Capacitance-voltage spectroscopy on InAs quantum dot valence band states in tilted magnetic fields

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Abstract. We have performed capacitance-voltage (C-V) spectroscopy on the valence band states of InAs quantum dots (QDs) in magnetic fields tilted with respect to the sample plane. We observe an unexpected behaviour for the height of the capacitance signal as function of the in-plane magnetic field, when varying the perpendicular field component, for the first two charging peaks corresponding both to an s-like ground state. With increasing perpendicular field component, the signal height for the first peak decreases strongly and for the second peak the maximum signal height is observed at finite in-plane field values. These observations are not in agreement with the usual assumption that the height-vs.-in-plane-field traces reflect the in-plane k-space probability distribution of the charged QD level because an s-like state should not vary its general shape with perpendicular field. The qualitatively different behaviour of the two peaks is attributed tentatively to correlation effects when the second electron is charged.

1. Introduction
InAs quantum dots (QDs) have been intensively studied in the past decades because they are model systems for strong three-dimensional carrier confinement as well as building blocks for novel optoelectronic devices, e.g. for quantum information technology [1]. One point of interest is the carrier-carrier interaction in QDs, which have been intensively studied by charging spectroscopy employing capacitance-voltage (C-V) measurements [2,3]. Extending the capabilities of C-V spectroscopy, it was recently possible to map the in-plane k-space probability distribution corresponding to the individual charging peaks for conduction as well as valence band states of InAs QDs [4,5]. In these experiments, based on an approach of Patanè and co-workers for magneto-tunneling spectroscopy [6], C-V measurements at certain frequencies (for which the charging dynamics becomes relevant) were employed and the k-space mapping was realized by a variable in-plane magnetic field.

In this paper, we present C-V experiments on the valence band states of InAs QDs in tilted magnetic fields intended to take the wave function mapping one step further. The idea of the work was to manipulate the wave function by the perpendicular component of the magnetic field and to map the altered probability distribution by the in-plane field component. We will see that this straightforward interpretation is not sufficient to explain our experimental finding.

2. Experimental Details
The InAs QD samples were prepared by solid source molecular beam epitaxy on a GaAs(100) substrate. The active part of the layer sequence consists of a 300 nm thick, carbon doped (3×10^{18} cm^{-3}) GaAs back-contact, a 19 nm thick GaAs tunnelling barrier, an InAs QD layer, 30 nm GaAs and 32 periods of a (3 nm AlAs)/(1 nm GaAs) superlattice, followed by a 10 nm thick 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 sample was mounted on a rotatable holder so that, for a fixed spatial B-field direction, the B-field orientation with respect to the sample could be varied from in the sample plane (in-plane field) to perpendicular to the sample plane (perpendicular field). The samples could be mounted in two orientations so that the in-plane component of the field is either along the [0-11] or the [011] surface direction. In the experiments, the absolute value of the magnetic field B and the tilt angle \( \alpha \) (see Fig. 1 for a sketch of the geometry) were changed simultaneously so that the perpendicular component stayed constant and the in-plane component was varied. For each configuration a C-V measurement was performed at 8 kHz for the first two charging peaks (see Fig. 2 for the peak labeling).

The height of the charging peaks, which should be for an appropriate measurement frequency approximately proportional to the tunneling rate [4,5,7], was determined by subtracting first a background due to the capacitance of the Schottky diode and then fitting Gaussians to the individual charging peaks. The heights of the capacitance signal were normalized to their corresponding values in the absence of the magnetic field and plotted as a function of the in-plane field for various values of the perpendicular component.
3. Results and Discussion

Fig. 2 shows the first two charging peaks for various in-plane magnetic fields oriented along [011]. Dispersion measurements supported the assignment that these two peaks belong to the charging of a two-fold degenerated s-like ground state [3,5]. For \( B_{\perp} = 0 \) T (Fig. 2a), the height of the capacitance signal decreases monotonically with increasing in-plane field as reported before [5] and expected for an s-like ground state. For \( B_{\perp} = 18 \) T (Fig. 2b), the situation has changed: The height of the capacitance signal in general has decreased significantly for both peaks, which indicates that the perpendicular field hampers somehow the tunnelling into the ground state. The most significant change occurs for peak 2, whose maximum value is not measured for zero in-plane field, but for fields around 12 T, which is totally unexpected for tunnelling into an s-like ground state.

