Electrical Control of Electron Spin Steers Spin-Based Technologies Toward Real World

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Santa Barbara, Calif. --Researchers at the University of California at Santa Barbara (UCSB) and at the University of Pittsburgh have provided "proof of concept that quantum spin information can be locally manipulated using high-speed electrical circuits," according to the abstract of their paper being published expeditiously at 2:00 p.m. Jan. 23 on the "Science Express" website, Science Magazine's rapid portal for publication of significant research findings to appear subsequently in print in Science.

The findings are significant because they demonstrate a solid-state quantum logic gate (i.e, control mechanism) that works with gating technologies in today's electronics, today's computers. This research also moves esoteric spin-based technologies of spintronics and quantum computing from the futuristic closer to within reach of present-day possibilities.

The research was carried out in a joint venture between David Awschalom, Professor of Physics and Electrical and Computer Engineering at UCSB and Director of the Center for Spintronics and Quantum Computation (part of the California NanoSystems Institute [CNSI]), and Jeremy Levy, Associate Professor of Physics at the University of Pittsburgh and Director of the Center for Oxide-Semiconductor Materials for Quantum Computation.

A year ago at a program on Quantum Information held at the Kavli Institute for Theoretical Physics at UCSB, the two physicists fell into a conversation that led them to wonder how electron spins in semiconductors could be manipulated in all three dimensions.

The problem was an old one. So-called "spin resonance" techniques, used extensively for magnetic resonance imaging (MRI) and chemical identification, manipulate electron and nuclear spins in three dimensions using rapidly alternating magnetic fields. However, such magnetic fields are difficult to generate and control on a local scale. By contrast, local control over electric fields forms the basis of all of electronics, from CPUs to cell phones. The challenge was how to figure out a way to control electron spins using electric fields.

Awschalom and Levy realized that if a host for electrons could be designed for which the axis of spin rotation changed with an applied electric field, the spin direction could itself be controlled. That is, they could turn electric fields into effective magnetic fields.

The two researchers realized that semiconductor sandwiches made of aluminum gallium arsenide and gallium arsenide could provide just this sort of control. The material was built atomic layer by atomic layer in the Molecular Beam Epitaxy (MBE) laboratory of UCSB Materials Professor Art Gossard by Roberto Myers and Dan Driscoll, graduate students of Gossard and Awschalom. Myers and Driscoll guided the deposition of the material such that the parabolic quantum wells (PQWs) "are grown by varying the aluminum concentration x, ranging from 7% at the center to 40% at the barrier, to shape the conduction band into a parabolic potential," according to the paper "Gigahertz Electron Spin Manipulation Using Voltage Controlled g-Tensor Modulation."

The "Science Express" results provide just such a demonstration. Awschalom's physics graduate student, Yuichiro Kato, conducted the low temperature experiments at Santa Barbara. He used microfabrication techniques to construct the semiconductor devices and operate them, and experimental techniques developed by Awschalom and Levy to show that the researchers have indeed accomplished what they set out to accomplish.

Harkening back to that conversation of conceptual breakthrough between Levy and him, Awschalom said, "We realized that if we write down the equations of motion of the electron that are normally operated on by magnetic fields, we can replace the magnetic fields with electric fields. Then we thought if that is the case, we could use miniature gates to operate on spins instead of magnetic fields for scalable architecture for computing."

Key to understanding the far-reaching implications of this proof of concept is the use of electrical fields, instead of magnetic fields, to control the electrons. Today's semiconductor, charge-based technologies (including computers) operate by control of electrical fields. Most researchers approaching the spin-based paradigm for spintronics and quantum computing technologies have assumed that the behavior of spins must be controlled by magnetic fields. The prospect of controlling 100 million magnets each independently on the equivalent of a chip has boggled the imagination of researchers. By contrast, controlling 100 million devices with electrical gates is what we already do in computers sitting on a multitude of desks throughout the world.

The parabolic quantum wells are grown with varying concentrations of aluminum gallium arsenide, sandwiched between gallium arsenide, flanked by metal plates, grown by deposition on the gallium arsenide. Think of a sandwich with Swiss cheese in the middle (aluminum gallium arsenide quantum wells) flanked by meat (gallium arsenide) in turn flanked by bread (the metal plates). The plates are the gates with one lead for the application of electrical current that in turn creates the electrical fields, which enable manipulation of the electrons through the material whose varying concentrations of aluminum govern the rotational speed of the electrons and the direction of their axes.

The result is "electron spin resonance (ESR) on a chip." This engineered nanostructure allows use of very small voltages in traditional gates to operate on electron spin in all three directions in which the axis can point without requiring fast alternating magnetic fields. "The experiments show that it is possible to build a very scalable array of quantum gates using semiconductors in a relatively straightforward manner," said Awschalom.

The experiments were conducted at low temperature and at a 50-micron scale, but designing them to operate at higher temperatures and smaller scales will likely not be difficult, according to Levy. "This work describes and demonstrates how to replace magnetic with electrical fields for the control of spin information in semiconductors," said Levy. He described the findings as an "enabling technology" for spintronics and a "feasibility demonstration" for quantum information processing. For the latter, the size of the gates must be reduced so that the spin of a single electron can be precisely controlled. Such a feat would enable electron spins to be used as quantum bits or "qubits" for a quantum computer. "Ultimately," the researchers write at the end of their paper, "these electrical gates may be scaled down for operation on single spins and in quantum dots to form qubits."

In contrast to bits, the "1"s and "0"s of present-day computers, qubits can be in both the "1 state" and "0 state" at the same time, enabling a much richer and more powerful paradigm for computation. The orientation of an electron spin can be used to store one qubit of information. Quantum gates are then needed to reorient the electron spins and perform "quantum information processing".

And then there is the issue of spin-spin interactions, the next research hurdle to be overcome to enable another milestone in this line of progression toward full feasibility demonstration for quantum information processing. As the researchers write, "Control over single spin operations is sufficient for universal quantum gating, provided there is a 'backbone' of spin-spin interactions."

But, said Awschalom. "For the industrial sector looking at quantum information processing and asking whether there's a future, there is a trillion dollars of semiconductor technology for leveraging, and electrical control of spin makes the leveraging far more feasible and cost-effective than control with magnets. The only thing new here is the concept; the technology is today's technology. There's nothing so special that would keep anybody anywhere from doing this experiment. Our hope is that people will do this much better in the next generation."

And, adds Awschalom the physicist in contradistinction to Awschalom the technologist, "This work points towards a way for potentially manipulating quantum states and entangling them to test some of the fundamental aspects of quantum mechanics with existing technology."

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