

Toward dissipationless spin transport in semiconductors

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Spin-based electronics promises a radical alternative to charge-based electronics, namely the possibility of logic operations with much lower power consumption than equivalent charge-based logic operations. In this paper we review three potential means of dissipationless spin transport in semiconductors with and without spin-orbit coupling: the use of spin currents, propagating modes, and orbital currents. Spin and orbital currents induced by electric fields obey a fundamentally different law than charge transport, which is dissipative. Dissipationless spin currents occur in materials with strong spin-orbit coupling, such as GaAs, while orbital currents occur in materials with weak spin-orbit coupling, such as Si, but with degenerate bands characterized by an atomic orbital index. Spin currents have recently been observed experimentally. Propagating modes are the coupled spin-charge movement that occurs in semiconductors with spin-orbit coupling. In contrast to normal charge transport, which is diffusive, the spin-charge mode can exhibit propagating transport, with low energy loss over relatively large distances ($>100\text{ }\mu\text{m}$), by funneling energy between the spin and the charge component through the spin-orbit coupling channel. This opens the possibility for spin-based transport without either spin injection or spin detection. The schemes discussed in this paper are analyzed in comparison with schemes based on molecular electronics phenomena, dilute magnetic semiconductors, etc.

Introduction

Conventional microelectronic devices are based on the ability to store and control the flow of electronic charge. As reflected in the number of transistors per chip, the performance of such devices has increased exponentially, by more than eight orders of magnitude since the first integrated circuit was fabricated more than forty years ago. Underlying this remarkable evolution in technology have been advances in materials and processing, as well as inventions and innovations. Nevertheless, it is now widely recognized that the achievement of improved performance has become more difficult with each succeeding CMOS generation. For example, the amount of power required by modern CMOS-based logic and memory devices is now increasingly limiting progress.

The increase in the number of transistors per chip since 1970 has been phenomenal, of the order of 10^6 . For

example, the latest Intel processor, the Intel Itanium** 2, accommodates 410,000,000 transistors. While Moore's law has thus far been applicable, the increase in the number of transistors per chip makes it obvious that that will have to change. Expectations are that Moore's law will fail at the beginning of the next decade. **Figure 1** shows the evolution of the average power density in a chip vs. minimum feature size (or technology node). State-of-the-art chips contain features down to 90 nm in width. Modern processor chips consume $\sim 100\text{ W}$ of power, with 20% wasted in transistor gate leakage. The local power densities within chips at present are even higher than those indicated in Figure 1. The current method of coping with increasing power levels is to scale down the operating voltages of the chips. Unfortunately, those voltages are reaching the lower limits set by thermal fluctuation effects.

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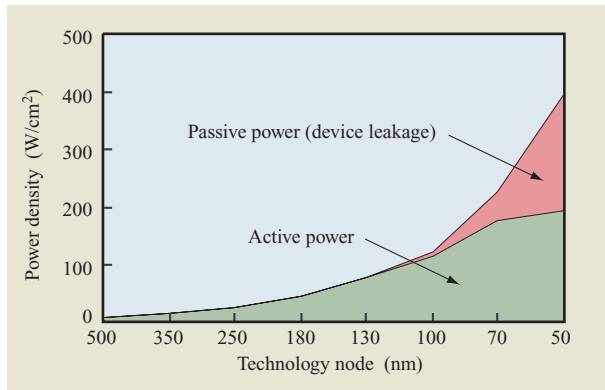


Figure 1

Local power density per chip technology node.

Measures to deal with the associated, relatively high power densities are being developed (for example, the use of improved materials for heat transfer between the chips and their heat sinks, and liquid cooling through channels in the chips). However, such methods are essentially stopgap measures. They will ultimately be insufficient to deal with the rapid power density increases anticipated in the next two or three technology generations. There is an emerging consensus among the semiconductor industry experts that a major paradigm shift away from the charge state device will be needed in order to meet the power dissipation challenge.

