Device for charge- and spin-pumped current generation with temperature-induced enhancement

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We have proposed a device, a superconducting-lead/quantum-dot/normal-lead system with an ac voltage applied on the gate of the quantum dot induced by a microwave, based on the one-parameter pump mechanism. It can generate a pure charge- or spin-pumped current. The direction of the charge current can be reversed by pushing the levels across the Fermi energy. A spin current arises when a magnetic field is applied on the quantum dot to split the two degenerate levels, and it can be reversed by reversing the applied magnetic field. The increase of temperature enhances these currents in certain parameter intervals and decreases them in other intervals. We can explain this interesting phenomenon in terms of the shrinkage of the superconducting gap and the concepts of photon-sideband and photon-assisted processes.

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Nowadays progressing nanotechnology allows one to fabricate ultrasmall quantum dot (QD) devices, where the energy levels are discrete and the length scale is less than the phase-breaking length. In such a system the quantum mechanism plays an important role.[1] Due to its potential application in future quantum computation and quantum information technology, the transport properties of a QD system have been studied extensively both theoretically and experimentally. Many interesting effects, such as Coulomb blockade,[1] Kondo effect,[2] electron pump,[3,4] etc., have drawn much attention in recent years.

The electron pump is an effect by which an electric current flowing through the QD arises when there is no voltage bias across it but some parameters of the system vary with time. To produce a pumped current at least two varying parameters are needed in the adiabatic regime (i.e., parameters vary very slowly). The pumped charge in one cycle is proportional to the area of the surface enclosed by the evolution loop in the parametric space,[3] and the pumped current reaches its maximum near the resonant level.[5] Kouwenhoven *et al.* have observed an integer number of electrons pumped through the QD in each cycle in the Coulomb blockade regime using a turnstile device.[4] If any of the spin-dependent mechanisms works, a spin pump effect may arise.[6–8] If the pumped currents carried by the electrons with opposite spins flow oppositely and cancel each other completely, a pure spin current results.[8–11] Watson *et al.* realized such a pure spin pump in a QD system by the application of an in-plane Zeeman field.[12]

Outside the adiabatic regime only one varying parameter is enough to give rise to the pump effect. A first-principle calculation implies that the photon-assisted (PA) process is the key concept to understand it,[13] and it has a relation to the evolution of the system in phase space.[14] The theory of a nonadiabatic pump is under development by now. Experimentally, Switkes *et al.* observed that the pumped current does not vanish when the two parameters vary in phase (which is equivalent to the one-parameter pump).[15] A calculation in Ref. 13 qualitatively agrees with their experimental result. A one-parameter spin pump is also possible theoretically, but no experiment has supported it up to now.

In this paper, we theoretically proposed a device, a BCS superconductor-lead/quantum-dot/normal-lead system with an ac voltage applied on the gate of the QD induced by a microwave, based on the one-parameter pump mechanism. It can generate either a charge current or a pure spin-pumped current. Our calculation is carried out by means of the Green's function method in Nambu space. The calculated current is up to the order of 10^{-11} A for a set of typical parameters, which is detectable experimentally. The direction of the charge current can be reversed by pushing the levels across the Fermi energy. A spin current arises when a magnetic field is applied to the quantum dot to split the two degenerate levels, and it can be reversed by reversing the magnetic field. To our surprise, the increase of temperature suppresses these currents in some parameter intervals but enhances them in other intervals. We explain the interesting temperature-enhancement effect in terms of the shrinking of the superconducting gap and the concepts of the photon-sideband and photon-assisted processes.

We start with the model Hamiltonian of the device:

