Electrical preparation and readout of a single spin state in a quantum dot via spin bias

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Based on the device in recent experiments [S. M. Frolov *et al.*, Phys. Rev. Lett. **102**, 116802 (2009); Nature (London) **458**, 868 (2009)], we propose an all-electrical scheme to prepare and readout a single spin state in a quantum dot (QD). We consider that the QD, which is subjected to a spin bias, has a single spin-degenerate energy level ϵ_d in the presence of Coulomb interaction U. By tuning the energy level controlled experimentally by a gate voltage, write in and read out the spin information can be achieved in the following way. When the level ϵ_d is within the spin bias window, a spin state can be written into the dot even for very weak spin bias. When both ϵ_d and ϵ_d+U are tuned to be out of the spin bias window, the initialized spin state can be preserved on the dot for a very long time (e.g., on the order of second), during which many qubit manipulations can be accomplished. Finally, by tuning the level ϵ_d+U to the spin bias window, the spin state can be read out by measuring the charge current.

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How to initialize and readout a single electron spin state in quantum dots (QDs) is one of the important issues in condensed-matter physics. Isolated QDs spin states have been proposed as an promising candidate for a quantum bit (qubit),[1] which is the basic requirement for quantum information processing. This issue is also extremely important in the realization of spintronics devices.[2] Recent advances in nanotechnology enable nearly complete control of the electronic properties of QDs. Single spin state has been prepared in QDs based on various methods, such as spin blockade,[3] optical pumping or laser cooling,[4–6] and photoluminescence polarization techniques,[7] etc. Using oscillating magnetic field,[3] ultrafast optical pulses,[4,8] and spin-to-charge conversion techniques,[9,10] the initialized spins of the dot can also be fully manipulated and read out. Although great progress has been made using methods mentioned above, how to precisely adjust the magnetic or optical field is still a formidable challenge.

Since the discovery of the giant magnetoresistance effect (GMR) in ferromagnetic and nonmagnetic alternating thin-film layers, spin-based devices have been intensively investigated both experimentally and theoretically. Compared with those conventional charge-based devices, spintronic devices have many attractive advantages, such as faster data-processing speed, less electric power consumption, increased integration densities, etc.[11,12] The relevant commercial products using GMR effect, for example, the magnetic field sensor and magnetic hard-disk read heads, have greatly influenced the development of current electronic industry. However, due to the low efficiency and various other drawbacks of traditional spin control methods, which mainly rely on optical techniques and the usage of magnetic field or ferromagnetic material, designing of a pure electrical manipulation scheme is an important research topic in last few years.[13] Very recently, pure spin current, which is one of the central issues in spintronics, was electrically generated in a microwide quantum wire defined by electrostatic gates on top of a GaAs/AlGaAs heterostructure.[14,15] A pure spin bias is generated in the quantum wire, in which the spin-up and spin-down chemical potentials ($\mu_\uparrow$ and $\mu_\downarrow$) are separated but $\mu_\uparrow+\mu_\downarrow$ keeps as a constant everywhere.[16] This spin bias can be detected by using a quantum point contact (QPC) or a coupled QD.[14,15,17] These detection schemes do not rely on optical equipment, magnetic material, or spin-orbit interactions, and hence the experimental complexity is greatly reduced. But till now, work about using the spin bias to prepare and detect a single spin state in a QD is still lacking, although a recent work has studied the spin manipulation and detection in a coupled QDs in terms of the spin bias.[18]

In this paper, based on the device of Refs. 14 and 15, we propose an all-electrical method to control a single spin state in a QD including the preparation of spin state in the QD and its readout, which may experience an arbitrary rotation.[19] By using several gates that are applied by the negative voltage, a QD is defined in the right side of the quantum wire [see Fig. 1(a)]. Other parts of the device are the same as those of Refs. 14 and 15. While a voltage is applied across the injector QPC, spin-polarized charge current enters into the quantum wire and flows into the left terminal of the quantum wire. In this process, spin population emerges near the QPC because of the spin-selective injector, driving a pure spin current to the right side of the quantum wire. This has been realized in recent experiments.[14,15] As a result, the spin-up and spin-down chemical potentials in the left lead of the QD ($\mu_{L\uparrow}$ and $\mu_{L\downarrow}$) are separated and a spin bias is generated accordingly. Hereafter, we assume that $\mu_{L\uparrow}=V_s$ and $\mu_{L\downarrow}=-V_s$ (V_s denotes the spin bias). The chemical potential in the right lead μ_R is still independent of spin and remains to be zero since there is no bias voltage on the QD. In the following we use this spin bias together with the gate voltage V_g which tunes the QD level to achieve the spin preparation and readout processes.

