

Control of shell filling with Coulomb interaction in quantum dots side-coupled to quantum wires

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We report the control of the orbital occupation by using the intra-orbital Coulomb interaction in quantum dots T-coupled to quantum wires. With the change of the confinement potential, intra-orbital Coulomb interaction exceeds orbital level spacing and influences the orbital oc-

cupation. We realize such potential modification by changing either the gate design or the voltages applied to the gates. The rearrangement of the orbital occupation is confirmed from the response of the addition energy spectroscopy to the magnetic field.

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1 Introduction Semiconductor quantum dots show a good analogy with natural atoms and are referred to as “artificial atoms”. For example shell structures and Hund’s rule in energy level occupation have been observed in vertical type quantum dots [1, 2]. In natural atoms, lowering of the potential symmetry by ligand fields brings the change in single-electron energy and the mutual Coulomb interaction, which result in the rearrangement of the orbital occupation. In quantum dots, the confinement potential is controllable with higher degree of freedom. In this paper, we report the control of the orbital occupation by changing the confinement potential.

The essence of the occupation control is to use different dependencies of the orbital energy and the intra-orbital Coulomb interaction on the confinement potential size. Here, the intra-orbital Coulomb interaction arises when two electrons occupy the same orbital. The relative importance of the Coulomb interaction becomes enhanced with the increase of the confinement size. The Coulomb repulsion will exceed the orbital level spacing and non-monotonic orbital occupation in which the electrons do not occupy from the lower orbital levels will be observed.

The potential control in quantum dots has been performed in vertical type quantum dots. The change of single-electron energies was reported by preparing elliptic

quantum dots [3]. However, the large orbital level spacing in vertical quantum dots restricts the condition for observing the Coulomb related phenomena only near the orbital level crossing at high magnetic fields [4]. It is difficult to change the level occupation at zero magnetic field.

In recent years, few-electron states have also been realized in lateral quantum dots [5] which have a possibility of confinement in wider potential. But in the conventional single electron transistor structure, we must optimize the two connection between the dot and the leads for practical measurement and there is little room to control the confinement potential. To overcome this problem, we adopted T-coupled geometry, in which a quantum dot is side-coupled to a quantum wire. Because there is only one connection between the dot and the wire, we have large freedom in controlling the confinement potential even in few-electron regime [6].

2 Experimental Figure 1(a) shows the scanning electron micrographs of samples. Light gray regions are Au/Ti Schottky gates deposited on a wafer containing a GaAs/AlGaAs hetero-interface 60 nm beneath the surface. By applying negative voltages to the gates, we can form the T-coupled quantum dots indicated with white dashed lines. We can control the number of electrons in the dot N

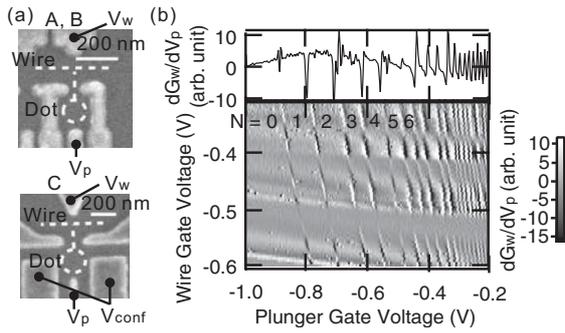


Figure 1 (a) Scanning electron micrographs of samples. The light gray regions show Au/Ti Schottky gates deposited on a GaAs/AlGaAs wafer. (b) Upper: the derivative of the wire conductance dG_w/dV_p in sample B. Lower: a gray scale plot of dG_w/dV_p as a function of the wire gate voltage and the plunger gate voltage.

through the voltage of the plunger gate V_p , and the number of conducting channels in the wire through the voltage of the wire gate V_w . Sample A and B are prepared for the occupation control through the gate size. They are identical in gate design (the upper figure of Fig. 1(a)), but different in the size. Sample A has the enclosed area for the dot as 150^2 nm^2 and sample B has 110^2 nm^2 . Both samples are fabricated from a same wafer (sheet carrier density of $3.8 \times 10^{15} \text{ m}^{-2}$ and mobility of $90 \text{ m}^2/\text{Vs}$ at 4.2 K). A simple simulation shows sample B produces the larger confinement than sample A on the condition that the dots contain the same number of electrons.