$$H = H_S + H_N + H_d + H_T, \tag{1}$$

where $H_S=\Sigma_{k\sigma}\epsilon_k c^\dagger_{k\sigma}c_{k\sigma}+\Sigma_k\Delta(c^\dagger_{k\uparrow}c_{-k\downarrow}+\text{H.c.})$, $H_N=\Sigma_{q\sigma}\epsilon_q b^\dagger_{q\sigma}b_{q\sigma}$, and $H_d=\tilde{\epsilon}_\uparrow(t)d^\dagger_\uparrow d_\uparrow+\tilde{\epsilon}_\downarrow(t)d^\dagger_\downarrow d_\downarrow$ are the Hamiltonians of the BCS superconductor lead, normal lead, and quantum dot. $H_T=\Sigma_{k\sigma}V_k c^\dagger_{k\sigma}d_\sigma+\Sigma_{q\sigma}V_q b^\dagger_{q\sigma}d_\sigma+\text{H.c.}$ is the tunneling Hamiltonian. $c^\dagger_{k\sigma}$ $(c_{k\sigma})$, $b^\dagger_{q\sigma}$ $(b_{q\sigma})$, and $d^\dagger_\sigma$ (d_σ) are the creation (annihilation) operators of the superconducting lead, normal lead, and QD localized levels. Δ is the superconducting order parameter of the superconductor, which is presumed to be real. The Fermi energy is regarded as the energy reference (i.e., $\epsilon_F=0$). Only two levels in the QD are taken into account. The two levels in the QD, $\tilde{\epsilon}_\sigma(t)=\epsilon_\sigma+V\cos(\omega t)$, are oscillating with the same manner (the same frequency and amplitude) with ω and V being the angular frequency and the amplitude of the ac gate voltage, respectively. The influence of the ac gate voltage is modeled as the oscillation of all the levels in the QD with the same manner but without a transition between them. This description of the effect of ac gate voltage is widely adopted by many authors, and it gives a sound result compared to the experimental one.[16,17] The ac voltage is applied to the gate by coupling a microwave to it.[16] For simplicity, the Coulomb on-site repulsion of the electrons in the QD is neglected. Therefore, the Kondo effect is not considered, which is important only when the temperature is below the Kondo temperature.[2]

The time-dependent pumped current carried by the electrons with spin σ from the QD to the normal lead is $J_\sigma(t) = \mathrm{Re}[i\Sigma_p V_p \langle b^\dagger_{p\sigma}(t) d_\sigma(t)\rangle]$ ($\hbar$ and e are set to be 1). In the following, the Green's function method[18,19] is used to calculate the pumped current. It is convenient to carry out the calculation in Nambu space in a superconducting-normal hybrid system. The Green's function of the QD in Nambu space is

$$\mathbf{G}(t,t') = \begin{bmatrix} \langle\langle d_\uparrow(t), d^+_\uparrow(t')\rangle\rangle & \langle\langle d_\uparrow(t), d_\downarrow(t')\rangle\rangle \\ \langle\langle d^+_\downarrow(t), d^+_\uparrow(t')\rangle\rangle & \langle\langle d^+_\downarrow(t), d_\downarrow(t')\rangle\rangle \end{bmatrix}. \quad (2)$$

Hereafter we will use boldfaced letters to denote matrices. By using the equation of motion method and the Keldysh relation, the dc components of the pumped current are given by

$$J_\uparrow = \int \frac{d\epsilon}{2\pi} f(\epsilon)\mathbf{J}_{11}(\epsilon),\ J_\downarrow = -\int \frac{d\epsilon}{2\pi} f(\epsilon)\mathbf{J}_{22}(\epsilon), \quad (3)$$

where $f = 1/(1+e^{\epsilon/T})$ is the Fermi distribution function of each lead (the Boltzmann constant is set to be 1). $\mathbf{J}$ is a matrix representing the current carrying density of state, and it is expressed as

$$\mathbf{J}(\epsilon) = \sum_n [\mathbf{\Gamma}^N_0 \mathbf{G}^r_{0n} \mathbf{\Gamma}^S_n \mathbf{G}^a_{n0} - \mathbf{\Gamma}^N_n \mathbf{G}^r_{n0} \mathbf{\Gamma}^S_0 \mathbf{G}^a_{0n}], \quad (4)$$

where $\mathbf{\Gamma}^{N/S}_n = \mathbf{\Gamma}^{N/S}(\epsilon + n\omega)$, $\mathbf{G}^{r/a}_{mn} = \mathbf{G}^{r/a}(\epsilon + m\omega, \epsilon + n\omega)$ with $\mathbf{G}^{r/a}(\epsilon,\epsilon')$ being the Fourier transform of $\mathbf{G}^{r/a}(t,t')$. $\mathbf{\Gamma}^{N/S}(\epsilon) = i[\mathbf{\Sigma}^r_{N/S}(\epsilon) - \mathbf{\Sigma}^a_{N/S}(\epsilon)]$ is the linewidth matrix of the normal/superconducting lead in Nambu space. $\mathbf{\Sigma}^r_{N/S}(\epsilon)$ is the retarded self-energy matrix defined as

$$\Sigma^r_S(\epsilon) = -\frac{i}{2}\gamma\rho(\epsilon)\begin{bmatrix} 1 & -\Delta/\epsilon \\ -\Delta/\epsilon & 1 \end{bmatrix},$$

