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Singularities in tunneling through InAs dots in high magnetic fields

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Abstract

Self-assembled InAs quantum dots embedded in an AlAs barrier and three-dimensional GaAs electrodes are investigated by resonant magneto-tunneling experiments. We observe Fermi-edge singularities which are strongly increasing in high magnetic fields. The enhancement in the tunneling current is most pronounced for electrons carrying the majority spin of the emitter. The singularities are caused by the Coulomb interaction between the tunneling electron and the partial spin polarized and Landau quantized three-dimensional emitter. We model our experimental findings with theoretical calculations.

Keywords: Resonant tunneling; Fermi-edge singularities; Self-assembled dots

1. Introduction

After a rapid development in the growth [1,2] of self-assembled InAs quantum dots (QDs) first investigations of their properties concentrated on optical methods [3–5]. Subsequently, resonant tunneling experiments through these dots were realized by several groups in the past years [6–8]. Such experiments are an efficient tool to investigate the electronic properties of InAs QDs. In magnetic fields the degeneracy of the QD states is destroyed and spin resolved measurements are possible at low temperatures [9].

Here we report on magneto-tunneling experiments through resonant tunneling diodes with self-assembled InAs quantum dots embedded symmetrically in an AlAs barrier and highly doped GaAs electrodes. IV-characteristics on these samples show Fermi-edge singularities which become strongly enhanced in high magnetic fields. The interaction of the localized electron on the dot with the emitter Fermi sea is responsible for this feature and increases strongly with higher fields.

2. The samples

The InAs QD samples were prepared by molecular beam epitaxy. The active layers are deposited on a highly Si-doped ($2\times10^{18}\,cm^{-3}$) GaAs wafer

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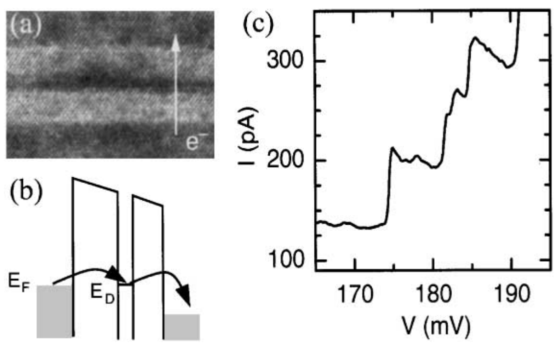

Fig. 1. (a) TEM micrograph of an InAs QD in an AlAs barrier. For positive bias electrons tunnel from the base to the apex. (b) Sketch of the conduction band profile under positive bias. E_F and E_D mark the emitter Fermi energy and the QD ground state, respectively. (c) IV-characteristics with typical steps at 0.5 K.

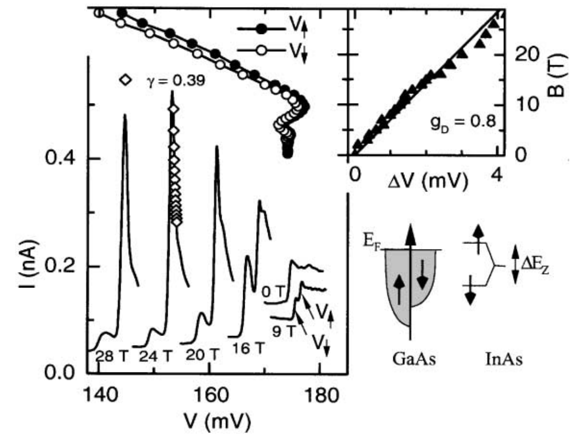

Fig. 2. Top: Positions of the onset voltages of the steps in dependence of the magnetic field. Bottom: IV-characteristics for different high magnetic fields up to 28 T at 0.5 K. Right: Zeeman splitting of the steps. Sketch of the spin configuration in the GaAs emitter and the InAs dot.

starting with a 1 μm GaAs buffer layer with the same doping as the bottom contact. In the next layers the doping was reduced to $1 \times 10^{16}\,\mathrm{cm}^{-3}$. To avoid Si diffusion into the active area a 15 nm undoped GaAs spacer separates the electrode from the following 10 nm AlAs barrier. The InAs QDs are deposited after 5 nm in the middle of the AlAs barrier. The InAs coverage of 1.8 monolayers leads to the formation of the self-assembled QDs in the Stranski-Krastanov growth mode. The structure was completed symmetrically with a 15 nm GaAs spacer and buffer layer to form the top contact. The high doping in the vicinity of the barriers leads to 3D electrodes. From the wafers grown we processed squared diodes with macroscopic sample sizes of 200 μm down to 40 μm. Ohmic contacts were realized by annealed AuGe/Ni.

