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Magnetic-field-induced modification of the wave-functions in InAs quantum dots

W. Lei[a,c], O. Wibbelhoff[a], C. Notthoff[a], B. Marquardt[a], D. Reuter[b], A.D. Wieck[b], A. Lorke[a,*]

[a]*Fachbereich Physik and CeNIDE, Universität Duisburg-Essen, Lotharstr. 1, 47048 Duisburg, Germany*
[b]*Fakultät für Physik, Ruhr-Universität Bochum, Universitätsstr. 150, 44780 Bochum, Germany*
[c]*Department of Electronic Materials Engineering, Australian National University, ACT 0200, Australia*

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Abstract

The probability density of electrons in self-assembled InAs quantum dots is investigated by tunneling magnetocapacitance–voltage spectroscopy. A magnetic field in the plane of the tunneling layer is used to shift the momentum of the electrons tunneling into the dots and this way map the wave functions in k-space. When an additional perpendicular magnetic field is applied, a clear modification of the shape of the "p-state" wave functions is observed. In particular, the p^+-state changes from x, y-symmetry with a node along one crystal orientation to an almost circularly symmetric shape when the perpendicular magnetic field is increased from 0 to 9 T.

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The wave function of a particle can be considered the most fundamental manifestation of its quantum nature. Imaging the wave functions (or rather the probability density, given by the square modulus of the wave function) therefore gives valuable insight into the quantum structure of confined particles. Only few imaging techniques are available, however. The most common technique uses scanning tunneling microscopy. The local tunneling current is given by the overlap of the tip and sample wave functions, and thus reflects the local probability density of the quantum state in the sample [1,2]. A complementary approach was developed by Vdovin et al. [3], where wave functions are not probed by scanning a local emitter in real space but rather by scanning the *momentum* of tunneling carriers through a magnetic field perpendicular to the tunneling direction. This technique was successfully used to map the wave functions in self-assembled InAs quantum dots, embedded in a tunneling diode structure [3]. Recently, magneto-capacitance–voltage (MCV) spectroscopy, which records the ac tunneling current, was found to be a valuable tool to image the many-particle states of electrons and holes in self-assembled InAs dots [4–6].

In the present investigation, we will show that MCV spectroscopy not only allows us to *image* the wave functions in InAs dots. By tilting the magnetic field, we can *modify* the probability density and monitor the resulting shape change in situ.

The investigated samples are GaAs-$Al_xGa_{1-x}As$ MIS-FET-structures [7], grown by molecular beam epitaxy, with a layer structure as described in Wibbelhoff et al. [4]. The InAs dots, which are fabricated by the well-established Stranskii–Krastanov growth technique, are separated from the highly Si-doped back contact by a GaAs tunneling layer of thickness $d_z = 40\,\mathrm{nm}$. Schottky diodes are prepared by alloying ohmic contacts and depositing NiCr top gates, and the MCV spectra are recorded by standard lock-in technique. The frequency is appropriately chosen so that the capacitance amplitude reflects the tunneling rate [8].

Let us define the tunneling direction as the z-axis and the plane of the dots as (x, y). When a magnetic field is applied along x, the Lorentz force will shift the momentum of a tunneling electron by an amount $\Delta k_y = d_z e B_x/\hbar$ [3]. Thus,

*Corresponding author.
E-mail address: Axel.Lorke@Uni-DuE.de (A. Lorke).

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by systematically recording the amplitude of the MCV signal as a function of gate voltage and in-plane magnetic field (B_x, B_y), the shape of the wave functions for different occupation numbers $n = 1 \ldots 6$ can be mapped in momentum space.

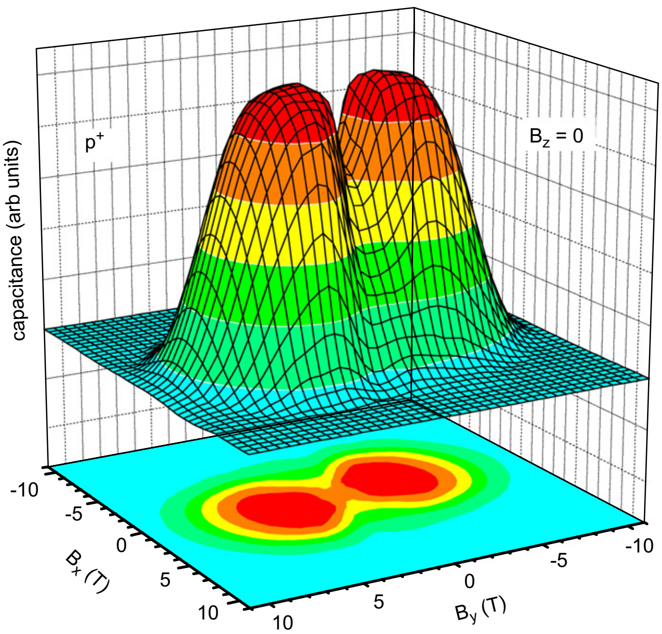

Fig. 1. (Color online) Amplitude of the MCV charging peak of the p^+-state as a function of in-plane magnetic field (B_x, B_y). The recorded signal is a representation of the electronic probability density. For details, see text.

