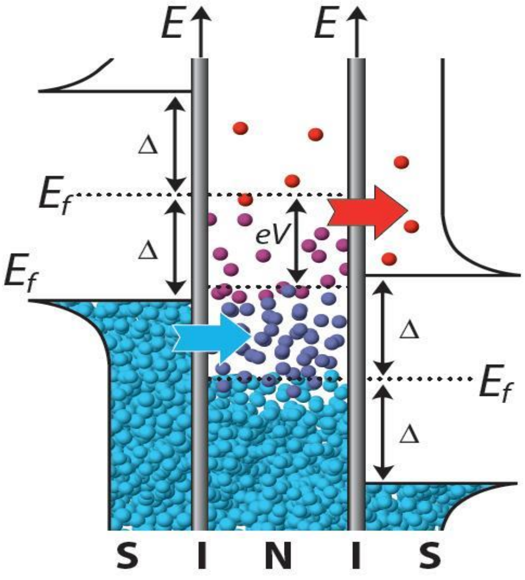
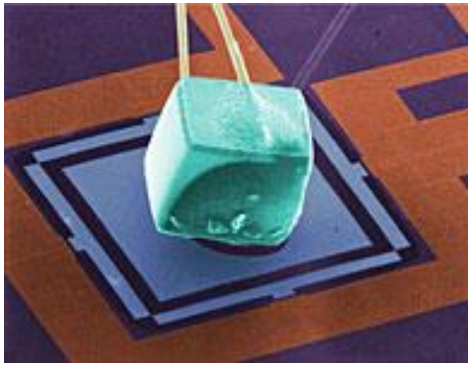
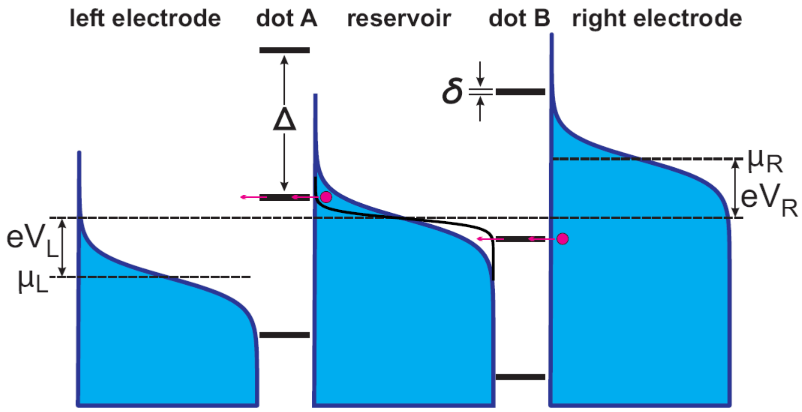
LECTURE 3: Refrigeration

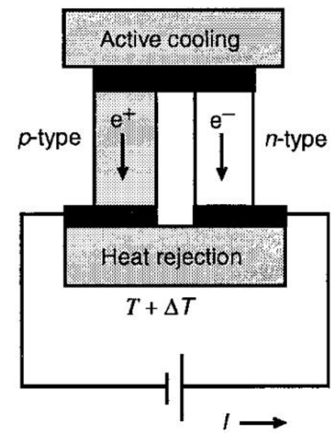






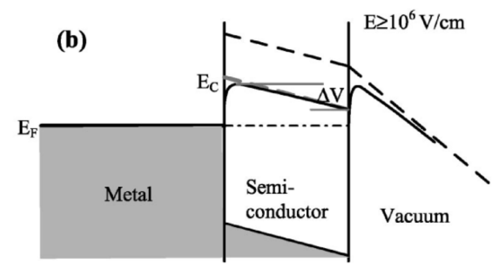
Refrigeration ”on-chip”

Thermoelectric refrigeration



Peltier refrigerators,
Peltier 1834

Thermionic refrigeration,
Mahan, 1994
Korotkov and Likharev, 1999



Quantum-dot refrigerator,
Edwards et. al., 1993
Experiment: Prance et al.,
PRL 102, 146602 (2009).

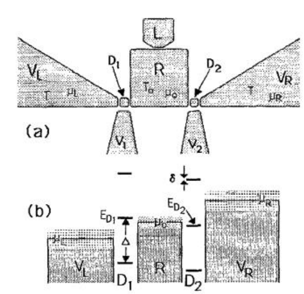
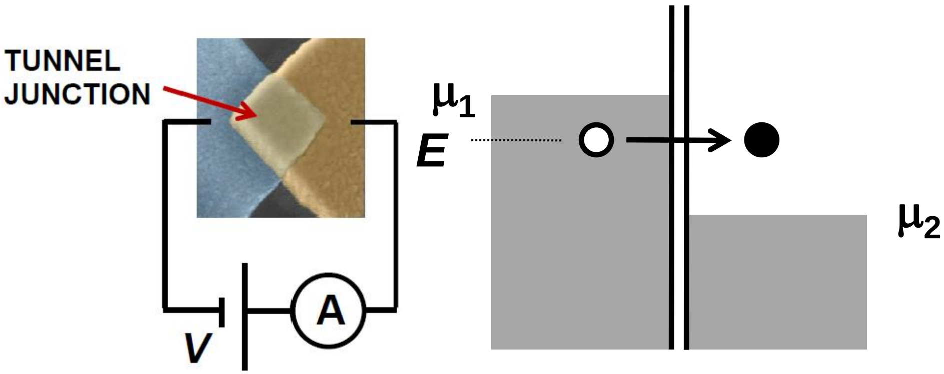


FIG. 1. (a) Schematic and (b) energy-level diagram of a theoretical design for a quantum-dot refrigerator which could be made using a 2DEG in $GaAs/Al_xGa_{1-x}As$. The reservoir R is cooled to T_0 as its Fermi-Dirac distribution is sharpened by resonant tunneling through quantum dots D_1 and D_2 to the electrodes V_L and V_R. A heat load L can be coupled electronically to R via tunneling.

Dissipation in transport through a barrier - tunneling



Dissipation generated by a tunneling event in a junction biased at voltage V

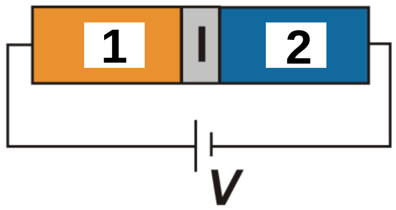
$$\Delta Q = (\mu_1 - E) + (E - \mu_2) = \mu_1 - \mu_2 = eV$$

$\Delta Q = T\Delta S$ is first distributed to the electron system, then typically to the lattice by electron-phonon scattering

For average current I through the junction, the total average power dissipated is naturally

$$P = (I/e)\Delta Q = IV$$

Energy current in a tunnel junction



Energy current (from conductor 1)

$$P(V) = \frac{1}{e^2 R_T} \int (E - eV) n_1(E - eV) n_2(E) [f_1(E - eV) - f_2(E)] dE$$

Compare to: $I(V) = \frac{1}{e^2 R_T} \int e N_1(E - eV) N_2(E) [f_1(E - eV) - f_2(E)] dE$

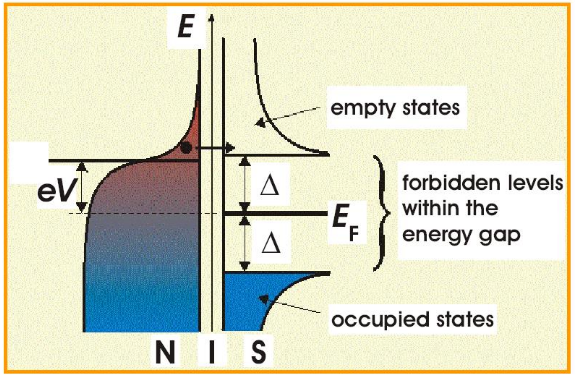
For a NIN junction (constant DOSes)

$$P(V) = \frac{1}{e^2 R_T} \int (E - eV) [f(E - eV) - f(E)] dE = -\frac{V^2}{2R_T}$$

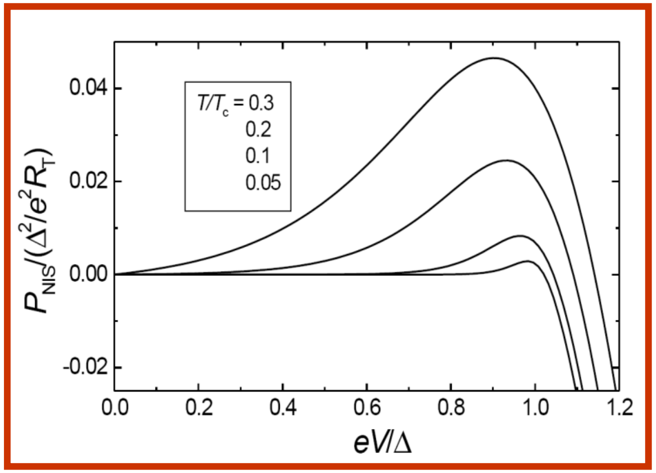
$= -IV/2$

The Joule power is distributed equally between 1 and 2 in this case.

