Thermoelectric Current in a Graphene Cooper Pair Splitter

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Outline:

- Background

  Andreev Reflection, Cooper pair splitting, Elastic co-tunneling

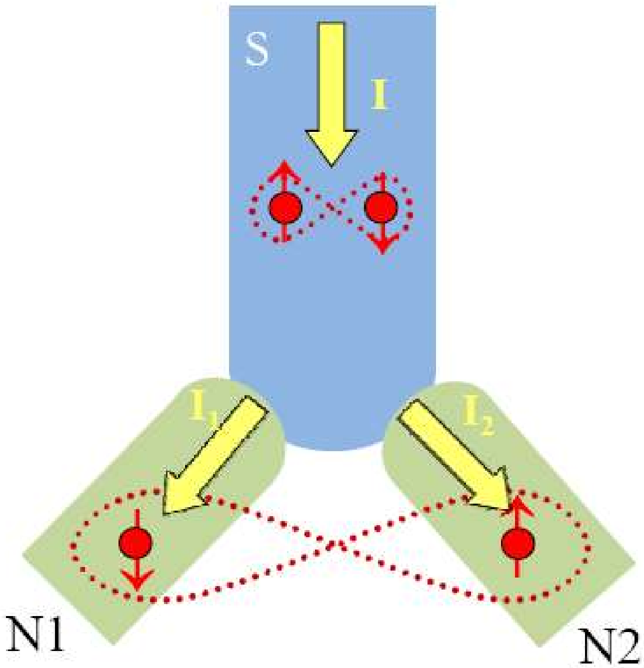
- Results in graphene

  Cooper pair splitting in graphene

  Thermoelectric effect

- Summary

Background



conventional Cooper pair:
spin singlet

$$[\Psi_{+k}(r_1)\Psi_{-k}(r_2)+\Psi_{+k}(r_2)\Psi_{-k}(r_1)]$$
$$\otimes(|\uparrow,\downarrow\rangle-|\downarrow,\uparrow\rangle)$$

split Cooper pair:

$$[\Psi_{N1}(r_1)\Psi_{N2}(r_2)+\Psi_{N1}(r_2)\Psi_{N2}(r_1)]$$
$$\otimes(|\uparrow,\downarrow\rangle-|\downarrow,\uparrow\rangle)$$

Mobile pairs of spatially separated entangled electrons

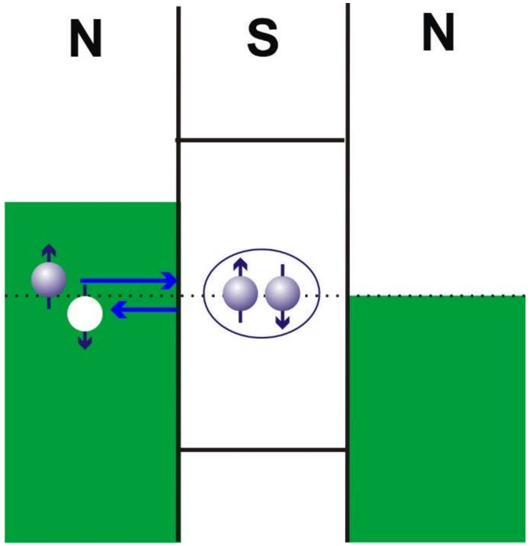
Flying electron Qubits

Correlated electrical currents

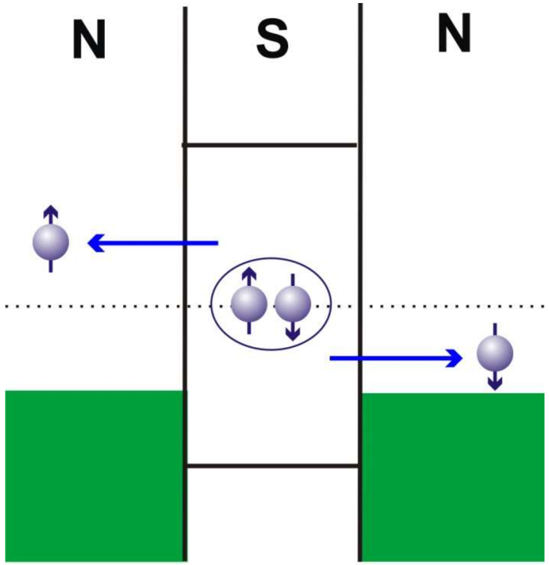
Background

Cooper pair splitting (Crossed Andreev reflection\Nonlocal Andreev reflection)

Andreev reflection

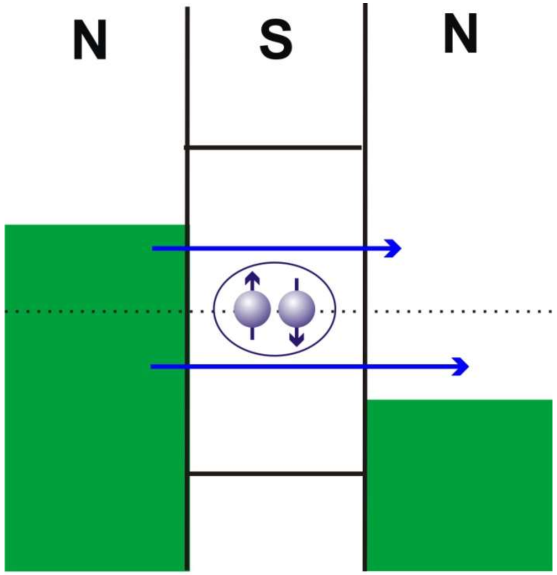


Cooper pair splitting



CPS

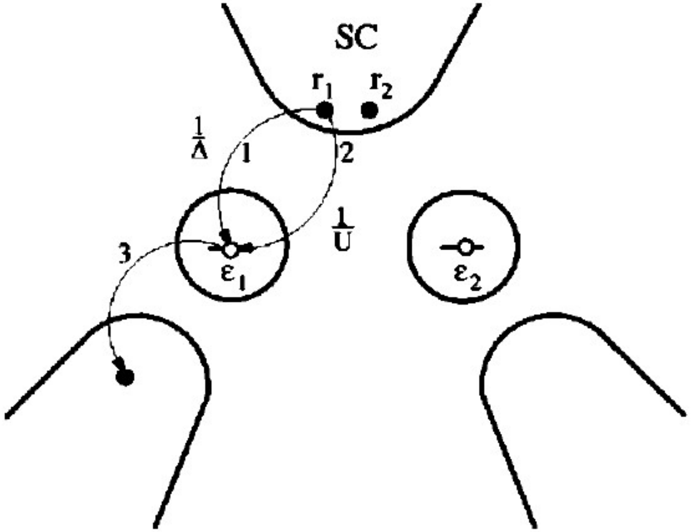
Elastic Cotunneling



EC

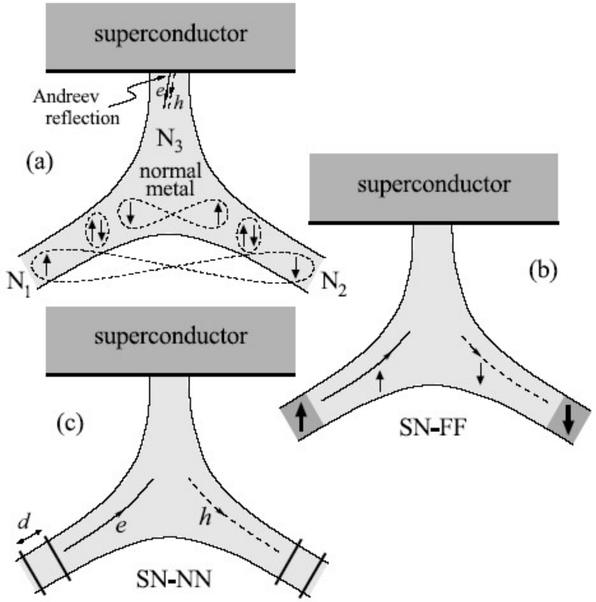
Background

Spatially separate entangled electrons



Andreev-Tunneling, Coulomb Blockade, and Resonant Transport of Non-Local Spin-Entangled Electrons
Recher, P., Sukhorukov, E. V. & Loss, D. Phys. Rev. B 63, 165314 (2001).

