Diamonds are a spin's best friend

June 9, 2009

Understanding and controlling single-electron spins is viewed as the future of information and communication technologies. UCSB's spintronics center is figuring out how to work with this phenomenon at room temperature, making such devices practical for the real world.

Spintronics, the exploitation of spin as well as charge in electrons, became a commercial reality in 1998. That year, hard disc drive heads based on giant magnetoresistance (GMR), a phenomenon resulting from spin, made possible a dramatic increase in data density in storage devices. Even your notebook computer now has data storage measured in hundreds of gigabytes rather than hundreds of megabytes—a thousand-fold increase.

David Awschalom, a UC Santa Barbara professor of physics and of electrical and computer engineering, believes that huge performance increase is modest compared to what's coming, and he should know?Awschalom and his research group have been paving the way for more than fifteen years, continuously advancing spintronics both in...
theory and in the tools and methods to verify and implement that theory.

?The accelerating pace of discovery in this area is extremely exciting,? commented Awschalom, who is director both of UCSB?s California NanoSystems Institute (CNSI) and of the institute?s Center for Spintronics and Quantum Computation. ?We?re seeing semiconductor spintronic devices now where transistors were in the ?50s?within a few years of being able to change radically the size, capacity, and speed of computing and communications devices.? 

Spin, closely related to magnetism, is a property of elementary particles complementing mass and charge. Spin in electrons causes them to behave like tiny bar magnets. Spin has been understood and accepted in physics since the 1920s, but it took more than seventy years for it to be exploited commercially. The GMR drive heads are based on spin-polarized current flow (current flow in which the spins of all the electrons are aligned) in metallic materials; so is the latest commercial form of non-volatile memory, MRAM (Magnetoresistive Random Access Memory), which offers the speed of conventional SRAM (Static Random Access Memory) with the non-volatility of flash memory.

Solid-state spintronic devices, now looking toward commercialization, are still based on spin-polarized current flow, but in semiconductors instead of metals. The first commercial semiconductor spintronic devices may be spin torque non-volatile memory, with multifunctional devices?single devices capable of logic, storage, and communication?farther out. Both MRAM and spin torque memory can make possible ?instant-on? computers which would not have to laboriously reload programs and data from hard drives or from flash memory ?solid-state drives,? which are faster than hard drives but substantially slower than spintronic memory.

?The beauty of semiconductor spintronics,? commented Awschalom, ?is that, unlike systems based on metallic materials, these systems have electronic, optical, and magnetic properties?those properties may be used separately or combined in new schemes, making possible highly multifunctional capabilities for future technologies.? 

Semiconductor spintronics also has the potential to lead to quantum devices, which will be based on controlling the precession of single electron spins, either electrically or optically. Electron spins in semiconductors can be created ?coherently? in states that point up, point down, or point in a superposition of up and down states ?a quantum mechanical state that may serve as the basis for future quantum machines. That?s where diamonds enter the picture. Synthetic diamond has long interested semiconductor engineers as a material for conventional electronics, for multiple reasons:

- It can be ?doped? with select impurities to make it a semiconductor rather than an insulator, which it is when pure.
- It?s the best thermal conductor on the planet.
- It?s compatible with the CMOS (complementary metal oxide semiconductor) technology widely used in integrated circuits for everything from computer CPUs to image sensors.
- It has a high refractive index, and is transparent to ultraviolet light and to most
frequencies of visible light.

- It has an extraordinarily wide band gap, an expression of the energy necessary to move an electron from the valence band (the highest orbital band containing electrons) to the conduction band, where electrons flow freely.

Awschalom’s work in spintronics has been very timely. He and his research team have been making breakthrough discoveries in spintronics, and in the tools and techniques needed to observe, measure, and control spin states, since 1992.

Until recently, however, high cost and difficulties during growth in controlling the crystalline structure of the diamond films were major obstacles to taking advantage of diamond’s inherent suitability for electronic and photonic devices. (Earlier research in this area sometimes used polished natural diamonds, as they were purer and larger than then-available synthetic diamonds, and contained naturally-occurring impurities and vacancies (missing carbon atoms in the crystal matrix) that combination made them good, though expensive, semiconductors.)

