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Meso Spin-Crystallites for New Electronics

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Abstract

Mesoscopic smart materials like Dilute Magnetic Semiconductors (DMS) and Quantum Dots (QD) have squeezed electrons and holes in a size of the Bohr excitonic radius. Different synthesis procedures create vacancies and other defects that impart special spin based properties in crystallites of nanometric size to make them proper for new spin controlled functionalities. The Potential field of a new electronics is based on a coherent transport of electron spin. Traditional Electronics relies only on the charge and its transport, completely ignoring the electron spin. The spin of electron provides us an unprecedented chance and new starting point to explore the future of modern semiconductor and information industry. It needs materials as a source of spin-polarized carriers or electron spins to form a spin current. Coherent transport of moving electron spin tunneling through the interfaces and long spin coherence time of carriers implement the desirable operations. The mechanisms which break the conservation of a spin current include magnetic impurities scattering, spin-orbit coupling, and nuclear spin. Consequently, a spin current cannot be transported for a long distance. The metallic spin- device has made significant progress. Spin injection in a diluted magnetic semiconductor has been enhanced significantly. Exploiting the subtle quantum property of the electrons to develop a new generation of electronic devices needs the motivation, understanding physical fundamentals, and recent experimental progress which forms the essence of this review.

Keywords: Quantum dots; Dilute magnetic semiconductors; Spin current; Spin injection.

Introduction

Spin stands for either the spin of a single electron, detected by the measurement of associated magnetic moment, or by the ensemble average spin of electrons in magnetic nanoparticles. With the development of nanotechnology, we became able to access nanometer sizes in crystallites in which range flips the spin of electrons, making charge-based electronics of macro particles insensible to spin effects. In mesoscopic regime, it is possible to observe spin effects, and one such effect is a large resistance of thin multilayer that awarded Nobel Prize in 2007 for the discovery of Giant Magneto-Resistance (GMR), done in 1988-1989 jointly by Albert Fert and Peter Grunberg. Thus, the spin-dependent electron transport phenomena in solid-state devices came to mesoscopic regime research in the 1980s. Spin-polarized electron injection from a ferromagnetic metal to a normal metal [1] and the discovery of GMR [2,3] supported the idea that was formed upon the ferromagnetic to superconducting interface and tunneling experiments of Meservey and Tedrow, and initial experiments on magnetic tunnel junctions by Julliere [4], a theoretical proposal of a spin field-effect-transistor came in 1990 by Datta and Das [5].

For the carriers of charge with spin, the working principle of conventional semiconductor devices is practically unaffected by spin because there is no net imbalance between spins pointing in different directions (‘up’ and ‘down’, for example) in the environment in which they are transported. However, the spin imbalance could be produced by changing the environment and be useful in a wide range of applications, from computer hard drives and magnetic random access memories, to innovative technologies, such as spin transistors, spin-lasers, or even in spin- based quantum computing. In most cases the spin injection means spin-polarized current injection. There are three steps needed in spin-based devices of future technology: spin injection, spin manipulation by the external field and spin detection for measuring the physical consequences of spin coherent states in promising devices.

Recent research in the spin field has focused on the study of mesoscopic crystallites for magnetism in doped semiconductors. Examples include experimental and computational investigations in Dilute magnetic oxides (DMOs) like Sn-oxide, or ZnO based DMOs and TiO_2-based DMOs [6,7], non-oxide ferromagnetic semiconductor sources like GaMn As, etc. We discuss the concepts and issues of spin current, spin relaxation in mesoscopic crystallites having spins, and potential spin devices [8-10].

The Spin Current

The theory of spin-polarized current initiated with the understanding of GMR in multilayer ferromagnetic thin films. GMR marked as much larger in these than Magnetoresistance (MR) in metal, indicates that the orientation of magnetization in ferromagnetic layers determine the mechanism of spin-dependent scattering. When the magnetizations of the two layers are parallel to each other then the mean free path increases. In the opposite case, when the magnetizations of two layers are antiparallel to each other the mean free path decreases. As

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a result, the resistance of the system varies with the relative orientation of magnetizations in the two ferromagnetic layers. Spin-dependent scattering is schematically represented in Figure 1.

charge current arising from charge transport carrying information and energy, and spin current arising from coherent spin transport. These are defined using velocities derived from Hamiltonian containing kinetic energy and potential energy of interaction. Let the Hamiltonian H of many-particle system be written as

$$H = \sum_{i,\sigma} \frac{1}{2m}\left(p_i - \frac{e}{c}A_\sigma\right)^2 + \sum_{i \neq j} V_{ij}$$

