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Spin electronics and spin computation

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Abstract

We review several proposed spintronic devices that can provide new functionality or improve available functions of electronic devices. In particular, we discuss a high mobility field effect spin transistor, an all-metal spin transistor, and our recent proposal of an all-semiconductor spin transistor and a spin battery. We also address some key issues in spin-polarized transport, which are relevant to the feasibility and operation of hybrid semiconductor devices. Finally, we discuss a more radical aspect of spintronic research—the spin-based quantum computation and quantum information processing. © 2001 Published by Elsevier Science Ltd.

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1. Introduction

Spintronics, or spin electronics, refers to the study of the role played by electron (and more generally nuclear) spin in solid state physics, and possible devices that specifically exploit spin properties instead of or in addition to charge degrees of freedom [1]. For example, spin relaxation and spin transport in metals and semiconductors are of fundamental research interest not only for being basic solid state physics issues, but also for the already demonstrated potential these phenomena have in electronic technology [1–4,81,82]. The prototype device that is already in use in industry as a read head and a memory-storage cell is the giant-magnetoresistive (GMR) sandwich structure [1] which consists of alternating ferromagnetic and nonmagnetic metal layers. Depending on the relative orientation of the magnetizations in the magnetic layers, the device resistance changes from small (parallel magnetizations) to large (antiparallel magnetizations). This change in resistance (also called magnetoresistance) is used to sense changes in magnetic fields. Recent efforts in GMR technology have also involved magnetic tunnel junction devices where the tunneling current depends on spin orientations of the electrodes.

Current efforts in designing and manufacturing spintronic devices involve two different approaches. The first is perfecting the existing GMR-based technology by either developing new materials with larger spin polarization of electrons or making improvements or variations in the existing devices that allow for better spin filtering. The second effort, which is more radical, focuses on finding novel ways of both generation and utilization of spin-polarized currents. These include investigation of spin transport in semiconductors and looking for ways in which semiconductors can function as spin polarizers and spin valves. The importance of this effort lies in the fact that the existing metal-based devices do not amplify signals (although they are successful switches or valves), whereas semiconductor based spintronic devices could in principle provide amplification and serve, in general, as multi-functional devices. Perhaps even more importantly, it would be much easier for semiconductor-based devices to be integrated with traditional semiconductor technology.

While there are clear advantages for introducing semiconductors in novel spintronic applications, many basic questions pertaining to combining semiconductors with other materials to produce a viable spintronic technology remain open. For example, whether placing a semiconductor in contact with another material would impede spin transport across the interface is far from well-understood. In the past, one of the strategies to advance understanding of spin transport in hybrid semiconductor structures was to directly

