Antiresonance induced spin-polarized current generation*

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(Received 17 May 2011; revised manuscript received 21 May 2011)

According to the one-dimensional antiresonance effect (Wang X R, Wang Y and Sun Z Z 2003 *Phys. Rev.* B **65** 193402), we propose a possible spin-polarized current generation device. Our proposed model consists of one chain and an impurity coupling to the chain. The energy level of the impurity can be occupied by an electron with a specific spin, and the electron with such a spin is blocked because of the antiresonance effect. Based on this phenomenon our model can generate the spin-polarized current flowing through the chain due to different polarization rates. On the other hand, the device can also be used to measure the generated spin accumulation. Our model is feasible with today's technology.

Keywords: antiresonance, spin-polarized current, impurity

PACS: 72.25.–b, 73.63.–0b, 73.23.Hk **DOI:** 10.1088/1674-1056/20/12/127201

The recently developing field of spintronics steps over conventional electronics by simultaneously manipulating both the electron spin and the charge degrees or the spin degree alone to carry information, and has drawn much attention in the past decades.[1−3] The generation and detection of spin-polarized current is one of the key tasks in spintronics for the future development of spin-based devices.[1−7] The spin-polarized current and the spin accumulation generated by spin Hall effects have been largely investigated and realized in experiment.[8−12] For the benefits of lower energy consumption and high integration efficiency in electronics, proposals for spin-polarized current generation in one-dimensional nanoscale structures without magnetic field or ferromagnetic electrodes have been proposed,[13−22] for instance, in quantum wires[16,17] and in quantum point contact.[6] The spin–orbit coupling is an important mechanism to break the degeneracy of spin-up and spin-down and is widely used in many proposals. However, to realize the proposals based on spin–orbit coupling is still challenging.[6,7] The magnetic impurities or quantum dots are also used to control the transport properties and to generate the spin-polarized current (or spin filter),[4,13−15,23−25] which are promising candidates for future development of spintronics devices. In the present paper, we propose a feasible model based on the antiresonance effect[26] caused by special impurities in one-dimensional nanostructures to generate the spin current and to measure the spin accumulation.

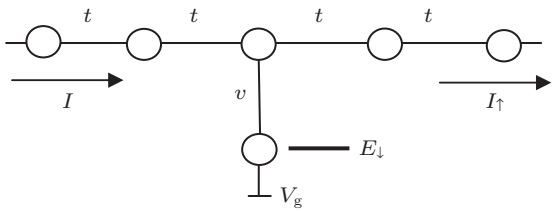


Fig. 1. Illustration of the model. Our model consists of a chain and a special impurity. Only one energy level is correlated in each site, and the coupling between sites is t. The impurity coupling to one of the sites has a spin-correlated energy level with energy $E_\downarrow$, which can be occupied by a spin-down electron. The energy $E_\downarrow$ can be tuned by the applied gate voltage V_g. The coupling between impurity and the site is manipulated by v. The spin-down electron suffers the antiresonance effect and is 'blocked'. The currents with spin-up can be generated in this chain.

Our model is illustrated in Fig. 1. The model consists of a chain and an impurity. Electrons can tunnel from site to site through the chain, and the impurity is coupling to one of the sites (for simplicity, this site is labeled as site-0). Without considering the electron–electron interaction, the Hamiltonian of such a system can be written as

$$H = t\sum_{i,s} c_{is}^{\dagger} c_{i+1,s} + E_\downarrow d_\downarrow^{\dagger} d_\downarrow + v c_\downarrow^{\dagger} d_\downarrow + \mathrm{H.c.}, \quad (1)$$

*Project supported by the National Natural Science Foundation of China (Grant Nos. 10904082 and 10875072).
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where $c_{is}^{\dagger}$ (c_{is}) is the electron creation (annihilation) operator of the i-th site with spin s; $d_{\downarrow}^{\dagger}$ ($d_{\downarrow}$) is the creation (annihilation) operator of the electron in the impurity with spin-down; $E_{\downarrow}$ is the energy of impurity state (spin-down); t is the coupling coefficient between the chain sites while v is the coupling coefficient between the impurity and site-0. We want to stress that the impurity used here is a special one because this impurity can be occupied by an electron with special spin.

