How to build a better iPod*: Spintronics holds the key

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(Dated: February 19, 2008)

When the Royal Swedish Academy of Sciences announced the winners of the 2007 Nobel Prize for physics in October of last year, they made it clear that the prize was being awarded for ground-breaking fundamental research that has rapidly led to a new paradigm for the electronics industry [1]. The recipients of the award, Albert Fert of France and Peter Grünberg of Germany (see Fig. 1), independently discovered an effect in 1988 [2, 3] known as "Giant Magnetoresistance" (or GMR).

GMR is a phenomenon that converts a very small magnetic moment, arising from the spin degree of freedom of electrons, into a change in resistance to electrical (charge) current. This method of converting spin information into charge–known as a "spin valve"–has been incorporated into the read heads of super-dense hard drives over the last 10 to 15 years. This new technology has made it possible for users to cram 100's of gigabytes of software onto ultra-portable laptops and up to 40 000 of their favourite songs onto an iPod* that can be slipped into a shirt pocket. The benefits do not stop there, according to a growing number of scientists in the nascent field of "spintronics" (short for spin electronics).

One of the great spin-offs of GMR technology was the realization that there was an entire degree of freedom (the electron spin) that had previously been ignored in the development of electronic technology. Traditional electronic devices operate by turning transistors on and off, storing and pushing electron charges around a circuit. Although these techniques have served us well to this point, there are three potential disadvantages to this way of doing things. First, storing charges for a long time is very difficult unless a voltage is continuously applied to keep capacitors charged, so charge memory (what your computer uses for RAM) is usually volatile; it only works when the computer is on. Second, pushing electric charge through resistive elements in a circuit dissipates a lot of power, generating a great deal of heat, with potentially disastrous consequences for expensive hardware [4]. Finally, as circuits are rapidly miniaturized to squeeze more processing power into a smaller package, the rules of quantum mechanics begin to take over; consideration of all relevant microscopic degrees of freedom, including the spin, becomes inevitable.

Figure 1: Winners of the 2007 Nobel Prize in physics Albert Fert (left) and Peter Grünberg (right).

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Proponents of spintronics research hope that spin-based devices may cure many ills of the electronic world. It is well known that magnetic materials are much better suited for the development of robust memory. In fact, tunnelling magnetoresistance (TMR), a close cousin of GMR, is the basis for a spintronic magnetoresistive random-access memory (MRAM), which is now being marketed by Freescale [5]. MRAM is fast and non-volatile, which means that one day it may replace existing hard-drive technology, resulting in a near-instantaneous boot-up. Less energy is required to rotate spins than is typically required to squish electrons through resistors, so many hope that spintronic components would operate more energy efficiently (benefiting the environment) and cooler (benefiting the ambient temperature of your lap). Some spintronic devices show promise to operate much more quickly than their electronic counterparts. Additionally, spin-based devices introduce a new 'knob' to tune the relevant components; they often rely on magnetic-field (rather than electric-field) control. This additional degree of freedom suggests that it may be possible to change physical spin-logic gates on the fly.

There are many fundamental physical questions yet to be answered before new spintronic devices can outstrip conventional electronics in areas other than hard-drive read heads. Some of the most important questions for researchers are: Is it possible to develop semiconducting ferromagnets at room temperature? Can we find simpler ways to combine metallic ferromagnets and semiconductors on the same chip? What are the limitations of "spin injection" (the introduction of spin-polarized electrons

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*iPod is a trademark of Apple Inc.

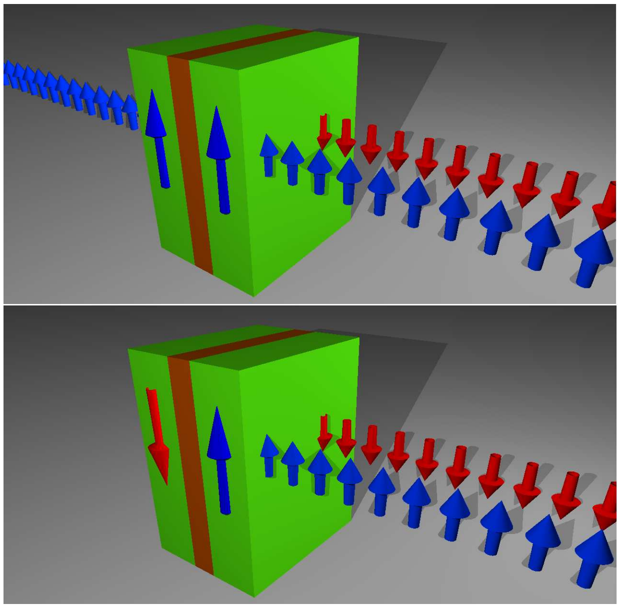

Figure 2: Cartoon of a spin-valve device, similar to those used in hard-drive read heads. Incoming spins with both polarization directions (“up” (blue) and “down” (red)), incident from the right, can only pass with high probability through a ferromagnetic material with similar spin orientation. Only “up” spins pass with high probability when both ferromagnets are oriented in the “up” direction (top) (this is the “open” configuration of the spin valve, allowing current flow). Neither spin orientation can pass through the device when the ferromagnets are oriented in opposite directions (bottom) (this corresponds to the “closed” configuration).

