Signatures of Wigner localization in epitaxially grown nanowires

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It was predicted by Wigner in 1934 that an electron gas will undergo a transition to a crystallized state when its density is very low. Whereas significant progress has been made toward the detection of electronic Wigner states, their clear and direct experimental verification still remains a challenge. Here we address signatures of Wigner molecule formation in the transport properties of InSb nanowire quantum-dot systems, where a few electrons may form localized states depending on the size of the dot (i.e., the electron density). Using a configuration interaction approach combined with an appropriate transport formalism, we are able to predict the transport properties of these systems, in excellent agreement with experimental data. We identify specific signatures of Wigner state formation, such as the strong suppression of the antiferromagnetic coupling, and are able to detect the onset of Wigner localization, both experimentally and theoretically, by studying different dot sizes.

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Overview

• Motivation

• Devices

• Wigner crystals are…

• Theoretical modeling of filling scheme

• Experimental evidence of Wigner loc. in charge stab. Diagrams

• Conclusions
Motivation

Nature physics 4, vol4: the 1D Wigner crystal in CNT’s

One could use the many body Wigner crystal as a chain of quantum bits towards realizing spin based quantum computing in carbon.

Fig. 1  SEM images of R-TiO$_2$ arrays: (a) a bird’s-eye view of a large number of nanoflowers, (b) a close-up view of two nanoflowers. (c) a photograph of a garden-cosmos.
Device

• Epitaxial growth of InSb Nanowires

• Wire dimensions:  \( R=35\,\text{nm} \)
  \( L=70\,\text{nm} / 160\,\text{nm} \)

• Schottky barriers to Au-contact stripes

• Highly doped Si substrate used as BG, \( \text{SiO}_2 \) gate dielectric

• Meas. done at \( T=300\,\text{mK} \) with standard Lockin technique
Wigner crystal (localization)

• Transition to Wigner crystal → contest: Coulomb repulsion – QM kinetic energy

• Take very low density 2DEG
  • Consider coul. interaction
    (classical picture, $E_C >> kT$)
  • Minimize Energy
    → furthest geometrical spacing

→ Wigner crystal

predicted by Eugene Wigner in 1934 observed in

1D: CEO wires and for holes in CNT’s

2D: electrons on LHe surface
Wigner localization in 1D

• Most simple 1d confinement potential
  → Infinite potential well

• Solve Schrödinger equation:

  $H \Psi_n = E_n \Psi_n$

  $\Psi_n = a \cdot \sin\left(\frac{\pi n}{L}\right)$

  $\Rightarrow E_n = \frac{\hbar^2 n^2}{8m^* L^2}$

• Single particle energy spectrum
  2e- per level → Spin

• Classical limit → very long wire, low density

• Limit of 2 electrons:
  • short wire: singlett
  • long wire: charge separation
    (4 fold degenerate)
Crossover in InSb – rough estimate

• Take ground state energy as QM kin. energy scale
  \[ E_K = \frac{\hbar^2}{8m^*L^2} \]

• Coulomb energy for 2 separated electrons:
  \[ E_C = \frac{e^2}{4\pi\varepsilon_0\varepsilon_r} \int_{-\infty}^{L} \frac{-1}{r^2} dr = \frac{e^2}{4\pi\varepsilon_0\varepsilon_rL} \]

• Crossover: QM (single particle) level scheme
  \[ E_K = E_Q \Rightarrow L = \frac{\pi\varepsilon_0\varepsilon_r\hbar^2}{2m^*e^2} \]

• Material parameters for Sb: \[ m^* = 0.013m_e \]
  \[ \varepsilon_r = 17.7 \]
  \[ \Rightarrow L = 350\text{nm} \]

• Adjustments: Potential not hard, better approximation harmonic
  \[ \text{Charges not located completely at edge of wire in localized state (increases EC and reduces crossover length)} \]
Theoretical modeling

- Electron transport treated with master equation using calculated many particle states.
- Calculated electron density for the two particle state:
  - Whatever length the wire is, siglett is lowest energy state.
  - In limit $L \to \infty$ single and triplett degenerate $\to$ 4 fold degen.

- What to look for in transport measurements?
  - Determine $E_C$ and energy splitting $E_K$ via exitet state lines.
Calculated charge stab. diagram

- Calc. charge stab. diagram for a 70nm InSb Nanowire
$E_C$, $\Delta\varepsilon$, $\Delta E_2$

- Source-Drain position with respect to the chemical potential and the dot levels

$E_C$ given by half width (in $V_{SD}$) of 1st coulomb peak
Theory vs exp. 70nm wire

Theory: \[ \Delta \epsilon = 12\text{meV} \]
\[ \Delta E_2 = 11\text{meV} \]

Experiment: \[ \Delta \epsilon = 16\text{meV} \]
\[ \Delta E_2 = 15\text{meV} \]

Experiments agree with calculations for 60nm wire (bending of levels at contacts → wire eff. shorter than lithographic length)

Charging energy is 6.5meV, clearly smaller than level spacing (\(E_K > E_C\))
Theory vs exp. 160nm wire

Theory: \[ \Delta \varepsilon = 1\text{meV} \]
\[ \Delta E_2 = 2.8\text{meV} \]

Experiment: \[ \Delta \varepsilon = 1\text{meV} \]
\[ \Delta E_2 = 3.2\text{meV} \]

Experiments agree with calculations for 160nm wire

Here the charging energy is already larger than the level spacing, which marks the onset of the wigner localization \( (E_K < E_C) \)
Predictions for 300nm wire

Completely separate peaks in electron density along wire

Almost degenerate 2 particle ground state (9μeV separation btw. singlet, triplet)

Charging energy $E_C \gg \Delta E_2$

Attempts to fabricate such devices failed because of accidental production of double dots
Conclusions

• Very clean QD‘s on InSb Nanowires were produced that show nice periodic shell filling structure due to the equal energy shift of the extended BG.

• For the small wire for 70nm length, small and large coul. diamonds alternate (starting with a small diamond) indicating the regime where $E_K$ dominates $E_C$.

• The long wire (160nm) shows smaller level spacing than charging energy (cond. line of 2nd e- appears after excited state line in stab. diagram when going from more neg. to pos. BG voltage) $\rightarrow$ indicates transition.

• Theroretical cond. calculations agree well with experiments. Calculations suggest a complete transition for a 300nm long wire.