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FIGURES

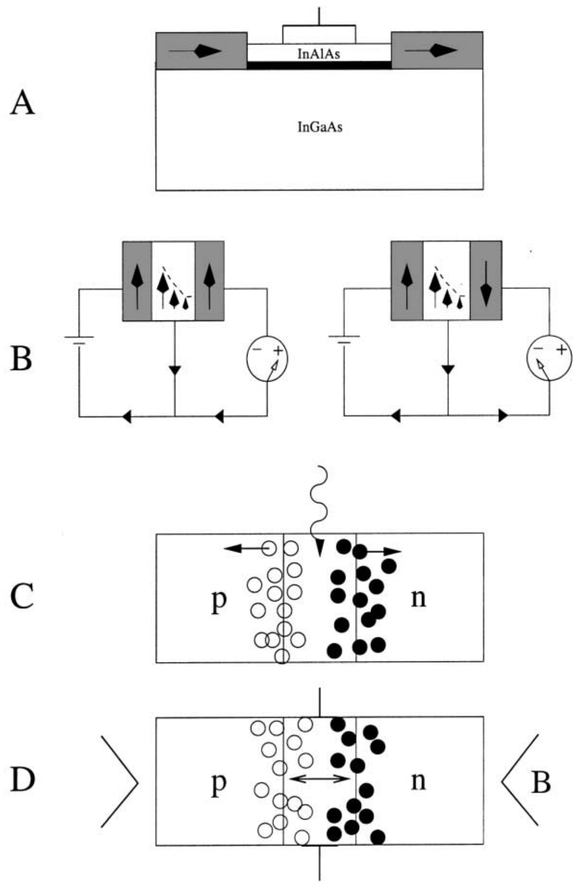

Fig. 1. Schemes of selected spintronic devices. (A) The Datta-Das spin transistor. Electrons travel in the two-dimensional inverted region channel (filled region) between two ferromagnetic electrodes. Electron spins precess in the Rashba field which can be controlled by the gate voltage, modulating the current. (B) The Johnson spin transistor. Depending on the orientation of the magnetizations in the two ferromagnetic layers, the current in the collector circuit flows either from the base into the emitter (left) or from the emitter into the base (right). (C) Spin-polarized solar battery. Filtered solar light (circularly polarized) generates electron-hole pairs in the depletion region. The polarization is carried only by electrons if the semiconductor is III–V, like GaAs. The resulting current flowing in an external circuit that connects the *n* and *p* regions is spin-polarized. (D) Magnetic field effect transistor (MFET). Magnetic field *B* is applied along the p–n junction. The current in the circuit connecting the junction in the transverse direction depends critically on the size of the depletion layer (it is small for a larger layer and large for a smaller layer). If the *g*-factors of the electrons or holes are large, a change in *B* can lead to a large change in the width of the depletion layer and in the magnitude of the transverse current.

borrow knowledge obtained from studies of more traditional magnetic materials. However, there is also an alternative approach involving the direct investigation of spin transport in all-semiconductor device geometries. In such a scenario a combination of optical manipulation (for example, shining circularly polarized light to create net spin polarization) and material inhomogeneities (e.g. by suitable doping as in the recently discovered $Ga_{1-x}Mn_xAs$ type ferromagnetic materials where Mn impurities act as dopants) could be employed to tailor spin transport properties.

In addition to the near-term studies of various spin transistors and spin transport properties of semiconductors, a long-term and ambitious subfield of spintronics is the application of electron and nuclear spins to quantum information processing and quantum computation. It has long been pointed out that quantum mechanics may provide great advantages over classical physics in physical computation [5–8]. However, the real boom started after the advent of Shor's factorization algorithm [9] and quantum error correction schemes [10,11]. Among the many quantum computer hardwares that were proposed are the ones based on electron and nuclear spins [12]. Obviously, the spins of electrons and spin-1/2 nuclei provide perfect candidates for quantum bits (qubits) as their Hilbert spaces are generally well-defined and their decoherence relatively slow [13–15].

In this paper we review several of the important issues in spintronics that are mentioned above. In particular, in Section 2 we review some past and recent attempts at achieving the goals of building practical spintronic devices. We discuss perhaps the first scheme of a spin FET device, the Datta and Das spin transistor [16] in which current is modulated by spin precession in the Rashba field controlled by a Schottky barrier voltage. Next, an all-metal transistor of Johnson [17] is reviewed. In the Johnson transistor, spin up and spin down states play a similar role as that of electrons and holes in semiconductor transistors, and the direction of the current in the working circuit can be switched by flipping the direction of an applied magnetic field. Finally, we describe our recent proposal [18] in designing new schemes of all-semiconductor spintronic devices, namely, spin-polarized solar battery [84], which generates spin-polarized currents without the need of ferromagnetic electrodes, and magnetic field effect transistor where an external magnetic (instead of the traditional electric) field controls the current output. In Section 3 we review some aspects of spin transport (and more generally spin-polarized transport) in hybrid structures. This is in part motivated by devices that we discuss in Section 2, some of which include semiconductors. We discuss some of our results for spin transport in semiconductor/superconductor hybrid structures and suggest possible directions for future research. In Section 4 we briefly review several of the spin-based quantum computer schemes. In particular, we discuss the electron spin based proposals in quantum dots and donors controlled by external magnetic fields, gates, and by electron–electron exchange or electron–photon interaction. We then discuss the nuclear spin based Si quantum computer proposal and its possible extensions. Finally, we discuss a possible source of error in the exchange-based quantum computer schemes that we recently studied, which demonstrates the multitude of difficulties one would face in trying to implement any solid state spintronic schemes for quantum computation.