$$\Sigma^r_N(\epsilon) = -\frac{i}{2}\gamma\mathbf{I}, \quad (5)$$

where $\mathbf{I}$ is the 2×2 identity matrix, $\rho(\epsilon) = \epsilon/\sqrt{\epsilon^2 - \Delta^2}$ is the dimensionless density of state of the superconductor, and $\gamma = 2\pi\Sigma_k |V_k|^2 \delta(\epsilon - \epsilon_k) = 2\pi\Sigma_q |V_q|^2 \delta(\epsilon - \epsilon_q)$ is the linewidth functions related to both leads in the normal state (assuming they are equal and energy independent). The Andreev process is not included in Eq. (4) because the two leads have the same Fermi energy. So only the PA quasiparticle tunneling contributes to the pumped current.

One can obtain some interesting features of the pumped current from Eqs. (3) and (4). If the two levels are spin degenerate (i.e., $\epsilon_\uparrow = \epsilon_\downarrow$), $J_\uparrow$ is equal to $J_\downarrow$ and a pumped current $J_c = J_\uparrow + J_\downarrow = 2J_\uparrow$ arises. But if $\epsilon_\uparrow = -\epsilon_\downarrow$, then $J_\uparrow = -J_\downarrow$. So the pumped charge current $J_c = J_\uparrow + J_\downarrow = 0$ vanishes and a pure spin current $J_s = J_\uparrow - J_\downarrow = 2J_\uparrow$ arises. In both cases we have

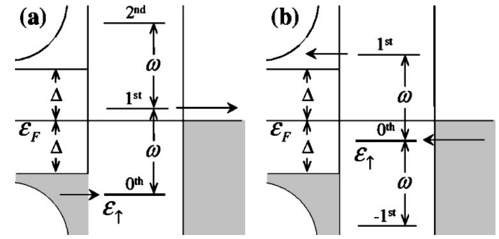

FIG. 1. A sketch of the pump effect induced by level oscillation in the QD at zero temperature for the (a) $\omega > \Delta$ case and (b) $\omega < \Delta$ case. Only one-PA paths contributing to the pumped current are demonstrated. The level $\epsilon_\downarrow$ is not depicted.

$J_\uparrow|_{\epsilon_\uparrow = E} = -J_\uparrow|_{\epsilon_\uparrow = -E}$. Supposing the two levels both line up with the Fermi energy, one can apply a dc gate voltage to push the levels upward or downward from the Fermi energy so as to generate a positive or negative pumped current. Furthermore, one can apply a magnetic field upon the QD to split the two levels and thus a pure spin current is generated. The direction of it can be reversed by reversing the magnetic field. Moreover, some general properties of the pumped current in the system are revealed by Eqs. (3) and (4). For example, the pumped current vanishes as soon as one of the conditions $\epsilon_{\uparrow,\downarrow} \to \pm\infty$, $\Delta \to 0, \infty$, and $\omega \to 0, \infty$ is satisfied.

Combining all the $\mathbf{G}^{r/a}_{mn}$ into an infinite-dimensional matrix, we obtain the corresponding Green's function $\widetilde{\mathbf{G}}^{r/a}$ for the QD in Floquet representation. It can be worked out easily using Dyson's formula

$$[(\widetilde{\mathbf{G}}^{r/a})^{-1}]_{mn} = \begin{cases} [\mathbf{g}(\epsilon + n\omega)]^{-1} - \Sigma^{r/a}(\epsilon + n\omega), & m = n, \\ \frac{1}{2}\mathrm{Diag}[V, -V], & m = n \pm 1, \\ 0, & \text{otherwise}. \end{cases} \quad (6)$$

Here $\mathbf{g}(\epsilon) = \mathrm{Diag}[(\epsilon - \epsilon_\uparrow)^{-1}, (\epsilon + \epsilon_\downarrow)^{-1}]$ is the Green's function of the isolated QD without ac gate voltage. Diag$[\cdots]$ represents the diagonal matrix. After the Green's functions are obtained, the pumped current is calculated numerically straightforward. In the following, we will launch a discussion about our numerical result. At first we concentrate on the zero-temperature case to clarify the mechanism of the one-parameter pump effect in our system. Next, we analyze the temperature-induced enhancement effect based on the analysis method at zero temperature.

