Level anticrossings in quantum dots

J. Könemann*, E. Räsänen†, M. J. Puska†, R. M. Nieminen† and R. J. Haug*

*Institut für Festkörperphysik, Universität Hannover, Appelstrasse 2, D-30167 Hannover, Germany
†Laboratory of Physics, Helsinki University of Technology, P.O. Box 1100, FIN-02015 HUT, Finland

Abstract. We have studied the single-electron transport spectrum of a localized level embedded into a double-barrier resonant tunneling structure. The experimental spectrum shows clear deviations from the Fock-Darwin model indicating a broken circular symmetry. We interprete our observations in terms of the existence of an additional multiple-charged impurity in the vicinity of the quantum dot.

Semiconductor quantum dots (QD) have attracted broad interest in experimental [1] and theoretical works [2]. The understanding of the electronic transport through such systems plays an important role in the future development of electronic devices like single-electron transistors. Due to their quantum confinement QD's can be considered as artificial atoms [3]. The modeling of QD spectra is usually based on the assumption of a perfect 2D harmonic confining potential giving the well-known Fock-Darwin (FD) single-electron spectrum [4]. Such FD spectra have been observed in several experiments [5].

Anticrossings of orbital single-electron energy levels in QD's always indicate a symmetry-breaking mechanism, which distorts the harmonic confining potential of the QD. In our experiment we have studied the single-particle transport spectrum of a single localized electronic state embedded in a double-barrier resonant tunneling structure. The experiment was performed with a highly asymmetric double barrier resonant tunneling device grown by molecular beam epitaxy on n^+-type GaAs substrate. The heterostructure consists of a 10 nm wide GaAs quantum well sandwiched between two $Al_{0.3}Ga_{0.7}As$-tunneling barriers of 5 and 8 nm. The contacts are formed by 0.5 μm thick GaAs layers highly doped with Si up to $4. \times 10^{17}$ cm^{-3} and separated from the active region by 7 nm thin spacer layers of undoped GaAs. DC measurements of the I-V-characteristics were carried out in a dilution refrigerator at 20 mK base temperature and in high magnetic fields up to 14 T.

The resulting I-V curves are presented as a function of the magnetic field oriented parallel to the tunneling current (see Fig. 1). The additional field-induced lateral confinement shifts the bias position of the first step (single-electron ground state) to higher voltages. Moreover, most of the steps appear to approach the first step at higher magnetic fields. Additionally, we observe a fluctuation pattern reflecting the local density of states of the emitter and its highly-disordered Landau bands [6].

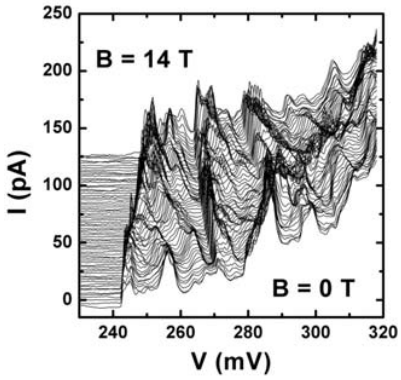

FIGURE 1. Experimental I-V curves between zero and 14 T. Curves are plotted with a vertical offset of 1 pA.

The grey-scale plot Fig. 2 depicts the differential conductance $G = dI/dV$ as a function of bias voltage and magnetic field (numerically obtained from the current data). The black lines $V_{n,l}$ of high differential conductance G trace the position of the states $E_{n,l}$ of the spectrum

$$V_{n,l} = V_0 + 1/(e\alpha)E_{n,l}, \qquad (1)$$

with the energy-voltage conversion factor $\alpha = 0.4$ obtained from measurements of the broadening of the step edge with temperature and the onset voltage V_0 from modelling of the experimental spectrum. We observe clear deviations from an ideal single-electron FD spectrum. At zero magnetic field the lifting of the degeneracy of orbital states is observed. At intermediate magnetic fields we find strong level repulsions, whereas at high

CP772, *Physics of Semiconductors: 27th International Conference on the Physics of Semiconductors,*
edited by José Menéndez and Chris G. Van de Walle

magnetic fields the traces of the electronic levels follow parallel lines with an equal spacing and a constant slope in magnetic field showing the condensation into the lowest lying 2D-Landau band.