Let us first analyze the working principle of the spin preparation and spin readout. Figures 1(b) and 1(c), respectively, show the diagrams of the QD level and the corresponding gate voltage at three stages, the preparation, manipulation, and readout stages. Here we consider that the QD has a level ϵ_d with the spin degeneracy and the intradot electron-electron Coulomb interaction U. First in the spin

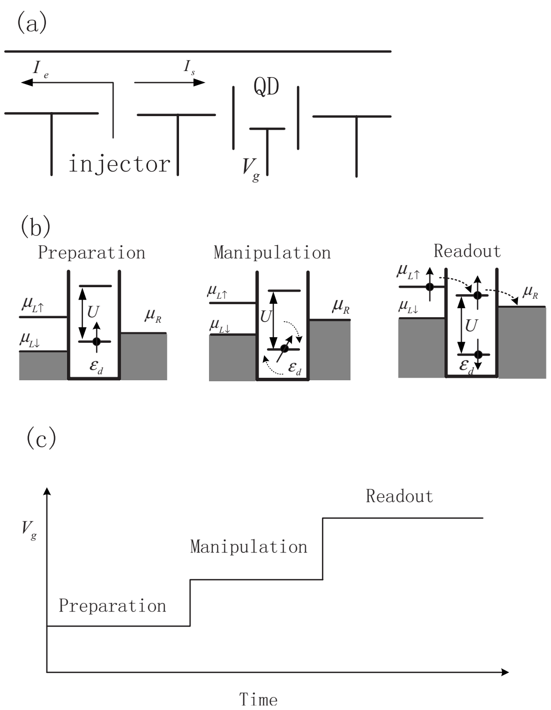

FIG. 1. (a) Schematic diagram for the proposed device in which a QD and a quantum wire are defined by some gates on top of a GaAs/AlGaAs heterostructure. (b) and (c) are, respectively, the QD's level diagrams and the corresponding gate voltage during the initialization, manipulation, and readout stages.

state preparation stage, the QD level ϵ_d is tuned to between the left-side spin-down chemical potential $\mu_{L\downarrow}$ and the right-side chemical potential μ_R. Due to the strong Coulomb interaction U, the level ϵ_d+U is much higher than all the chemical potentials ($\mu_{L\sigma}$ and μ_R), so the double-electron occupation cannot occur. Now spin-up electron can be injected into the QD because of $\mu_{L\uparrow}$, $\mu_R>\epsilon_d$ and the spin-down electron can tunnel out the QD to the left lead because of $\epsilon_d>\mu_{L\downarrow}$. If the device is kept in this stage for a period of time, the QD will be occupied by a spin-up electron regardless of its initial occupation state. In other words, at the end of the preparation stage, a spin-up state is written into the QD. In the second stage (manipulation stage), we tune V_g so that $\epsilon_d<\mu_{L\sigma}$ and $\mu_R<\epsilon_d+U$, which means that both the levels ϵ_d and ϵ_d+U are out of the spin bias window and no electrons can tunnel between the QD and the leads in the first-order tunneling process. So the spin state of the QD is quite stable and may be rotated by present technologies (such as oscillating magnetic field[3] or optical pulses[4]) or by using the spin bias itself. Finally in the readout stage, we continue to lower ϵ_d and set the energy level ϵ_d+U between $\mu_{L\uparrow}$ and μ_R. Now spin-up electron may tunnel through ϵ_d+U and the corresponding current magnitude depends on the spin state in ϵ_d, which is then detectable in terms of the current through the system.