Spintronics (spin-based electronics) promises a radical alternative, offering the possibility of logic operations with much lower power consumption than equivalent charge-based electronics [1]. One fundamental advance in the field of spintronics has been the groundbreaking research on solid-state nonvolatile magnetic random access memory (MRAM) [2]. Recent theoretical work [3, 4] suggests that spin transport is fundamentally different from the transport of charge. Ohm's law governing the flow of charge current describes the inevitable dissipation of power in current microelectronic devices. However, the generalized version of Ohm's law that governs the flow of spins indicates that the generation of spin current by an electric field can be reversible and non-dissipative. Interestingly, the practical problem of power dissipation in semiconductor devices may be related to the fundamental physics of time-reversal symmetry: While the charge current is odd under time-reversal symmetry, the spin current is even under time-reversal symmetry. Because both the spin current and the electric field transform in the same manner under time reversal, their intrinsic coupling can be non-dissipative.

To exploit the energy-saving potential of spin currents, it is essential to be able to control them, as in the case of charge flow. Historically, spins have been manipulated by magnetic fields, which will be more difficult to control as we approach the nanometer feature level. Recently it has been recognized theoretically that through intrinsic spin-orbit coupling it is possible to manipulate spin currents via electric fields [4–10]. New experiments have indeed demonstrated that electron spins may be controlled with traditional electric gates [11, 12]. This would appear to be a significant approach to spin control and manipulation. Control of electric fields forms the basis for integrated circuit technology and is therefore very highly developed. Electric-field rather than magnetic-field control of spin, via spin-orbit coupling, should provide a more viable path for developing spin-based devices for technological use.

According to theory, spin-orbit coupling profoundly changes the nature of spin transport in semiconductor devices [9, 13, 14]. In the standard set of drift-diffusion equations used in semiconductor modeling, the dynamics of charge and spin are essentially decoupled; thus, it is possible to have a charge current in the absence of a spin current, and vice versa. Including the spin-orbit interaction leads to an entirely new set of drift-diffusion equations, in which spin and charge dynamics are tightly coupled. In their simplified form, these equations formally resemble Maxwell equations, where spin and charge play the role of electric and magnetic fields [14]. Thus, gradients of spin density drive charge-density fluctuations, and vice versa. In particular, the equations predict propagating modes of spin and charge (analogous to light propagation) in certain parameter regimes of spin-orbit coupling and spin relaxation. In stark contrast to a diffusive mode, these propagating modes exhibit low energy loss over large distances. Owing to the suppression of the relaxation time within two-dimensional channels of finite width [15], the propagating mode can easily be accessed and enhanced with appropriate materials engineering.

In the absence of spin-orbit coupling, one can use the local (atomic) orbital moment of the carriers in a fashion similar to their spin. This is not possible for s-orbitals, but it is possible for p- or d-like orbitals coupled to the carrier momentum, as occurs in the valence band of semiconductors such as Si, GaP, and GaN, which display weak spin-orbit coupling. An electric field applied to the system creates a current of holes perpendicular to the field [16]. The holes tend to preferentially occupy atomic orbitals (or their remnants) in a direction perpendicular to both the electric field and the direction of movement. For all practical purposes, this is similar to a spin current and is detectable in Kerr rotation measurements.

In this paper, we review these phenomena and propose theoretical and experimental roadmaps for future advances in the field.