Such avoided crossings and lifted degeneracies were studied theoretically by Halonen *et al.* [7] within a model of QD's distorted by repulsive Gaussian scattering centers. We have applied a more sophisticated model by expressing the realistic Coulomb-impurity as

$$V_{\rm imp}(\mathbf{r}) = \frac{|q|}{4\pi\varepsilon_0\varepsilon_r\sqrt{(\mathbf{r}-\mathbf{R})^2+d^2}}, \qquad (2)$$

with the negative charge q of the impurity, $\varepsilon_r = 13$ being the dielectric constant of GaAs, and R and d the lateral and vertical distances of the impurity from the QD center, respectively. The confining part is written as

$$V_{\rm conf}(\mathbf{r}) = \begin{cases} \frac{1}{2}m^*\omega_0^2 r^2, & r \le r_c \\ m^*\omega_0^2\left[s(r-r_c)^2 - r_c(\frac{r_c}{2}-r)\right], & r > r_c, \end{cases} \qquad (3)$$

where the parameter s defines the strength of the rounding (softening) term. As shown below, the rounding of the confinement is crucial in obtaining a good agreement with the experimental energy spectrum. The single-electron energies are calculated numerically from the discretized eigenvalue equation on a 2D point grid using a Rayleigh quotient multigrid method [8]. The resulting calculated eigenenergies are plotted as dashed lines in Fig. 2 (a) with the model potential plotted in Fig. 2 (b). As can be seen, the agreement between the experimental traces and the calculated eigenvalues is good and the positions of the anticrossings are predicted with a good accuracy. The confinement is given by $\hbar\omega_0 = 13.8$ meV, $r_c = 15.5$ nm, and $s = -0.2$, and the impurity parameters are given by $q = -2e$, $R = 14.5$ nm, and $d = 2$ nm, whereas the voltage offset is $V_0 = 172$ mV.

The fitting parameter suggest a double-charged impurity located very close to the quantum dot plane, probably embedded inside the GaAs quantum well. The impurity might be a Si-dopant atom migrated from the highly-doped emitter through the thin spacer layer, and breaking now the spatial symmetry of the system.

We have presented an experimental single-electron spectrum with lifted level degeneracies and level repulsions indicating a broken circular symmetry. We are able to model quantitatively our experimental data with a realistic model of a harmonic QD potential containing a repulsive Coulomb-impurity term. As a result we identified the existence of a double-charged Si-dopant atom very close to the QD plane.

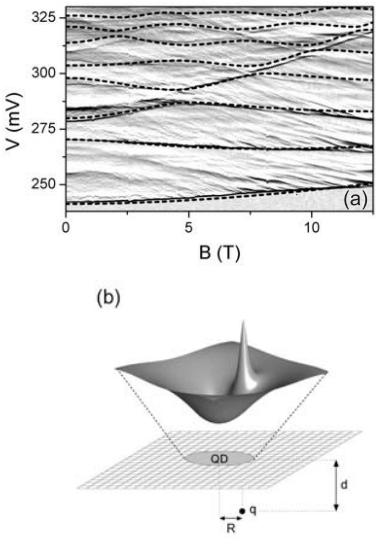

FIGURE 2. (a) Measured transport spectrum and calculated single-electron spectrum. (b) Potential profile used in the simulation.

ACKNOWLEDGMENTS

We acknowledge sample growth by V. Avrutin and A. Waag and financial support by BMBF.

REFERENCES

1. For review, see, e.g., L. P. Kouwenhoven, D. G. Austing, and S. Tarucha, Rep. Prog. Phys. **64**, 701 (2001).
2. For review, see, e.g., S. M. Reimann and M. Manninen, Rev. Mod. Phys. **74**, 1283 (2002).
3. S. Tarucha, D. G. Austing, Y. Tokura, W. G. van der Wiel, and L. P. Kouwenhoven, Phys. Rev. Lett. **84**, 2485 (2000).
4. V. Fock, Z. Phys. **47**, 446 (1928).
5. J. Weis, R. J. Haug, K. v. Klitzing, and K. Ploog, Phys. Rev. B **46**, 12837 (1992); M. Ciorga, A. S. Sachrajda, P. Hawrylak, C. Gould, P. Zawadzki, S. Jullian, Y. Feng, Z. Wasilewski, Phys. Rev. B **61**, R16315 (2000); R. H. Blick, T. Schmidt, R. H. Haug, K. von Klitzing, Semicond. Sci. Technol. **11**, 1506, (1996); J. Könemann, D. K. Maude, V. Avrutin, A. Waag, and R. J. Haug, Physica E **22**, 434 (2004).
6. P. König., T. Schmidt, and R.J. Haug, Europhys. Lett. **54**, 495 (2001).
7. V. Halonen, P. Hyvönen, P. Pietiläinen, and T. Chakraborty, Phys. Rev. B **53**, 6971 (1996).
8. E. Räsänen, J. Könemann, R. J. Haug, M. J. Puska, R. M. Nieminen, to appear in Phys. Rev. B.