Some Really Catching Title

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Motivation

Experimental results of electron transport through InSb nanowires [1] indicated signatures of Wigner crystallization. Theoretical modelling needed to support or reject the hypothesis.

Wigner Crystallization

- Wigner crystallization is the localisation of electrons, when interaction energy dominates kinetic energy.
- Predicted by Wigner in 1934 [2].
- Not yet observed in semiconductor nanowires.
- We report signatures of Wigner crystallization and the possibility of detecting full Wigner crystallization in semiconductor nanowires.

Experiments and Modelling

(a) InSb wire on a SiO_2 capped highly doped Si substrate, with gold contacts (source, drain) grown across. The length of the quantum dot is $l = 160$ nm.

(b) Modelling of the wire.

Figure 1 : (a) SEM image of a 160 nm long, 70 nm diameter InSb nanowire quantum dot device, and (b) a schematic diagram of the modelling of a nanowire of length l and dielectric constant ϵ_{in}.

- Measurements of electron transport [1]:
  - InSb nanowires (see Fig. 1(a));
  - Diameter 70 nm and lengths 70 nm and 160 nm;
  - At temperature 300 mK.
- Model electron transport through the wire:
  - **1D model.** We derive the effective 1D Coulomb interaction by modelling the wire as an infinite cylinder of 70 nm diameter and relative permittivity $\epsilon_{in} = \epsilon_{InSb} = 16$, embedded in a medium of relative permittivity ϵ_{out}, and integrating out the radial and angular degrees of freedom. The ϵ_{out} is used as a fitting parameter to experiments. It is taken as a weighted average of the substrate and the surrounding air, with the screening of the gold contacts taken into account;
  - Combined with **master equation approach** (transport simulation).

Results

- Experiments and simulations:
  - Fit the width of the Coulomb diamonds via ϵ_{out} (dielectric constant of medium outside wire);
  - Other features of the charge stability diagrams which are not fitted by hand, match very well between theory and experiment, both for 70 nm (not shown) and 160 nm (compare Figs. 2(b) and (c), e.g. the lines marked by ② and ④).
- No Wigner crystallization:
  - Interaction is non-essential;
  - Independent particle approximation: Many-particle energy levels in the wire can be found by simply ordering the electrons into single-particle levels, applying the Pauli principle;
  - The energy needed to excite a single electron from the ground state to the 1st excited single-electron state, ΔE_1, is approximately the same as the energy difference between the 2-electron ground and 1st excited state, ΔE_2 (see inset in Fig. 2(a));
  - *Experimental recognition:* Distance between lines ① and ② is the same as between lines ③ and ④.
- Onset of Wigner crystallization:
  - Interaction is non-negligible, simple single-electron calculations will not do;
  - $\Delta E_1 \gg \Delta E_2$ (see inset in Fig. 2(b)).
  - *Experimental recognition:* Distance between lines ① and ② is considerably larger than the distance between lines ③ and ④.
- Wigner crystallization:
  - Simulations only, no successful experiments yet!
  - The lowest singlet and triplet states are practically the same, as a result of the localisation -- the relative spin orientation of the two electrons does not matter as they are separated;

Results (cont.)

Figure 2 : Charge stability diagrams: Differential conductance (dI/dV_{sd}) vs. source-drain bias voltage (V_{sd}) and gate energy (E_g) or gate voltage (V_{bg}).
(a) Simulations of a $l = 70$ nm wire. (b) Simulations of a $l = 160$ nm wire. (c) Experimental results for a $l = 160$ nm wire. (d) Simulations of a $l = 300$ nm wire. In all panels, lines corresponding to transport through the 1- and 2-electron ground state and 1st excited state are labelled by the symbols ①, ②, ③ and ④ (see legend). The separation of these lines provides the excitation energies from the 1- and 2-electron ground state. In panels (a) and (b) these are marked by ΔE_1 and ΔE_2, respectively.

Summary

We have modelled electron transport through InSb nanowires. Our theoretical results are consistent with the existing experimental data. They confirm the detection of the onset of Wigner crystallization, and predict at which wire length complete Wigner crystallization is to be expected.

References

[1] Nilsson, H. A., Caroff, P., Thelander, C., Larsson, M., Wagner, J. B., Wernersson, L.-E., Samuelson, L., and Xu, H. Q. *Nano Lett.* **9**(9), 3151 (2009).

[2] Wigner, E. *Phys. Rev.* **46**, 1002 (1934).

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