The spin-up electrons are not allowed to occupy the impurity state because the energy is too high, thus their transport property through the chain is not affected by the impurity. All the electrons moving from the left side of the chain can tunnel through the region around the impurity and transport to the right side of the chain without loss. The transport property of the spin-up electron in this chain is exactly the same as the tunnel property in a chain without an impurity. The tight-binding model can give the energy band structure of the electrons with spin-up $\epsilon_{\uparrow} = 2t\cos ka$, where k is the wave vector and a is the lattice constant of the chain. For a chain with length L, the wave vector is $k = n\pi a/L$, where n is an integer. In the following we assume that the electrons transporting through the chain have energies far from the band edge $\epsilon_{\text{edge}} = \pm 2t$ (wide band approximation).

The case is different from the spin-down electrons. Under the effects of the impurity, the spin-down electrons will be virtually scattered between site-0 and the impurity, and thereby inducing the so-called antiresonance effect as proposed in Ref. [26]. Suppose that the energy of the spin-down electron is ϵ, the transmission probability is[26]

$$T_{\downarrow} = \frac{4t^2(\epsilon - E_{\downarrow})^2|1 - (\epsilon/2t)^2|}{4t^2(\epsilon - E_{\downarrow})^2|1 - (\epsilon/2t)^2| + v^4}. \tag{2}$$

This expression implies that the spin-down electron has zero transmission rate when its energy ϵ equals the energy level of the defect $E_{\downarrow}$, or the spin-down electron with energy $\epsilon = E_{\downarrow}$ is 'blocked'.

The different transport properties of the spin-up and spin-down electrons in such a model can be used to generate spin-polarized current. Suppose that the electrons of spin-up and spin-down move from the left to the right along the chain. The spin-down electron with energy $\epsilon = E_{\downarrow}$, will experience the antiresonance effect and is blocked but the spin-up electron is not affected by the impurity and will transport through the chain. Thus the current transmitted through the chain will be spin-up as illustrated in Fig. 1. As usual, the current polarization is defined as $P = (I_{\uparrow} - I_{\downarrow})/(I_{\uparrow} + I_{\downarrow}) = (T_{\uparrow} - T_{\downarrow})/(T_{\uparrow} + T_{\downarrow})$.[24] With or without the impurity, the transmission property of a spin-up electron is always one $T_{\uparrow} = 1$. The spin-down electron with an energy of special value $\epsilon = E_{\downarrow}$ is totally blocked (the transmission rate $T_{\downarrow}(E_{\downarrow}) = 0$). The transmission rates of spin-down electrons with other energy values have different values. In Fig. 2, we show the transmission probability of spin-down electrons and the current polarization each as a function of energy ϵ, where we have chosen other parameters to be $t = -1$, $v = -0.5$, and $E_{\downarrow} = 0.8$. The curves show that around $\epsilon = E_{\downarrow}$, the transmission probability of spin-down electrons is close to zero and corresponding current polarization is near one. The energy deviation from $\epsilon = E_{\downarrow}$ will reduce the current polarization that approaches zero far away from the resonance. The current polarization curve is symmetric around $\epsilon = E_{\downarrow}$.