The device can be described by the following Hamiltonian,

$$H=\sum_{\sigma}\epsilon_d d_\sigma^\dagger d_\sigma+Ud_\uparrow^\dagger d_\uparrow d_\downarrow^\dagger d_\downarrow+\sum_{k,\sigma,\alpha}\epsilon_{k\alpha\sigma}c_{k\alpha\sigma}^\dagger c_{k\alpha\sigma}+\sum_{k,\sigma,\alpha}(t_\alpha c_{k\alpha\sigma}^\dagger d_\sigma+\text{H.c.}), \quad (1)$$

where $d_\sigma^\dagger$ (d_σ) creates (annihilates) an electron in the QD with spin $\sigma(=\uparrow,\downarrow)$, $c_{k\alpha\sigma}^\dagger$ ($c_{k\alpha\sigma}$) is the creation (annihilation) operator of the electrons with momentum k, spin σ, and energy $\epsilon_{k\alpha\sigma}$ in lead α ($\alpha=L,R$); $t_{L(R)}$ describes the energy-independent QD-lead tunneling coupling constant. Here the main task is to calculate the time evolution of the electron number of each spin components in the QD and the current flowing through the whole system. Now the QD has total four possible electron states, namely, the empty state, the spin-up and spin-down occupied states, and the doubly occupied state, with their probabilities described by ρ_0, $\rho_\uparrow$, $\rho_\downarrow$, and ρ_d, respectively. The time evolutions of the probabilities obey the following master equations,[20]

$$\dot\rho_0=-f_{L\uparrow}(\epsilon_d)\Gamma_L\rho_0-f_{L\downarrow}(\epsilon_d)\Gamma_L\rho_0-2f_R(\epsilon_d)\Gamma_R\rho_0+\bar f_{L\uparrow}\Gamma_L\rho_\uparrow+\bar f_{L\downarrow}\Gamma_L\rho_\downarrow+\bar f_R\Gamma_R\rho_\uparrow+\bar f_R\Gamma_R\rho_\downarrow, \quad (2)$$

$$\dot\rho_\uparrow=f_{L\uparrow}(\epsilon_d)\Gamma_L\rho_0+f_R(\epsilon_d)\Gamma_R\rho_0+\bar F_{L\downarrow}\Gamma_L\rho_d+\bar F_R\Gamma_R\rho_d-\bar f_{L\uparrow}\Gamma_L\rho_\uparrow-\bar f_R\Gamma_R\rho_\uparrow-F_{L\downarrow}\Gamma_L\rho_\uparrow-F_R\Gamma_R\rho_\uparrow, \quad (3)$$

$$\dot\rho_\downarrow=f_{L\downarrow}(\epsilon_d)\Gamma_L\rho_0+f_R(\epsilon_d)\Gamma_R\rho_0+\bar F_{L\uparrow}\Gamma_L\rho_d+\bar F_R\Gamma_R\rho_d-\bar f_{L\downarrow}\Gamma_L\rho_\downarrow-\bar f_R\Gamma_R\rho_\downarrow-F_{L\uparrow}\Gamma_L\rho_\downarrow-F_R\Gamma_R\rho_\downarrow, \quad (4)$$

$$\dot\rho_d=-\bar F_{L\uparrow}\Gamma_L\rho_d-\bar F_{L\downarrow}\Gamma_L\rho_d-2\bar F_R\Gamma_R\rho_d+F_{L\uparrow}\Gamma_L\rho_\downarrow+F_R\Gamma_R\rho_\downarrow+F_{L\downarrow}\Gamma_L\rho_\uparrow+F_R\Gamma_R\rho_\uparrow, \quad (5)$$

where $\bar f_\beta=1-f_\beta(\epsilon_d)$, $F_\beta=f_\beta(\epsilon_d+U)$, and $\bar F_\beta=1-F_\beta$ with $\beta=L\uparrow,L\downarrow,R$. $f_\beta(\epsilon)=\{1+e^{(\epsilon-\mu_\beta)/k_BT}\}^{-1}$ is the Fermi distribution function of the left and right leads with chemical potential μ_β, temperature T, and Boltzmann constant k_B. $\Gamma_{L(R)}=2\pi\rho_{L(R)}|t_{L(R)}|^2$, where $\rho_{L(R)}$ is the density of states of the left (right) lead, denotes the coupling strength between the QD and the leads. In the above equations, we have dropped the time variable t in ρ for simplicity. Each term in Eqs. (2)–(5) describes a single tunneling process. For example, the first one to the right of Eq. (2) means that the QD is originally in empty state and a spin-up electron with energy ϵ_d tunnels from the left lead into it. Such a tunneling process has negative contribution to the empty state, which is indicated by the minus sign. As usual, the occupation probabilities must satisfy the normalization condition $\rho_0+\Sigma_\sigma\rho_\sigma+\rho_d=1$. After obtaining the probabilities $\rho_{0,\uparrow,\downarrow,d}$, the charge current flowing from the QD to the right lead is calculated straightforwardly as,[20]

