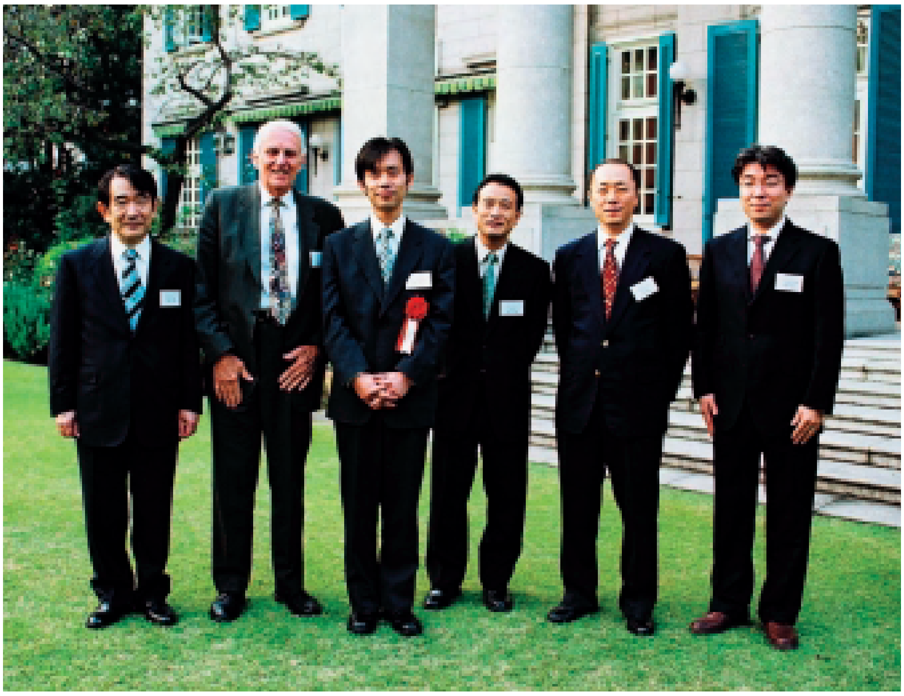
Research Matters SPRING 2005

Semiconductor spintronics:

electrical spin injection in ferromagnetic semiconductor heterostructures



From left to right: Professor Miura, Tokyo University, Chairman of the Millennium Science Forum; Sir Martin Wood; Dr Ohno (Tohoku University) 2004 Prize winner; Professor Shimizu (Osaka University) 2000 Prize winner; Professor Kizuka (Tsukuba University) 2000 Prize winner; Professor Shirahama (Keio University) 2001 winner, at the Millennium Science Forum held at the British Embassy Tokyo May 2004.

The emergent field of spintronics (spin-based electronics) exploits the propensity of electrons to hold a spin state, as well as charge state, for the development of quantum information technology. The spin itself is recorded as a weak magnetic field, characterising the electron as being in either a "spin up" or "spin down" state. The long-term goal for spintronics is to develop mass-storage devices in which trillions of quantum bits could be stored per square inch of material. A more immediate application could be to double the bandwidth of cabling by running a pair of signals through a single wire, using differently spin-polarised electrons in the wire to carry two separate signals. To develop such applications, however, it is necessary to be able to align, store, and manipulate the degrees of spin freedom in a non-magnetic semiconductor and, subsequently, to be able to detect these conditions.

Injecting spin

The injection of spin-polarized electrical current into non-magnetic semiconductors is a key element for the generation of practical semiconductor spintronic devices. For many spin-based device schemes, the preferable mode of electrical spin injection is via high-quality semiconductor heterojunctions in the absence of a magnetic field. Ferromagnetic semiconductors that can be epitaxially grown on high-quality nonmagnetic heterostructures are candidate materials to induce spin-polarized current in nonmagnetic semiconductors. (Ga,Mn)As, which exhibits a ferromagnetic phase at relatively high temperatures (T_C~160 K), is a natural choice, as it can be combined with existing devices made of III-V compounds.

