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Optical communication of spin information between light emitting diodes

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For the full implementation of spintronic circuits, it is necessary to transmit spin information from one device to another. Electrons in semiconductors often suffer from high spin relaxation rates, making electrical transport of spin information highly inefficient. Here, we propose optical transport of spin information as an alternative. We demonstrate that the spin information associated with electrons injected from Co_2FeSi and Fe layers into the quantum wells of spin light emitting diodes (spin-LEDs) can be transported optically in the form of circularly polarized light and deciphered electrically via the magnetic field dependence of the photocurrent in a distant detector spin-LED. [doi:10.1063/1.3582917]

In 1999, the concept of a spin light emitting diode (spin-LED) was introduced, demonstrating the ability to determine the degree of spin injection from a magnetic injector layer into the underlying semiconductor LED structure by measuring the degree of circular polarization of the emitted light.[1,2] Although light has often been utilized to measure spintronic properties, it has not been used to transmit spin information between spintronic devices. Such usage would be desirable, given that light can maintain its circular polarization (and hence spin information) over macroscopic distances, eliminates waste heat associated with moving charges, and travels at high speed.

Significant advances have been made over the past decade toward efficient spin injection in spin-LEDs.[3–9] According to the selection rules of the LED quantum well, injection of 100% polarized spins (e.g., only spin-up) would lead to 100% circularly polarized emission (e.g., only right-handed helicity). The Heusler alloy Co_2FeSi is an excellent candidate as an injector layer due to its predicted half-metallicity, meaning that the carriers at the Fermi level are expected to be 100% spin-polarized. Furthermore, Co_2FeSi exhibits a high Curie temperature of ~1100 K and close lattice matching of ~0.08% to GaAs. Investigations of Co_2FeSi/(Al, Ga)As spin-LEDs have shown spin injection efficiencies greater than 50%.[10]

Recently, it has been shown that spin-LEDs can detect the circular polarization of incoming laser light due to a spin-filtering effect at the ferromagnet/semiconductor interface.[11] Namely, the photoexcited spins at this interface experience a contact resistance that depends on their orientation relative to the ferromagnet.[12,13] Here, we combine the spin injection and detection capabilities in spin-LEDs to optically transfer spin information over macroscopic distances from one spin-LED device to another.

The spin-LEDs investigated here contain either Co_2FeSi or Fe injector layers and consist of epitaxially grown intrinsic GaAs/$Al_{0.1}Ga_{0.9}As$ or $In_{0.2}Ga_{0.8}As$/GaAs quantum wells sandwiched between *n*-type and *p*-type barrier layers (*n*-type on top). The LED growth recipe for the case of the GaAs/$Al_{0.1}Ga_{0.9}As$ structure is described in Ref. 14 and can be adapted to the $In_{0.2}Ga_{0.8}As$/GaAs structure by using a quantum well thickness of 5 nm instead of 10 nm. These layers were all grown at 580 °C, except for the $In_{0.2}Ga_{0.8}As$ layer, which was grown at 525 °C. For the Co_2FeSi injector layers, the LED structures were transferred under ultrahigh vacuum to the metal growth chamber, where a 9 nm thick Co_2FeSi layer was grown at a substrate temperature of 280 °C. Details of the Co_2FeSi growth can be found elsewhere.[15–17] For the Fe injector layer, the GaAs/$Al_{0.1}Ga_{0.9}As$ LED structure was capped with an additional 3 nm of GaAs to avoid Al_2O_3 formation and transferred in air to a radio-frequency sputtering chamber for the deposition of a 3 nm thick ZnO layer at a substrate temperature of 200 °C as a tunnel barrier, followed by electron beam evaporation of a 10 nm thick Fe injector layer with no substrate heating. After electron beam evaporation of Ti/Au ring-shaped contacts, the spin-LEDs were lithographically processed into circular mesas with a diameter of 450 μm.