Spin currents

The spin Hall effect is the generation of a transverse spin current by an applied electric field. The extrinsic version of the effect arises from the skew scattering against impurities, which are spin-orbit-coupled to the charge carriers [17–19]. However, the cross section for skew scattering is extremely small, and so is the predicted value of the spin Hall effect. Recently, considerable interest has been generated by theoretical predictions that under certain conditions the spin Hall current could arise from the intrinsic spin-orbit coupling in the band structure; it would be relatively large and would flow without dissipation, potentially enabling control over spin currents through applied electric rather than magnetic fields. The effect appears in the analysis of semiconductors with spin-orbit coupling; two examples are the spin-3/2 valence band of GaAs, described by the Luttinger model, and the conduction band of asymmetric quantum wells, described by the Rashba model,

$$H_L = \frac{\hbar^2}{2m} \left[\left(\gamma_1 + \frac{5}{2}\gamma_2 \right) k^2 - 2\gamma_2 (\vec{k} \cdot \vec{S})^2 \right]$$

and

$$H_R = \frac{\hbar^2}{2m} k^2 + \alpha (\vec{k} \times \vec{\sigma}) \cdot \hat{z}, \quad (1)$$

where $\vec{S}$ is a spin-3/2 matrix describing the $P_{3/2}$ valence band state, γ_1 and γ_2 are material constants called Luttinger parameters, and α is the Rashba constant describing the two-dimensional spin-orbit coupling.

The origin of the spin current is a topological phase acquired by the carrier wave functions as they move through momentum space. This is a generalization of the U(1) Berry phase, which has found application in a wide range of fields; however, the phase is richer because of the twofold degeneracy of the bands in time-reversal and inversion-symmetric materials. As Berry showed, the origin of such a phase is the topological structure of the parameter space which arises from the presence of degeneracy (level crossings) in the band structure. In our case, we have found that the fourfold degeneracy in the valence hole spectrum at the gamma point ($k = 0$) in diamond and zinc-blende lattices leads to a Berry phase for states that move through momentum space. The phase can be thought of as the result of a sort of gauge field, which, as in the quantum Hall effect, leads to an anomalous velocity. This anomalous velocity is dependent on the orientation of the carrier spins, hence leading to a net flow of spins, although it does not contribute to the total flow of charge. It has been shown

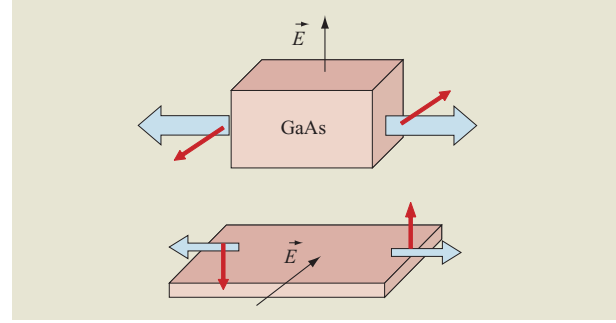


Figure 2

Spin current directions for bulk and two-dimensional semiconductors. The applied electric field, the spin polarization (red arrows), and the direction of motion (blue arrows) constitute an oriented triad.

[3] that the response of the spin current J_i^j to an electric field E_k has the form

$$J_i^j = \sigma_{\text{SH}} \varepsilon_{ijk} E_k, \quad (2)$$

which predicts, for example, that an electric field in the x direction induces a spin current J_y^z (spins polarized along z and flowing in the y direction) as shown in **Figure 2**.

In this equation, the intrinsic transport coefficient σ_{SH} is determined by the spin-dependent properties of the ground state (not by the random scattering processes that determine the ohmic conductivity), and ε_{ijk} is the totally anti-symmetric tensor in three dimensions. We should mention in passing that since spin is not conserved in semiconductors, defining a spin current is not as straightforward as defining the charge current. However, one can still write down a spin continuity equation which is similar but not analogous to the one for charge [see Equation (9)]. It differs from the charge continuity equation by a term which incorporates the essence of spin relaxation in semiconductors due to spin-orbit coupling (the Dyakonov–Perel term). The other terms in the spin-continuity equation are in one-to-one analogy with the charge continuity equation and hence enable us to define a spin current which relates the change in time of the spin density to its variation in space.