2. Spintronic devices

The first scheme for a spintronic device based on a FET-like geometry is the Datta and Das high mobility field effect spin transistor [16], shown in Fig. 1(A). The heterostructure (here InAlAs/InGaAs) provides an inversion layer channel for two-dimensional electron transport between two ferromagnetic electrodes. One acts as an emitter, the other a collector. The emitter emits electrons with their spins oriented along the direction of the electrode's magnetization (along the transport direction in Fig. 1), while the collector (with the same electrode magnetization) acts as a spin filter and accepts electrons with the same spin only. In the absence of spin relaxation and spin dependent processes during transport, every emitted electron enters the collector. The perpendicular field at the heterostructure interface, however, induces a spin-orbit-like interaction which acts as an effective (momentum dependent) magnetic field, in the direction perpendicular to both the transport direction and the direction of the heterostructure field (that is, in Fig. 1(A), perpendicular to the page). The field (also called Rashba field) leads to spin precession of the electrons. Depending on the amount of the electron spin (when entering into the collector) in the direction of the collector magnetization, the electron current is modulated: an electron passes through if its spin is parallel and does not if it is antiparallel to the magnetization. The current is in effect modulated by the external electric field induced spin-orbit field naturally existing in asymmetric zinc blende semiconductor structures (Rashba effect). The field can be, in turn, modulated by the applied perpendicular field at the gate [19]. The Datta-Das interference effect should be most visible for narrow-gap semiconductors like InGaAs which have relatively large spin-orbit interactions. The effect is yet to be demonstrated experimentally.

The Johnson spin transistor [17] is a trilayer structure consisting of a nonmagnetic metallic layer sandwiched between two ferromagnets (for a popular account see Ref. [20]). It is an all-metal transistor using the same philosophy as GMR devices: the current flowing through the structure is modified by the relative orientation of the magnetic layers which, in turn, can be controlled by an applied magnetic field. In this scheme, demonstrated in Fig. 1(B), the battery is applied in the control circuit (emitter-base), while the direction of the current in the working circuit (base-collector) is effectively switched by changing the magnetization of the collector. The current is drained from the base in order to allow for the working current to flow under the 'reverse' base-collector bias (antiparallel magnetizations). Neither current nor voltage is amplified, but the device acts as an effective switch or spin valve to sense changes in an external magnetic field. A potentially significant feature of the Johnson transistor is that, being all-metallic, it can in principle be made extremely small using nanolithographic techniques (perhaps as small as tens of nanometers). An important disadvantage of Johnson transistor is that, being all-metallic, it will be difficult to integrate this spin transistor device into the existing semiconductor microelectronic circuitry.

An interesting and nontrivial variation of the GMR-like scheme is a proposal by Monsma et al. [21,22] in which the base itself is a metallic nanostructure sandwich of alternating magnetic-nonmagnetic-magnetic (Co–Cu–Co) layers, while both the emitter and the collector are semiconductors (Si), providing Schottky barrier contacts that allow only hot ballistic carriers to be transmitted from the emitter to the collector. As the relative orientation of magnetization affects the carrier mean free path (the path is smaller for antiparallel orientation), the structure is extremely sensitive to external magnetic fields.

A critical disadvantage of metal-based spintronic devices is that they do not amplify signals. There is no obvious metallic analog of the traditional semiconductor bipolar transistor (e.g. *n–p–n*), in which draining of one electron from the base allows, say, about fifty electrons to pass from the emitter into the collector (by reducing the electrostatic barrier generated by electrons trapped in the base). Motivated by the possibility of having both spin polarization and amplification, we have recently studied a prototype device, the spin-polarized *p–n* junction [18]. In our scheme we illuminate the surface of the *p* region of a GaAs-based *p–n* junction with circularly polarized light to optically orient minority electrons. By performing a realistic device modeling calculation we have discovered that the spin can be effectively transferred into the *n* side, via what we call the spin pumping through the minority channel (in analogy to the optical spin pumping in homogeneous semiconductors discovered by D'yakonov and Perel' [23]). In effect, the spin gets amplified going from the *p* to the *n* region through the depletion layer.