We begin by comparing the electroluminescence (EL) from GaAs/$Al_{0.1}Ga_{0.9}As$ quantum wells in spin-LEDs with Co_2FeSi and Fe injector layers, shown schematically in Fig. 1(a). These measurements were carried out at 20 K in an

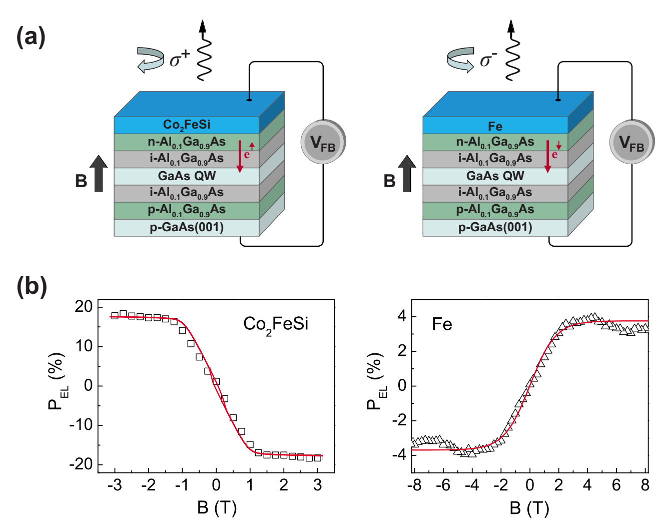

FIG. 1. (Color online) (a) Schematic diagrams of the spin-LEDs with a Co_2FeSi and Fe injector layer, indicating that injection of opposite spins into the quantum wells leads to the emission of circularly polarized light with opposite helicities and (b) the magnetic field dependencies of the EL polarization degrees (P_{EL}) for spin-LEDs with a Co_2FeSi and Fe injector layer, exhibiting opposite sign. The solid lines represent magnetization measurements displayed on an arbitrary scale.

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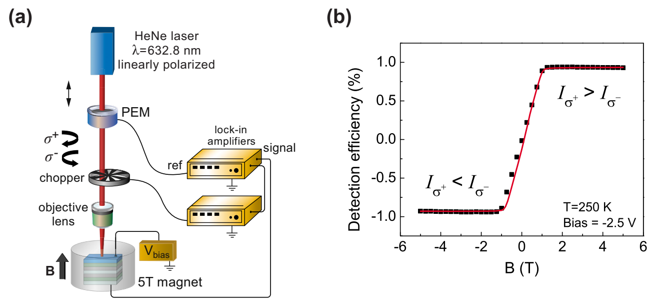

FIG. 2. (Color online) (a) Schematic diagram of the measurement configuration for photoexcited spin detection and (b) the magnetic field dependence of the resulting detection efficiency in a Co_2FeSi-covered spin-LED. The solid line represents the magnetization measurement displayed on an arbitrary scale.

optically accessible magnet cryostat in the Faraday geometry using gated photon counting in conjunction with a photoelastic modulator. The samples were placed under a forward bias in the range of 2–4 V, resulting in currents on the order of mA. The degree of circular polarization of the emitted light is defined as $(I_+ - I_-)/(I_+ + I_-)$, where I_+ (I_-) represents the intensity of right (left) circularly polarized light. The measured magnetic field dependencies of the circular polarization degrees for the two spin-LEDs, as shown in Fig. 1(b), exhibit opposite sign, indicating that spins of opposite sign are predominantly injected into the LED quantum wells. This behavior is presumably due to an opposite spin polarization in the Co_2FeSi and Fe injector layers. The solid lines in Fig. 1(b) indicate magnetometry measurements performed using a superconducting quantum interference device, appropriately reversed in sign for the case of the Co_2FeSi injector layer, to show the tracking of EL polarization with magnetization. These spin-LEDs will be used as emitters of spin information, and the final test in this work will be whether or not a distant spin-LED can detect their opposite spin polarizations, hence remotely deciphering the spin information.

Next, we investigate the electrical detection of photoexcited spins in the spin-LED with the Co_2FeSi injector layer and $GaAs/Al_{0.1}Ga_{0.9}As$ quantum well excited by a laser source with controlled circular polarization. The schematic diagram in Fig. 2(a) illustrates the measurement configuration for photoexcited spin detection. Incoming circularly polarized light from a laser source excites spin-polarized electrons in the spin-LED, where predominantly spin-up and spin-down electrons are generated by periodically modulated right- and left-circularly polarized light, respectively. The photoexcited electrons in turn drift toward the $Al_{0.1}Ga_{0.9}As/Co_2FeSi$ interface due to the potential inside the reverse-biased *p-n* junction. At this interface, a spin-filtering process takes place, where spins parallel (antiparallel) to the Co_2FeSi magnetization experience a lower (higher) potential barrier. Therefore, the detection efficiency, which is obtained from the difference between the photocurrents generated by right- and left-circularly polarized light normalized by the total photocurrent (~10 μA), exhibits a magnetic field dependence similar to the magnetization of the Co_2FeSi layer, as shown in Fig. 2(b). Additional experiments have shown that artifacts such as magnetic circular dichroism contribute only negligibly to the detection efficiency.[18]

