Issues, Concepts, and Challenges in Spintronics

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ABSTRACT:

We review from a theoretical perspective the emerging field of spintronics where active control of spin transport and dynamics in electronic materials may provide novel device application possibilities. In particular, we discuss the quantum mechanical principles underlying spintronics applications, emphasizing the formidable challenges involving spin decoherence and spin injection facing any eventual device fabrication. We provide a critical assessment of the current status of the field with special attention to possible device applications.

INTRODUCTION

Spintronics (sometimes also referred to as 'magneto-electronics' although we prefer the 'spintronics' terminology because a magnetic field or the presence of a magnetic material is not necessarily essential for manipulating spins) is the emerging field [1] of active control of carrier spin dynamics and transport in electronic materials (particularly, but not necessarily limited to, semiconductors). In some sense, existing technologies such as GMR-based memory devices and spin valves are elementary spintronic applications where the role of spin, however, is passive in dictating the size of the resistance (or tunneling current) depending on the spin direction controlled by local magnetic fields. Spintronics is projected to go beyond passive spin devices, and introduce applications (and possibly whole new technologies) based on the active control of spin dynamics. Such active control of spin dynamics is envisioned to lead to novel quantum-mechanical enabling technologies such as spin transistors, spin filters and modulators, new memory devices, and perhaps eventually quantum information processing and quantum computation. The possibility of monolithic integration on a single device of magnetic, optical, and electronic applications, where magnetic field and polarized light control spin dynamics, is an exciting new spintronic prospect for creating novel magneto-electro-optical technology. The two important physical principles underlying the current interest in spintronics are the inherent quantum mechanical nature of spin as a dynamical variable (leading to the possibility of novel spintronic quantum devices not feasible within the present-day charge-based electronics) and the inherently long relaxation or coherence time associated with spin states (compared with the ordinary momentum states). The fact that carrier spin in semiconductors can be easily manipulated noninvasively by using local magnetic fields, by applying external electric fields through controlled gates, and even by shining polarized light is an important impetus for developing spintronics applications.

In spite of the great current interest in the basic principles and concepts of spintronics a large number of obstacles need to be overcome before one can manufacture spintronics applications. For example, a basic spintronics transport requirement is to produce and sustain large spin-polarized currents in electronic materials (semiconductors) for long times. This has not yet been accomplished. In fact, it has turned out to be problematic to introduce spin-polarized carriers in any significant amount into semiconductor materials. Similarly, for quantum computation one requires significant and precisely controllable spin entanglement as well as single spin (i. e., a single Bohr magneton) manipulation using local magnetic fields. Currently there is no good idea about how to accomplish this. It is clear that a great deal of basic fundamental physics research will be needed before spintronics applications become a reality.

In this paper we highlight and summarize a few examples of spintronics research with the emphasis on understanding principles and operations with future device potential. We concentrate on the elementary aspects of spintronics which must be understood and developed before any possible applications can be discussed. These aspects are creating, maintaining, manipulating, and measuring spin currents in semiconductors (and related electronic materials), spin entanglement in semiconductor quantum dots in the context of quantum computation, and spin relaxation. The examples are drawn from our own theoretical research on spintronics, and we refer the reader to our existing publications for the details.

SPIN RELAXATION AND DECOHERENCE

The great promise of spintronic technology is based upon the fundamental ability of electron spins in electronic materials to preserve coherence for relatively long times. A typical electron "remembers" its initial spin orientation for a nanosecond. This time scale is indeed long when compared with the typical times–femtoseconds–for electron momentum relaxation. Perhaps a more revealing quantity than spin lifetime (which is usually called spin relaxation time T_1 or spin decoherence time T_2, depending on the context of the experiment) is the spin diffusion length L_S which measures how far electrons diffuse in a solid without losing spin coherence. The important fact that L_S is typically a micrometer makes spintronics a viable option for future micro- and nanoelectronics; any information encoded in electron spins will spread undisturbed throughout the device. Clearly, the longer the spin lifetime, the better and more reliable will be the spintronic devices. The study of spin relaxation is thus of great importance for spin-based technology (we reviewed the current understanding of spin relaxation processes in electronic systems in Ref. [2]).

