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Spin Transport from Doublet State to Triplet State in Vertical Quantum Dots

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We measured electron transport state spectra of an $In_{0.05}Ga_{0.95}As$ vertical double quantum dot. Both the ground and excited states of transport spectra from two electrons to three electrons are measured using a large source–drain voltage. In the obtained transition spectrum, the ground state transition from the $1S^2$ singlet state to the 1S2P triplet state is observed at 5 T. Zeeman splitting with a g-factor of 0.36 is clearly observed at magnetic fields higher than 5 T. The observation of two Zeeman sublevels instead of three for the triplet state is explained by the spin selection rules for the S_Z components between the two-electron and three-electron spin states. Transition with the total spin difference between the initial and final states larger than 1/2 is forbidden. Because the transition between doublet states is much longer than electron tunneling, both spin up and spin down can be the initial states from spin transitions. There are four transitions contributing to tunneling processes, but only two energy differences lead to the two Zeeman sublevels in the excitation spectra. [DOI: 10.1143/JJAP.47.3257]

KEYWORDS: quantum dot, spin selection rule

1. Introduction

A study of spin-dependent transport has attracted considerable attention over the past several decades, because the advantages of two intrinsic states and a long relaxation time result in the great potential of application of spintronics and quantum information.[1–4] A confined semiconductor quantum dot is a popular material to study, because it can be regarded as an artificial atom, since its electronic properties resemble the ionization energy and discrete excitation spectrum of atoms.[5] However, the spins in the confined semiconductor quantum dot often couple with other environmental freedom components; thus, to understand spin states is an important issue in the study. For single electron states, it is already well studied using a two-dimensional harmonic potential.[6] In non-single-particle electron systems, electron states are often characterized by the total electron number and electron spin in the presence of Coulomb interaction. Electron spin states have been identified in several systems, such as the two-singlet state replaced by a spin-polarized phase, at which electrons occupy some orbit states in the first and second Landau levels,[7] and a quantum two-level system based on the two-electron spin state in a double quantum dot.[8]

In spin-dependent transport, both spin states and effective transition processes are important. Recently, the Zeeman splitting peaks in a few-electron quantum have been investigated.[9] The excited state of Zeeman splitting depends on whether the total spin is raised or lowered. On the other hand, one-electron Zeeman splitting is clearly resolved at both zero-to-one and one-to-two electron transitions in a lateral quantum dot. The spin of the electrons transmitted through the dot is expected to be that of an electrically tunable, biploar spin filter.[10]

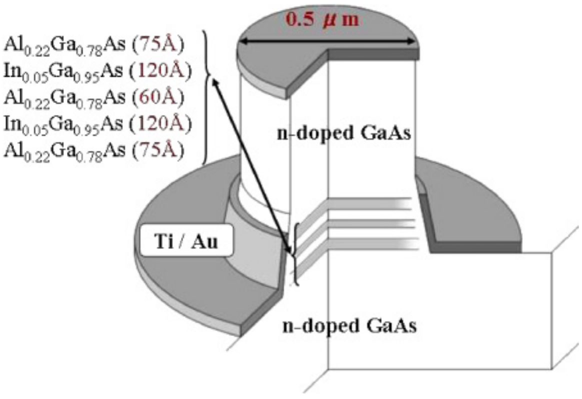

Fig. 1. (Color online) Structure of vertical quantum dots. The diameter of the mesa is 0.5 μm. The side gate is prepared by Schottky contact. From bottom to top, the dots consist of an n-doped GaAs substrate, undoped layers of 75 Å $Al_{0.22}Ga_{0.78}As$, 120 Å $In_{0.05}Ga_{0.95}As$, 60 Å $Al_{0.22}Ga_{0.78}As$, 120 Å $In_{0.05}Ga_{0.95}As$, and 75 Å $Al_{0.22}Ga_{0.78}As$, and an n-doped GaAs top layer.

In this study, we investigated the single-electron transport in a vertical double quantum dot and two-electron spin states and transitions. We observed spin-selection-rule-induced blockade. We also observed that a spin excitation spectrum is missing owing to the spin selection rule between the spin doublet and spin triplet states.

