Spin singlet-triplet transition in a Si-based two-electron double quantum dot molecule

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We report a successful measurement of the magnetic field-induced spin singlet-triplet transition in silicon-based coupled dot systems. Our specific experimental scheme incorporates a lateral gate-controlled Coulomb-blockaded structure in Si to meet the proposed scheme of Loss and DiVincenzo [1], and a non-equilibrium single-electron tunneling technique to probe the fine energy splitting between the spin singlet and triplet, which varies as a function of applying magnetic fields and interdot coupling constant. Our results, exhibiting the singlet-triplet crossing at a magnetic field for various interdot coupling constants, are in agreement with the theoretical predictions, and give the first experimental demonstration of the possible spin swapping occurring in the coupled double dot systems with magnetic field.

There are several proposals for scalable solid-state quantum bits (qubits). One type is charge qubits, such as superconducting boxes and excitons [2, 3]. The other type is spin qubits, whose dephasing times can be on the order of microseconds, several orders longer than those of charge qubits. Loss and DeVincenzo [1] first proposed a quantum gate mechanism based on spins of two laterally coupled QDs containing two electrons. In such a two-electron double QD the ground-state spin configuration can be either spin-singlet (S=0) or spin-triplet state (S=1), depending on the values of applied magnetic field and interdot coupling constant. The most remarkable feature is that the spin exchange J changes its sign from a positive to negative value at some magnetic field over a wide range of the interdot coupling constant. This singlet-triplet crossing at a magnetic field is an essential feature of their proposal for the quantum-gate operation since it allows making a spin swap, which can, combined with single-qubit rotations, assemble all quantum algorithms. This change of sign in J can be induced by magnetic and/or electric fields.

Despite its fundamental and practical importance, the progress in the experimental study of the spin exchange in the two coupled dots has been considerably slow as compared to extensive works for mesoscopic studies on electron transport [4]. This is not only because two-dimensional (2D) size fluctuations for each dot occurring during the fabrication process are inevitable, but also because it is difficult to probe the fine energy difference between spin singlet and triplet states of two electrons in the coupled QD systems. In our work we have overcome these difficulties by incorporating two specific experimental schemes for probing the spin exchange. Firstly, lateral gate-controlled Coulomb-blockade structures consisting of two coupled Si QDs are used. The gated Coulomb-blockade structure is essential since it can control both the number of electrons N and the interdot coupling constant in the double dots. The Coulomb blockade regime corresponding to N=2 must be specified, which meets the proposed scheme of Loss and Divincenzo [1]. Moreover, electrons in Si have extremely long spin lifetimes of about ms which is due to silicon's very weak spin-orbit coupling (~10⁴ times low as compared to GaAs [5–7]). Secondly, the single-electron tunneling spectroscopy in the presence of a finite source drain voltage allows us to probe the fine structures of the coupled double dots corresponding to the excited states as well as the ground states. This non-equilibrium transport spectroscopy was already used successfully to probe the excited states of a single quantum dot [8]. Here we report a successful measurement of the magnetic field-induced spin singlet-triplet transition in silicon-based coupled dot systems. Our results, exhibiting the singlet-triplet crossing at a magnetic field for various interdot coupling constants, are in agreement with the theoretical predictions, and give the first experimental demonstration of the possible spin swapping occurring in the coupled double dot systems in the presence of a magnetic field.

The lateral gated-two coupled dots were fabricated on silicon-on-insulator (SOI) structure by pattern-dependent oxidation (PADOX) method. The SOI wafer, prepared by unibond method, consists of p-type Si substrate, 180nm-buried SiO₂ and 80nm-top Si. Figure 1 shows a schematic diagram of the resulting Coulomb-blockaded device structure and a scanning electron micrograph picture of the active channel which consists of two coupled QDs. The channel was first defined by e-beam lithography and followed by reactive ion etching to a narrow wire of 100nm-length and 15nm-width which abruptly widens into source and drain carrier reservoirs. Subsequent PADOX process (i) further reduces the silicon channel, (ii) generates a small quantum island with a 80nm-length and 10nm-width by oxidation-induced stress at the central part of the wire, and (iii) creates tunnel barriers at both sides in a self-aligned manner [9 – 11]. Three independent metal gates are incorporated to the Coulomb island. Biasing the middle side gate results in a stronger electrostatic effect on the current channel and produces a potential barrier at the middle point in the channel, yielding two identical dots of a size < 30x10nm each. Both end-side gates Vgg1 and Vgg2 are auxiliary gates designed to give, respectively, electrostatic contact potential barriers between the source and channel and between the drain and channel, in addition to two tunnel barriers at both sides of the Coulomb island channel already generated in a self-aligned manner by oxidation-
induced stress of the PADOX process. The effect of interdot coupling on the SET current can be explored from weak to strong coupling regimes by adjusting the middle inter-gate $V_{sg2}$.

