

Hole and electron wave functions in self-assembled InAs quantum dots: a comparison

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We have investigated the conduction and the valence band states of self-assembled InAs quantum dots embedded in n- and p-type Schottky diodes, respectively, by magneto-capacitance voltage spectroscopy. The dispersion behaviour of the individual charging peaks in a perpendicular magnetic field shows qualitative differences between the two carrier types. By applying an in-plane magnetic field, the momentum space wave function corresponding to the individual charging peaks could be mapped. For electrons, the s-like wave function for the ground state is slightly asymmetric with the low energy direction along $[0\bar{1}1]$ in real space. Also the s-like wave function for the hole ground state is asymmetric but here the low energy direction is along $[011]$, i.e. orthogonal to that for electrons. This hints to an asymmetry in the confinement potential that is caused by piezoelectric effects.

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1 Introduction

Self-assembled InAs quantum dots (QDs) have been intensively studied in the past as model systems for strong three-dimensional carrier confinement [1]. Whereas the conduction band states have been intensively investigated, e.g., by capacitance–voltage (C–V) spectroscopy [2, 3], only very recently the hole charging spectra could be accessed with high resolution [4–6]. Compared to electrons, the charging peaks for holes show a significantly different dispersion behavior in perpendicular (parallel to the growth direction) magnetic field and, within a simple effective mass model, a charging sequence with an incomplete shell filling was proposed to explain the observed dispersion behavior [6]. Recent theoretical work [7, 8] discusses the use of the effective mass approximation for the hole system in InAs QDs critically and uses more sophisticated approaches to account for the experimental results given in [6].

By performing C–V spectroscopy at an appropriate ac-frequency and employing an in-plane magnetic field, one can map the in-plane momentum space wave function belonging to the corresponding charging peaks, which has been done recently for conduction band states [9, 10]. The wave functions for the individual charging peaks together with the dispersion in perpendicular magnetic field can be well explained by an effective mass approximation with an asymmetric harmonic confinement potential [3, 9, 10].

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In this paper, we will compare the charging spectra and the dispersion of the individual charging peaks in a perpendicular magnetic field for conduction and valence band states. Furthermore, the momentum space wave functions corresponding to the first charging peaks (ground state wave function) for electrons and holes will be presented. The paper is organized as follows: In Section 2 some experimental details are given before our results are presented and discussed in Section 3. Finally, we will give a brief summary in Section 4.

2 Experimental details

To investigate the conduction (valence) band states of InAs QDs, they were embedded in an n-type (p-type) Schottky diode grown with solid source molecular beam epitaxy: The active part of the structure has the following layer sequence: After growing either a n- or p-doped ($\sim 2 \times 10^{18} \text{ cm}^{-3}$) back contact, an undoped GaAs layer of thickness d , which serves as a tunneling barrier was deposited. The tunneling barrier was followed by a single layer InAs QDs. After the QDs, 30 nm GaAs and a 3 nm AlAs/1 nm GaAs superlattice were grown, followed by a 10 nm GaAs cap layer. The superlattice was approximately six-times (n-type samples) or ten times (p-type samples), respectively, thicker than the tunneling barrier. The InAs QDs were prepared by depositing a nominal coverage of 2.0 ML InAs at a substrate temperature of about 510 °C. We have grown two n-type samples ($d = 40 \text{ nm}$ and $d = 42.5 \text{ nm}$) as well as two p-type samples ($d = 17 \text{ nm}$ and $d = 19 \text{ nm}$). The ground state photoluminescence at 300 K for these four samples is observed at 1244 nm ($d = 19 \text{ nm}$), 1252 nm ($d = 42.5 \text{ nm}$), 1264 nm ($d = 17 \text{ nm}$), and 1276 nm ($d = 40 \text{ nm}$). The ground state emission of the samples is within 30 nm, which shows that the QD ensembles are quite similar. Also, there is no systematic difference in the emission wave length between n-type and p-type samples pointing to a difference between the corresponding QD ensembles. From these samples, Schottky diodes were prepared using Cr–Au gates. The C – V traces were recorded at 4.2 K with a standard LCR meter (Agilent 4284A).