One application of our proposed spin-polarized *p–n* junction is the spin-polarized solar cell [18], described in Fig. 1(C). As in ordinary solar cell batteries, light illuminates the depletion layer of a semiconductor (like GaAs), generating electron-hole pairs. The huge built-in electric field in the layer (typically 10^4 V/cm) swiftly sweeps electrons into the *n* and holes into the *p* regions. If a wire connects the edges of the junction, a current flows. If the light is circularly polarized (filtered solar photons), the generated electrons are spin polarized. (Holes in III–V semiconductors, which are most useful for opto-spin-electronic purposes, lose their spin very fast, so that their polarization can be neglected.) As the spin-polarized electrons created in the depletion layer pump the spin into the *n* region, the resulting current is spin polarized.

Finally, Fig. 1(D) shows our recent proposal of a magnetic field effect transistor (MFET) [18]. Electrodes of an external circuit are placed perpendicular to the *p–n* junction. The current is determined by the amount of available electrons in the region of the junction around the electrodes. If the depletion layer is wider than the electrodes, no (or very small) current flows. As the width decreases, more and more electrons come into contact with the electrodes and the current rapidly increases. Traditionally, FETs operate with an applied electric field (voltage) along the junction, as the width of the depletion layer is sensitive to the voltage. We propose to use instead a magnetic field. If the n or p region (or both) are doped with magnetic impurities which typically induce a giant g-factor to the current carriers, the magnetic (Zeeman) energy $g\mu_B B$, where μ_B is the Bohr magneton, is equivalent to having an external voltage of this magnitude. The width of such a junction could be effectively tailored by an external magnetic field (differently for spin up and spin down electrons: a spin-polarized current results as well). Such a device could find use in magnetic sensor technology like magnetic read heads or magnetic memory cells.

3. Spin-polarized transport

The pioneering experiments [24] on spin-polarized transport were performed on ferromagnet/superconductor (F/S) bilayers to demonstrate that current across the F/S interface is spin-polarized. Three decades later the range of materials where it is possible to study spin-polarized transport has significantly increased. Some of the examples now include novel ferromagnetic semiconductors [25], high temperature superconductors [26–28], and carbon nanotubes [29,30]. Several of the initial questions, such as the role of interface between different materials and how to create and measure spin polarization, still remain open and are of fundamental importance to novel spintronic applications. We first turn to the issue of spin transport across interfaces in semiconductor hybrid devices. This problem is still not completely resolved and some of the efforts to understand the remaining puzzles use analogies with better understood and well-studied charge transport and current conversion in normal metal/superconductor (N/S) structures [31–35]. With the effort to fabricate smaller devices it is possible to reach a ballistic regime (for example, as in the proposal by Monsma et al. [21,22]) where the carrier mean free path exceeds the relevant system size and the scattering from interfaces plays a dominant role. In hybrid structures the presence of magnetically active interfaces can lead to spin-dependent transmission (spin filtering) and consequently influence the operation of spintronic devices by modifying the degree of spin polarization.

An important case where these ideas are tested is a direct electrical spin injection from a ferromagnet into a nonmagnetic semiconductor (Sm). This is also an ingredient needed to implement various proposals for hybrid semiconductor devices, such as the spin transistor of Datta and Das [16] discussed in the previous section. In the absence of a complete picture which would describe transport across F/Sm interface it is helpful to review a simpler unpolarized case of N/Sm contact. The charge transport is affected by the substantial mismatch of carrier densities (or correspondingly Fermi velocities) and conductivities in the two materials. Some additional factors include band bending and pinning of the Fermi level. Two generic situations can be distinguished at the N/Sm interface: low transparency Schottky barrier and the formation of an accumulation layer leading to typically higher interfacial transparency. These two cases usually correspond respectively to GaAs and InAs placed in contact with a normal metal. One would expect an appropriate spin-dependent generalization of these cases when the normal metal is replaced by a ferromagnet or if nonmagnetic semiconductors are replaced by their ferromagnetic counterparts (Ga,Mn)As and (In,Mn)As.

