Improved quasiparticle thermalization for single-electron turnstiles

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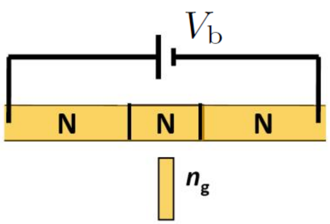
Outline

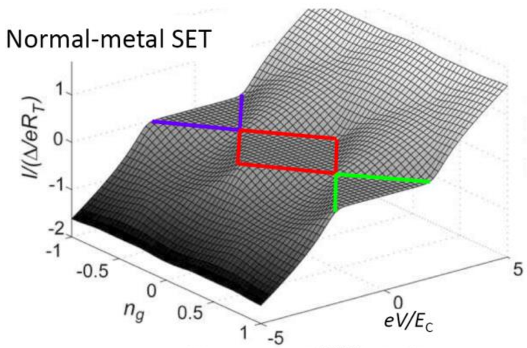
- background: charge pumping with metallic normal (N) – insulator (I) – superconductor (S) turnstiles
- active quasiparticle evacuation: local cooling of the S leads by a biased tunnel junction
- passive quasiparticle thermalization: thick S leads

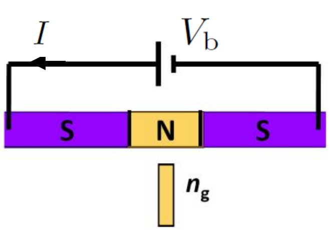
Charge pumping with a SINIS turnstile

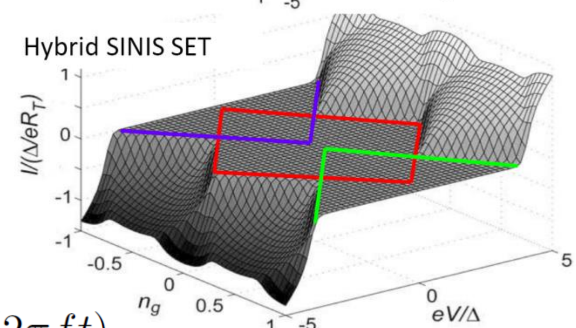
Quantized current $I = ef$ produced by a solid-state single-electron device driven periodically at frequency f

Requirements for metrological applications: current ~ 100 pA or larger, relative uncertainty ~ 10^{-7} or better

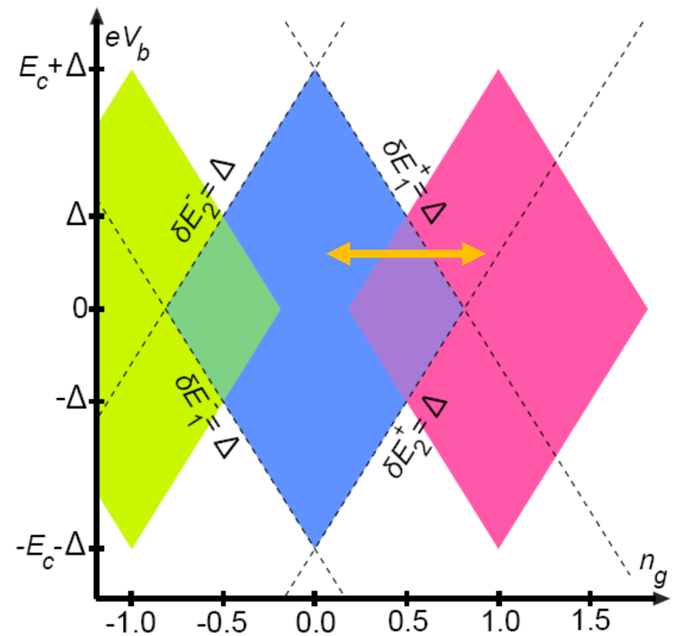








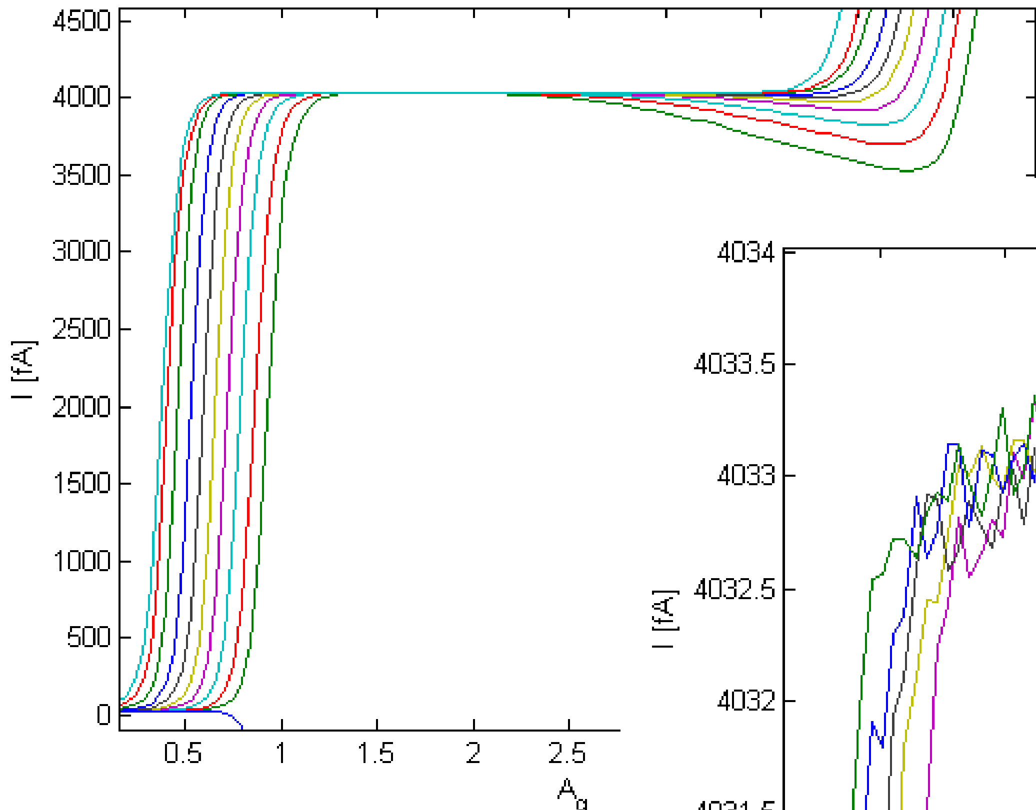
$$V_g = V_{g,0} + A_g \sin(2\pi f t)$$



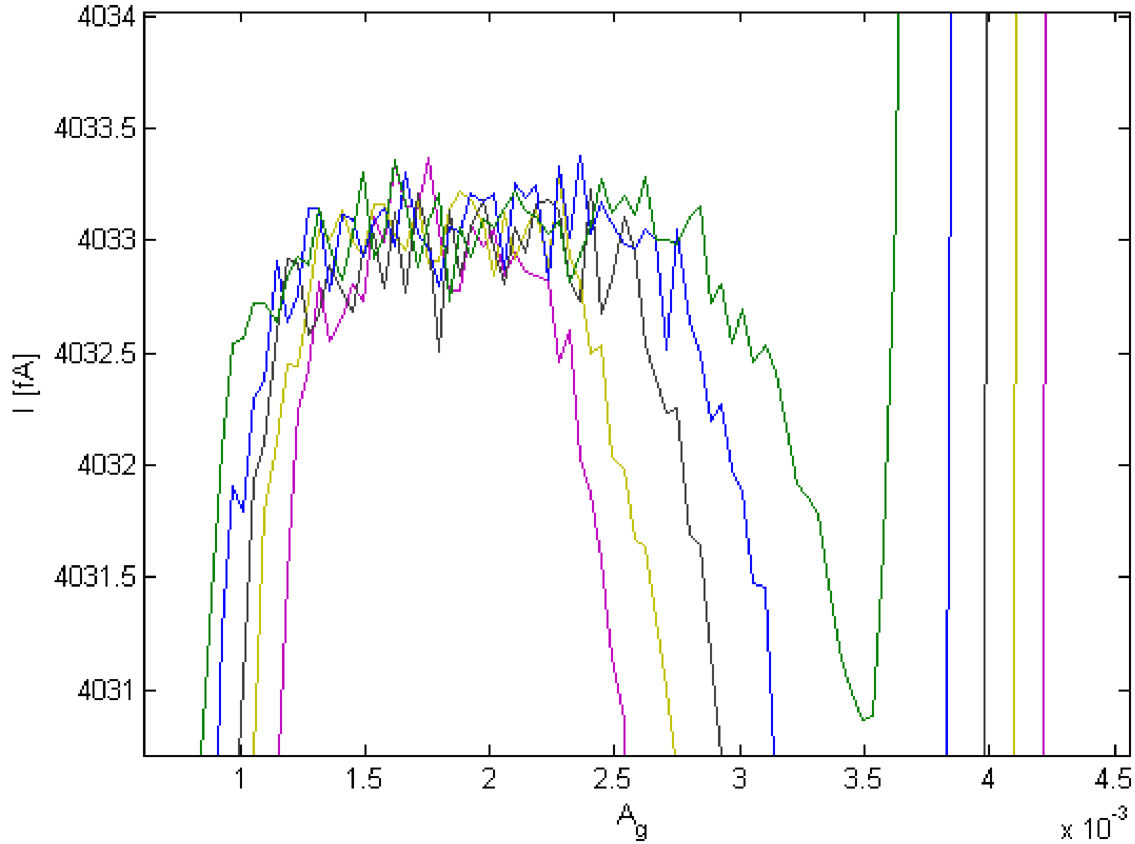
$$\delta E_i^{\pm} = \mp 2E_c(n - n_g \pm 1/2) \mp eV_i$$

J. P. Pekola *et al.,* Nature Phys. 4, 120 (2008)   J. P. Pekola *et al.,* Rev. Mod. Phys. 85, 1421 (2013)

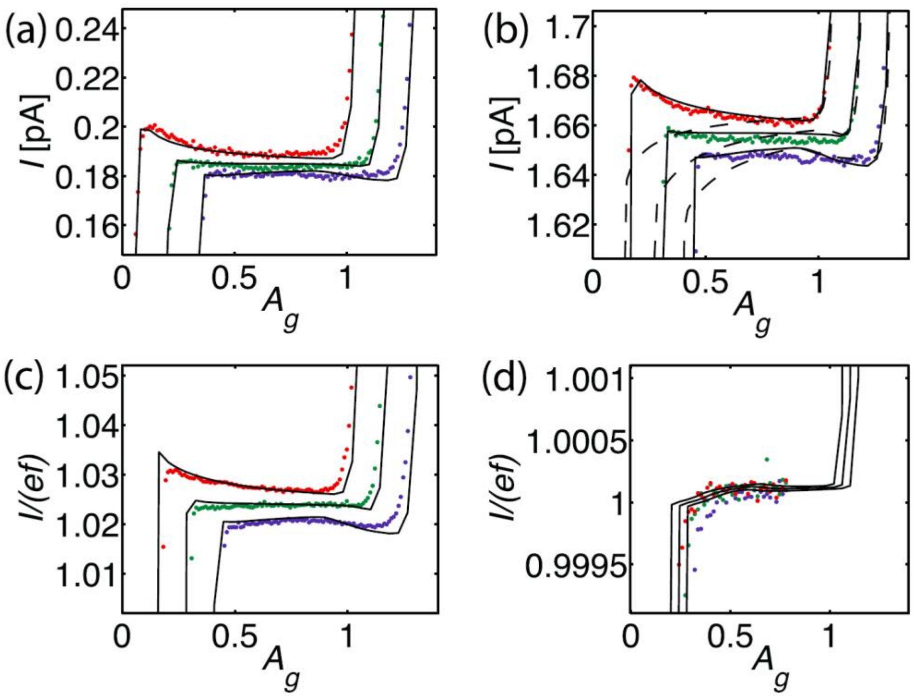
Typical 25 MHz pumping curves for an Al-Cu device

