Towards quantum transport measurements on individual self-assembled quantum dots

Florian Dettwiler
MMM-Talk
February 16th 2009
Outline

- Motivation
- Self-assembled InAs Quantum Dots
  - Growth
  - Shell structure
- Overview: Experiments (InAs near 2DEG)
- Some interesting Results
- In our Lab
- Summary & Outlook
Motivation

- Signal converters have a long history...
- Especially in communication

audio to digital

optical to digital
Motivation

- What about quantum information?
  - Can be encoded in photons (via polarization) or spin states
  - Store quantum information: “traps” like quantum dots
  - Transport quantum information: photons

- Known problems
  - Single photon emitters and detectors are necessary
  - For transport over long distances quantum repeaters are needed

quantum information converter
Motivation

- There are different ways to confine electrons in a 0-D system

  - **Lateral quantum dots**
    - 2DEG electrons confined electrostatically
    - tunable
    - “Easy” transport measurements

  - **Self-assembled quantum dots**
    - Confinement due to strain
    - Small but static confinement
    - Optically active
Self-assembled InAs Quantum Dots
Self-assembled InAs Quantum Dots

- Pyramidal- or lens-shaped InAs island on GaAs substrate
- Size:
  - Diameter 15 – 30nm
  - Height 2 – 5nm
InAs QD growth

Stranski-Krastanow Growth

- InAs DEPOSITION
- WETTING LAYER ~1.0 MONOLAYER
- DOT NUCLEATION ~1.5 MONOLAYERS
- Fully formed dots ~2.0-2.5 MONOLAYERS

First layer

InAs QD growth

- Lattice mismatch leads to a strain field
  - Stacked QDs -> double dot
  - Propagating trough capping layers -> position of QD detectable via AFM
InAs Shell structure
Experiments...
Experiments: Overview

- Articles on InAs self-assembled QD >8000 (Web of Science)
- Papers with InAs QDs near a 2DEG <50

  - Influence on 2DEG (Electron Density and Mobility)
  - Photoconductivity
  - Split gate experiments
    - Shell structure/Charging energies
    - Transport lifetimes
  - ...

16.02.2009
InAs QDs near an inverted 2DEG

Transport properties of two-dimensional electron gas in AlGaAs/GaAs selectively doped heterojunctions with embedded InAs quantum dots


Research Center for Advanced Science and Technology, University of Tokyo 4-6-1 Komaba, Meguro-ku, Tokyo 153, and Quantum Transition Project, JRDC, Park Building, 4F, 4-7-6 Komaba, Meguro-ku, Tokyo 153, Japan

(Received 3 August 1995; accepted for publication 9 October 1995)

Transport properties of two-dimensional electron gas (2DEG) are studied in selectively doped GaAs/AlGaAs heterojunctions, in which nanometer-scale InAs dots are embedded in the vicinity of the GaAs channel. When the distance $W_d$ between the InAs dot layer and the channel is reduced from 80 to 15 nm, the mobility $\mu$ of electrons at 77 K decreases drastically from $1.1 \times 10^5$ to $1.1 \times 10^3$ cm$^2$/V s, while the carrier concentration increases from $1.1 \times 10^{11}$ to $5.3 \times 10^{11}$ cm$^{-2}$. Such a reduction of mobility is found only when the average thickness of InAs layer is above the onset level (≈1.5 monolayer) for the dot formation. Origins of these changes in $\mu$ and $N_d$ are discussed in connection with dot-induced modulations of the electronic potential $V(r)$ in the channel. © 1995 American Institute of Physics.
Sakaki et. al.
Other Results

- Presence of InAs QD increases scattering
  - Low mobilities are expected

- Charging state of the dots strongly influences density and mobility
Density and mobility measurements are done in the regime of the classical Hall Effect

What can be seen at high magnetic fields?

\[ n = 5 \times 10^{10} \text{cm}^{-2} \]
\[ \mu = 2 \times 10^{5} \text{cm}^{2}/\text{Vs} \]
Takehana et. al.

FIG. 2: Magnetic field dependence of the (a) longitudinal ($\rho_{xx}$) and (b) Hall ($\rho_{xy}$) magnetoresistivity of the device at 0.5 K, respectively, with various applied gate voltage, before illumination of light.