Reports of spin injection into a semiconductor indicate that the obtained spin polarization is substantially smaller than in the ferromagnetic spin injector [34]. It was suggested [35], using the picture of current conversion developed for transport across the F/N interface in Ref. [33], that in the diffusive regime, a large mismatch in conductivities (between the F and the Sm region) presents a basic obstacle to achieve higher semiconductor spin polarization from injection. An interesting proposal was made to circumvent this limitation. It was shown that insertion of tunnel contacts between F and Sm region could eliminate the conductivity mismatch [36]. To reduce significant material differences between ferromagnets and semiconductors alternative methods for spin injection have concentrated on using a magnetic [37–39] semiconductor as the injector. While it was shown that this approach could lead to a high degree of spin polarization [38] in a nonmagnetic semiconductor, for successful room temperature spintronic applications, future efforts will have to concentrate on fabricating ferromagnetic semiconductors where ferromagnetism will persist at higher temperatures [40].

These issues involving spin injection in semiconductors, as well as efforts to fabricate hybrid structures, suggest a need to develop methods to study fundamental aspects of spin-polarized transport which are applicable to semiconductors, traditionally nonmagnetic materials. In our recent proposal [41] we suggested studying hybrid Sm/S structures for understanding spin transmission properties, where the presence of the superconducting (S) region can serve as a tool to investigate the interfacial transparency and spin-polarization. The main motivation is to employ the two-particle process of Andreev reflection [41]. In N/S structures, for a small applied bias V, Andreev reflection is responsible for current conversion: an incident electron with spin σ slightly above the Fermi energy $(E_F + \bar{\epsilon})$, together with an electron slightly below the Fermi energy and of opposite spin $\bar{\sigma}$ are transfered into the superconductor where they form a spin-singlet Cooper pair. Consequently, the charge of two electrons is transfered across the interface and normal current is converted into supercurrent.

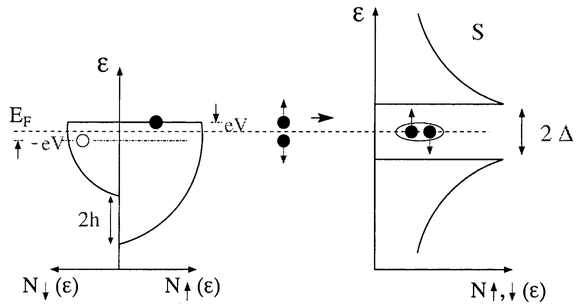

Fig. 2. Schematic illustration of Andreev reflection showing the density of states in the normal region and in the superconductor with energy gap Δ, With spin subband splitting $2h$, only a fraction of incident electrons with spin up will be able to find a partner of opposite spin and contribute to charge transfer by entering superconductor and forming a Cooper pair.

The same process can also be viewed as an incident electron on the N side being reflected at the N/S interface as a hole accompanied with the transfer of a Cooper pair in the S region. It was suggested [42] that Andreev reflection would be modified in the presence of spin polarization. Only a fraction of incident electrons from a majority spin subband will have partners with opposite spin and consequently can contribute to charge transfer across the interface through Andreev reflection,[1] as shown in Fig. 2. This was a motivation to develop experimental methods based on the conductance measurements to measure spin polarization [43,44]. Theoretical studies have also considered modifications of spin-polarized transport in the F/S structures when the S region is a high temperature superconductor [45–48]. Related experiments performed with highly polarized ferromagnets suggest that the surface spin polarization decreases faster with temperature than the corresponding bulk spin polarization [49]. In using spin-polarized Andreev reflection to accurately determine the degree of spin-polarization some care has to be taken to specify the appropriate definition of spin polarization [50,51] and to include the effects of Fermi velocity mismatch [41,46,47,51].

In addition to charge transport, which can be used to infer the degree of spin-polarization, one could also consider pure spin transport. We illustrate this in a hybrid Sm/S structure by employing the model and notations from Ref. [41]. We choose a geometry where semi-infinite Sm and S regions are separated by a flat interface at which particles can experience potential and spin flip scattering. In this approach we need to identify the appropriate scattering processes and the corresponding amplitudes [32]. Since all

[1] To better understand various scattering process, in a ballistic regime, it is helpful to use an optical analogy and Snell's law [46,47]. Consequently, depending on the incident angle and spin subband splitting, there are cases with no charge transport across the interface.