$$I(t)/e=\bar f_R\Gamma_R[\rho_\uparrow(t)+\rho_\downarrow(t)]+2\bar F_R\Gamma_R\rho_d(t)-2f_R(\epsilon_d)\Gamma_R\rho_0(t)-F_R\Gamma_R[\rho_\uparrow(t)+\rho_\downarrow(t)], \quad (6)$$

where e denotes the absolute value of the electron charge. The number of electron in each spin component is given in terms of the occupation probabilities by $n_\sigma=\rho_\sigma+\rho_d$.

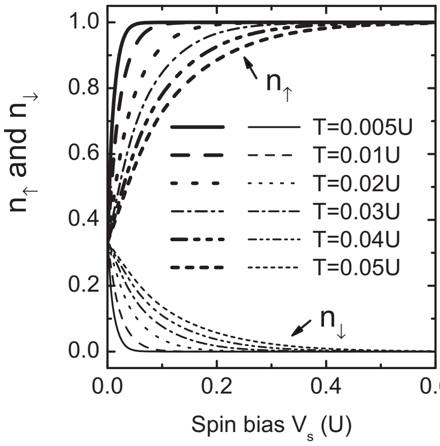

FIG. 2. Electron numbers $n_\uparrow$ (thick lines) and $n_\downarrow$ (thin lines) as a function of the spin bias for different temperatures.

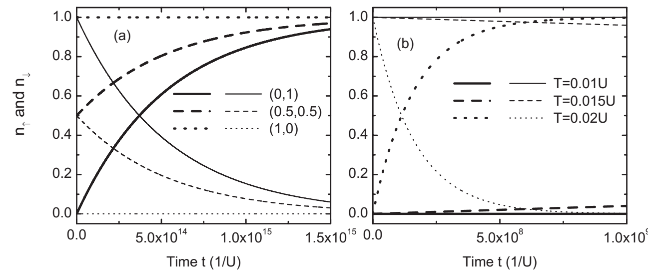

FIG. 3. (a) Time evolution of spin states $(n_\uparrow, n_\downarrow)$ for temperature $T=0.01U$. (b) Blowup of the time evolution of state (0,1) for different temperatures. The thick and the thin lines indicate $n_\uparrow$ and $n_\downarrow$, respectively. The spin bias V_s and the dot level ϵ_d are fixed at $0.2U$ and $-0.5U$, respectively.

In the following numerical calculations, we choose the intradot Coulomb interaction $U=1$ as the energy unit and fix $\Gamma_L=\Gamma_R=0.02$,[21] because Γ is one order of magnitude smaller than U in a typical QD. We also set $\hbar=e=k_B=1$ (unless noted otherwise), and then the temperature T and the reciprocal time $1/t$ are all in unit of energy. First, we study the preparation stage. We maintain the device in this stage for long enough time and it finally arrives at a steady state, so $\dot{\rho}(t)=0$.[20] By using $\dot{\rho}(t)=0$ combining with Eqs. (2)–(5) and the normalization condition, the probabilities in the steady state can be solved, and the number of electron n_σ are obtained straightforwardly. Figure 2 presents n_σ as a function of the spin bias V_s when the QD's level is at $\epsilon_d=-V_s/2$, i.e., it is located between μ_R and $\mu_{L\downarrow}$. For $V_s=0$, since all the chemical potentials are independent of spin, the numbers of spin-up and spin-down electron are equal to each other ($n_\uparrow=n_\downarrow$) as shown in the figure. With the increase in the spin bias, the QD is more likely to be occupied by a spin-up electron since $\epsilon_d<\mu_R$, $\mu_{L\uparrow}$, and $\epsilon_d>\mu_{L\downarrow}$. Typically, when $V_s>5T$, the difference between $n_\uparrow$ and $n_\downarrow$ is large enough to ensure the accomplishment of initializing a spin-up electron in the QD. For even larger spin bias, $n_\uparrow$ and $n_\downarrow$ approach to unit and zero, respectively. Let us now estimate the required value of the spin bias in this spin initialization stage. In the experiment, the value of the intradot Coulomb interaction can reach about $U=10$ meV.[22] For $T=1$ K, k_BT is then about 0.1 meV, which corresponds to $T=0.01$ in unit of U. Then the spin bias V_s is about $5k_BT\approx 0.5$ meV. Notice that the spin bias in recent experiment can reach as large as 5 meV.[14,15] With the increase in the temperature, it requires larger spin bias to inject spin-up electron into the QD as shown in Fig. 2. But even for the highest temperature $T=0.05$ studied here, the required spin bias is still smaller than that realized experimentally.[14,15]

