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Hickey, M.C.; Damsgaard, Christian Danvad; Farrer, I; Holmes, S N; Husmann, A; Hansen, Jørn Otto Bindslev; Jacobsen, Claus Schelde; Ritchie, D A; Pepper, M

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Spin injection between epitaxial Co$_{2.4}$Mn$_{1.6}$Ga and an InGaAs quantum well

M. C. Hickey$^{a)}$
Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge, CB3 0HE, United Kingdom
and Toshiba Research Europe Limited, Cambridge Research Laboratory, 260 Cambridge Science Park, Cambridge, CB4 0WE, United Kingdom

C. D. Damsgaard
Department of Physics, Technical University of Denmark, DK-2800, Lyngby, Denmark

I. Farrer
Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge, CB3 0HE, United Kingdom

S. N. Holmes and A. Husmann
Toshiba Research Europe Limited, Cambridge Research Laboratory, 260 Cambridge Science Park, Cambridge, CB4 0WE, United Kingdom

J. B. Hansen and C. S. Jacobsen
Department of Physics, Technical University of Denmark, DK-2800, Lyngby, Denmark

D. A. Ritchie, R. F. Lee, and G. A. C. Jones
Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge, CB3 0HE, United Kingdom

M. Pepper
Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge, CB3 0HE, United Kingdom
and Toshiba Research Europe Limited, Cambridge Research Laboratory, 260 Cambridge Science Park, Cambridge, CB4 0WE, United Kingdom

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Electrical spin injection in a narrow [100] In$_{0.2}$Ga$_{0.8}$As quantum well in a GaAs $p$-$i$-$n$ optical device is reported. The quantum well is located 300 nm from an AlGaAs Schottky barrier and this system is used to compare the efficiencies and temperature dependences of spin injection from Fe and the Heusler alloy Co$_{2.4}$Mn$_{1.6}$Ga grown by molecular-beam epitaxy. At 5 K, the injected electron spin polarizations for Fe and Co$_{2.4}$Mn$_{1.6}$Ga injectors are 31% and 13%, respectively. Optical detection is carried out in the oblique Hanle geometry. A dynamic nuclear polarization effect below 10 K enhances the magnetic field seen by the injected spins in both devices. The Co$_{2.4}$Mn$_{1.6}$Ga thin films are found to have a transport spin polarization of $\sim$50% by point contact Andreev reflection conductivity measurements. © 2005 American Institute of Physics. [DOI: 10.1063/1.1949722]

