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Quantum Thermal Conductance of Electrons in a One-Dimensional Wire

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One-Dimensional Wires

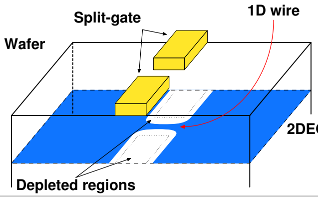
With semiconductors we can:

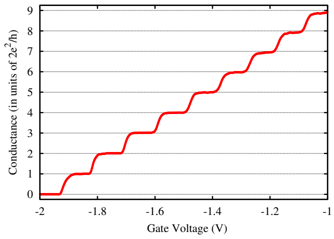
- control the electron density;
- grow crystals of high purity and high carrier mobility;
- engineer the band-structure;

All this allows us to fabricate low-dimensional electron gases (LDEG).

In an heterostructure electrons are confined to a plane: a two-dimensional electron gas (2DEG).

Lateral constriction using a pair of metallic gates produces a one-dimensional (1D) wire:





At low temperatures the mean free path is larger than the length of the 1D wire: transport is ballistic.

By varying the voltage on the gates, the width of the constriction, and the number N of occupied 1D sub-bands, is varied.

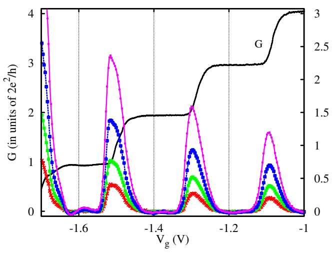
Each occupied 1D subband is fully transmitting and carries the same amount of current, so the conductance is given by the Landauer formula:

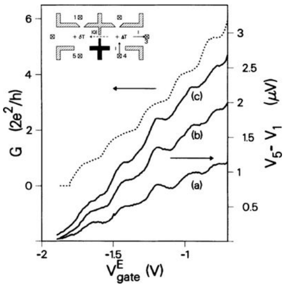
$$G = \frac{2e^2}{h} N$$

It can be shown that the thermo-electric power in the ballistic regime follows the Cutler-Mott relation:

$$S = \frac{\pi^2 k_B^2 T}{3e} \left(\frac{1}{G} \frac{dG}{dE} \right)_{E=E_F}$$

which means that the thermopower is proportional to the transconductance. In particular, the thermopower is zero in correspondence of the conductance plateaux:





Earlier measurements of the thermal conductance (*Molenkamp 1992*, see figure above) suggest that 1D wires in the ballistic regime follow the Wiedemann-Franz law:

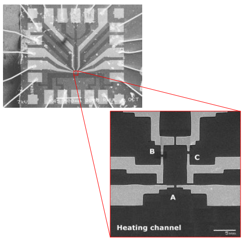
$$\kappa = \frac{\pi^2 k_B^2}{3e^2} TG$$

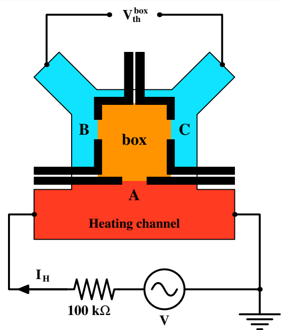
Experiment

Samples

The samples used in this work are of higher quality than in *Molenkamp 1992*.

The wafers were fabricated from a wafer grown by molecular beam epitaxy. The 2DEG is 100 nm below the sample surface, with a carrier density of 3×10^{11} cm^{-2} and a mobility of 5×10^6 cm^2/Vs.





The three split-gates have a gap 0.5 µm long and 0.65 µm wide, and form a 6 µm × 10 µm box containing about 2×10^5 electrons.

Design

The electrons in the *heating channel* are heated above the lattice temperature T_L by passing a current I_H through the electron gas. The electron-electron scattering rate is much faster than all other rates, and so electrons in the heating channel equilibrate at a local temperature $T_H > T_L$.

We modify the device of *Molenkamp 1992* by introducing a closed electron box, whose temperature T_{box} is measured from the thermopower in the linear regime of constrictions *B* and *C* (*Appleyard 1998*).

