Quantum confinement suppressing electronic heat flow below the Wiedemann-Franz law

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(Dated: June 14, 2021)

The Wiedemann-Franz law states that the charge conductance and the electronic contribution to the heat conductance are proportional. This sets stringent constraints on efficiency bounds for thermoelectric applications, which seek for large charge conduction in response to a small heat flow. We present experiments based on a quantum dot formed inside a semiconducting InAs nanowire transistor, in which the heat conduction can be tuned significantly below the Wiedemann-Franz prediction. Comparison with scattering theory shows that this is caused by quantum confinement and the resulting energy-selective transport properties of the quantum dot. Our results open up perspectives for tailoring independently the heat and electrical conduction properties in semiconductor nanostructures.

Wiedemann-Franz (WF)

$$L = \frac{\kappa}{\sigma T} = \frac{\pi^2 k_B^2}{3e^2} = L_0$$

$$L_0 = 2.45 \times 10^{-8} \mathrm{W\,\Omega\,K^{-2}}$$

Table 9.1. Experimentally derived values of the Lorentz number at 0 °C, $L = \lambda_E/\sigma T$, deduced from published data for electrical and thermal conductivity

Metal	$L\,(10^{-8}\ \mathrm{W\Omega/K^2})$
Na	2.10
Ag	2.31
Au	2.35
Cu	2.23
Pb	2.47
Pt	2.51

Solid states physics by: Ibach and Luth

Validity:

- Systems with noninteracting or weakly interacting electrons (e.g. Metals)

Violation:

Coloumb interaction

- sequential tunneling (Björn Kubala, et. al. Phys. Rev. Lett. **100**, 066801)
- Cotunneling processes (Björn Kubala, et. al. Phys. Rev. Lett. **100**, 066801)

Confinements

- Quasi-one-dimensional conductors (Nicholas Wakeham, et. al., Nature communications 2.1 (2011): 1-6)

Violation of WF law in transport through a QD

Landauer-Buttiker non-interacting model

$$I = \frac{2e}{h} \int_{-\infty}^{\infty} \mathcal{T}(E) \cdot \Delta f \; dE,$$

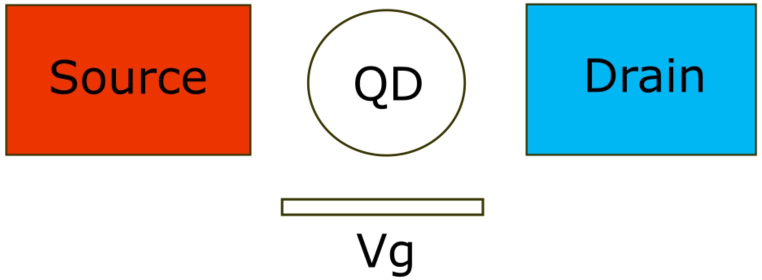
$$\dot{Q}_e = \frac{2}{h} \int_{-\infty}^{\infty} (E - \mu_s) \cdot \mathcal{T}(E) \cdot \Delta f \; dE,$$

