

Gate-controllable spin battery

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We propose a gate-controllable spin-battery for spin current. The spin battery consists of a lateral double quantum dot under a uniform magnetic field. A finite dc spin current is driven out of the device by controlling a set of gate voltages. Spin current can also be delivered in the absence of charge current. The proposed device should be realizable using present technology at low temperature. © 2003 American Institute of Physics. [DOI: 10.1063/1.1603331]

To be able to generate and control spin current is of great importance for spintronics.¹ Traditionally, spin injection from a ferromagnetic material to a normal metal or semiconductor material has been used to obtain spin polarized charge current. Spin injection into non-Fermi liquid² as well as by circularly polarized light³ have also been investigated. More recently, several theoretical proposals for spin battery were reported for the generation of pure spin current without charge current.^{4–6} The idea is that when spin-up electrons move to one direction while an equal number of spin-down electrons move to the opposite direction, the net charge-current $I_e = e(I_{\uparrow} + I_{\downarrow})$ vanishes and a finite spin current $I_s = \hbar/2(I_{\uparrow} - I_{\downarrow})$ emerges. Here $I_{\uparrow}$ ($I_{\downarrow}$) is the spin-up (spin-down) electron current. Although conceptually interesting, existing spin-battery proposals all involve time dependent external fields^{4–6} which make practical realization somewhat complicated. It is the purpose of this letter to propose and investigate a spin-battery design which is gate controllable involving no time varying fields.

The gate controllable spin battery is schematically shown in Fig. 1. It consists of a lateral double quantum-dot (QD) fabricated in two-dimensional electron gas (2DEG) with split gate technology. The two QDs are coupled to three leads: lead-1 and 3 couple to one QD each, lead-2 couples to both. The two QDs are separated by a high potential barrier so that tunnel coupling between them can be neglected. To distinguish spin of the electrons, a magnetic field B is applied to the QDs to induce a Zeeman splitting. Two gate voltages $V_{g,\alpha}$ control energy levels of the α -th QD, where $\alpha = \text{upper, lower}$ (u, l), indicating the upper and lower QD of Fig. 1. Finally, the terminal voltages for the three leads are set such that $V_1 > V_2 > V_3$ (Fig. 2), they provide energy source for the spin battery.

Before presenting results, we first discuss why the system of Fig. 1 can deliver a spin current. Due to field B , a spin degenerate level ϵ_{α} of the α -QD is split into spin-up/down levels $\epsilon_{\alpha\uparrow}/\epsilon_{\alpha\downarrow}$. Let us assume $\epsilon_{\alpha\uparrow} < \epsilon_{\alpha\downarrow}$. By adjusting

gate voltages $V_{g,\alpha}$, we shift these levels. In particular, we set $V_{g,\text{lower}}$ such that electron occupation number in the lower QD is changing between 0 and 1 (even to odd), with the level $\epsilon_{\text{lower},\uparrow}$ locating between μ_1 and μ_2 , where $\mu_i = eV_i$ is the chemical potential of lead i . Similarly, we set $V_{g,\text{upper}}$ such that the upper QD has an electron occupying state $\epsilon_{\text{upper},\uparrow}$, while the other state $\epsilon_{\text{upper},\downarrow}$ is pushed to higher energy $\epsilon_{\text{upper},\downarrow} + U$ due to Coulomb interaction U . This way, the electron occupation number in the upper QD is changing between 1 and 2 (odd to even), and the level $\epsilon_{\text{upper},\downarrow} + U$ locates between μ_2 and μ_3 . The energy level diagram shown in Fig. 2 is now established. From Fig. 2, it is clear that a spin-up electron in lead-1 can tunnel into the lower QD and further to lead-2. Similarly, a spin-down electron in lead-2 can tunnel into the upper QD and flows to lead-3. Therefore, in lead-2 spin-up electrons flow in and spin-down electrons flow out: they move in opposite directions so that a net spin current is generated. Hence, by adjusting gate potentials the device of Fig. 1 generates a spin current in the region labeled by (A,B).