Potential device for quantum information



Electronic entanglement in the vicinity of a superconductor, G. Lesovik, T. Martin and G. Blatter, European Physical J. B 24, 287 (2001).
J. Cayssol, Phys. Rev. Lett. 100, 147001 (2008)
M. Veldhorst et al, Phys. Rev. Lett. 105, 107002 (2010)
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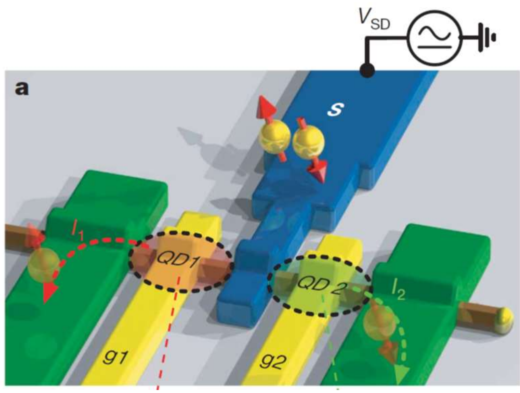
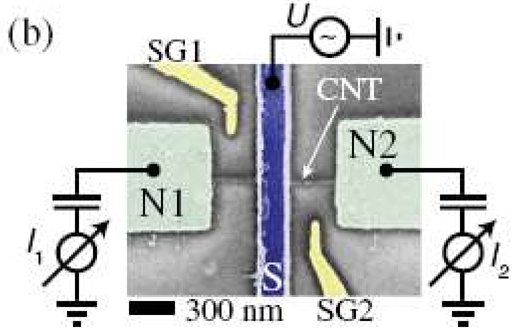
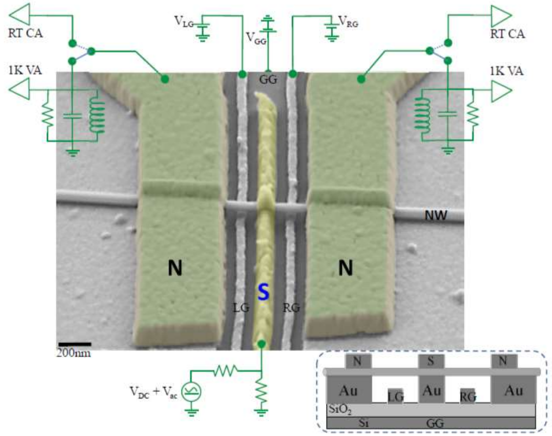
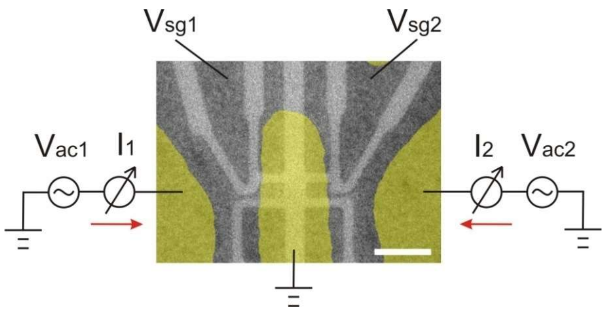
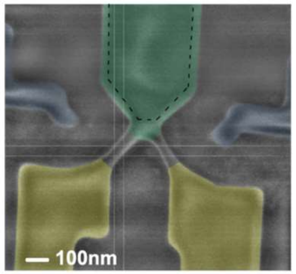
Background









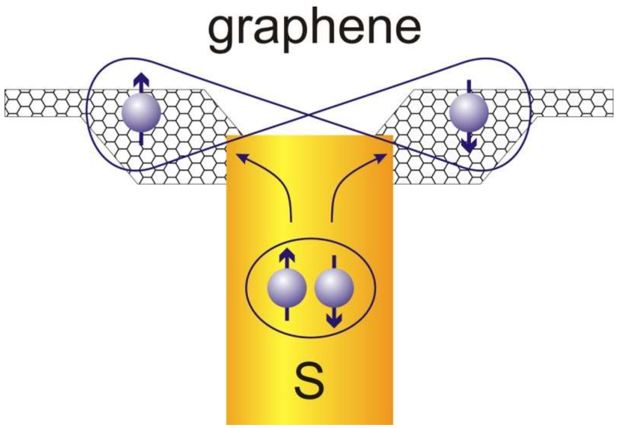


L. Hofstetter, et al., Nature 461, 960-963 (2009)
J. Schindele et al, Phys. Rev. Lett. 109, 157002 (2012)
A. Das et al, Nature Communications 3, 1165 (2012)
Z. B. Tan et al, Phys. Rev. Lett. **114**, 096602 (2015)
I. V. Borzenets et al, Scientific Reports 6, 23051 (2016)

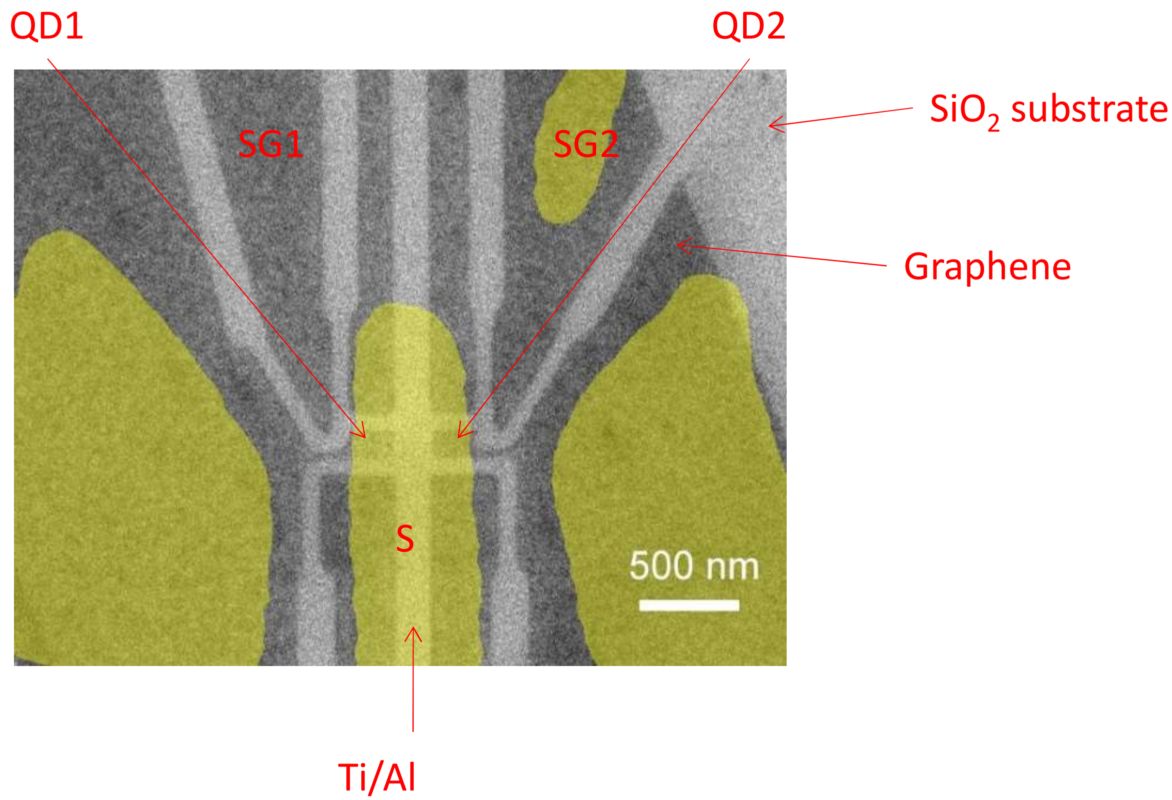
Results in graphene

Why graphene?

