Spin effects in InAs quantum dots: Tunneling experiments in tilted magnetic fields

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Abstract The Landé factor g^* of individual InAs quantum dots is measured experimentally by means of magneto-tunneling experiments. With the magnetic field applied parallel to the growth direction z we find $g^*_\parallel = 0.7...0.9$ for different dots investigated. When B is tilted away from z by an angle ϑ an increase of g^* following a phenomenological behavior $g^*(\vartheta) = \sqrt{(g^*_\parallel \cos\vartheta)^2 + (g^*_\perp \sin\vartheta)^2}$ is observed. In high magnetic fields where only the lowest Landau level in the three-dimensional emitter is occupied a strong enhancement of the resonant current is observed. These results are discussed in terms of a field-induced Fermi-edge singularity.

The quantized energy levels of InAs quantum dots (QDs) can be accessed efficiently with resonant tunneling experiments [1,2]. In particular it is possible to measure directly the g-factor of such structures [3–5]. In this paper we will show experimentally that the g-factor of InAs QDs strongly depends on the orientation of the magnetic field and the results will be modeled by a g-factor tensor with two independent components.

Our samples consist of InAs quantum dots embedded in an AlAs barrier and sandwiched between two highly doped GaAs electrodes. A detailed description of the sample structure can be found in [2]. Macroscopic AuGeNi contacts with a typical diameter of 50 μm were annealed into the top electrode and vertical tunneling diodes with the same diameter were processed using wet-chemical etching.

Applying a voltage between the top and the bottom electrode we measure the typical I-V characteristics of a single-barrier tunneling device [2]. Distinct current steps superimposed on the coarse I-V curve are assigned to resonant tunneling through individual InAs quantum dots [1,2]. Such a typical step for $T = 0.5$ K is shown in Fig. 1 for $B = 0$ T and $B = 9$ T applied parallel to the growth direction. As can be seen in the figure, the single step observed at zero magnetic field splits into two steps which we assign to the tunneling through the spin-split ground state of the dot. The splitting ΔV is linear in magnetic field and given by $\Delta V = g^*_\parallel \mu_B B/\alpha e$. Here $\alpha = 0.3$ the is energy-to-voltage conversion factor given by the ratio of the energy separation emitter-dot to the total voltage drop. For numerous dots investigated we find a Landé factor $g^*_\parallel$ in the range of 0.7 ... 0.9.

From the temperature dependence of the step heights in high magnetic fields we conclude that the low voltage step is related to the tunneling of the minority-spin electrons from the emitter [4]. Since the g-factor in GaAs is negative this results in a positive Landé factor in the InAs QDs. Our measured values of g^* are consistent with other experiments [3]. The strong deviation from the InAs bulk value ($g^* = -14.8$) is explained in terms of size quantization effects, strain and possible other effects such as alloying of AlAs into the InAs dot and leakage of the electronic wave function into the AlAs barriers and the GaAs electrodes.

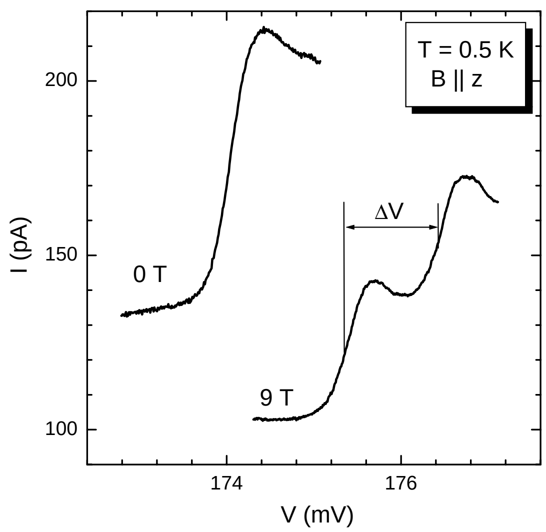

Fig. 1 Typical current step due to resonant tunneling through an InAs quantum dot. In a magnetic field the spin splitting of the ground state in the dot is resolved as two distinct sub-steps.

When the magnetic field B is tilted away from the growth direction z the splitting of the current steps gradually increases. As a function of the tilt angle ϑ between B and z the Landé factor deduced from this splitting follows a phenomenological behavior

$$g^*(\vartheta) = \sqrt{(g^*_\parallel \cos\vartheta)^2 + (g^*_\perp \sin\vartheta)^2}. \quad (1)$$

An example for $g^*(\vartheta)$ is shown in Fig. 2: I-V characteristics were measured at $B = 20$ T and $T = 0.5$ K for different tilt angles between the magnetic field and the growth direction and the Landé factor was extracted from the voltage split ΔV.