We now present detailed analysis. The lateral double-QD device is described by the following Hamiltonian:

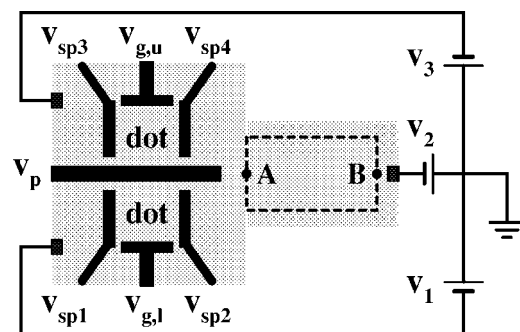


FIG. 1. Schematic diagram for the lateral quantum dot. The lightly shaded region represents two-dimensional electron gas, the darker regions are the metal gates (including split gates $V_{\text{sp},i}$, V_p , and gate voltage $V_{g,\alpha}$). The dotted box represents the region in which a pure spin current flows through.

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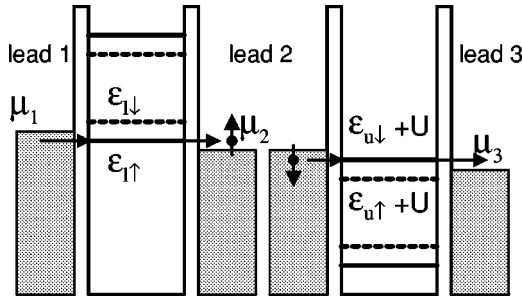


FIG. 2. Schematic plot of energy level position and the tunneling process during spin-battery operation.

$$H = \sum_{\alpha\sigma} (\epsilon_{\alpha} - \sigma g \mu_B / 2) d_{\alpha\sigma}^{\dagger} d_{\alpha\sigma} + \sum_{\alpha} U_{\alpha} d_{\alpha\uparrow}^{\dagger} d_{\alpha\uparrow} d_{\alpha\downarrow}^{\dagger} d_{\alpha\downarrow} + \sum_{nk\sigma} \epsilon_{nk} a_{nk\sigma}^{\dagger} a_{nk\sigma} + \sum_{nk\sigma\alpha} (t_{n,\alpha} a_{nk\sigma}^{\dagger} d_{\alpha\sigma} + \text{H.c.}) \quad (1)$$

where $a_{nk\sigma}^{\dagger}(a_{nk\sigma})$ and $d_{\alpha\sigma}^{\dagger}(d_{\alpha\sigma})$ are creation (annihilation) operators in lead- n and the α -QD, respectively. Each QD has a single particle energy level ϵ_{α} with spin index σ , and the intradot Coulomb interaction is U_{α} . To account for magnetic field B , ϵ_{α} has a term $-\sigma g \mu_B / 2$ where g is a constant. We permit $U_{\text{upper}} \neq U_{\text{lower}}$ and $B_{\text{upper}} \neq B_{\text{lower}}$, but these details do not affect our general results. The last term in the Hamiltonian describes the coupling between the QDs and the leads, and $t_{n,\alpha}$ is the coupling strength. We set $t_{1,\text{upper}} = t_{3,\text{lower}} = 0$, meaning there is no coupling between the upper-QD and lead-1 and between the lower-QD and lead-3.

We solve electron current $I_{n,\sigma}$ using standard Keldysh nonequilibrium Green's function method (NEGF)⁷ ($\hbar = 1$): $I_{n\sigma} = -2e \text{Im} \sum_{\alpha} f_n(\epsilon) \Gamma_{n\alpha} [f_n(\epsilon) G_{\alpha\sigma}^r(\epsilon) + \frac{1}{2} G_{\alpha\sigma}^<(\epsilon)]$ where $\Gamma_{n,\alpha} \equiv 2\pi \sum_k |t_{n,\alpha}|^2 \delta(\epsilon - \epsilon_{nk})$ is the linewidth function. $f_n(\epsilon)$ is the Fermi distribution function in lead- n . The NEGF $G_{\alpha\sigma}^r(\epsilon)$ is the Fourier transform of $G_{\alpha\sigma}^r(t)$: with $G_{\alpha\sigma}^r(t) \equiv -i \theta(t) \langle \{d_{\alpha\sigma}(t), d_{\alpha\sigma}^{\dagger}(0)\} \rangle$ and $G_{\alpha\sigma}^<(t) \equiv i \langle d_{\alpha\sigma}^{\dagger}(0) d_{\alpha\sigma}(t) \rangle$.