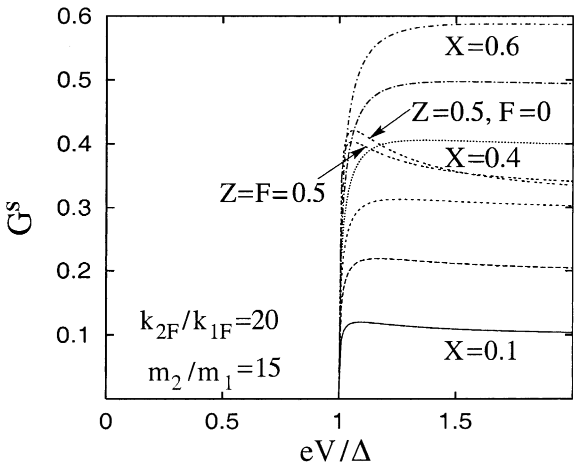

Fig. 3. Spin conductance $G^S(eV/\Delta)$ expressed in units of $(e^2/h)k_{1F}^2A/4\pi$, where k_{1F} is the Fermi wavevector in the Sm region (while k_{2F} corresponds to the S region). Curves from top to bottom correspond to $X \equiv h/E_F = 0.6,0.5,0.4,0.3,0.2,0.1$ with no intrinsic interfacial barrier, except for two curves representing $X = 0.4$ which are labeled by the appropriate interfacial scattering strengths Z and F (as defined in Ref. [33]) for potential and spin flip scattering, respectively. All the results correspond to the ratio of Fermi wavevectors and effective masses (for the S and the Sm region) as denoted in the figure.

the scattering probabilities should add up to unity, we can express various quantities of interest only in terms of scattering processes pertaining to the Sm region. For example, an electron with spin σ, incident at the Sm/S interface can undergo Andreev reflection (with amplitude a_σ), ordinary (potential) reflection (with amplitude b_σ), as well as experience the corresponding spin-flip process with amplitudes $a_{f\sigma}$ and $b_{f\sigma}$. Due to the translational invariance along the interface, the parallel component of the wavevector $k_{\|\sigma}$ is conserved in each scattering process, and by generalizing the Landauer-Büttiker formalism the spin current can be expressed as [41]:

$$I^S(V,T) = \frac{e}{h}\sum_{k_{\|\sigma},\sigma}\int_{-\infty}^{\infty} G_\sigma^S(\epsilon k_{k_{\|\sigma}})[f(\epsilon - \epsilon V) - f(\epsilon)]\mathrm{d}\epsilon, \quad (1)$$

where $f(\epsilon)$ is the Fermi function, $G_\sigma^S(\epsilon, k_{k_{\|\sigma}}) = [1 - (v'_{1\bar\sigma}/v_{1\sigma})(|a_\sigma|^2 + |b_{f\sigma}|^2) - |a_{f\sigma}|^2 - |b_\sigma|^2]\rho_\sigma$ is the dimensionless spin conductance, $\rho_\sigma = \pm 1$ for $\sigma = \uparrow\downarrow$, $v_{1\sigma}$ and $v'_{1\bar\sigma}$ are the normal components of Fermi velocity before and after reflection [41]. In Fig. 3 we show our calculated differential spin conductance $G^S = dI^S/dV$ as a function of applied bias for different spin polarization, represented by $X = h/E_F$, where $2h$ is the spin splitting (Fig. 2). Eq. (1)shows that non-vanishing amplitudes for Andreev Reflection as well as potential and spin flip scattering will in general reduce the magnitude of the spin current. This is expected since both potential and spin flip scatterings do not contribute to net transport (charge or spin) across the interface and Copper pairs transfered into superconductor via Andreev reflection are spinless.[2] Consequently, spin current is carried by quasiparticles, and at $T = 0$ (as can be seen from a sketch of density of states in Fig. 2) the spin current vanishes for bias less than the superconducting gap. While spin conductance in Fig. 3 shows high sensitivity to spin polarization, there remains an experimental challenge to directly measure the spin, rather than the usual charge current.

