

Mapping of the hole wave functions of self-assembled InAs-quantum dots by magneto-capacitance–voltage spectroscopy

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Abstract

We have performed magneto-capacitance–voltage spectroscopy for the valence band states of InAs quantum dots embedded in a p-type Schottky diode. By choosing the right measurement frequency and applying an in-plane magnetic field, we were able to map the k -space wave functions corresponding to the individual charging peaks. The wave functions belonging to the first two charging peaks show no nodes as expected for an s-like ground state. In contrast, nodes are observed for the next four charging peaks supporting the identification as excited states with finite orbital angular momentum. Peaks 3 and 4 show different wave functions compared to peaks 5 and 6, which points to different angular momenta for this two pairs of charging peaks.

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1. Introduction

Self-assembled InAs quantum dots (QDs) have been intensively studied in the past [1]. Whereas the investigations have mainly concentrated on the conduction band states, 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]. A unique incomplete shell filling violating the aufbau principle was observed by capacitance–voltage spectroscopy in perpendicular (parallel to the growth direction) magnetic field [6]. Whereas the electron addition spectra for InAs QDs can be described quite well by assuming a harmonic confinement potential and employing perturbation theory [3], the hole system is expected to require a more sophisticated approach [7] due to the more complicated structure of the valence band.

It was shown that tunneling [8,9] as well as C – V spectroscopy [10,15] in parallel (perpendicular to the

growth direction) magnetic fields allow to map the squared k -space wave functions corresponding to individual conductance/charging peaks. The situation is more complicated when analyzing charging spectra because strictly speaking differences between two many-particle wave functions are recorded [13]. Calculations by Rontani and Molinari showed that for systems with large quantization energies, as electrons and holes in InAs QDs, the measured probability distribution should reflect the single-particle wave functions. Wave functions in InAs QDs have so far only been investigated for conduction band states [8–10]. It was observed that the wave functions are quite well described by the eigenfunctions of a two-dimensional harmonic oscillator. In this paper we present maps of the square of the k -space hole wave functions of InAs QDs obtained by magneto-capacitance–voltage spectroscopy.

2. Experimental details

The sample was grown with solid source molecular beam epitaxy. The active part of the structure had the following

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layer sequence: after growing a p-doped ($2 \times 10^{18} \text{ cm}^{-3}$) back contact, followed by 19 nm undoped GaAs as tunneling barrier, the QD layer was prepared. After the QDs, 30 nm GaAs and 32 periods of a 3 nm AlAs/1 nm GaAs superlattice were grown, followed by a 10 nm GaAs cap layer. The InAs QDs were prepared by depositing a nominal coverage of 2.0 ML InAs at a substrate temperature of 510 °C. The ground state photoluminescence for these samples is between 1250 and 1270 nm at 300 K. 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).

For C – V spectroscopy a small AC-bias is superimposed on a DC-bias applied between gate and back contact. By tuning the DC-bias the energy levels of the QDs can be shifted with respect to the Fermi energy μ_{bc} in the back contact. When an energy level of the QD is in resonance with μ_{bc} , the carriers can tunnel between back contact and the QD and the QD ensemble is periodically charged by the small AC-component. This charging current is detected as an increase in the differential capacitance when sweeping the DC-bias [2]. The height of the charging signal from the QDs in the capacitance is independent of the AC-frequency as long as the frequency is much smaller than the tunneling rate. When the frequency is increased, the QDs are no longer charged during every cycle and the height of the charging signal becomes sensitive to the tunneling rate. The frequency dependence is not the same for all charging peaks, because high-energy levels face a lower tunneling barrier, i.e., higher frequencies are needed to suppress charging [12]. As Luyken and coworkers [12] have shown, the height of the capacitive signal from the QDs is roughly proportional to the tunneling rate, if the measurement frequency is chosen such that the signal has decreased approximately to half the low frequency value. If performing C – V spectroscopy with an applied in-plane magnetic field B , an additional in-plane momentum k_{\parallel} is perpendicular to the tunneling direction as well as to B . Its absolute value is given by

$$k_{\parallel} = \frac{deB}{\hbar}, \quad (1)$$

where d is the tunneling distance. It can be shown that the tunneling rate between the back contact and the QDs is proportional to the square of the QD wave function in k -space $|\phi(k_{\parallel})|^2$ [9]. Thus, by measuring the capacitance signal of the individual charging peaks, which is proportional to the tunneling rate, as a function of an in-plane magnetic field one can map $|\phi(k_{\parallel})|^2$ for the individual charging peaks.

