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Nonequilibrium spin transport through a diluted magnetic semiconductor quantum dot system with noncollinear magnetization

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The spin-dependent transport through a diluted magnetic semiconductor quantum dot (QD) which is coupled via magnetic tunnel junctions to two ferromagnetic leads is studied theoretically. A noncollinear system is considered, where the QD is magnetized at an arbitrary angle with respect to the leads' magnetization. The tunneling current is calculated in the coherent regime via the Keldysh nonequilibrium Green's function (NEGF) formalism, incorporating the electron–electron interaction in the QD. We provide the first analytical solution for the Green's function of the noncollinear DMS quantum dot system, solved via the equation of motion method under Hartree–Fock approximation. The transport characteristics (charge and spin currents, and tunnel magnetoresistance (TMR)) are evaluated for different voltage regimes. The interplay between spin-dependent tunneling and single-charge effects results in three distinct voltage regimes in the spin and charge current characteristics. The voltage range in which the QD is singly occupied corresponds to the maximum spin current and greatest sensitivity of the spin current to the QD magnetization orientation. The QD device also shows transport features suitable for sensor applications, i.e., a large charge current coupled with a high TMR ratio.

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The spin-dependent transport in quantum dot (QD) [1–9] systems has been analyzed extensively, from both theoretical and experimental aspects [10–12]. In particular, much attention is focused on the QD system which consists of a central QD coupled to two adjacent leads via magnetic tunnel junctions (MTJs). Such a QD–MTJ system may harbor potential for spintronic device applications [13, 10,14–16], due to its combined properties of single-electron tunneling [17–19] and magnetoresistive transport [20]. Previous research has focused on QD–MTJ systems consisting of a nonmagnetic QD coupled to ferromagnetic (FM) or nonmagnetic (NM) leads [10,12,14,15,21–27]. In this paper, we study QD–MTJ systems consisting of QDs made of diluted magnetic semiconductor (DMS) [28–30], which have been little studied so far. The presence of a ferromagnetic QD in such a system may pave the way for possible memory or quantum information applications, with the information being encoded by the magnetization state of the QD. There have been previous studies on similar systems, but with the DMSQD being replaced by ferromagnetic (FM) nanoparticle(s) [31–33]. Experimentally, such a system exhibits a large variability in its transport properties since the size and position of the nanoparticles cannot be precisely controlled. With recent progress in nanofabrication techniques, it is now possible to replace the nanoparticles with an individually patterned DMSQD in between the two leads [34], thus achieving a higher degree of reproducibility in its transport properties. Furthermore, the transport in these FM nanoparticles is studied in the incoherent regime [17], in which successive tunneling events are treated independently of one another. In this work, we consider the transport in the coherent regime, where the electron maintains its quantum coherence while tunneling through both tunnel junctions in the DMSQD device.

The DMSQD–MTJ system under consideration consists of two ferromagnetic (FM) leads coupling to a DMSQD, as shown schematically in Fig. 1. We consider the DMSQD–MTJ system to be in a noncollinear alignment, in which the magnetizations of the two FM leads are fixed and parallel to one another, while the orientation of the QD magnetization is at some arbitrary angle (denoted by θ) with respect to the leads' magnetization. The orientation of the QD magnetization can be varied by applying a magnetic field of a suitable magnitude and direction. The coherent spin-dependent transport through the DMSQD–MTJ system is studied under an arbitrary voltage bias, for which the Keldysh nonequilibrium Green's function (NEGF) formalism [21] is applicable. The NEGF formalism systematically takes into consideration the quantum many-body effects of the two leads (as self-energy terms) and the electron–electron interaction in the QD. The latter is described by the Anderson model [35], where if a particular QD level is already occupied by an electron, the second electron tunnelling to the same energy level would be of the opposite spin, and will experience an additional Coulomb interaction energy due to the first electron. On the basis of the NEGF formalism, we calculate the transport characteristics of the DMSQD–MTJ system, including its charge and spin currents, and the tunnel magnetoresistance (TMR) ratio, and study how these quantities vary with the degree of noncollinearity between the magnetizations of the QD and leads.

The rest of the paper is organized as follows. We first present the Hamiltonian for the noncollinear DMSQD–MTJ system with the additional Anderson term. On the basis of the Hamiltonian, the Green's function of the system is derived analytically by applying the equation of motion method and the Hartree–Fock approximation. The expression for the voltage driven tunneling current in the DMSQD–MTJ system is then obtained via the well-established Keldysh NEGF approach. By considering the spin transport model, we calculate various spin transport properties such as the spin and charge currents and the tunnel magnetoresistance (TMR) of the DMSQD–MTJ system, and investigate their dependence on the noncollinearity between the dot and lead magnetizations. A brief summary is provided at the end of the paper.

1. Theory

For the DMSQD–MTJ system shown in Fig. 1, the system Hamiltonian is given by

$$H = \sum_{\alpha} H_\alpha + H_d + H_t, \tag{1}$$

where $\alpha = \{L, R\}$ is the index denoting the lead states, k is the momentum and $\sigma = \{\uparrow, \downarrow\}$ denotes up-spin (down-spin) for the electrons. The lead's Hamiltonian H_α, the dot's Hamiltonian H_d, and the