

Magneto-spectroscopy of hole levels in InAs quantum dots

D. Reuter^{*†}, U. Zeitler^{*}, J. C. Maan^{*} and A. D. Wieck[†]

^{*}High Field Magnet Laboratory, NSRIM, University of Nijmegen,
Toernooiveld 7, 6525 ED, Nijmegen, the Netherlands

[†]Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum,
Universitätsstraße 150, 44780 Bochum, Germany

Abstract. We have performed capacitance-voltage-spectroscopy experiments of the hole states in InAs quantum dots for magnetic fields up to 32 T. From the field dependence of the charging peaks we conclude that the *p*-shell and the *d*-shell of the single-particle states are filled with up to four electrons with the same spin j_z . Only when the *d*-shell is half filled, occupation of the energetically lower lying single-particle *p*-states with opposite j_z starts.

Semiconductor quantum dots occupied by only few charge carriers are often referred to as artificial atoms [1]. The possibility of filling them with one by one particle opens the unique opportunity to study and understand electron-electron correlation effects on a few-particle scale. Self-assembled InAs quantum dots (QDs) form one of the prominent systems for this type of investigations [2]. In particular, capacitance-voltage (*C-V*) spectroscopy of electrons in InAs QDs allowed a closer insight into their energy-level structure and the electron-electron interaction inside the dots [3, 4, 5].

In this work we will report on our observation of a non-sequential shell filling of hole states in InAs QDs measured by means of capacitance spectroscopy in high magnetic fields up to 32 T. The results will be explained by the dominating role of interaction effects for strongly confined holes in InAs QDs.

Our samples, sketched in the insert of Fig. 1, consist of self-assembled InAs quantum dots embedded in GaAs. On the back-side of the structure, 17 nm away from the dots, a *p*-doped back gate was grown; the top is covered by a 3 nm AlAs/1 nm GaAs superlattice (27 periods), a 10 nm thick GaAs cap layer and a metallic Cr/Au Schottky gate. By applying a bias between the top gate and the back gate the energy levels of the hole states in the InAs QDs can be aligned with the Fermi energy of the *p*-doped back contact. This leads to a charging of the dots through the 17 nm tunnelling barrier measured as a change of the capacitance of the Schottky diode.

In Fig. 1 the *C-V* spectrum of our InAs QD hole system is shown. On the bottom *x*-axis the voltage applied to the Schottky diode was converted to an energy following the procedure outlined in [6]; the energies are normalized to the GaAs valence-band edge. Charging of the

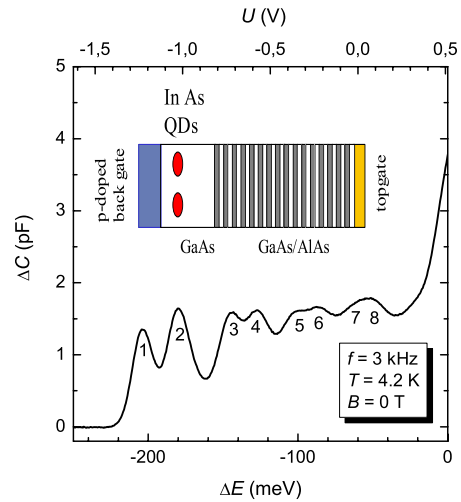


FIGURE 1. Capacitance-voltage spectrum for the hole system in InAs quantum dots at zero magnetic field. A linear background capacitance of the diode and the wires has been subtracted. The numbers denote energetic positions where the dots are charged with an additional hole.

Inset: Sketch of the sample structure.

dots with up to eight electrons is observed as peaks in the capacitance. For the first six electrons the Coulomb blockade is resolved.

In order to clarify the nature of the multi-hole QD states we have extended our *C-V* experiments to high magnetic fields (oriented along the growth direction). As plotted in Fig. 2, the peak positions of the states labelled

"1" to "6" in Fig. 1 display distinct differences in their field dependence.