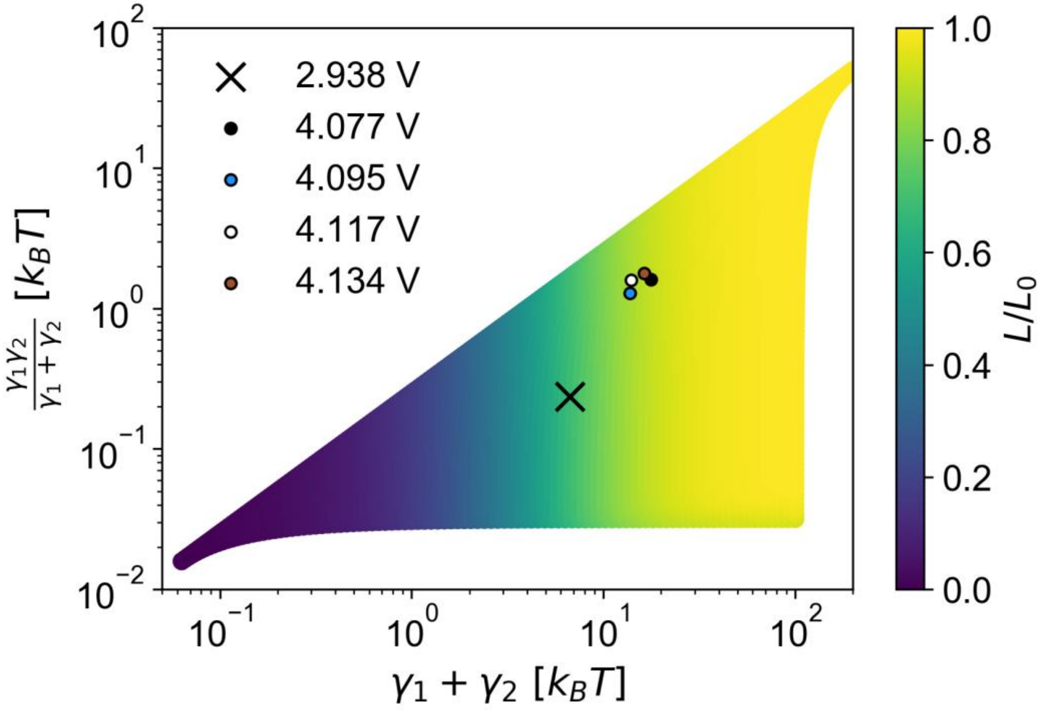
$$E_c \gg \gamma > k_B T,$$

$$\mathcal{T}(E) = \frac{4\gamma_s \gamma_d}{\gamma^2} \frac{\left(\frac{\gamma}{2}\right)^2}{(E - (\varepsilon - e\alpha V_g))^2 + \left(\frac{\gamma}{2}\right)^2},$$

$$\kappa_e = \left.\frac{\partial \dot{Q}_e}{\partial(\Delta T)}\right|_{I=0}, \qquad G = \left.\frac{\partial I}{\partial V_{NW}}\right|_{\Delta T=0} \qquad \mathrm{L} = \frac{\kappa_e}{GT}$$