The dissipationless nature of the spin Hall current follows from its properties under time reversal. For example, the dissipative ohmic current,

$$J_i = \sigma E_i, \quad (3)$$

having dimensions of *charge* times velocity, is odd under time reversal. Since the electric field E_i is even under time reversal, the charge conductivity σ is odd and hence dissipative, being dependent on random scattering processes such as momentum scattering. On the other

hand, the spin current, having dimensions of *angular momentum* times velocity, is even. Thus, the spin current induced by an electric field through spin-orbit coupling is not essentially tied to heat-generating processes such as scattering.

The intrinsic spin Hall conductivity has been predicted for semiconductors with both p-type and n-type doping [3, 5], in both bulk and two-dimensional semiconductors. In bulk p-doped semiconductors, the valence band is split into a light-hole (LH) band and a heavy-hole (HH) band by the spin-orbit coupling, with Fermi momenta k_F^L and k_F^H respectively. The associated intrinsic spin Hall conductivity is given by

$$\sigma_{\text{SH}} = \frac{e}{6\pi} (k_F^H - k_F^L). \quad (4)$$

For a two-dimensional electron gas, the conduction band can be split because of spin-orbit interaction in systems (such as a two-dimensional gas) that do not have inversion symmetry; this can be of either structural or bulk origin. For the simple Rashba model (structural inversion asymmetry), the spin Hall conductivity, predicted to be *universal*, is given by

$$\sigma_{\text{SH}} = \frac{e}{8\pi}, \quad (5)$$

It turns out to be the case that in the clean (free of impurities, long momentum relaxation time) limit, all of the two-dimensional n-doped (for which the conduction band is spin $\frac{1}{2}$) semiconductors with spin-orbit coupling have a universal spin Hall conductivity.

These theoretical predictions are valid for systems free of impurities for which the spin splitting is much greater than the lifetime broadening arising from impurity scattering. In the presence of impurity scattering, there are two main contributions, the self-energy correction and the vertex correction. Although the self-energy correction vanishes in the clean limit, the question of whether vertex correction also vanishes has required extensive consideration. After numerous debates in the recent theory literature, a unifying consensus has been reached. For semiconductors with p-type doping, with both bulk and two-dimensional planar band structures, it has been shown that the vertex correction vanishes for s-wave impurity scatterers [20, 21]. On the other hand, the vertex correction for the Rashba model has been shown to cancel theoretical prediction of the intrinsic spin Hall effect [22].

One consequence of the presence of spin current is spin accumulation at the boundary, as shown in **Figure 3**. Thus far, this is the only method that has been used to detect the spin Hall effect. Recently, Awschalom and collaborators [23] and Wunderlich et al. [24] have reported the detection of spin accumulation in an applied

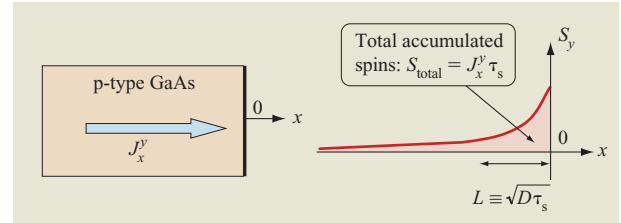


Figure 3

Spin accumulation at a boundary of the sample as a result of spin current J_x^y flowing in the x -direction (the spin vector being in the y -direction). The accumulation occurs over a distance of the order of the spin diffusion length. D is the diffusion coefficient and τ_s is the spin relaxation coefficient.

field in semiconductor structures, in n-type and p-type semiconductors, respectively. The spin direction reverses with the applied field E establishing the existence of spin Hall currents leading to nonzero spin accumulation at boundaries. What remains to be clarified is the mechanism for the spin Hall currents. Awschalom and collaborators conducted the experiment in the regime in which the spin splitting is smaller than the lifetime broadening, and concluded that the spin Hall mechanism may be extrinsic (e.g., impurity-related) in their samples. More recent analyses [25, 26] have shown that the experimental results can also be accounted for on the basis of the intrinsic spin-orbit coupling in the conduction band due to the breaking of bulk inversion symmetry (the Dresselhaus term). Wunderlich et al. have conducted the experiment in a hole-doped sample, in a regime in which the spin splitting is larger than the lifetime broadening, and it is commonly believed that in their system the spin Hall currents may have been intrinsic.