To map the first two charging peaks, a frequency of 8 kHz was chosen whereas for peaks 3–6 $f = 40 \text{ kHz}$ was employed. The AC-amplitude was 10 mV and the magnetic field was applied along the high symmetry directions of the (100) GaAs surface ([0 1 1] and [0 $\bar{1}$ 1]).

3. Results

Fig. 1 shows the differential capacitance as a function of the gate voltage for several magnetic fields. The first six charging peaks can be clearly identified. Based on the dispersion of these peaks in a perpendicular magnetic field, one can assign the first two peaks to charging into the s-like ground state, peaks 3 and 4 to charging of p-like states, and 5 and 6 correspond to d-like levels [6]. This means, that the p-like levels, which can be occupied by four holes, are not completely filled before the d-shell is filled, i.e., the aufbau principle found for electrons is violated here.

The dependence on an in-plane magnetic field is different for the individual charging peaks (see Fig. 1). For peaks 1 and 2, the peak height decreases monotonically, whereas for peaks 3–6 a non-monotonic behavior is observed. This is consistent with the assignment given above: For a more detailed analysis, the height of the capacitance signal is normalized with respect to the value at $B = 0$ and plotted versus the magnetic field for B along the two principal axes and all the six individual peaks. These data are shown in Fig. 2 and are discussed in the following.

For peaks 1 and 2, one observes for both directions a monotonic decrease of the signal with increasing magnetic field. This is expected for an s-like ground state with no orbital angular momentum. The shape of the charging peaks can be approximated by a Gaussian but around $B = 0 \text{ T}$ the trace is flattened. Both peaks are more extended along the [0 1 1] direction, which points to an asymmetry of the confining potential. A reason for this asymmetry might be the piezoelectric potential induced by the strain [11], possibly in combination with a slight elongation of the dots along one crystal axis. Furthermore, the second charging peak is found to be more extended than the first one in momentum space, i.e., has a smaller extension in real space. This is also observed for the electron system on similar

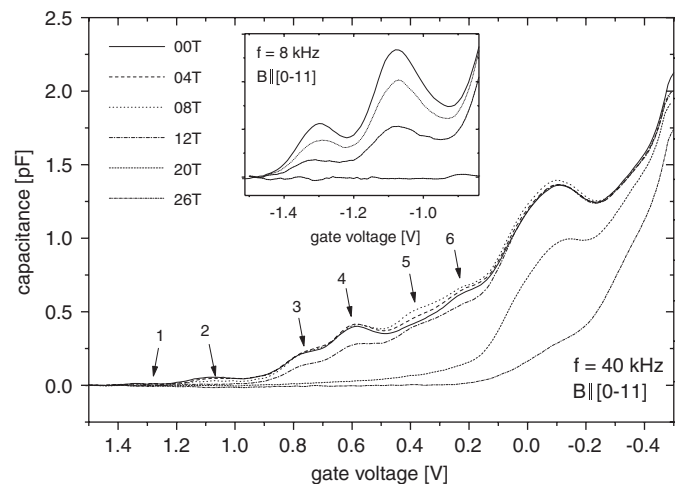


Fig. 1. C – V traces for different in-plane magnetic fields. A linear background was subtracted. For an AC-frequency $f = 40 \text{ kHz}$ the first two charging peaks are almost completely suppressed. The insert shows the first two charging peaks at an AC-frequency of $f = 8 \text{ kHz}$.