- ➢Good physical properties;
- ➢2D material, lithography advantage, design for splitter is open;
- ➢Spin-orbit coupling is weak;
- ➢Specular crossed Andreev reflection.

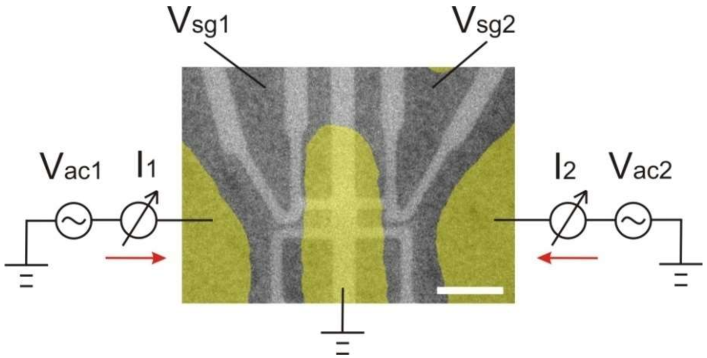


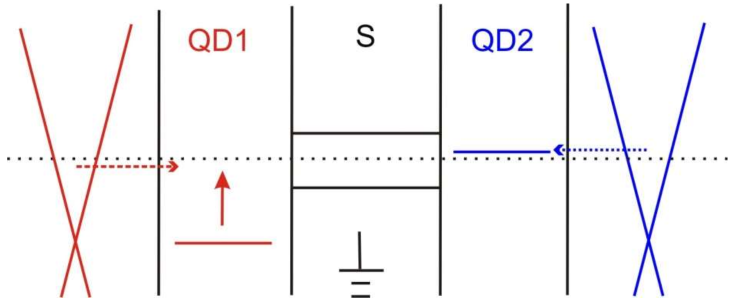
A Graphene Cooper Pair splitter

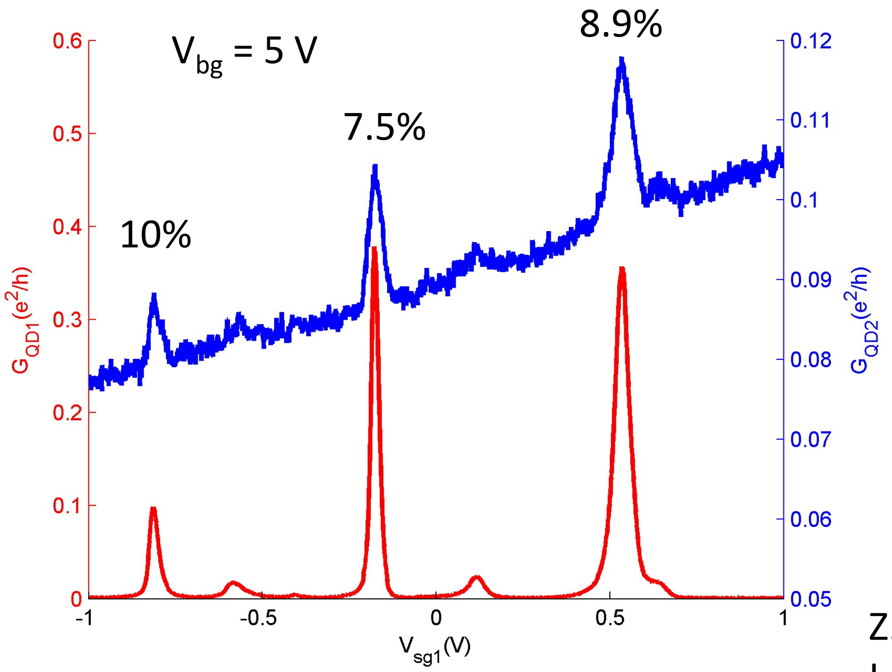


Physical separate two QDS: 1) bias can be tuned independently.
2) weak coupling between two QDs.

Evidence of CPS in graphene





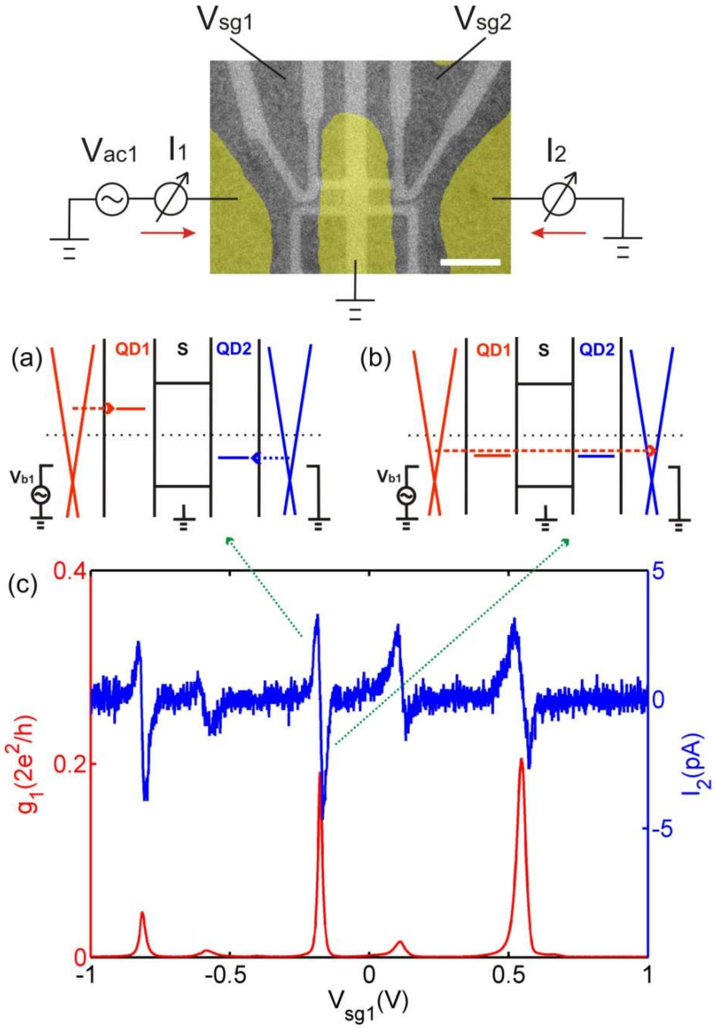


CPS efficiency:

$$\eta = \frac{split \quad Cooper \quad pairs}{total \quad Cooper \quad pairs} = \frac{2 \triangle I_2}{I_1 + I_2} = \frac{2 \triangle G_2}{G_1 + G_2}$$

Z. B. Tan, D. Cox, T. Nieminen, P. Lähteenmäki, D. Golubev, G. B. Lesovik, P. J. Hakonen, Phys. Rev. Lett. **114**, 096602 (2015)

Energy level filtering for CPS and EC

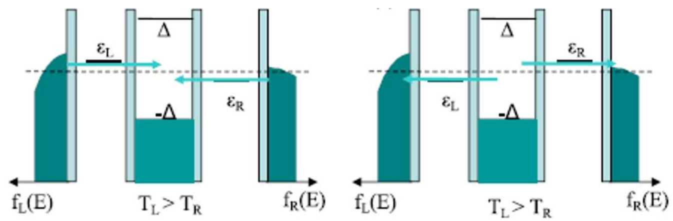


$$G_{CPS} = \frac{R_{\square}}{8} K_0 \left(\frac{\sqrt{2} r}{\xi} \right) \int \frac{G_1(E) G_2(-E)}{4T \cosh^2(E/2T)} dE$$

$$G_{EC} = \frac{R_{\square}}{8} K_0 \left(\frac{\sqrt{2} r}{\xi} \right) \int \frac{G_1(E) G_2(E)}{4T \cosh^2(E/2T)} dE$$

First direct observation of CPS or EC dominated when energy levels of two QDs are asymmetric or symmetric

Energy level filtering is crucial for nonlocal thermoelectric effect!