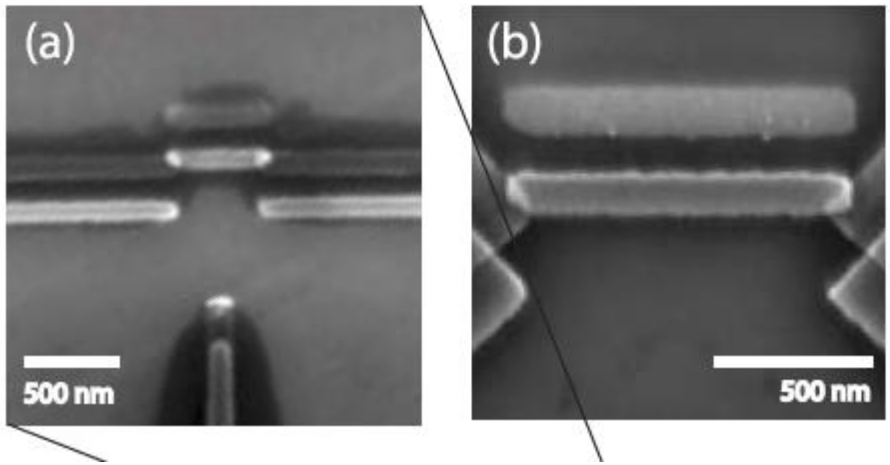


Different curves: Stepping the bias voltage around $eV_b = \Delta$



Quasiparticle-limited accuracy of the turnstile





- injected power $P_{\rm inj} \approx \Delta f \approx 1.6\ {\rm fW}$ (Al, 50 MHz drive for 8 pA current)
- thicker, wider and less resistive leads + more effective qp trapping needed to avoid S overheating and to approach metrological accuracy

H. S. Knowles *et al.,* Appl. Phys. Lett. 100, 262601 (2012)

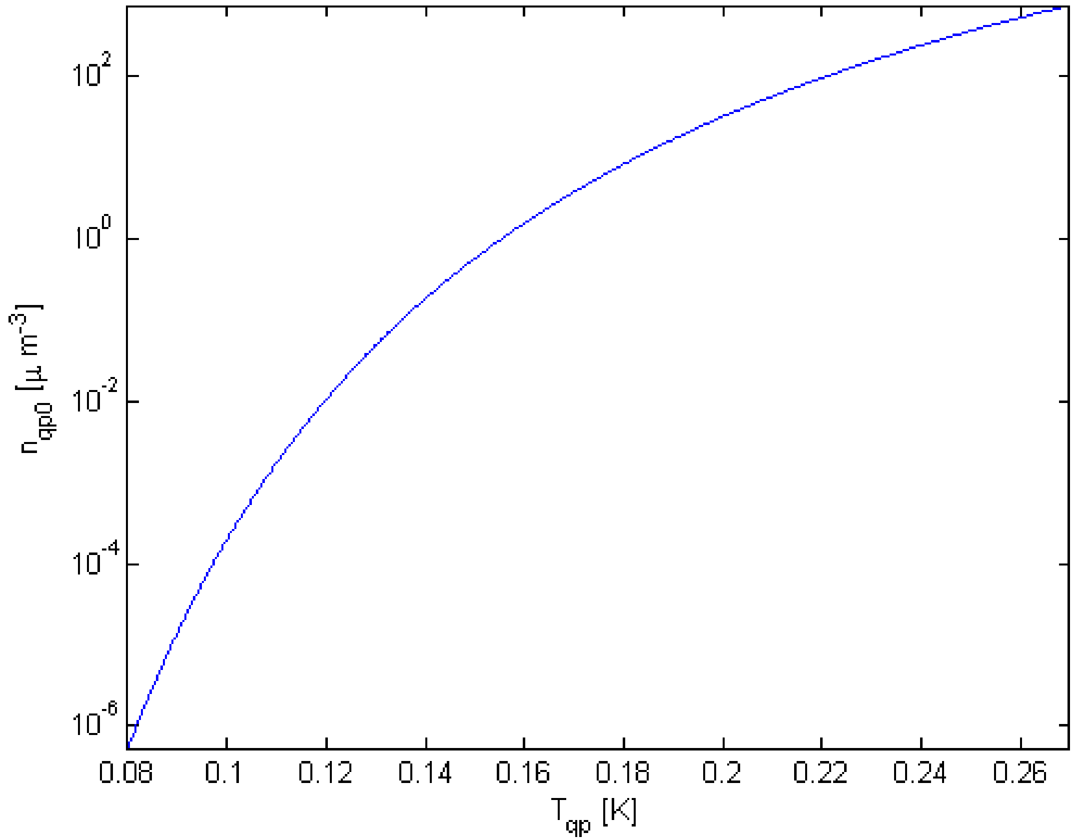
Density of quasiparticle excitations

$$n_{\mathrm{qp}} = 2D(E_{\mathrm{F}}) \int_{\Delta}^{\infty} dE\, n_{\mathrm{S}}(E) f_{\mathrm{S}}(E)$$
$$\approx \sqrt{2\pi} D(E_{\mathrm{F}}) \sqrt{k_{\mathrm{B}} T_{\mathrm{qp}} \Delta}\, e^{-\frac{\Delta}{k_{\mathrm{B}} T_{\mathrm{qp}}}}$$

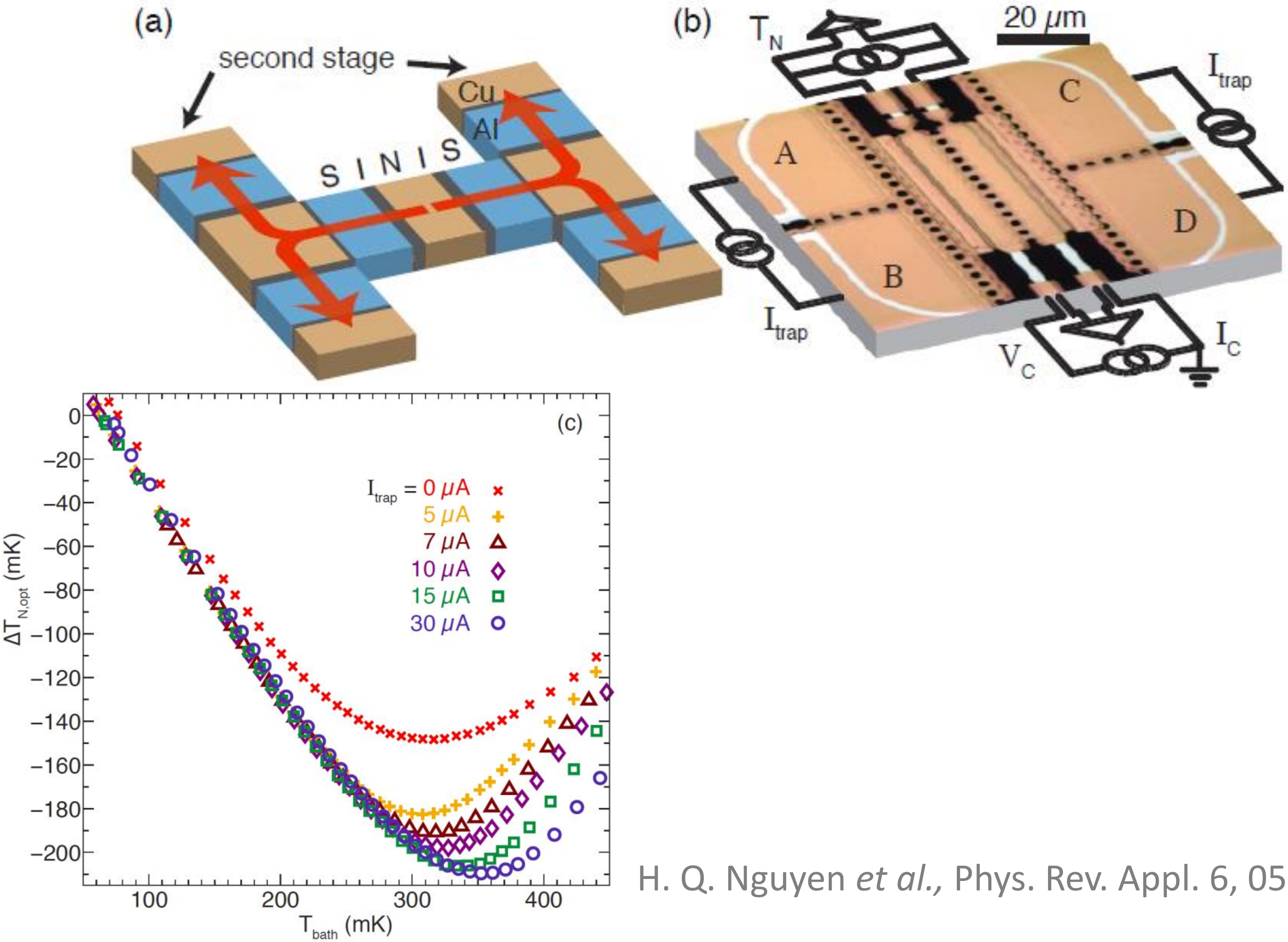
- aluminium:

$$D(E_{\mathrm{F}}) = 1.45 \times 10^{29}\ \mathrm{J}^{-1} \mu\mathrm{m}^{-3}$$

$$\Delta = 200\ \mu\mathrm{eV}$$

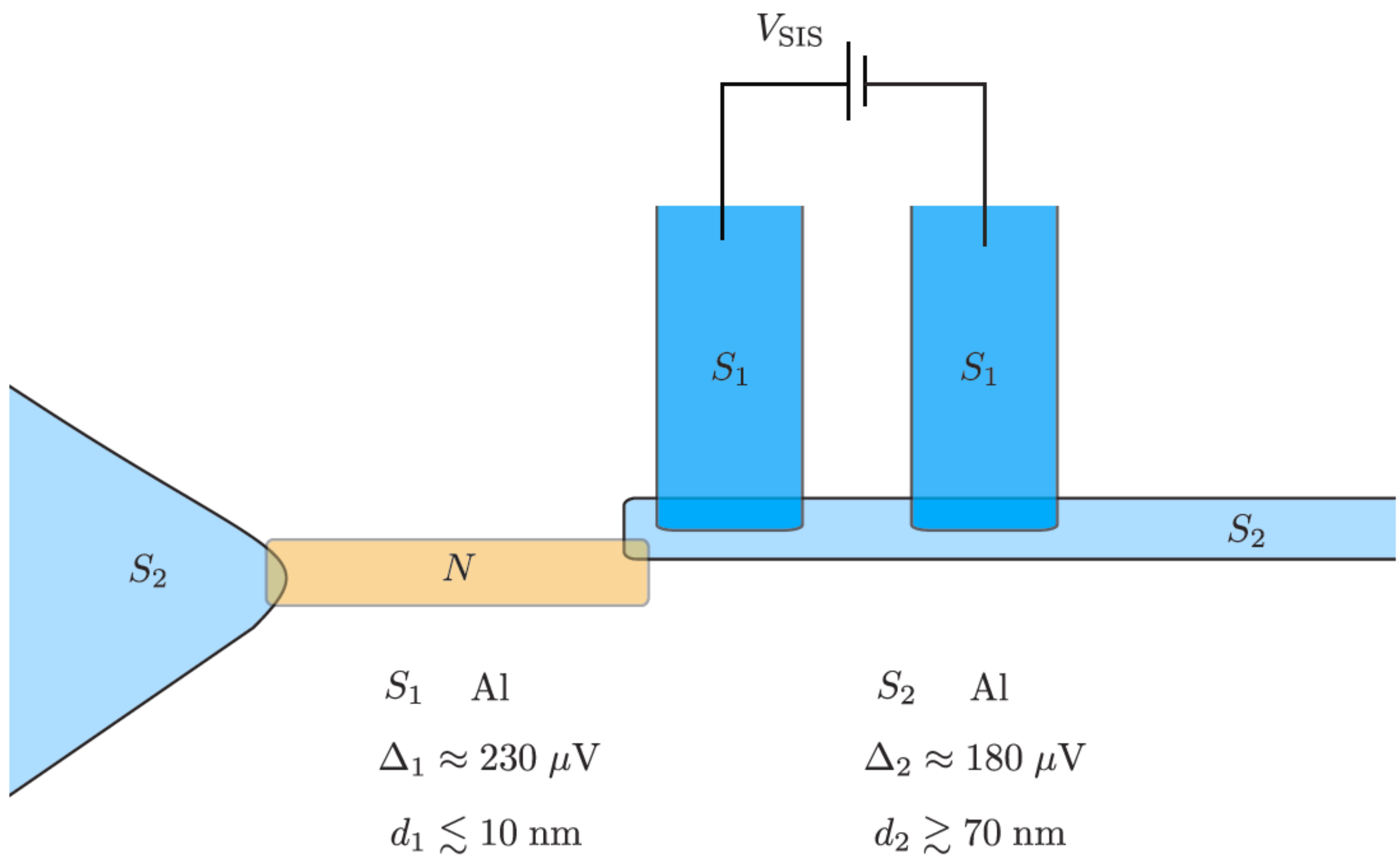


Cascade cooling of the S electrodes of a SINIS structure



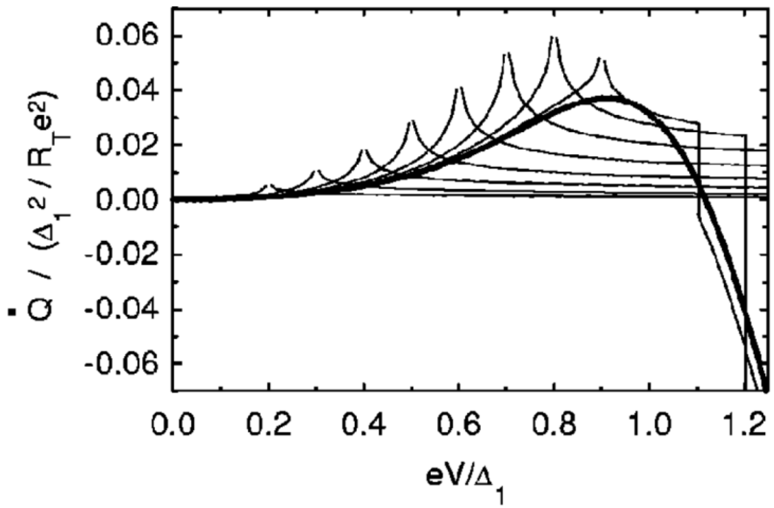
H. Q. Nguyen *et al.,* Phys. Rev. Appl. 6, 054011 (2016)

Active quasiparticle evacuation: turnstile with an integrated S_1IS_2 cooler



qp cooling of the S electrode with smaller gap

Cooling by qp tunneling in an S_1IS_2 junction

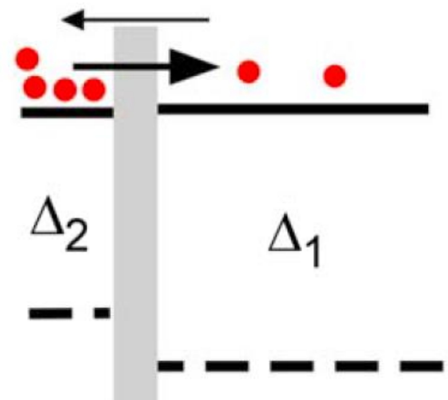


A. J. Manninen *et al.*,
Appl. Phys. Lett. 74, 3020 (1999)

O. Quaranta *et al.*,
Appl. Phys. Lett. 98, 032501 (2011)

D. S. Golubev *et al.*,
Phys. Rev. B 87, 094522 (2013)

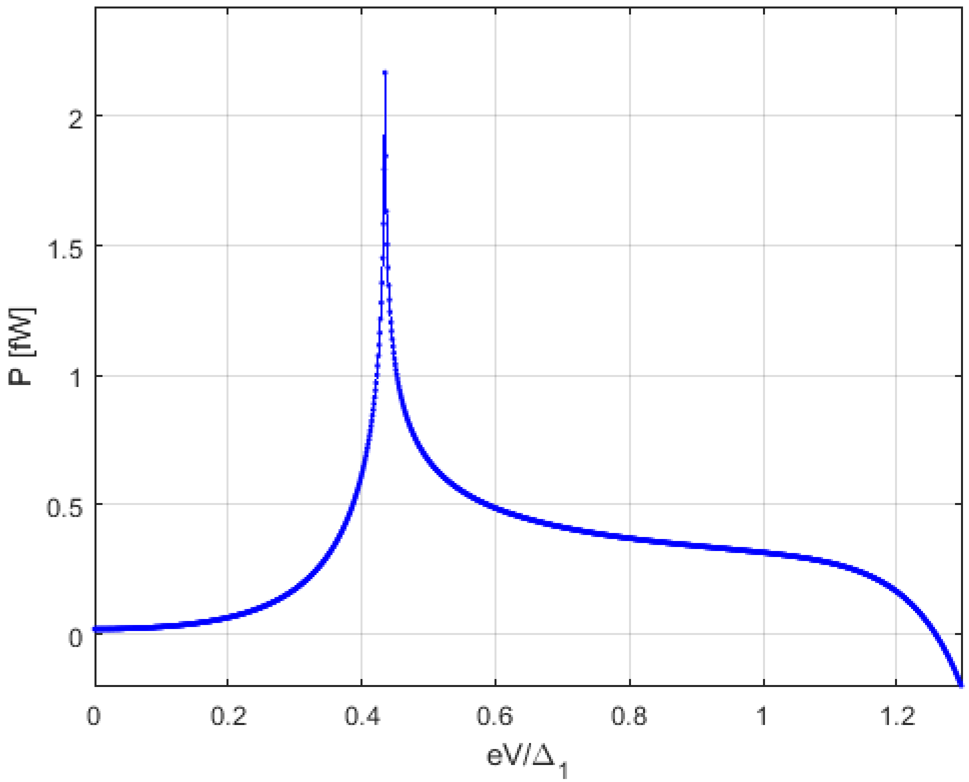
FIG. 1. Calculated heat flow $\dot{Q}$ from S_2 through an ideal S_2IS_1 junction which is biased at voltage V at a constant temperature $T_{e1}=T_{e2}=0.15\Delta_1/k_B$, which corresponds to 0.37 K for our sample. Different lines have been calculated for $\Delta_2/\Delta_1=0$ (NIS structure; thick line), 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8, respectively. The cooling power diverges when $|eV|=\Delta_1-\Delta_2$. For our sample, $\Delta_2/\Delta_1\simeq 0.29$ at $T=0.37$ K.



maximum cooling at $eV_{\rm SIS} = \Delta_1 - \Delta_2$

$$\dot{Q} = \frac{1}{e^2 R_{\rm T,SIS}} \int_{-\infty}^{\infty} dE\, E\, n_2(E) n_1(E - eV_{\rm SIS}) \left[f_2(E) - f_1(E - eV_{\rm SIS})\right]$$