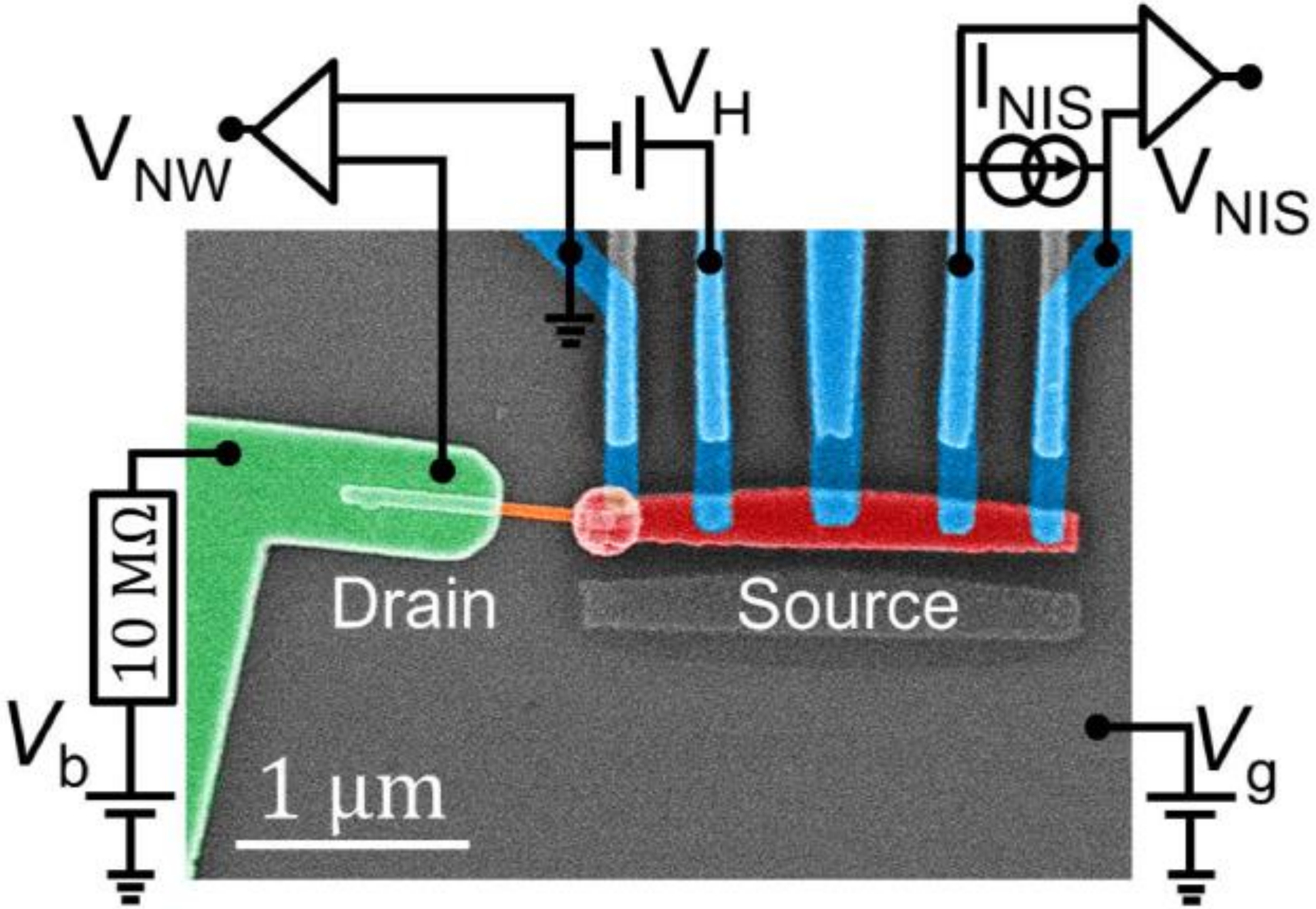
$$L \stackrel{?}{=} L_0$$





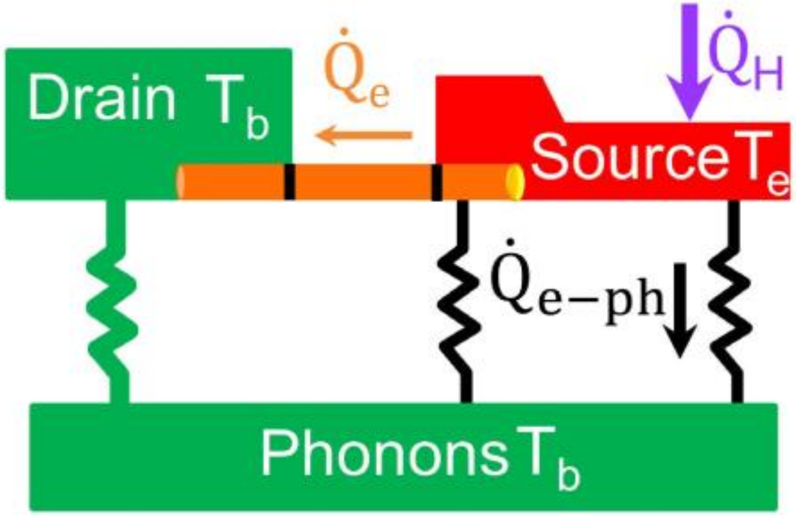
Calculated L/L_0 on resonance as a function of the width $(\gamma_1 + \gamma_2)$ and amplitude $\left(\frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2}\right)$ of $\mathcal{T}(\mathrm{E})$

Device



- InAs nanowire D70 nm
- Source: A few micron length metallic island (Ni+Au, Cu)
- Drain (Ni(30 nm)+Au(60 nm))
- Back gate (p-doped Si 1-30 Ω cm)+200 nm oxide
- 5 Al gates (NIS heater + NIS thermometer)
- Base temperature=100 mK