As discussed by Wibbelhoff and co-workers [9, 10] adapting an argument given by Patané and co-workers [11] for tunneling spectroscopy to C – V spectroscopy, one can show that, for the appropriate measurement frequencies, the momentum space wave function is proportional to the height of the capacitance signal of the QDs and the following relation holds:

$$C(\mathbf{B}_{\parallel}) \sim |\phi_{\text{QD}}(\mathbf{k}_{\parallel})|^2 \quad \text{with} \quad k_{\parallel} = deB_{\parallel}/\hbar. \quad (1)$$

Here, d is the thickness of the tunneling barrier and B_{\parallel} is the in-plane magnetic field. By recording the height of the capacitance signal as a function of an in-plane magnetic field, one can map the in-plane momentum space probability distribution of the individual charging peaks. The appropriate measurement frequency is different for different charging peaks because the height of the tunneling barrier is different for the different charging peaks [9, 10, 12]. We have recorded C – V spectra for various in-plane magnetic fields at ac frequencies between 5 and 40 kHz. The field direction was changed by rotating the sample and then the field strength was varied for a fixed direction. From the C – V spectra, the height of the capacitive signal of the individual charging peaks was extracted by a fit procedure using Gaussian peak shapes. The values were then normalized to the height of the individual charging peak at $B = 0 \text{ T}$, converted to a grey-level scale, and plotted as function of (k_x, k_y) .

3 Results and discussion

Figure 1a shows a hole charging spectrum for InAs QDs without magnetic field. Six clearly resolved charging peaks and an additional broad one probably composed from two peaks are observed. By converting the gate voltage scale to an energy scale, employing a method described in [5], one can determine the energetic position for the first six charging peaks. In Fig. 1b, the shift of the peak position as function of a perpendicular magnetic field is shown for the individual charging peaks. For peaks h1 and h2 no shift is observed which is consistent with the charging of a twofold degenerated s-like ground state. This

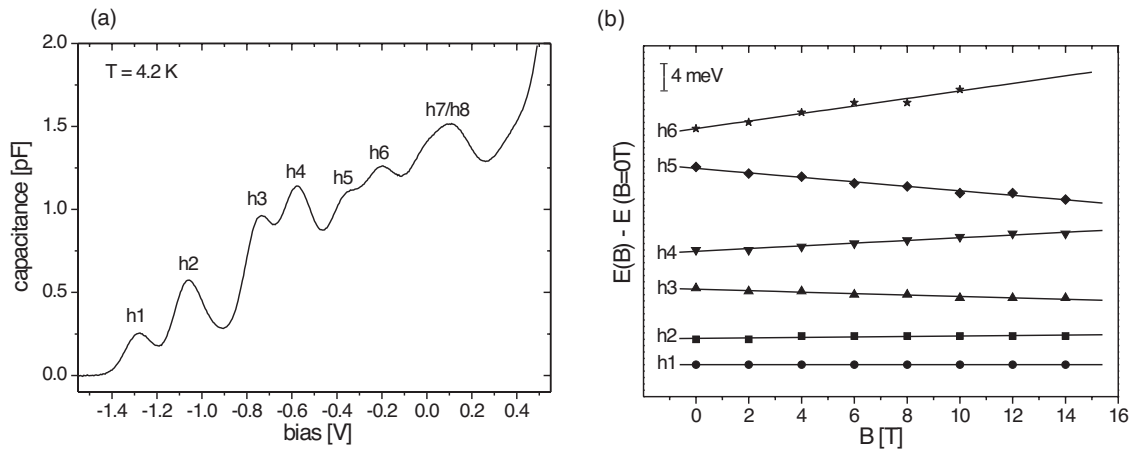


Fig. 1 a) Hole charging spectra for InAs QDs embedded in a p-type Schottky diode with $d = 19$ nm measured for $\sim 10^7$ QDs. The ac-frequency employed was 8 kHz and the amplitude 10 mV. The sign convention for the dc-bias is such that the metallic gate is grounded. A linear background capacitance was subtracted from the raw data. In b), the shift in the energetic position of the individual charging peaks with perpendicular magnetic field is depicted. The peak energy was extracted from a $C-V$ spectrum measured at the corresponding magnetic field converting the gate voltage scale to an energy scale.

is very similar to the results for electrons, where also no dispersion with magnetic field is observed for the first two charging peaks [13]. Peaks h3 to h6 shift downward and upward in energy in an alternating fashion. This points to the charging of excited states with finite orbital angular momentum. The dispersion behaviour for electron states is different [13]: Here peaks e3 and e4 shift downwards while peaks e5 and e6 shift upwards in energy. Extracting the Coulomb energy in the ground state from the energetic distance between the first two charging peaks one obtains slightly larger values for holes (~ 22 meV) than for electrons (~ 19 meV).

