

Rectification Suppression in Magnetic-Ge Heterojunction Diode Shown to Be Magnetization-Dependent

The potential for spin-polarized electronics to advance solid-state electronics by enabling logic and memory to be integrated into a single device or chip has prompted research efforts focused on spin-dependent effects in semiconductors. While electronic spin devices have previously shown relatively small effects, a team of researchers from the Department of Physics and Astronomy at the University of North Carolina in Chapel Hill has demonstrated the viability of producing multifunctional spin devices.

As reported in the August 4 issue of *Applied Physics Letters*, F. Tsui, L. Ma, and L. He have observed magnetization-dependent diode behavior in a heterojunction consisting of a CoMn-doped *p*-type Ge magnetic semiconductor grown epitaxially on a lightly doped *n*-type Ge substrate. Under electrical bias, the current rectification of the diode can be suppressed by applying a magnetic field. The researchers grew magnetic germanium (M-Ge) films of the form $\text{Co}_{2x}\text{Mn}_x\text{Ge}_{1-3x}$ on Ge(001) substrates using molecular-beam epitaxy (MBE) techniques to create heterojunctions with $x < 0.05$ (see figure). However, the researchers only achieved smooth two-dimensional M-Ge growth and created heterojunctions with a good low-temperature, magnetization-dependent rectification effect for doping concentrations of $x < 0.03$.

Below the 150°C Curie temperature (T_c) of this M-Ge film, a magnetization-dependent suppression of the current rectification effect, which was shown to be a consequence of the film's ferromagnetic order, was reported. Under reverse bias and zero magnetic field ($\mathbf{B} = 0$), the diode operated in the "on state" whereas, at either high magnetic field or under forward bias, the diode operated in the "off state" causing suppression of electron injection into the Ge substrate. At low temperature and a bias of -2 V, a current ratio of 30 was observed, which corresponds to a field-dependent current ratio, $\Delta I/I_0$, of 97%, that is, the ratio of the difference between the zero-field current and the current with an applied magnetic field, $\Delta I = I_0 - I(\mathbf{B})$, to the zero-field current, $I_0 = I(\mathbf{B} = 0)$. With a field on the order of 100 Oe, the current rectification was suppressed to half of its zero-field value. According to Tsui, "the low magnetic field required to cause the rapid and large suppression of current rectification makes this Ge-based magnetic heterojunction diode a technologically important device."

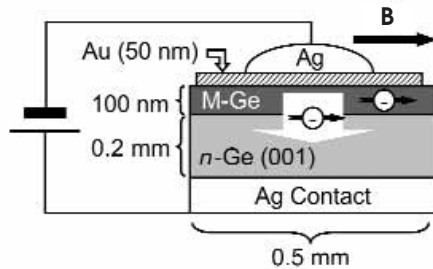


Figure. Schematic of the heterojunction with a doped magnetic Ge (M-Ge) film grown epitaxially on an *n*-type Ge(001) substrate (*n*-Ge). Reproduced with permission from *Applied Physics Letters* **83** (2003); © 2003 American Institute of Physics.

By examining the field-dependent current ratios as a function of the state variable for magnetization-dependent phenomena, $\mu_B \mathbf{B}/k_B T$ (where μ_B is the Bohr magneton and k_B is the Boltzmann constant), the researchers demonstrated that the low field current ratios of the device behave differently than those of nonmagnetic Ge depending on the bias directions. These observations differ from previously reported phenomena including magneto-resistance effects in magnetic multilayers or field-dependent carrier trajectory effects, both of which would result in the same field dependence regardless of bias direction. In their initial description of the rectification-suppression phenomena observed in this study, the researchers speculate that there exists a nearly half-filled impurity band in the *p*-type M-Ge film, which is spin-split below T_c such that it is half-metallic in zero field and insulating in high field.

"This magnetization-dependent diode is exciting," said Tsui, "because it not only exhibits a large field-dependent suppression of current rectification at low temperature, but it is also based on a materials system that is structurally and electronically compatible with current Si-based device technology. This work is a result of our intense effort on materials synthesis."

