

Theoretical Perspectives on Spintronics and Spin-Polarized Transport

S. Das Sarma, Jaroslav Fabian, Xuedong Hu, and Igor Žutić

Abstract—Selected problems of fundamental importance for spintronics and spin-polarized transport are reviewed, some of them with a special emphasis on their applications in quantum computing and coherent control of quantum dynamics. The role of the solid-state environment in the decoherence of electron spins is discussed. In particular, the limiting effect of the spin-orbit interaction on spin relaxation of conduction electrons is carefully examined in the light of recent theoretical and experimental progress. Most of the proposed spintronic devices involve spin-polarized transport across interfaces in various hybrid structures. The specific example discussed here, of a magnetic semiconductor/superconductor interface, displays many intricacies which a complex spin-dependent interface introduces in the spin-polarized transport. It is proposed that pairs of entangled electrons in a superconductor (Cooper pairs) can be transferred to a nonsuperconducting region, and consequently separated for a transport study of the spin entanglement. Several important theoretical proposals for quantum computing are based on electronic and nuclear spin entanglement in a solid. Physical requirements for these proposals to be useful are discussed and some alternative views are presented. Finally, a recent discovery of optical control of nuclear spins in semiconductors is reviewed and placed in the context of a long-standing search for electronic control of nuclear dynamics.

Index Terms—Andreev reflection, quantum information, semiconductor structures, spin-based quantum computation, spin coherence, spin entanglement, spin-hot-spot model, spin injection, spin-polarized transport, spintronics.

I. INTRODUCTION

SPINTRONICS is a new branch of electronics where electron spin (in addition to electron charge) is the active element for information storage and transport [1], [43]. Spintronic devices have the potential to replace and complement various conventional electronic devices with improved performance. In a broader sense, spintronics also includes new fields such as spin-based quantum computation and communication [2]. To determine the feasibility of spintronic devices and more generally of various applications of spin-polarized transport (such as solid-state quantum computing) it is essential to answer questions like how to create and detect spin-polarized carriers, how to maintain their spin coherence, or, conversely, how the spin polarization and spin coherence are destroyed.

In this paper we will explore the question of how conduction electrons (and holes) lose their spin coherence in view of our

recent theoretical investigation of spin decoherence in metals [3]–[5], [44]. The conduction-electron spin relaxation time T_1 (which is the same as the transverse decoherence time T_2 for electronic systems with nearly spherical Fermi surfaces) also determines the quality of spintronic devices. The longer the conduction electrons remain in a certain spin state (up or down) the longer and more reliably can they store and carry information.

One important realization of spintronic devices is based on hybrid semiconductor structures [6]. In spite of the initial proposal over three decades ago [7] and numerous experimental efforts, one of the key ingredients, the direct electrical spin injection into nonmagnetic semiconductor has only recently been realized [8], [9], [45]. Nevertheless by fabricating a novel class of ferromagnetic semiconductors [10] based on Mn-doped GaAs, and employing extensive experience with semiconductor technology which dominates traditional electronics, a significant progress is expected. One of the important limitations, however, is the influence of interfaces between the different materials in such hybrid structures. In this context, we will discuss here spin-polarized transport in hybrid semiconductor structures including our proposal to study semiconductor/superconductor structures [11], which provide a means to measure the degree of spin polarization and to investigate the interfacial scattering.

Quantum computation has been one of the most actively studied areas in general physics in the past few years [2]. The dream of using quantum objects such as electrons as the basic unit of a computer, which is the ultimate of circuit miniaturization, together with the promise of exponential speed-up due to quantum mechanics, has drawn intense interest of scientists from a wide range of specialties. Electron and nuclear spins are the quantum bits (qubits) of some promising proposals for quantum computers (QC) [12]–[15]. For these proposals to work, one needs to be able to precisely manipulate the dynamics of these spins, in particular, to rotate single spins and entangle two spins. Here we will focus on several proposals to produce and to detect spin entanglement.