With the recent materials advances of creating spin polarization (e.g. GaMnAs, InMnAs, etc.) in semiconductors [41] it is possible to consider various semiconductor based hybrid structures which in the past have relied on ferromagnets for providing spin polarization. For example, there are studies which consider heating effects on the transport properties of mesoscopic F/S structures [52], or the possibility of implementing switches and logic circuits using transitions between normal and superconducting states controlled by the direction of magnetization in the ferromagnetic region [53]. One of the implementations could be to consider replacing a conventional ferromagnet by a Mn-doped ferromagnetic semiconductor.

4. Spin-based quantum computation

One of the most ambitious spintronic devices is the spin-based quantum computer (QC) in solid state structures [54–57]. Using electron (or nuclear) spin for QC purposes is a manifestly obvious idea since a fermion with spin 1/2 is a natural and intrinsic qubit. Quantum computation requires both long quantum coherence time and precise external control [58]. Because of the requirement of very long coherence time for a QC, both nuclear spin and electron spin have been proposed as qubit in a QC [13–15,59]. Since more and more schemes are being proposed (for example, see [60,61]), we will not attempt a complete review of the field. Instead, we only review some of the representative schemes proposed during the past several years, and discuss mostly our own recent work on electron spin based quantum computation.

One of the earliest proposed solid state QC schemes uses the spin of a single electron trapped in a quantum dot as its qubit [62–66]. Local magnetic fields are used to manipulate single spins, while inter-dot exchange interaction is used to couple neighboring qubits and introduce two-qubit entanglement. A single trapped electron in a quantum dot implies an extremely low carrier density, which means very low spin-orbit coupling as the electrons occupy states at the bottom of the GaAs conduction band and have essentially S type states [66]. Thus the electron spin coherence time should be much longer than in the bulk. However, to trap a single electron in a gated quantum dot is a difficult task experimentally. In addition, to apply a local magnetic field on one quantum dot without affecting other neighboring dots and trapped spins may also be impossible in practice. To overcome the potential problem of local field, an exchange-based QC model has recently been proposed [67], which uses solely the exchange interaction between nearest neighbors to fulfill both single and two-qubit operations. Here qubits are combinations of single spin quantum dots (or other basic units such as donor and nuclear spins) which form the so-called decoherence-free subspace [68,69]. Regarding the difficulty of trapping single electrons in an array of quantum dots, we recently have showed through a multi-electron calculation that an odd number of trapped electrons in a quantum dot can be effectively used as a qubit subject to certain conditions [70]. In addition to the above operational problems of this QC proposal, there is still the question of how to reliably measure single electron spins (or two-spin states). Various proposals have been put forward [62–64,71,72], while an extensive experimental exploration is still needed for any consensus to emerge. No experimental results on this issue have yet been reported in the literature.

The major role played by quantum dots in the above proposal is to provide tags for individual qubits through a parabolic confinement of the individual electrons, thus donor nuclei is a natural alternative to quantum dots. Indeed, such a scheme has been proposed [73], although it was originally motivated by the nuclear spin based silicon QC proposal that we will discuss below. In this scheme the variation of g-factor due to varying composition in SiGe alloys is used together with external gates to selectively provide single-qubit operations. Two-qubit operations are again provided by the exchange interaction between neighboring donor electrons and are controlled by a combination of external gates and variation of the g-factor.

Another variant of the quantum dot QC is a combination of quantum dot trapped electron spin and semiconductor microcavity [74,75]. Here a single cavity photon in the whispering gallery mode plays the role of intermediary between two quantum dots. The self-assembled quantum dots are embedded in a microdisk cavity. Each of the dots is doped by one extra electron and is addressed individually by lasers from fiber tips using near-field techniques. Single-qubit operations can be achieved through a Raman coupling of the spin up and down states of the conduction electron by using two laser beams from the fiber tips. Two-qubit operations are based on cavity-photon-mediated Raman transition for the two relevant spins analogous to the atomic cavity QED schemes [76]. Since this scheme uses external laser fields extensively, the relation between a high Q cavity and all the coupling to external fields has to be dealt with carefully. On the other hand, coherent control has been most

[2] There is also support for possible triplet superconductivity in different materials, for example, in quasi-one-dimensional organic superconductors. In that case Andreev reflection contributes both to spin and charge current (two electrons of equal spin are transfered across the interface). Conductance measurements could be used to distinguish between the spin-singlet and spin-triplet superconductivity [51,83].

successfully demonstrated with light, so a photon-mediated QC scheme should certainly be seriously explored.