Here the σ runs over two spin states of electrons, and the last sum is for interaction of electrons with one another or with environment and is assumed not an explicit function of vector potential A_σ, so that velocities are given by

$$v_\sigma = -\frac{c}{e}\frac{\partial H}{\partial A_\sigma}$$

Here, the subscript runs over two spin states $\left|+\frac{1}{2}\right\rangle$ and $\left|-\frac{1}{2}\right\rangle$ of an electron. Using the two velocities from here, we define charge current density as

$$j_c = (-e)[v_{+\frac{1}{2}} + v_{-\frac{1}{2}}]$$

As the electromagnetic vector potential does not involve spin, the velocities in the bracket are equal.

The spin current density is defined as

$$j_s = \frac{\hbar}{2}[v_{+\frac{1}{2}} - v_{-\frac{1}{2}}]$$

Here the vector potential involves spin of electrons and the two velocities are unequal in general. In particular, they may be opposite in signs and equal in magnitudes, in which case charge current will be zero but not the spin current. The existence of spin current requires the dependence of vector potential on a spin state.

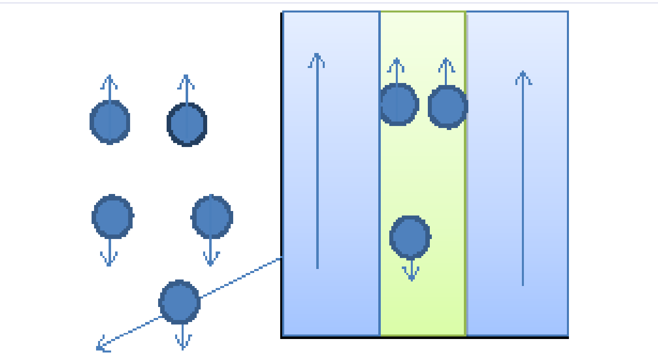

Figure 1: Spin current and GMR mechanism: parallel alignment of spin (low resistance) and anti-parallel alignment of spin (high resistance) relative to the spin of medium. Two types of current are now in a picture:

For an electron in an electric field, the spin is coupled to orbital motion as seen in atoms, and it may become significantly large in mesoscopic spin-crystallites (meso spin-crystallites), as it is evidenced by experiments on energy splitting cases. Consequently, the electron velocity becomes spin dependent. And a force acts on moving electron perpendicular to both the electric field and the spin current whose spin polarization is projected along the electric field as depicted in Figure 2 [11].

The spin current is invariant under time reversal, which makes it less or no dissipative. The charge current breaks this symmetry and is dissipative. Dissipation requires spin-phonon coupling and is yet an open issue. A spin current is a second-rank pseudotensor, given by not only the flow direction of electron spin but also spin orientation, different spin orientations possibly producing different physical effects. The coupling between the spin current and system crystal is rather weak and has no direct coupling with phonon. This is one of the advantages of the spin current.

When a spin current gets scattered by impurities or spin-dependent band structure, a difference arises here in transmission co-efficients between two opposite spin states. The two opposite spin states, thus, cause an electric current (electric field and potential). Electric current, can also be induced by inverse spin Hall Effect [12-14].

There are several mechanisms which break the conservation of a spin current, such as magnetic impurities scattering, spin-orbit coupling, and nuclear spin; a spin current cannot be transported for a long distance. It puts a limit on possible technological applications. For a typical semiconductor material, the distance of spin-current transport is about several to hundred microns. Recent experimental data, however, indicates the spin coherence length can be tuned by an external field or become a quite long along some axis in new materials.

Spin Hall Effect

A pure spin current (j_s) can exist even when charge current (j_c) is zero. Can such a spin current produce electric field? The answer is affirmative as magnetic moment is in motion along with spin [15]. The field is small but measurable. Similarly, an electric field can exert a force on a spin current as exemplified in Figure 2. Authors feel the force as similar to Lorentz one but it is proportional to the square of a field as observed in semiconductors and photonic crystals. In spin Hall Effect there is an accumulation of spin on the boundary piece of material as an accumulation of charges near the boundary in charge Hall Effect. But it is different from latter in that it does not exert a force on further accumulating electrons. The equilibrium of spin density is reached by diffusion that is described by a diffusion length and spin relaxation time.

