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. [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 liquid[2] as well as by circularly polarized light[3] 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 α=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:

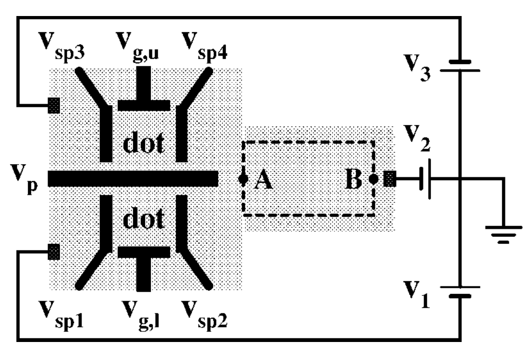

FIG. 1. Schematic diagram for the lateral quantum dot. The lightly shaded region represents two-dimensional electron gas, the darker regions are the metal gates (including split gates V_{spn}, V_p, and gate voltage $V_{g,\alpha}$). The dotted box represents the region in which a pure spin current flows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

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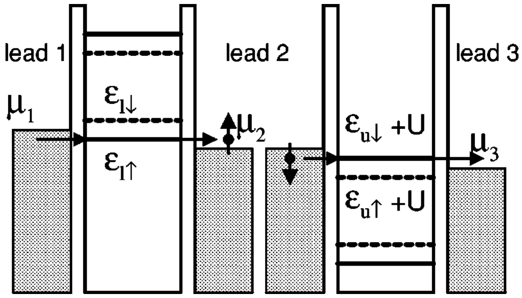

FIG. 2. Schematic plot of energy level position and the tunneling process during spin-battery operation.

$$H=\sum_{\alpha\sigma}(\epsilon_\alpha-\sigma g\mu B_\alpha/2)d^\dagger_{\alpha\sigma}d_{\alpha\sigma}+\sum_\alpha U_\alpha d^\dagger_{\alpha\uparrow}d_{\alpha\uparrow}d^\dagger_{\alpha\downarrow}d_{\alpha\downarrow}$$

$$+\sum_{nk\sigma}\epsilon_{nk}a^\dagger_{nk\sigma}a_{nk\sigma}+\sum_{nk\sigma\alpha}(t_{n,\alpha}a^\dagger_{nk\sigma}d_{\alpha\sigma}+\text{H.c.}) \qquad (1)$$

where $a^\dagger_{nk\sigma}(a_{nk\sigma})$ and $d^\dagger_{\alpha\sigma}(d_{\alpha\sigma})$ 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 $-\sigma g\mu B_\alpha/2$ 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] ($\hbar=1$): $I_{n\sigma}=-2eIm\Sigma_\alpha\int(d\epsilon/2\pi)\,\Gamma_{n\alpha}[f_n(\epsilon)G^r_{\alpha\sigma}(\epsilon)+\frac{1}{2}G^<_{\alpha\sigma}(\epsilon)]$ where $\Gamma_{n,\alpha}\equiv 2\pi\Sigma_k|t_{n,\alpha}|^2\delta(\epsilon-\epsilon_{nk})$ is the linewidth function. $f_n(\epsilon)$ is the Fermi distribution function in lead-n. The NEGF $G^{r,<}_{\alpha\sigma}(\epsilon)$ is the Fourier transform of $G^{r,<}_{\alpha\sigma}(t)$: with $G^r_{\alpha\sigma}(t)\equiv -i\theta(t)\langle\{d_{\alpha\sigma}(t),d^\dagger_{\alpha\sigma}(0)\}\rangle$ and $G^<_{\alpha\sigma}(t)\equiv i\langle d^\dagger_{\alpha\sigma}(0)d_{\alpha\sigma}(t)\rangle$.

We solve the retarded Green's function $G^r_{\alpha\sigma}$ in by the standard equation of motion technique where indirect tunneling processes such as upper QD→lead-2→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 obtain[6]

$$G^r_{\alpha\sigma}(\epsilon)=\frac{\epsilon^-_{\alpha\sigma}+U_\alpha n_{\alpha\bar\sigma}}{(\epsilon-\epsilon_{\alpha\sigma})\epsilon^-_{\alpha\sigma}+\frac{i}{2}\Gamma_\alpha(\epsilon^-_{\alpha\sigma}+U_\alpha n_{\alpha\bar\sigma})}, \qquad (2)$$

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

$$\int\frac{d\epsilon}{2\pi}G^<_{\alpha\sigma}(\epsilon)=-\int\frac{d\epsilon}{2\pi}\sum_n\frac{\Gamma_{n\alpha}f_n}{\Gamma_\alpha}[G^r_{\alpha\sigma}(\epsilon)-G^a_{\alpha\sigma}(\epsilon)].$$

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 indradot 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.