Electronic NIS-coolers



Cooling power of a NIS junction:



$$P_{\rm NIS} = \frac{1}{e^2 R_T}\int dE(E-eV)n_S(E)[f_N(E-eV)-f_S(E)]$$

Optimum cooling power is reached at $V \cong \Delta/e$:

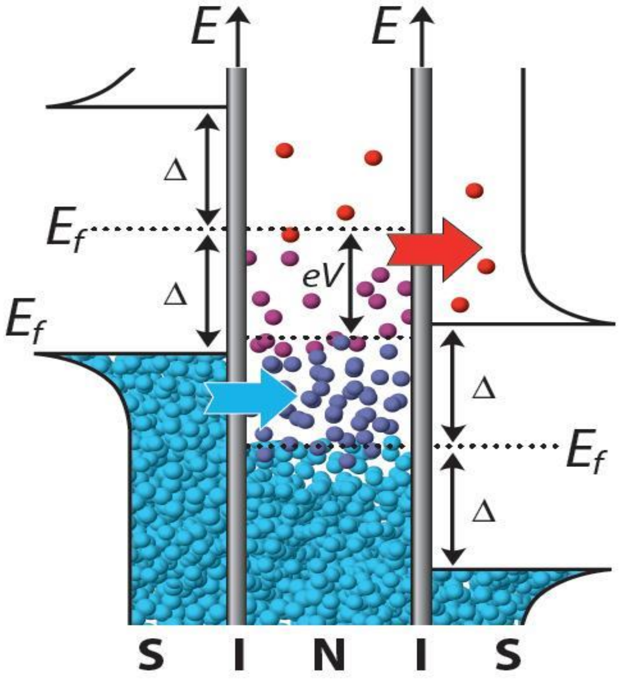
$$P_{\rm NIS} \approx 0.6\frac{\Delta^2}{e^2 R_T}(\frac{k_B T_N}{\Delta})^{3/2}$$

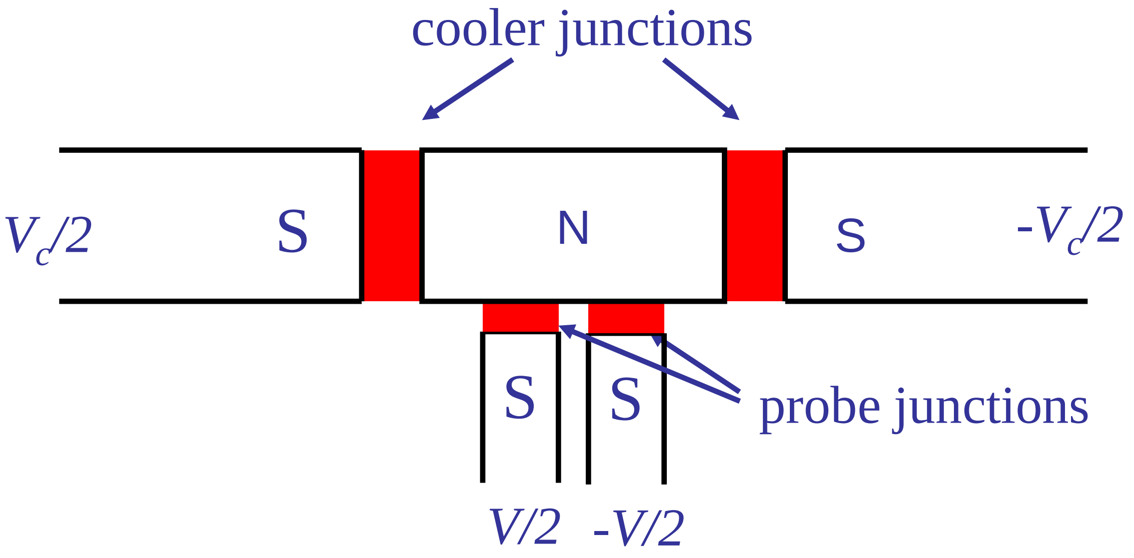
Efficiency (coefficient of performance) of a NIS junction cooler:

$$\eta \simeq k_B T/\Delta$$

For reviews, see Giazotto et al., Rev. Mod. Phys. 78, 217 (2006); Muhonen et al., Reports on Progress in Physics 75, 046501 (2012).

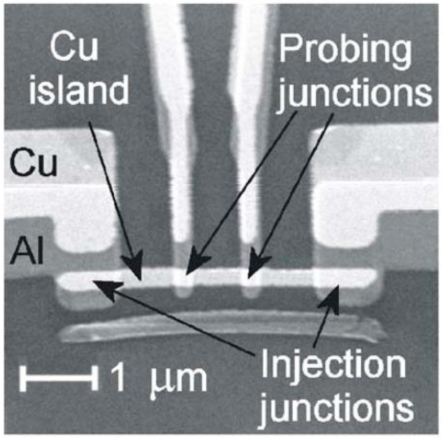
SINIS structure

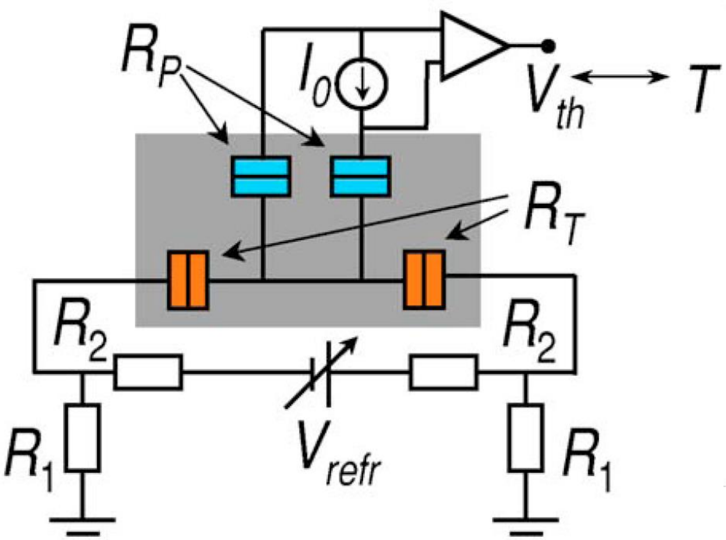


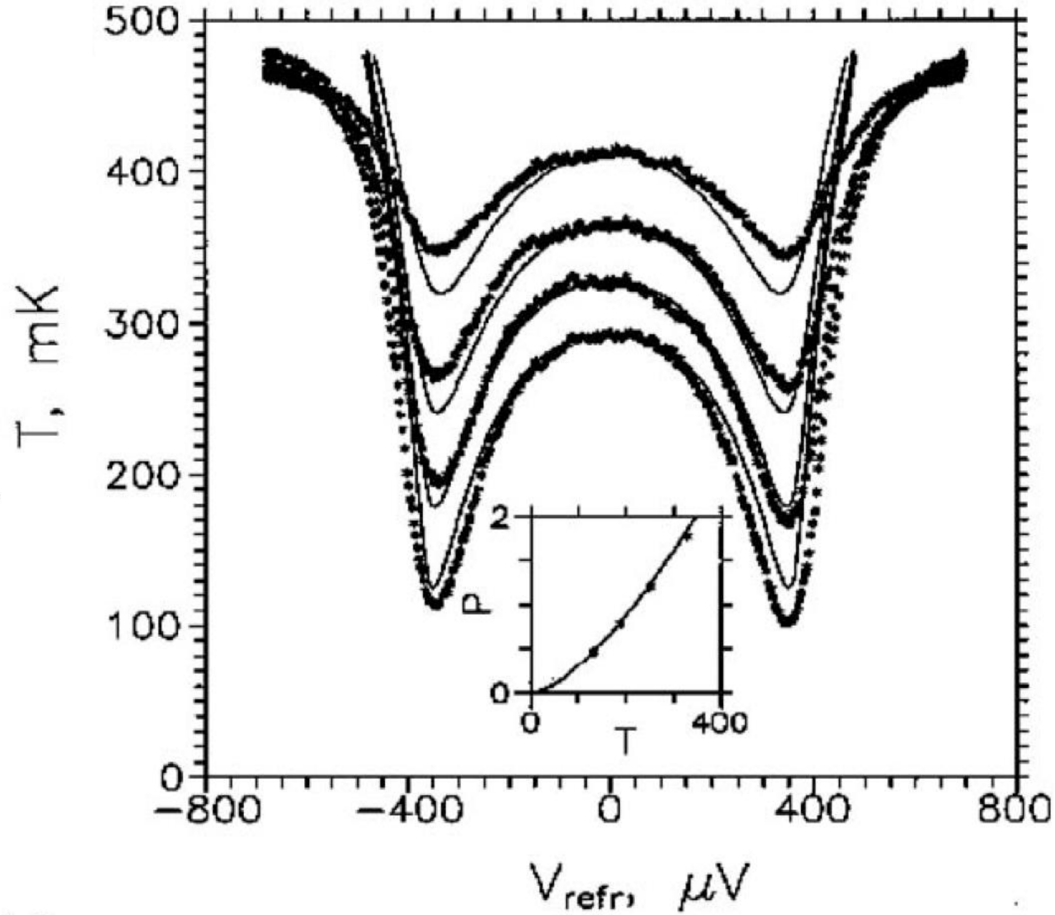


Symmetric back-to-back structure provides equal cooling by the two junctions.