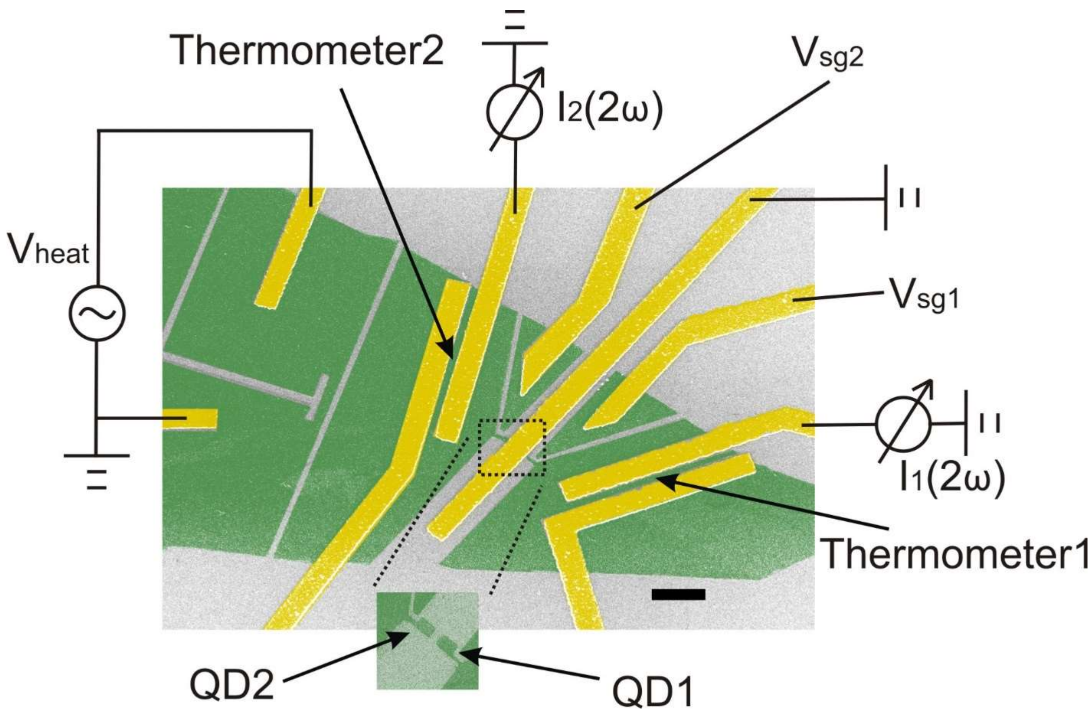


Z. Cao et al, Appl. Phys. Lett. 107, 212601 (2015)

Z. B. Tan, D. Cox, T. Nieminen, P. Lähteenmäki, D. Golubev, G. B. Lesovik, P. J. Hakonen, Phys. Rev. Lett. **114**, 096602 (2015)

False Color SEM Image

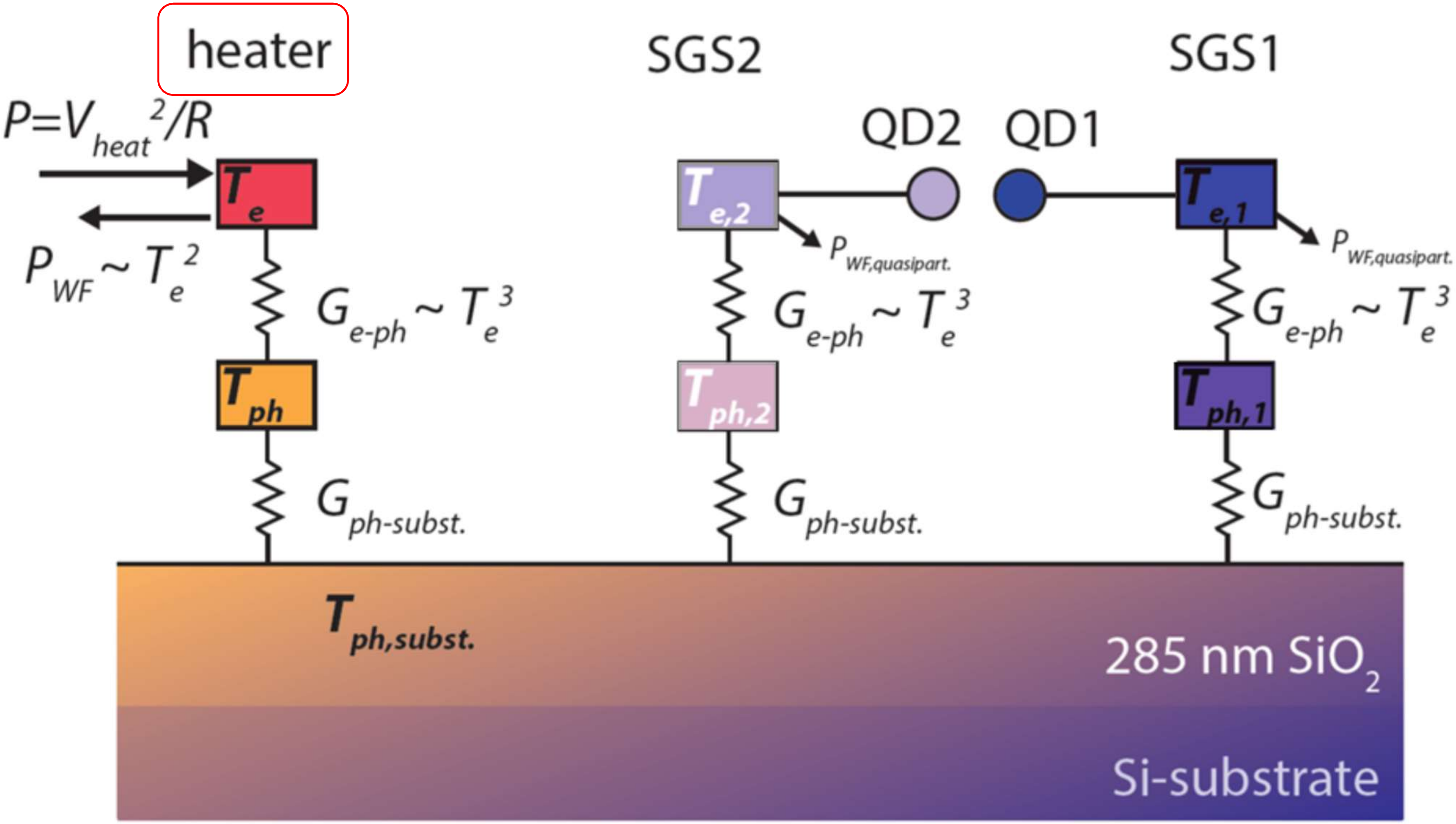
$$P = \frac{V_0^2 sin^2\omega t}{R} = \frac{V_0^2(1 - cos2\omega t)}{2R} = \frac{V_0^2(1 + sin(2\omega t - \frac{\pi}{2}))}{2R}$$