Fig. 1 shows the results of the MCV spectroscopy for the p^+-state, i.e. the state, which becomes occupied by the fifth and sixth electron (the first and second electron occupy the s-state, the third and forth the p^--state). It can clearly be seen that the p^+-state exhibits a node along B_y, which can be attributed to a structural or crystal anisotropy of the confining InAs quantum dot [9,10].

To further illustrate this, Fig. 2 shows calculated wavefunctions (in real space) of an elliptical dot with a confining potential $V(x,y) = \frac{1}{2}m^*\omega_0^2(0.9x^2 + 1.1y^2)$ with $\hbar\omega_0 = 50\,\text{meV}$ [10,11]. The upper panels depict the probability density at $B_z = 0$, corresponding to the experimental situation in Fig. 1. Here, the lower, p^--state is oriented along the x-direction, the higher p^+-state has a node along the y-direction. When a perpendicular field is applied, the Hamiltonian no longer separates in x, y-coordinates, and the p^x and p^y-states begin to mix. Loosely speaking, the magnetic forces impose a stronger and stronger circular symmetry onto the quantum dot states, and at infinite magnetic fields both p-states will exhibit circular (ring) symmetry. At intermediate fields, the states will have partly ring shape, but with maxima along the rim, which are remnants of the original elliptical symmetry. This situation is depicted in the lower panels of Fig. 2.

To experimentally demonstrate the modification of wave functions by magnetic-field-induced mixing of states, we

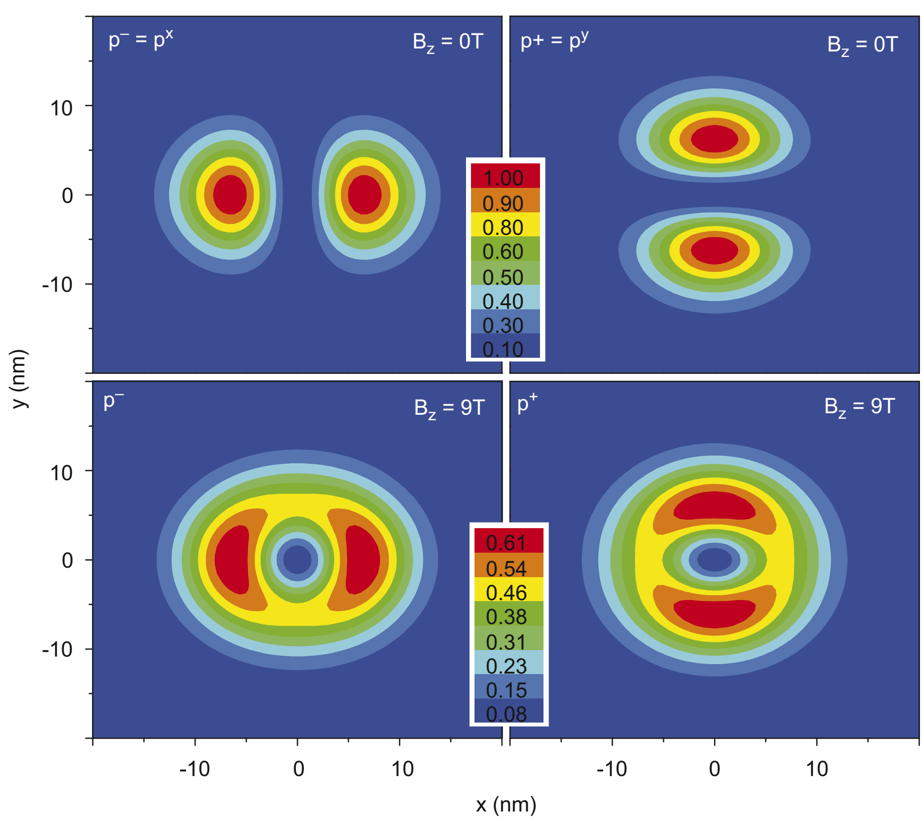

Fig. 2. (Color online) Top: calculated probability densities of the p-states in an anisotropic, parabolic confining potential $V(x, y)$. When a magnetic field is applied in the z-direction, state mixing occurs and the hybrid wave functions develop towards circular symmetry (bottom).