Now diamond manufacturing costs are dropping, and progress in chemical vapor deposition makes possible the consistent creation of single-crystal diamond thin films, typically a few dozen microns thick over areas as large as many square centimeters, with controllable implantation of dopants and creation of vacancies. Nitrogen is typically used for the dopant, because nitrogen and an adjacent vacancy in the lattice constitute what is termed an N-V center, an ideal environment for exploring the spin of single electrons and single photons.

Diamond’s band gap is 5.5 electron volts—five times as large as that of silicon and about twice the energy in a visible-light photon. That means that an electron trapped in an N-V center can be excited by optical-wavelength light without bumping it all the way up to the conduction band; when the electron falls back into the N-V center’s ground state it emits a single photon; it fluoresces. This can happen millions of times per second under continuous illumination.

It appears that spins in diamond may well also have a significant impact in photonics. N-V centers function as single impurities in diamond, and are thus able to emit one photon at a time. That’s a key capability for the nascent fields of quantum cryptography and quantum communication. Each photon carries one qubit (quantum bit), which represents information just as conventional? electronic bits do. There is a big difference, however? conventional bits can carry only one of two values, either 0 or 1, while qubits can carry either or both spin states (down or up, or a combination of the two, called a superposition), yielding an infinite number of values.

David Toyli, a graduate student in Awschalom’s research group, notes, “One of the most remarkable characteristics of N-V centers is that we can manipulate their quantum properties at room temperature. That gives us tremendous flexibility in the types of
experiments we can perform. He continued, “This work with N-V centers is truly exciting; every few months there’s a new series of discoveries that dramatically changes our perception of what’s possible with this system.”

Awschalom’s work in spintronics has been very timely. He and his research team have been making breakthrough discoveries in spintronics, and in the tools and techniques needed to observe, measure, and control spin states, since 1992. They’ve moved from looking at multiple spins at cryogenic temperatures, knowledge reflected in spin current devices, to examining and manipulating single spins at room temperature, which is the basis for practical quantum devices. Over the same time span, microelectronics, in the form of CMOS integrated circuits, has been following Moore’s Law, which states that the number of components on a chip will double every two years, carrying with it proportional increases in performance and/or capacity and decreases in component size and cost.

Moore’s Law has limits, however, in conventional microelectronics, and we’re approaching them. We can now cram more than two billion transistors on a chip—to do that, the smallest circuit elements are down to 32nm (slightly over one millionth of an inch) in size. That size is getting very close to the point where the behavior of elementary, sub-atomic particles is governed by quantum mechanics rather than by the laws of classical physics. When that threshold is crossed, conventional microelectronic circuits and devices can no longer function as intended. Spintronic devices, built on quantum functionality, will have to take their places, if we’re to continue advancing the size, speed, capacities, and costs of computing and communications systems.

Diamond’s advantages in spintronics are compelling, both as a platform for researching single spins and other quantum phenomena and as a medium for eventual production of commercial quantum devices, and the Awschalom group’s work has kept it clearly at the leading edge of the research in that area. That leadership was emphasized recently when a research consortium led by UCSB’s CNSI and with Awschalom as Principal
Investigator, received research funding totaling $6.1 million for two projects to explore the use of diamond in quantum information processing and communications.

One of the projects is sponsored by DARPA (Defense Advanced Research Projects Agency), and the other by the Air Force Office of Scientific Research (AFOSR). Those two agencies are among those government research sponsors looking far into the future. Both projects will focus on developing new quantum measurement techniques to manipulate and read single electron spins in diamond, the fabrication and demonstration of prototype quantum bits, and on their on-chip integration with photonics for communication.

The projects will also involve creating at UCSB a world-class materials growth and device research facility dedicated to synthetic crystal diamond and diamond heterostructures. Diamond fabricated by the team will support not just the team’s spin and quantum research, but will also complement many ongoing research initiatives on the UCSB campus and around the world, including programs in solid state lighting, nanoelectronics, and atomic-level storage.

Other participants in the UCSB-led consortium include Hewlett-Packard Research Labs and faculty members from Lawrence Berkeley National Lab, Harvard, MIT, the University of Iowa, and the Delft University of Technology.

Links:

Center for Spintronics and Quantum Computation
www.csqc.ucsb.edu [2]

California NanoSystems Institute at UC Santa Barbara
cnsi.ucsb.edu [3]

Awschalom Group