Early experiments

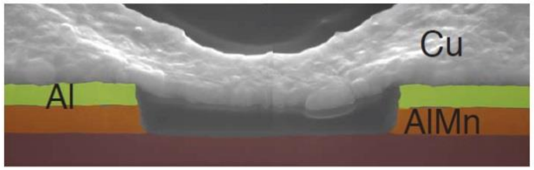




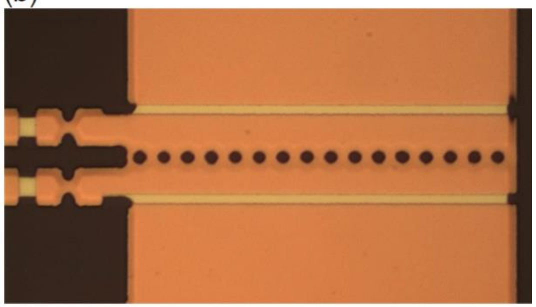


M. Leivo et al., 1996

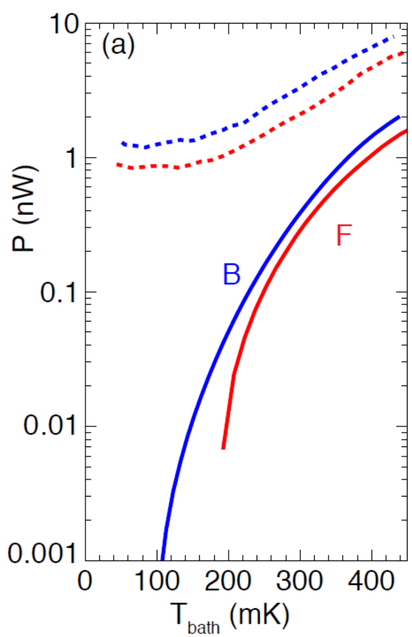
Large cooling power NIS refrigerators

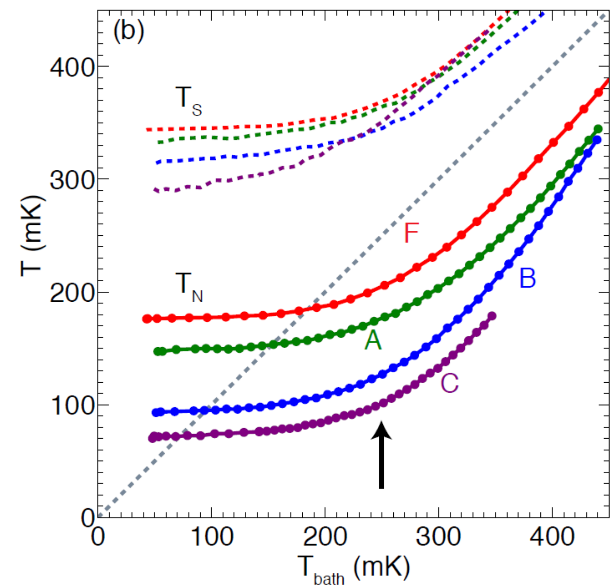


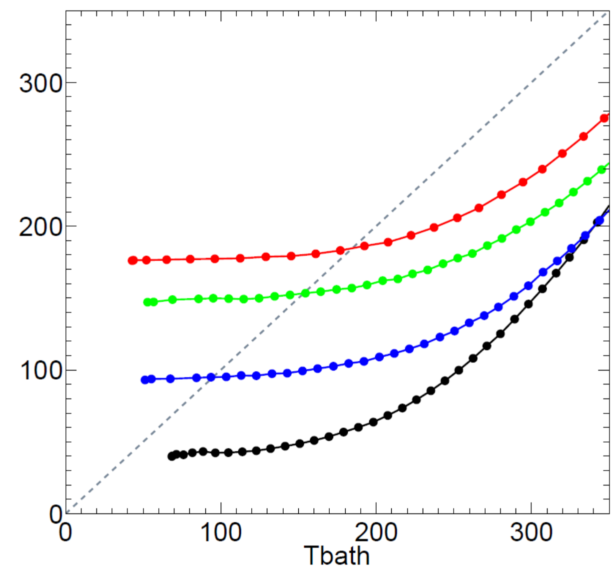
(b)



Large-area (70 X 4 μm^2) photolithographic junctions, cooling power 1 nW at 300 mK
Nguyen et al. 2013

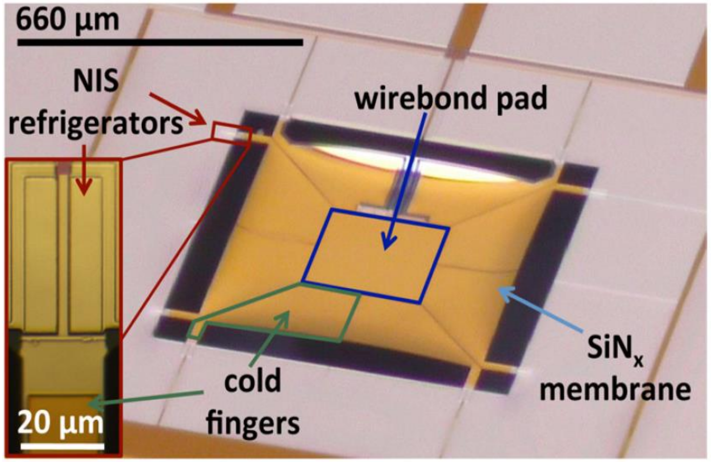


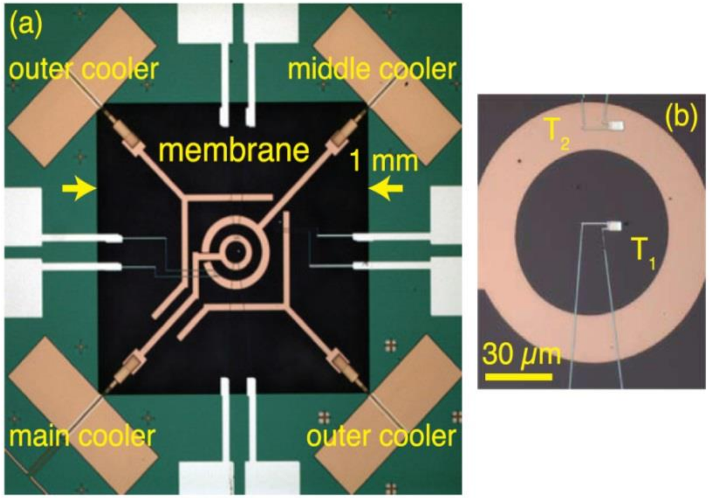




More recent NIS coolers

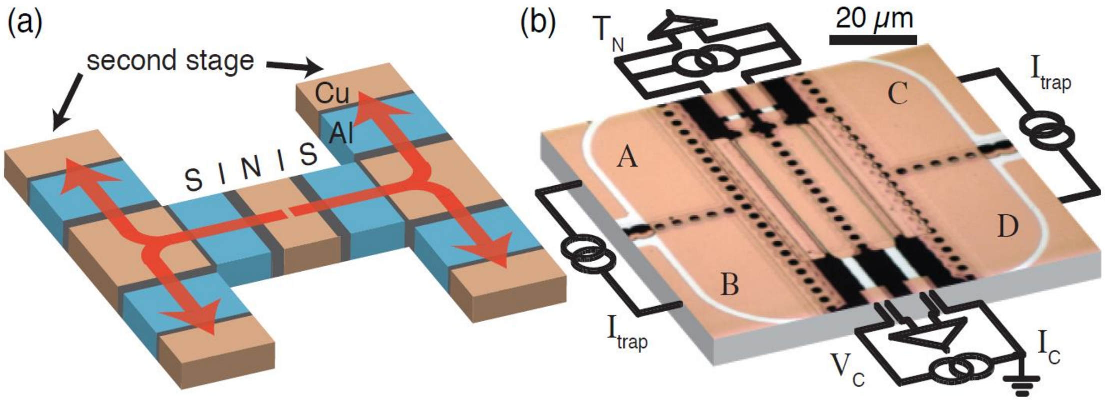
Platform refrigerators





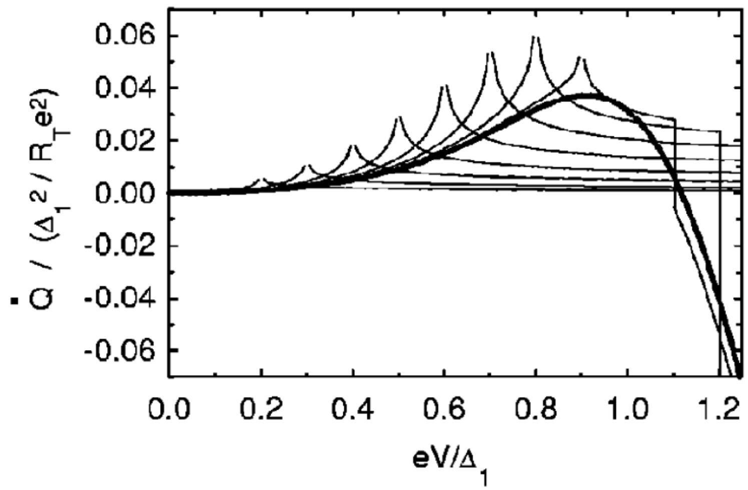
P. Lowell et al., NIST, 2013

H. Nguyen et al., Helsinki, 2015



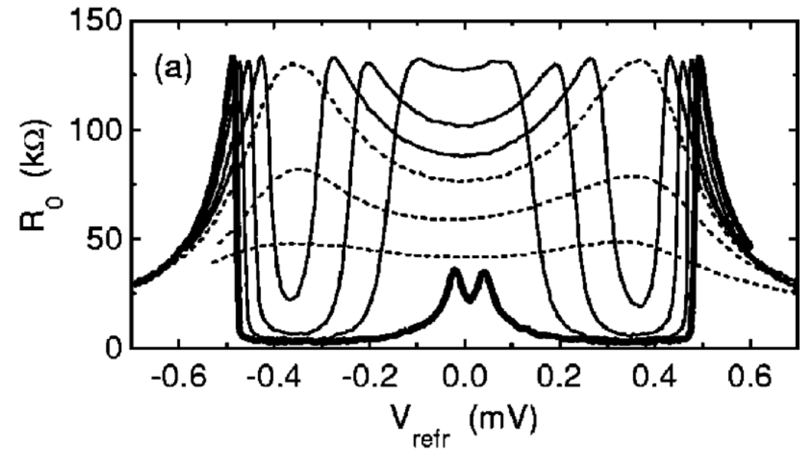
Two-stage refrigerator, H. Nguyen et al., 2016

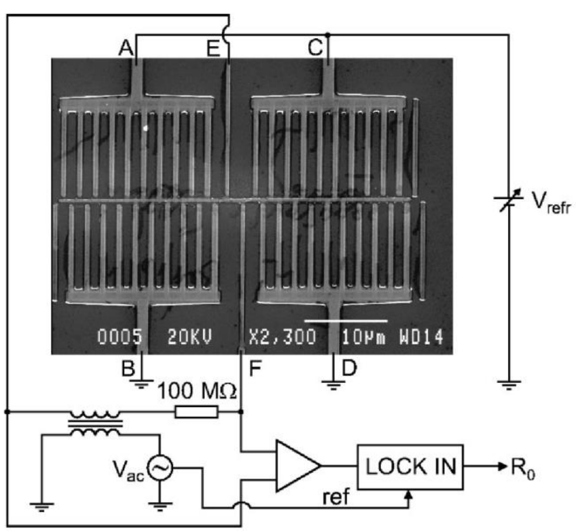
Cooling of a superconductor (SIS'IS cooler)



$$\dot{Q} = \frac{1}{e^2 R_T} \int_{-\infty}^{\infty} [f(\epsilon, T_{e2}) - f(\epsilon - eV, T_{e1})]$$