We solve the retarded Green's function $G_{\alpha\sigma}^r$ in by the standard equation of motion technique where indirect tunneling processes such as upper QD $\rightarrow$ lead-2 $\rightarrow$ lower QD are neglected, this is reasonable because the long middle barrier between the QDs helps to block such events to a large extent. We obtain⁶

$$G_{\alpha\sigma}^r(\epsilon) = \frac{\epsilon_{\alpha\sigma}^{-} + U_{\alpha} n_{\alpha\sigma}^{-}}{(\epsilon - \epsilon_{\alpha\sigma}) \epsilon_{\alpha\sigma}^{-} + \frac{i}{2} \Gamma_{\alpha} (\epsilon_{\alpha\sigma}^{-} + U_{\alpha} n_{\alpha\sigma}^{-})}, \quad (2)$$

where $\epsilon_{\alpha\sigma}^{-} \equiv \epsilon - \epsilon_{\alpha\sigma} - U_{\alpha}$, $\epsilon_{\alpha\sigma} \equiv \epsilon_{\alpha} - \sigma g \mu_B / 2$, $\Gamma_{\alpha} = \sum_n \Gamma_{n\alpha}$, and $n_{\alpha\sigma}^{-}$ is the intradot occupation number of state $\bar{\sigma}$ in the α -QD. $n_{\alpha\sigma}^{-}$ needs to be calculated self-consistently from the self-consistent equation $n_{\alpha\sigma}^{-} = -i \int (d\epsilon / 2\pi) G_{\alpha\sigma}^<(\epsilon)$. As usual, $G_{\alpha\sigma}^r(\epsilon)$ has two resonances: one at energy $\epsilon_{\alpha\sigma}$ for which the associated state $\epsilon_{\alpha\sigma}^{-}$ is empty; the other is at $\epsilon_{\alpha\sigma} + U_{\alpha}$ for which the associated state $\epsilon_{\alpha\sigma}^{-}$ is occupied.

Following the approach of Ref. 8, we obtain $\int d\epsilon G_{\alpha\sigma}^<(\epsilon)$ which is needed in computing current and occupation number

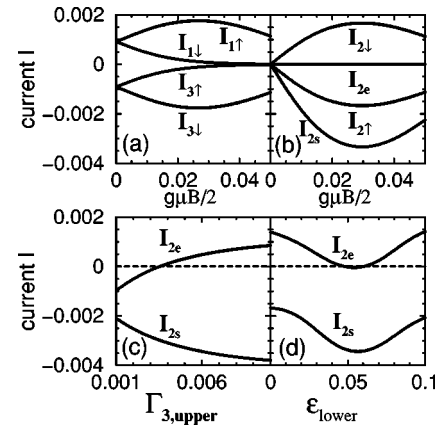


FIG. 3. (a) and (b) for electron currents $I_{n\uparrow}$ and $I_{n\downarrow}$, charge current I_{2e} (unit e), and spin current I_{2s} (unit $\hbar/2$), vs magnetic field parameter $g\mu_B/2$. Other parameters are $\Gamma_{1,\text{lower}} = \Gamma_{2,\text{lower}} = \Gamma_{2,\text{upper}} = \Gamma_{3,\text{upper}} = 0.005$, $k_B T = 0.01$, $U_{\text{lower}} = 1.0$, $U_{\text{upper}} = 0.9$, $\epsilon_{\text{lower}} = \mu_1$, and $\epsilon_{\text{upper}} + U_{\text{upper}} = \mu_3$. (c) I_{2e} and I_{2s} vs $\Gamma_{3,\text{upper}}$ with $g\mu_B/2 = 0.03$. Other parameters are: $\Gamma_{1,\text{lower}} = 0.004$, $\Gamma_{2,\text{lower}} = 0.005$, and $\Gamma_{2,\text{upper}} = 0.006$. (d) I_{2e} and I_{2s} vs ϵ_{lower} with $g\mu_B/2 = 0.03$. Here $\epsilon_{\text{upper}} + U_{\text{upper}} = -0.06$ which is slightly different from $\mu_3 = -0.05$. Other parameters in (c) and (d) are the same as those in (a) and (b).