Thermopower measurement
2ω method

- Cooper pair splitter
- Heater
- Thermometer

Thermal Model



Heater

$\nabla(\kappa \nabla \mathrm{T_e}) \approx P_{Joule}$,
where $\kappa = \sigma L T_e$ (Wiedemann-Franz law)

-When $\sigma(T) = \sigma_0$

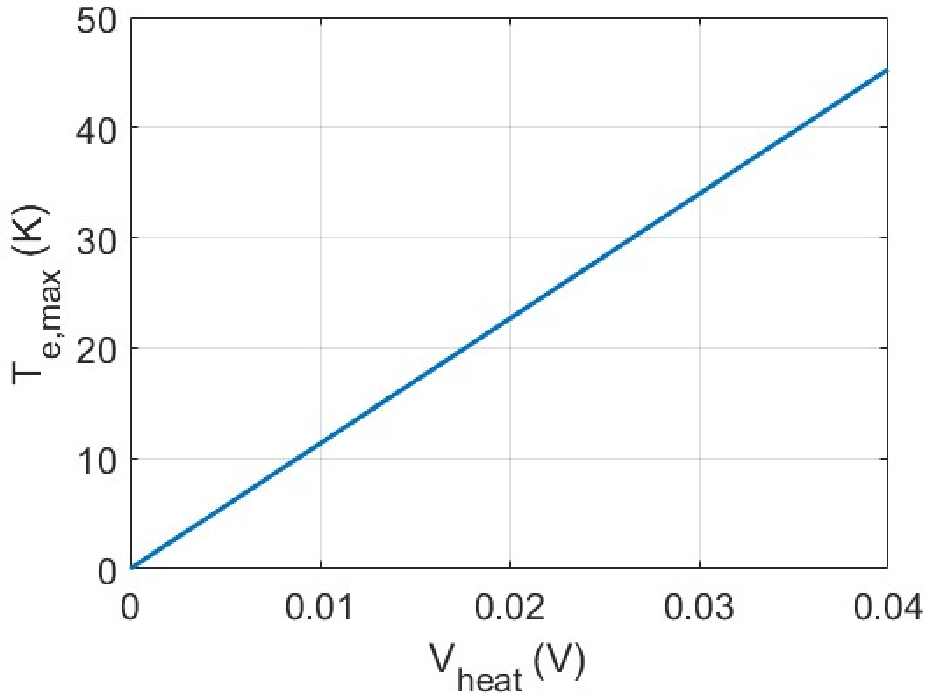
$$\nabla(T_e \nabla \mathrm{T_e}) = \frac{V_{heat}^2 / R}{\sigma L}$$

Analytical solution for max temperature

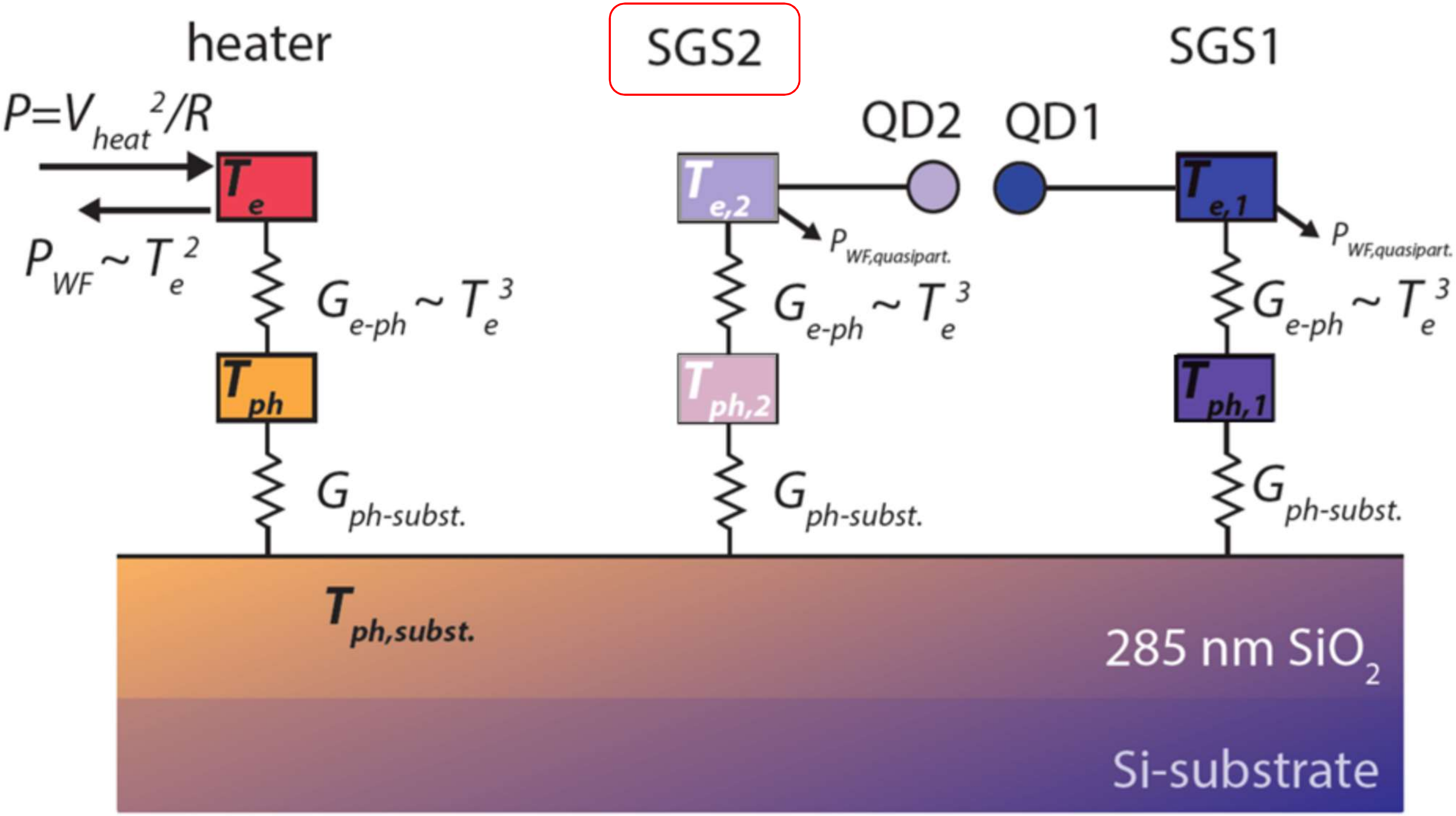
$$T_{e,max} = \sqrt{\frac{V_{heat}^2 / R}{4\sigma L}}$$