$$\times N_2(\epsilon) N_1(\epsilon - eV) \epsilon \, d\epsilon$$





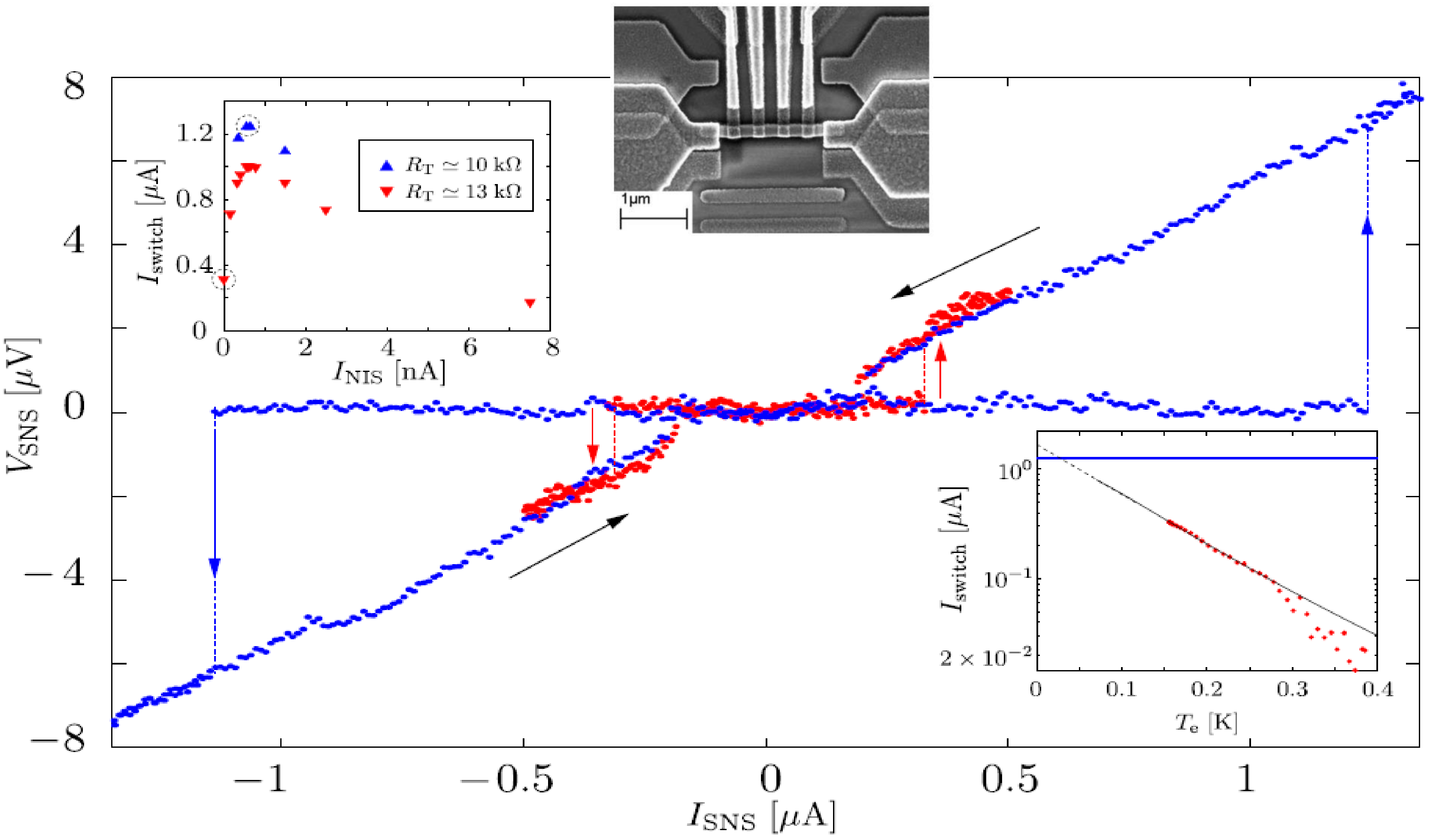
Ti – Al sample [T_C(Ti) = 0.5 K, T_C(Al) = 1.3 K]

COOLING FROM NORMAL TO SUPERCONDUCTING STATE

A. J. Manninen et al., Appl. Phys. Lett. **74**, 3020 (1999).

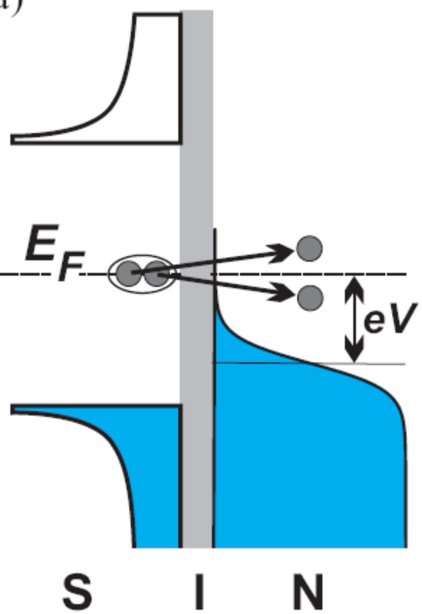
Low temperature limit

SNS proximity Josephson junction is a low-dissipative, unsaturating thermometer at low *T*: lowest *T* = 20 mK (+/- 10 mK). J. Peltonen et al, unpublished.



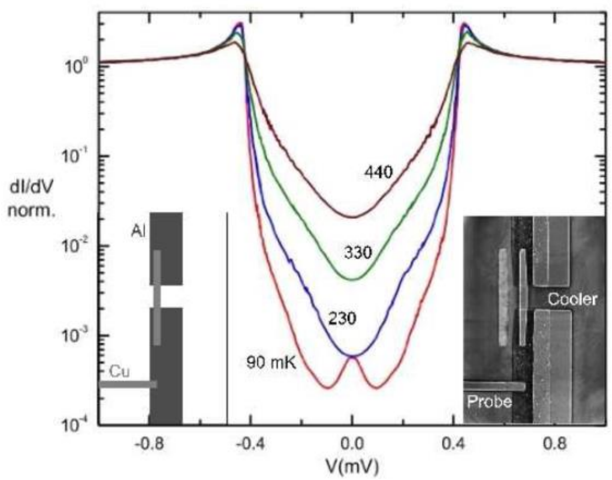
Influence of Andreev current on electron cooling

(a)

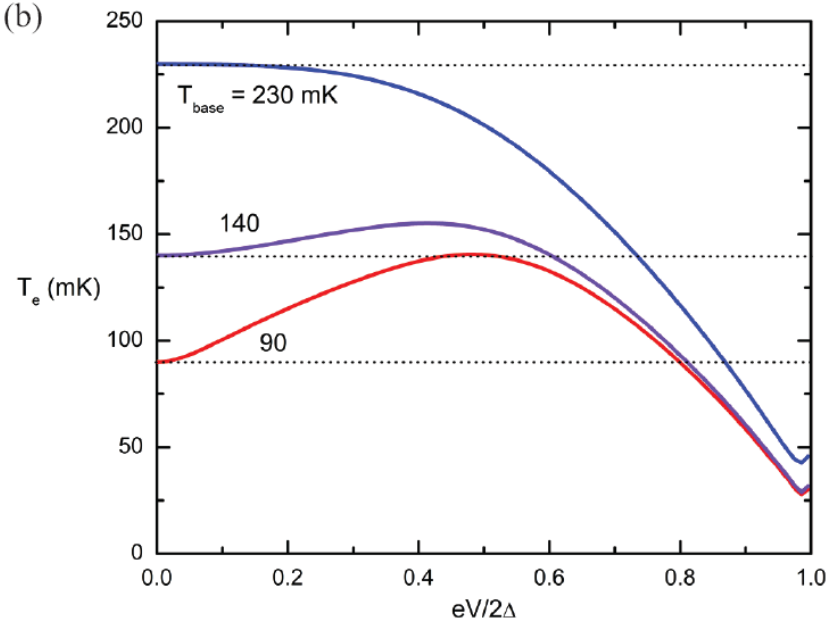


Two-electron tunneling becomes important in transparent junctions.
Maisi et al. 2011, 2013

Effective at low bias voltages, dissipation $I_{AR}V$ in N electrode.



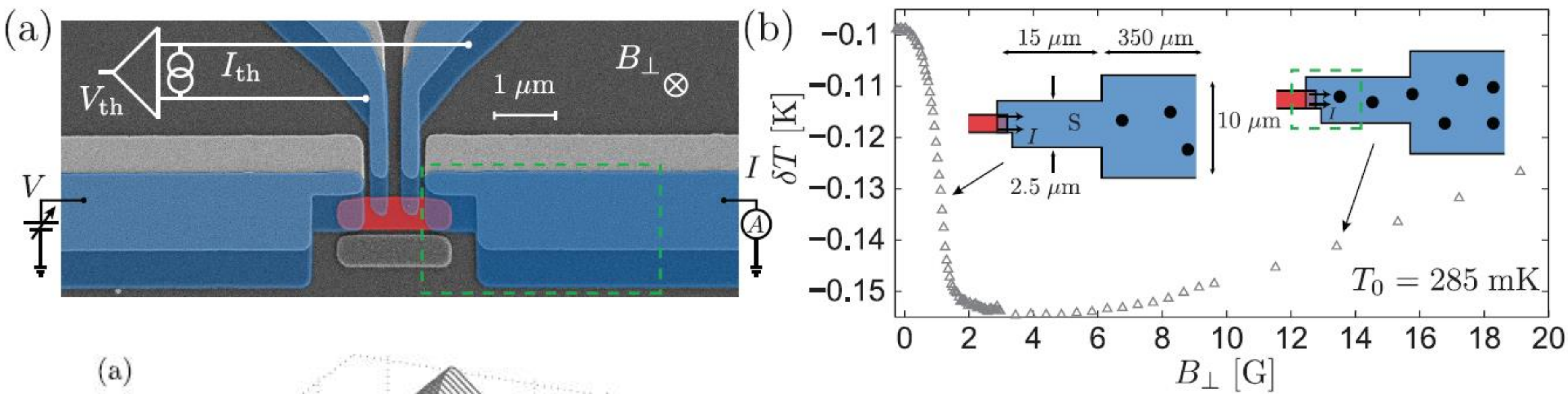
(b)