Cooling by qp tunneling in an S_1IS_2 junction



$$\Delta_1 = 230\ \mu\text{eV}$$

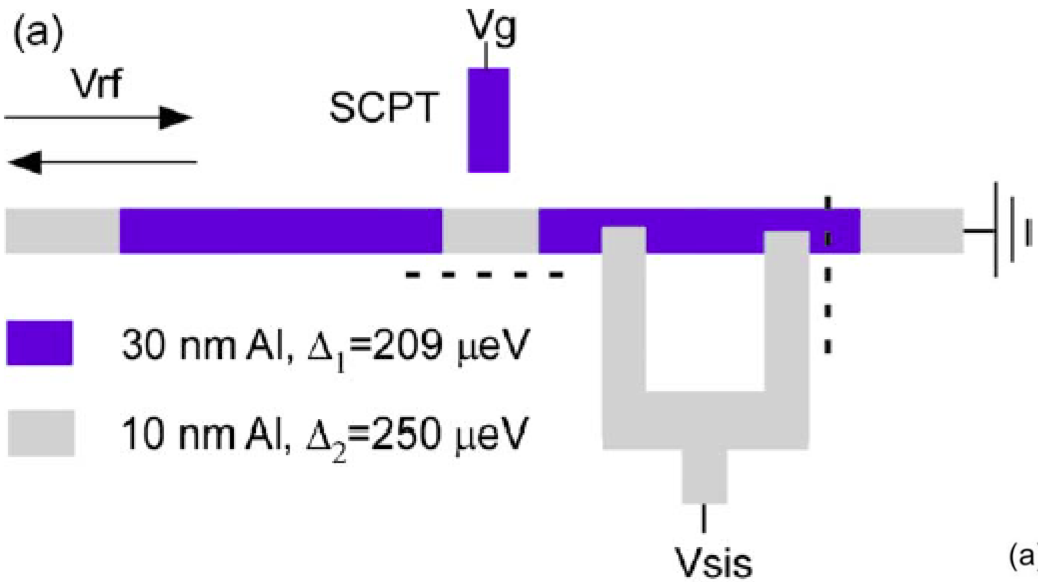
$$\Delta_2 = 180\ \mu\text{eV}$$

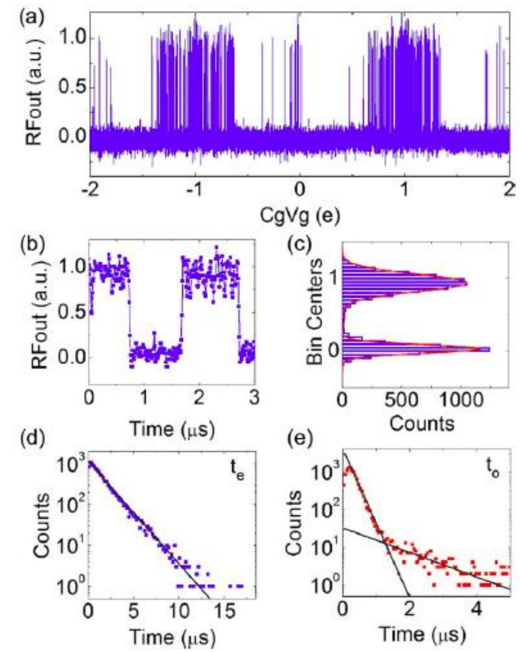
$$T_1 = 100\ \text{mK}$$

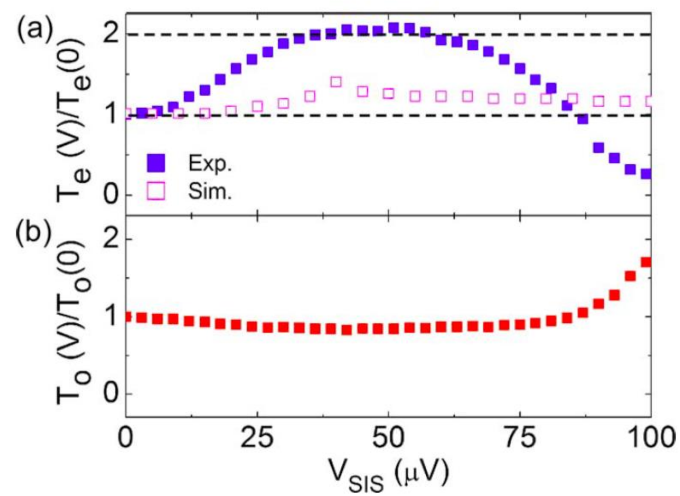
$$T_2 = 150\ \text{mK}$$

$$R_\text{T} = 100\ \Omega$$

Quasiparticle cooling of a single-Cooper-pair transistor

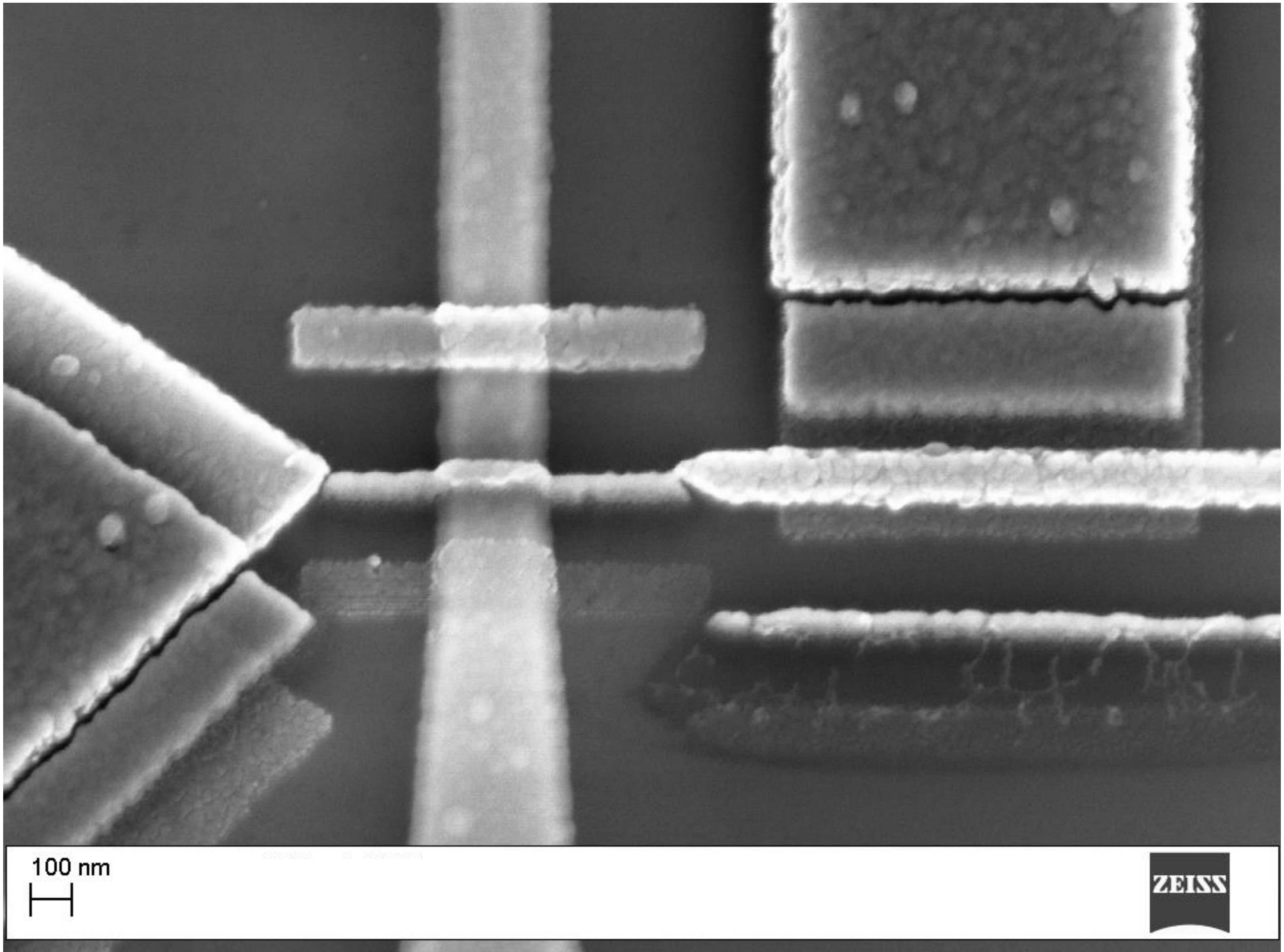




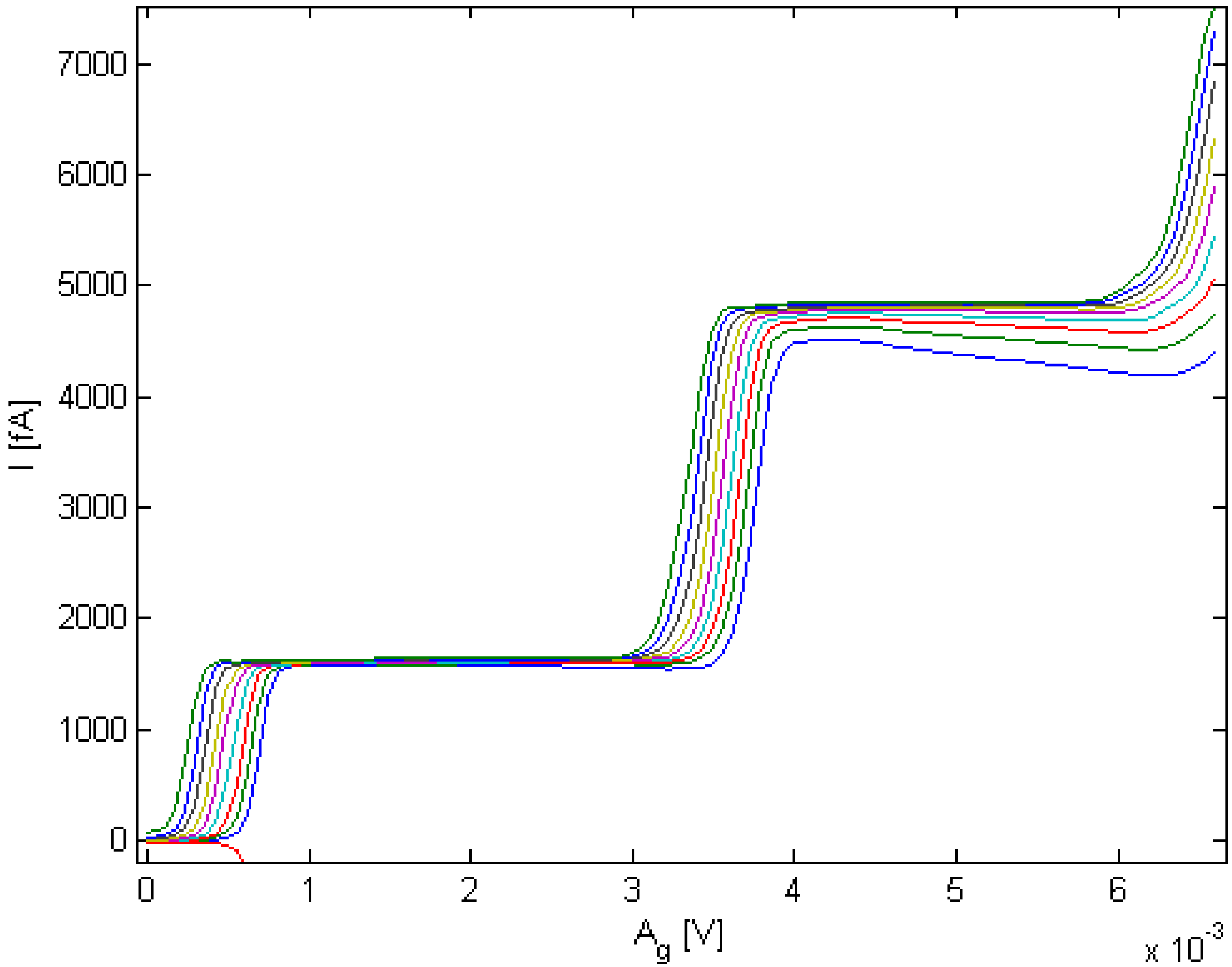


A. J. Ferguson, Appl. Phys. Lett. 93, 052501 (2008)

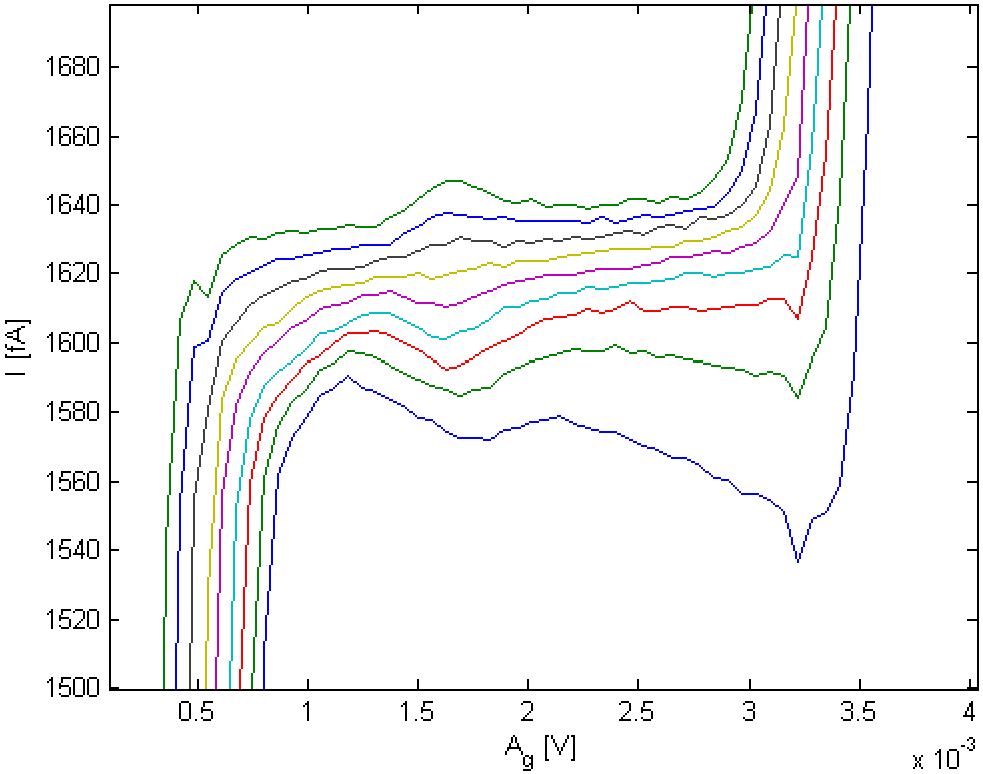
Turnstile with an integrated S_1IS_2 cooler



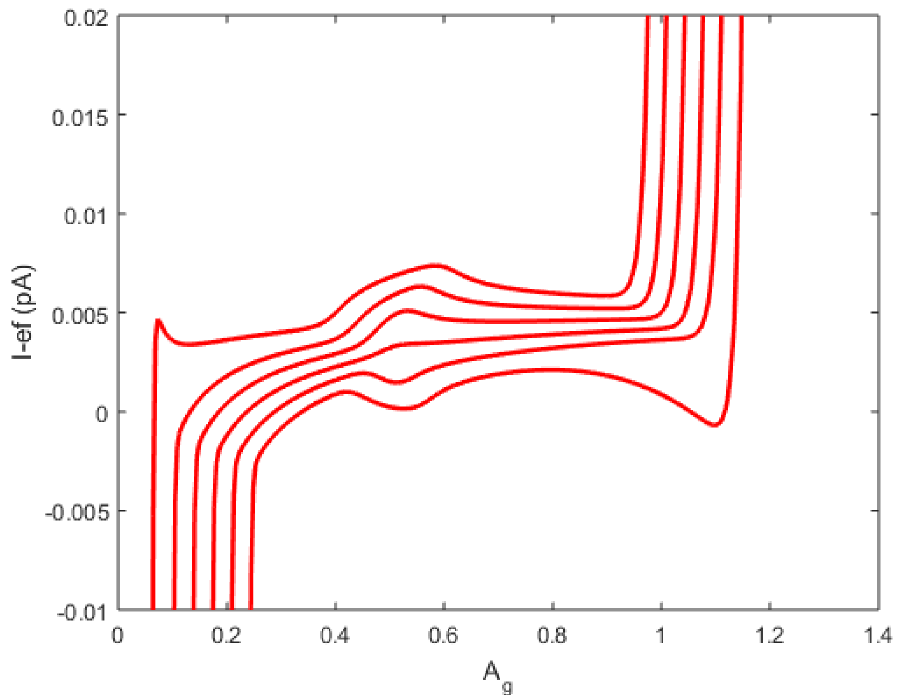
Typical pumping experiment (f = 10 MHz, dc offset n_{g0} = 0.5, S_1IS_2 cooler not active)



