each electron all pointed in the same direction or were aligned. The question, Awschalom said, was whether a cloud or bundle of electrons all spinning the same way would retain that same spinning when the cloud is moved to an adjacent semiconducting material. When transferring an electron spin across an interface between the semiconductors GaAs and ZnSe in a magnetic field, the researchers found that the spins stayed aligned, even as the temperature of the materials was raised, in some cases, to room temperature.

Furthermore, the researchers observed that the GaAs semiconductor serves as a spin reservoir. Awschalom said that if spin was pulled from one material (e.g., GaAs) to another (e.g., ZnSe), the spins in the adjacent layer acquire the original spin frequency and lifetime of the reservoir. Therefore the total transferred spin current can have the properties of either the reservoir or the adjacent layer, and an external electric field gates the transition between the two very different regimes.

Under electrical bias, the relative increase in spin-coherent injection was up to 500% in the *n*-GaAs/*n*-ZnSe junction. Significantly, this increase was nearly 4000% in the *p*-GaAs/*n*-ZnSe junction. The results in the *n*-*n* junction are due to the GaAs spin reservoirs whereas in the *p*-*n* junction, the data suggest that there is enhancement in spontaneous transfer mechanisms. These results, particularly for the *p*-*n* heterostructures, could point the way toward spin transistors.

Cobalt-Doped Anatase Titanium Dioxide Thin Films Behave as Room-Temperature Magnetic Semiconductors

Scientists at Pacific Northwest National Laboratory (PNNL) have created a thin-film semiconductor material made of titanium, oxygen, and cobalt. Their material demonstrated improvement of magnetic strength by nearly a factor of five over that currently demonstrated.

In order to be practical, spintronics will need to use semiconductors that maintain their magnetic properties at room temperature. This is a challenge because most magnetic semiconductors lose their magnetic properties above critical temperatures that are well below room temperature, and would require expensive and impractical refrigeration in order to work in an actual computer.

Scott Chambers, a chemist and PNNL senior chief scientist, and his team of scientists achieved these properties in a crystalline oxide film known as anatase titanium dioxide that is infused with a small amount of cobalt, a magnetic impurity. As described in a poster presentation at the 2001 Spintronics Workshop in Washington, D.C., in August, Chambers and his team created this magnetic semiconductor material using molecular-beam epitaxy. A team of scientists at IBM, led by research staff scientist Robin Farrow, then characterized the material's magnetic properties.

Ion-Beam Mixing Used to Synthesize Cu-Ag Nanocomposites

Using analytic modeling, atomistic simulations, and experiments, researchers from the University of Illinois at Urbana-Champaign (UIUC) have proposed the use of ion-beam mixing with controlled irradiation conditions to synthesize nanocomposites. Researchers Raúl A. Enrique and Pascal Bellon determined that the nanocomposites are directly stabilized during irradiation because of a dynamical self-organization reaction.

Last year (*Physical Review Letters* **84** [2000] p. 2885), the researchers identified analytically that certain irradiation conditions can lead to a dynamical stabilization of nanocomposites. They later confirmed the analytical predictions by using atomistic kinetic Monte Carlo simulations (*Physical Review B* **63** [2001] p. 134111). In a publication this past summer (*Applied Physics Letters* **78** [2001] p. 4178), Enrique and Bellon demonstrated that this approach works by synthesizing Cu-Ag nanocomposites using 1-MeV Kr irradiations.

"In fact," said Bellon, "the two phases are mixed at such a fine scale that the decomposition cannot be directly seen by electron microscopy imaging techniques."

According to the researchers, the self-organization reaction results because the various dynamical processes operating during irradiation occur at different length scales. The researchers predict that the length scale of these nanocomposites can be continuously tuned by varying the irradiation conditions, such as the irradiation temperature.

"This would be a very important point for the synthesis of optimized nanocomposites, which almost always require a tight control of grain or phase size," said Bellon.

In a separate study, researchers G.C. Rizza and H. Bernas from CNRS in France and M. Strobel and K.-H. Heinig from Forschungzentrum Rossendorf in Germany reported related results on the stabilization of nanoprecipitates in irradiated SiO_2 with gold inclusions (*Nuclear Instruments and Methods in Physics Research B* **178** [2001] p. 78). They are currently applying this method to synthesize active dots in thin films for optical and

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electronic devices, while the group at UIUC are using their approach to synthesize magnetic nanocomposites for permanent magnet applications.

More Accurate Atomic Clocks May Be Enabled by Optical Frequency Combs from Femtosecond Lasers

Physicist Scott Diddams of the National Institute of Standards and Technology (NIST) and visiting scientist Thomas Udem of the Max Planck Institute for Quantum Optics are part of the NIST team that has developed an optical atomic clock with the potential to be 1000 times more accurate than currently available atomic clocks.

Current atomic clocks operate at microwave frequencies to measure the oscillations of cesium atoms, about 9 billion per second, accurately. The new optical clock operates at a much higher optical frequency, about 100,000 times higher than a microwave clock. Building a clock based on such a high-frequency transition was previously impractical because it requires both "capturing" the ion and holding it very still to get accurate readings, and having a mechanism that can "count" the ticks accurately at such a high frequency. To accomplish this, the scientists use lasers that can deliver pulses of laser light that last just a few femtoseconds. Such lasers typically have their longitudinal optical modes locked to produce a stable optical frequency comb.

As reported in the August 3 issue of *Science*, the clock combines recent advances in three areas of research: the trapping and cooling of atoms and ions with lasers, frequency-stabilized lasers, and an optical frequency "comb" that combines a femtosecond laser with nonlinear optical fibers to provide a simple, direct, and exact linkage between microwave and optical frequencies. It is the last development that enables the device to count individual cycles of such a high frequency without skipping any, and thus permits the readout of time.

The femtosecond laser-based clockwork divides the optical frequency of the clock's "pendulum" into a countable microwave frequency. A single mercury ion serves as the reference for the optical atomic clock, providing long-term stability and accuracy.

Strontium Naturally Tags Salmon from Specific Geologic Areas

Researchers Brian Kennedy, Andrea Klaue, and Joel Blum at the University of Michigan and Carol Folt of Dartmouth College have found that the element strontium, relatively common in bedrock beneath streams, accumulates in the bony tissues of Atlantic salmon and leaves a specific chemical signature, depending on the geology of the watershed in which the fish are living. By taking advantage of the natural variation in strontium isotopes, scientists now can differentiate fish from specific geologic areas without having to use a human-made marker previously attached to a fish.

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