Spin Hall Effect was experimentally detected by Kerr Rotation method in Ga (Gallium arsenide) As and InGaAs thin films [16].

Detection and Devices

In a mesoscopic crystallites, such as a metallic nanoparticle, electronic wave functions form Kramer doublets, resulting from

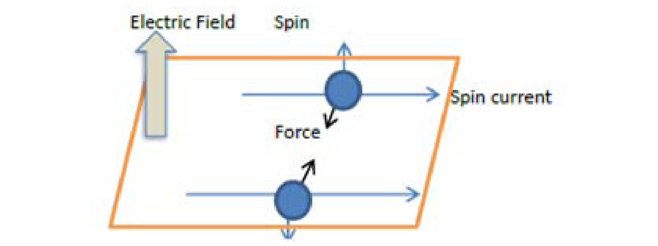

Figure 2: Transverse Force on Spin current.

mixing of the two spin sets of an electron through spin-orbit coupling in zero magnetic field. In a non-zero magnetic field, the degeneracy is lifted by Zeeman Effect. The wave functions get affected by the strength of spin-orbit interaction which is described in terms of spin-orbit scattering rate and spacing between Kramer doublets of the meso-crystallite. In a weak spin-orbit scattering, the wave functions have well-defined spins while in strong spin-orbit scattering the wave functions have uncertain spins. In the former case, the detection of spin current is performed but not in the latter case.

Spin relaxation

The process of attaining equilibrium spin distribution of spins from a non-equilibrium distribution is known as spin relaxation. Several devices need quick spin relaxation, and for such cases mechanisms of spin relaxation are important.

A non-equilibrium distribution of spins is caused by interfaces or spin injections and relaxation to equilibrium can be fast or slow depending on the dominating mechanism. Four important ways of relaxation are Elliot-Yafet (EY), Drank Nov-Perel (DP), Bir-Aronov-Pikus (BAP), and Hyperfine Interactions (HF). The rate of spin relaxation can be calculated quantum mechanically [17]. The HF mechanism has recently been recognized for spin relaxation in QDs [18].

Devices and challenges

The spin current concept initiated the era of spin-dependent devices. Soon after, a new event in the name of the Tunneling Magneto-Resistance (TMR) was observed and was much larger than GMR. It was put to extensive applications in commercial products. In the case of the new type of spin field effect transistor, it is proposed that Datta-Das transistor and conventional transistor have almost the same structure; however, the former uses the gate voltage to control the spin orientation of electron, and the later uses the gate voltage to change the direction of motion of electrons. The energy needed to change the spin orientation is much smaller, and the time is much shorter, and the efficiency is much higher. The proposal has not actualized in laboratory because : (1) it needs materials as source of spin polarized carriers or electron spins to form a spin current; (2) the moving electron spin can transport coherently and tunnel through the interfaces; (3) the spin coherence time of carriers is long enough to implement the desirable operations.

Short Spin lifetime of conduction electrons is another problem. The life time in metals are relatively short (less than 1 nanosecond) and is too small on technologically relevant timescales. Recent experiments, such as the current-induced magnetization and spin Hall Effect in metals and semiconductors, that need coherence of electron spin, have shown that the spin coherence lengths of electrons in semiconductors are much longer than those in metal, and we expect that more applications can be realized in semiconductors. Just a few years back IBM scientists have mapped the creation of persistent spin helices of synchronized electrons persisting for more than a nanosecond. This is a 30-fold increase from the previously observed results and is longer than the duration of a modern processor clock cycle, and is looked as encouraging for using electron spins for information processing [19]. In confined structures, spin dephasing can be suppressed, leading to spin lifetimes of milliseconds in semiconductor quantum dots at low temperatures. Despite the challenges, considerable effort is marked in device designing.