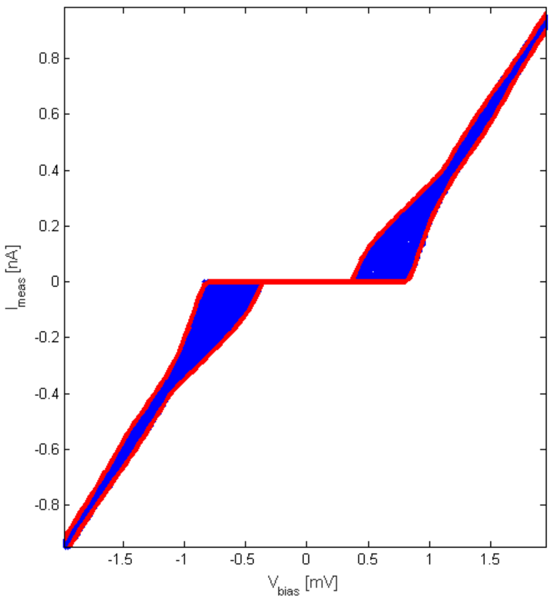
Signatures of nonequilibrium qps for a sample with high charging energy

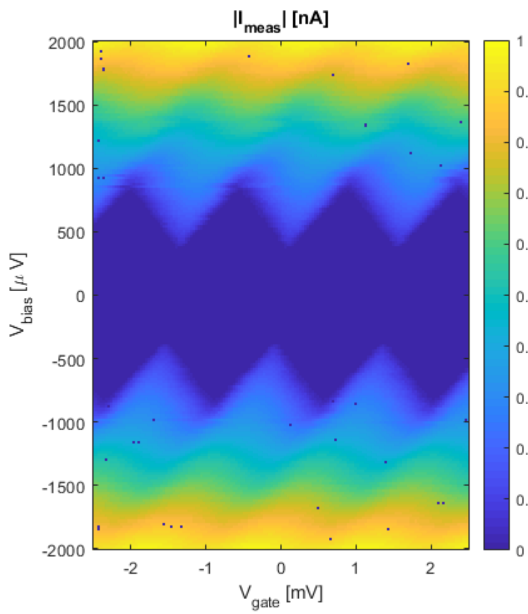


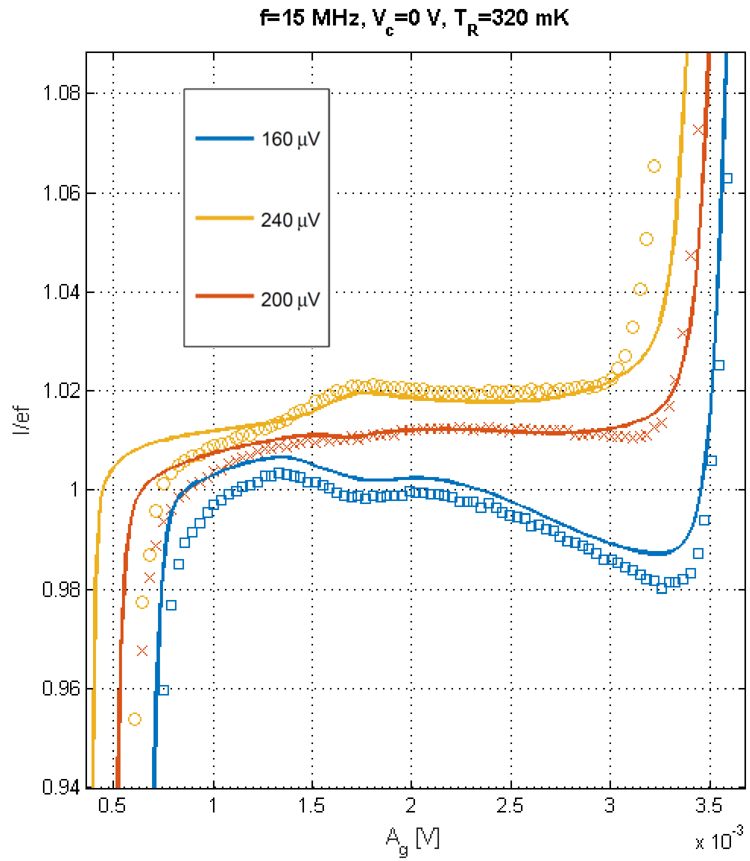
Good qualitative agreement with a model based on the orthodox theory of single-electron tunneling, assuming elevated temperature in both S electrodes



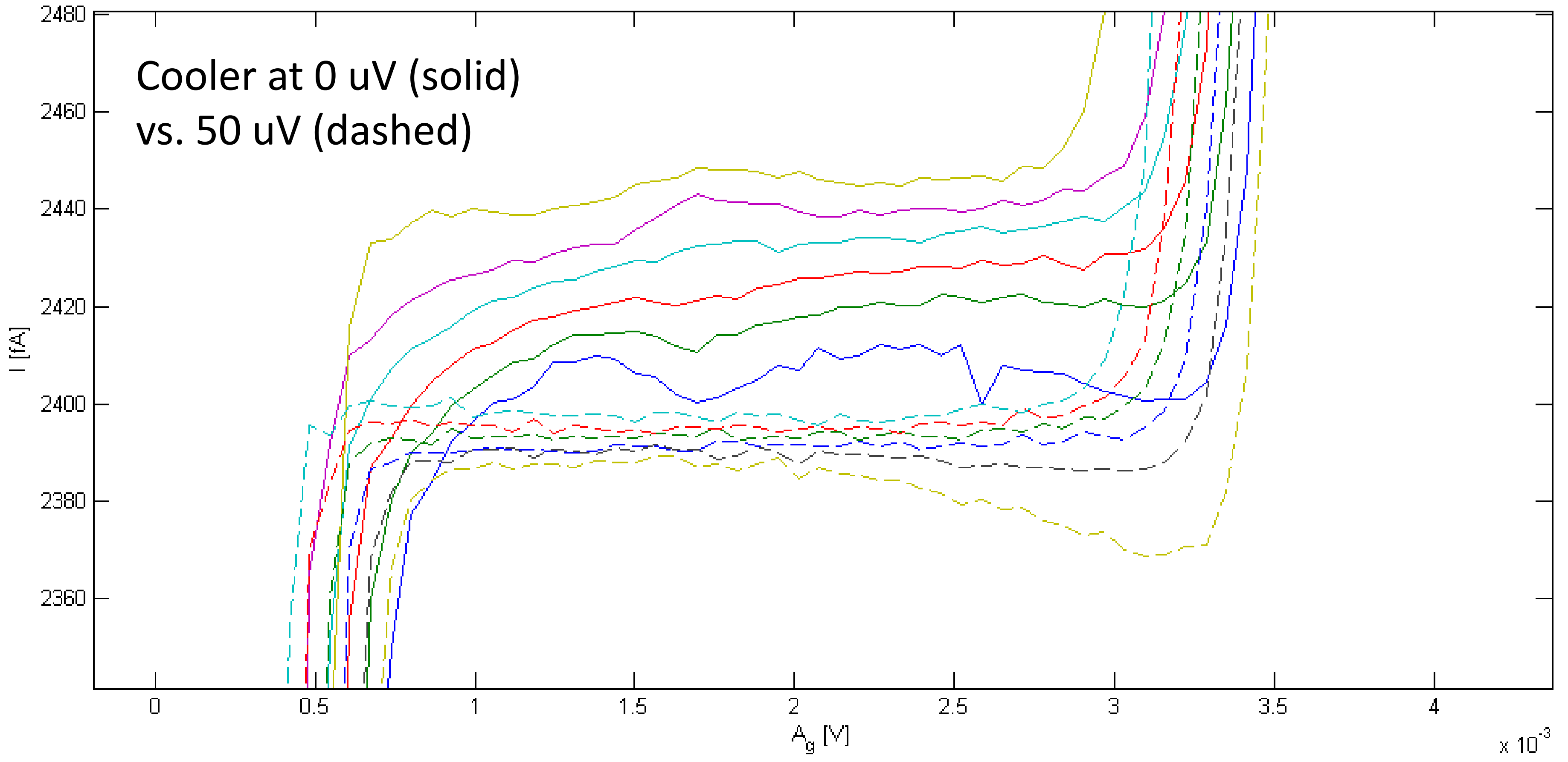
Signatures of nonequilibrium qps for a sample with high charging energy



