QUANTUM ELECTRON SPIN DYNAMICS IN COUPLED DOUBLE QUANTUM DOTS

Thesis

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Abstract

Recent advance of nanotechnology has stimulated much interest in the study of quantum transport in mesoscopic structures. The present thesis is divided into two parts. In the first part of the thesis, the spin current through a quantum dot system is calculated using a quantum master equation approach in the weak-coupling regime. To be able to efficiently calculate, also at low temperatures, the time evolution of the reduced density matrix in the present approach which includes a sum over Matsubara terms, a high-temperature approximation was derived which proves to be rather accurate in comparison to the exact results. In the present model it is assumed that the energy levels of the dot are split by a constant magnetic field. An additional external (laser) field is used to control the currents of the two spin polarizations. This is either done using the phenomenon of coherent destruction of tunneling or optimal control theory. Scenarios are studied in which the spin current is reversed while the charge current is kept constant.

The aim of the second part is to study the quantum transport properties of a mesoscopic device in the presence of an external microwave field. A model for such mesoscopic device is proposed and it is formed of a superconductor quantum dot coupled to two ferromagnetic reservoirs via two quantum point contacts.

An expression for the conductance was derived using Landauer-Büttiker formula. The effect of an external magnetic field was taken into consideration. Also, the spin polarization is expressed in terms of both Andreev-reflection probabilities for spin-up and spin-down. Numerical calculations are performed for the present proposed nanoscale device. This device operates in the mesoscopic regime as indicated from the dependence of the conductance on the temperature. From the results, two peaks appeared due to the Zeeman splitting of the quasiparticle density of states. The dependence of spin polarization on the considered parameters confirms that the spin flip of electrons when Andreev-reflection tunneling occurs through the junction. The spin polarization of the tunneled electrons through the junction gives rise to a non-equilibrium spin density in the superconductor and also due to Zeeman splitting of the quasiparticle density of states. Both equations for the conductance and spin polarization show a dependence on the magnetic field, the geometrical dimensions of the device, temperature, bias voltage and charging energy of the quantum dot.

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1 INTRODUCTION

In addition to the electron charge, the electron spin corresponds to an additional degree of freedom, which could be used for information storage and processing. To control electron and its spin states, one has to measure different physical quantities. Electrical properties are characterized by electrical conductivity, carrier mobility and voltage profile, while the spin properties are characterized by magnetization, magnetic resonance frequencies and spin relaxation rates. There are also different tools that can be used to manipulate electron charge and spin state. Electronic devices are controlled predominantly by applied voltages, while for the manipulation of spin state one has to use magnetic field. In contrast to the voltages, the magnetic field cannot be applied locally. For those reasons spintronics needs sophisticated solutions for the various classes of spintronic materials [1]

1.1 Spintronics

The electron was discovered in 1897 by J.J. Thomson as an elementary particle embodying a finite amount of charge. The charge property makes a (moving) electron in free space interact with electromagnetic fields via the Coulomb and Lorentz forces and enables metals and semiconductors to carry an electrical current. The observation of the Zeeman effect in 1896 and fine structure anomalies in the line spectra of atoms led to the suggestion in 1925 by Uhlenbeck and Goudsmit [2] that the electron also has a spin, an intrinsic angular momentum and directly coupled to it a magnetic moment. The electron spin provides another degree of freedom for the electron to interact with a magnetic field. Spintronics is a multidisciplinary field whose central theme is the active manipulation of spin degrees of freedom in solid-state systems [3].

Recently a lot of attention has been attracted by the field of spin-dependent electron transport in nanostructures. Injection, transport and control of spin-polarized current through nanostructures (spintronics) [4] has become an area of intense activity in the past few years. This is due to its advantages in increasing processing speed and decreasing power consumption compared with conventional semiconductor devices. Proposals for generating spin-polarized currents include spin injection by using ferromagnetic metals [5] or magnetic semiconductors have been made [6]. Alternatively, quantum dots (QDs) can be used as spin filters or spin pumps [7–10]. New devices are now being designed relying on the spin [4, 11, 12]. Such devices should have faster switching times and lower power consumption than conventional devices, mainly because spins can be manipulated faster and at lower energy cost than charges. Theoretical studies of electron pumping and spin filter in a single and double quantum dot system have been carried out [13, 14]. Spin based devices are very important for future applications [15] especially in the field of quantum computer [16] which would represent a great breakthrough in the processing time of certain physical and mathematical problems [17]. In particular, the electron spin in quantum dots has been proposed as a building block for the implementation of quantum bits (qubits) for quantum computation [18, 19]. The goal of spintronics is to understand the interaction between the particle spin and its solid-state environments and to make useful devices using the acquired knowledge. Fundamental studies of spintronics include investigations of spin transport in electronic materials, as well as understanding spin dynamics and spin relaxation have been made [3, 11, 12]

1.2 Spin in Classic Semiconductor

In non-magnetic metals and semiconductors, magnetism plays a secondary role. Because of the Pauli principle, the equal filling of the up and down spin subbands leads to the cancellation of magnetic moment. In an external magnetic field a weak carrier magnetization appears, but the Pauli susceptibility is very low. In most metals and semiconductors the dependence of electrical properties on spin properties is negligible. The connection between electrical and magnetic properties is visible only in exceptional cases. One of them is the dependence of the resistance of a two-dimensional electron gas on its spin polarization. The only mechanism linking electrical and magnetic properties is the existence of spin-orbit coupling which leads to the spin splitting of the bands [1, 11, 12].

1.3 Polarization of the Spin

Spin polarization is the degree to which the spin is aligned with a given direction. This property may pertain to the spin, hence to the magnetic moment, of conduction electrons in ferromagnetic metals giving rise to spin polarized currents. Generation of such spin polarization can be achieved in several ways. While traditionally spin has been oriented using optical techniques in which circularly polarized photons transfer their angular momenta to electrons, for device applications electrical spin injection is more desirable. In electrical spin injection a magnetic electrode is connected to the sample. When the current drives spin-polarized electrons from the electrode to the sample, nonequilibrium spin accumulates there. The rate of spin accumulation depends on spin relaxation (the process of bringing the accumulated spin population back to equilibrium). There are several relevant mechanisms of spin relaxation, most involving spin-orbit coupling to provide the spin-dependent potential, in combination with momentum scattering providing a randomizing force [1,3,12]. Experimentally, the first determination of the spin polarization of the conduction band in a ferromagnetic material has been performed by Tedrow and Meservey in the early 70's [20]. This was achieved by studying the magneto conductance of a ferromagnet/Al_2O_3 /Al tunnel junctions. The tunneling current between the two metallic electrodes separated by a thin insulating layer depends on the product of the densities of states of the two electrodes. The advantage of using superconducting Al as one of the electrodes is that the difference in densities of states at the Fermi level, i.e. the spin polarization, is exactly known. The physical origin of the spin subband polarization in a superconductor is the Zeeman splitting of the two sharp Bardeen, Cooper, and Schrieffer (BSC) peaks in the densities of states.

1.4 Spin-Polarized Transport

A basis for our understanding of spin-polarized transport was provided by