into a conducting region)? What limits the lifetime of a spin? and How can one create and control the analogue of electrical currents (spin currents)? Each of these questions has resulted in its own sub-field of research, drawing significant interest from engineers trying to develop clever designs for new components, chemists trying to develop new and exciting materials for nanometre-scale systems, and physicists interested in the inner workings of classical and quantum mechanics (the driving forces behind these devices).

I. HOW DOES IT WORK?

One of the most important fundamental circuit elements in spintronics is the spin valve. A spin valve is a device that allows the passage of one spin orientation, while blocking another. This allows one to create a spin-polarized “beam” of electrons from a typically unpolarized Fermi sea and allows for the readout of spin information through a measurement of electrical current.

One example of a spin valve device is shown schematically in Fig. 2. This device consists of a thin piece of material (shown here in red, which is insulating in the case of TMR and metallic in the case of GMR) sandwiched between two conducting ferromagnetic materials (shown in green). “Up” spins can enter a ferromagnet that is polarized “up” with high probability, whereas “down” spins have a significantly lower probability to enter an “up”-polarized ferromagnet. When both of the ferromagnetic sandwich slices are polarized “up” (top of Fig. 2), there is significant electronic current through the device due to the flow of “up” spins. In contrast, if one of the ferromagnets flips its spin, current is inhibited for both spin orientations. The presence or absence of current through such a device determines the relative orientation of the two ferromagnets. Such a device is routinely used in hard-disk read heads, where the orientation of one of the ferromagnets is fixed and the other acts as a tiny magnetometer, sensing the 1’s and 0’s encoded in the magnetic domains of a hard drive.

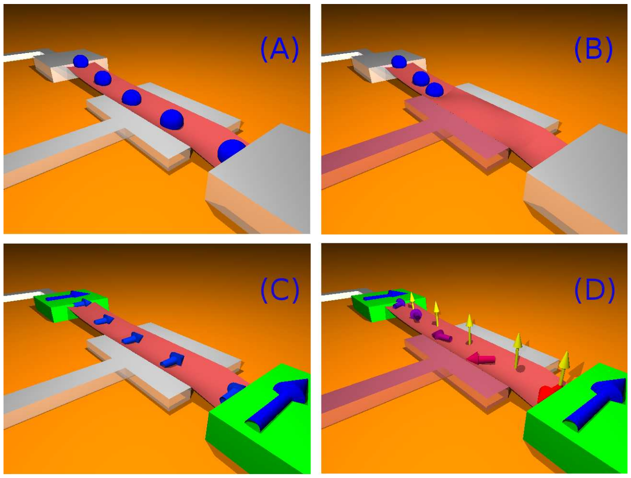

Figure 3: Comparison of a typical field-effect transistor (FET) (Figs. (A) and (B)) with the proposed operation of a Datta-Das spin-FET (Figs. (C) and (D)). When the FET gate is open (Fig. (A)), electrons (blue spheres) flow from the source to the drain through a narrow channel. If a voltage is applied to the FET gate (shown in red, Fig. (B)), the potential in the channel is raised and electron charge can no longer flow from source to drain. In a spin-FET, the source and drain electrodes would be replaced by spin valves (see Fig. 2). When the spin-FET gate is open (Fig. (C)), electrons of a fixed spin orientation emerge from the source and enter the drain, giving rise to a finite current. If a voltage is applied to the gate (Fig. (D)), the electron spins experience an effective magnetic field due to the spin-orbit interaction (yellow arrows). This effective magnetic field causes the spins to precess as they travel from source to drain along the channel. If the spins precess by 180 degrees, they are blocked from entering the spin valve at the drain, resulting in no current flow.