In order to obtain more information about the structure and size of the InAs QDs transmission electron microscope (TEM) and atomic force microscope measurements were performed on these samples. The dot size is about 10–15 nm in diameter and 4 nm in height [10]. Fig. 1(a) shows a TEM micrograph of one InAs QD and the wetting layer (dark shadow) embedded in the AlAs barrier (bright stripes). The surrounding material is GaAs. Due to the finite height of the dots the effective thickness of the upper barrier is smaller. The resulting conduction band profile is sketched in Fig. 1(b). For positive bias the electrons tunnel through the thicker barrier first and leave the dot through the thinner barrier.

3. Magneto-transport

The transport measurements on the QD samples cover a temperature range from 4.2 K down to 0.5 K and magnetic fields up to 28 T. The magnetic field is oriented along the growth axis i.e. the tunneling direction of the electrons. Fig. 1(c) shows a section of a typical IV-characteristics at a temperature of $T = 0.5\,\mathrm{K}$ with two current steps. In several samples we observe such steps which occur when the Fermi level of the emitter E_F passes an energy level of the QD E_D.

The magnetic field dependence of the first step at 174 mV will be investigated in the following sections in more detail. In a magnetic field the degeneration of the QD states is destroyed and therefore the steps split into two smaller steps (See Fig. 2 bottom, curve labeled 9 T). The difference in the onset voltages is linear with increasing magnetic field B, $\Delta V = \Delta E_Z/\alpha e = g_D \mu_B B/\alpha e$ with ΔE_Z the Zeeman energy, α the lever factor for converting voltages to energies, μ_B the Bohr magneton. We determine a g-factor for this InAs dot of $g_D = 0.8$. For numerous other dots investigated in several samples the g-factor varies in the range $g_D = 0.7$–0.9.

Assuming that the g-factor is positive, as determined by Thornton et al. [9], and the g-factor of GaAs is of opposite sign, we get the spin configuration sketched in Fig. 2 on the right. Also the emitter is influenced in a magnetic field by a partial spin polarization. Therefore, the first step at voltages $V_\downarrow$ results from tunneling of electrons carrying the minority spin of the emitter through the lower QD level. The second step at the voltage labeled $V_\uparrow$ is a consequence of tunnel events from electrons carrying the majority spin of the emitter. The following two arguments confirm this assignment. First, temperature dependent measurements show an increase in the maximum current value for the minority spin tunnel events with higher temperatures in high magnetic fields, when all electrons are in the lowest Landau level. The tunnel current is rised by the additional thermal occupation of the minority spins in the emitter. Second, a comparison of our experimental data with theoretical calculations underlines the chosen assignment (see below).

4. High magnetic fields

In high magnetic fields we observe not only Zeeman splitting of the current steps but additional features. Fig. 2 displays in the top part the positions of the onset voltages for several magnetic fields. For low fields the positions of the spin split steps oscillate, for higher fields the onset positions shift to smaller voltages. The oscillations are a consequence of the oscillating Fermi energy in the emitter due to Landau quantization. In higher fields only the lowest Landau level is occupied and shifts to higher energies. This results in a smaller energy difference between the emitter Fermi energy and the QD states and therefore the shift of the onset positions to smaller voltages. As the dot is very small we can neglect the diamagnetic shift of the QD states in this context. The occupation of only the lowest Landau level leads to drastic changes in the IV-characteristics. The spin split steps both develop into separate peaks. The second peak resulting from tunneling of the majority spins in the emitter gets strongly enhanced with a peak height of one order of magnitude higher compared to zero field. This strong increase in the tunneling current is a result of the Coulomb interaction of the localized electron on the dot and the Fermi energy of the emitter. We attribute this effect to a Fermi-edge singularity which shows a strong dependence on the spin polarization of the Landau quantized emitter.