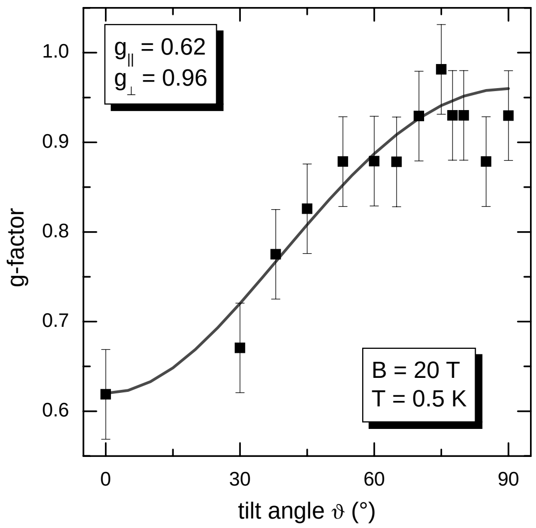

Fig. 2 Angular dependence of the experimentally measured g-factor at $B = 20$ T compared to the phenomenological model.

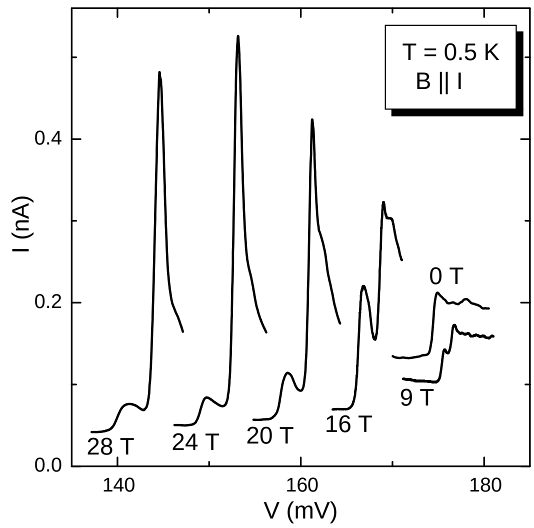

Fig. 3 Evolution of the spin-split current peaks in strong magnetic fields.

The behavior observed can be understood by modeling an InAs quantum dot by a flat disc with a height $h \approx 3$ nm and a diameter $d \approx 15$ nm [2]. Then the g-factor tensor with generally nine independent real components [6] reduces to a diagonal tensor with two independent components $g^*_\perp = g_{xx} = g_{yy}$ and $g^*_{\|} = g_{zz}$ describing precisely the angular dependence observed.

Our experimental results clearly prove the anisotropic nature of the spin in an InAs quantum dot. Due to size quantization effects one would expect a maximum g-factor when the magnetic field is applied in the direction of the strongest confinement, i.e. the growth direction z. Such quantum-confinement effects have indeed been observed in quantum wells [7] and quantum wires [8]. However, in our case we observe the minimum value of g^* along the strongest confinement. Therefore, other mechanisms such as spatially dependent strain, AlAs alloying into the InAs quantum dots and leakage of the electronic wave functions into the AlAs barriers are dominating in the observed g-factor anisotropy.

Apart from the spin splitting of the two current steps another spin effect can be obseved in very high magnetic fields (up to 28 T) where a dramatic enhancement of the spin-split current steps is observed, see Fig. 3. In particular electrons carrying the majority spin in the emitter display an current enhancement of more than an order of magnitude in high magnetic fields. These spectacular experimental observations can be explained in terms of a field-induced Fermi-edge singularity [4].

The singularity is due to the Coulomb interaction between the local potential in the dot and the Fermi edge in the emitter. In a strong quantizing magnetic field applied parallel to the current direction all the electrons in the emitter are confined in the lowest Landau level. Therefore, the emitter can be regarded as a one-dimensional (1D) channel with a momentum perpendicular to the boundary. The strong variation of the Fermi momentum for these 1D channels leads to the singularities observed, for more details see [4].

In conclusion we have determined the anisotropic nature of the Landé factor in InAs QDs by means of resonant tunneling experiments in tilted magnetic field. We find an angular variation of g^* which can be described by two independent tensor components $g^*_{\|}$ and $g^*_\perp$. In high magnetic fields a huge enhancement of the spin-split current steps is observed which we assign to a field-induced Fermi-edge singularity.

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