The spin valve is a convincing demonstration of some of the advantages to using spin in electronic devices (without this device, hard drives would never have reached such small proportions). However, to capitalize on all aspects of the spin, it would be necessary to develop other circuit elements that might channel and manipulate tiny magnetic moments. In a classic paper [6], Datta and

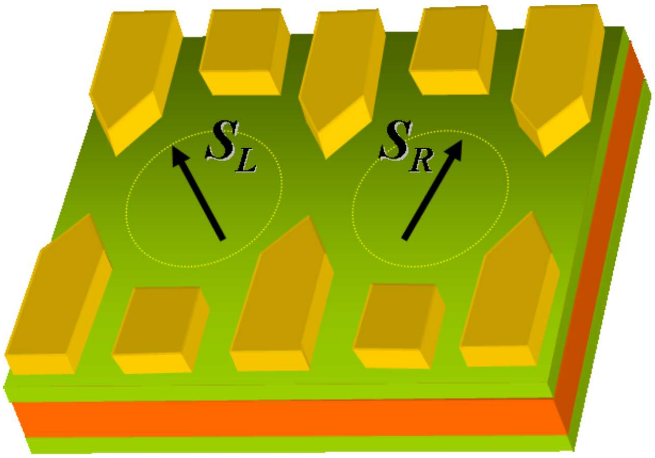

Figure 4: Two electrons confined to a double quantum dot. By applying appropriate voltages to electrodes (shown in yellow), the electrons can be pushed together, increasing the overlap of their wave functions and the exchange coupling between their spins ($\mathbf{S}_L$ and $\mathbf{S}_R$). Changing the voltages to separate the electrons turns the coupling off.

Image by V. N. Golovach

Das proposed one such device: a *spin field-effect transistor*, or spin-FET. A conventional electronic FET operates according to the schematic diagrams in Figs. 3(A) and 3(B). When no voltage is applied to the gate electrode (Fig. 3(A)), electrons (blue spheres) travel from the source to the drain along a narrow channel. A voltage applied to the gate electrode (Fig. 3(B)) changes the potential landscape of the channel, preventing current from flowing. In a spin-FET (Figs. 3(C) and 3(D)), the source and drain electrodes are replaced by spin valves (see Fig. 2). If no voltage is applied to the gate electrode in a spin-FET (Fig. 3(C)), spin-polarized electrons retain their polarization as they travel from the source to drain unimpeded, much as unpolarized electrons do in Fig. 3(A). However, when a voltage is applied to the gate of a spin-FET (Fig. 3(D)), the primary effect is not to change the potential landscape of the channel, but rather to enhance spin-orbit coupling. The spin-orbit interaction couples the momentum of the travelling electrons (orbital motion) to the spin degree of freedom. The result of this coupling for electrons moving along the channel is to generate an effective magnetic field (illustrated in Fig. 3(D) with yellow arrows). As the electrons travel down the channel, their spins precess in this effective magnetic field, with the result that the spin may be anti-aligned with the drain valve at the end of the road. If the spin is anti-aligned, with high probability it will not be able to enter the spin valve, and current through the device will be blocked.

II. GETTING MORE OUT OF SPINS

The "conventional" spin-based devices discussed so far (the spin valve and spin-FET) present a significant step forward for computing and electronics. However, harnessing the quantum mechanical properties of these spins could sow the seeds of a revolution. With the full power of quantum mechanics, it would be possible, in theory, to crack codes in a fraction of the time of a classical computer, search databases extremely quickly, send secret messages with guaranteed security, or simulate complicated physical problems with ease. In order to perform many of these tasks, it is first necessary to find some physical realization of an idealized quantum two-level system in which to encode quantum information. These two-level systems, quantum bits or *qubits*, would act as reservoirs of quantum information in a quantum computer, in direct analogy with the bits (zeroes and ones) of a classical computer.

There are many potential qubit-contenders in the race to develop working quantum computers, including trapped atoms and ions, nuclear spins, photon polarization states, superconducting devices, and many others. Since the majority of the electronics industry has developed the art of pushing electrons around in semiconductors in the last 50 years, and the two states of an electron spin-1/2 ("up": $|\uparrow\rangle = |0\rangle$ and "down": $|\downarrow\rangle = |1\rangle$) form the basis for a well-defined quantum two-level system, one natural choice for a qubit is the spin state of a single electron confined in semiconductors. To ensure that only a single two-level system is available for quantum information processing, electrons are often confined to quantum dots (tiny puddles of electron charge that can be designed to hold single electrons – see Fig. 4). Although it is possible to confine single two-level systems constructed from electron spins in such structures, this alone does not yet make a good qubit. The major requirements for any useful qubit can be roughly summarized with two C-words: control and coherence.