2. Experiment

Double quantum dots are prepared from semiconductor multibarrier heterostructures surrounded by metal gate electrodes. $In_{0.05}Ga_{0.95}As$ dots are located between $Al_{0.22}Ga_{0.78}As$ heterostructure barriers. From bottom to top, the dots consist of an n-doped GaAs substrate, undoped layers of 75 Å $Al_{0.22}Ga_{0.78}As$, 120 Å $In_{0.05}Ga_{0.95}As$, 60 Å $Al_{0.22}Ga_{0.78}As$, 120 Å $In_{0.05}Ga_{0.95}As$, and 75 Å $Al_{0.22}Ga_{0.78}As$, and an n-doped GaAs top layer. The structure is shown in Fig. 1. The electrons in the dots are confined in all directions. By decreasing the gate voltage V_g, we can reduce the effective dot area and hence tune the effective electron number one by one down to zero in the dots.

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A sample is mounted on the mixing chamber of a dilution refrigerator with a base temperature of 20 mK. We apply magnetic fields up to 15 T vertical to the heterostructures.[5)]

Applying a large source–drain voltage V_{sd} is effective for probing the ground and excited states simultaneously. By increasing the source–drain voltage, and hence increasing the transport window between the Fermi energies of the source and drain, both ground and excited states lie within the transport window and contribute to current. When electron states lie within the transport window, electrons can tunnel from the source through the dots to the drain and induce the current I_{sd}.

The inherent asymmetry in the tunneling barriers of few electron dots induces intrinsically different tunneling currents for forward and reverse source–drain biases in a nonlinear transport regime.[11)] We set the tunneling rate of the incoming barrier to be much smaller than that of the outgoing barrier. As a result, more excited state spectra are shown and the intensity of the current increases.

3. Results and Discussion

Figure 2(a) shows the measured differential conductance $dI_{\mathrm{sd}}/dV_{\mathrm{g}}$ as a function of V_{g} and magnetic field B. The three colors, blue, red, and white, represent negative, positive, and zero differential conductances, respectively. As shown in Fig. 2(a), we label electron number states as ($N1$, $N2$) in different regions, where $N1$ and $N2$ are the total numbers of electrons in Dot 1 and Dot 2, respectively. The middle stripe denotes the third electron transport spectrum, which shows the transport states of the $(1,1) \leftrightarrow (1,2)$ transition.

In the $(1,1) \leftrightarrow (1,2)$ transition spectrum, we can observe that the color of the lower half region is lighter than that of the upper half region. The differential conductance, i.e., the transition rate, in the lower regime is smaller than that in the upper regime. At low temperatures, high-order transport processes can dominate tunneling processes. As shown in Fig. 2(b), although only the energy state of Dot 2 lies within the transport window, electrons can also tunnel through Dot 1 directly into the energy state of Dot 2 via high-order transport processes. This is commonly known as a cotunneling event.[12)]

From now on, we will focus our discussion only on the middle transport spectrum in Fig. 2(a). At zero magnetic fields, the ground state of Dot 2 follows the Pauli exclusion rule indicating that two electrons have opposite spins of the same angular momentum quantum number $L = 0$. The total electron spin is zero, indicating the spin singlet state. The Coulomb interaction and single-particle states become important when a magnetic field changes the size of an electron state. In the presence of a magnetic field, the electron state shrinks in the redial direction. When two electrons occupy the same angular momentum state, the average distance between the two electrons decreases with B, and hence, the Coulomb interaction increases. At a critical magnetic field B_{c}, the Coulomb interaction is reduced by an exchange energy. One electron occupies the $L = 0$ angular momentum state and the other one occupies the $L = 1$ state. The two electrons can take on parallel spins. The ground state is considered the spin triplet state, in which one electron is in the angular momentum state $L = 0$ and the other electron in the angular momentum state $L = 1$, to reduce the Coulomb interaction. The spin singlet–triplet transition is observed at 5 T, which agrees with the literature well.[13)]