Analytical modeling

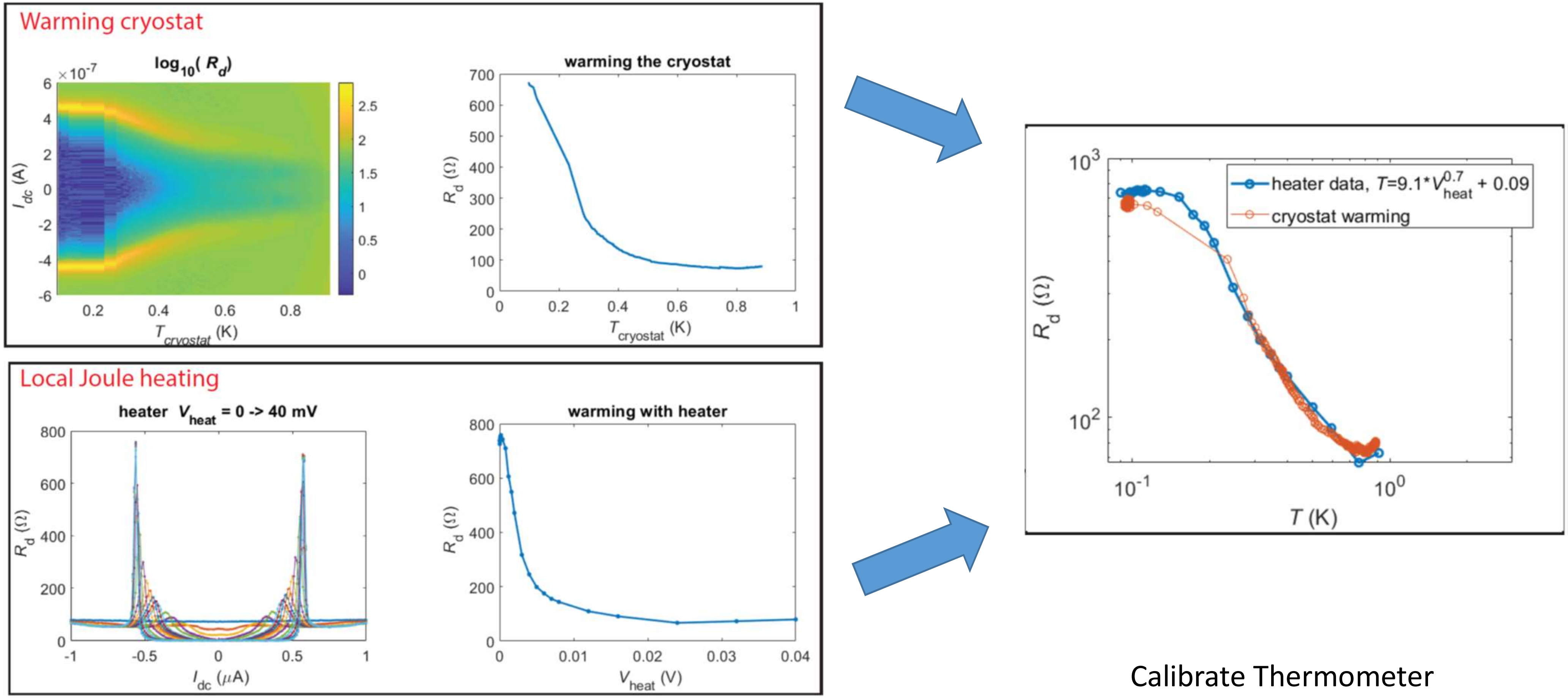
$T_{e,max}$ for heater voltage range used in experiment