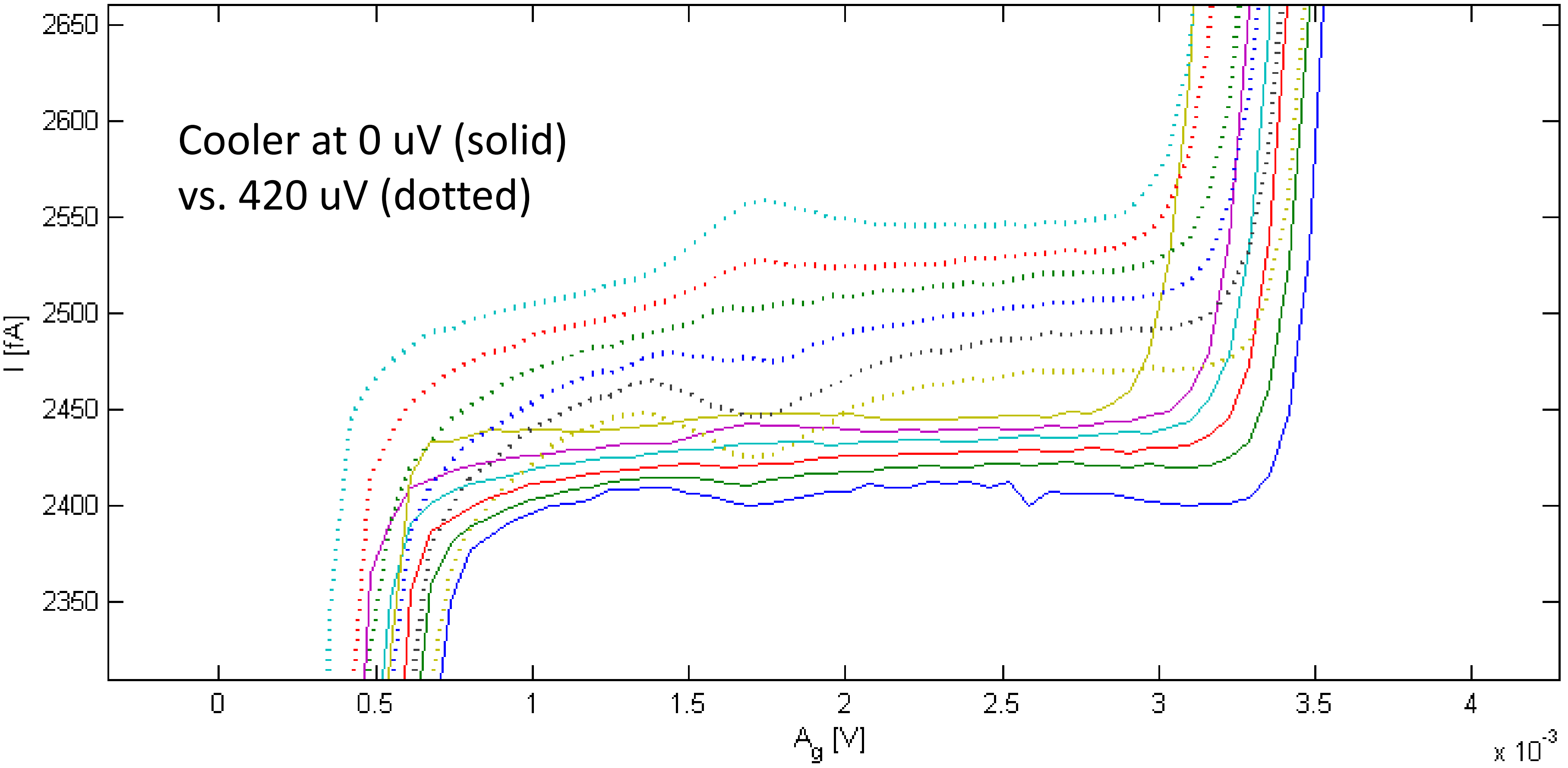




Improved pumping step at cooler bias close to expected gap difference

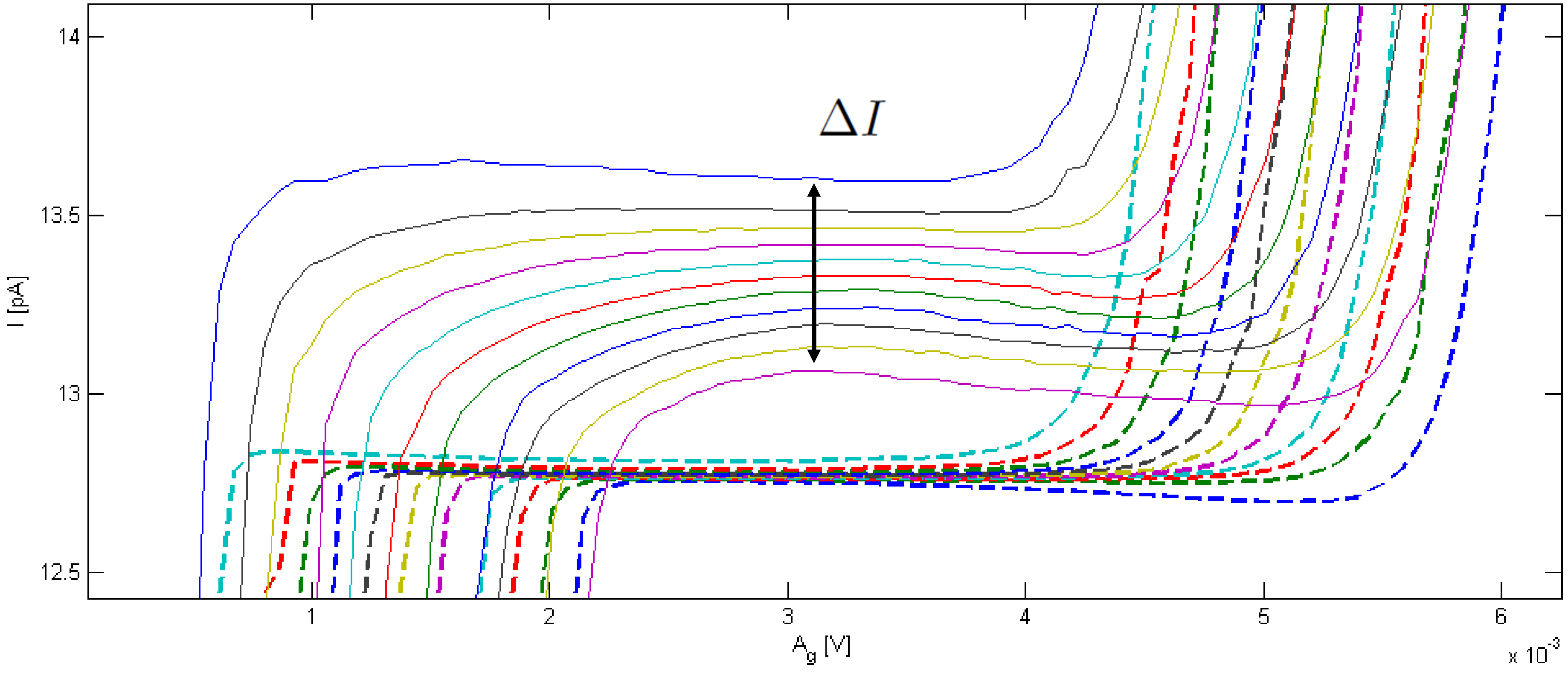


Heating at high S_1IS_2 cooler bias

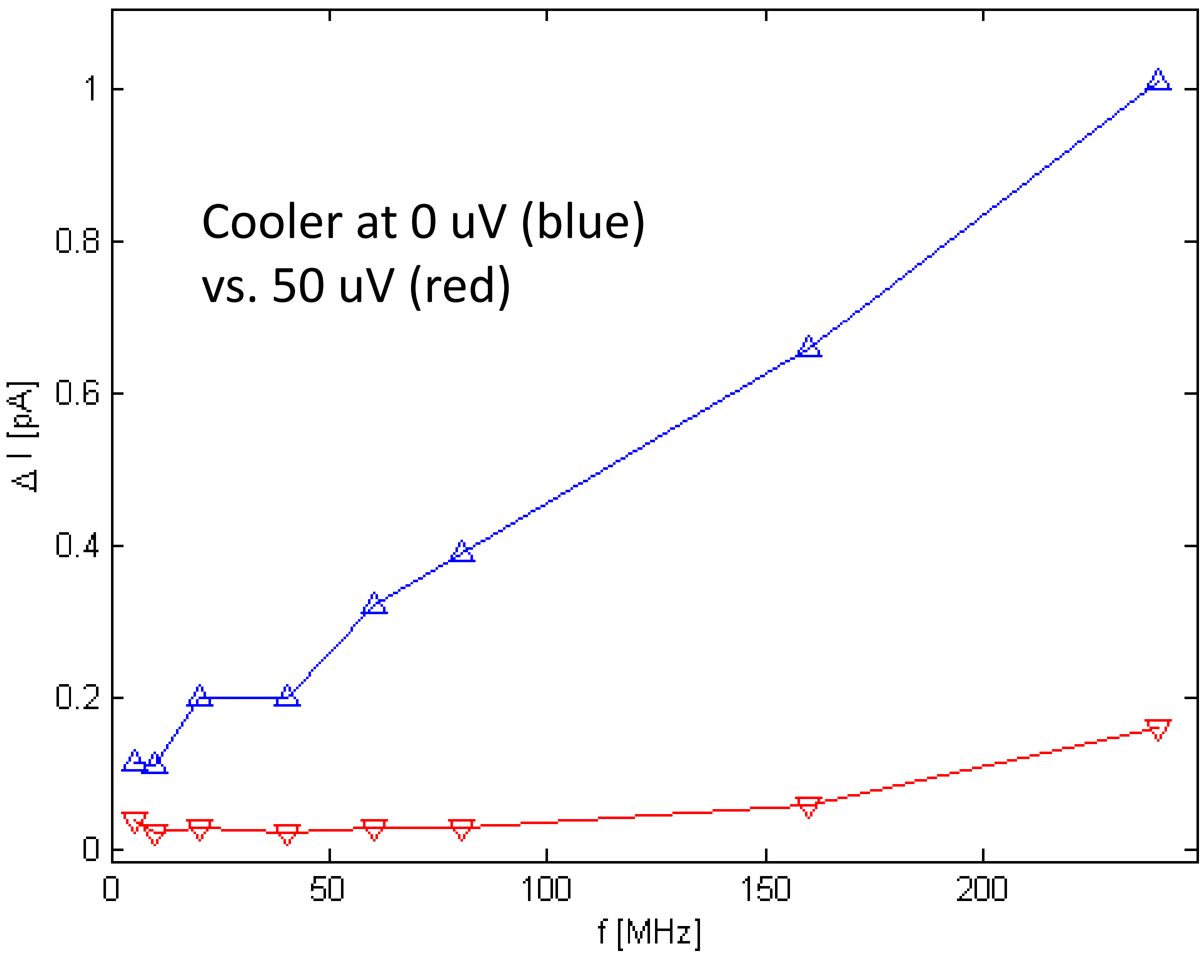


Strong effect in turnstiles with lower tunnel resistance

f = 80 MHz; cooler biased at 0 uV (solid) vs. 50 uV (dashed, close to expected S_1IS_2 gap difference)



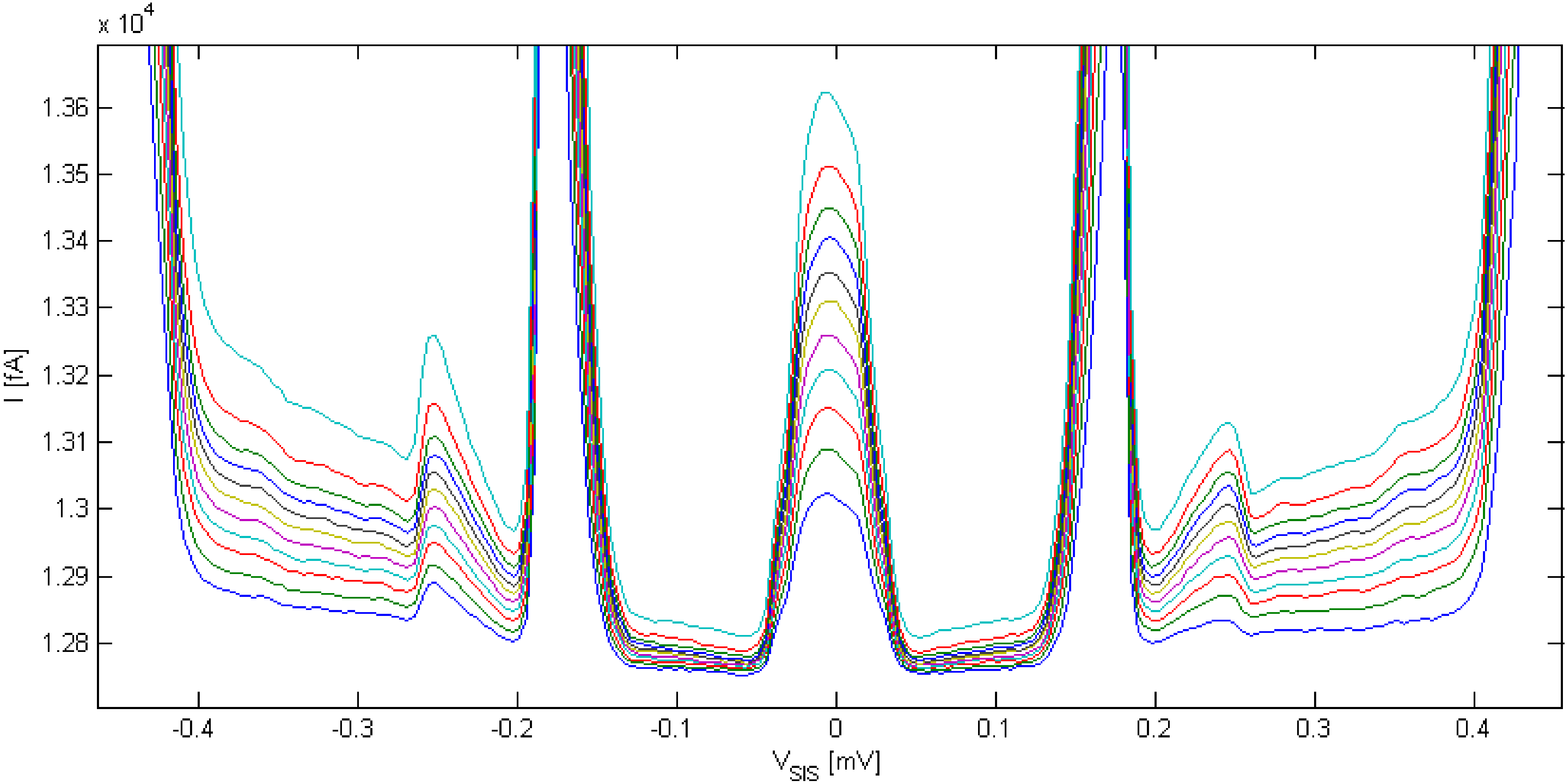
Improved flatness of the *ef*-plateau



Saturation at low drive frequencies with cooler ”on” due to residual qps (sample holder not well shielded), Andreev tunneling (low resistance junctions), ...?