STEFFEN K. KALDOR

Coated Microcantilevers Detect Plastic Explosives

High explosives such as pentaerythritol tetranitrate (PETN) and hexahydro-1,3,5-triazine (RDX) exhibit very low vapor pressures, in the range of parts per trillion at ambient temperatures. Currently, the most sensitive detection techniques report limits on the order of hundreds of picograms, but the technologies involved are often expensive and not easily miniaturized. A team of researchers from the

Oak Ridge National Laboratory and the University of Tennessee has recently employed coated microcantilevers in a detection method that offers limits of detection of a few femtograms and has the potential to be portable and reusable.

As reported in the August 18 issue of *Applied Physics Letters*, the researchers took advantage of the ability of microcantilevers to sensitively respond to surface-analyte interactions. These interactions induce large surface forces and, if limited to one surface, lead to bending of the cantilever. The team used silicon microcantilevers, which were coated on one side with gold. Each cantilever was immersed in a solution of 4-mercaptobenzoic acid (4-MBA) to produce a uniform, self-assembled monolayer of acid molecules on the gold surface. This carboxyl-terminated monolayer was selected because of its ability to interact with nitro-substituted explosive molecules through hydrogen bonding.

The coated cantilever was held in a vacuum-tight flow cell, and a vapor stream with a trace concentration of PETN or RDX was passed over it. The light of a laser diode was reflected by the gold surface of the cantilever and used to determine both bending response and resonance frequency. Response of the cantilevers to both explosive compounds was clear and fast, with maximum bending observed in 20–25 s. After the stream containing explosive vapors was turned off, the cantilever quickly relaxed to its starting position and could be used for further detections. For both PETN and RDX, the limit of detection was determined to be on the order of several femtograms.

These results demonstrate direct vapor detection of plastic explosives at parts-per-trillion levels. Because of the small size of the cantilevers as well as the speed and reversibility of this detection method, the team said that this work "can lead to the development of a portable detection device for rapid and sensitive detection of explosive vapors."

CATHERINE OERTEL

Ga-Filled Single-Crystalline MgO Nanotube Serves as Thermometer with a Wide Temperature Range

Tubular metal oxide nanostructures combine the multifunctionality of carbon nanotubes and the industrially important applications of oxides. However, established template methods for fabricating oxide nanotubes produce polycrystalline structures, which form weaker nanostructures than do single-crystalline nanotubes. In addition, while carbon nanotubes filled with liquid metals have been previously studied, the encapsulation of liquid metals

within oxide nanotubes heretofore has not. Researchers from Y. Bando's group at the National Institute for Materials Science, Ibaraki, Japan, have synthesized single-crystalline MgO nanotubes and demonstrated that such a structure filled with Ga serves as a nanothermometer with a very wide temperature range. The synthesis of the nanotubes and *in situ* Ga filling was accomplished using a one-step process.

As reported in the August 4 issue of *Applied Physics Letters*, National Institute for Materials Science researcher Y.B. Li and co-workers used Ga₂O₃ and Mg powders in a vertical induction furnace to obtain *in situ*-filled oxide nanotubes. With the Ga₂O₃ placed in the high-temperature (1300–1400°C) zone and the Mg placed in a lower-temperature (800–900°C) zone, a white powder was collected from the surface of a graphite inductor, used as a heating element, located near the Mg. An x-ray diffraction pattern shows that the product is composed of only two crystal phases: cubic MgO and orthorhombic Ga. The researchers performed a chemical composition analysis by means of an energy-dispersion spectrometer attached to a transmission electron microscope to confirm that the nanotubes are composed of Mg and O in an atomic ratio of 1:1.

In addition to verifying that the nanostructures are Ga-filled MgO nanotubes, transmission electron micrographs (TEMs) show that the nanotubes are several micrometers long, have an outer dimension of ~30–100 nm, and have a uniform inner dimension ranging from 20 nm to 60 nm. Most nanotubes are closed at both ends but are not entirely filled with Ga. In one frequently observed morphology, a continuous column of Ga fills the nanotube except for a short section near one tip; in another, a central portion of the nanotube is left unfilled.

Unlike polycrystalline oxide nanotubes, the MgO nanotubes produced by Li and co-workers have square cross sections. A high-resolution TEM shows that the spacing between two neighboring parallel fringes both in the longitudinal and transverse direction is 2.10 Å, which is equal to the spacing between the [200] planes of cubic MgO. The researchers deduced that the nanotubes' growth direction, and therefore the nanotube axis, is the [100] direction of cubic MgO.