Initial measurements of spin lifetimes were conducted in metals like Na or Li by conduction electron spin resonance (CESR) technique [3]. The most important outcome of these experiments concerned the magnitude of T_1 (nanoseconds) and its temperature behavior: T_1 is constant at low temperatures (below, say, 50 K) and is increasing linearly with increasing temperature at elevated temperatures (above, say, 200 K). These two observations helped to shape the theoretical understanding of the processes behind spin relaxation in metals. It is now generally accepted that electron spins in (nonmagnetic) metals decay by scattering off impurities (at low temperatures where T_1 is constant) and phonons (at higher temperatures where T_1 grows linearly with increasing temperature). The spin-flip probability of such processes is finite because of the finite spin-orbit interaction induced by either host ions or impurities (this is the so called Elliott-Yafet mechanism of spin relaxation [4]). We have recently performed the first realistic calculation of T_1 in a metal (aluminum) [5]. Our calculation not only provides the first direct proof of the validity of the Elliott-Yafet mechanism, but also shows that by engineering the band structure of metals (or semiconductors) it is possible to tailor spin relaxation (e.g., T_1 can be changed by orders of magnitude by doping, straining, alloying, or changing dimensionality).

An important development came with the discovery of spin injection by Johnson and Silsbee [6]. In the original experiment spin-polarized electrons were injected from a ferromagnetic electrode (permalloy) into a nonmagnetic metal (aluminum), and the spin diffusion length was monitored. This method of measuring L_S (and thus spin lifetime) has a great potential since, unlike CESR, spin injection does not need an applied magnetic field which, in some cases, radically affects spin relaxation processes. In addition to providing a useful method for measuring spin relaxation, the Johnson-Silsbee spin injection experiment brought about a whole new field of electronics: spintronics. Indeed, spin injection is the most natural way to integrate spin dynamics with electronic transport in electronic devices. There is no need for magnetic field or radiation to excite spin-polarized electrons. One only needs ferromagnetic electrodes. The last truly fundamental obstacle in the progress towards integrating the new spintronic with the traditional semiconductor technology has been recently overcome with the discovery of spin injection into a semiconductor [7, 8].

In addition to be able to create the population of spin-polarized carriers, we also need a way to monitor and control the dynamics of spin processes in electronic materials. This quest has been pioneered by Kikkawa and Awschalom [9]. In a typical experiment spin-polarized electrons in a semiconductor like GaAs are excited by a circularly-polarized light and then the electrons' spin evolution is monitored at small (picosecond) time intervals. Several new exciting results came from such experiments on semiconductors [10]: a dramatic (two orders of magnitude) increase of electron spin lifetime with increased doping, unusually large (hundreds of micrometers) spin diffusion length, and the ability to optically control nuclear spin polarization (with electron spins acting as intermediaries between light and nuclear spins).

SPIN-POLARIZED TRANSPORT

The goal of employing both spin and charge transport (spin-polarized transport) in potential novel device applications imposes intrinsic limitations on their design: they should consist of either heterostructures or inhomogeneous materials. While similar design constraints have been extensively investigated and well understood in the case of pure charge transport in conventional electronics, it is not clear how the spin degrees of freedom will behave in transport across interfaces in a heterostructure or through an inhomogeneous material. For example, by placing a semiconductor in contact with a nonmagnetic metal a Schottky barrier is formed whose properties will govern charge transport across the semiconductor/metal junction. Currently there is no physical understanding for the corresponding spin-dependent Schottky barrier relevant for spin-polarized transport across interfaces. This is an important issue as some of the proposed spintronic devices [11] rely on the direct electrical spin injection from a ferromagnet into a semiconductor [7, 8]. The situation is further complicated by the possibility of spin-flip scattering at magnetically active interfaces. These considerations have to be included in assessing the feasibility of various spintronic devices because they imply that the degree of carrier spin-polarization can be strongly modified during transport across semiconductor/ferromagnet interfaces.

Fabricating hybrid structures which would combine a semiconductor and a superconductor would allow investigating some of the aforementioned features and determining the degree of an extrinsically induced carrier spin polarization in the semiconductor. This could be realized by using Andreev reflection which governs transport properties at low applied bias. In this two-particle process an electron incident to the interface at the semiconductor side is accompanied by a second electron of the opposite spin. Both electrons are then transfered into the superconductor where they form a Cooper pair. The probability (measured by, e.g., conductance) of such processes strongly depends on the amount of spin polarization and the spin transparency of the interface [12, 13].