Heat transport Experiment

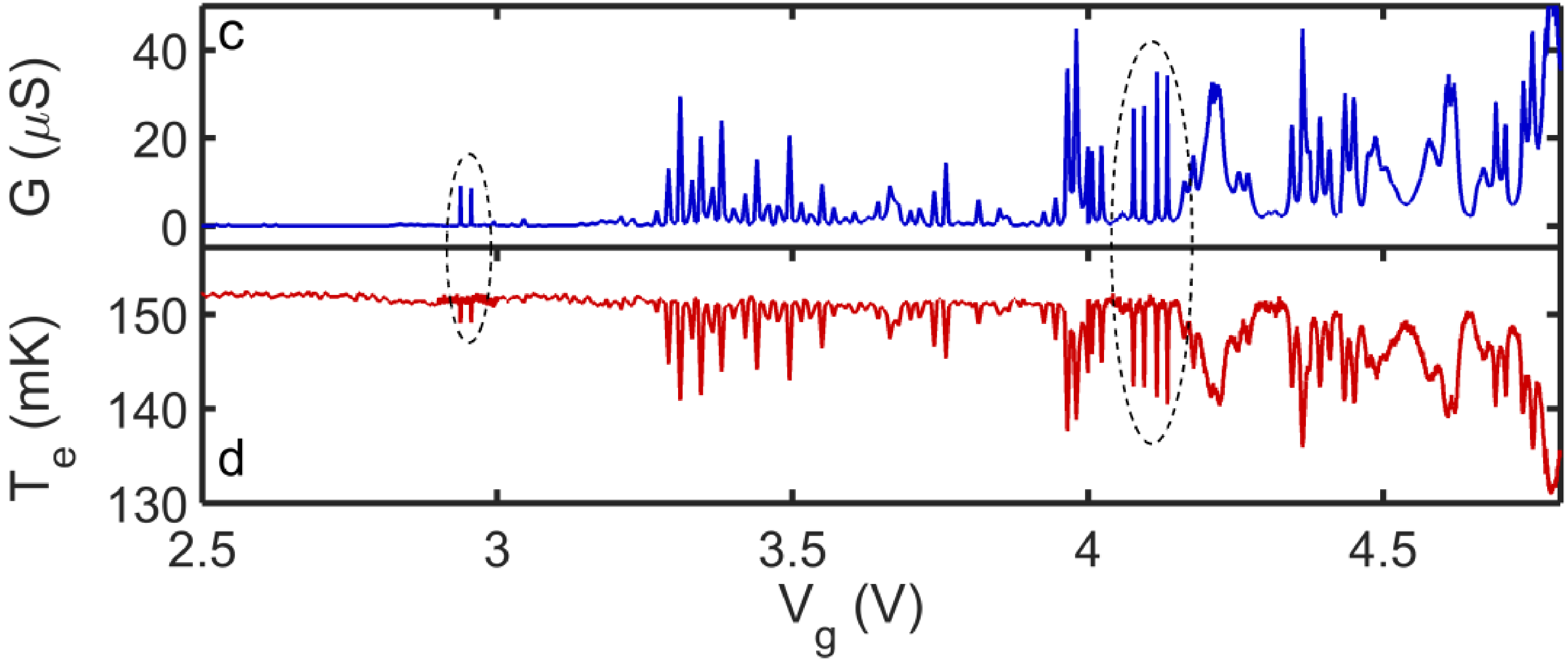


Goals:
Comparing the conductance properties with WF and LB scattering theory

Obstacle:
-Parasitic heat scape via other channels (e.g e-ph coupling)