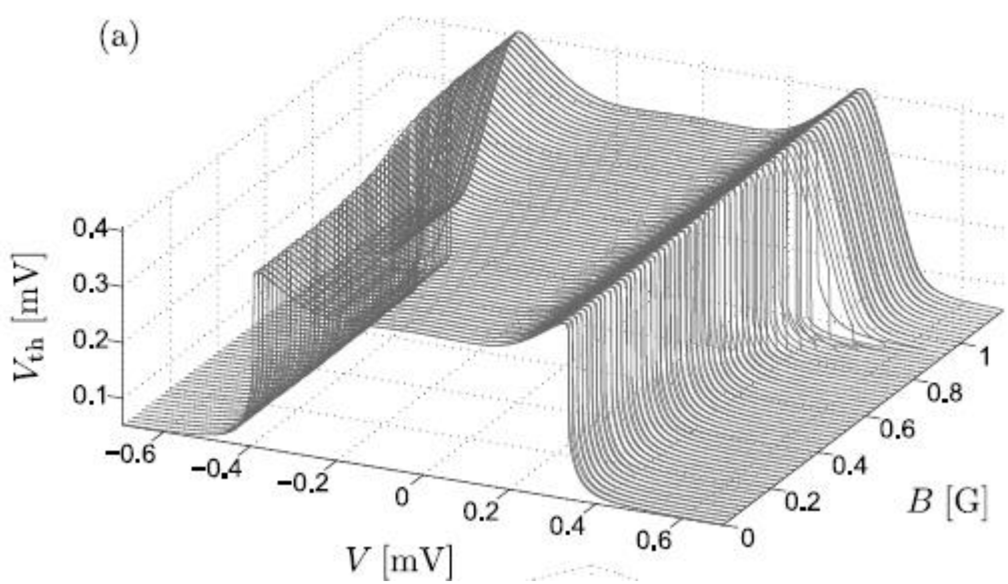


Rajauria et al., 2008

Energy relaxation by magnetic field in coolers

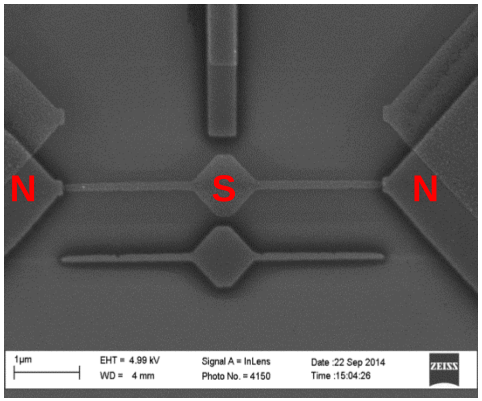
Magnetic field enhanced cooling



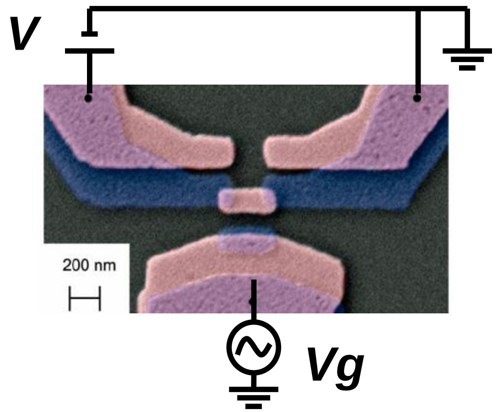


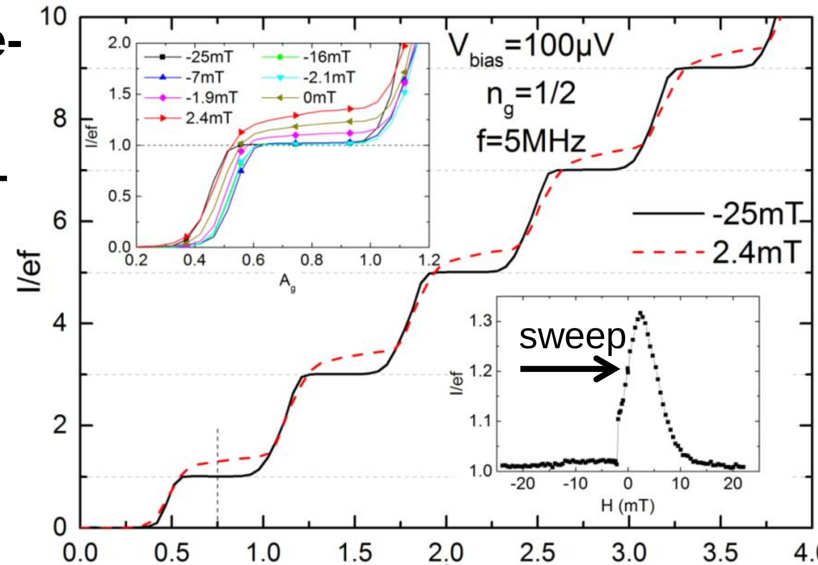
Quasiparticle relaxation is improved in the superconductor due to the presence of vortices Peltonen et al. 2011

Sc aluminium dot in magnetic field

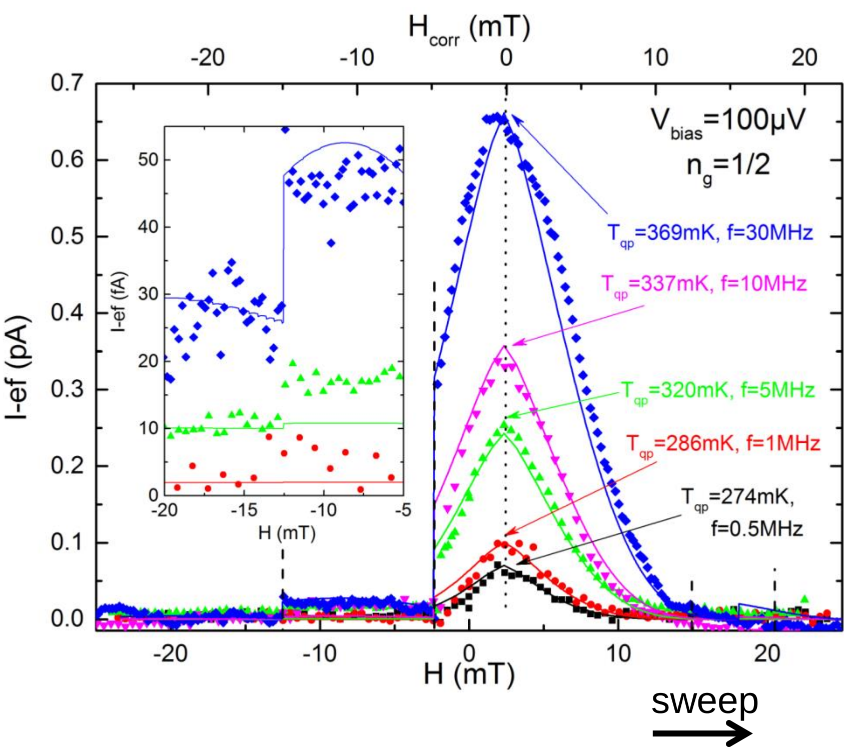


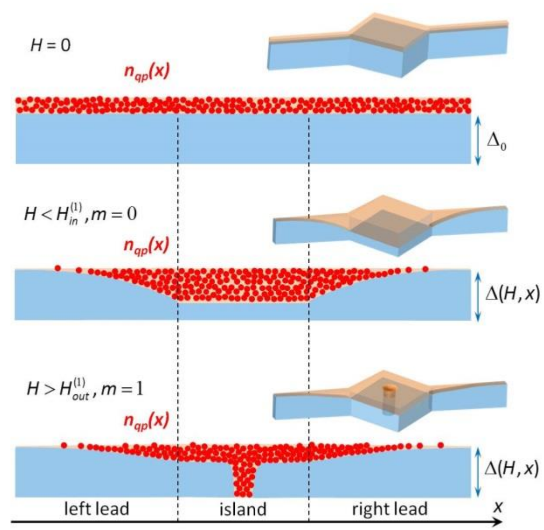
Operation as a single-electron turnstile





