Spinning Holes in Semiconductors

H.A. Fertig*

Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055 USA

*E-mail: fertig@pa.uky.edu.

The electron spin is emerging as a new powerful tool in the electronics and optics industries. Many proposed applications involve the creation of spin currents, which so far have proven to be difficult to produce in semiconductor environments. A new theoretical analysis shows this might be achieved using holes rather than electrons in semiconductors with significant spin-orbit coupling.

Perhaps the most prominent characteristic of the electron is the fact that it carries electric charge. Together with the rules of quantum mechanics, the electric forces among electrons and nuclei determine the chemical properties of atoms and molecules. Manipulation of electrons in semiconductors using electric forces, which couple to the charge, is the principle behind the revolution in the electronics industry of the last few decades.

Another fundamental feature of electrons is their spin, a property in which the charge apparently spins like a top, endowing the electron with a magnetic dipole moment much like that of a bar magnet. Incorporating and exploiting this spin in microelectronic and optoelectronic applications is the central idea of spintronics[1]. While a number of commercially successful applications of this already exist (most prominently as memory for computers), many proposed
future applications await the development of methods to produce and manipulate spin currents. An important theoretical step in this direction by Shuichi Murakami, Naoto Nagaosa, and Shoucheng Zhang is reported in this issue of Science [2].

Unlike charge, electron spin is specified by a direction through its rotation axis. If one tries to measure the direction of this spin – say, by passing the electrons through a magnetic field gradient – one finds that the spin will point either “up” or “down”; the rules of quantum mechanics forbid any other result upon measurement. One could thus imagine using the spin as a bit in a computer, with a down spin state representing 0 and up representing 1. Quantum mechanics however allows much richer possibilities than this. The electron spin can be in a state that is not just up or down, but one that is a combination of the two. The full range of possibilities may be represented by an arrow directed toward any point on a “Bloch sphere” [3] (see Fig. 1). It is only upon measurement of the spin component along some direction that quantum mechanics allows only two possible results.

This richness of possible states makes electron spin an ideal candidate for a qubit, the basic component of the (as yet undeveloped) quantum computer. Quantum computers exploit the quantum dynamics of spins to vastly improve the speeds of tasks such as Fourier transformation and factorization of large integers, which can often not be performed by existing digital technology on reasonable time scales. Factorization in particular plays a key role in cryptographic schemes, so government security agencies around the world have a keen interest in quantum computers.

Materials that support spin currents can play a crucial role in the practical development of quantum computers. While there are many proposals for systems that could support spins or their analogs as qubits, one also needs practical means to initialize the spin states as well as read them. In semiconductor-based proposals for quantum computers, such as quantum dots [4], one can use interactions between a spin-current carrying wire and a qubit to read the qubit state, and
“spin-injection” to initialize it. Moreover, qubits need to interact in ways that do not dissipate the information stored in their quantum states (as happens when an electron spin is directly measured). Spin currents have been demonstrated to preserve their coherence over remarkably long distances and times\cite{5}, so materials capable of supporting them could provide a medium through which the dots could interact in a controllable manner.

One possible approach to creating spin currents is to exploit spin-orbit coupling, an effect in which the trajectory of an electron moving under the influence of an electric field depends on its spin state. For example, a recent proposal \cite{6} suggests passing electrons through a heterostructure engineered so that spin-orbit coupling might be made relatively strong, generating a spin current perpendicular to the electric current. Murakami et al. demonstrate that spin currents via spin-orbit coupling can be generated more simply using holes rather than electrons, because relatively strong spin-orbit coupling naturally exists for holes in many semiconducting systems in which it is small or absent for electrons. This idea offers several practical advantages.

First, many of the materials needed are commonly available and can easily be processed. Second, because the direction of spin and electric currents are connected, the information carried by the spin currents could in principle be translated into normal electric currents. This would facilitate the integration of spintronics with traditional microelectronic devices. The use of common semiconducting materials is a further benefit in developing such integrated devices. Finally, the polarization of the current is fixed not by a magnetic field but by the direction of the currents themselves, obviating the need for magnets to fix the spin polarization. This property may prove important in miniaturized systems, where one may not wish to have magnetic fields in every part of a given device.

Once spin currents can be created and manipulated in this way, quantum computers will arguably represent their most exciting possible application. Other applications may emerge much sooner, including spin diodes and transitors\cite{7}, which could be at the heart of high speed re-
programmable logic circuit elements and non-volatile memory applications, electro-optic light modulators[8], and circularly polarized light emitting diodes[9].

**References and Notes**

[1] See S.A. Wolf et al., Science 294, 1488 (2001) and references therein.

[2] S. Murakami, N. Nagaosa, S.-C. Zhang, Science 301, 1348 (2003).

[3] M.A. Nielsen and I.L. Chuang, *Quantum Computation and Quantum Information*, (Cambridge University Press, New York, 2000).

[4] D. Loss and D. Vincenzo, Phys. Rev. A 57, 120 (1998).

[5] I. Malajovich et al., Nature 411, 770 (2001).

[6] P. Streda and P. Seba, Phys. Rev. Lett. 90, 256601 (2003).

[7] M.E. Flatté and G. Vignale, Appl. Phys. Lett. 78, 1273 (2001).

[8] S. Datta and B. Das, Appl. Phys. Lett. 56, 665 (1990).

[9] R. Fiederling et al., Nature 402, 787 (1999).

10. The author acknowledges the support of the NSF through Materials Theory Grant No. DMR-0108451.
**Figure.** An electron spin may be represented by an arrow, and its quantum state specified by a point on a spherical surface towards which the arrow points. A measurement of the spin along some direction (e.g., one of the coordinate axes) always results in the spin being parallel or antiparallel to the measurement direction. The quantum state determines the probability for each of these two results. By allowing multiple spins to interact without directly measuring them, the full range of possible states would be exploited by a quantum computer.
This figure "holes_fig.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0309154v1