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New Technique to Tip Electron Spins Makes Way for All-Optical Quantum Computation in Solids

Santa Barbara, Calif.-- "Ultrafast Manipulation of Electron Spin Coherence," published in the June 29 issue of Science, reveals a new way to manipulate optically quantum spin states on ultrafast time scales (femtoseconds). The authors suggest that the ability to quickly manipulate electron spins could pave the way for all-optical quantum computation in solids by loosening the stringent requirements on coherence times. Featured on the Science cover, the research findings are also discussed in the "Perspectives" section.

University of California at Santa Barbara (UCSB) physicist David Awschalom heads the research effort that conducted the experiments reported in Science. He is director of the UCSB Center for Spintronics and Quantum Computation, a central component of the new California NanoSystems Institute (CNSI) located jointly at UCSB and UCLA.

Awschalom's long-time collaborator is Penn State University materials physicist Nitin Samarth. Together with their graduate students, the pair had recently published related experiments in the June 14 issue of Nature. By hooking a battery up to a semiconductor structure, tunable electric fields were generated that move spin-aligned electrons from one semiconductor material to another.

Just like the charge currents that flow in ordinary electronics, this spin current may form the foundation for a new type of "spintronics" that researchers hope will improve speed in devices for information processing including hard disk drives and nonvolatile RAM.

In the Science paper Awschalom, Samarth, and graduate students Jay Gupta and Robert Knobel focus not on moving spin-aligned electrons, but on controllably rotating the axis of electron spins. They do so by using ultra fast pulses of laser light to "tip" the spin alignment of the electrons. "Ultra fast" in this case means 10-13 seconds; a trillion such pulses would fit in the time it takes to blink an eye.

Some elementary particles such as electrons spin or rotate. Classically, physicists describe spin (e.g. of a top) by specifying the direction of the axis of rotation and the rate of rotation (i.e., angular momentum). But in the more fundamental framework of quantum mechanics, a measurement of an electron's spin can only have discrete values. Thus the spin-state of the electron along a particular axis can be visualized as either clockwise or counterclockwise with a basic discrete unit of angular momentum. These states are referred to as spin up or spin down along the chosen axis of rotation.

The binary bit of conventional computing--either 0 or 1--corresponds in the spin quantum-computing paradigm to a quantum bit consisting of a particle spin that is either up or down. What is different and what makes quantum computation a potentially richer computational approach is that the electron spin can be in a superposition of spin up and spin down. This feature of quantum mechanics has intrigued physicists since the 1920s, and means that a bit can encode not just one piece of information (for instance whether a light is on or off), but much more, like the light's color, intensity, etc.

As Awschalom puts it, "Conventional computer bits consist of miniature electronic switches that are either off or on (0 or 1). Quantum-bits can be any combination thereof, for example 41% on, 59% off." This property, he says, "enables computational algorithms with exponentially improved speed and fundamentally different functionality."

Other researchers have explored quantum-bit models based on nuclear spins, atoms, or trapped ions. That work, says Awschalom, "has provided some of the founding principles of the rapidly emerging field of quantum computation. But a limitation of these model systems is their potential scalability to the large number of quantum bits desirable for real computational problems."

Awschalom and Samarth are looking at solid-state systems to solve the scalability problem because semiconductor microprocessing technology is already so advanced. However, a tradeoff with this approach is a shorter "coherence time" which is the length of the time that the electron spins stay aligned before they succumb to environmental influences that cause the spin alignment to randomize.

As Awschalom says, "The coherence time sets the duration over which quantum-bits maintain a well-defined state, for example, the state '41% on, 59 off' versus some other random combination." The coherence time is one of the critical parameters in quantum computation proposals. In essence, the coherence time must be much greater than the "clock speed" of the quantum computer for the device to work, because a large number of operations on the quantum-bits (analogous to flipping the switch back and forth) must be performed in order to produce a computation.

While previous research has been aimed at increasing the coherence time of electron spin in semiconductor quantum structures (which is typically less than 1 microsecond), the experiments reported in the Science article present an alternate approach. In effect, the researchers have discovered a technique that can potentially circumvent the otherwise stringent constraint of the electron spin coherence time in solid-state materials. The use of ultra fast laser pulses to manipulate spins would represent a speed-up of the process by 100,000 times when compared with conventional methods, and opens new directions for research into solid-state implementation of quantum computers.

As Awschalom explains, "These rotations are made possible by an effective magnetic field that arises when very intense light of a certain energy interacts with the electron spins in a semiconductor. Although the degree of rotation is currently about half of what is needed to perform a full operation, many avenues exist for further optimization."

The Penn State researchers engineered the materials used in the UCSB experiments through molecular beam epitaxy (MBE), a materials synthesis technique that allows the custom-design of complex materials with atomic monolayer control.

"The goal of developing a quantum computer provides an exciting opportunity for combining cutting edge materials synthesis with sophisticated physical measurements. Tailoring the material to this experiment was a real challenge," said Samarth. "In this case, we had to meet several constraints imposed by both the physics and technology of the experimental measurements. Since MBE allows us to act as 'atomic scale architects,' we met the tight conditions needed for the measurements by building 'digital' quantum structures, one atomic layer at a time."

Awschalom said, "It is hard to separate materials from ideas and experiment. This work is truly interdisciplinary. We could never do these experiments without the Penn State materials science expertise and creativity."

DARPA (Defense Advanced Research Project Agency) funds the collaborative research between UCSB and Penn State through two programs, SPINS and QUIST.

Note: Professor Awschalom is in Europe where he is presenting these findings to the NATO Advanced Research Workshop on Quantum Transport in Semiconductors in Maratea, Italy, as well as at two scientific conferences. He can be reached by e-mail awsch@physics.ucsb.edu or through UCSB contact Jacquelyn Savani (805) 893-4301. Professor Samarth is at 814-863-0136.

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