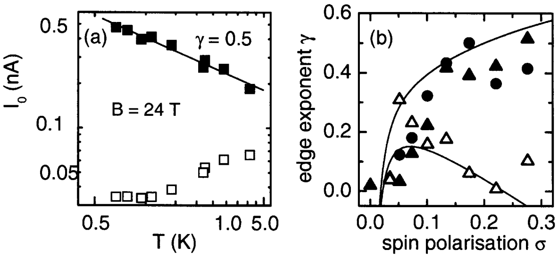

Fig. 3. (a) Development of the peak heights of the minority spin (open symbols) and majority spin (filled symbols) at 24 T with increasing temperatures. (b) Edge exponents in dependence of the spin polarization. Filled triangles and circles represent data for the majority spin from fitting the slope and the temperature dependent peak height, respectively. Open triangles: data for the minority spin from fitting the slope.

5. Analysis

In order to analyze the Fermi-edge singularity we investigated the current slopes of both peaks, the minority and the majority spin peak. They can be described by a power law $I \sim (V - V_0)^{-\gamma}$ [11], where V_0 is the voltage at the maximum peak current and γ is an edge exponent. We determine the edge exponent γ for different magnetic fields by fitting the slope of the peaks. Fig. 2 shows downleft a fit of the majority spin peak for 24 T. The edge exponent is determined to $\gamma = 0.39$ in this particular case.

Temperature dependent measurements offer an additional way to determine the edge exponent. Fig. 3(a) displays the development of the peak height I_0 of the minority spin peak (open squares) and the majority spin peak (filled squares) with increasing temperatures for a fixed field of 24 T. The temperature dependence of the peak height of the majority spin peak is found to behave as $I_0 \sim T^{-\gamma}$ with the same exponent γ as extracted from the IV-curve. By fitting the data $I_0(T)$ we can determine γ for several magnetic fields. This method is inapplicable for the minority spin. The additional thermal occupation in the emitter already leads to a significant increase of the tunneling current with increasing temperature which is unrelated to the Fermi-edge singularity.

6. Results

The experimentally determined edge exponents are compiled in Fig. 3(b) as a function of the spin polarization $\sigma = (B/B_0)^3$ of the emitter. $B_0 = 43\,\mathrm{T}$ is the field where the emitter is totally spin polarized. Landau level broadening is neglected here. Filled symbols represent data concerning the majority spin, open symbols refer to the minority spin. The circles are exponents extracted from fitting the temperature dependence of peak height of the majority peak, the triangles are related to the method of fitting the slope of the current peaks for both spin directions. The solid lines are results of a theoretical calculation. The model takes into account the electrostatic potential of the charged dot and its impact on the three-dimensional electrons in the emitter (Landau level broadening not included). In high magnetic fields all electrons are in the lowest Landau level. Electron transport happens through one-dimensional channels with momentum parallel to the growth axis. The calculated field dependence of the edge exponents is influenced by two variables: First, the Fermi momenta for the electrons of different spins, and second, the effective potential in the one-dimensional channels varies with increasing magnetic field. Including Landau level broadening leads to a less dramatic spin polarization and therefore to a moderation of the field dependence. For further details see [12]. The edge exponents for the majority spin both, experimental and theoretical data, show a strong dependence on the spin polarization in the emitter. For a large spin polarization, i.e. for high magnetic fields, the exponents reach high values of $\gamma = 0.5$ above polarizations of $\sigma = 0.17$. The minority spin exponents retain small values, especially for high polarizations.

7. Conclusions

Magneto-tunneling experiments through self-assembled InAs quantum dots show field induced Fermi-edge singularities. The enhancement in the current resulting form tunnel events of electrons in the emitter which carry the majority spin is significant in high magnetic fields. In this case only the lowest Landau level in the emitter is occupied. The edge exponents γ, which depend strongly on the interaction of the localized charge on the dot and the Landau quantized emitter, reach very high values of $\gamma > 0.5$.

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