$A_g = C_g V_g / e$



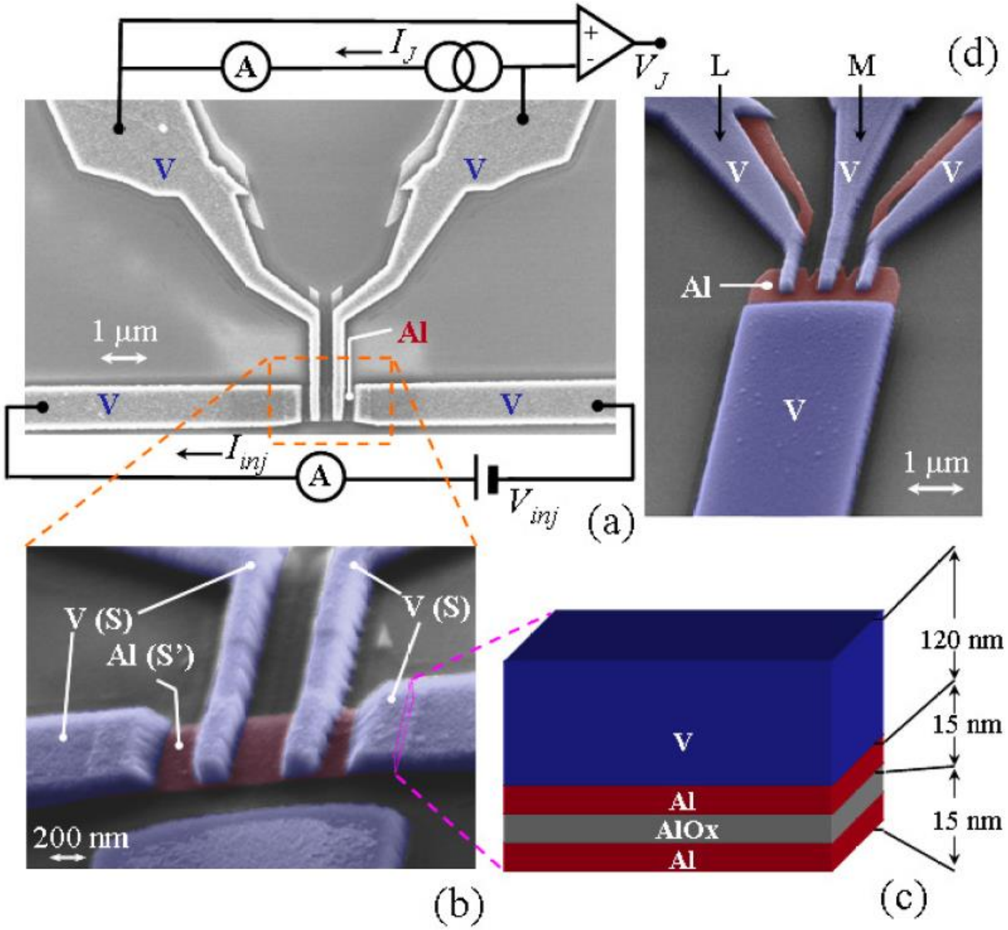


Meissner state and a single vortex

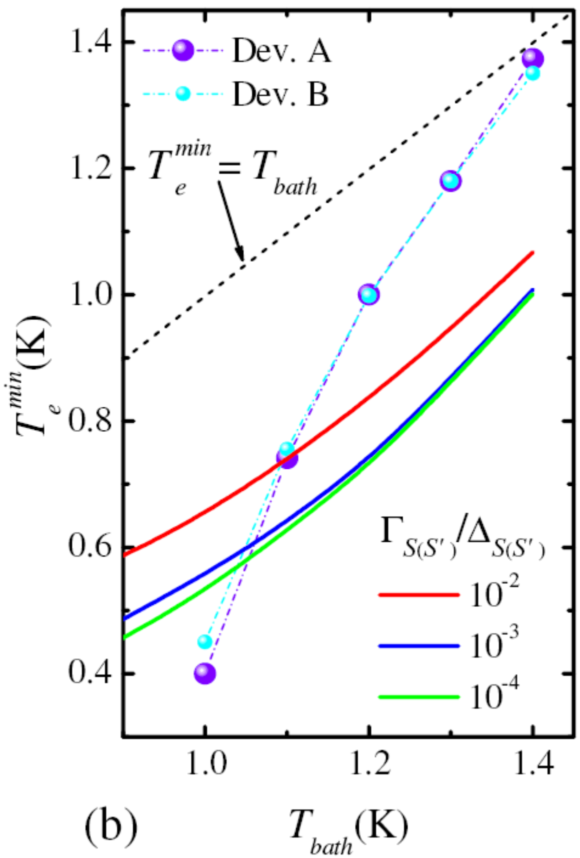
Magnetic field improves qp relaxation and leads to redistribution of the gap profile

M. Taupin et al., Nature Communications 6, 10977 (2016).

Higher temperatures

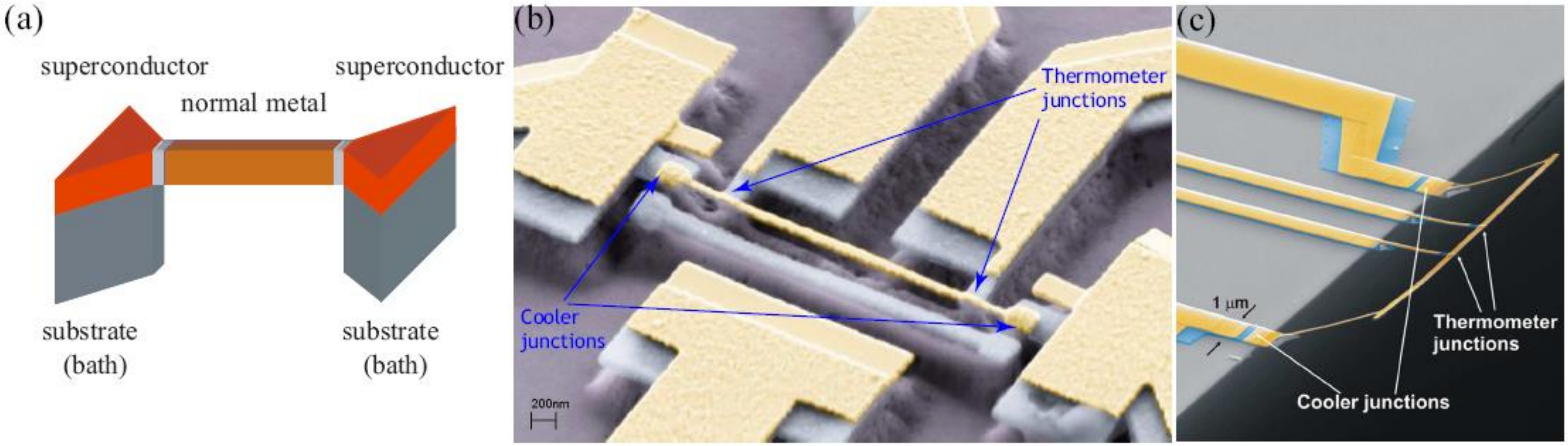


Vanadium as a superconductor, Tc = 4 K.



O. Quaranta et al., APL **98**, 032501 (2011): Cooling Al from 1 K to 0.4 K.

Cooling nanomechanical beams

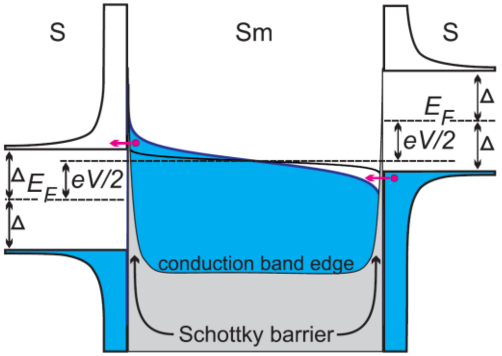


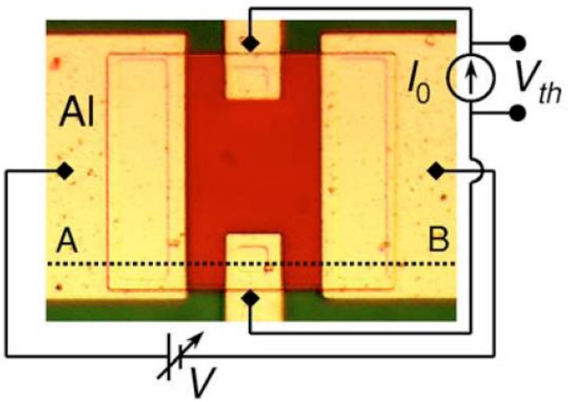
Cooling phonons as well
Koppinen et al PRL 2009
Is e-ph coupling as in bulk? T^3 instead of T^5?
Hekking et al, PRB 2008, Muhonen et al, APL 2009

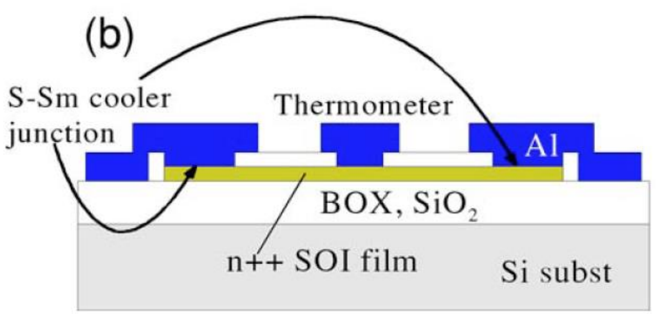
Schottky barrier cooler

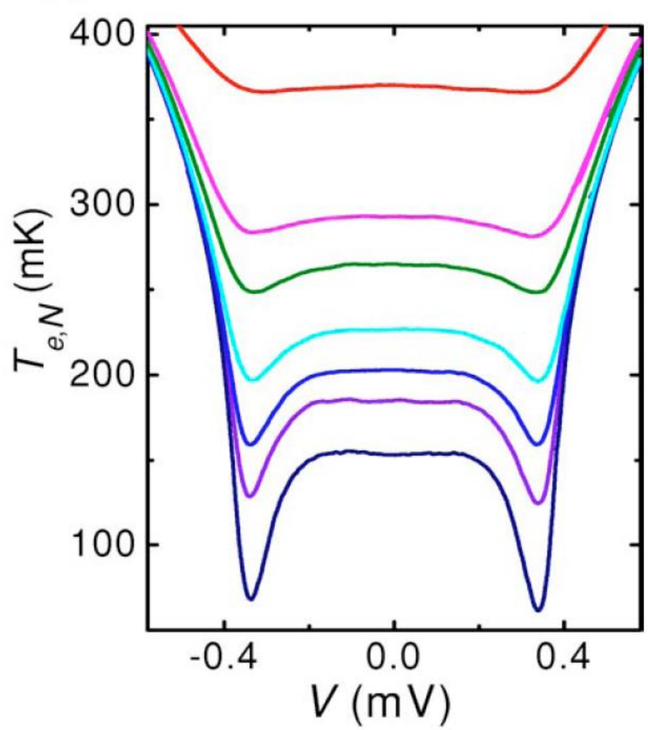
Same working principle as in SINIS, but no oxide barrier needed: S-Sm interface forms a Schottky barrier.