From the early days of nuclear magnetic resonance we know how to manipulate nuclear spins by radio frequency (rf) fields. In particular, rf fields can induce transitions between Zeeman states and even saturate spin population. A recent discovery [16] claims to do the same with optical fields, for which nuclear spins are normally transparent. Electrons, however, can be spin-polarized by light and transfer the polarization to nuclei through the hyperfine coupling. By a periodic modulation of the electronic spin population one can resonantly flip nuclear spins: the resulting oscillating hyperfine coupling acts as an effective rf field. Efforts to polarize nuclear spins through the hyperfine coupling are not new. It was earlier proposed that a nuclear polarization

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The authors are with the Department of Physics, University of Maryland, College Park, MD 20742 USA (e-mail: {dassarma; jfabian}@physics.umd.edu; xdhu@glue.umd.edu; igor@cooperon.umd.edu).

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can arise from saturating spins of conduction electrons by a rf field (Overhauser effect [17]), or purely electronically by generating hot carriers (Feher effect [18]). Here we will review some of these proposals and discuss their merits in the current context of spintronics and coherent control of nuclear spin dynamics.

II. SPIN DECOHERENCE IN ELECTRONICS MATERIALS

Conduction electrons lose memory of their spin orientation through collisions with phonons, other electrons, and impurities. The interaction which provides the necessary spin-dependent potential is the spin-orbit interaction. The spin-orbit interaction is a relativistic effect which can have various sources in electronic materials; the two most important sources being the interactions between electrons and impurities, and electrons and (lattice host) ions. The impurity-induced spin-orbit interaction (Overhauser [19]) is a random-site potential and, as such, it can induce momentum scattering accompanied by spin flip. The ion-induced spin-orbit interaction is a different story. This interaction is nicely periodic and by itself would not lead to any spin relaxation at all. However, the ion-induced spin-orbit interaction becomes a viable source of spin relaxation when combined with a momentum scattering mechanism (impurities or phonons). This was first realized by Elliott [20]: because the periodic lattice potential (that includes a spin-orbit interaction) yields Bloch states which are, in general, not spin eigenstates, even a spin-independent scattering (by impurities or phonons) can induce spin flip [20]. This mechanism of spin relaxation in metals and semiconductors is now called Elliott–Yafet mechanism (Yafet [21] made a significant contribution to the theory by studying spin-flip electron-phonon interactions). We note that in materials without a center of inversion (like GaAs and many other interesting semiconductors), there are other relevant mechanisms of spin-relaxation. These mechanisms along with recent attempts of modulating spin dynamics in semiconductors are reviewed in [5].

Spin relaxation times T_1 in metals are typically nanoseconds (the record, $T_1 \approx 1 \mu\text{s}$, is held by a very pure Na sample at low temperatures [22]). Spin relaxation is an incredibly long process when compared with momentum relaxation; momentum relaxation times τ are just tens of femtoseconds at room temperature. That electron spins are a promising medium for information storage follows from the large value of the factor T_1/τ . A crude estimate of T_1 is $T_1 \approx \tau/b^2$, where $b \approx V_{SO}/E_F$, with V_{SO} denoting an effective strength of the spin-orbit interaction, and E_F the Fermi energy. Since $V_{SO} \ll E_F$, it follows that $T_1/\tau \gg 1$. The temperature (T) dependence of $1/T_1$ is similar to the temperature dependence of resistivity ρ : At low T (below 20 K) the spin relaxation is dominated by impurity scattering and is temperature independent. At higher temperatures electrons lose spin coherence by colliding with phonons. Above the Debye temperature, where the whole spectrum of phonons is excited and the number of phonons increases linearly with increasing temperature, $1/T_1 \sim T$, similar to resistivity. In an intrinsic sample (with negligible amount of impurities), $1/T_1$ follows the Yafet law [21], $1/T_1 \sim T^5$ (again similar to ρ),

which is yet to be seen in experiment. The case of semiconductors [5] is less clear-cut. Typical magnitudes of T_1 in semiconductors are nanoseconds too, but T_1 varies strongly with magnetic field, temperature, doping, and strain. The task of sorting different mechanisms at different regimes is very difficult and remains to be completed [5].