One of the most intriguing and influential QC schemes is the nuclear spin based Si QC [77,78]. Here spin-1/2 donor nuclei are qubits, while donor electrons together with external gates provide single-qubit (using external magnetic field) and two-qubit operations (using hyperfine and electron exchange interactions). Here donor electrons are essentially shuttles between different nuclear qubits and are controlled by external gate voltages. In addition, the final measurement is also over the donor electrons by converting spin information into charge information [71]. A significant advantage of silicon is that its most abundant isotope is spinless, thus providing a 'quiet' environment for donor nuclear spin qubits. In general, nuclear spins have very long coherence times because they do not strongly couple with their environment, and are thus good candidates for qubits. However, this isolation from the environment also brings with it the baggage that individual nuclear spins are difficult to control. This is why donor electrons play a crucial role in the Si QC scheme. Another potential advantage of a QC based on Si is the prospect of using the vast resources available from the Si-based semiconductor chip industry. In addition, the exchange-only schemes can also be applied here, with hyperfine and electron exchange interaction together providing the nuclear spin exchange interaction.

One attempt to overcome problems of bulk solution NMR QC and to reproduce their successes involves using planes of spins in a crystal lattice [79]. In this scheme an inhomogeneous magnetic field is used to differentiate atomic planes in a lattice. Within each plane the spins form a mini-ensemble, leading to the possibility of producing sufficiently strong signal for measurement. Furthermore, in such a scheme nuclear spins can be initialized, thus overcoming the worst problem in bulk solution NMR schemes — the unavoidable ensemble average. Since Maxwell equations dictate that magnetic field cannot vary linearly along one direction while remaining uniform along the other two directions, the equal-field surface must have certain curvature, which means that only part of the spins in a plane contribute to the signal. Nevertheless, even if this particular scheme may turn out to have intractable experimental difficulties, the idea of combining NMR spectroscopy and nanostructure manipulation is certainly worth pursuing further.

Aside from exploring various schemes to utilize spins for the purpose of qubits in quantum computation, an equally important task is to clarify the type of errors in spin-based QCs and how they can be corrected. For example, one possible error in the two-qubit operations of the exchange-based spin QCs is caused by inhomogeneous magnetic fields [80]. Such a field may come from magnetic impurities or unwanted currents away from the structure. Magnetic field affects both orbital and spin part of the electron wavefunction. The orbital effect is accounted for by adjusting the exchange coupling J, while the spin effect is accounted for through Zeeman coupling terms:

$$H_S = J(B)S_1 \cdot S_2 + S_2 + \gamma_1 S_{1z} + \gamma_2 S_{2z}, \tag{2}$$

where S_1 and S_2 refer to the spins of the two electrons; $J(B)$ is the exchange coupling (singlet-triplet splitting); γ_1 and γ_2 are the effective strengths of the Zeeman coupling in the two quantum dots. In an inhomogeneous field, $\gamma_1 \neq \gamma_2$, so that the Zeeman terms do not commute with the exchange term in the Hamiltonian (Eq. 2). We have done a detailed analysis on how to achieve swap with such a Hamiltonian, and found that there is at the minimum an error proportional to the square of field inhomogeneity in the swap. For example, if the initial state of the two electron spin is $|\phi(0)\rangle = |\uparrow\downarrow\rangle$, the density matrix of the first spin after the optimal swap is:

$$\rho_1 = \frac{1}{1+x^2}|\downarrow\rangle\langle\downarrow| + \frac{x^2}{1+x^2}|\uparrow\rangle\langle\uparrow|, \tag{3}$$

where $x = (\gamma_1 - \gamma_2)/2J$. In other words, the first spin can never exactly acquire the state ($|\downarrow\rangle$) of the second spin. Its state will remain mixed and the smallest error from an exact swap is $x^2/(1+x^2)$, which needs to be corrected. We have estimated [80] that in GaAs a Bohr magneton can lead to an error in the order of 10^{-6}, which is within the capability of currently available quantum error correction schemes.

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