In the context of quantum computing, sufficient control is only achieved if two conditions are fulfilled. First, it must be possible to manipulate *single* qubits, independent of each other, with a high degree of accuracy. Second, it is important to be able to perform operations on *pairs* of qubits, typically by selectively coupling and decoupling them. For electrons in quantum dots, single-spin manipulation can be performed using sufficient magnetic field gradients and magnetic resonance techniques. Pairs of electron spins can be coupled selectively through the same strong interaction that generates magnetism: the exchange interaction. Exchange coupling is proportional to the overlap of electron wave functions, and is therefore local and selective for localized electrons. The interaction can be turned on and off between pairs of electrons simply by pushing them closer together or separating them in neighbouring quantum dots (see Fig. 4). One promising extension of this idea suggests that electron spins could be coupled selectively even at long range in

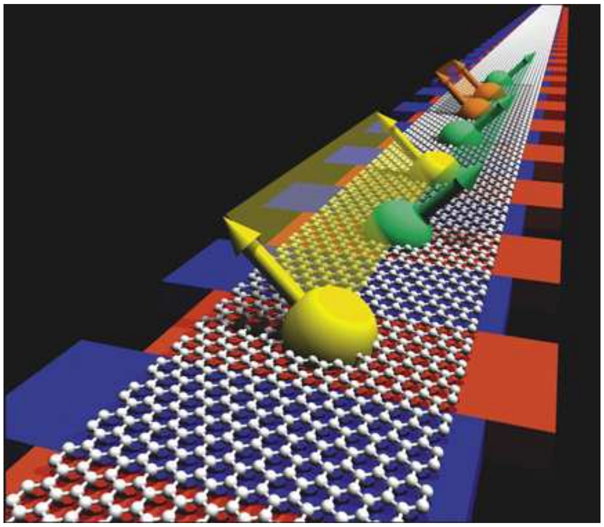

Figure 5: Electron spins in graphene (a two-dimensional strip of carbon atoms) could, in principle, be coupled at long range, forming the building blocks for a spintronic quantum computer.

Image by D. V. Bulaev

materials such as graphene [7] (a two-dimensional sheet of carbon, see Fig. 5).

All the clever coupling schemes in the world do not help to build a quantum computer if, in addition, it is not possible for the qubits to remain coherent for a sufficiently long time. Coherence describes the ability of a qubit to maintain it's identity. That is, if a quantum bit is prepared in a superposition of its two basis states: $\alpha\left|0\right\rangle+\beta\left|1\right\rangle$, how long will it remain in this same superposition? This question is one of the most rich and intriguing physical problems associated with quantum computing. On the surface, it also appears to be one of the shortcomings of spintronic quantum computers.

Qubits lose their coherence through interaction with uncontrollable degrees of freedom in the environment. Many physical qubits are designed to minimize this interaction by removing the environment entirely, suspending the qubits in free space. This is the usual approach for trapped atoms and ions. Such isolation does not appear possible for electron spins in semiconductors, where the environment is provided by the semiconducting crystal that holds the electrons in the first place. Instead of removing the environment from spintronic qubits, the strategy of choice is often to control it, by "cooling" the environment to low temperature, judiciously choosing the states of qubits to reduce the environmental influence, or by performing a sequence of quantum mechanical measurements on environmental observables. A new round of experiments is currently underway to determine the viability of these decoherence-minimization techniques. Preliminary results are very promising, but the jury is still out on whether truly useful quantum computation will be possible with such environmental interactions.

III. CONCLUSIONS

As the size scale of conducting channels built into today's transistors reaches a few tens of nanometres, the rules of quantum mechanics become increasingly important, and traditional methods for building faster and cheaper devices will be abandoned. It is not yet clear which new strategies will win out, but some spin-based electronic devices have already taken off. These devices (spin valves in hard-drive read heads and MRAM) may only be the tip of the iceberg.

By exploiting the coherence of quantum spin states fully, it may be possible to build a truly *scalable* quantum computer (one that does not become worse as the number of qubits is increased). With such a device, it should be possible to perform old tasks more quickly, and may give us access to new solutions that were entirely inaccessible with conventional technology.

IV. FURTHER READING

For further reading, see Ref. [8] for a review of GMR, Refs. [9], [10], [11], and [12] for reviews of semiconductor spintronics, and Refs. [13], [14], and [15] for reviews of spintronic quantum computing.

V. ABOUT THE AUTHOR

Bill Coish started in September as a post-doctoral fellow in the Department of Physics and Astronomy and the Institute for Quantum Computing at the University of Waterloo. He completed a B.Sc. (Hons.) in physics from the University of Manitoba in 2000, an M.Sc. from McMaster University in 2002, and a Ph.D. in theoretical physics in 2006 at the University of Basel in Basel, Switzerland under the supervision of Daniel Loss. Bill held a brief (1-year) postdoctoral position in Basel before arriving in Waterloo.

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[1] Information about the 2007 Nobel Prize in Physics, including video of the Nobel lectures by Albert Fert and Peter Grünberg is available at: http://nobelprize.org/.

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