Figure 1 is a sketch of the pump effect of our model at zero temperature for $\omega > \Delta$ and $\omega < \Delta$. When the levels of the QD are oscillating, photon sidebands separated by ω appear beside them. Electrons can go from each lead into these sidebands in the QD, and it absorbs photons to jump into other sidebands and finally get out of the QD. Because of $J_\uparrow|_{\epsilon_\uparrow = E} = -J_\uparrow|_{\epsilon_\uparrow = -E}$ for $\epsilon_\uparrow = \pm\epsilon_\downarrow$, we will limit our discussion in $\epsilon_\uparrow < 0$.

The solid curves in Fig. 2 show $J_\uparrow$ versus $\epsilon_\uparrow$ in the case of $\epsilon_\uparrow = \epsilon_\downarrow$ at zero temperature. The features of these curves are understood qualitatively via the concepts of photon-sideband and PA processes. We consider the case $\omega > \Delta$ at first [Fig.

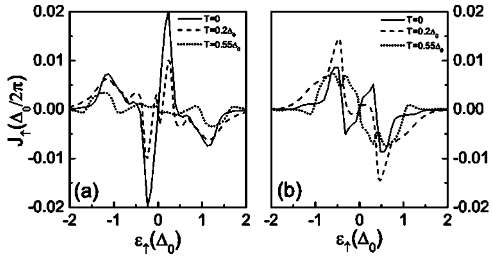

FIG. 2. Variation of $J_\uparrow$ with $\epsilon_\uparrow$ in the case of $\epsilon_\uparrow=\epsilon_\downarrow$. The solid, dashed, and dotted curves correspond to $T=0$, $T=0.4\Delta_0$, and $T=0.55\Delta_0$, respectively. Δ_0 is taken to be the unit of energy scale. Other parameters are (a) $\omega=1.3$, $V=0.5$, and $\gamma=0.1$ and (b) $\omega=0.7$, $V=0.5$, and $\gamma=0.1$.

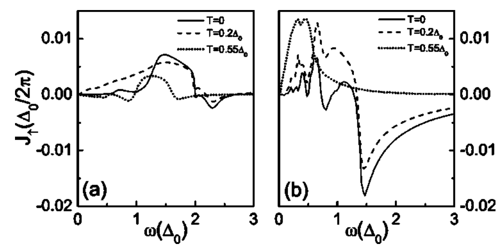

FIG. 3. Variation of $J_\uparrow$ with ω in the case of $\epsilon_\uparrow=\epsilon_\downarrow$. The solid, dashed, and dotted curves correspond to $T=0$, $T=0.2\Delta_0$, and $T=0.55\Delta_0$, respectively. Δ_0 is taken to be the unit of energy scale. Other parameters are (a) $\epsilon_\uparrow=-1.3$, $V=0.5$, and $\gamma=0.1$ and (b) $\epsilon_\uparrow=-0.4$, $V=0.5$, and $\gamma=0.1$.

2(a)]. If $-\omega<\epsilon_\uparrow<-\Delta$, the first sideband lies beyond the Fermi energy and the zeroth one below the superconducting gap [see Fig. 1(a)]. So electrons can enter the zeroth sideband from the superconducting lead and get out from the first sideband to the normal lead, which is a single-PA process and has a positive contribution to $J_\uparrow$. Therefore, the curve experiences a positive maximum when $\epsilon_\uparrow$ is within this interval. Because the zeroth sideband is near the edge of the superconducting gap for the parameters selected in Fig. 2(a), the leakage of electrons in the dot is very large, leading to a suppression of the PA process to some extent. If $-(\omega-\Delta)<\epsilon_\uparrow<0$, the first sideband lies above the superconducting gap and the zeroth one below the Fermi energy. In this case electrons are pumped from the normal lead to the superconductor lead via the path N→zeroth→first→S as shown in Fig. 1(b) (N, *n*th, and S denote the normal lead, the *n*th sideband of the level $\epsilon_\uparrow$, and the superconducting lead), and a negative contribution to $J_\uparrow$ is obtained. Therefore, the curve has a negative maximum within this interval and the peak is much greater than the former one. Next, we consider the case $\omega<\Delta$ [Fig. 2(b)]. In this case the one-PA path (we call the electron tunneling through the QD with *N* photons assisted as the *n*-PA path for short) is forbidden and the pumped current is induced by multi-PA processes, the peaks induced by which is smaller than that induced by the one-PA processes as $V/\omega\leqslant 1$. The positive peak near $\epsilon_\uparrow=-\omega$ and the negative peak near $\epsilon_\uparrow=-(2\omega-\Delta)$ are caused by the two-PA paths S→−first→first→N and N→zeroth→second→S, respectively. When $\epsilon_\uparrow=0$ or $\epsilon_\uparrow\rightarrow\infty$, the current vanishes, which verifies the conclusions drawn before.