$$\int \frac{d\epsilon}{2\pi} G_{\alpha\sigma}^<(\epsilon) = - \int \frac{d\epsilon}{2\pi} \sum_n \frac{\Gamma_{n\alpha} f_n}{\Gamma_{\alpha}} [G_{\alpha\sigma}^r(\epsilon) - G_{\alpha\sigma}^a(\epsilon)].$$

This completes the analytical derivation.

We set bias voltages $\mu_1 = 0.05$, $\mu_2 = 0$, $\mu_3 = -0.05$ so that $\mu_1 > \mu_2 > \mu_3$. We set gate voltages $V_{g,\alpha}$ such that at zero magnetic field, $\epsilon_{\text{lower}} = \mu_1$ and $\epsilon_{\text{upper}} + U_{\text{upper}} = \mu_3$. With this condition there is one electron in the upper QD. Figures 3(a) and 3(b) shows electron current $I_{n\uparrow}$ and $I_{n\downarrow}$; charge current in lead-2 $I_{2e} = e(I_{2\uparrow} + I_{2\downarrow})$; and spin current in lead-2 $I_{2s} = (\hbar/2)(I_{2\uparrow} - I_{2\downarrow})$, versus a uniform field strength B . At zero B , electron current is nonpolarized so that $I_{n\uparrow} = I_{n\downarrow}$, and both I_{2e} and I_{2s} vanish. When B increases from zero, the intradot level ϵ_{α} is split. Then levels $\epsilon_{\text{lower},\uparrow}$ and $\epsilon_{\text{upper},\downarrow} + U_{\text{upper}}$ are moved into the bias “window” between $\mu_1(\mu_3)$ and μ_2 , while levels $\epsilon_{\text{lower},\downarrow}$ and $\epsilon_{\text{upper},\uparrow} + U_{\text{upper}}$ are moved out of the window, see Fig. 2. In this situation the electron current in lead-1 and lead-3 are polarized with $I_{\alpha\uparrow} \neq I_{\alpha\downarrow}$. Moreover, we have $|I_{1\uparrow}| > |I_{1\downarrow}|$ and $|I_{3\uparrow}| < |I_{3\downarrow}|$. In the following, we focus on current in lead-2, shown in Fig. 3(b). In lead-2 the value of electron current $I_{2\uparrow}$ equals to the value of $I_{2\downarrow}$, but their flow direction is exactly opposite to each other, hence, we have $I_{2\uparrow} = -I_{2\downarrow}$. We therefore obtain zero charge current $I_{2e} = 0$; and a net spin current I_{2s} emerges. When parameter $g\mu_B/2 \approx 0.03$, the intradot levels $\epsilon_{\text{lower},\uparrow}$ and $\epsilon_{\text{upper},\downarrow} + U_{\text{upper}}$ are in the middle of the bias window, leading to the maximum spin current. If field B increases further, the spin current slightly decreases.