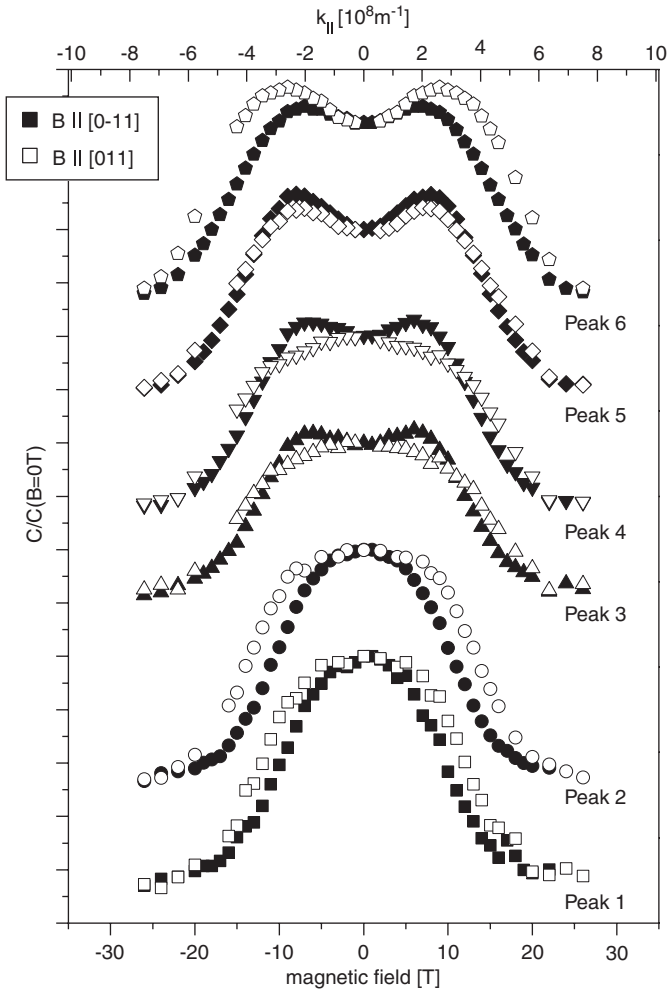


Fig. 2. Normalized capacitance $C/C(B=0\text{T})$ of the six charging peaks for different field orientations along the principal axes of the GaAs (100) surface. Filled symbols indicate a field $B\parallel[0\bar{1}1]$ and empty symbols a field $B\parallel[011]$. Different peaks are shifted for clarity. The upper scale shows the momentum k_{\parallel} corresponding to the applied field. Note, that k_{\parallel} is perpendicular to B .

quantum dots [15], and might be due to the fact that the second charging state corresponds to a completely filled shell, which might have a smaller radius than a singly occupied level.

As can be seen in Fig. 2, the capacitance signal belonging to the peaks 3–6 show a non-monotonic behavior with a node-like structure for $B=0\text{T}$. This is consistent with the wave functions of excited states with finite orbital angular momentum. The signals look similar for the pairs 3,4 and 5,6, which supports the assignment given above: 3,4 belong to p-like and 5,6 belong to d-like states. This is also consistent with the fact that the maxima for 5,6 are at larger values for B than for 3,4, because a maximum at larger momentum values can be expected for a larger orbital angular momentum.

Peaks 3 and 4 show a significant anisotropy with the same preferential axis as the ground state. It is surprising that the symmetry for the charging peaks 3 and 4 is identical. From a simple shell filling model it is expected

(and found experimentally for electrons [15]) that the two different p-orbitals have orthogonal symmetry. A possible explanation is proposed by He and co-workers [14] based on an atomistic model: peaks 3 and 4 belong to charging into the same orbital state which would explain that both wave functions look very similar. A detailed calculation has to show if the theory can also reproduce the energy dispersion of the charging peaks with perpendicular magnetic field. For the peaks 5 and 6 basically the same as discussed above holds. However, one can see a difference between the two charging peaks. Whereas peak 5 shows almost circular symmetry, peak 6 is asymmetric with the maximum extension along $[0\bar{1}1]$ (opposite to peaks 1 to 4).

Looking at the single-particle wave functions, either calculated for a two-dimensional harmonic potential or with more sophisticated methods, one finds that the excited states have a node at $B=0\text{T}$. Therefore, one should expect that the signal drops to zero for $B=0\text{T}$, which is not observed in our experiments. This finite tunneling probability is also observed for experiments with electrons [10,15] and the reason is not clear so far. From theoretical considerations [13], one can expect to measure probability distributions that reflect the single-particle wave functions although measuring the addition spectra. One reason might be that not only holes from the back contact with $k_{\parallel}=0$ contribute to the tunneling current as assumed in Ref. [9]. This would smear out the wave functions.

4. Summary

We have successfully mapped the hole wave functions in k -space by magneto- $C-V$ spectroscopy of InAs QDs. It could be verified that the first two charging peaks belong to an s-like ground state. The peaks 3 to 6 show maxima for finite values for B identifying them as excited states with finite orbital angular momentum.

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