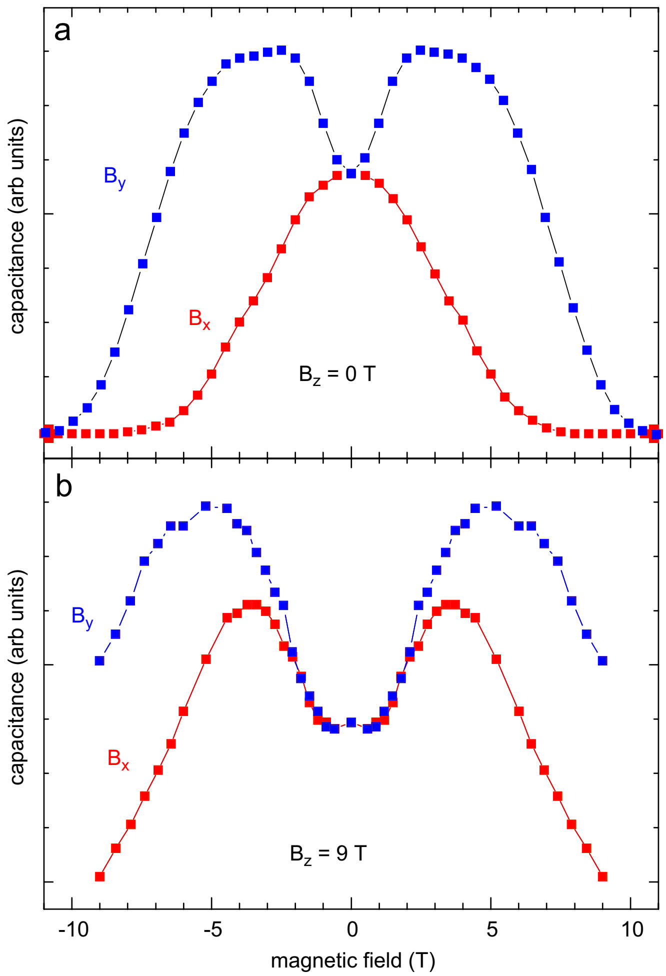

Fig. 3. (Color online) (a) Capacitance signal as a function of B_x and B_y, showing the anisotropy of the wave function, with a node in just one direction. (b) Influence of an additional magnetic field $B_z = 9\,\text{T}$. Note how in comparison to (a), the wave function develops a more isotropic geometry.

use a sample holder with *in situ* adjustable azimuth and polar angle. Similar to the measurement discussed above (see Fig. 1), we record the MCV tunneling current as a function of in-plane magnetic field, however, with an additional, constant magnetic field along the z-direction. Fig. 3 gives a comparison between the data recorded at $B_z = 0$ and $B_z = 9\,\text{T}$. Here we focus on the two major axes of symmetry (x, y), which give all essential properties of the mixing of the wave functions. Fig. 3(a), which represents sections along the B_x and B_y-directions in Fig. 1, clearly shows that the wave function at $B_z = 0$ only exhibits a node along the B_y-direction and a monotonic decrease along B_x. This changes when the perpendicular field is applied. As seen in Fig. 3(b), at $B_z = 9\,\text{T}$, the wave function exhibits a clear minimum also along the B_x-direction. The two lobes that develop are somewhat less pronounced than those along B_y. In Fig. 3(b), the magnetic field is not sufficient to map the tails of the wave function, which indicates a larger extent of the wave function in k-space. We attribute this to the fact that the perpendicular magnetic field results in sharper features of the wave functions in real space and thus a wider spread in momentum space (see, e.g., the sharpness of the peaks in Fig. 2, top and bottom).

These observations are in good qualitative agreement with the model calculations and show that we have indeed modified the shape of the p^+-state in self-assembled InAs quantum dots by magnetic forces.

Care has to be taken when comparing the data in Figs. 2 and 3, since the former is in real space and the latter in k-space. However, when going from real to momentum space (corresponding to a Fourier transformation) qualitative features like the presence or absence of nodes and lobes remain unchanged. This is particularly true in a harmonic oscillator, where the quantum states are given by the same set of Hermite polynomials in both real and momentum representation. Also, we would like to point out that the relation $\Delta k_{x,y} = d_z e B_{y,x}/\hbar$ [3] has been derived for purely in-plane magnetic fields. A full treatment of the tunneling dynamics in the presence of an oblique magnetic field, however, is beyond the scope of this work. Finally, we would like to mention that the spectroscopy of the p^--state (not shown here) also shows a transformation from x, y to circular symmetry with increasing B_z. Here, however, the minimum in the center vanishes and the overall shape becomes almost s-like. This behavior is not understood at present and will be the subject of more detailed future studies.

In summary, we have mapped out the probability density of the p^+-state (occupied by the fifth and sixth electron) in self-assembled InAs quantum dots by MCV spectroscopy. We find that a magnetic field component perpendicular to the plane of the dots will change the shape of the wave function from x, y towards circular symmetry. To the best of our knowledge, this is the first demonstration of quantum state manipulation monitored by in situ wave function mapping.

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