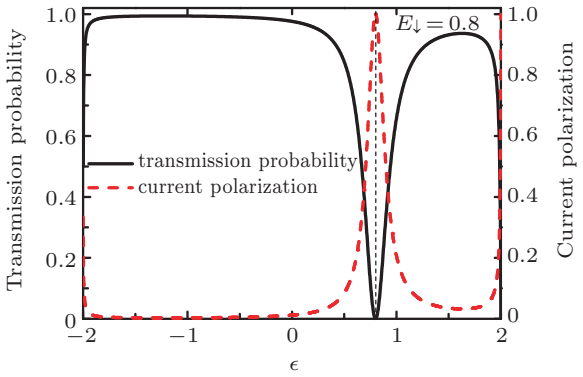


Fig. 2. (colour online) The transmission probability of spin-up electron and the current polarization each as a function of energy ϵ. At $\epsilon = E_{\downarrow}$ the spin-down electron suffers the antiresonance effect and its transmission probability is zero, correspondingly, the current is totally spin polarized (spin-up). Deviation from $\epsilon = E_{\downarrow}$ will reduce the current polarization. The parameters are chosen as $t = -1$, $v = -0.5$, and $E_{\downarrow} = 0.8$.

To apply the spin-polarized current generator, the chain can be connected to metal contacts on the ends. Suppose that the left contact has higher chemical potential than the right contact, i.e. $\mu_{\text{L}} > \mu_{\text{R}}$, the electrons with energy $\mu_{\text{L}} > E > \mu_{\text{R}}$ will flow through the chain. When high current polarization is required, the energy of electron should be around $E \sim E_{\downarrow}$. Moreover, the energy of the impurity $E_{\downarrow}$ can be tuned when a gate voltage V_{g} is applied to the impurity as shown in Fig. 1. Thus, by applying a little bias $|\mu_{\text{L}} - \mu_{\text{R}}| \ll 1$ and tuning the gate voltage V_{g} to make the energy level of the impurity $\mu_{\text{L}} > E_{\downarrow} > \mu_{\text{R}}$, a near 100% polarized spin current can be generated. Of course, in

a realistic wire, the polarized current and its polarization will depend on the detail of how the bias or gate voltage is applied as explained in Ref. [27]. In the nonlinear transport regime, one should also expect other phenomenon such as negative differential resistance that is important and useful in nonlinear dynamics and applications.[28]

Several proposals have been given to generate the spin accumulation,[11,29] for instance, the transverse spin accumulation in a semiconductor channel can be achieved because of the spin Hall effect.[10] So far, the measurement of spin accumulation is performed mainly by the optical methods. Our model can be used to measure the spin accumulation, as an electrical approach, where we can *tune the spin direction* s_i of the state in the impurity. To measure the spin accumulation of this kind of system, the left end of the chain in our model can be connected to the spin accumulation region but the right end of it is connected to a metal contact with lower chemical potential. The accumulated spin polarized electrons with spin s_m will tunnel into the chain and transport through the chain, and the current can be measured. In general, $s_i \neq s_m$, the spin part of the state of the input electrons Ψ_{s_m} can be expressed as superposition of two states: the impurity state Φ_{s_i} with spin s_i and the state with opposite spin $-s_i$ Φ_{-s_i}, i.e.

$$\Psi_{s_m} = \alpha\Phi_{s_i} + \beta\Phi_{-s_i}, \tag{3}$$

where α and β are the coefficients. As discussed previously, the Φ_{s_i} part is blocked and the Φ_{-s_i} part can tunnel through the chain. We can tune the value of s_i, the spin of state in the impurity, and measure transport current as a function of s_i. The only case for the current to be zero is when $s_i = s_m$. Moreover, the spin accumulation ratio[5,25] can be derived based on the behaviour of the current as a function of s_i, especially its minimum value $I_{\min}$ and maximum value $I_{\max}$. When $I_{\min} = 0$ and $I_{\max} = 1$, the spins of the electrons are totally polarized. When $I_{\min} \neq 0$, the accumulated spins are not totally polarized. In this case, our model can be used to measure the spin accumulation of any direction in space.

