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Potential dependent intra-dot Coulomb interaction in quantum dots side-coupled to quantum wires

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Abstract

We present experiments on electronic states in few-electron lateral quantum dots side-coupled to quantum wires. The side-coupled structure enabled us to prepare the dots with various spatial sizes. The Coulomb energy and the quantum confinement energy depend on the dot size in different ways and thus the change in the size causes the change in the relative amplitude of the two energy scales. This results in non-monotonic occupation of single-electron energy levels. We have observed such non-trivial occupation through the collapse of the magic numbers and the response to magnetic field.

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Keywords: Quantum dot; Quantum wire; Coulomb repulsion

1. Introduction

Semiconductor quantum dots are termed 'artificial atoms' in that they show well-defined single-electron energy levels and shell structures when the confinement potentials have high spatial symmetries [1,2]. In real atoms, the spatial symmetry can be lowered, for instance, by attaching ligand fields. Such modification of potential alters not only the single-electron energy spectrum but also mutual Coulomb interaction. The latter results in complicated movements of many-body energy levels versus the strength of ligand fields.

In quantum dots, even more drastic change can be expected through direct control of confinement potential. However, an experimental obstacle is that the controllability is greatly reduced in few-electron regimes. In vertical type quantum dots, the orbital energy level spacing tends to be large [3,4] while in lateral type dots, the constraint to keep finite conductance largely limits the freedom in potential design [5].

Here we adopt side-coupled lateral geometry to avoid the above problems. This geometry has a single contact between the dot and the nearby wire and can have a large variety in the shape of potential. The difference in the confinement potential causes qualitative change in the order of occupation, which we observe through the collapse of the shell structure and the response to magnetic field.

2. Experiment

Fig. 1(a) is a scanning electron microscope (SEM) image of our device. In this side-coupled structure, the interference effect between the direct path and the path with a bounce to the dot is observed [6]. In addition, the change in the number of electrons in the dots is also detected through the electrostatic effect, i.e., so-called 'charge detection by quantum point contact' [7,8]. We use these effects to explore inner levels of the dot.

A wafer with a GaAs/AlGaAs interface 60 nm below the surface and sheet carrier density of $3.8\times10^{15}\,\mathrm{m}^{-2}$ and mobility of $90\,\mathrm{m}^2/\mathrm{V\,s}$ was processed into three samples, which have different scales in the gate electrodes. Sample A has the enclosed area for a quantum dot (indicated by the circle in Fig. 1(a)) of $150^2\,\mathrm{nm}^2$, which is larger than those for sample B and C ($110^2\,\mathrm{nm}^2$). The wire gate voltage V_w and the plunger gate voltage V_p are applied to adjust the

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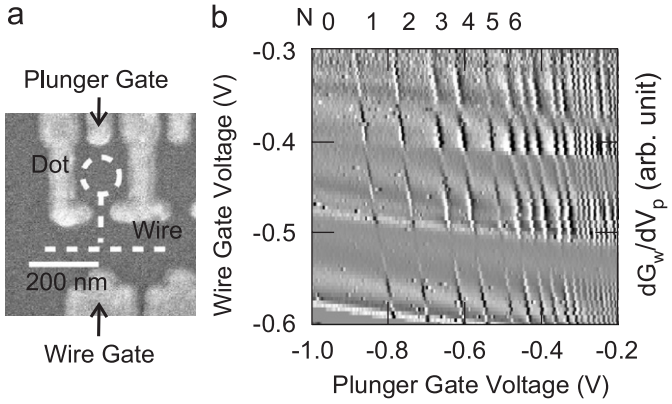

Fig. 1. (a) A SEM image of sample A. Visible are Au/Ti Shottkey gates (light gray) deposited on the wafer surface (dark gray). (b) Numerical differential of the conductance dG_w/dV_p as a function of V_p, V_w in sample B. In this sample, the effect of the charge detection is dominant.

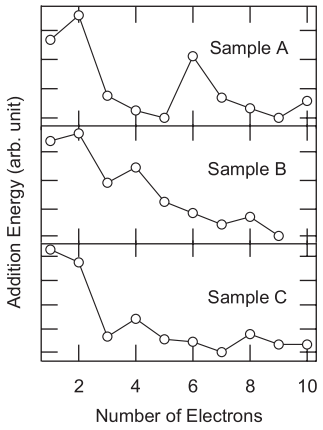

Fig. 2. Addition energy spectra of samples A, B and C.

number of conduction channels of the quantum wire and the number of electrons N in the dot, respectively.

To check the effect of the gate size, we performed simple simulation of electrostatic potential. We found that the larger gate size results in more closely packed equi-potential surfaces due to requirements of the larger negative gate voltages. In other words, the orbital level spacing increases with the gate size. Hence in samples B and C, the averaged level spacing is expected to be smaller than that in sample A.

The samples were cooled with a dilution refrigerator (base temperature of 30 mK), and the conductance through the wire G_w was measured using a standard lock-in technique.