The solid curves in Fig. 3 show $J_\uparrow$ versus ω at zero temperature. We attribute the peaks of these curves to the PA processes as discussed above. In the case of $\epsilon_\uparrow<-\Delta$ [Fig. 3(a)] the curve has only one wide peak. When $\omega>|\epsilon_\uparrow|$, the one-PA path S→zeroth→first→N is open, but when $\omega>\Delta+|\epsilon_\uparrow|$, the opposite directional path N→zeroth→first→S is open. Therefore, a wide peak forms within $-\epsilon_\uparrow<\omega<\Delta-\epsilon_\uparrow$. The wide peak is not so high and the peaks of multi-PA processes are not so apparent compared to those in Fig. 3(b) due to the large leakage mentioned before. One may notice that there is an unexpected "dark resonance" at the right edge of the wide peak near $\omega=2$, which is due to the correlation between the two levels. For the case of $-\Delta<\epsilon_\uparrow<0$ [Fig. 3(b)] the strongest negative peak appears near $\omega=\Delta+|\epsilon_\uparrow|$ due to the one-PA path N→zeroth→first→S, and a weaker positive peak near $\Delta-|\epsilon_\uparrow|$ appears due to the two-PA path S→−first→first→N.

The dashed and dotted curves in Figs. 2 and 3 show the variation of $J_\uparrow$ at $T=0.2\Delta_0=0.35T_c$ and $T=0.55\Delta_0=0.96T_c$ in the case of $\epsilon_\uparrow=\epsilon_\downarrow$ (Δ_0 is the superconducting gap at zero temperature and T_c is the crictical temperature of the superconductor; $T_c=0.57\Delta_0$, according to the BCS theory). The corresponding superconducting gaps are $\Delta=0.99\Delta_0$ and $\Delta=0.33\Delta_0$, respectively, according to the BCS theory.[20] It is interesting to note that the pumped current can not only be suppressed but also be enhanced in some special intervals by the temperature increasing. This temperature-induced enhancement can be explained as following. When the temperature is nonzero but below T_c, some electrons (quasiparticles) in the normal (superconducting) lead situated below the Fermi energy are exited to above it and leave some holes below the Fermi energy, but the quasiparticles in the superconductor are less affected by the temperature than the electrons in the normal lead due to the superconducting gap. The holes below the Fermi energy provide some room to accommodate electrons from the other lead. Therefore some new PA paths are opened, which are closed at zero temperature. Figures 4(a) and 4(b) demostrate the one-PA paths opened by the temperature increasing. Meanwhile, the electrons above the Fermi energy shrink the capacity of accommodating new electrons from the other lead; then some PA paths are suppressed, which are already allowed at zero temperature. Figures 4(c) and 4(d) show the one-PA paths weakened by the temperature increasing. On the other hand, the superconducting gap shrinks with the temperature increasing when the temperature is close to T_c. Therefore, the peaks of the pumped current curves are displaced (the position of some peaks is Δ dependent) if $T\approx T_c$. Whether the pumped current is enhanced or suppressed induced by the temperature increasing depends on the total effect of these PA paths and the displacement of the current peak. For example, we consider the dashed curve in Figs. 2(b) and 3(b), corresponding which $T=0.2\Delta_0$ and $\Delta=0.99\Delta_0$ (the superconducting gap almost remains unchanged). The peak of the dashed curve in Fig. 2(b) near $\epsilon_\uparrow=-(2\omega-\Delta)$ is suppressed because of the open of the one-PA path S→−first→zeroth→N [see Fig. 4(a)] whose direction is opposite to that of the path N→zeroth→second→S, which results in the peak at $T=0$. However, this new opened path enhances the peak near $\epsilon_\uparrow=-\omega$ because