-The part of the nanowire below the source

$$\dot{Q}(T_e, V_g) = \dot{Q}_H(T_e, V_g) - \dot{Q}_H(T_e, 0)$$

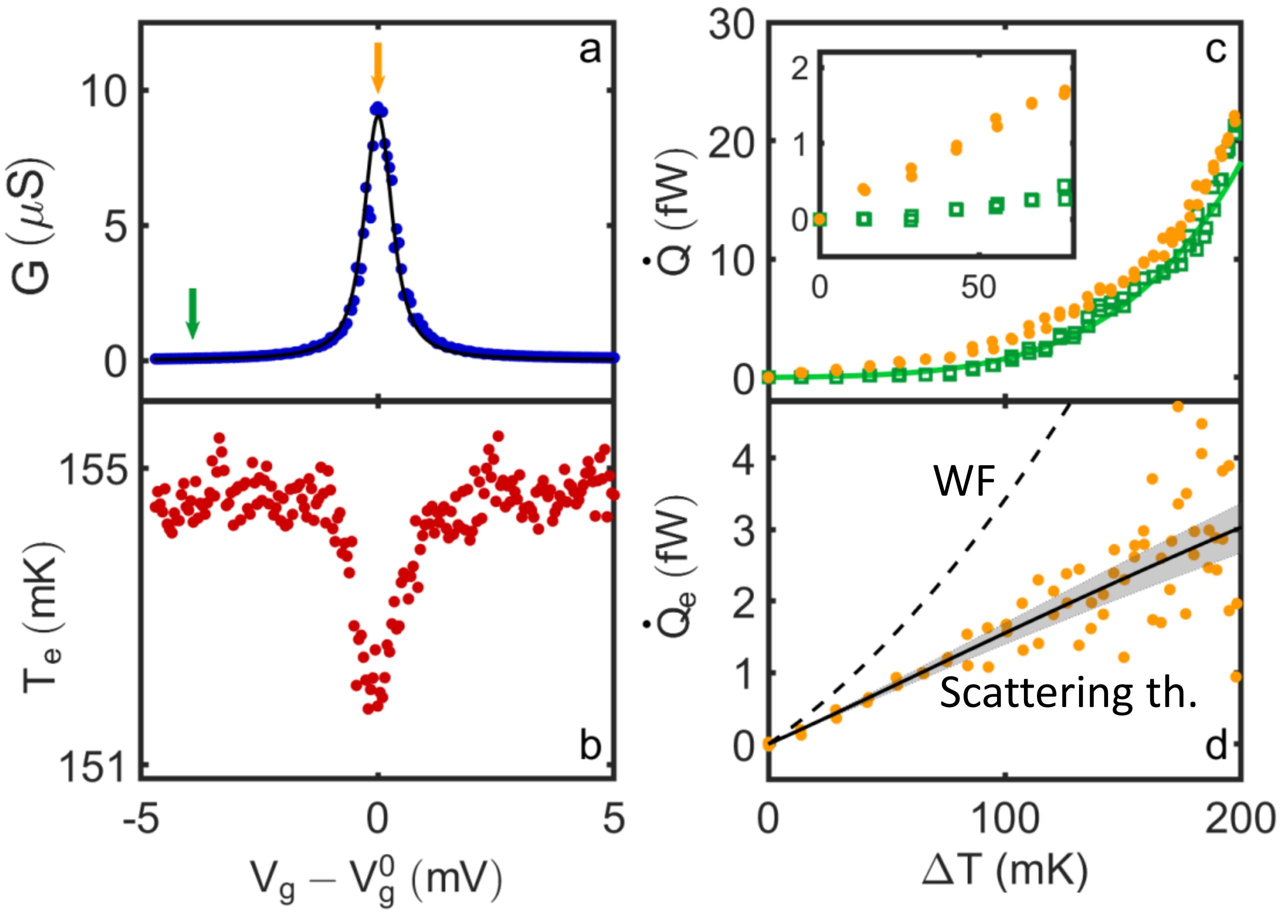


The very first conductance resonance

electronic heat flow through the nanowire

$$\dot{Q}_e(T_e, V_g^0) = \dot{Q}(T_e, V_g^0) - \dot{Q}(T_e, V_g^0 + \Delta V_g)$$