A. Savin et al, APL **79**, 1471 (2001)





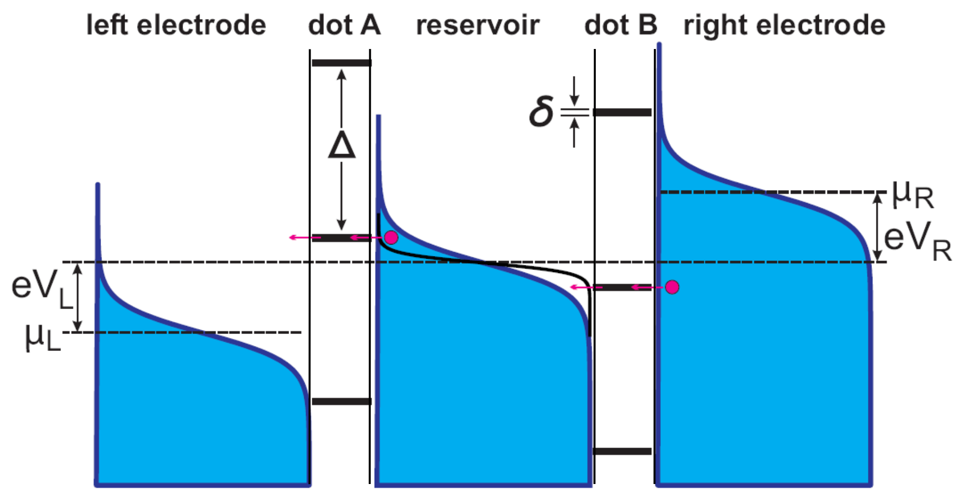


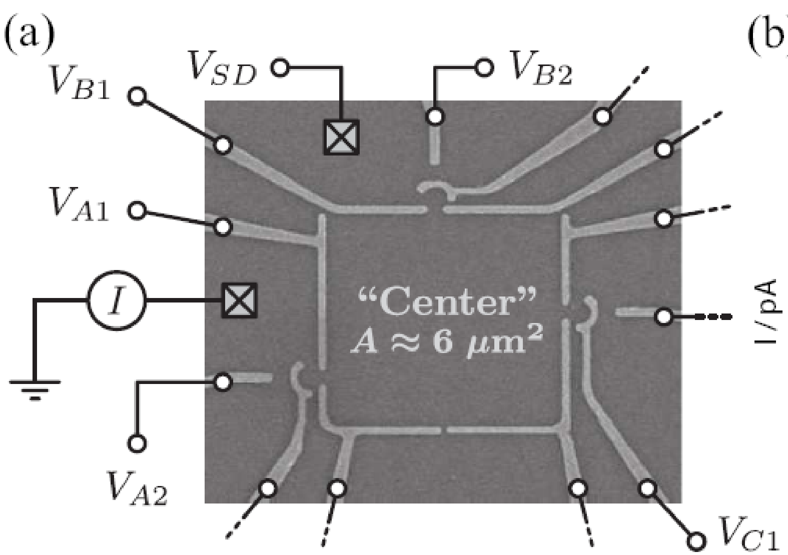


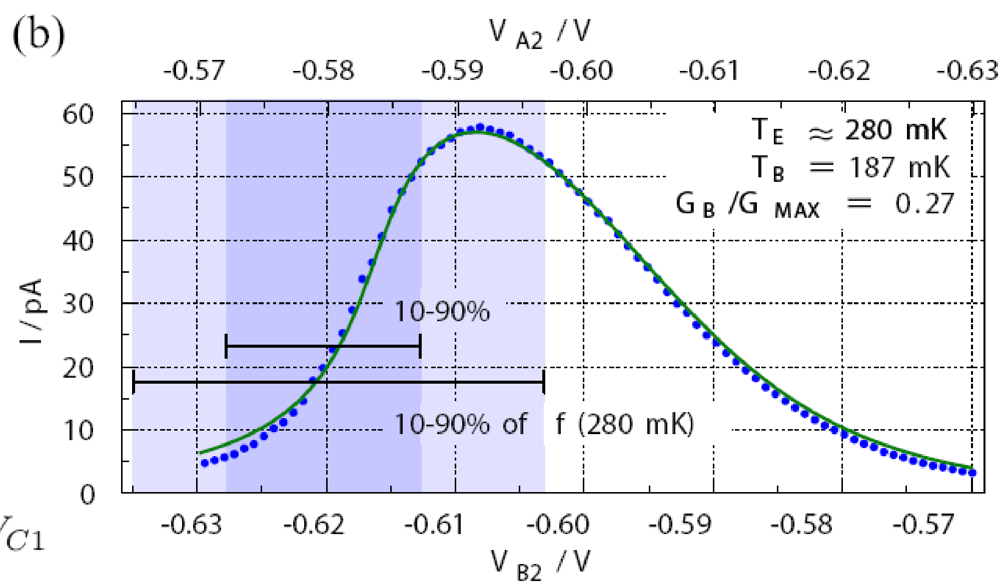
Quantum dot cooler

Edwards, 1993 (proposal)
Prance et al, 2009

Cooling 280 mK -> 187 mK demonstrated

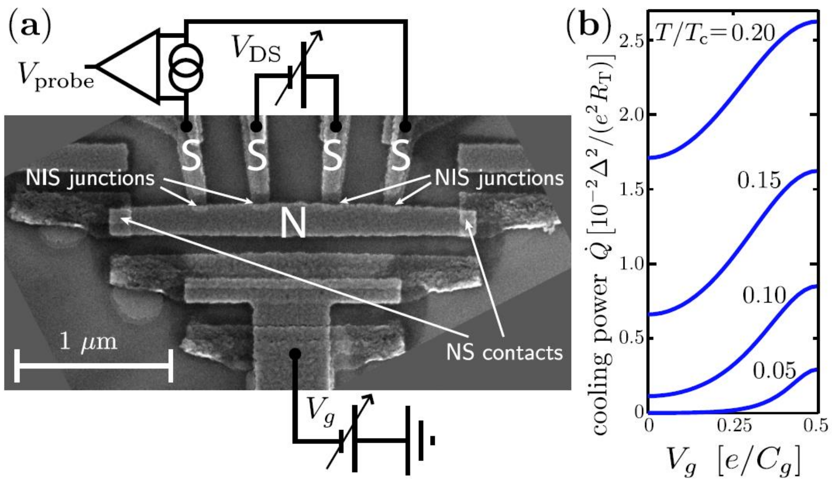


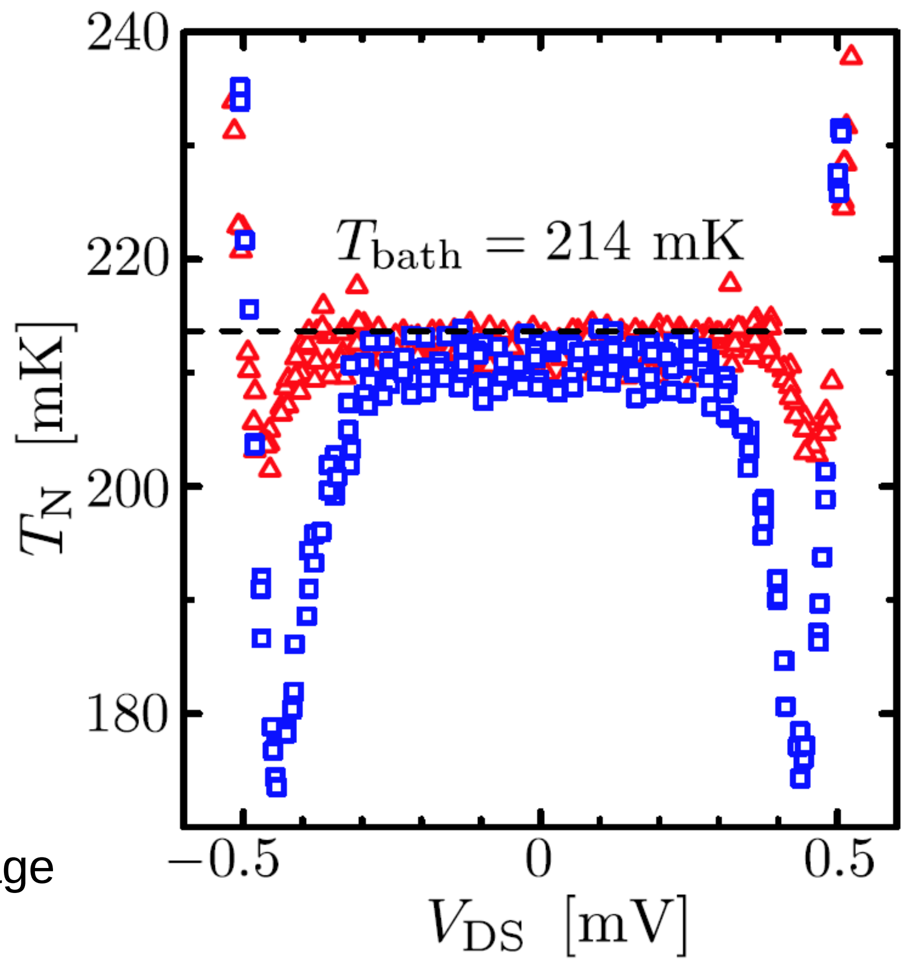




Tunable NIS refrigerator – ”heat transistor”

O. Saira et al., PRL 99, 027203 (2007)



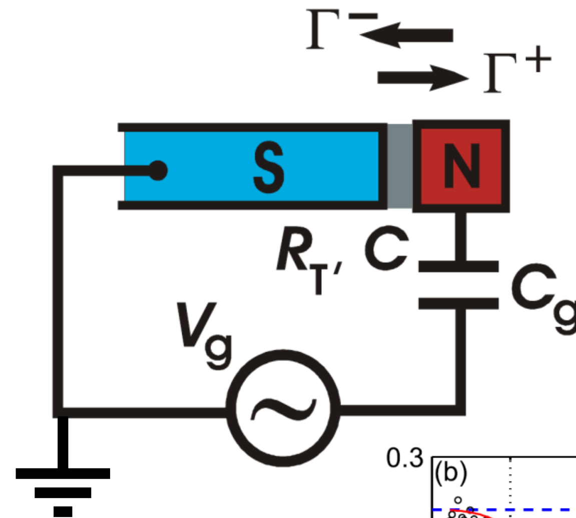


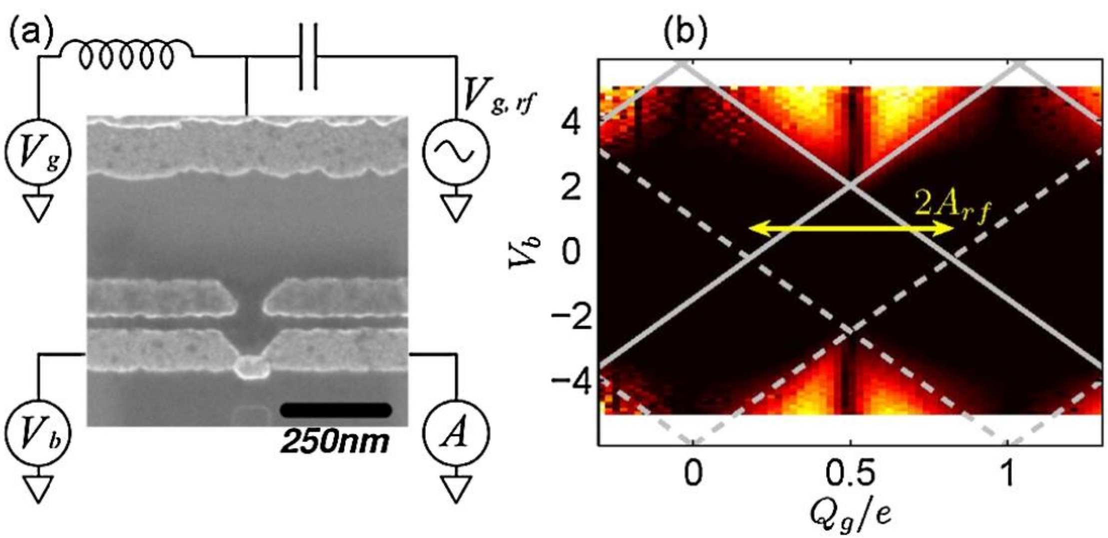
Cooling power can be tuned by gate voltage