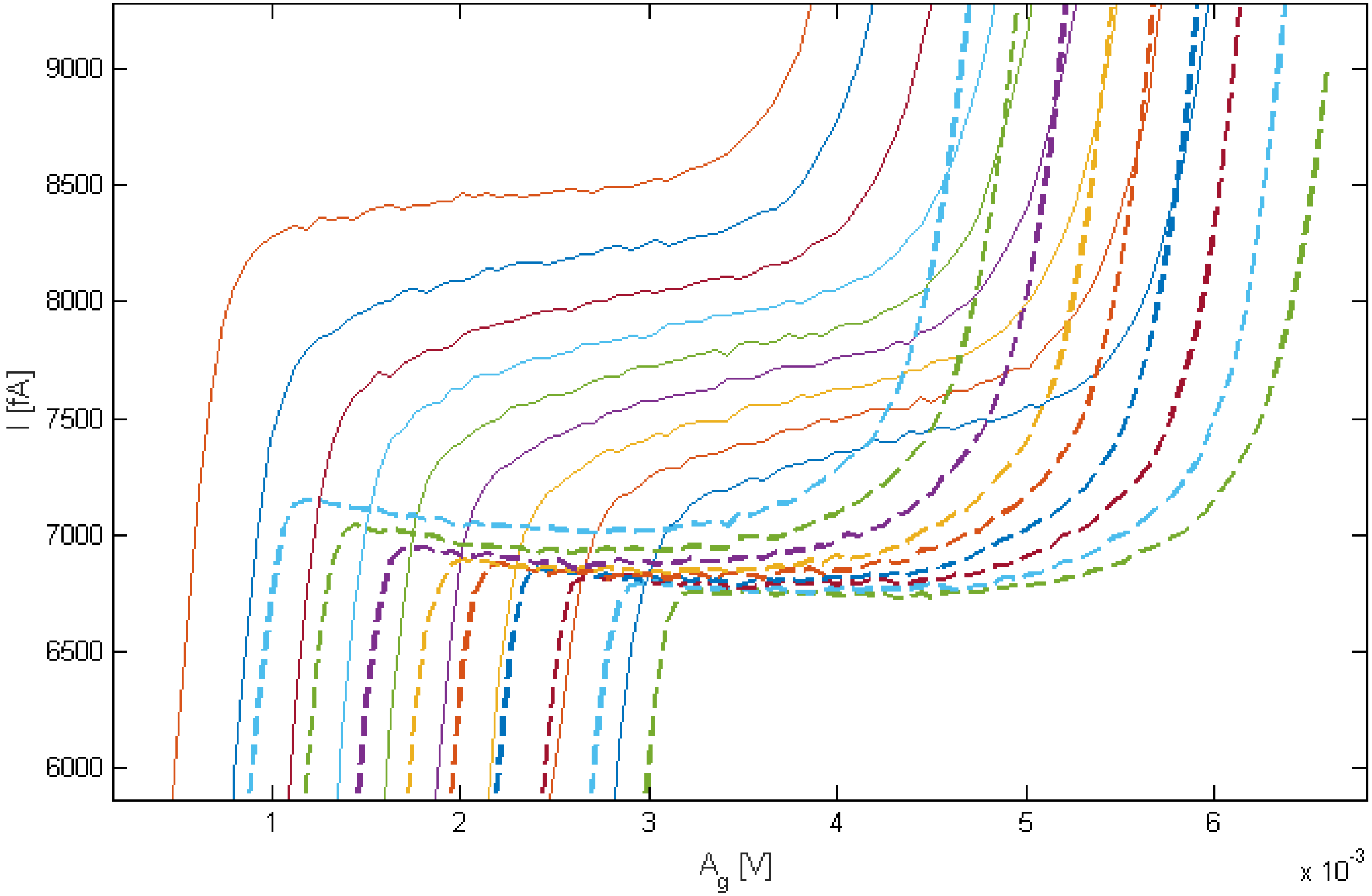
Pumping at 80 MHz at constant amplitude

Peak structure at voltages above 100 uV resembles the sub-gap IV of the SQUID

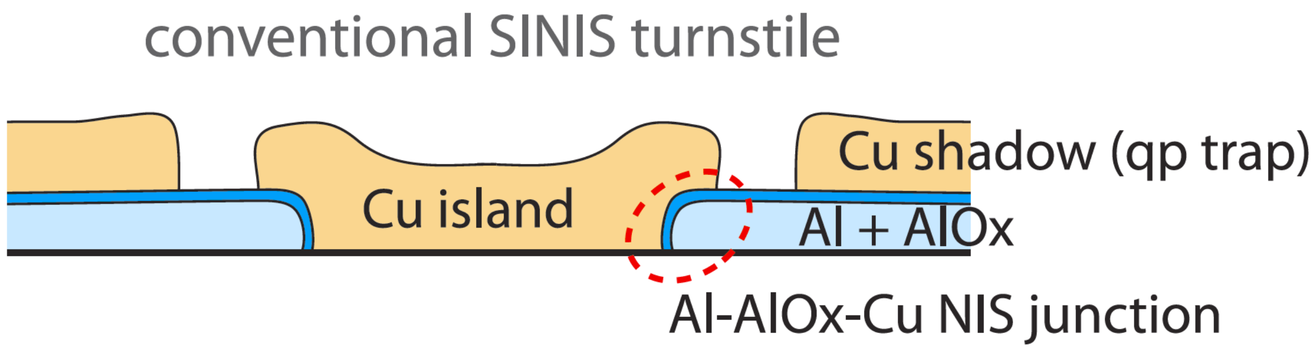


Change in the functional form of the *ef*-plateau

f = 40 MHz; cooler biased at 0 uV (solid) vs. 50 uV (dashed)



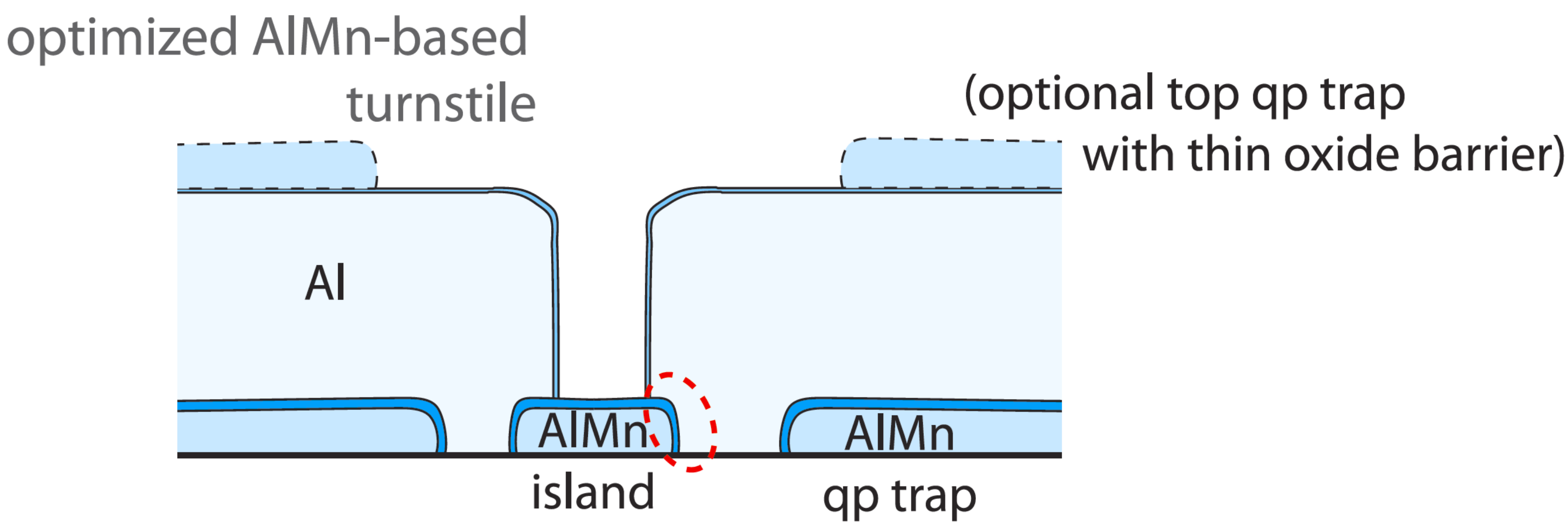
Schematic cross-section of a conventional Al-Cu device



- optimization and good control of junction resistances and charging energies needed to avoid errors due to higher order tunneling processes

$$E_{\mathrm{C}} = e^2/2C_{\Sigma} \gtrsim 2\Delta$$

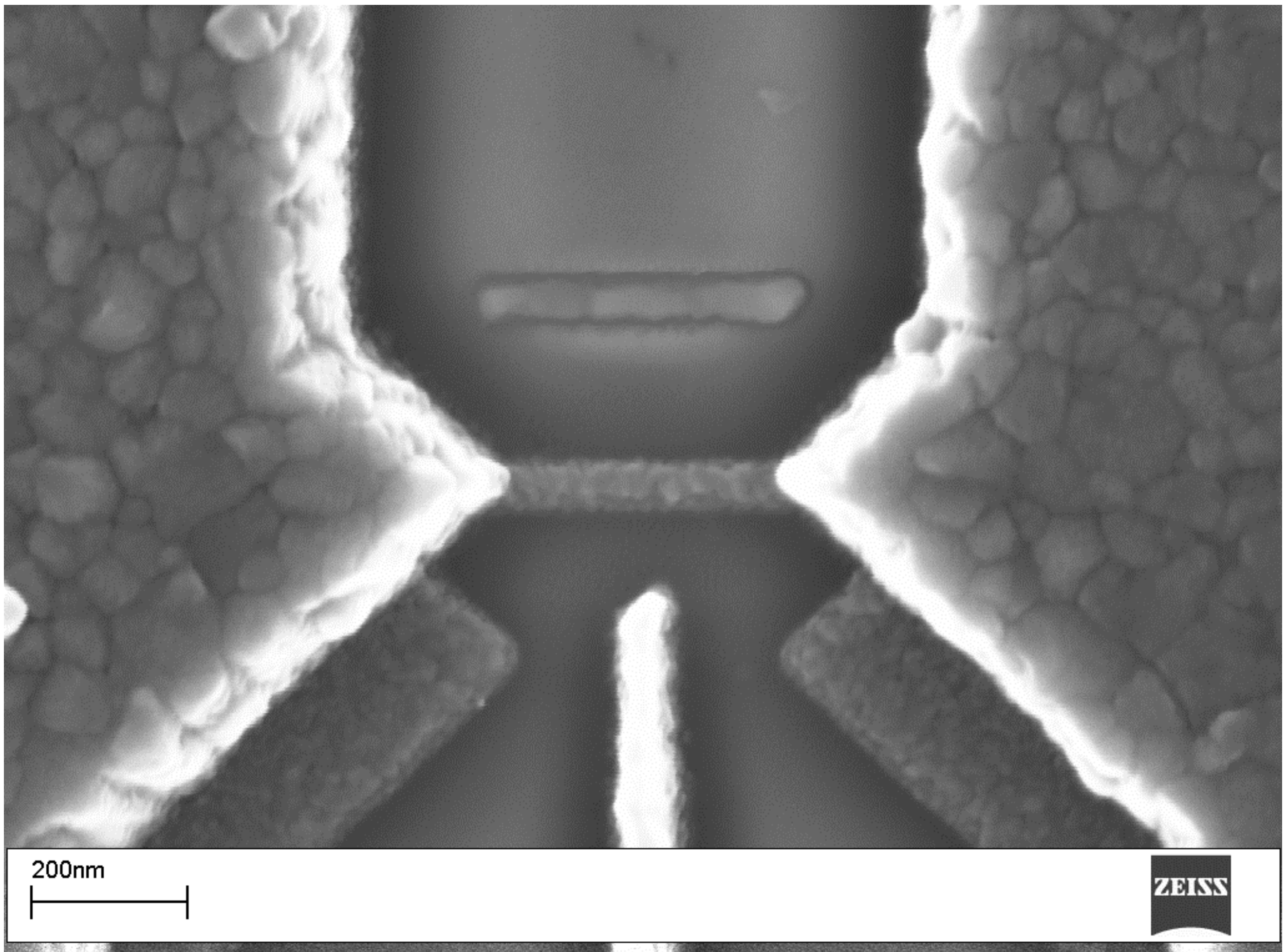
Cross-section of a turnstile with thick S electrodes