Dr. Yuzo Ohno of Tohoku University and his colleagues have demonstrated a novel method of spin injection into standard semiconductor materials (Figure 1). The initial phase of the project involved the fabrication of light emitting diodes (LEDs), which consisted of pn junctions of p-type ferromagnetic semiconductor (Ga,Mn)As and non-magnetic n-GaAs with a strained (In,Ga)As quantum well (QW) inserted as an active region (Figure 1a). In this case, the p-type (Ga,Mn)As is used as a spin polarizer: spin-polarization of the injected holes is determined directly from the electroluminescence (EL) polarization emitted after the recombination with unpolarised electrons according to the optical selection rule. EL is collected from the cleaved facet to minimize magneto-optical effects due to the nearby (Ga,Mn)As, and its polarization was investigated with variable magnetic field applied parallel to the easy axis of the (Ga,Mn)As layer, i.e. in Faraday configuration by using the Oxford Instruments Spectromag SM4000 (the experimental setup at Tohoku Univ. is shown in Figure 2). The Spectromag magneto-optical system allows samples to be optically characterised in a low temperature / high magnetic field environment.

Dr. Ohno's team observed that the EL polarization below TC draws a clear hysteresis loop: the remanence EL polarization at zero magnetic field is about ±1% at a temperature of 6 K. This followed the magnetization of (Ga,Mn)As, which was independently measured by a Superconducting Quantum Interference Device (SQUID) type of magnetometer.

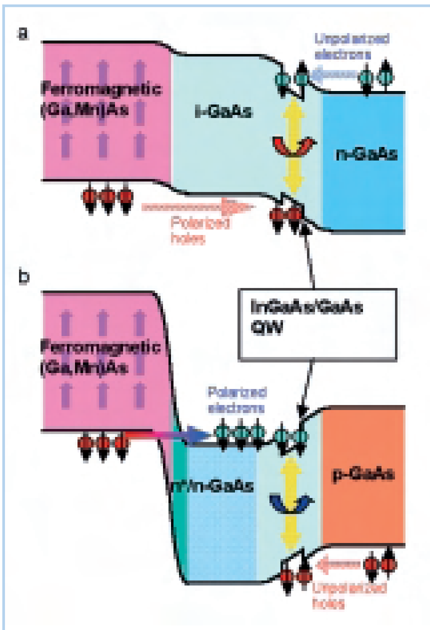


Figure 1 Schematic band diagrams of spin-LEDs.

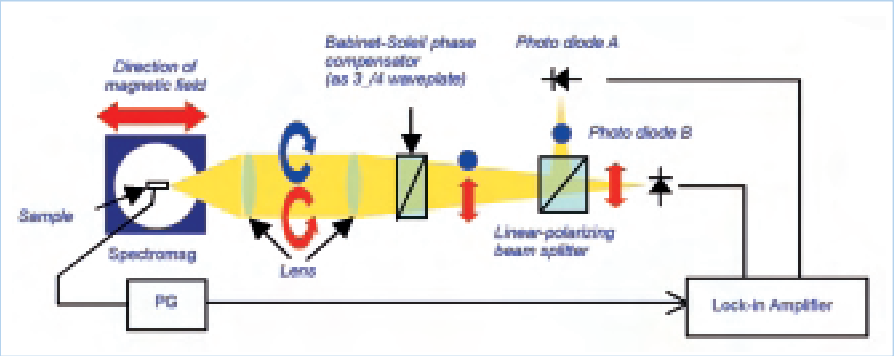


Figure 2 The experimental setup of EL polarization measurements for spin-LEDs with a magnetic field applied parallel to the optical axis.

The presence of hysteretic EL polarization indicated that the hole spins can be injected and transported in non-magnetic GaAs.