Magnetic field sensors can be developed using spin currents. For this, a net spin polarization can be achieved either through creating an equilibrium energy splitting between spin up and spin down such as putting a material in a large magnetic field (using Zeeman Effect) or the exchange energy present in a ferromagnet; or forcing the system out of equilibrium. The simplest method of generating a spin-polarized current in a metal is to pass the current through a ferromagnetic material and GMR indicates magnetism. Another way is to use a typical GMR device that consists of at least two layers of ferromagnetic materials separated by a spacer layer. When the two magnetization vectors of the ferromagnetic layers are aligned, the electrical resistance will be lower than if the ferromagnetic layers are anti-aligned at constant voltage. This essentially constitutes a magnetic field sensor applied in spin devices.. Two variants of GMR have been applied in spin devices: (1) current-in-plane (CIP), where the electric current flows parallel to the layers and (2) current-perpendicular-to-plane (CPP), where the electric current flows in a direction perpendicular to the layers. Other metals based spin devices include:

- In tunnel magnetoresistance (TMR), the CPP transport is achieved by using quantum-mechanical tunneling of electrons through a thin insulator separating ferromagnetic layers.
- Spin-transfer torque, due to a current of spin-polarized electrons here is used to control the magnetization direction of ferromagnetic electrodes in the device.
- Spin-wave logic devices utilize the phase to carry information. Interference and spin-wave scattering are utilized to perform logic operations.

Spin-based population inversion

Spin-polarized lasers can, potentially, offer lower threshold currents and reach higher emission intensities. To achieve spin-polarized lasing emission, a material should possess a slow spin relaxation and a high propensity to be injected with spin-polarized currents. These stringent requirements, so far, have limited the choice of candidate materials for spin-lasers. Recently these requirements have been relaxed by using a new self-polarized spin mechanism. Here Fe_3O_4 nanoparticles are coupled to GaN-nanorods to form an energy band structure that induces the selective charge transfer of electrons with opposite spins. In turn, this selection mechanism generates the population imbalance between spin-up and spin-down electrons in the emitter's energy levels without an external bias. Using this principle, laser emission from GaNNano-rods with spin polarization up to 28.2% at room temperature under a low magnetic field of 0.35 T has been possible, without requiring optical pumping with circularly polarized light or electrical pumping with magnetic electrodes. Using such mechanism, potentially a wide range of semiconductors can be used as spin-nano-lasers [20].

Device for Spin detection in semiconductors

The following techniques are used in the detection of spin. Faraday or Kerr rotation of transmitted and reflected photons [21], Circular polarization analysis of electroluminescence [22], Nonlocal spin valve (adapted from Johnson and Silsbee's work with metals) [23] and Ballistic spin filtering [24]. The latter technique resolved the difficulties due to lack of spin-orbit interaction and materials issues to achieve spin transport in silicon [25].

Spin transistor: Using spin-polarized electrical injection a spin-based transistor having advantages over MOSFET devices such as steeper sub-threshold slope may be developed and Magnetic tunnel transistor can be devised.

Ferromagnetic versus Antiferromagnetic Storage Media

In ferromagnetic storage material the bits 0 and 1 are in use (the usual definition implies 0 for 'magnetization upwards', 1 for 'magnetization downwards')**.** Recently antiferromagnetic storage media have been studied, where one may define 0 for 'vertically-alternating spin configuration' and 1 for 'horizontally-alternating spin configuration" (This corresponds mathematically to the transition from the rotation group SO (3) to its relativistic covering, the "double group" SU (2)). The main advantages of using antiferromagnetic materials lie in their non-sensitivity against perturbations by stray fields, and shorter switching times.

Quantum computing

Electron spins in quantum confined structures such as QDs and DMS nanoparticles are under consideration, as a spin of an electron is the most natural candidate for qubit [26], satisfying all the requirements for a scalable quantum computer. In particular, spin-entangled electrons can be created in coupled QDs and provide the necessary resource for quantum communication.

Conclusion

It is possible to get spin current in meso spin-crystallites for new electronics. Recently, the studies of spin current have emerged hot for device designs and heading to an era of non-traditional, spin based, electronics. It is yet in infancy as regards to efficiently generate, manipulate and detect spin current. The metallic spin- device has made significant progress and spin injection in Diluted magnetic semiconductor (DMS) has been enhanced significantly. Spin-based devices include not only ferromagnetic but anti-ferromagnetic materials also. In mesoscopic size crystallites such as Quantum dots (QDs) and dilute magnetic semiconductors (DMS), spin dephasing can be suppressed, at least at low temperatures. Studying spin-polarized currents in new materials, DMS and QDs, and their decay mechanisms, not only improve the performance of existing practical devices but also help to solve more fundamental problems of condensed matter physics leading to an era of new electronics based on control over spin states of electrons. By studying new materials and decay mechanisms, we hope to improve the performance of practical devices as well as solving more fundamental problems of condensed matter physics and new electronics.

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