Spin-charge propagating mode—spintronics without spin injection or spin detection

The spin-orbit interaction of electrons in GaAs quantum wells is described by Rashba and Dresselhaus terms (H_R and H_D , respectively) in the spin Hamiltonian. These terms describe the magnetic field experienced by electrons (in their rest frame) arising from static electric fields in the rest frame of the crystal lattice. The strength of the terms determines how the internal magnetic field depends on the electron wave vector $\vec{k}$. Between collisions, the spin of the electron precesses in the internal field at a $\vec{k}$ -dependent rate. The dependence of the precession vector on momentum leads to a strong correlation between the propagation of the electron in position space and its angular momentum in spin space.

In a two-dimensional electron gas, the confining potential breaks the inversion symmetry and leads to an electric field perpendicular to the two-dimensional plane

of the electron gas. Specifying the confining electric field as being in the z direction in Equation (2), Rashba [8] has pointed out that there is a spin current in the ground state, of the form of

$$J_i^j = \sigma_S \varepsilon_{ij} = \alpha n \varepsilon_{ij}, \quad (6)$$

where α is the spin-orbit coupling constant, n is the electron density, and i and j take on values of the two-dimensional coordinates x and y . Similarly, one can show that the electron spin also makes a contribution to the charge current, of the form of

$$J_i = \alpha \varepsilon_{ij} S_j, \quad (7)$$

where S_j is the electron spin density. As Rashba has indicated, the spin current in the ground state in the absence of external fields cannot cause transport or spin accumulation *as long as the system is in equilibrium*. However, when the system is driven out of equilibrium, as in the familiar case of local spin or charge packets excited in semiconductors, the spin current in the ground state is predicted to have remarkable consequences. The existence of the dissipationless ground-state spin current profoundly changes the spin transport in semiconductor devices and, as we shall see, leads to the possibility of spin injection purely by electric means. The standard charge and spin transport equations are given by

$$\begin{aligned} \frac{\partial n}{\partial t} + \partial_i J_i &= 0, \quad J_i = -D \partial_i n; \\ \frac{\partial S_j}{\partial t} + \partial_i J_i^j &= -S_j / \tau_s, \quad J_i^j = -D \partial_i S_j, \end{aligned} \quad (8)$$

where D is the diffusion constant and τ_s is the spin relaxation time. These equations only account for diffusive behavior as a result of charge and spin transport. However, taking into account the effects of the spin-orbit coupling and substituting the additional contributions of the spin and the charge currents (6) and (7) into the standard transport equations (8), it follows that, in a two-dimensional electron gas with Rashba spin-orbit coupling, the equations become

$$\begin{aligned} \frac{\partial n}{\partial t} + \partial_i J_i &= 0, \quad J_i = -D \partial_i n - \alpha \varepsilon_{ij} S_j; \\ \frac{\partial S_j}{\partial t} + \partial_i J_i^j &= -S_j / \tau_s - \sqrt{D / \tau_s} \partial_j S_3, \\ J_i^j &= -D \partial_i S_j + \alpha \varepsilon_{ji} n + \delta_{ij} \sqrt{D / \tau_s} S_3. \end{aligned} \quad (9)$$

The second term in the spin current is the dissipationless spin current. By restricting to the in-plane components of the spin S_j , $j = 1, 2$, the following two continuity equations are easily obtained:

$$\begin{aligned} \frac{\partial n}{\partial t} &= D \partial_i \partial_i n - \alpha \varepsilon_{ji} \partial_i S_j; \\ \frac{\partial S_j}{\partial t} &= D \partial_i \partial_i S_j - \alpha \varepsilon_{ji} \partial_i n - S_j / \tau_s - 2 \sqrt{D / \tau_s} \partial_j S_3. \end{aligned} \quad (10)$$

The first term on the right-hand side of each of the equations represents the usual diffusion current; the second term represents the dissipationless spin-current contribution; the third term of the second equation is the usual Dyakonov–Perel relaxation time, and the last term of that equation represents the coupling of diffusion terms with spin-current terms.