Sample C is designed for the voltage tuning of orbital occupation in one device. It has a gate design shown in the lower figure of Fig. 1(a). We can control the size of the confinement and the coupling strength independently by tuning the gate voltages. (On the other hand, potential symmetry would be lowered compared to sample A and B.) This sample was fabricated from a wafer with sheet carrier density of $2.1 \times 10^{15} \text{ m}^{-2}$ and mobility of $32 \text{ m}^2/\text{Vs}$ at 4.2 K.

To explore the inner electronic states of the quantum dot, we measured the conductance of the wire G_w . The signals of the quantum dot appeared in G_w through two effects. The first is the charge detection effect. When N changes, the surrounding electrostatic potential also changes and this affects G_w [7]. The second is the interference effect. When the energy level in the dot matches the Fermi energy in the quantum wire, electrons have two representative paths. One of them directly goes through the wire and the other has a bounce to the dot. These paths produce the interference and G_w is changed [8]. In general, the mixed effects of the above two are observed in T-coupled quantum dots [9]. We measured G_w and used these effects to explore the electronic states in the dot. Following measurements were all performed at the base temperature of 30 mK.

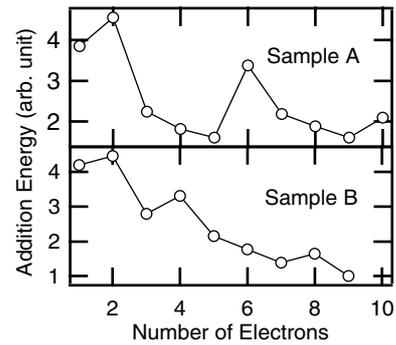


Figure 2 Addition energies for sample A and B.

3 Results and discussion

3.1 Occupation control through the gate size

Figure 1(b) shows typical data of the derivative of the wire conductance with respect to the plunger gate voltage dG_w/dV_p . On the condition that electron number changes, dips (or peaks) in the derivative signal emerges. The lower graph of Fig. 1(b) shows a gray scale plot of dG_w/dV_p as a function of the wire gate voltage and the plunger gate voltage. We can see vertical lines which consist of above mentioned dips. In the far negative region of V_p ($V_p < -0.8 \text{ V}$), we could not observe any lines and this corresponds to the $N = 0$ valley. We can count up N for each region from this valley and the resulting N are shown in the graph. Also the intervals of lines have the information of the needed energy to add an electron into the dot and we can obtain the relative addition energy.

Figure 2 shows the obtained addition energy. In the result of sample A, we can see clear peaks at $N = 2$ and 6 . These results are the consequence of the shell structure of 2-dimensional circular harmonic potential like the results reported in vertical quantum dots [1] and showing normal orbital level occupation from the lower energy orbital. But in sample B, the result becomes different. The peak at $N = 6$ disappears and the shell structure is broken.

To examine the detail of the electronic states in sample B, we performed magneto-spectroscopy and determined which orbital each electron occupies. We applied magnetic field perpendicular to the dot and measured G_w . The resulting dG_w/dV_p as a function of the plunger gate voltage and the magnetic field is shown in Fig. 3 with gray scale. The magnetic field dependence of the orbital energy appears in the shift of the dip position. The level crossings of orbitals produces kinks in the line of the dip movement. These features allow us to assign the orbital of each electron. In this process, we found non-monotonic occupation of orbitals in the enlarged area of Fig. 3. The figure shows fifth and sixth lines (from the bottom) have different slopes. This means the fifth and sixth electrons occupy different orbitals, and is consistent with the disappearance of the $N = 6$ peak in the addition energy. The same slope with fifth line is observed at eighth line and the orbital of fifth electron is filled at last