$$L/L_0 \approx 0.65 \pm 0.1$$



$$V_g^0 = 2.938 \text{ V}. \qquad (\gamma_s + \gamma_d)/k_B T_b \approx 7$$

The fit to the green data

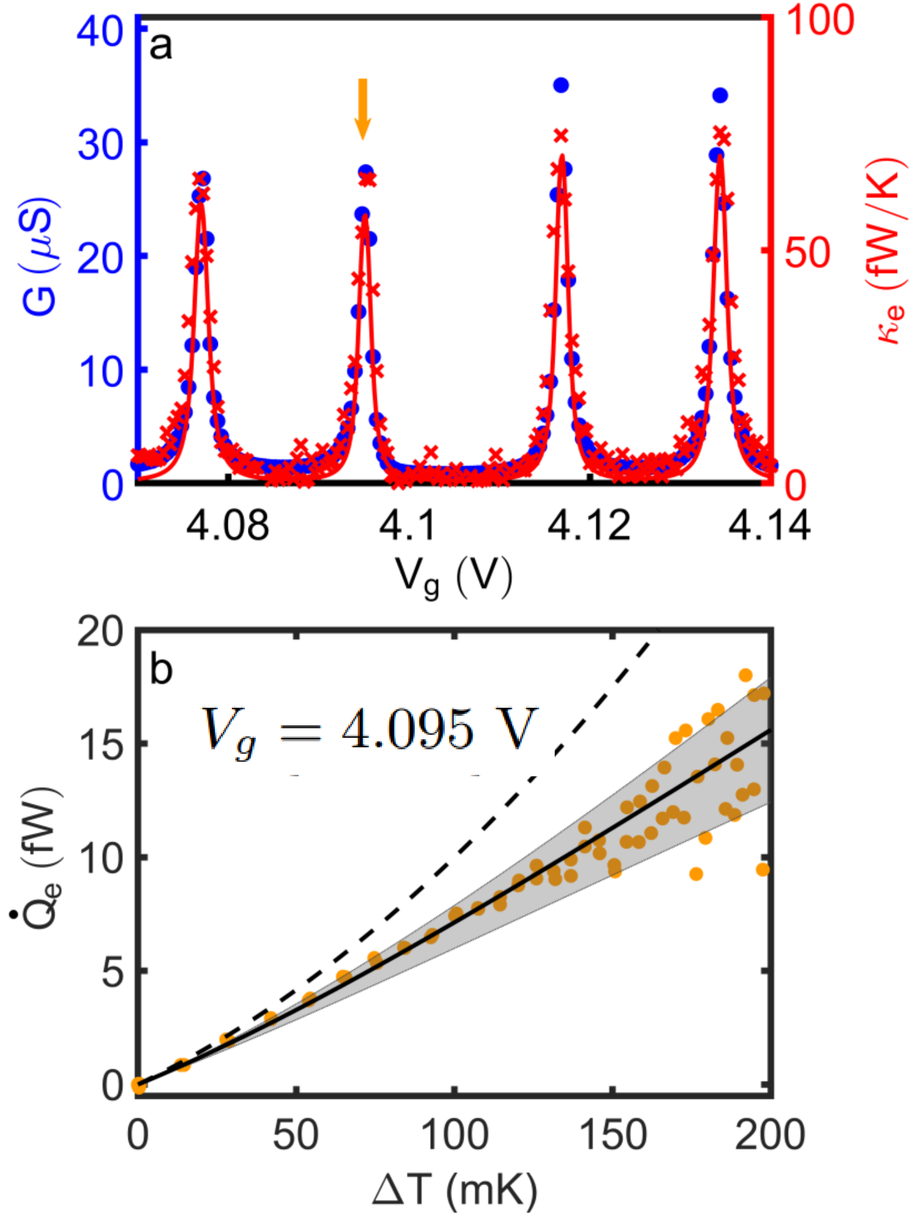
$$\dot{Q} = \beta(T_e^6 - T_b^6) \text{ with } \beta = 35 \pm 5 \text{ pW/K}^6$$

Investigating the other resonance peaks

The $L/L0$ for the four peaks are 0.99, 0.97, 0.87 and 0.90 (±0:05) from left to right