If for the moment we neglect the D and τ_s terms, we see that the coupled spin and charge-transport equations formally take the same form as the Maxwell equations in two dimensions, provided we interpret the charge density n as being a magnetic field B in two dimensions (in two spatial dimensions a magnetic field has only one component) and we interpret the two in-plane spins S_x, S_y as being the two electric fields E_x, E_y . The first equation of continuity then becomes Faraday’s induction law, $\partial_t B = \alpha \varepsilon_{ij} \partial_i E_j$, while the second equation becomes Ampere’s law, $\partial_i E_i = -\alpha \varepsilon_{ij} \partial_j B$. The only difference between the behavior of the system and the behavior of light rests in the value of the “speed of light,” which in this case is the Rashba coefficient $\alpha \approx 10^{-4} c$.

The analogy with Maxwell’s equations for the case in which we neglect the D and τ_s terms is very helpful for two reasons: First, it predicts the existence of a propagating mode of the system—a mode in which energy propagates rather than dissipates. As shown above, this mode is the dissipationless spin current in the ground state. Second, as is usually the case in Maxwell physics, a disturbance in the magnetic field (the charge density) creates an electric field (a spin density), thus predicting the appearance in spin-orbit-coupled systems of spin density from pure charge density.

A complete analysis of the above equations shows that the existence of a propagating mode is linked to a large spin-orbit coupling given by the condition

$$\alpha \gg \sqrt{D / \tau_s}. \quad (11)$$

For the generic values of $D \approx 10^{-2} \text{ m}^2/\text{s}$, $\tau_s \approx 1 \text{ ns}$ [12], the condition reads $\alpha \gg 3 \times 10^3 \text{ m/s}$, which is easily realizable with today’s experimental techniques [27]. For these values of the parameters, the propagating mode should have weak damping if its wavelength is within $0.1 \mu\text{m} < \lambda < 10 \mu\text{m}$ and its frequency is within the domain $10 \text{ GHz} < \omega < 100 \text{ GHz}$.

The development of a propagating mode (depicted in **Figure 4**) is clearly seen by solving the equations numerically for the situation in which a one-dimensional stripe of charge is assumed to be created along the y