3. Results and discussion

An increase or decrease of N causes a steep variation of G_w versus V_p, due to the interference and the electrostatic effect mentioned in the previous section. Hence the changes of N are detected by peaks (dips) in the derivative dG_w/dV_p. An example is shown in Fig. 1(b), where the derivative is plotted in a gray scale versus the V_p–V_w plane. Clear lines indicating peaks (dips) are running almost vertically. The small slanting of the lines mainly comes from the electrostatic coupling between the wire gate and the dot. The absence of lines at $V_p < -0.8$ V manifests that this region corresponds to the $N = 0$ valley, from which we can count up N at respective valleys. Note that the change in N is detected by the conductance through the wire, not through the dot, and we need not be bothered by the case in which unmeasurably small conductance through the dot hinders the detection of changes of N in the few-electron regime.

From the spacing of the adjacent lines, the addition energy E_{add} is obtained as shown in Fig. 2. In the present structure, the direct conduction through the dots cannot be measured and it is not possible to obtain the dot

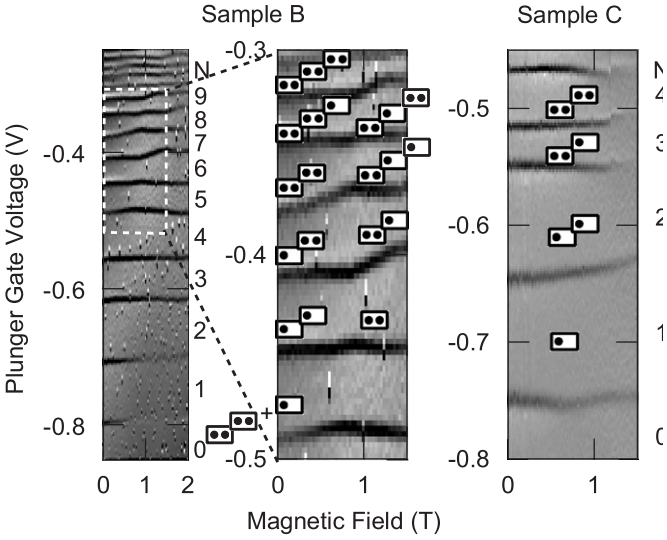

Fig. 3. Magnetic field dependence of dG_w/dV_p. The boxes with dots show level occupations. The data for sample C is numerically processed in order to align the lowest line at $V_w = -0.75$ V.

parameters directly from Coulomb diamonds structure. Hence here we only discuss the relative values of E_{add}.

In sample A, the spectrum has clear peaks at $N = 2$ and 6, corresponding to the first and second filled shells of a circular harmonic potential, respectively. The spectra dramatically change for samples B and C. The $N = 6$ peak disappears, and new peaks appear at $N = 4$ and 8. For sample C, even the $N = 2$ peak disappeared. The shell at $N = 6$ is the consequence of level degeneracy due to high spatial symmetry of the confinement potential, and its disappearance may be attributed to the asymmetry. On the other hand, the disappearance of the $N = 2$ peak cannot be interpreted from this perspective, as it originates from the Kramers degeneracy.

The addition energy spectrum alone is not sufficient to distinguish the single-electron orbital. To obtain insight into the level occupation, we apply magnetic field

perpendicular to the dot. Fig. 3 shows magnetic field dependence of dG_w/dV_p in a gray scale with V_p as the vertical axis. Slopes show magnetic development of orbital levels and kinks indicate level-crossings. These work as keys to assign orbitals. The Zeeman energy is negligible in the range of Fig. 3.

In sample B, the $N = 5$ and 6 lines have different slopes in low magnetic fields (<0.9 T), revealing the fifth and sixth electrons occupy different orbitals. Looking for the line with the same slope as the $N = 5$ line, we identify the orbital is filled at last by the eighth electron. These imply that filling the third lowest level with two electrons produces the large Coulomb repulsion between the two and the sixth and seventh electrons prefer to occupy the higher orbital. The boxes with dots given in Fig. 3 show level occupations. Each box indicates each orbital, and the inner dots show occupying electrons. Here, the higher positions of the boxes mean the larger energies of the orbitals. The level crossing occurs at around 0.9 T, and the orbital with large Coulomb repulsion moves to the $N = 7$ state at higher fields.

We are also able to assign the order of occupation in sample C, as displayed in Fig. 3. The $N = 1$ and 2 lines have different slopes, indicating that the second electron occupies the first excited level. This is in accordance with the disappearance of $N = 2$ peak in addition energy spectrum in Fig. 2.

Such 'non-monotonic' level occupation cannot be attributed to the potential asymmetry. Many-body effect originating from Coulomb interaction provides the most plausible explanation. As noted in the previous section, the single-electron level spacing is smaller in B and C. The Coulomb effect is also smaller due to the larger potential size. However the size dependencies of the level spacing and the Coulomb energy are different and the relative importance should change with the size. We thus infer that the size diminishment makes the Coulomb interaction effect more important and causes the observed non-trivial level occupation.

In summary, we have explored the level occupation of quantum dots in side-coupled geometry in few-electron regimes. We have found that diminishment of the gate size results in enhancement of the Coulomb interaction effect and non-monotonic level occupation breaking simple shell structure. The experiment demonstrates that we can control the relative importance of interaction effect through the confinement potential.

Acknowledgments

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