From an application and development point of view, the injection of spin-polarized electrons, not holes, is preferable, as due to the effects of small spin-orbit coupling, electrons usually exhibit a longer spin lifetime. The known ferromagnetic semiconductors compatible with high-quality heterostructures are, however, all p-type (this is believed to be caused by the small exchange interactions between magnetic spins and conduction band electron spins). Due the lack of an n-type ferromagnetic semiconductor, the investigators employed a spin Esaki diode (Figure 1b) and demonstrated electrical spin injection from the valence band of a p-type ferromagnetic semiconductor, (Ga,Mn)As, into the conduction band of a non-magnetic semiconductor via interband tunnelling. A clear hysteresis loop with ±4% remanence was observed in the magnetic field dependence of the EL polarization from an integrated p-(Ga,Mn)As/n-GaAs/(In,Ga)As/p-GaAs LED (Figure 3). This confirmed successful spin injection
in the interband tunnel junction heterostructure.

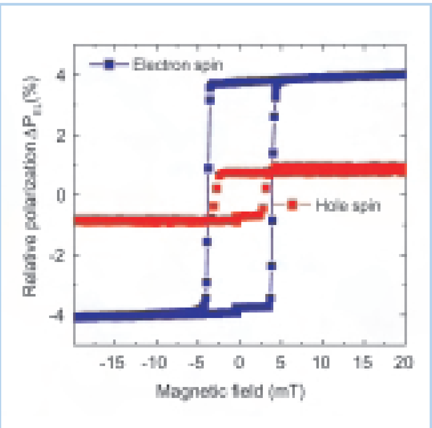


Figure 3 Magnetic field dependence of EL polarization of hole-spin (red curve) and interband electron spin (blue curve) injections.

Although the production of spintronics-based hard drives is still more than a decade out, Dr. Ohno's work constitutes the solid foundation from which many future developments in the field of semiconductor spintronics are likely to be based. In recognition of this, Dr. Ohno was awarded the 2004 Sir Martin Wood Prize for outstanding research in the area of condensed matter science. This demonstration of spin injection in semiconductors has removed another hurdle in the path of the fabrication of magnetic/non-magnetic semiconductor nanostructures and future spintronic devices.

SIR MARTIN WOOD PRIZE LECTURE

Reference
Ohno Y, Young DK, Beschoten B, Matsukura F, and Ohno H. Electrical spin injection in a ferromagnetic semiconductor heterostructure. Nature, vol. 402, December 1999: 790-792.

*Contact: **Dr. Yuzo Ohno,** Laboratory for Nanoelectronics and Spintronics, Aoba ku, Sendai, Japan.*
oono@riec.tohoku.ac.jp

Oxford Instruments Superconductivity

UK
Tubney Woods, Abingdon
Oxfordshire OX13 5QX
Tel: +44 (0)1865 393 200
Fax: +44 (0)1865 393 333

China
Rm. 14-F, No.1 Plaza
No.800 Nanjing East Road
Shanghai 200001
Tel: +86 21 63608530/1/2/3
Fax: +86 21 63608535

Germany
Otto-von Guericke Ring 10
D-65205 Wiesbaden
Tel: +49 6122 937 171
Fax: +49 6122 937 175

Italy
Via Leone Tolstoi 86
20098 San Giuliano
Milanese
Milan
Tel: +39 02 98 2215
Fax: +39 02 98 2414

Japan
Haseman Building
2-11-6 Tomioka, Koto-ku
Tokyo 135-0047
Tel: +81 03 5245 3261
Fax: +81 03 5245 4472

Spain
Avda Mata Piñonera, 2
28700 San Sebastian de los Reyes
Madrid
Tel: +34 91 659 0740
Fax: +34 91 654 6794

U.S.A.
130A Baker Ave. Ext.
Concord, MA 01742-2121
Tel: +1 978 369 9933
Fax: +1 978 369 6616

E-mail:
superconductivity@oxinst.co.uk

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