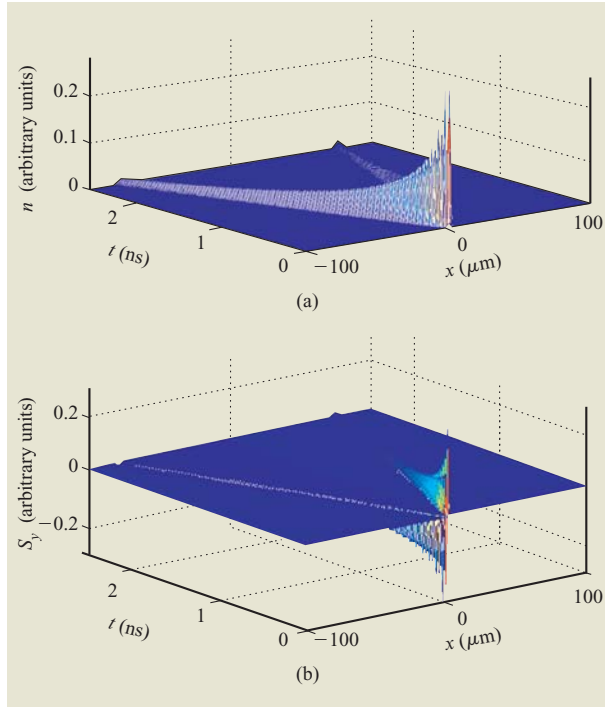


Figure 4

As the spin-orbit coupling strength is increased so as to satisfy the condition $\alpha \gg \sqrt{D/\tau_s}$, a propagating mode appears, as evidenced by the behavior of the charge density (a) and the induced spin density (b). Time is plotted in units of $\tau_s/10$, whereas the distance x is plotted in units of $\alpha\tau_s/10$ (roughly $1 \mu\text{m}$).

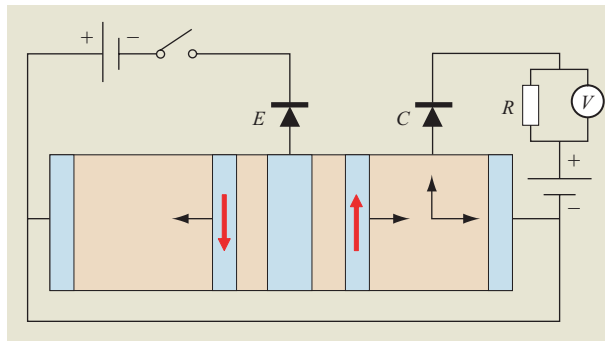


Figure 5

Proposed experiment: a modified version of the classic Haynes–Shockley experiment. A density packet injected by the emitter spontaneously splits into two counter-propagating packets with opposite spin. Unlike the settings of the Haynes–Shockley experiment, one of the two packets propagates to the collector without experiencing a sweeping electric field. The time delay between the injection pulse and the collecting pulse should give a purely electric determination of the Rashba spin-orbit coupling constant.

direction (with resulting motion along the x direction) [28].

Through spin-orbit coupling, the charge disturbance creates a non-zero spin density. This would not happen in the absence of spin-orbit coupling. As the spin-orbit coupling strength is increased, the induced spin density increases, and its motion changes from a diffusive to a propagating regime.

For two-dimensional wells of finite width, it has been shown that the Dyakonov–Perel (DP) spin relaxation time increases as the width is decreased [15]. In the limit when the width is decreased such that the two-dimensional well transforms into a quantum wire, the DP part of the relaxation time $\tau_s \rightarrow \infty$. In this limit, a propagating mode should be possible as the condition $\alpha \gg \sqrt{D/\tau_s} \rightarrow 0$ becomes easier to realize for increasing spin relaxation times.

The discovery of the propagating mode would have profound theoretical and experimental implications. First, the mode should facilitate long-range spin manipulation by manipulation of the charge packet. Second, if we are not interested in the spin motion, we can see that, owing to the reactive coupling to the spin, the charge of the packet should propagate over large distances with little dissipation. This suggests a remarkably simple experiment in the spirit of the classic Haynes–Shockley experiment but without sweeping electric field. **Figure 5** depicts such a proposed experiment using a narrow sample with light p-doping. Two rectifying metal-to-semiconductor point contacts would respectively be forward- and reverse-biased to serve as emitter and collector electrodes. After the emitter pulse was turned on, an electron density packet would be injected into the sample. In conventional Haynes–Shockley setup, the electron packet would be swept to the collector electrode by a electric field. In our case, no sweeping electric field would be applied, but the density packet would spontaneously split into two counter-propagating packets with opposite spin orientations, with a velocity directly given by the Rashba coupling constant α . Upon capture of the rightward-moving packet by the collector electrode, a voltage pulse should be registered. From the time delay and the shape of the voltage pulse, one should be able to determine the Rashba coupling constant and the diffusion constant; this could be done by controlling only the charge. This experiment suggests that the injected density pulse should be able to take advantage of the spin current in the ground state and propagate without any applied voltage.