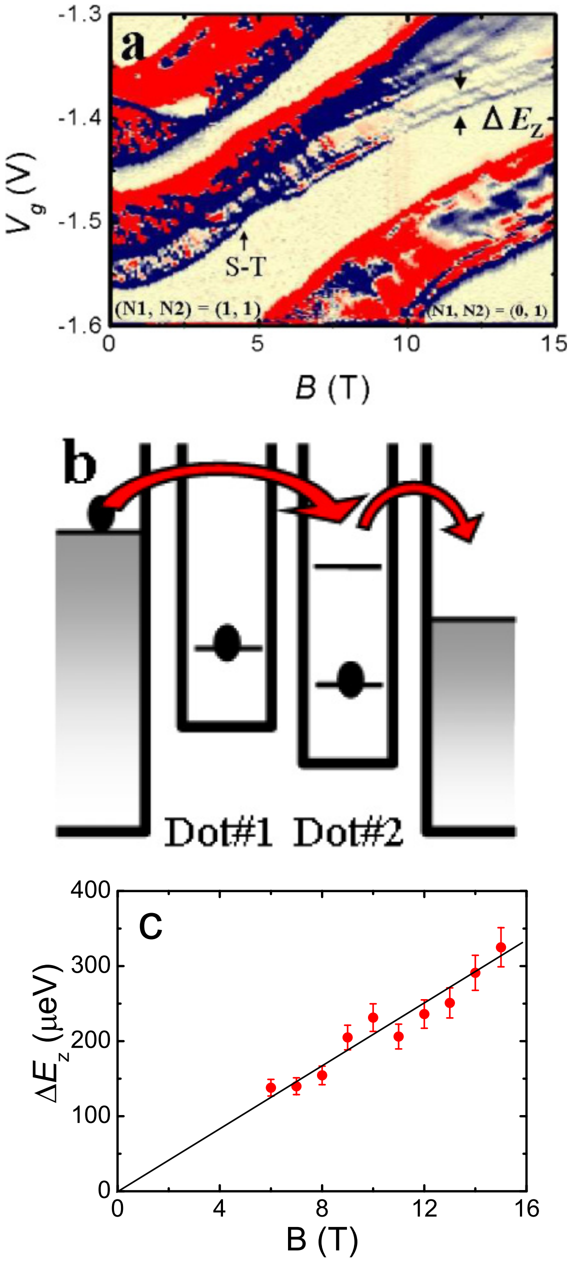

Fig. 2. (Color online) (a) Spectra of $\mathrm{In}_{0.05}\mathrm{Ga}_{0.95}\mathrm{As}$ quantum dots. From bottom to top, the electron transition spectra of $(0,1) \leftrightarrow (1,1)$, $(1,1) \leftrightarrow (1,2)$, and $(1,2) \leftrightarrow (2,2)$ are shown. A singlet–triplet transition is observed at 5 T and two Zeeman splitting lines are observed above 6 T. (b) Model of cotunneling. Although only the state of Dot 2 is within the transport window, electrons can also tunnel through Dot 1 to the state of Dot 2 via high-order tunneling contribution. (c) Extracted Zeeman splitting energy from Fig. 1(a) as function of applied magnetic field. The Zeeman splitting energy is linear to the magnetic fields and the g-factor is 0.36.

In Fig. 2(a), we observe two Zeeman splitting lines in the $(1,1) \leftrightarrow (1,2)$ transition spectrum when the magnetic field is above 6 T. The Zeeman splitting energies are labeled as ΔE_{Z}. Figure 2(c) shows the extracted Zeeman splitting energies ΔE_{Z} as a function of magnetic field. The Zeeman splitting energy is linear in B and the effective Zeeman g-factor is 0.36 ± 0.02. To confirm the accuracy of the result,

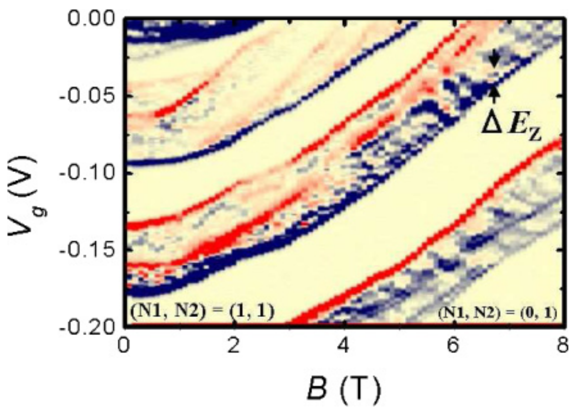

Fig. 3. (Color online) Spectra of GaAs quantum dots. From bottom to top, the electron transition spectra of $(0,1) \leftrightarrow (1,1)$, $(1,1) \leftrightarrow (1,2)$, and $(1,2) \leftrightarrow (2,2)$ are shown. Two Zeeman splitting sublevels are also observed in the $(1,1) \leftrightarrow (1,2)$ transport spectrum. The effective g-factor is $g = 0.25 \pm 0.02$.

we also measure the transport spectra of GaAs double quantum dots by the same method. As shown in Fig. 3, two Zeeman splitting lines are also observed in the $(1,1) \leftrightarrow (1,2)$ transport spectrum. This result shows that $g = 0.25 \pm 0.02$, which agrees with the literature well.[10,14,15)]

The optical detection of conduction-electron spin resonance was previously performed in a bulk $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ system, where x ranges from 0 to 0.1.[16)] The measured g-factor of pure bulk GaAs is -0.44, and the g-factor decreases if Ga is replaced by In. The g-factor of bulk $\mathrm{In}_{0.05}\mathrm{Ga}_{0.95}\mathrm{As}$ is -0.6. It is often found that the absolute g value in confined electron systems is reduced from the bulk modulus.[10,14,15,17)] The ratio of the g-factor of pure bulk GaAs to that of pure bulk $\mathrm{In}_{0.05}\mathrm{Ga}_{0.95}\mathrm{As}$ is 0.72, which is near the ratio of our confined quantum dots of 0.69.