The first two peaks merely shift with magnetic field. It is therefore reasonable to assign them an s -type character with no angular momentum. Their energetic separation, $\Delta E = 24$ meV, can be identified as the Coulomb energy of the ground state occupied with two holes of opposite spin $j_z = \pm 3/2$.

The following two peaks, labelled "3" and "4" show a linear shift with opposite directions for fields up to 15 T. We assign them to the filling of two p -type states with opposite angular momentum $l = \pm 1$ and the same spin $j_z = -3/2$. This non-sequential filling of the p -shell is a manifestation of Hund's rule known from atomic physics and the shell filling in lithographically defined QDs [1]. Such an uncomplete shell filling has not yet been observed in InAs QDs charged with electrons.

When a fifth and a sixth electron are filled into the QDs, one would expect a complete filling of the energetically lowest lying (single-particle) p -shell. Our experiments, however, rather suggest a filling of the higher d -shell before the p -shell is completed. We deduce this from the fact that the peak positions of peaks "5" and "6" approximately shift two times faster than peaks "3" and "4" for $B < 15$ T.

In this low-field region the resulting six-hole ground state is then $(s^\downarrow s^\uparrow p_-^\downarrow p_+^\downarrow d_-^\downarrow d_+^\downarrow)$, the subscripts denote the direction of the angular momentum, the superscripts indicate the spin orientation $j_z = \pm 3/2$. This state is nearly completely spin-polarized with respect to the Bloch character of the holes, i. e. for five out of six holes $j_z = -3/2$. To our knowledge it is indeed a quite unique feature of holes in InAs QDs that higher shells are filled prematurely. In contrast to our findings, the six *electron* ground state of lithographically defined QDs [1] as well as of InAs QDs [5] is unpolarized at zero magnetic field.

Around $B = 15$ T the energy levels of the multi-hole system cross. In particular, the d_- -state moves below the p_+ -level. Starting from the fourth electron, now first a d_- -state with $j_z = -3/2$ is filled, followed by a p_+ -state with $j_z = -3/2$ and again a d_- -state with opposite $j_z = +3/2$. The six-hole ground state in high magnetic fields, $(s^\downarrow s^\uparrow p_-^\downarrow d_-^\downarrow p_+^\downarrow d_+^\downarrow)$, has now a lower spin polarization as compared to the low field state $(s^\downarrow s^\uparrow p_-^\downarrow p_+^\downarrow d_-^\downarrow d_+^\downarrow)$. This a priori surprising result is explained straightforwardly by the dominance of orbital quantization in high magnetic fields.

Quantitatively, the field dependence of all the data presented above can be described within a Fock-Darwin model using one single effective hole mass $m_h^* = (0.31 \pm 0.03)m_e$. However, due to the relatively strong charging energy, the absolute values of the peak positions can not be predicted correctly in a simple harmonic oscillator model as used in [5].

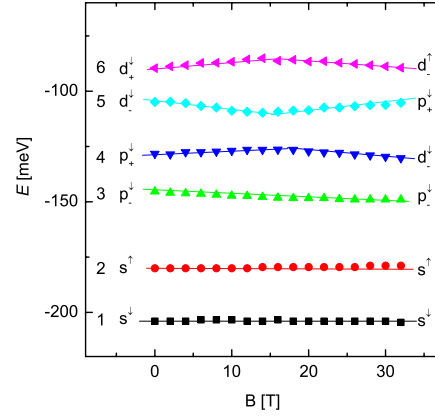


FIGURE 2. Positions of the peaks in the C - V spectrum for InAs QDs charged with up to six holes as a function of the magnetic field. The peaks are numbered according to Fig. 1 and labelled with the angular momentum state, l (subscript) and j_z superscript of the highest filled Fock-Darwin state. The lines serve as guide to the eye.

In summary, we find a pronounced non-sequential, incomplete shell filling of holes in InAs QDs, a behavior not present in the corresponding electron system. This results into a highly polarized six-hole ground state at low magnetic fields. We explain our findings by a strong Coulomb interaction in the InAs hole system, which exceeds the spacing between single-particle levels and favors incomplete shell filling.

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