Thermal Model

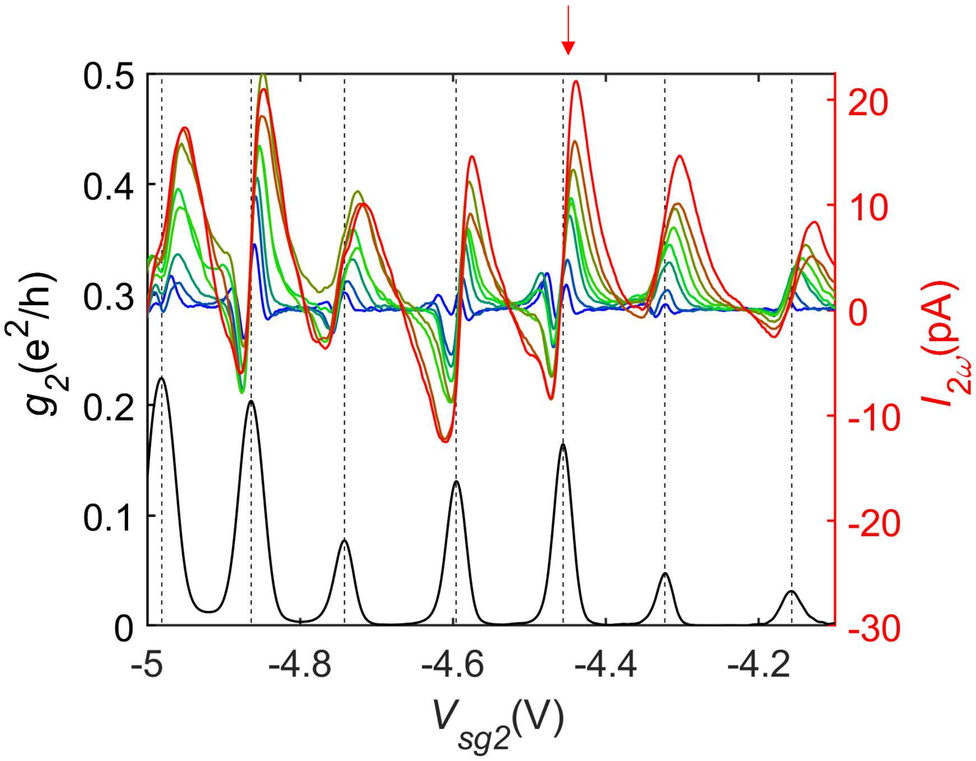


SGS Thermometer

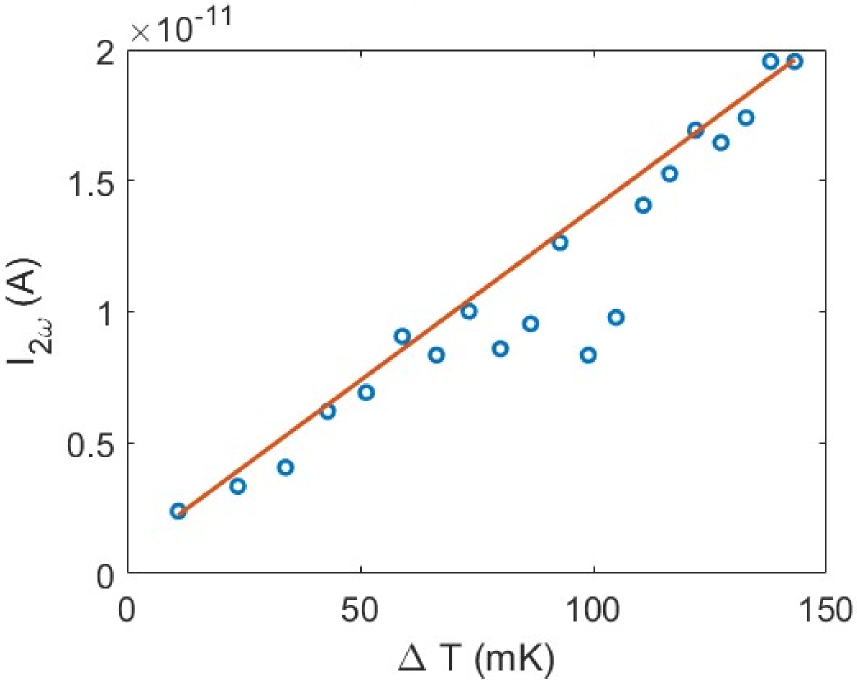


Calibrate Thermometer

Local Thermoelectric Current

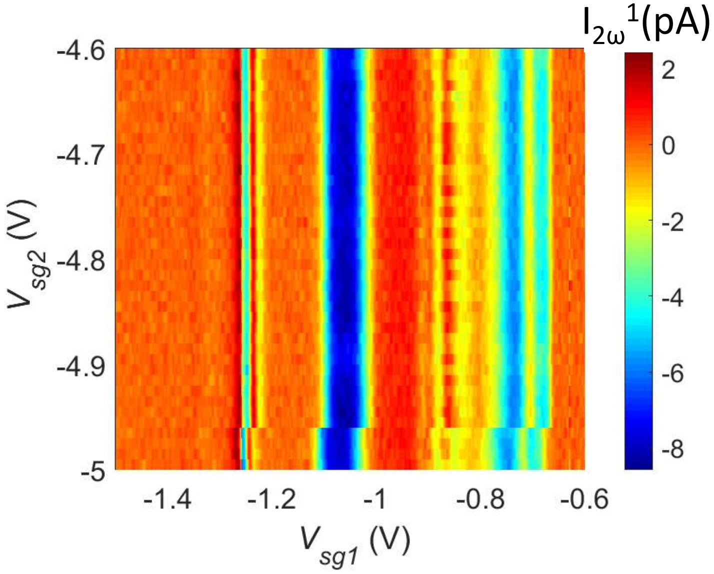


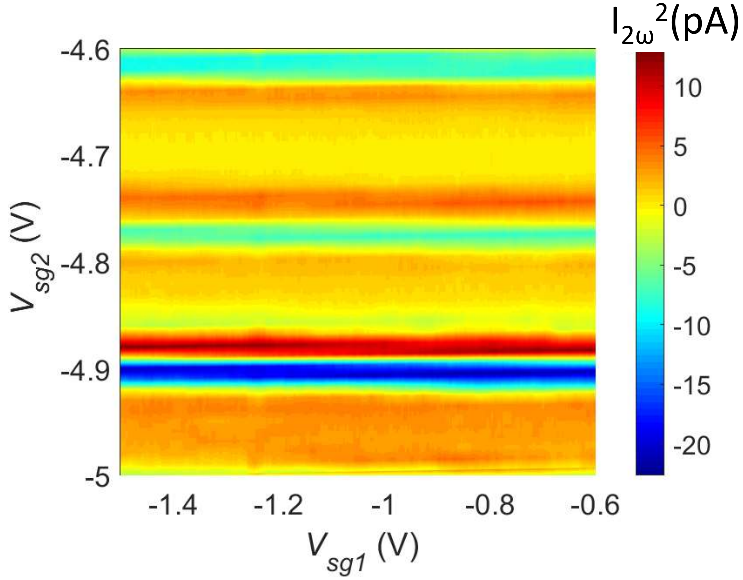
V_{heat} from 1 mV to 29 mV



Thermoelectric current linear with ΔT

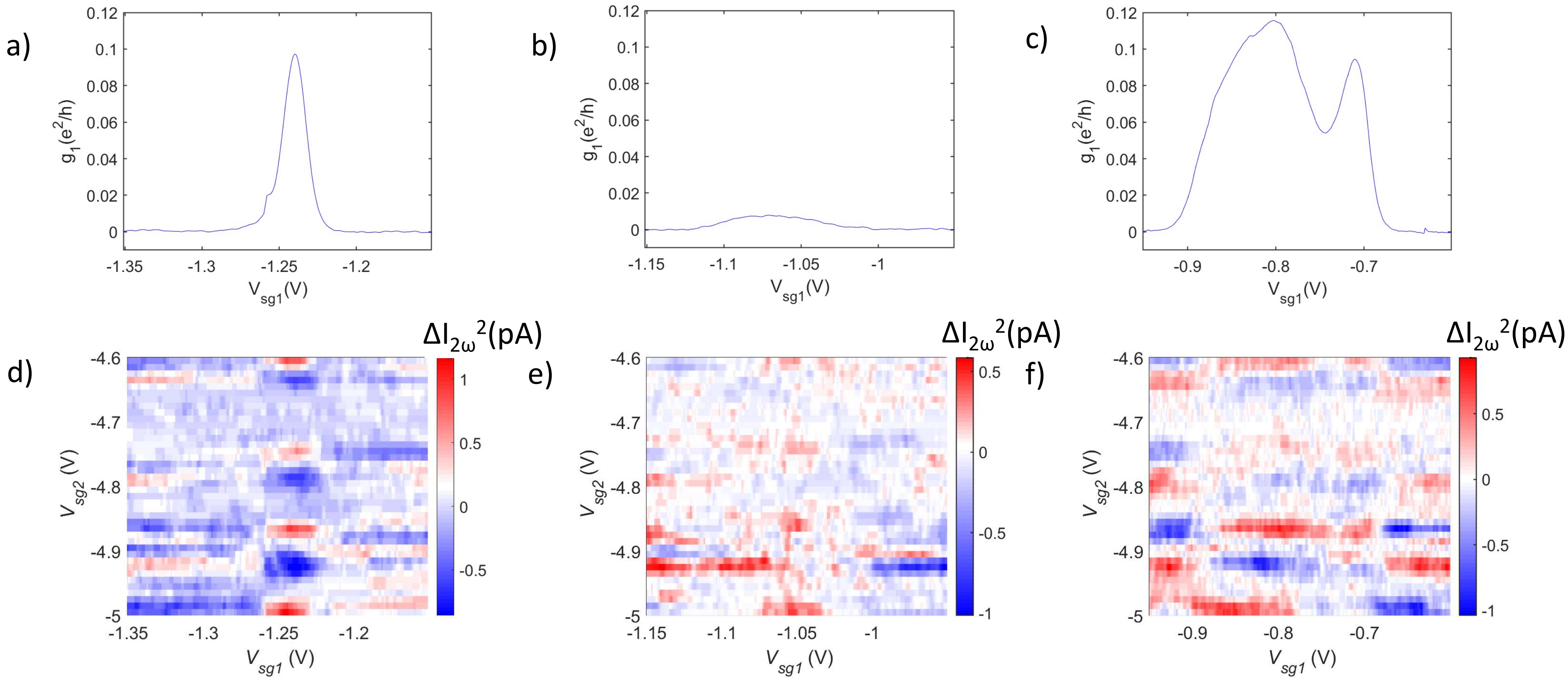
Thermoelectric Current in Two QDs





In preparation

Nonlocal Thermoelectric Current: Experiment

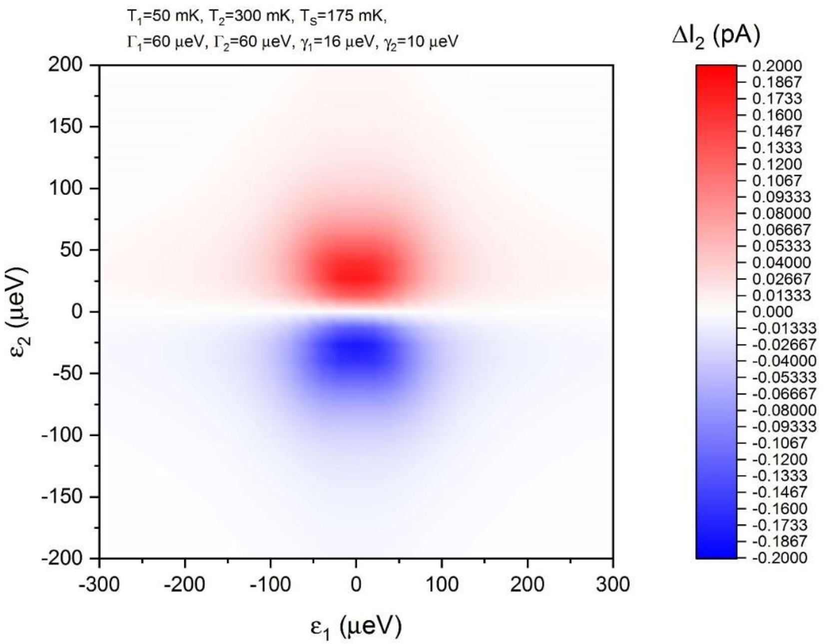


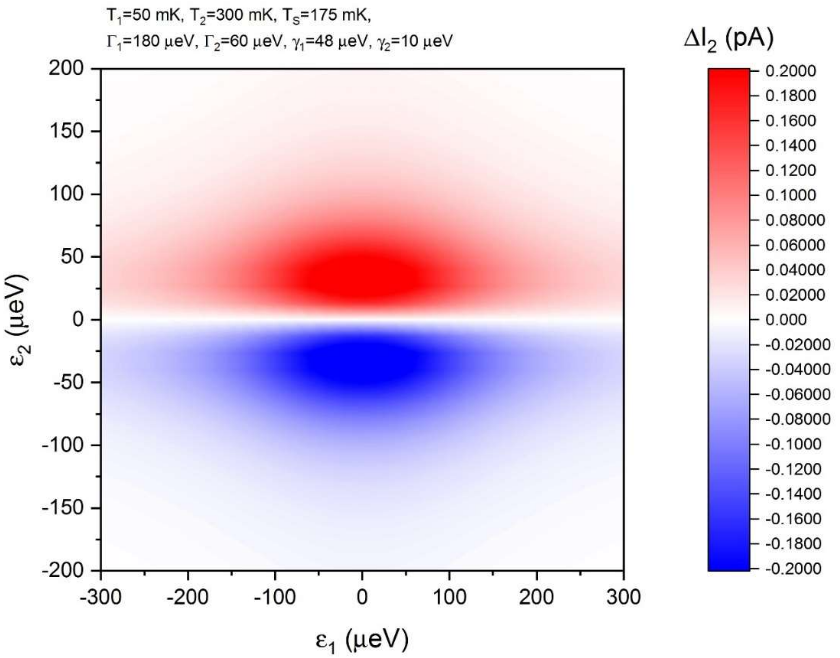
In preparation

Nonlocal Thermoelectric Current: Theory

$$I_e^L = \frac{2\pi^2}{3}\frac{dg_N^L(0)}{dE}g_N^R(0)\frac{e^3\mathcal{R}_S^{LR}(2i\Delta/\hbar)}{h^2}T\Theta$$

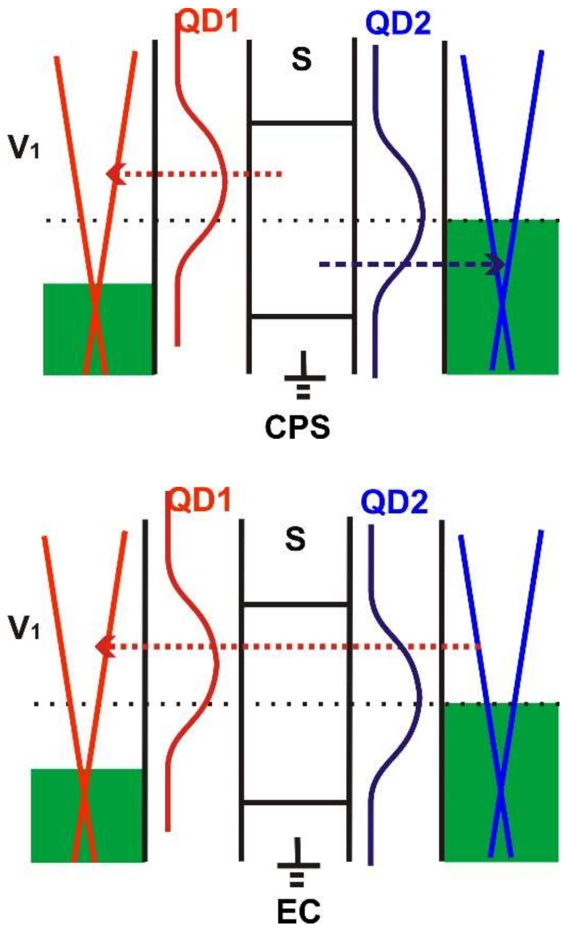
Dmitry Golubev