Silicon orbitronics

The small spin-orbit coupling in silicon, as measured by the energy of the split-off band relative to the top of the valence band, $\sim 44 \text{ meV}$, renders the spin Hall

effect relatively small at room temperature. Given the dominance of silicon in the semiconductor industry, it is important to find a similar dissipationless transport process which does not rely on the spin-orbit coupling. In [16], we have investigated the possibility of replacing the spin degree of freedom with the orbital degree of freedom, and have designated the associated field of study as *orbitronics*. The valence band of Si consists largely of three p-orbitals. The three orbital degrees of freedom transform as a (pseudo-) spin-1 quantity under rotation, are odd under time reversal, and couple to the crystal momentum of the holes in the Si. We have shown that p-doped Si under the influence of an electric field develops an intrinsic orbital current of the p-band hole orbitals. The polarization of the p-orbitals, the direction of flow, and the direction of the electric field are mutually perpendicular. The transport equation is similar in form to the spin Hall equation [3]:

$$J_i^j = \sigma_{ijk}^e E_k, \quad (12)$$

where J_i^j is the orbital current flowing along the j direction, and the local orbitals are polarized along the direction perpendicular to both the applied field and the current. For an electric field on the y -axis, we expect an orbital current flowing in the positive x direction to be polarized in the $+z = p_x + ip_y$ direction, while the orbital current flowing in the negative x direction is polarized in the $-z = p_x - ip_y$ direction. As in the case of the spin current, the orbital current is even under time reversal, and the above response equation is dissipationless. The orbital current should appear as a result of the coupling between the hole momentum $\vec{k}$ and the local orbital $\vec{l}$, which is apparent in the Hamiltonian for Si close to the gamma point of the valence band:

$$H = Ak^2 + (A - B)(\vec{k} \cdot \vec{l})^2. \quad (13)$$

It should be possible to detect the effect by using techniques similar to those used in detecting the spin current. Several recent experiments involving detection of spin currents via the associated spin accumulation at the boundary [23, 24] should provide us with a basis for attempting to detect the intrinsic orbital current in Si. Because Si is an indirect-gap semiconductor with low efficiency for light emission, an LED-type experiment like that described in [24], in which the polarization of the emitted light gives information about the orbital in which the emitting electron resides, is not experimentally viable. However, Kerr and Faraday rotation measurements are insensitive to the Si indirect gap and should be suitable for probing the orbital polarization.

Concluding remarks

The potential means for achieving dissipationless spin transport reviewed in this paper constitute theoretical

and associated, potential experimental directions with technological implications. A number of alternatives to the current semiconductor technology have recently been proposed, including technologies based on carbon nanotubes, molecular electronics, and dilute magnetic semiconductors. Spin-based electronics, discussed in this paper, is based on the use of spin-orbit coupling in conventional semiconductor materials. As such, it leverages the tremendous investment of semiconductor materials processing, and should lead to an easier path of adoption. We regard the prediction and discovery of the intrinsic spin Hall effect as an important step toward developing integrated spin logic devices and achieving low-energy computing. One of the future challenges for the field is to develop a way to measure the intrinsic spin Hall effect directly instead of through spin accumulation. Other important theoretical and experimental challenges involve the use of the spin current to inject and manipulate spins. In materials without (strong) spin-orbit coupling, one of the future efforts should be to try to detect the orbital Hall effect and to investigate whether the orbital moment can be transferred to spin and hence be used for spin injection. Moreover, experimental techniques should be devised to enhance the amount of spin polarization arising from spin current.

The spin-charge-propagating mode predicted in systems with strong spin-orbit coupling should be another way of manipulating spin. Because of its propagating character, it should almost conserve energy. Moreover, it should be possible to use the mode without regard to the spin: Use would be made of only its propagating charge packet. The experimental detection of this mode, as well as proposals for real devices, constitutes a focus for future research in spin-based electronics.

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