For how long an electron can travel in a solid-state environment without flipping its spin? Is there a limit on T_1 ? In an ideal impurity-free sample, T_1 would approach infinity as temperature gets to the absolute zero. Thus a recipe to increase T_1 at low temperatures is to produce very pure samples. But the most interesting region is at room temperature. Here phonons are the limiting factor, not impurities. Since we cannot get rid of phonons, increasing T_1 means reducing the spin-orbit coupling (b^2). Typically, the heavier is the atom, the stronger is the spin-orbit coupling. Therefore lighter metals like Na, Cu, or Li have longer T_1 than heavy metals like Hg or Pb. We do not know how large T_1 can be at room temperature, but an educated guess would be a microsecond for the materials of current technological interest.

Is there a way to control the spin relaxation rate at least within a few orders of magnitude? To answer this question we need to understand more where the strength of the spin-orbit interaction b comes from. We already pointed out that in general $b \approx V_{SO}/E_F$. This is indeed what a typical electron on the Fermi surface recognizes as the spin-orbit scattering: an electron with a spin up in the absence of the spin-orbit interaction acquires a spin down amplitude of magnitude b when the interaction is turned on. Perturbation theory gives $b \approx V_{SO}/\Delta E$, with ΔE being the typical (vertical) energy difference between neighboring bands. For a general Fermi surface point $\Delta E \approx E_F$ and one recovers $b \approx V_{SO}/E_F$. But there can be points on the Fermi surface with $\Delta E \ll E_F$! Such points occur near Brillouin zone boundaries or accidental degeneracy lines. In the former case $\Delta E \approx V_G \ll E_F$, where V_G is the G th Fourier component of the electron-ion interaction (G is the reciprocal lattice vector associated with the Brillouin zone boundary); in the latter case ΔE approaches zero and degenerate perturbation theory gives $b \approx 1$. We call the points on the Fermi surface where $b \gg V_{SO}/E_F$ spin hot spots [3]–[5], [44]. The area of the Fermi surface covered by spin hot spots is not large, so it may seem that on the average these points will not contribute much to spin relaxation. It turns out [3], [44], however, that despite their small weight, spin hot spots dominate the average b^2 which is then significantly enhanced (typically by 1–4 orders of magnitude). Spin relaxation time T_1 is correspondingly reduced.

Spin hot spots are ubiquitous in polyvalent metals. Our theory predicts that spin relaxation in polyvalent metals proceeds faster than expected (the significance of the points of accidental degeneracy for spin relaxation in Al was first pointed out by Silsbee and Beuneu [23]). This is indeed what is observed. Long before the theory was developed, Monod and Beuneu [24] collected $T_1(T)$ for different metals with the expectation to confirm the formula $1/T_1(T) \approx b^2/\tau(T)$, with the simple estimate of $b \approx V_{SO}/E_F$. This indeed worked for several metals (monovalent alkali and noble metals like Na or Cu), but not for polyvalent Al, Pd, Be, and Mg (these remain the only polyvalent metals measured thus far). Spin relaxation

times for the measured polyvalent metals were 2–4 orders of magnitude smaller than expected. The explanation of this unexpected behavior came with the spin-hot-spot model (see the comparison between the measured and calculated T_1 of Al in [4]).