Our model can be realized using a quantum dot system. A number of quantum dots with the same configuration can be arranged into a line to construct the main chain in our model, and another quantum dot coupling to one of the quantum dots in the chain can be simulated as the impurity. The quantum dots in the main chain are arranged in a manner such that only one energy level is correlated. The quantum dot as impurity should provide a level on which only a spin-down (or spin-up) electron can occupy. To achieve this aim, two proposals can be used. The first one is to apply a local magnetic field to the quantum dot. The degenerations of spin-up and spin-down energy levels will be broken under Zeeman effect $|E_\uparrow - E_\downarrow| = g\mu_{\rm B}B$, where B and an appropriate gate voltage $V_{\rm g}$ can be used to make $\mu_{\rm L} > E_\downarrow > \mu_{\rm R}$ while $E_\uparrow > \mu_{\rm L}$, thus the energy structure of the quantum dot is like that of the special impurity. The other proposal is to trap an electron with special spin in the quantum dot instead of applying the magnetic field. Suppose that a spin-up electron is trapped, and its energy is tuned by the gate voltage to be lower than the bottom band edge of the main chain $E_\uparrow < -2|t|$. This will localize the electron in this quantum dot. Because of the on-site Coulomb interaction and Pauli exclusive principle, only an extra electron of spin-down with energy $E_\downarrow = E + U$ can occupy the quantum dot. While $\mu_{\rm L} > E + U > \mu_{\rm R}$ is satisfied (tuned by the gate voltage), this quantum dot is equal to an impurity with a vacant spin-down energy level. In the second proposal the on-site Coulomb interaction is used. A similar phenomenon is also mentioned in zigzag-like polymer with side radicals in Ref. [30].

We should emphasize that our model is essentially based on the electron interference property and the spin transport is coupled with the charge transport. The pure spin current, in which two spin polarized currents flow in opposite directions so the charge current is zero, cannot be generated using our model. So far, the experimental measurement of the pure spin current is still a challenge.[31] Moreover, in our proposal the impurity level affects only the electrons with energy around $E_\downarrow$ while keeping other electrons insusceptible. The effect is very like the optical polarizer. Our model can generate the current with spin polarization only around a special energy, which can be used to investigate the spin injection.

Our model is based on the antiresonance effect and we should emphasize that this effect is different from the famous Fano effect. The difference between the two effects has been fully discussed in Ref. [26]. The spin filters using the Fano resonance have been proposed in quantum dot systems.[23,24] In their models, the effects of magnetic field B and the on-site Coulomb interaction U on spin filter are investigated numerically based on the Fano resonance. But in our model, according to the antiresonance effect, we show

more clearly and straightforwardly [Eq. (2)] that the most essential factor for the spin filter is the energy level of the impurity instead of B and U. In addition, the magnetic field B is not necessary in the implementation of our model (the second proposal). The antiresonance effect is a coherent transport property, thus the temperature and the dephasing will reduce the efficiency of the spin current generation.[15] Moreover, the additional impurities or defects in the chain will scatter the tunneling electrons to reduce the electron spin polarization.[26] Therefore, our model can properly be used to study low temperature and clean materials. On the other hand, in discussing the model, we have assumed that the level number $N \to \infty$. To make our model applicable, N should be large enough to avoid the effect of the boundary states on the scattering of the impurity. In our model, the impurity couples only to site-0 in chain. As discussed in Ref. [26], the antiresonance effect can also be present when the impurity couples to more than one site or more than one band, and in such cases our model is still applicable.

Our proposal is feasible in experiment. The technologies of incorporating quantum dots are widely used in experiments.[33,34] On the other hand, the impurity in our model is not in the main chain, and the transport current through the chain does not tunnel through the impurity, which is different from the case where the impurities are embedded in the transport channel.[4,14−17,25,35] Thus a large current can be generated in our model.

In conclusion, we proposed a model to generate the spin current in one-dimensional nanostructures. The structure of our model is provided and the mechanism is explained. The model can also be used to measure the spin accumulation or the spin current. In comparison with other proposals, our model is feasible with today's technology.

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