The researchers used a heating holder in a transmission electron microscope to investigate the thermal expansion of liquid Ga columns inside MgO nanotubes. After plotting the distance between the tips of two Ga fragments within a MgO nanotube as a function of temperature and obtaining a linear relationship with no hysteresis,

the researchers realized that they had fabricated a virtually perfect nanothermometer. The researchers said that carbon nanotubes degrade quickly in air as the temperature approaches 600–700°C, while MgO, by contrast, is an extremely temperature-stable refractory compound. The researchers calibrated one particular nanothermometer by expressing the temperature as a function of two independent parameters—the total length of the column of Ga in the nanotube and the distance between two fragments of Ga at some reference temperature. Although the ultimate range of the nanothermometer is limited only by the melting and boiling points of Ga (about 30°C and 2205°C, respectively) the two parameters determine the working temperature range; for a typical Ga-filled MgO nanotube, it is about 30–800°C.

Li and co-workers said that MgO nanotubes filled with In were prepared by a similar process whereby In₂O₃ powder was substituted for Ga₂O₃ powder. They therefore believe that their method may be universal for preparing metal-filled oxide nanotubes.

STEVEN TROHALAKI

100-Fold X-Ray Source Brightness Improvement Possible with Liquid-Metal-Jet Anode

Compact electron-impact x-ray sources dominate diagnostics and imaging in medicine, industry, and science. Their key figure of merit, the source brightness, is proportional to the electron-beam power density at the anode. Higher brightness results in higher-resolution imaging. In this respect, the current industry standard—rotating anode and microfocus technologies—show little potential for further improvement due to their intrinsic thermal heat-transfer limitations. Recently, O. Hemberg and co-workers of the Hertz Group at the Royal Institute of Technology in Stockholm have developed an x-ray source based on a liquid-metal-jet-stream anode potentially allowing a more than 100-fold brightness increase for such devices, as reported in the August 18 issue of *Applied Physics Letters*.

The experimental system consisted of a liquid-metal-jet system with a high-pressure tank enclosed in an IR heater, a 75- μ m ruby pinhole nozzle, and a sintered stainless-steel particle filter. The chosen Sn/Pb metal alloy was heated to 250°C and forced through the nozzle by applying pressure up to 200 bars, producing a laminar jet with a speed of up to 60 m/s. The electron beam was focused onto the liquid-metal jet to give a 150- μ m full width at half maximum focal spot, exhibit-

ing about 100 W power. The jet absorbed 42% of the electron beam, leading to a maximum x-ray brightness of 1.4×10^{10} photons/(mm² sr s eV) at the Sn K α peak with an average electron-beam power density of 3 kW/mm². Boiling and evaporation were observed at very high electron-beam powers, relative to the jet speeds.

The ideal jet materials for this application are metals and alloys with a low melting point, due to their high electric conductivity, high thermal heat capacity, and high Z. In particular, the thermal heat capacity is crucial to achieve high-brightness operation. The selected material was a Sn/Pb solder with a melting point of 183°C, which combines favorable thermodynamic properties with a Sn x-ray line emission that is particularly suitable for mammography.

The unique feature of this anode technology is the possibility of tailoring the system to high-brightness operation, primarily because a stable liquid-metal jet has the potential to achieve a higher speed than a rotating anode, and its regenerative nature results in a higher thermal heat capacity and heat-transfer rate due to the achievable high mass throughput.

ALFRED A. ZINN

AlGaAs Microcooler with 2°C Maximum Cooling at 100°C Demonstrated

Cooling of semiconductor laser diodes can enhance performance by reducing threshold currents, increasing power output, and enhancing spectral stability. Cooling can also boost GaAs integrated-circuit performance in power microwave and millimeter wave applications, since it lowers noise and increases gains. Integrated microcoolers are, in many cases, the most efficient approach to such cooling tasks. Conventional thermoelectric coolers such as Bi₂Te₃-based systems, however, are fundamentally incompatible with the most common semiconductor phases Si, GaAs, and InP, rendering them impractical for integrated applications. J. Zhang and N.G. Anderson at the University of Massachusetts, Amherst, and K.M. Lau at the Hong Kong University of Science & Technology have fabricated a stand-alone AlGaAs-based superlattice microcooler, which represents an important step toward monolithically integrated microcooler structures for GaAs-based microelectronic devices.

Even though Si, GaAs, and InP are not considered thermoelectric materials, recent investigations have shown that significant improvements of their thermoelectric figures of merit can be