In addition to providing a theoretical explanation for the longstanding problem of why electron spins in metals like Al or Mg decay unexpectedly fast, our theory also shows a way of tailoring spin dynamics of conduction electrons. Spin hot spots arise from band structure anomalies which can be shrunk or swollen by band-structure engineering. Strain, for example, can make a Fermi surface cross through Brillouin zone boundaries, thus increasing the hot-spot area and correspondingly $1/T_1$. Other possibilities include alloying, applying pressure, changing dimensionality of the system, or doping (if dealing with semiconductors). Any effect that changes the topology of the Fermi surface will have a severe effect on spin relaxation. This prediction remains to be verified experimentally. The important result of Kikkawa and Awschalom [25] which shows that T_1 of some III–V and II–VI semiconductors can be significantly (by two orders of magnitude) enhanced by doping, is not a manifestation of spin hot spots, but it is still most probably (directly or not) a band structure effect.

III. SPIN-POLARIZED TRANSPORT IN HYBRID SEMICONDUCTOR STRUCTURES

We next consider the spin-polarized transport in semiconductors and how the studies of semiconductor/superconductor (Sm/S) hybrid structures can be used to investigate the feasibility of novel spintronic devices. With the prospect of making spintronic devices [1], [43] which consist of hybrid structures, it is necessary to understand the influence of interfaces between different materials. In the effort to fabricate increasingly smaller devices, it is feasible to attain a ballistic regime, where the carrier mean free path exceeds the relevant system size. Consequently, the scattering from the interfaces plays a dominant role. In a wide variety of semiconductors the main sources of interfacial scattering at the interface with normal metal are arising from the formation of a native Schottky barrier and the large difference in carrier densities, i.e., Fermi velocity mismatch in the two materials. In the absence of spin-polarized carriers this leads to reduced interfacial transparency and different techniques are employed to suppress the Schottky barrier which can be examined using the low temperature transport measurements in Sm/S structures [26]. For a spin-polarized transport in a nonmagnetic semiconductor where the polarized carriers are electrically injected from a ferromagnet or ferromagnetic semiconductor, the situation is more complicated. Magnetically active interface can introduce both potential [11] and the spin-flip scattering leading to the spin-dependent transmission (spin filtering) across the interface and the change of the degree of carrier spin polarization. The latter possibility has profound effect on spintronic devices as they rely on the controlled and preferably large carrier spin polarization.

While there are alternative ways available to create spin-polarized carriers and spin-polarized transport [11], [27]

in a semiconductor, an important obstacle to develop semiconductor based spintronic devices [6] was to achieve direct spin injection from a ferromagnet [7]. Previous experiments demonstrating spin injection into the nonmagnetic metal [28] and into superconductor [29] have created strong impetus to advance studies of spin-polarized transport in the corresponding materials. In the experiment by Hammar *et al.* [8], permalloy ($\text{Ni}_{0.8}\text{Fe}_{0.2}\text{Py}$) was used as a ferromagnet for the spin injection in two-dimensional electron gas. It was theoretically suggested [30] that limitations for achieving higher degree of spin polarization are consequences of working in a diffusive regime and the current conversion near the ferromagnet/semiconductor interface. A different approach, which would circumvent such difficulties, was proposed by Tang *et al.* [31] who have considered spin injection and detection in a ballistic regime. Subsequent experiments on spin injection in semiconductors have also employed diluted magnetic semiconductors and ferromagnetic semiconductors as sources of spin-polarized carriers [9], [45]. In these cases the effect of reduced interfacial barrier and Fermi velocity mismatch (as compared to the interface of semiconductor with metallic ferromagnet) should facilitate injection of carriers across the interface with a substantial degree of spin polarization. Investigating this point is another reason to perform experiments and theoretical studies focusing on the role of interfacial scattering.