After the initialization stage, we then lower the QD level so that it is out of the spin bias window with $\epsilon_d<\mu_{L\sigma}$, μ_R and $\epsilon_d+U>\mu_{L\sigma}$, μ_R. In this stage (the manipulation stage), the first order tunneling process cannot occur because of the Pauli exclusion principle and the Coulomb-blockade effect. Now the spin in the QD can be well maintained for a very long time. During this period one can take many spin manipulations. In the following we examine how long the spin can be maintained before evolving to other state. The time evolution of the occupation probabilities is calculated from the master Eqs. (2)–(5) and the normalization relation for a given initial state $[\rho_0(0),\rho_\uparrow(0),\rho_\downarrow(0),\rho_d(0)]$. Considering the arrangement of the QD level, we set $\rho_0(0)=0$ and $\rho_d(0)=0$ in the following calculation, and then the initial state can also be labeled as $[n_\uparrow(0),n_\downarrow(0)]$. As shown in Fig. 3(a), the single spin-up state (1,0) is very stable and does not change with time t (the dotted lines). The (0.5,0.5) and (0,1) states will evolve into the (1,0) state as shown by the solid and the dashed lines in Fig. 3(a). In particular, all the states can be well maintained up to 10^{13} time scale for temperature $T=0.01$. Assuming that $U=10$ meV and $T=1$ K for $k_BT\approx 0.01U=0.1$ meV, the time $t=10^{13}$ equals to $10^{13}\hbar/U\approx 0.6$ in unit of second. This means that all spin states can be well preserved up to the time scale of second for the system temperature of 1 K and $U=10$ meV. This time scale is long enough to carry many qubit manipulations. For example, the spin operation time is reported to be a few microseconds by applying oscillating magnetic field bursts in gated QDs.[3] Using optical pulses, the QD spin can even be rotated in picosecond time scale.[4,23] With the increase in the system temperature, the initial state will begin to evolve in shorter time scale [see Fig. 3(b)]. For example, when $T=0.015$ and 0.02, it starts to change at about 10^9 ($\approx 6\times 10^{-5}$ s) and 5×10^7 ($\approx 3\times 10^{-6}$ s), respectively. These time scales are still long enough for the qubit manipulation.

During the above discussions, we have only considered the influence of the QD-lead coupling on the spin state lifetime. In real devices, there are also other scattering mechanisms, such as magnetic impurities, nuclear spins, spin-orbit interaction, and phonon. These extra scattering mechanisms limit the spin lifetime, in particularly, at very low-temperature regime (e.g., $T<0.01$). Some recent theoretical and experimental works have investigated the spin lifetime. Their results exhibited that the spin lifetime can reach millisecond or second time scales.[9,24–26] In fact, the millisecond spin lifetime is still enough long to accomplish many spin operations.

Let us discuss how to manipulate the spin state in the QD. There have been many spin-rotation methods, such as oscillating magnetic field[3] or optical pulses.[4] These methods can also be applied to the present spin state. But they are not electrical ones. Here we propose an all-electrical scheme to manipulate the spin state by the spin bias. The spin bias is a vector and its spin-polarized direction can be experimentally tuned. When the spin-polarized direction of the spin bias is different from the spin direction of the spin state, the spin bias can cause a spin torque on the spin state.[27] Then it induces the precession of the spin and can realize the manipulation of the spin state.