The device discussed here should be realizable using present technology because lateral double-QD structures have already been fabricated.⁹ Our analysis also show that the device does not have a very strict parameter requirement. (i) The sizes of the two QDs need not be the same; the intradot Coulomb interaction parameters $U_{\text{upper}}, U_{\text{lower}}$ need not be the same. (ii) The field B may or may not be uniform, it may also point to any direction. For different directions of $\mathbf{B}$, a spin current is still induced but the spin polarization would depends on the field direction. (iii) The four coupling

strengths ($\Gamma_{1,\text{lower}}, \Gamma_{2,\text{lower}}, \Gamma_{3,\text{upper}}, \Gamma_{2,\text{upper}}$) between the QDs and the leads can be controlled by split gate voltages ($V_{\text{sp}1}, V_{\text{sp}2}, V_{\text{sp}3}, V_{\text{sp}4}$) as shown in Fig. 1, and they do not need to be the same. In fact, one may fix any 3 of the 4 and only regulate the last one to obtain a pure spin current with zero charge current. For example, fixing $\Gamma_{1,\text{lower}} \neq \Gamma_{2,\text{lower}} \neq \Gamma_{2,\text{upper}}$, the spin current I_{2s} and charge current I_{2e} vs $\Gamma_{3,\text{upper}}$ is shown in Fig. 3(c). At a special value of $\Gamma_{3,\text{upper}}$ given by relation $\Gamma_{3,\text{upper}}\Gamma_{2,\text{upper}}/\Gamma_{\text{upper}} = \Gamma_{1,\text{lower}}\Gamma_{2,\text{lower}}/\Gamma_{\text{lower}}$, I_{2e} vanishes and only I_{2s} exists. (iv) So far we have set $\epsilon_{\text{lower}} = \mu_1$ and $\epsilon_{\text{upper}} + U_{\text{upper}} = \mu_3$, but these conditions can be relaxed. For example, if $\epsilon_{\text{upper}} + U_{\text{upper}} = -0.06$, somewhat different from μ_3 , by regulating the lower-QD level ϵ_{lower} using gate voltage $V_{g,\text{lower}}$, we can easily find the operation point for large I_{2s} with zero I_{2e} , as shown in Fig. 3(d). (v) As for the parameter values, in Fig. 3 we have used $k_B T = 0.01$. Assuming this is equivalent to 100 mK,¹⁰ other parameter values used to generate Fig. 3 can be deduced. We find: $V_1 = \mu_1/e \approx 43 \mu\text{V}$, $V_2 = 0$, $V_3 \approx -43 \mu\text{V}$, $U_\alpha \approx 1 \text{ meV}$, and $B \approx 0.8/g \text{ T}$ for $g\mu_B/2 = 0.03$.¹¹ These parameters are in the standard range of QD devices.¹²

Finally, we discuss in what sense the proposed device behaves as a spin battery with two poles. Note that the region indicated by the dotted box in Fig. 1 is reserved for spintronic devices: any application of spin current should be done in this region. The lateral QD plus the external circuit constitute the spin battery: the two poles of the spin battery are points "A" and "B" as shown in Fig. 1. If there exists direct connection between A and B, a spin current is driven through by the spin battery. On the other hand, if there is no direct connection, a spin-motive force will be established between A and B. Importantly, even if there are not spin flip mechanisms in whole device, the spin battery can still work, which is different from the one-pole systems.^{4,5} Finally, the distance between points A and B can be as large as the spin coherence length which can reach many microns at low temperatures.^{13,14} Such as large distance should allow useful applications of the flowing spin current.

In summary, we have shown that gate-controllable spin battery for spin current is possible. Such a device should be fabricable using present technology. We believe the present design to be superior as no time-dependent field is involved. In the present work, we did not discuss detection of pure spin current without charge current, but such discussions already exist in literature^{13,15,16} and we refer interested readers to them.

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¹⁰If temperature is too high, e.g., $k_B T > 5g\mu_B$, spin current will be diminished due to thermal fluctuations.

¹¹For typical GaAs/AlGaAs 2DEG, $g \sim 0.45$ so that $B \approx 2 \text{ T}$.

¹²In our model Hamiltonian, we consider only one level for each QD. This is reasonable if the level spacing Δ is larger than the bias $|V_{1/3} - V_2|$. This should be realizable in present technology. For example, for a $0.2 \mu\text{m} \times 0.2 \mu\text{m}$ QD, its Δ is about $\pi\hbar/(m^* \text{area}) \approx 90 \mu\text{V} > |V_{1/3} - V_2| \approx 43 \mu\text{V}$.

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