Material inhomogeneities can also act favorably and be tailored to give desired effect for spin-polarized transport. We illustrate this in our proposal of the spin-polarized p-n junction [14]. Its simple realization would consist of shining circularly-polarized light on the p-doped side of a usual p-n junction. This would create a spin-polarized population of electron-hole pairs. By considering a p-n junction shorter than the spin-diffusion length, combined with a sharp doping profile, it is feasible to create enhanced magnetization in the interior of the semiconductor with the spatial dependence following that of the carrier concentration. Such a p-n junction could be used as a building block for a novel spin transistor applications which would utilize both spin and charge degrees of freedom [14].

SPIN-BASED QUANTUM COMPUTATION

Among all possible spintronic devices, by far the most revolutionary is the proposed spin-based quantum computer (QC) which has the promise to vastly outperform classical computers in certain tasks such as factoring large numbers and searching large databases [15]. In QCs electron or nuclear spins are used as the basic building blocks. The spin-up and -down states of an electron or a nucleus provide the quantum bit (qubit), in analogy with "0" and "1" in a classical computer. However, as a quantum mechanical object, a spin can have not only up and down states, but also arbitrary superpositions of these two states. This inherent parallelism and other quantum mechanical properties such as entanglement and unitary evolution are the fundamental differences between QCs and classical computers.

In the search for appropriate hardwares for a QC, many proposals have been put forward [15]. Here we focus on the spin-based solid-state models [16]. One of the first proposals [17] suggests using quantum-dot-trapped electron spins as qubits. Here a single electron is trapped in a gated horizontal GaAs quantum dot, with pulsed local magnetic field and inter-dot gate voltage governing the single-qubit and two-qubit operation. Another proposal replaces the quantum dot electrons by donor electrons [18]. Here varying the gyromagnetic ratio in a compositionally modulated SiGe alloy allows electron spin resonance for single qubit operations and exchange interaction for two-qubit operations. One important advantage of electron spins is their "maneuverability": electrons are mobile and can be manipulated by both electric and magnetic fields.

Aside from electron-spin-based QC models, there are also nuclear-spin-based proposals, such as the one using nuclear spins of phosphorus donor atoms in Si as qubits [19]. Here external gates are used to tune the nuclear magnetic resonance frequency, and donor electrons are the intermediaries between neighboring nuclear spins, introducing two-qubit operations through electron exchange interaction and hyperfine interaction. The main advantage of nuclear spin qubits is their exceedingly long coherence time, which allows many coherent operations. Indeed, bulk solution NMR is one of the most advanced QC architectures [15], even though its ensemble-average character prompts some researchers to question [20] whether it really possesses all the quantum mechanical powers needed for tasks such as factoring.

The major difficulties facing various QC models are achieving precise control over unitary evolutions and maintaining quantum mechanical coherence. While traditional electronic devices deal with large numbers of electrons at a time, while in spin-based QCs one has to be able to precisely control spins of individual electrons. Furthermore, the electron spins need to be essentially isolated from their environment so that their dynamics is governed by quantum mechanics. If this isolation is imperfect, the spins' quantum information will leak into their environment, and the dynamics of the spins will become irreversible and classical, so that the QC operation will be disrupted.

Spin decoherence has many different channels such as spin interaction with boundaries, impurities, host nuclei, even with external controls. For example, one common approach to tune the exchange interaction between electrons or electrons and nuclei is to use electrical gates which are connected through a transmission line to the outside. External noise such as Johnson-Nyquist noise can thus cause fluctuations in the gate voltage, which in turn cause errors in the exchange. The rate of this error can be as large as a few MHz [16], which corresponds to the limits of the currently available error correction schemes. Another error during exchange is caused by inhomogeneous magnetic fields [21]. In essence, the different Zeeman couplings of two neighboring electrons cause mixing of the two-electron singlet and triplet states, therefore preventing the electron spin states from complete disentanglement for swap. This error is proportional to the square of the inhomogeneity [21], and can usually be corrected. Indeed, there is an existing scheme which can circumvent this error [22]. Furthermore, it has been proposed [23] that one can utilize certain decoherence-free subspace of four quantum dots as qubits, relying completely on exchange for all operations and eliminating the use of any external magnetic field. Such a scheme is more difficult to realize experimentally, but it does provide the advantage of smaller decoherence because of fewer noise channels.

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