Figure 2 shows the momentum space wave function corresponding to the first charging peak for conduction band and valence band states. For both carrier types, a clear maximum of the signal at $k_{\parallel} = 0$ m $^{-1}$

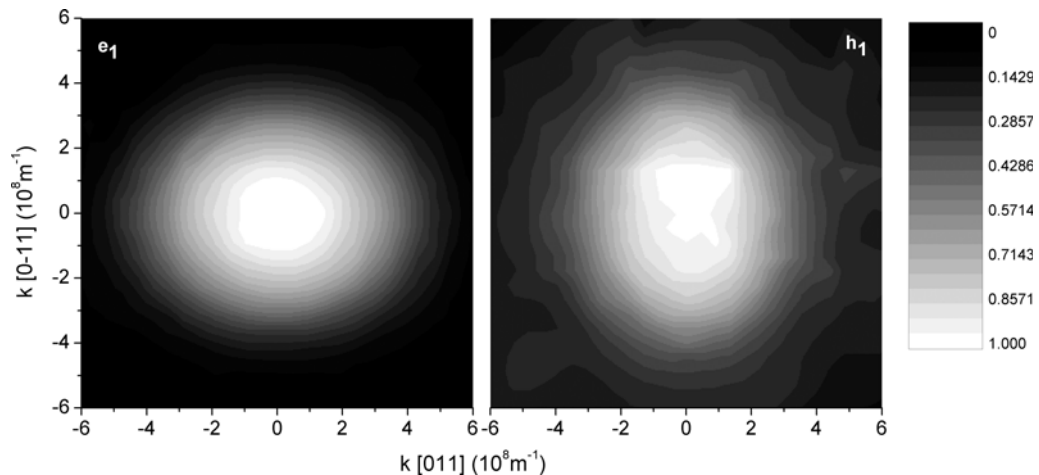


Fig. 2 Momentum space in-plane wave functions $|\phi_{\text{QD}}(k_x, k_y)|^2$ corresponding to the first electron (e1) and the first hole (h1) charging peak as measured by $C-V$ spectroscopy employing an in-plane magnetic field (see text for details). Please note that these are momentum space maps and that the low energy axis in real space is the short axis in momentum space.

and a monotonic decrease towards larger values of k_{\parallel} can be observed. This is the behaviour expected for a s-like ground state with no orbital angular momentum. The results from the wave function mapping agree with the dispersion behaviour for the electron as well as the hole ground state. For electrons as well as for holes one observes an asymmetric wave function shape, which hints to an asymmetric in-plane confinement potential. It is not too surprising that the wave functions are slightly asymmetric because a perfect circular dot shape seems not very probable taking the twofold symmetry of the GaAs(100) surface into account. However, it is intriguing that the low energy axis for electrons and holes are orthogonal to each other, namely $[0\bar{1}1]$ for electrons and $[011]$ for holes (real space). This can either mean that we have different shapes of the QDs with orthogonal long axis in n-type and p-type samples or that the asymmetry in the confinement is not purely due to an asymmetry in shape. As discussed already in Section 2, we believe that the QDs in all four samples are quite similar. This is also supported by the fact that we have observed identical asymmetries for the two different samples of each carrier type investigated. We propose that the orthogonal asymmetries for electrons and holes are caused by a piezoelectric contribution to the confinement potential. This effect was investigated theoretically by Stier and co-workers [14] for pyramidal InAs QDs and they have found an orthogonal alignment of electron and hole wave functions for their QD shape. The geometry of our QDs is most probably not pyramidal but piezoelectric contributions to the confinement potential may qualitatively account for our observations.

4 Summary

The comparison of the charging spectra for conduction and valence band states of self-assembled InAs QDs reveals similarities but also significant differences:

- (i) The first two charging peaks belong for both carrier types to an s-like ground state.
- (ii) For electrons, peaks e3 and e4 shift both to lower energies with a perpendicular magnetic field, whereas for holes, peaks h3 and h4 shift in opposite directions.
- (iii) For electrons as well as for holes, the ground state wave function is asymmetric. However, for the two carrier types, the low energy axes are orthogonal to each other. We attribute this behaviour to a significant piezoelectric contribution in the lateral confinement potential.

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