We have proposed [11] employing spin-polarized transport in Sm/S hybrid structures to address the role of interfacial scattering and detecting the degree of spin polarization. Introducing the S region in the semiconductor structures has a dual purpose. Choosing S as a conventional, spin-singlet metallic superconductor (Al, Sn, ...) implies forming of Schottky barrier at the Sm/S interface which we want to investigate and by cooling these materials below the temperature of superconducting transition, T_C , scattering processes [32], [46] present exclusively in the superconducting state can serve as a diagnostic tool. At temperatures much lower than T_C , and at low applied bias voltage the transport is governed by the process of Andreev reflection [32], [46]. Prior to work in [11], spin-polarized Andreev reflection has been investigated theoretically [33], [47]–[50] and experimentally [34], [51], [52] only in the context of ferromagnets. In this two-particle process, an incident electron, together with a second electron of the opposite spin (with their total energy $2E_F$, slightly above and below E_F , respectively) are transferred across the interface into the superconductor where they form a Cooper pair. Alternatively, this process can be viewed as an incident electron which at a Sm/S interface is reflected as a hole belonging to the opposite spin subband, back to the Sm region while a Cooper pair is transferred to the superconductor. The probability for Andreev reflection at low bias voltage is thus related to the square of the normal state transmission coefficient and can have stronger dependence on the junction transparency than the ordinary single particle tunneling. For spin-polarized carriers, with different populations in two spin subbands, only a fraction of the incident electrons from the majority subband will have a minority subband partner in order to be Andreev reflected. In the superconducting state, for an applied voltage smaller than the superconducting gap, single particle tunneling is not allowed in the S region and the

modification of the Andreev reflection amplitude by spin polarization or junction transparency will be manifested in transport measurements. To our knowledge, there have not yet been performed experiments on the spin-polarized transport in Sm/S structures. High sensitivity to the degree of spin polarization displayed in the experiments on ferromagnets [34], [51], [52] (including measurements of the spin-polarization for the first time in some materials), should serve as a strong incentive to examine semiconductors in a similar way. Performing such experiments in semiconductors would enable the use of advanced fabrication techniques, tunable electronic properties (such as carrier density and the Fermi velocity) and well-studied band structure needed in the theoretical interpretation.

Introducing superconducting regions in the S/Sm structures is not limited to the diagnostic purpose. They can give rise to new physical phenomena relevant to the device operation. For example, different application of spin-polarized transport in Sm/S structures has been suggested by Kulić and Endres [35]. They consider properties of thin films in the ferromagnetic insulator/superconductor/ferromagnetic insulator (FI/S/FI) configuration which display qualitatively different behavior from the previously studied structures where the FI is replaced by the metallic ferromagnet (F). In such F/S/F systems it is known that there are important proximity effects of extending superconducting order parameter in the nonsuperconducting material. Consequently, it has been shown [36] that they give rise to oscillations in T_c as a function of the thickness of the superconducting region. In contrast, for FI/S/FI structures it was shown that T_c is independent of the thickness of superconducting thin film and can be tuned by changing the angle of magnetization direction lying in the planes of each FI region. It was proposed [35] that these features and the simpler physical properties compared to the F/S/F systems can be used to implement switches and logic circuits. For example, switching between the normal and superconducting state could be performed by changing the magnetization directions (for a spin singlet superconductor T_c depends only on the relative angle between the two magnetization vectors). Here we note that the novel ferromagnetic semiconductors [10] may be suitable candidates for the FI regions discussed above. With the appropriate Mn doping they would display insulating behavior and effectively suppress proximity effects.

IV. SPIN-BASED SOLID-STATE QUANTUM COMPUTATION

For spins in solids to be useful in quantum computing, it is important that one has certain ways to move information regarding these spins. This transfer can be achieved through nearest (fixed) neighbor interactions, such as among nuclear spins; or one can use mobile objects like conduction electrons in semiconductors. While the later approach gives us more freedom in manipulating the system, it is also more susceptible to relaxation caused by transport.