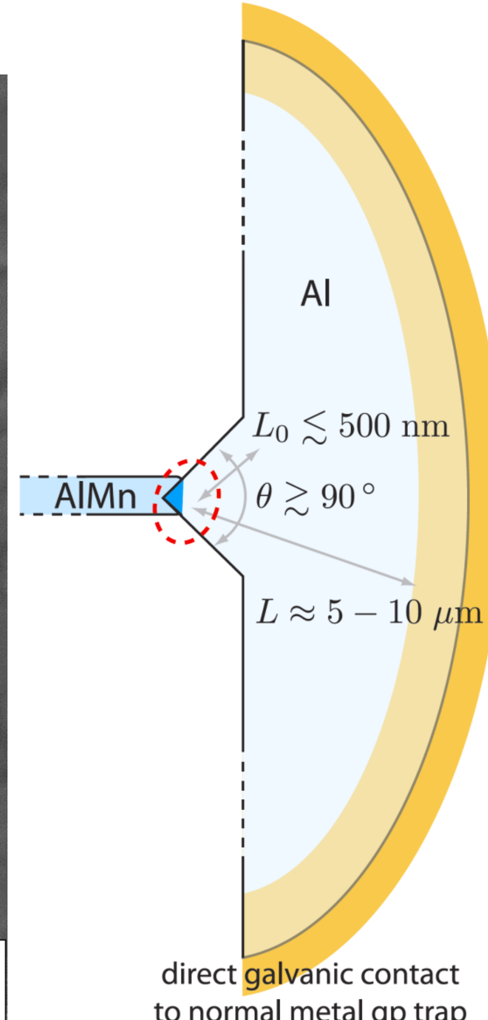


- main goal: retain high charging energy independent of the S lead thickness
- suppress superconductivity on the island by Mn impurities (e-beam evaporation target Goodfellow Al 99.7 % / Mn 0.3 %)

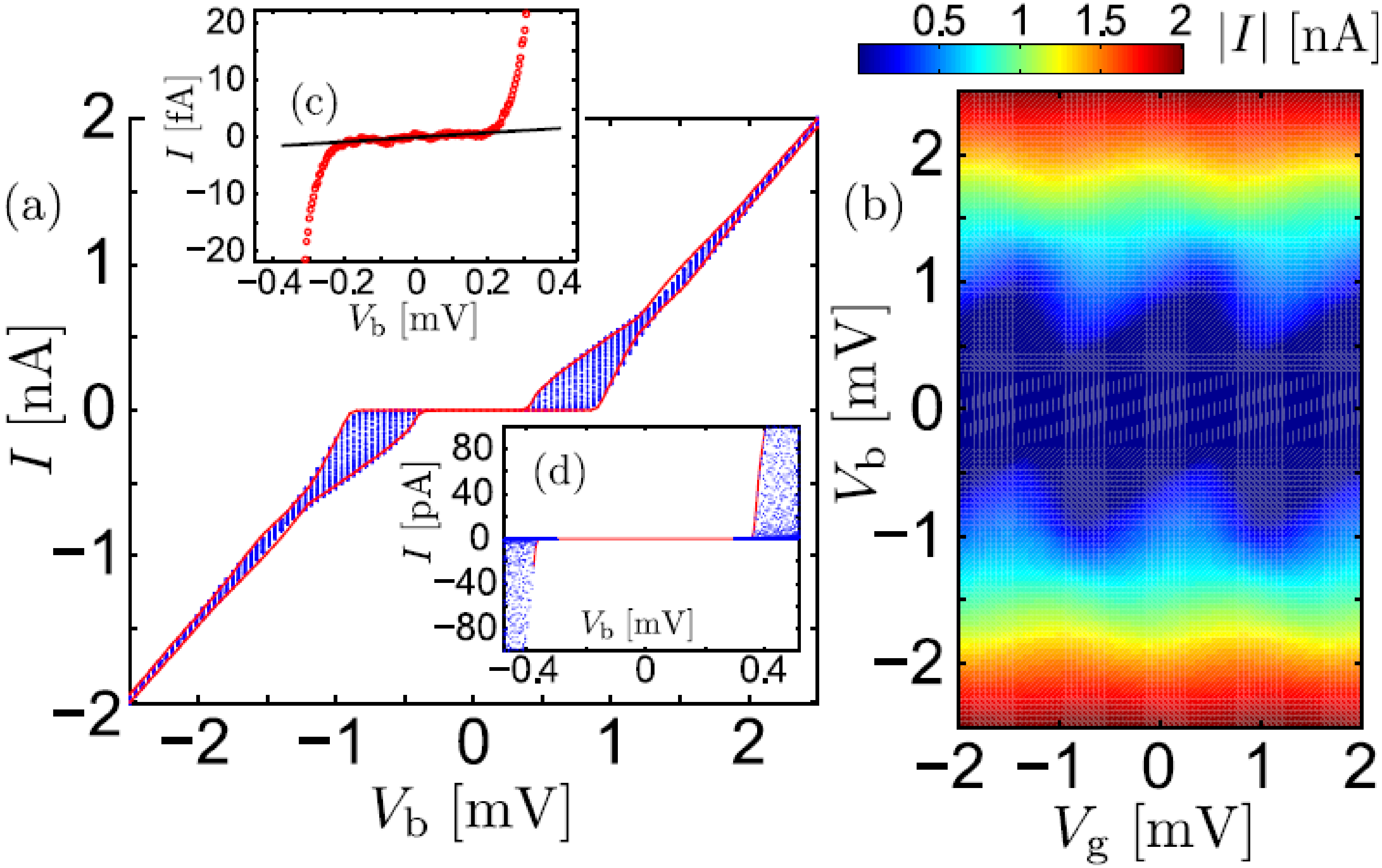
Typical device with wide and thick leads

- 30 nm AlMn + close to 500 nm Al while retaining high charging energy





AlMn turnstile: DC characterization

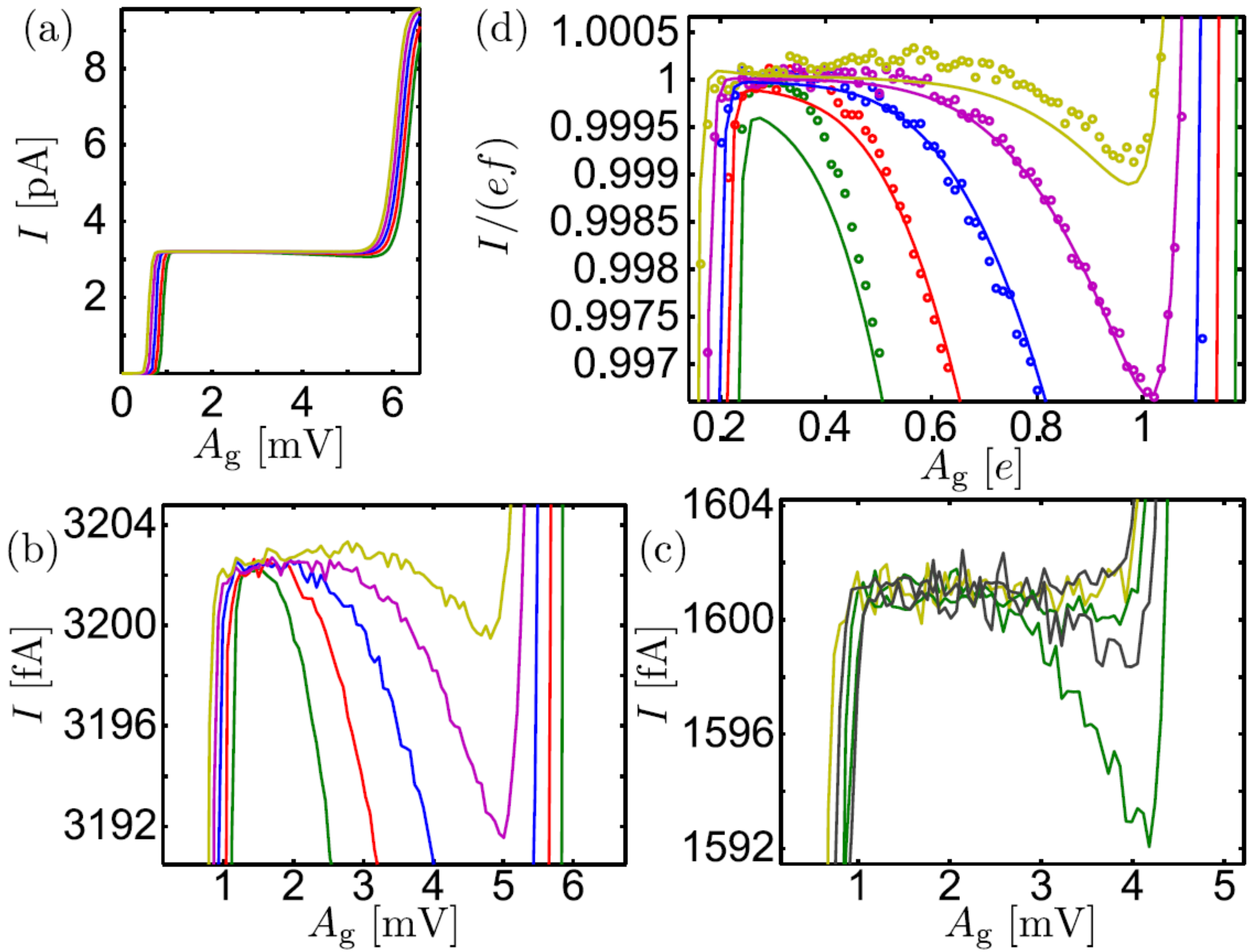


- high charging energies and low sub-gap currents still possible
- simple fabrication

$$\eta = R_T/R_0 \approx 3.5 \times 10^{-6}$$

JTP, A. Moisio, V. F. Maisi, M. Meschke, J. S. Tsai, and J. P. Pekola, arXiv:1709.09832 (2017)

AlMn turnstile: pumping



JTP, A. Moisio, V. F. Maisi, M. Meschke, J. S. Tsai, and J. P. Pekola, arXiv:1709.09832 (2017)

Conclusions

- initial investigation of direct cooling of the turnstile S leads by S_1IS_2 tunnel junctions
- turnstiles with bulky Al electrodes for more efficient qp thermalization

Future directions

- verification of low qp density in a charge counting experiment
- experiments on the limits of S_1IS_2 cooling
- floating SINIS cooling and thermometry on the turnstile electrodes