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Citation: AIP Conference Proceedings **772**, 815 (2005); doi: 10.1063/1.1994356
View online: http://dx.doi.org/10.1063/1.1994356
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/772?ver=pdfcov
Published by the AIP Publishing

Anisotropy of Zeeman-splitting in quantum dots

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Abstract. By single-electron tunneling spectroscopy we investigate the difference in spin splitting of single-electron resonances in a double-barrier structure subjected to a magnetic field perpendicular ($\Delta_\perp$) and parallel ($\Delta_\|$) to the plane of quantum well. The observed anisotropy of spin splitting is interpreted within a model of spin-orbit coupling in quantum dots.

Spin in semiconductor nanostructures like quantum dots has attracted wide interest with respect to future applications like spin transistors[1] or spin valves[2]. In quantum dots the orbital degrees of freedom and the spin degree of freedom can be tuned electrostatically and by an applied magnetic field. In our work we applied single-electron resonant tunneling spectroscopy[3] to investigate the anisotropy of spin splitting of electrons in quantum dots with respect to different configurations of an applied magnetic field and compare it to the gyromagnetic ratio, the effective Landé-factor. We explain our results by an interplay between spin-orbit coupling and quantum dot confinement of the electrons[4].

The experiment was performed with two highly asymmetric double barrier resonant tunneling devices of different pillar diameters grown by molecular beam epitaxy on n^+-type GaAs substrate. The heterostructures consist 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 4×10^{17} cm^{-3} and separated from the active region by 7 nm thin spacer layers of undoped GaAs. We carried out DC measurements of the I-V-characteristics in a dilution refrigerator at 20 mK base temperature in high magnetic fields up to 27 T. We were able to measure the transport spectrum of single localized states with different confinement strength in both samples for $B \| I$ and $B \perp I$. Sample A contains a weakly confined state with a confinement energy $\hbar\omega_0$ of 13 meV[5]. Fig. 1 (a) displays the diamagnetic shift of two conductance peaks P1 and P2 found in sample A for $B \| I$, whereas for $B \perp I$ in Fig. 1 (b) no diamagnetic shift can be seen. In the spectrum of sample B only a single conductance peak P0 with a much weaker diamagnetic shift is analyzed attributed to a strongly bound localized state with $\hbar\omega_0 = 31$ meV. Besides the diamagnetic shift, all peaks in dI/dV resolve into two peaks at high enough field values, manifesting the spin splitting of each single localized state. These spin splitting data have been analyzed in detail for sample A, see Fig. 2, and B[6]. The graph includes splittings measured in two geometries. Full and empty symbols stand for splittings measured

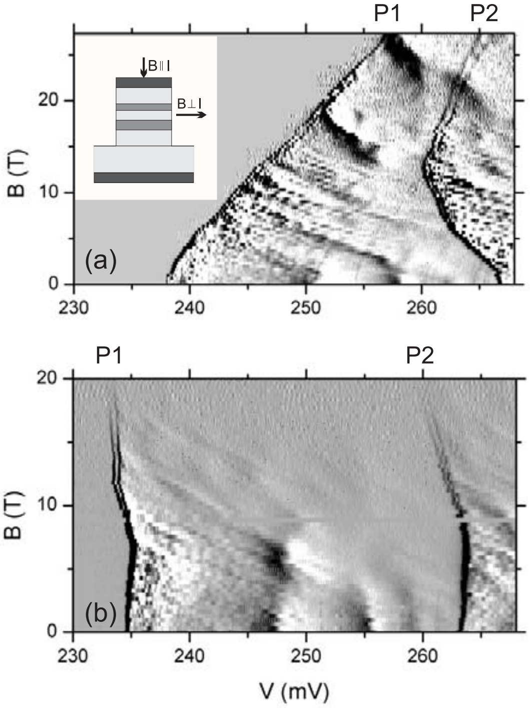

FIGURE 1. G(V,B)-plot of the transport spectrum of sample A for (a) the $\vec{B} \| \vec{I}$ and (b) the $\vec{B} \perp \vec{I}$-configuration. P1 and P2 indicate the first spin-split conductance-peaks.

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

in the field perpendicular ($\mathbf{B} = B\hat{\mathbf{e}}_z$) and parallel to the plane of the double-barrier structure, respectively (*i.e.*, oriented in and across the tunneling directions).

The data for both samples display a distinct anisotropy of peak splitting, where the splitting caused by the out-of-plane field is systematically larger in comparison to the splitting observed with an in-plane field. In sample B, that means in the regime of strong spatial confinement ($\hbar\omega_0 > \hbar\omega_c$), we observe for the in-plane-magnetic field orientation a smaller slope of the linear spin-splitting than for the out-of-plane-magnetic field orientation. For the low-field asymptotic, that is for $\omega_c < \omega$, we assume $\Delta_\perp - \Delta_\parallel \approx \frac{-g^*}{|g^*|} B\hbar e^2 B_{\mathrm{so}}/(2\omega(m^*)^2)$. The internal magnetic field $B_{\mathrm{so}} \propto (\rho_{\mathrm{BR}}^2 - \rho_{\mathrm{D}}^2)$ reflects here the difference of the spin orbit coupling parameter ρ_{BR} for the Bychkov-Rashba[7] and ρ_{D} for the Dresselhaus-mechanism[8].

In contrary, we find in sample A, that means in the weak confinement regime ($\hbar\omega_0 < \hbar\omega_c$), the same slope of the spin splitting for both magnetic field orientations. But we find for the out-of-plane-magnetic field orientation in the spin splitting dependence a constant energy offset compared to the spin splitting in the in-plane-magnetic field orientation. We assume now for the high-field asymptotics, that is for $\omega_c < \omega$, $\Delta_\perp - \Delta_\parallel \approx \frac{-g^*}{|g^*|} \frac{e\hbar}{m^*} B_{\mathrm{so}}$ for $\omega_c \gg \omega$. That means, the anisotropy of spin splitting of few lowest quantum dot states transforms into an offset with the sign being dependent on the sign of B_{so} and on the sign of electron g^*-factor of our sample, which is known to be negative from a previous experiment[9]. So, we are able to determine the spin-orbit coupling characteristics which appeared difficult to separate in previous experiments[10].

In conclusion, we have applied single-electron resonant tunneling spectroscopy to investigate the anisotropy of spin splitting of single-electron resonances. As a result, we are able to explain the anisotropy of spin splitting with an interplay of the spin-orbit coupling characteristics and the quantum confinement of our samples.

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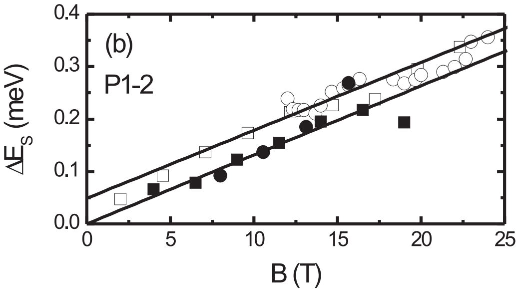

FIGURE 2. Spin splitting of the states P1 (squares) and P2 (circles) of sample A for $\vec{B} \parallel \vec{I}$ (open symbols) and (b) $\vec{B} \perp \vec{I}$-configurations (filled symbols). Solid lines are fits to the experimental data.

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