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Spin-flip mesoscopic transport through a toroidal carbon nanotube coupled to normal metal terminals

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Abstract

The spin and charge currents tunnelling through coupled toroidal carbon nanotube (TCN) system is investigated in the presence of rotating magnetic field and an Aharonov–Bohm magnetic flux. The charge current and spin current coexist in the same system as $eV \neq 0$. The charge conductance, charge current, and spin current are sensitively determined by the applied magnetic fields and the quantum nature of coupled TCN system. Zeeman splitting and spin-flip effect make different contributions to the spin and charge currents due to symmetrically energy splitting and asymmetric resonant behavior. The spin current is strongly adjusted by the frequency of rotating field, which is associated with the photon-absorption and resonance procedure in TCN.

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The toroidal carbon nanotube (TCN) is a form of carbon structure, which is a torus structure by bending the carbon tube such that the two edges are connected. The tori proposed are constructed by introducing a single pentagon–heptagon pair into the perfect hexagon bonding pattern to connect carbon tubules. There is no technique question for the fabrication of TCNs from single-wall carbon nanotubes (SWCNs) [1–4]. Compared with normal metal or semiconductor ring, TCN can carry larger persistent current due to the modification of energy structure and energy gap [5]. The research on electron transport through hybrid device structure is presented for the new stage of investigation, in which the carbon devices are coupled to different materials [6–8]. As a TCN is coupled to different

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kinds of terminals, the combination of terminal structures and TCN together forms coupled density of state (DOS), and the tunnelling current is determined by the detailed constructions [9–11]. This kind of devices can be found applications in electronics due to the interference properties and structures.

Spintronics is one of the most attractive investigation frontier both for the theoretical and experimental aspects due to the potential application of nanodevices. The spin polarized resonant transport through a ferromagnetic film enhances the nonequilibrium spin population due to the spin accumulation [12,13]. The concept of spin coherent field effect transistor was proposed associated with the spin precession due to the spin–orbit coupling in narrow-gap semiconductors[14]. These could make us to consider the application of spin degree of freedom analog to the charge transport. Recent experiments on the control and manipulation of spin made it possible for the application of spintronic nanodevices [15,16]. The spin-current circuit and generator phenomena are also proposed to develop the spintronics, such as the spin-battery proposals [17,18]. The spin field effect transistor (SFET) is presented to be induced by a rotating external magnetic field without involving magnetic materials [19]. In this Letter, we investigate the mesoscopic transport through a coupled TCN system in the presence of spin-flip effect. A rotating magnetic field is applied to the TCN to induce spin-dependent tunnelling, which acts as spin generator in the TCN. The source and drain are biased by chemical potential difference $\mu_R - \mu_L$ in general. Therefore, the charge and spin currents can exist at the same system. An static magnetic field is applied to produce a magnetic flux threaded through the TCN. This magnetic flux induces Aharonov–Bohm oscillation, and it controls the tunnelling behavior due to adjusting the flux. The detailed structure of TCN dedicates important contribution to the spin-flip mesoscopic transport, and the metal–semiconductor transition obviously governs current characteristics. We employ the nonequilibrium Green's function technique to investigate the mesoscopic transport.

The TCN is formed by rolling a finite graphite sheet from the origin to the vectors $\mathbf{R}_x = m_1\mathbf{a}_1 + m_2\mathbf{a}_2$, and $\mathbf{R}_y = p_1\mathbf{a}_1 + p_2\mathbf{a}_2$ simultaneously. It is denoted by $(m_1, m_2; p_1, p_2)$ as convention, and it satisfies the periodical boundary conditions along both of the longitudinal and transverse directions [5]. Two kinds of TCN with highly symmetric structures are armchair $(m, m; -p, p)$ TCN and zigzag $(m, 0; -p, 2p)$ TCN. The armchair TCN possesses the symmetry with armchair structure along the transverse direction and zigzag structure along the longitudinal direction. The zigzag TCN has the structure in both of the directions being zigzag. We denote the diameter of carbon nanotube (CN) as d_t, and the diameter of mesoscopic ring as D_t. Therefore, the diameters of the armchair $(m, m; -p, p)$ TCN are $d_t = 3bm/\pi$, and $D_t = 3^{1/2}bp/\pi$; the diameters of the zigzag $(m, 0; -p, 2p)$ are given by $d_t = 3^{1/2}bm/\pi$, and $D_t = 3bp/\pi$, with the $c - c$ bond length $b = 1.44$ Å [20]. In the absence of magnetic flux, the armchair TCN is a metal as $p = 3\nu$ (type I TCN), while it is a semiconductor with narrow energy gap as $p = 3\nu \pm 1$ (type II TCN) where ν is an integer. For the zigzag TCN in the absence of magnetic flux, there exists large energy gap as $m \neq 3\nu$ (type III TCN). We consider the system of TCN with the diameter ratio of the tube to the ring as $d_t/D_t \ll 1$. In this Letter, we only consider the system composed of an armchair TCN coupled to two normal metal leads.

The system is composed of three parts: the right and left normal metal terminals, and the central TCN. We consider the system that the TCN is exposed to a rotating magnetic flux $\mathbf{B}_0(t) = B_0[\sin\theta\cos(\omega t)\mathbf{e}_x + \sin\theta\sin(\omega t)\mathbf{e}_y + \cos\theta\mathbf{e}_z]$, where ω and θ are the angular frequency and tilted angle between the z-axis and the magnetic field. This kind of magnetic field is used to produce pure spin current in a quantum dot system in Ref. [19]. We restrict this field so that there is no magnetic flux threaded through TCN. Another static magnetic field $\mathbf{B}_1$ is applied in $\mathbf{e}_z$ direction, which produces a static magnetic flux ϕ threaded through TCN. The static magnetic field $\mathbf{B}_1$ does not applied on the ring, but only produces an Aharonov–Bohm magnetic flux. This magnetic flux induces Aharonov–Bohm effect, and the electron energy spectrum is modified by it [5]. The magnetic field $\mathbf{B}_0(t)$ is screened in order not to affect the leads. The schematic diagram of this system is shown in Fig. 1 to help understanding our geometric structure. The rotating field applies a magnetic field with maximum magnitude of the field on the ring, and the magnetic field varies with the angles θ, and $\varphi(t) = \omega t$. This means that at a definite point of the TCN, the magnetic field varies with time periodically, and an electron at this point feels this field. This also