Single-electron tunneling measurements were carried out in a non-equilibrium transport regime. Figure 2(a) shows typical SET currents measured as a function of top-gate voltage under a bias. Some of our samples exhibit a modulation beating in Coulomb oscillations, probably due to disorder in the dots. In contrast, samples studied here do not display such a beating, which indicates that two coupled dots are nearly identical to each other. This is mainly because two coupled dots are formed simultaneously in the same channel by the electrostatic potential barrier at the middle point. The first current peak appears at $V_g=3.15V$. Its magnitude is very weak, only a few pA level as compared to other peaks, but still clearly seen for all magnetic fields. The amplitudes of the Coulomb peaks fall exponentially with decreasing $V_g$, and extrapolate to zero near the small peak at $V_g=3.15V$. This is consistent with the theory that the transmission peak amplitudes fall exponentially with electron number. Moreover, as seen in Fig. 2(b), the slope of the first Coulomb diamond becomes nearly infinite, in contrast to those of the 2nd and 3rd diamonds, which indicates no further Coulomb peak is present below 3.15V. Therefore, we identify the first peak as the current associated with the tunneling of the first electron into the dot system. We focus on the 2nd current peak since it corresponds to the electron transport through the energy states of two-electron coupled QDs. This 2nd Coulomb peak is seen to split into a set of two peaks. We point out that the higher energy peak in the 2nd current set starts to appear when $V_{ds}>500\mu V$, as seen in Fig. 2(b), which is a grey scale contour plot of $I_{ds}$ as a function of $V_{ds}$ and $V_g$. This implies that transport occurs in the non-equilibrium regime for $V_{ds}>500\mu V$ and the higher peak corresponds to the excited state of the two-electron QDs, while the lower peak its ground state. The x- and y-scales of the Fig. 2(b) are chosen to make a clear display of the bias-dependent spin splitting. To prevent the sample from a possible damage due to the high voltage bias we did not measured $I-V_g$ when the bias voltage is above 10mV. However, one can already see the presence of a half diamond in the range 3.27-3.33V.

We explain qualitatively the feature of the 2nd set of two peaks as follows. Fig. 3 illustrates the schematic diagram for the lateral potential energy of the two coupled QD system in a non-equilibrium regime. The ground state of the double dot is assumed to be the spin singlet state. The 2nd electron tunnels through the singlet ground state $\epsilon_s$ when the value of the top-gate voltage $V_g$ is such that the singlet state approaches the Fermi level of the source metal (Fig. 3(a)). This gives a rise to the 1st peak in the 2nd set of two peaks. When $V_g$ increases further, the singlet ground state goes down below the bottom of the energy of the source metal, and the current stops to flow since there is no density of states (DOS) in the source metal available for tunneling (Fig. 3(b)). In this regime, the current is zero, not because it is Coulomb-blockade, but because of the absence of available DOS. When $V_g$ increases even more, an excited triplet-state goes down below $\epsilon_t$ of the source (Fig. 3(c)), and the 2nd electron can now tunnel through the triplet state. Finally, when $V_g$ increases further and the triplet state goes down below the bottom of the energy of the source (Fig. 3(d)), the current stops again. According to this model, the currents of the 2nd set of two peaks flow always through either singlet or triplet states of two electrons in the double dot. We remark here that this explanation is valid because the DOS of 2DEG source is small, $D_s=5x10^{10}cm^{-2}$, and its corresponding Fermi level $\epsilon_f \approx 300\mu eV$. Moreover, the single-electron charging energy $U$,
is the characteristic frequency of each dot, which results in only one peak even in the equilibrium magnetic field dependence of the 2nd set of two current peaks measured at 1.5K. As magnetic field increases the split between two peaks becomes decreasing first, approaching almost zero at B≈3T. For B>3T, it increases again and finally decreases to zero.

Burkard et al have calculated the exchange energy J of two electrons in coupled dots defined by the potential, 
$$V(x,y) = \frac{m\omega^2}{2} \left[ \frac{1}{4a^2} (x^2-a^2)^2 + y^2 \right] + e\alpha E,$$
where $2a$ is the interdot distance, $\omega$ is the characteristic frequency of each quantum dot potential, $m$ is the effective mass, and $E$ is the electric field between the source and drain. We calculate the energy difference between the lowest energy the triplet state and the singlet state using the expression for J...
obtained by Burkard et al. The inset in Fig. 5 displays this energy difference $J$ for three different values of $\alpha$. We have used the following parameters: the characteristic frequency of the quantum dot $\omega = 1.5 \text{meV}$, Si effective mass of $0.2m_0$, the interdot distance $2d = 19.6, 19.8, 20\text{nm}$, the Zeeman splitting $g\mu_B B = 0.1168[\text{meV}]$, and the voltage drop between the dots $eE_a = 3.5 \text{meV}$. Note that overall features of the magnetic field dependence are in qualitative agreement with the measured values. (The experimental data can be also fitted using a slightly different model which contains the barrier height as an input parameter [15]. In this model the values of $J$ for different barrier heights will cross each other at some magnetic field values, in agreement with the experimental data. In this model the absolute magnitude of $J$ is always the largest for the smallest barrier height, in disagreement with the experimental data for high-field regime of $B > 5\text{T}$). From these theoretical considerations we estimate that $J$ is of order $1\text{meV}$. Figure 6 shows the inter-gate voltage dependence of the split of two peaks at a fixed magnetic field. As illustrated in the inset, for three different magnetic fields the splits decay exponentially as a function of the interdot coupling, which is also consistent with the theoretical prediction on the exchange coupling for large interdot distance [14, 15]. This agreement implies that adjusting the central potential barrier and/or interdot separation by the inter-gate voltage can give an efficient control of the splitting between the singlet and triplet states.

The vanishing of $J$ at a magnetic field can be exploited for spin swapping and for the implementation of two-qubit gate. A constant uniform magnetic field $B \approx 3\text{T}$ can be applied to the two coupled QDs to tune $J$ close to zero, and following this a small gate pulse or a small local magnetic field can be applied for switching $J$ on and off. Note that our coupled two-dot system was fabricated on silicon wafer. Electrons in silicon are very promising for spintronics and quantum information processing since they have extremely long spin lifetimes of about ms which is due to silicon's very weak spin-orbit coupling. Moreover, the silicon VLSI technology is expected to accelerate our progress towards solid-state implementations of the scalable quantum computer in Si.

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