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Semiconductor pumps modulated by planar external fields

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ABSTRACT

Semiconductor pumps modulated by external fields in the spin-momentum plane are investigated in this work. The central pump comes from the driving of the double time-dependent delta potentials, which are formed in interfaces of the Dresselhaus spin–orbit coupling (SOC) region attached to two normal leads. Floquet scattering matrix method calculations show that charge currents pumped from the system can be strengthened by modulations of the planar external fields besides the potentials and SOCs. Even in fixed parametric semiconductor pumps, enhanced pure spin currents can be achieved with some strength and direction coeffects of the planar external fields.

1. Introduction

Quantum pump transports in the mesoscopic structures have attracted considerable attentions over these years [1–12]. The pumping mechanism comes from the way of generating directed quantized currents by the cyclic adiabatic change of two or more system parameters in the absence of any external bias voltage, as Thouless original suggested in 1983 [1]. Expansion theoretical and experimental works were processed subsequently [2–7], and these investigations make the understanding and realization of the quantum pumping sound more and more clearly. Usually, cyclic pumped currents are determined by the area enclosed in parametric space during the corresponding evolution. Variations of the systemic parameters are generally realized by applying time-dependent potentials to a double-barrier junction [2–4].

The typical parametric pumps driven by double-barrier junctions are extensively investigated recently. Quantum pump transport properties follow the sinusoidal behavior of adiabatic quantum pumps with the weak potential driving [2], and vary to the anharmonic manner beyond linear response approximation as consider the high-order time-dependent scattering matrix [13]. However, one of the most important mechanisms established with help of ferromagnetic materials, the spin quantum pumping which comes from an external magnetic field modulation between the driving potentials has been focused particularly [14–16]. Such quantum pumps can carry out oscillation currents in different energy traversal paths, have very sensitive dependence on parameters control including the potentials, the spin–orbit coupling (SOC) and the magnetic fields [7,14–18]. Pure spin currents without accompanying charge current can always be pumped in some appropriate parametric regulations.

Usually, when the time potentials are not weak in the pumping processes, viable method is taken into account the Floquet theorem, the photon-assisted transport to solve the problems [19]. Developed theoretical works were applied to the quantum pump in mesoscopic conductors by many works [4,20,21], which show that the quantum charge and spin currents can be pumped by the complicated parametric modulations. While consider the semiconductor pump driven by double delta

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potentials and due to the external fields, i.e., with the external field, potential and spin–orbit coupling (SOC) modulations, interesting quantum pump phenomena appear and the physical substances are worth discussing. In this paper, the pumped currents modulated by the Dresselhaus SOC [22] and the planar external fields are calculated. Charge and spin pumped current variations are studied in related parametric modulations, and the enhanced pure spin current pumping are discussed.

The paper is organized as follows. In Section 2 the system is introduced and related theoretical formalisms are provided. Section 3 gives some analytic and numerical results, and Section 4 presents a brief conclusion of this work.

2. Model and formulation

The quantum pumping, which consists of three different regions, can be realized by placing two time dependent delta potentials formed by the controllable laser beams in the interfaces between the leads and the semiconductor, as shown in Fig. 1. The left and the right region are normal leads described as N_L and N_R, in which no SOC is presented. While dynamic direction of the electron is chosen along the x axis, the system can be described as a quasi-one-dimensional quantum wire transport. Hamiltonian of the leads including driving potentials can be written as [4,23]

$$H_{\text{Lead}}(x,t) = \frac{p_x^2}{2m_f} + \sum_\alpha u_\alpha(t)\delta(x - x_\alpha), \tag{1}$$

where p_x, m_f is the momentum operator and the effective mass of an electron, respectively. The time dependent delta potentials are corresponding to the second part of the Hamiltonian, where x_α are positions of the interfaces with $\alpha = L, R$ the left and right side of the leads, and the semiconductor length is set as $\ell = x_R - x_L$. We consider the identical static (driving) potentials $u_{\alpha s} = u_s$ ($u_{\alpha d} = u_d$) to $u_\alpha(t) = u_s + u_d\cos(\omega t + \phi_\alpha)$, with ω the oscillation frequency and $\varphi = \phi_R - \phi_L$ the phase difference.

As affected by the time dependent potentials, the Floquet eigenstates are given by series position wave functions with different Floquet energies as [4,20,24]

$$\Psi_\alpha^\varepsilon(x,t) = \sum_{n=-\infty}^{\infty} \psi_\alpha^n(x)\exp\left[-\frac{i(\varepsilon + n\hbar\omega)t}{\hbar}\right], \tag{2}$$

where $\varepsilon, n, \hbar\omega$ are corresponding to the incoming energy, propagating mode and an energy quantum and here the evanescent parts of the propagating modes are neglected. With the x spin operator of the normal leads $\hat{\sigma}_x|\alpha_\sigma\rangle = \pm|\alpha_\sigma\rangle$, the spinors can be all invariable written as $|\alpha_+\rangle = \frac{1}{\sqrt{2}}(1,1)^T, |\alpha_-\rangle = \frac{1}{\sqrt{2}}(1,-1)^T$, and $\sigma_\alpha = \sigma = +,-$ are the spin of the electrons. Moving in normal leads with the nth propagating mode an electron generally has the x-component spin wave functions [24,25], for the left lead

$$\psi_L^n(x) = \sum_\sigma \left(a_{Ln}^\sigma e^{ik_n(x-x_L)} + b_{Ln}^\sigma e^{-ik_n(x-x_L)}\right)|L_\sigma\rangle, \quad x \leqslant x_L, \tag{3}$$

and for the right lead

$$\psi_R^n(x) = \sum_\sigma \left(a_{Rn}^\sigma e^{-ik_n(x-x_R)} + b_{Rn}^\sigma e^{ik_n(x-x_R)}\right)|R_\sigma\rangle, \quad x \geqslant x_R, \tag{4}$$

where $a_{\alpha n}^\sigma, b_{\alpha n}^\sigma$ are corresponding to the incoming and outcoming amplitudes, and $k_n = \sqrt{\frac{2m_s}{\hbar^2}(\varepsilon + n\hbar\omega)}$ denote the wave vectors.

In the semiconductor region, the Hamiltonian due to the planar external field takes the form as [26,27]

$$H_{\text{soc}}(x) = \frac{p_x^2}{2m_s} - \beta\sigma_x p_x + \vec{B}\cdot\vec{\sigma}, \tag{5}$$

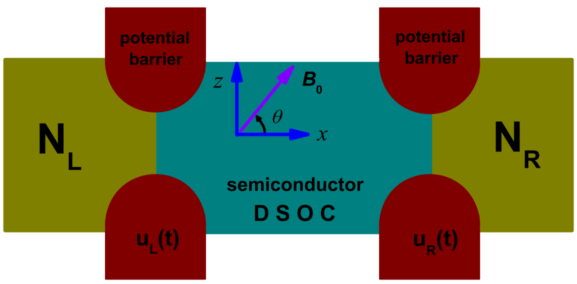

Fig. 1. Schematics of the semiconductor pump. The left and right regions are normal leads and the middle region due to the Dresselhaus SOC and the planar external fields. Interfaces of the SOC region and leads are subjected to the time dependent potentials.