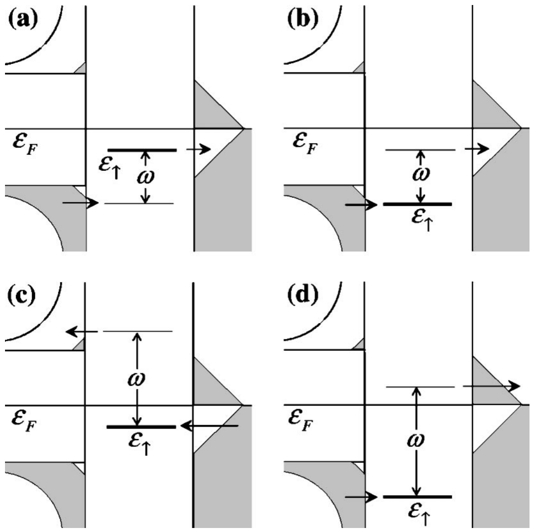

FIG. 4. A sketch of the one-PA paths influenced by nonzero temperature in the case of $\epsilon_\uparrow < 0$. (a) and (b) show the opening of new one-PA paths, which are not allowed at $T=0$. (c) and (d) show the suppression of one-PA paths, which exist already at $T=0$.

of the coincidence of the directions of it with that of the path bringing on the peak at $T=0$. This path also magnifies the pumped current in $\epsilon_\uparrow < -\omega$. The negative peak near $\omega=\Delta + |\epsilon_\uparrow|$ of the dashed curve in Fig. 3(b) decreases because of the diminishment of the PA path N→zeroth→first→S [see Fig. 4(c)]. The positive peak near $\omega=\Delta-|\epsilon_\uparrow|$ is enhanced by the open of the one-PA path S→first→zeroth→N [see Fig. 4(a)]. This path also magnifies the pumped current as $\omega < \Delta - |\epsilon_\uparrow|$. When the temperature increases close to T_c, the superconducting gap shrinks markedly and the shape of the current curves is changed distinctly. For instance, we consider the dotted line in Fig. 2(b), corresponding which $T = 0.55\Delta_0$ and $\Delta = 0.33\Delta_0$. Assuming the level $\epsilon_\uparrow$ moves from $-\infty$ to the Fermi level, when $\epsilon_\uparrow$ approaches to $\epsilon_\uparrow = -\omega$ the pumped current increases because of the opening of the PA path S→zeroth→first→N. When the level moves on and if it near $\epsilon_\uparrow = -(\omega - \Delta)$, $J_\uparrow$ decreases because an opposite PA path N→zeroth→first→S is open. When $\epsilon_\uparrow$ passes the lower edge of the superconducting gap, the (S→N)-oriented path S→zeroth→first→N is enhanced due to the large density of states near the gap edges of the superconductor. Therefore, a peak near $\epsilon_\uparrow = -\Delta$ appears. The dotted curve in Fig. 3(b) has only one positive peak near $\omega = |\epsilon_\uparrow|$ on this curve because of the one-PA path S→zeroth→first→N. The notch on the top of the peak is led by the competition of this path and some multi-PA path with opposite direction. If the temperature is more close to T_c, all peaks are diminished, and the pumped current vanishes when the temperature exceeds T_c. The features of curves with nonzero temperature in Figs. 2(a) and 3(a) can also be explained similarly, but we skip on to avoid the tediousness.

We have discussed the current curves in the case of $\epsilon_\uparrow = \epsilon_\downarrow$ only. The current curves in the case $\epsilon_\uparrow = -\epsilon_\downarrow$ share most features as those in the case $\epsilon_\uparrow = \epsilon_\downarrow$. They differ quantitively from each other because of the correlation between the two levels $\epsilon_\uparrow$ and $\epsilon_\downarrow$ induced by the superconducting lead. There are few anomalies of the current curves, for example, the dip at $\omega \approx 2$ of the solid curve in Fig. 3(a), which cannot be explained if the correlation is ignored. We do not try to do so for it is not our aim in this paper. In the case of neither $\epsilon_\uparrow = \epsilon_\downarrow$ nor $\epsilon_\uparrow = -\epsilon_\downarrow$, we have $|J_\uparrow| \neq |J_\uparrow|$. Therefore, there are both charge and spin currents through the QD. One can discuss the features of the current curves similar to the above.

Typically, the superconducting gap at zero temperature is of the order of 10^{-4} eV. In our model the corresponding pump frequency and ac voltage induced by it are of the order of 10^{10} Hz and 10^{-4} V, respectively, which are reachable experimentally. The pumped current is of the order of 10^{-11} A. The amount of current such as this is experimentally detectable.

In summary, we have proposed a device to generate both charge and spin pump currents, the amount and direction of which are controlled by a dc gate voltage and a magnetic field. The temperature increasing enhances the pumped current in certain parameter intervals and decreases it in other parameter intervals.

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