In preparation

CPS and EC for Refrigerator



$I_2 = I_{CPS} - I_{EC} = 0$
$\Delta I_1 = I_{CPS} + I_{EC} = 2I_{CPS}$

Balance between CPS and EC current in QD2
Cooling the right part of graphene, as a refrigerator.

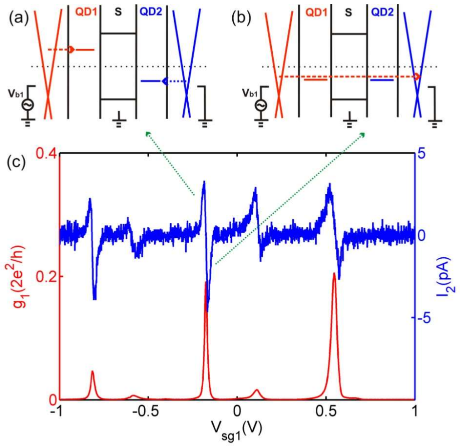
10 pA, 20 µV → 2e-16 W

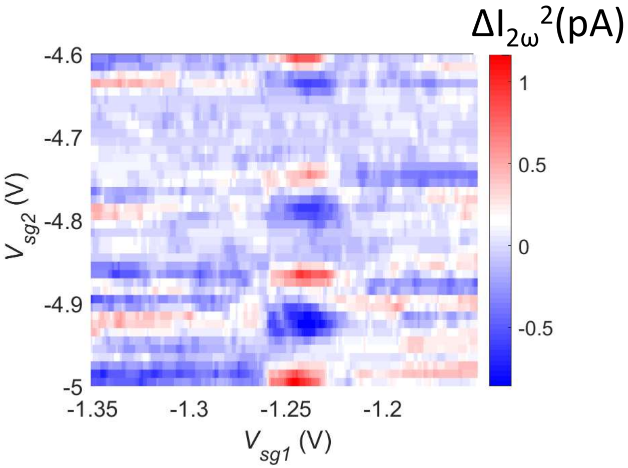
N. S. Kirsanov, Z. B. Tan, D. Golubev, P. J. Hakonen, and G. B. Lesovik, Phys. Rev. B **99**, 115127 (2019)

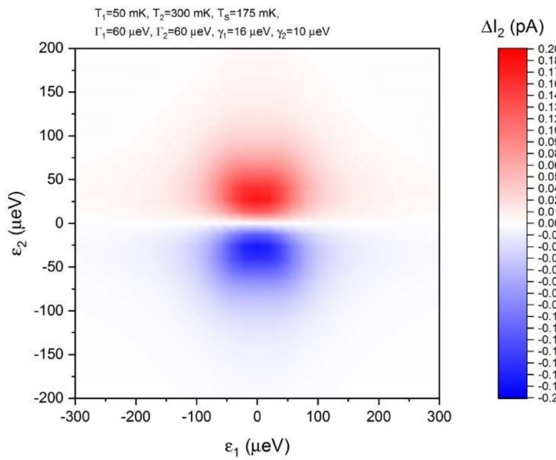
Summary:

➢Tuning the energy level of the two sides of the Cooper pair splitter is crucial for studying the thermoelectric effects.

➢We observed thermoelectric current in a Cooper pair splitter, and have qualitatively understanding on that.







Acknowledgments:

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