One of the first proposal to use electron spins in solids as qubits of a QC [12] suggests confining electrons in quantum dots. The spins of trapped electrons serve as qubits, while quantum dots in which they reside serve as tags for each qubit. There is one electron in each quantum dot so that each qubit

can be readily identified. The individual electron spins can be easily manipulated by a pulsed local magnetic field. It is conceivable that such field can be produced by local magnetic moments such as a magnetic quantum dot or an STM tip. Furthermore, if the electrons can be moved in the structure to an area away from the rest of the qubits, without losing its identity, the requirement on the magnetic field can be loosened. Such transport of electrons might be achieved through, for example, channels or STM tips. Controlled exchange interaction between electrons in the neighboring quantum dots can produce desired entanglement between electron spins [12], [37], while finite magnetic field can be applied to reduce the error rate in this process [38]. It has also been proposed that optically mediated entanglement can be achieved if the quantum dots are placed in a microcavity [15].

To produce a practical electron-spin-based quantum dot QC is going to be an extremely challenging experimental problem. For example, because electrons are identical particles, exchange errors are always looming whenever two electrons have wavefunction overlaps [38]. Stray electrons (trapped on surface or impurities) can easily cause information loss through this channel. If electronic qubits are not moved around, single qubit operations would require precisely controlled local magnetic fields which should not affect unintended electrons. Similarly, two-qubit operations would require well controlled tuning of the gate voltage between neighboring quantum dots. Electron spins relax much faster (in the order of ns to μ s [39]) than nuclear spins (minutes to hours [13]), which would invariably decrease the signal-to-noise ratio and require error correction. The above-mentioned problems can be dealt with one by one. For example, swap gate (or square root of swap) is an essential ingredient for two-qubit operations. Thus it would be a big step forward if one can demonstrate the swap action in a double dot, even if the swap efficiency is far less than 100%. In the spirit of converting spin information into transport properties, one approach might be to inject two streams of electrons into the two coupled quantum dots, with one stream fully polarized. By adjusting the speed of injection, one can control the time that electrons remain in the dots, so that it is possible that at the output the originally unpolarized electron stream would acquire a finite spin polarization, which can then be measured.

Electron spins are not the only possible building blocks for proposed spin-based solid state QC. One proposal that has attracted a lot of attention [13] attempts to combine the extremely long coherence time for nuclear spins and the immense industrial experience with silicon processing to produce a scalable QC. Donor nuclear spins are employed as qubits in this scheme. Donor electrons also play important roles here. Controlled by two types of gates, electrons are used to adjust nuclear resonance frequency for one-qubit operations and to transfer information between donor nuclear spins through electron exchange and hyperfine interaction, crucial for two-qubit operations. The fabrication of regular array of donors may be a daunting task. The additional "layer" of the QC structure (the electrons, as the intermediary) may provide major decoherence channel. However, despite all the problems, the exceedingly long life time of qubits means that the proposal is one of the more promising QC models in the long run.

V. SPIN ENTANGLEMENT IN SOLIDS

Spin entanglement is an essential ingredient for spin-based quantum computer, quantum communication, quantum cryptography, and other applications. It has been theoretically proposed that two-electron spin entanglement can be measured using an ordinary electron beam splitter or through a loop consisted of double-dot in which electrons undergo cotunneling [40], [53]. Another proposal distinguishes singlet and triplet states by detecting their energy difference [41]. The common theme here is to measure transport properties of electrons and infer spin information from transport. Direct spin measurement is not impossible with the current technology (using SQUID), but it is slow and not quite sensitive enough for the purpose of quantum computing.