The ground state with two electrons in a dot at zero magnetic fields, for example, two electrons in Dot 2, is the spin singlet state $(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$. The first excited states are spin triplet states. The three triplet states are degenerate at zero magnetic fields, and energies split in the presence of magnetic fields. These states are $|\uparrow\uparrow\rangle$, $(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/2$, and $|\downarrow\downarrow\rangle$. When the magnetic field is higher than B_c, the singlet state energy increases rapidly and becomes much higher than the triplet state energy.[18,19)] Assuming that the initial state is $|\uparrow\rangle$, only $|\uparrow\uparrow\rangle$ and $|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$ could be the final states. The transition from $|\uparrow\rangle$ to $|\downarrow\downarrow\rangle$ is forbidden because of the spin selection rule. The total spin difference between $N-1$ and N electrons cannot be more than $1/2$.[20)] There are two transition processes for the initial $|\uparrow\rangle$ state, and the Zeeman energy difference is $g\mu_{\mathrm{B}}B$.

Hanson *et al.* have measured the spin relaxation time of a single electron confined in a semiconductor quantum dot.[17)] They observed a lower bound at a spin relaxation time of 50 µs at 7.5 T. The relaxation time is longer than the electron tunneling time of 1 µs at 15 T in the $(1,1) \leftrightarrow (1,2)$ transport. The doublet transition is much slower than the tunneling; therefore, wether the initial state is $|\uparrow\rangle$ or $|\downarrow\rangle$, both electrons with spin up or spin down can tunnel through the dot before the spin relaxation occurs. Both $|\downarrow\rangle$ and $|\uparrow\rangle$ can be the initial states. As shown in Fig. 4, there are four transition processes but only two effective Zeeman split energies.

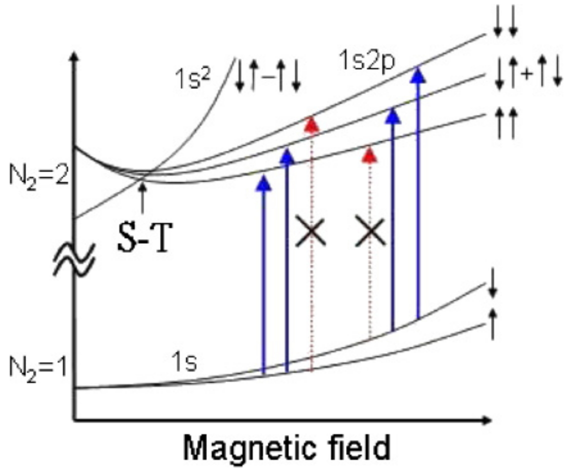

Fig. 4. (Color online) Transition model of third electron. N_2 indicates the total number of electrons in Dot 2. The transitions $|\uparrow\rangle$ to $|\downarrow\downarrow\rangle$ and $|\downarrow\rangle$ to $|\uparrow\uparrow\rangle$ are forbidden because of the spin selection rule. There are four transitions in tunneling processes, but only two effective Zeeman splitting energies.

4. Conclusions

We measured the $(1,1) \leftrightarrow (1,2)$ electron transport state spectra of an $\mathrm{In}_{0.05}\mathrm{Ga}_{0.95}\mathrm{As}$ vertical double quantum dot by a large-source–drain-voltage method. A spin singlet–triplet transition is observed at 5 T, followed by the observation of two clear Zeeman splitting lines at magnetic fields higher than 5 T. Zeeman splitting energies are linear with magnetic fields up to 15 T. Doublet spin relaxation is much slower than electron tunneling; therefore, both $|\uparrow\rangle$ and $|\downarrow\rangle$ can be the initial electron states. On the basis of the spin selection rule, the transitions $|\uparrow\rangle \rightarrow |\downarrow\downarrow\rangle$ and $|\downarrow\rangle \rightarrow |\uparrow\uparrow\rangle$ are forbidden, because the total spin difference between the initial and final states is larger than $1/2$. There are four transitions in tunneling processes, but only two energy differences lead to the two Zeeman sublevels in the obtained excitation spectrum.

Acknowledgements

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