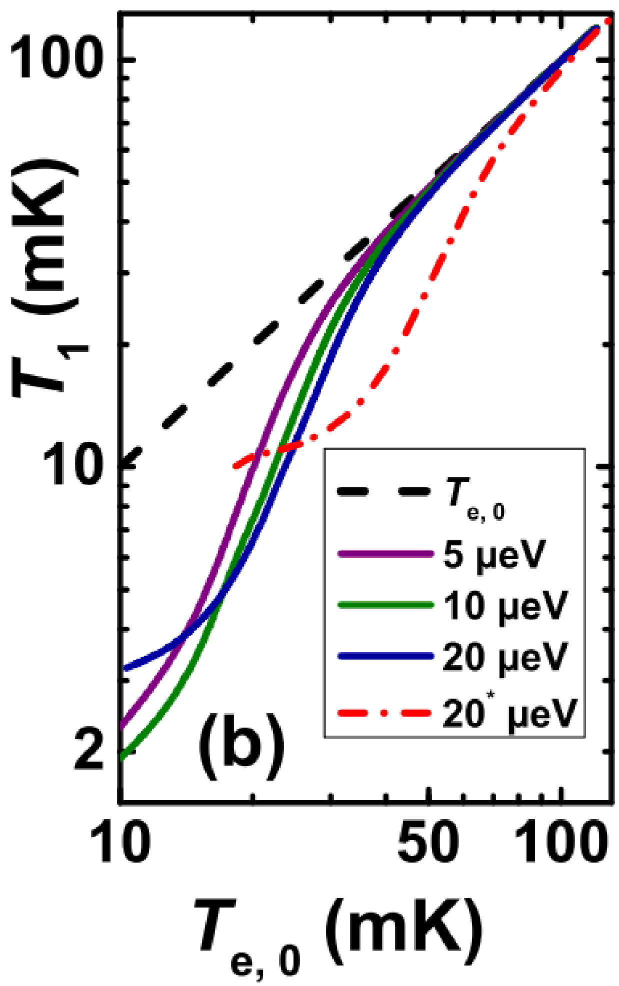
Extracted cooling



Points are averaged realizations for 60, 40 and 20 μeV in the range of ± 5 μeV from top to bottom.

Lines are theoretical prediction of Δ***T***.

Cotunneling as cooling limitation



Solid lines are theoretical prediction of T_1 for $10^* \boldsymbol{R_T}$.

Future possible improvements

- Higher tunneling resistance of the junctions $\boldsymbol{R_T}$
- Lower bias voltage $\boldsymbol{V}$
- Lower starting base electronic temperature (better shielding)

A. V. Feshchenko, J. V. Koski, and J. P. Pekola, **Experimental realization of a Coulomb blockade refrigerator**, Phys. Rev. B **90**, 201407(R) (2014)

This work has been done by:

A. F.,
Jonne Koski,
Jukka Pekola

In a collaboration with
Ivan Khaymovich and Dmitri Averin

- *J. P. Pekola, J. V. Koski and D. V. Averin*, **Refrigerator based on the Coulomb barrier for single-electron tunneling**, Phys. Rev. B **89**, 081309**(R)** (2014)
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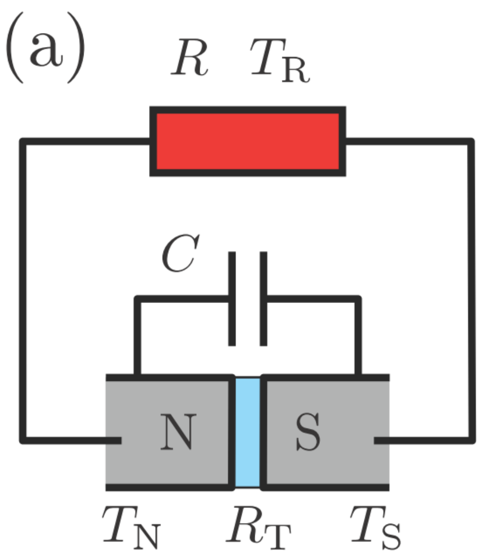
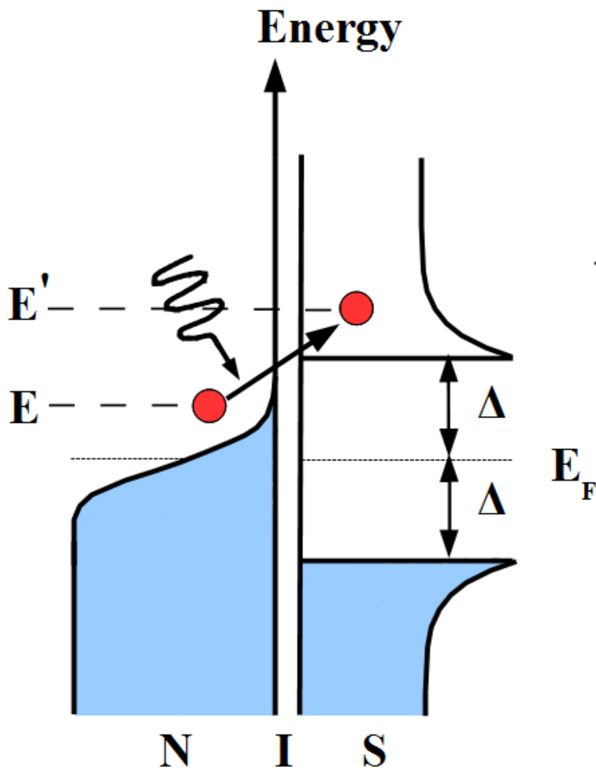
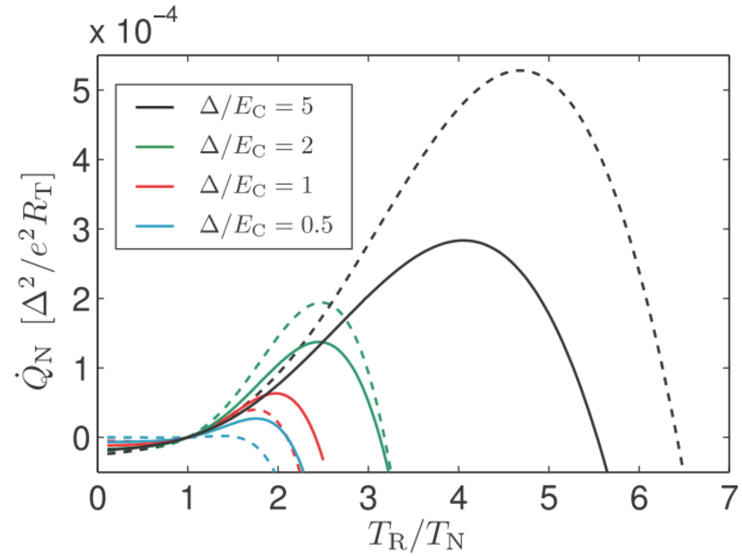
Next: Brownian refrigerator, 'cooling by heating'







- *J.P. Pekola and F.W.J. Hekking*, **Normal-metal-superconductor tunnel junction as a Brownian refrigerator**, PRL **98**, 210604 (2007)
- *J. T. Peltonen, M. Helle, A. V. Timofeev, P. Solinas, F. W. J. Hekking, and J. P. Pekola* **Brownian refrigeration by hybrid tunnel junctions**, Phys. Rev. B **84**, 144505 (2011)
- *B. Cleuren, B. Rutten, and C. Van den Broeck*, **Cooling by Heating: Refrigeration Powered by Photons**, PRL 108, 120603 (2012)
- A. Mari and J. Eisert, **Cooling by Heating: Very Hot Thermal Light Can Significantly Cool Quantum Systems**, PRL 108, 120602 (2012)

Thank you for your attention!