The spin light-emitting diode (spin-LED) has become a self-contained experimental platform in which to explore spin dynamics and spin transport in semiconductors as well as the interplay between spin and charge degrees of freedom. The requirements for spin qubit-based quantum computing$^1$ in the solid state has motivated intense research to create the ideal materials system and device design for probing spin states and generating completely spin-polarized currents in semiconductors. The search for such ideal spin-injection devices based on semiconductors has divided into three research avenues: (1) use of a tunnel barrier oxide or semiconductor Schottky barrier with ferromagnetic metallic thin film as spin injectors, (2) the use of dilute magnetic semiconductors (DMS) as spin aligning contacts, and (3) the use of the theoretically predicted half-metallic ferromagnetic materials as 100% spin polarized contacts. Jiang et al.$^2$ have recently demonstrated injected spin polarization of 60% from an Fe/MgO contact at 100 K and spin polarizations of 80% have been recently seen in a DMS spin-LED-based on GaMnAs.$^3$ For half-metals, the conductivity mismatch between the metal and semiconductor may not be an issue for spin injection and high $T_C$ ferromagnetic metals offer the possibility of spin-injection devices operating at room temperature. The purpose of this work is to examine the feasibility of injecting spins from the half-metallic$^{4,5}$ ferromagnetic ternary alloy Co$_{2.4}$Mn$_{1.6}$Ga in the device architecture of an InGaAs quantum well (QW) spin-LED. III-V layers are grown by molecular-beam epitaxy (MBE) to form a $p$-$i$-$n$ doping structure with a surface $n$-AlGaAs barrier and a 5 nm wide InGaAs QW, 300 nm from the ferromagnetic metal-semiconductor (FM/SC) interface. The device consists of 15 nm $n$-Al$_{0.3}$Ga$_{0.7}$As ($3 \times 10^{18}$ cm$^{-3}$), 15 nm $n$-Al$_{0.3}$Ga$_{0.7}$As ($1 \times 10^{18}$ cm$^{-3}$), 100 nm $n$-GaAs ($1 \times 10^{18}$ cm$^{-3}$), 200 nm GaAs, 5 nm In$_{0.2}$Ga$_{0.8}$As, 500 nm GaAs, and 500 nm $p$-GaAs ($1 \times 10^{18}$ cm$^{-3}$). The AlGaAs Schottky barrier is designed to enable tunneling of spin-polarized carriers with a spin-dependent resistance at the FM/SC interface and satisfies the Rowell criteria for single-step tunneling.$^6$ The spin-LED wafer was arsenic capped and then transferred to a ternary metal MBE chamber where the arsenic layer was thermally desorbed. A 5 nm thick Co-Ga buffer layer is grown followed by a 10 nm Co$_{2.4}$Mn$_{1.6}$Ga film (at a growth rate of 0.75 Ås$^{-1}$) and then a 5 nm capping layer of Au. The Co-Ga buffer layer was grown as an inter-
rupt layer so as to retain the $\text{Co}_2\text{Mn}_1\text{Ga}$ spin-transport properties at the AlGaAs interface. The growth temperature of the $\text{Co}_2\text{Mn}_1\text{Ga}$ layer was 200 °C. Stoichiometric analysis by inductively coupled plasma optical emission spectrometry of the wafer indicates a composition of $\text{Co}_2\text{Mn}_1\text{Ga}$ rather than the ideal Heusler structure with a composition of $\text{Co}_2\text{Mn}_1\text{Ga}$. The Fe wafers were deposited by MBE onto an identical LED wafer in order to compare spin-injection effects from both metals. The device structure is depicted in Fig. 1.

Room-temperature emission from the InGaAs quantum well is observed at 1.30 eV. We use the emission arising from the QW electron ground state to heavy-hole valence band transition to determine the optical polarization efficiency ($P_{\text{EL}}$), as defined by

$$P_{\text{EL}} = \frac{I(\sigma^-) - I(\sigma^+)}{I(\sigma^-) + I(\sigma^+)},$$

(1)

where $I(\sigma^\pm)$ is the intensity of positive helicity luminescence and $I(\sigma^\mp)$ is the intensity of negative helicity luminescence. The oblique Hanle effect (OHE) geometry is used with the magnetic field applied at an angle of 30° to the plane of the device mesa as outlined by Motysny et al. 7 This geometry requires small magnetic fields ($B < 1$ T) to saturate the spin-polarized signal. A LED with an epitaxial Au contact shows 1.3 ± 0.1% at 300 K. The $\text{Co}_2\text{Mn}_1\text{Ga}$ spin-LED exhibits an optical polarization of 5.0 ± 0.5% and a fit to Bloch theory. From this fit, the effective spin lifetime was calculated. The data show a small MCD linear component (<0.2%).

The injected spin polarization from the Fe device at 8 K measured in the OHE geometry showing a hard-axis magnetic field dependence. The DNP offset is marked with an arrow. (d) The temperature dependence of the injected spin polarization in the $\text{Co}_2\text{Mn}_1\text{Ga}$ device.