The electrons in the closed box have a well-defined temperature and for a given I_H it produces larger thermovoltages than the more open structures. The temperature T_{box} is determined by the *heat balance equation*:

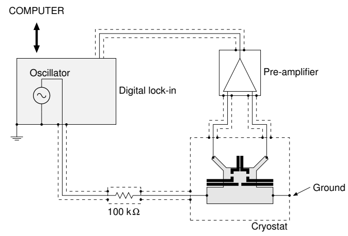
$$\kappa_A(T_H - T_{box}) = (\kappa_B + \kappa_C)(T_{box} - T_L) + \dot{Q}_{el-ph}$$

where the last term on the right is the heat lost through electron-phonon interaction.

Setup

The internal oscillator of the digital lock-in was used to apply the heating current at frequency $f = 32$ *Hz*. The thermovoltage V_{th}^{box} was measured by the same lock-in at a frequency $2f$, after being pre-amplified.

The voltages on the split-gates were applied by a digital-analog converter (not shown in the drawing).

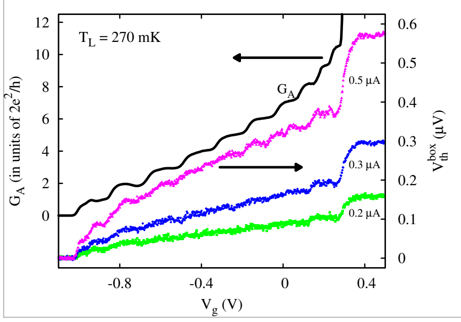


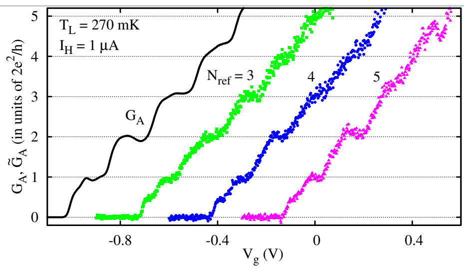
Results

Quantized Thermal Conductance

The measurements were performed by fixing the gate voltage for constrictions *B* (the thermometer) and *C* (the reference), while sweeping the voltage for *A*. At low temperatures ($T < 0.5$ *K*) the electron-phonon interaction is negligibly small, therefore the variation of T_{box} is determined by the variation of κ_A.

The measured thermovoltage characteristics $V_{th}^{box}(V_g)$ follow the shape of the conductance characteristic $G_A(V_g)$, which means that the thermal conductance $\kappa_A(V_g)$ shows the same subband structure.





Wiedemann-Franz law

Since κ_A shows the same structure as G_A, we can assume that it follows a Wiedemann-Franz relation, although the proportionality constant is not defined. We define a *thermally derived conductance* (*Chiatti 2006*):

$$\tilde{G}_A = (G_B + G_C) \frac{T_{box}^2 - T_L^2}{T_H^2 - T_{box}^2} = (G_B + G_C) \frac{V_{th}^{box}}{V_{th}^H - V_{th}^{box}}$$

where $V_{th}^H = V_{th}^{box}(0.5\ V)$ is the thermovoltage when constriction *A* is not defined, and so the electron thermometer is in direct contact with the heating channel.

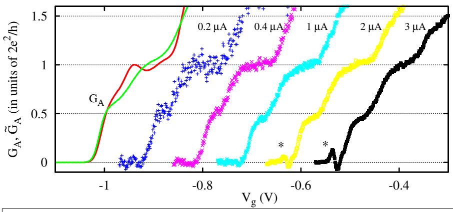
We can see in the figure above that, for $G_A \geq 2e^2/h$, $\hat{G}_A(V_g)$ shows the same quantization as $G_A(V_g)$ for the first four subbands.

0.7 structure

For $G_A < 2e^2/h$ the Wiedemann-Franz law is violated:

- $G_A \sim 0.7(2e^2/h)$, know as the "0.7 structure";
- $\hat{G}_A \sim e^2/h$.

This is more evidence that the single electron picture breaks down below $2e^2/h$. However, a theoretical explanation is still lacking.



References

- Summary of the results: Chiatti *et al.*, *Phys. Rev. Lett.* **97**, 056601 (2006)
- Previous thermal conductance measurements: Molenkamp *et al.*, *Phys. Rev. Lett.* **68**, 3765 (1992)
- Thermopower of 1D constriction as electron thermometer: Appleyard *et al.*, *Phys. Rev. Lett.* **81**, 3491 (1998)
- Review of quantum transport in semiconductor nanostructures: Beenakker and Van Houten, *Solid State Physics* **44**, 1 (1991); cond-mat/0412664

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