FIG. 3: Magnetic field dependence of the (a) $\rho_{xx}$ and (b) $\rho_{xy}$ of the device at 0.5 K, respectively, with various applied gate voltage, after illumination of weak light.
Experiments: Overview

- Articles on InAs self-assembled QD >8000 (Web of Science)
- Papers with InAs QDs near a 2DEG >50

- Influence on 2DEG (Electron Density and Mobility)
- Photoconductivity
- Split gate experiments
  - Shell structure/Charging energies
  - Transport lifetimes
- ...

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Split Gate Experiments

- Split gate with countable but random number of dots
- Low mobility (<$10^4$cm$^2$/Vs)
- Shell structure and charging energy measurements (s-shell: 2 electrons $E_C \approx 20$meV, p-shell: 4 electrons $E_C \approx 12$meV)

- Some references
  - Vdovin et. al. JETP 105 (2007) 145
Electron transport: Schmidt et. al.

- Towards single InAs dots

InAs islands were embedded in the channel of an $n$-doped GaAs/AlGaAs high electron mobility transistor structure and a $60 \times 100 \text{ nm}^2$ constriction was defined by lithography based on the atomic-force microscope and subsequent wet chemical etching. Compared to an unpatterned device a strong shift of the threshold voltage to higher gate voltages and well-defined peaks were observed at the onset of the conductance. The energetic position as well as the magnetic-field-induced shift of the peaks confirm that electron transport through the $p$ shell of a single InAs quantum dot (QD) is observed. Our experimental data are in excellent agreement with calculations based on a simple parabolic quantum dot potential. A Coulomb blockade energy of $\approx 12 \text{ meV}$ is determined for electrons in the first excited QD state.
Schmidt et. al.
Various samples:

- **A**
- **B** point contact
- **C** point contact
- **D** point contact
- **E**
- **F** point contact

\[
\begin{align*}
\text{n} &= 5 \times 10^{11} \text{cm}^{-2}, \mu = 1.5 \times 10^{3} \text{cm}^{2}/\text{Vs} \\
\text{dot density} &\approx 10^{10} \text{cm}^{-2}
\end{align*}
\]

\[
\begin{align*}
\text{n} &= 3 \times 10^{11} \text{cm}^{-2}, \mu = 1.5 \times 10^{3} \text{cm}^{2}/\text{Vs} \\
\text{dot density} &\approx 10^{10} \text{cm}^{-2}
\end{align*}
\]

\[
\begin{align*}
\text{n} &= 3 \times 10^{11} \text{cm}^{-2}, \mu = 1 \times 10^{5} \text{cm}^{2}/\text{Vs}
\end{align*}
\]
Schmidt et. al.
Schmidt et. al.
Result Summary

- Transport through single dot
  - Low mobility sample
  - Random positioning
- Coulomb peaks due to tunneling through p-states
- Zeeman splitting also observed
Our Project
Own Experiment

- Coupling individual InAs QDs to a 2DEG
- Primary difference: choose precisely one single dot
- Gate dot and 2DEG individually (as much as possible)
Own Experiment
Own Experiment

- Single dot?
  - Dot gradient on the wafer
  - Optically detectable (Photoluminescence)
  - Buried dots also visible on AFM images, if surface is clean
  - Coordinates relative to a marker grid can be assigned
Own Experiment

- 2DEG characterization (Hallbar setup)

- Density and mobility at 20 mK
  - \( n = 1.1 \times 10^{11} \text{ cm}^{-2} \) \( (R_H = 5800 \text{ Ohm/T}) \)
  - \( \mu = 1.4 \times 10^6 \text{ cm}^2/\text{Vs} \) \( (\rho_{xx} = 40 \text{ Ohm}) \)

- Mobility larger by a factor of 10 (in sample without dots)!
Outlook

- Charge Sensing
- Real time tunneling
- $T_1$
- Effective g-factor
- ...
- Couple lateral and self-assembled quantum dot
So far transport experiments were done mostly on InAs QD ensembles, although single dots have also been investigated:
- Density and mobility of 2DEG are affected
- Shell structure and charging energies in agreement with calculated values

Coupling of individual dot to 2DEG still not done yet!
Thanks for your attention

More questions?