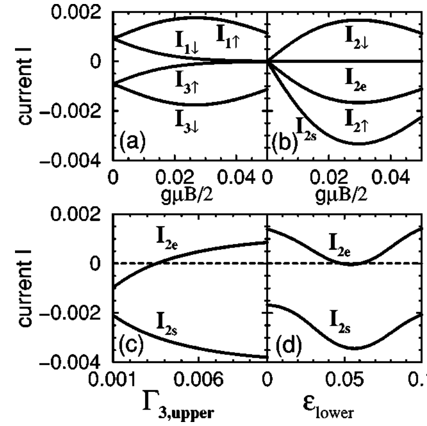

FIG. 3. (a) and (b) for electron currents $I_{n\uparrow}$ and $I_{n\downarrow}$, charge current I_{2e} (unit e), and spin current I_{2s} (unit $\hbar/2$), vs magnetic field parameter $g\mu B/2$. Other parameters are $\Gamma_{1,\text{lower}}=\Gamma_{2,\text{lower}}=\Gamma_{2,\text{upper}}=\Gamma_{3,\text{upper}}=0.005$, $k_BT=0.01$, $U_{\text{lower}}=1.0$, $U_{\text{upper}}=0.9$, $\epsilon_{\text{lower}}=\mu_1$, 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).

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 **B**, a spin current is still induced but the spin polarization would depends on the field direction. (iii) The four coupling strengths ($\Gamma_{1,\mathrm{lower}},\Gamma_{2,\mathrm{lower}},\Gamma_{3,\mathrm{upper}},\Gamma_{2,\mathrm{upper}}$) between the QDs and the leads can be controlled by split gate voltages ($V_{\mathrm{sp1}},V_{\mathrm{sp2}},V_{\mathrm{sp3}},V_{\mathrm{sp4}}$) 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 $\Gamma_{1,\mathrm{lower}}\neq\Gamma_{2,\mathrm{lower}}\neq\Gamma_{2,\mathrm{upper}}$, the spin current I_{2s} and charge current I_{2e} vs $\Gamma_{3,\mathrm{upper}}$ is shown in Fig. 3(c). At a special value of $\Gamma_{3,\mathrm{upper}}$ given by relation $\Gamma_{3,\mathrm{upper}}\Gamma_{2,\mathrm{upper}}/\Gamma_{\mathrm{upper}}=\Gamma_{1,\mathrm{lower}}\Gamma_{2,\mathrm{lower}}/\Gamma_{\mathrm{lower}}$, I_{2e} vanishes and only I_{2s} exists. (iv) So far we have set $\epsilon_{\mathrm{lower}}=\mu_1$ and $\epsilon_{\mathrm{upper}}+U_{\mathrm{upper}}=\mu_3$, but these conditions can be relaxed. For example, if $\epsilon_{\mathrm{upper}}+U_{\mathrm{upper}}=-0.06$, somewhat different from μ_3, by regulating the lower-QD level $\epsilon_{\mathrm{lower}}$ using gate voltage $V_{g,\mathrm{lower}}$, 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 $k_BT=0.01$. Assuming this is equivalent to 100 mK,[10] other parameter values used to generate Fig. 3 can be deduced. We find: $V_1=\mu_1/e\approx 43\ \mu\mathrm{V}$, $V_2=0$, $V_3\approx -43\ \mu\mathrm{V}$, $U_\alpha\approx 1$ meV, and $B\approx 0.8/\mathrm{g}$ 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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[10] If tempearture is too high, e.g., $k_BT>5g\mu B$, spin current will be diminished due to thermal fluctuations.
[11] For typical GaAs/AlGaAs 2DEG, $g\sim 0.45$ so that $B\approx 2$ T.
[12] In 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 μm $\times 0.2$ μm QD, its Δ is about $\pi\hbar/(m^* area)\approx 90\ \mu\mathrm{V}>|V_{1/3}-V_2|\approx 43\ \mu\mathrm{V}$.
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