To display the changes induced by the magnetic field in more detail, Fig. 3 shows the normalized height of the capacitance signal as function of the in-plane field for various values of \( B_{\perp} \) for the first two charging peaks. At \( B_{\perp} = 0 \) T, for both peaks and both high symmetry directions a bell-like shape with a maximum at \( B_{\parallel} = 0 \) T is observed. This is expected for an s-like ground state under the assumption that the normalized height of the capacitance signal reflects quite well the in-plane k-space probability distribution of the charged energy level [4,5]. The extension in k-space is different for the two high symmetry directions pointing to an elliptically shaped QD as discussed in detail in [5].

![Figure 3: Normalized height of the capacitance signal for the first two charging peaks as function of the in-plane magnetic field component for various values of \( B_{\perp} \). The orientation of the in-plane component is indicated in the panels. The trace for negative in-plane fields was generated by mirroring the values measured for positive in-plane fields.](image-url)
If $B_\perp$ is increased up to 12 T, the bell shape is nearly conserved for peak 1 but the maximum height decreases monotonically. For $B_\perp = 18$ T almost a plateau is observed between -10 T and 10 T (see Fig. 3a and 3b). The area under the trace decreases significantly with increasing $B_\perp$. This is surprising and not understandable with the interpretation that the trace reflects the in-plane probability distribution, because then the area under the trace should stay constant. It seems that the perpendicular field alters the tunnelling rate beyond changing the QD wave functions.

For charging peak 2, the changes induced by the perpendicular field are even more drastic (see Fig. 3c and d). For $B_\perp = 8$ T and higher, a dip at $B_\parallel = 0$ T develops and the largest signal height is found around $\pm 10$ T. This shape becomes more pronounced with increasing $B_\perp$ and for $18$ T the signal in the maximum is approximately a factor 2 higher than at $B_\parallel = 0$ T. The development of the bone-like structure with increasing $B_\perp$ cannot be understood with the simple assumption that the perpendicular field component modifies the k-space probability distribution and the parallel field component is just used to map it because an s-like ground state wave function is expected to retain its bell-like shape under the influence of a perpendicular magnetic field.

The results are quite surprising and difficult to interpret but two remarks can be made:

a) Although the signal height is determined by fitting, the first two charging peaks are well resolved and the non-monotonic bone-like shape for peak 2 can be directly seen in the C-V traces (see Fig. 2). Therefore, we are quite sure that this shape is not a fitting artefact.

b) It is interesting that the two charging peaks show significantly different behaviour, although both arise from tunnelling into the same state. This means that the observations for peak 2 are connected to correlation effects between the two holes in the QD.

In our opinion, to understand the experimental observations, it is necessary to perform calculations of the tunnelling probability taking into account the influence of the field on the whole heterostructure, especially the p-doped back-contact. A chirality induced here by $B_\perp$ might be reflected in the measured tunnelling probabilities.

4. **Summary**

We have investigated the tunnelling dynamics into InAs QDs under the influence of a tilted B-field by employing C-V spectroscopy. For the first charging peak the tunnelling probability decreases monotonically with increasing in-plane field component, resulting in a bell-shaped trace. This holds for perpendicular fields up to 18 T, but the area under the trace decreases significantly with increasing $B_\perp$. For the second peak, the bell-like trace at $B_\perp = 0$ T is transformed to a bone-like shape for increasing $B_\perp$. This behaviour cannot be explained by simply assuming that the tunnelling probability reflects only the in-plane k-space probability distribution for the corresponding energy level, because for an s-like ground state a bell-like trace should be observed even under perpendicular B-field.

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