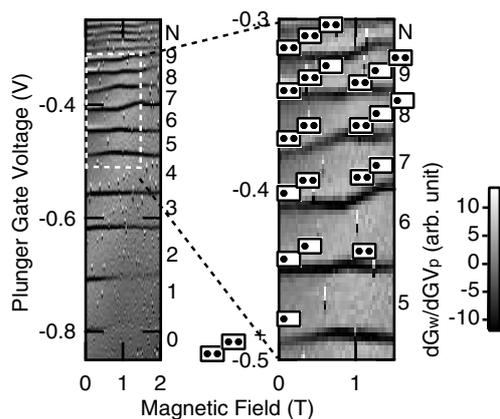


Figure 3 Gray scale plots of dG_w/dV_p as a function of the plunger gate voltage and the magnetic field in sample B. The $N = 5$ to 9 area is enlarged. The assigned occupation of orbitals is shown in the figure with boxes and dots; the boxes correspond to orbitals and the dots indicate occupying electrons. Higher position of the box means higher orbital energy.

by the eighth electron. This shows that the larger confinement is realized and the Coulomb interaction exceeds the orbital level spacing between the third and fourth lowest orbitals. These results demonstrate the control of the orbital level occupation through the gate size.

3.2 Voltage tuning of orbital occupation Finally, we report on the result of the voltage tuning of orbital occupation in sample C. Figure 4 shows the magnetic field dependence of dG_w/dV_p . The left and right figures show the results with the confinement gate voltage $V_{\text{conf}} = -0.24$ V and $V_{\text{conf}} = -0.26$ V, respectively. Tilting of the lines show the movement of the dip positions. Vertical stripes originate from the change of the wire state and are not the signal from the dot. In the case of $V_{\text{conf}} = -0.24$ V, the first and second lines show the similar magnetic field dependence and the first two electrons occupy the same lowest orbital. The third and fourth lines also shift in pairs, and the next two electrons occupy the second orbital. Monotonic occupation from the lower orbital is observed in this case. But the result becomes different, when we changed V_{conf} to -0.26 V. The first and second lines show different magnetic field dependencies, which means the second electron occupies the second orbital rather than fills the first orbital. This result shows the change of the orbital occupation at $N = 2$ with V_{conf} . In this sample C, the potential symmetry is lowered by its gate geometry. An elliptic confinement potential would be formed. By changing V_{conf} from -0.24 V to -0.26 V, the elliptic confinement with a long axis perpendicular to the quantum wire is elongated and produce larger confinement in the direction. This lowers the energy of the second orbital and Coulomb interaction becomes influential in or-

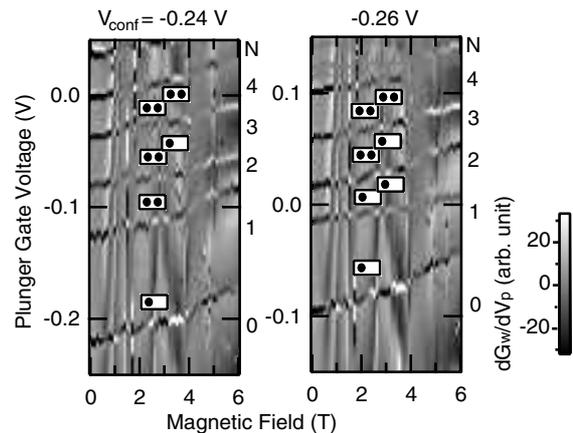


Figure 4 Gray scale plots of dG_w/dV_p in sample C. The left figure shows the result with the confinement gate voltage $V_{\text{conf}} = -0.24$ V and the right figure is the result with $V_{\text{conf}} = -0.26$ V.

bit level occupation. This result shows realization of the voltage tuning of orbital occupation.

4 Conclusion In summary, we have demonstrated the control of the orbital occupation by using the intra-orbital Coulomb interaction. With the change of the potential, intra-orbital Coulomb interaction could exceed orbital level spacing and affects the orbital occupation. The needed potential control was realized by changing the gate design or changing the voltages of the gates in one sample.

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