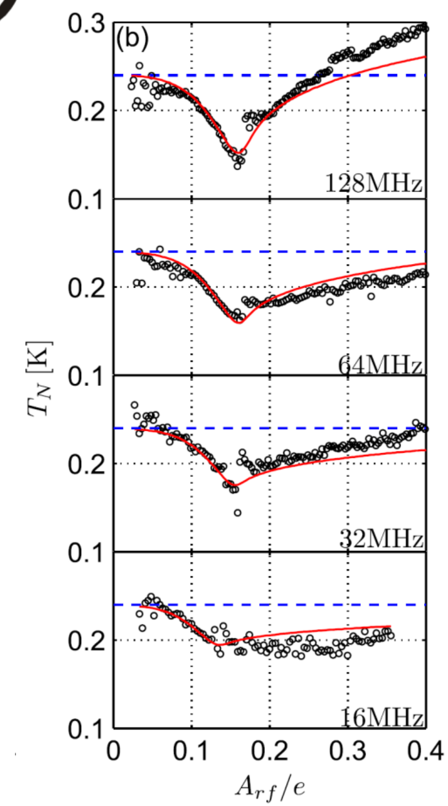
RF NIS-refrigerator

No net charge current, but finite cooling power

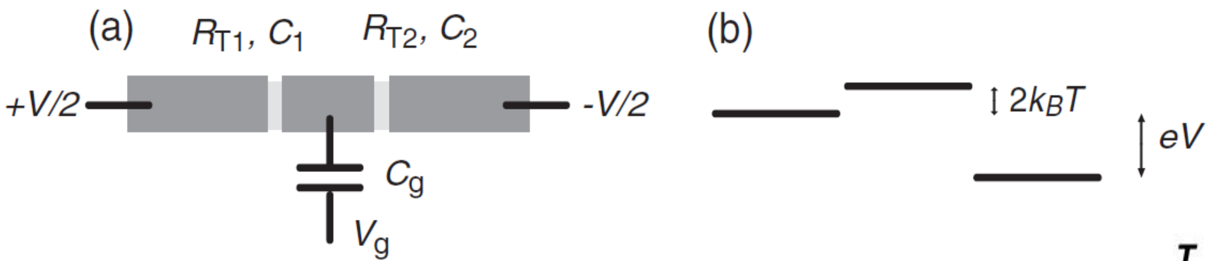
JP et al., PRL 98, 037201 (2007);
S. Kafanov et al., PRL 103, 120801 (2009)

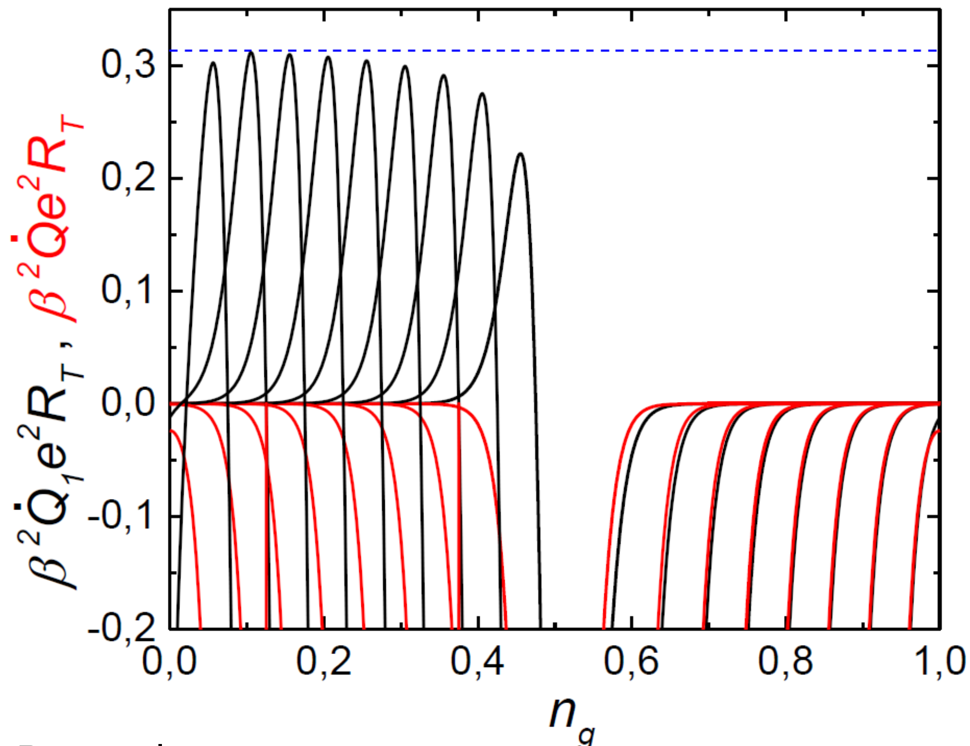


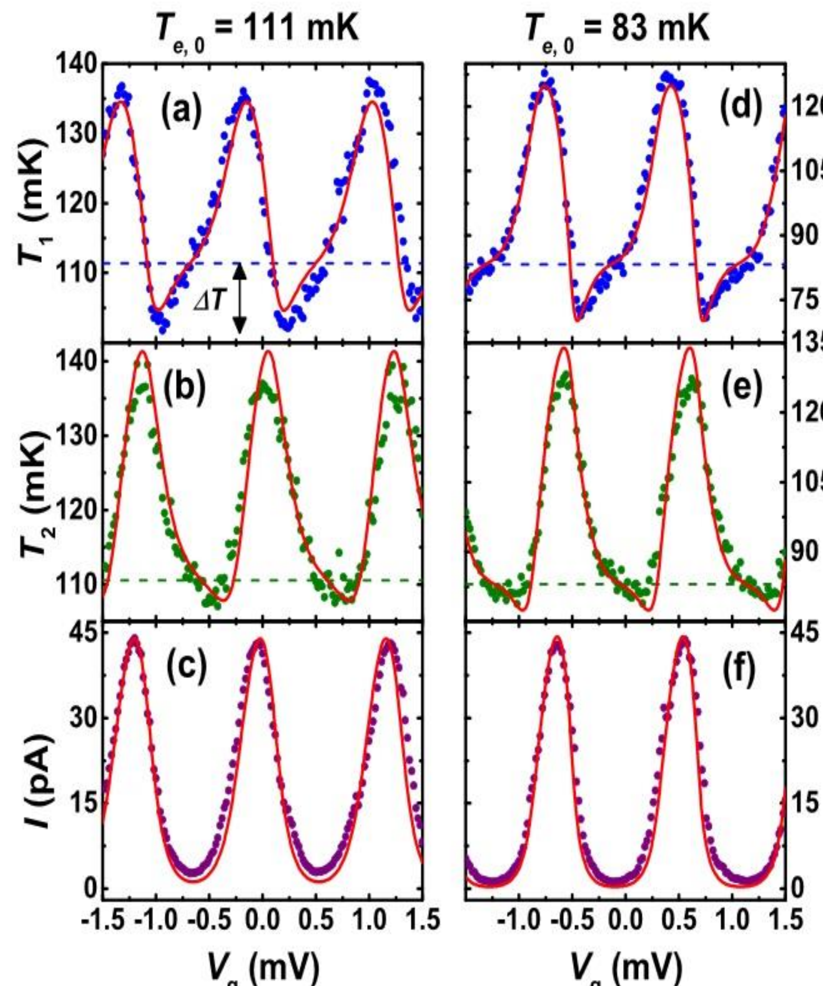




SET-cooler





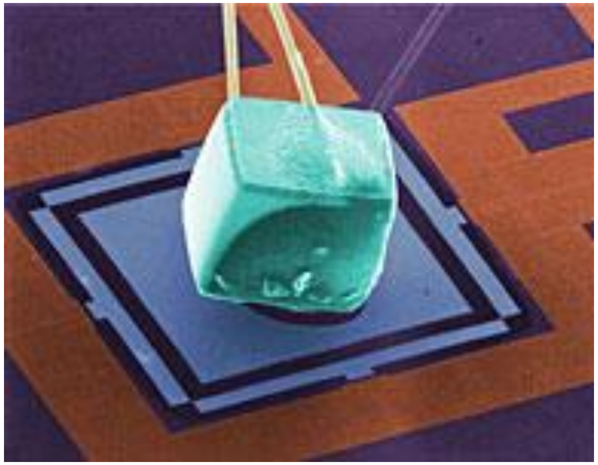


Proposal
JP et al., PRB **89**, 081309 (2014);
experiment
A. V. Feshchenko et al., PRB **90**, 201407(R) (2014)

Experimental status of electronic refrigeration

Nahum et al. 1994 *Demonstration of NIS cooling*
Leivo et al. 1996 *Cooling electrons 300 mK -> 100 mK by SINIS*
Manninen et al. 1999 *Cooling by SIS'IS*
Manninen et al. 1997, Luukanen et al. 2000 *Lattice refrigeration by SINIS*
Savin et al. 2001 *S – Schottky – Semiconductor – Schottky – S cooling*
Clark et al. 2005, Miller et al. 2008 *x-ray detector refrigerated by SINIS*
Prance et al. 2009 *Electronic refrigeration of a 2DEG*
Kafanov et al. 2009 *RF-refrigeration*
Quaranta et al 2011 *Cooling from 1 K to 0.4 K*
Lowell et al. 2013 *Macroscopic NIS refrigerator*
Nguyen et al 2013 *Cooling power up to 1 nW*
Nguyen et al. 2016 *Cascade refrigerator*

Refrigeration of a "bulk" object



A. Clark et al., Appl. Phys. Lett. **86**, 173508 (2005).

For reviews, see Rev. Mod. Phys. 78, 217 (2006); Reports on Progress in Physics 75, 046501 (2012).