The magnetic field dependence of the injected polarization in the $\text{Co}_2\text{Mn}_1\text{Ga}$ device [see Fig. 2(a)] shows a departure from Bloch theory at 3 A cm$^{-2}$. This data was taken with a slower magnetic field sweep rate (~0.002 T s$^{-1}$ compared with 0.01 T s$^{-1}$) and would indicate a coupling to phe-
nomena with long relaxation times such as the orientation of nuclear spins. The use of the OHE geometry provides sensitivity to the onset of dynamic nuclear spin polarization (DNP) as previously observed as a current density-dependent effect\textsuperscript{11} generating effective nuclear fields of up to 0.9 T. Injected spin-polarized electrons interact with the nuclear spins via hyperfine coupling and the dynamically polarized nuclear field enhances the applied field seen by the injected electron spins according to the relation \( B_{el} = B_p + C B_{d} \langle S \rangle \cdot B_{el} / B_{el} \)\textsuperscript{2} as suggested by previous work\textsuperscript{12}, where \( B_p \) is the applied field, \( \langle S \rangle \) is the time-averaged electron spin and \( C \) depends upon the overlap between the electron and nuclear wave functions. In our experimental geometry, the DNP-enhanced magnetic field is observed simply as an offset to the applied field in the polarization in both the Fe (which vanishes at 15 K) and \( \text{Co}_2\text{Mn}_1\text{Ga} \) (which vanishes at 10 K) devices at current densities of 2.4 A cm\(^{-2}\) (for Fe) and 3 A cm\(^{-2}\) for the \( \text{Co}_2\text{Mn}_1\text{Ga} \) spin-LED. The observed offsets are 0.14 and 0.2 T for the \( \text{Co}_2\text{Mn}_1\text{Ga} \) and Fe devices, respectively (see Figs. 2(a) and 2(c)). This suggests that the DNP effect is dependent upon the polarization of the injected spins. This voltage tunability of DNP has been demonstrated recently in an Fe/GaAs Schottky diode.\textsuperscript{13} Although we have demonstrated injection from Fe up to 300 K in this spin-LED structure, the injected polarization from the \( \text{Co}_2\text{Mn}_1\text{Ga} \) layer disappears at \( ~20 \) K on the same device substrate (see Fig. 2(d)). Temperature-dependent antisite defects\textsuperscript{14} as well as moderate tetrahedral lattice strain\textsuperscript{15} at interfaces have been known to heavily reduce the Fermi level spin polarization of Heusler alloys to \( \sim 55\% \).

Using point contact Andreev reflection (PCAR) conductance measurements\textsuperscript{16} at low temperature, we have measured independently the transport spin polarization of the \( \text{Co}_2\text{Mn}_1\text{Ga} \) wafer. In Fig. 3 we show the conductance (ratio to the normal conductance) as a function of applied bias in a Nb-\( \text{Co}_2\text{Mn}_1\text{Ga} \) point contact at 6 K. Numerical fits of this data to Blonder-Tinkham-Klapwijk (BTK) theory\textsuperscript{17} provide a spin polarization of 50±1\% and an interface impedance \( Z \) of 0.23. For a perfect ballistic contact \( Z=0 \), and for a tunneling contact \( Z \to \infty \). The reduced values of spin-polarization efficiency determined optically and electrically are in agreement with a half-metallic alloy possessing Co antisite defects and could be due to the imperfect thin-film stoichiometry. PCAR measurements\textsuperscript{18} on bulk samples of \( \text{Co}_2\text{MnGe} \) have shown significantly lower spin polarizations than 100\%.

In summary, we have compared spin injection from \( \text{Co}_2\text{Mn}_1\text{Ga} \) and Fe into a [100] InGaAs QW LED structure. We have measured the transport spin polarization of the \( \text{Co}_2\text{Mn}_1\text{Ga} \) injector and compared this measurement with the estimated injected spin polarization injected across 300 nm of GaAs into the QW. We have outlined discrepancies between measured transport spin polarization and spin-injection efficiency from the \( \text{Co}_2\text{Mn}_1\text{Ga} \) film, and we attribute its poor comparison with Fe to interfacial disorder. While the aforementioned effects are observed in our films, a comparison with a perfectly stoichiometric Heusler thin film is desirable. Recent work\textsuperscript{19} has demonstrated that the Heusler alloy \( \text{Co}_2\text{MnGe} \) shows an injected spin polarization of 27\% with a GaAs/AlGaAs QW detector. We found that optical detection in the OHE geometry is sensitive to magnetic anisotropy, dynamic nuclear spin polarization, and the effective spin lifetime. The spin-LED device demonstrates the possibility of using dynamic nuclear polarization to manipulate nuclear spins in semiconductor spintronic devices with an optical readout mechanism.

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\textsuperscript{1}Semiconductor Spintronics and Quantum Computation, edited by D. Awschalom, D. Loss, and N. Samarth (Springer, Berlin, 2002).