Due to the many obstacles we mentioned before in the pursuit of creating and detecting controlled spin entanglement in solids, it is useful to separate the two tasks and treat them individually. For example, to test a detecting scheme, it would be ideal if we have a well-established source of entangled electrons, so that we can test the sensitivity and other properties of the detecting scheme. Here we propose to use Cooper pairs as such a source. In many ordinary superconductors, the Cooper pairs are in a singlet state. Our goal is to transfer a Cooper pair from the superconducting region into a nonsuperconducting region as *two* spin-entangled electrons (a Cooper pair injection process in analogy to the inverse of previously discussed Andreev reflection). One conceivable scenario is to use heterostructures with discrete energy levels to satisfy energy conservation and to enhance the cross section of the process. If these entangled electrons can be successfully led out of the superconductor and into a normal region through the above procedure, they can then be separated using means such as Stern-Gerlach type of techniques [27] so that the opposite spin electrons are separated and propagate in two separate channels. We thus obtain a source of two streams of entangled electrons. By controlling the size of the point contact between the superconducting and the normal regions, the arrival-time-correlation between two entangled electrons can be enhanced so that they can produce signatures of a spin singlet state. Indeed, if the Cooper pairs in the superconductor source are triplets (as suspected for quasi-one-dimensional organic superconductors and for Sr_2RuO_4), signatures of spin triplet state would be present. To have such controlled source of entangled electrons would be important both for testing the entanglement detection schemes and for applications in areas such as quantum communication.

VI. OPTICAL AND ELECTRONIC CONTROL OF NUCLEAR SPIN POLARIZATION

The recent discovery by Kikkawa and Awschalom [16] of the optically induced nuclear spin polarization in GaAs gives an impetus to the search for new ways of controlling coherent dynamics of nuclear spins. In the experiment a sample of GaAs held at 5K was placed in a magnetic field of about 5 T. Short laser pulses (100 fs) of circularly-polarized light with the frequency tuned to the GaAs band gap (1.5 eV) were then shot on the sample (perpendicularly to the applied field) to create a nonequilibrium population of spin-polarized conduction

electrons (as a result of the circular light polarization). The electron spins then rotated about the total magnetic field which now consisted of the applied field and whatever field generated by polarized nuclei. By measuring the rotational frequency, the field induced by the polarized nuclei was measured as a function of time. The experiment found that by pumping the electron population with 76 MHz repetition rate laser pulses, the nuclei became polarized. After about 250 seconds of pumping the polarization field was about 0.1 T. It is not clear what exactly is the mechanism behind the nuclear polarization (a simple picture [16] based on the Overhauser effect [17] disagrees with the experiment), but there is little doubt that the polarization is nuclear (because of the large relaxation times of order minutes) and that it is induced optically.

An even more fascinating possibility, also studied by Kikkawa and Awschalom [16], is a dynamical control of the nuclear spins. In the standard nuclear magnetic resonance experiments nuclear spins which rotate about an applied field can be flipped by applying a microwave radiation of the frequency of the spin rotation. This happens because the microwave field has a component of the oscillating magnetic field perpendicular to the applied field. But such a perpendicular oscillating field can be created purely electronically! One just has to create a nonequilibrium population of spin-polarized electrons with the spin orientation perpendicular to the applied field, and repeat this process periodically with the period of the nuclear spin rotation. The hyperfine interaction is then the required oscillating interaction and should be able to resonantly tip nuclear spins. This was indeed observed [16].

That nuclear spins can be controlled electronically was first suggested by Feher [18] as early as in the late 1950's. Feher pointed out that nuclear polarization can be induced by the hyperfine interaction if the effective temperature T_R characterizing the electronic velocity distribution differs from the electronic spin temperature T_S which determines the occupation of electronic Zeeman states. Feher proposed several mechanisms that would lead to $T_R \neq T_S$ [18], [42]: hot-electron transport, electron drift in an electric field gradient or in a perpendicular magnetic field, and the injection of electrons whose g-factor differs from the one of the electrons inside the sample. All these methods rely on the fact that spin equilibration proceeds slower than momentum equilibration (see Section II). One practical use of this idea would be a dc-driven maser [42], in which paramagnetic impurities are polarized electronically to an effective negative temperature. We believe that the Feher effect will be revived by new experiments since it shows how to manipulate nuclear spins purely electronically (without the need of either rf or optical fields) which can be of great interest in the efforts of integrating standard electronics with quantum information processing.

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