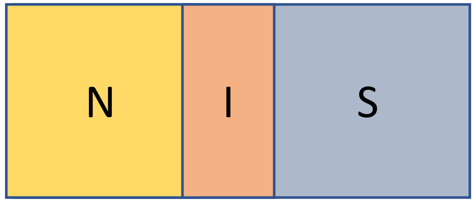
Sizable deviation from WF requires going beyond linear response

The ratio of both vertical scales is set to $T_b L_0$



Conclusion

- Non interacting Landauer Buttiker scattering theory can provide a good description of the heat transport through the quantum dot



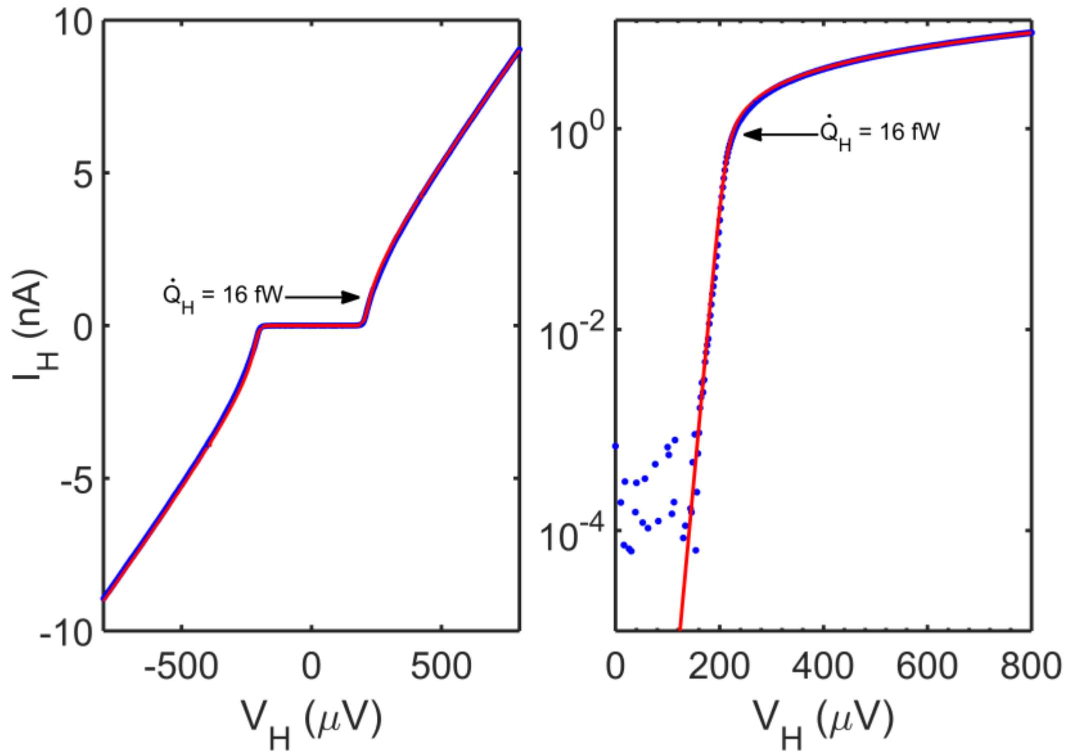
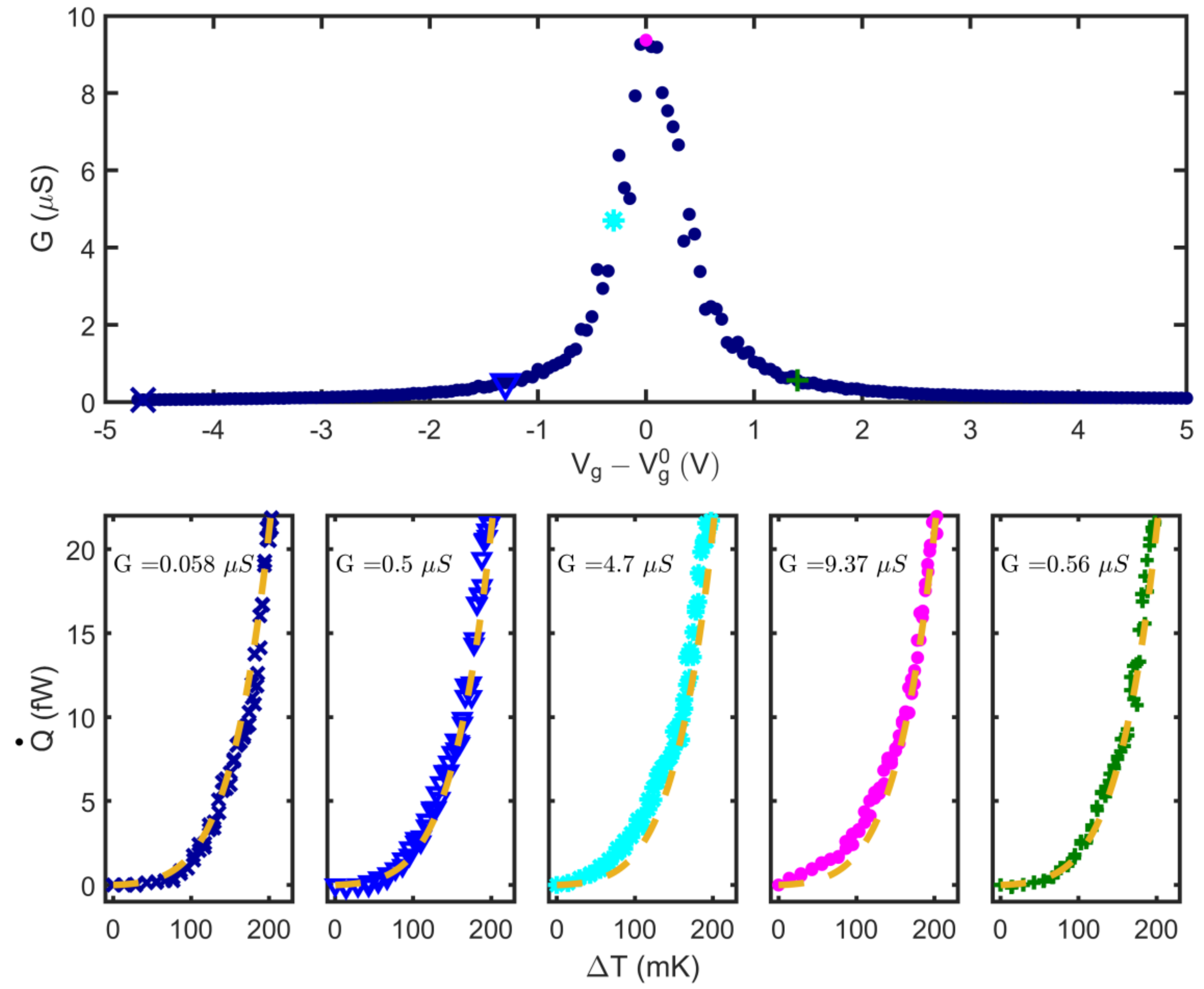


FIG. S5. Current–voltage curve of the heater NIS junction using linear (left) and logarithmic (right) scale. Fit to Eq. (S3) is shown as red lines: $\Delta = 209\ \mu eV$, $R_T = 85.6$ kΩ and T_b= 100 mK. A typical heater current level of I_H= 0.9 nA resulting in $\dot{Q}_H = 16$ fW and $\Delta T \approx 50$ mK (see Figs. 1 and 2 of the main article) is indicated with a black arrow.

$$I = \frac{1}{2eR_T} \int_{-\infty}^{+\infty} n_s(E,\Delta) \times [f_N(E-eV) - f_N(E+eV)]\, dE$$

$$\dot{Q}_H(E) = \frac{1}{e^2 R_T} \int_{-\infty}^{+\infty} (E-eV)\, n_s(E,\Delta) \times [f_N(E-eV) - f_S(E)]\, dE$$



G (μS)
$V_g - V_g^0$ (V)
G =0.058 μS
G =0.5 μS
G =4.7 μS
G =9.37 μS
G =0.56 μS
$\dot{Q}$ (fW)
ΔT (mK)