In the readout stage, our aim is to measure the spin state in the QD. Here we propose a fast and all-electrical readout method. At the end of the manipulation stage, the level is lowered further by the voltage V_g. Now ϵ_d+U is located between $\mu_{L\uparrow}$ and μ_R [see Figs. 1(b) and 1(c)] and allows the transport process of spin-up electrons. If the level ϵ_d is originally occupied by a spin-down electron, a spin-up electron can tunnel from the left lead through the QD to the right lead because of $\mu_{L\uparrow}>\epsilon_d+U>\mu_R$, and a finite charge current $I(t)$ emerges. On the other hand, if there is a spin-up electron on ϵ_d, spin-down electron cannot transport through the QD because the level ϵ_d+U is not in the spin-down bias window. In addition, the spin-up electron cannot leave the QD because of $\epsilon_d<\mu_{L\uparrow}$, μ_R, and the Pauli exclusion principle. In this case the charge current is very small. So we can read out the spin state by measuring the charge current.

Figure 4(a) shows the time-dependent current $I(t)$ for three possible initial states $(n_\uparrow, n_\downarrow)$. As shown by the dotted line, the current for state (1,0) is always very small because there is a spin-up electron on ϵ_d. When the QD is partially or totally occupied by a spin-down electron, e.g., for states of (0.5,0.5) and (0,1), the current is generated at $t=0-300$. Meanwhile, the magnitude of the current of state (0,1) is larger than that of (0.5,0.5). $I(t)$ approaches to zero for sufficiently long time since all the states will eventually evolve to (1,0). The current has a maximum value at about $t=30$. Therefore, the spin state can be read out at $t<30$. As was estimated above, $t=30$ in unit of U^{-1} corresponds to several picoseconds if $U=10$ meV, which is comparable to the time in experiments based on optical pulses.[4,23] In Fig. 4(b), we show the current $I(t)$ as a function of the initial spin-down electron occupation number $n_\downarrow$ at different time t. The current linearly increases with $n_\downarrow$. In particular, the linear relation of the current with $n_\downarrow$ keeps very well in the whole region because the split of the states ϵ_d and ϵ_d+U is much larger than Γ and k_BT. This means that we can directly read out the spin state by measuring the current. Finally, we show the total number of charge Q [$Q\equiv\int_0^\infty I(t)dt$] flowing through the QD in the readout stage [see the dotted line in Fig. 4(b)]. The dependence of Q on $n_\downarrow$ exhibits a well linear relation as well. So by measuring the number of charge Q, one can also read out the spin state. In fact, this readout method is more feasible experimentally because that we do not need to fix the time t.

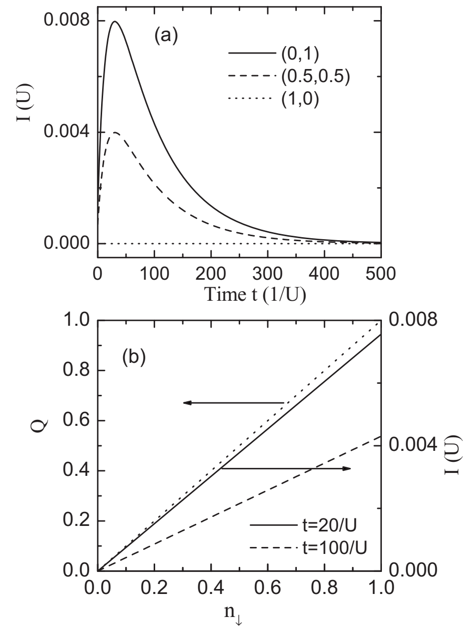

FIG. 4. (a) Charge current vs time t for different spin states $(n_\uparrow, n_\downarrow)$. (b) Charge current and charge number as a function of the spin-down electron number $n_\downarrow$ measured at different time. Other parameters are chosen as $T=0.01U$ and $\epsilon_d=-0.9U$.

In summary, we propose an all-electrical scheme to initialize and read out a single spin state in a QD. The single spin state can be prepared in the QD by properly adjusting its energy level using the gate voltage in the presence of a weak spin bias. The estimated spin bias magnitude is within the reach of current experiments. The initialized spin can be maintained on the dot by tuning the dot level to a suitable regime. In this stage, the spin state lifetime can reach on the time scale of second, which is long enough to perform many qubit manipulations with the existing methods. In the readout stage, we find that the charge current and the number of charge flowing through the dot depend linearly on the spin-down occupation number, thus the spin state can be detected by measuring the charge current or the number of charge.

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