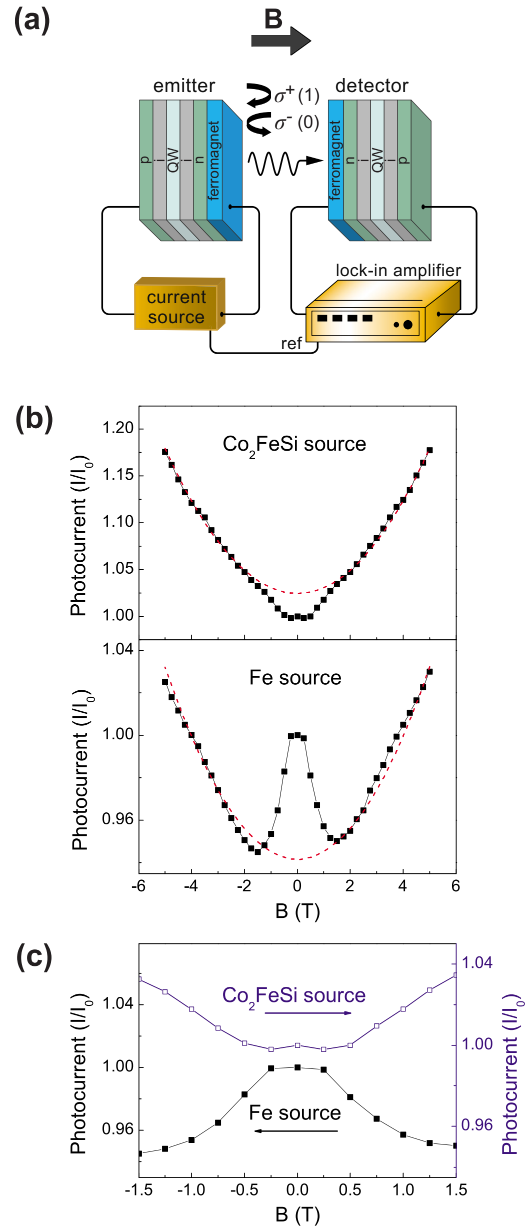

FIG. 3. (Color online) (a) Schematic diagram of the optical communication experiment and (b) the magnetic field dependence of the photocurrent (normalized to the zero-field value) in a Co_2FeSi-covered detector spin-LED upon irradiation by emitter spin-LEDs with a (top panel) Co_2FeSi and (bottom panel) Fe injector layer. The dashed lines indicate a parabolic background behavior; (c) a comparison of the data shown in (b) at low magnetic fields. The solid lines are guides to the eye.

Up to this point, we have demonstrated two key features: (i) circularly polarized light with opposite helicity, which thus carries opposite spin information, can be generated from spin-LEDs with Co_2FeSi and Fe injector layers, and (ii) opposite helicities of circularly polarized light from a laser source generate photocurrents in the Co_2FeSi-covered spin-LED whose relative magnitudes depend on the magnetization of the Co_2FeSi layer. We are now in a position to demonstrate optical transfer of spin information from one spin-LED to another.

A schematic diagram depicting the optical communication experiment is shown in Fig. 3(a). The emitter and detector spin-LEDs are placed face-to-face in the magnet cryostat, separated by a few millimeters, at a temperature of 20 K. The emitter spin-LED is placed under a forward bias at a dc current of 10 mA and a low-frequency modulation of 3 mA. This modulation provides the reference signal for a lock-in amplifier that measures the photocurrent in the detector spin-LED, which is on the order of nA. We now construct a hypothesis for the expected magnetic field dependence of the photocurrent in the detector spin-LED, which contains a Co_2FeSi injector layer and an $In_{0.2}Ga_{0.8}As/GaAs$ quantum well to enhance the absorption of photons from the emitter spin-LEDs, which contain a Co_2FeSi or Fe injector layer and a $GaAs/Al_{0.1}Ga_{0.9}As$ quantum well. For the case of using an emitter spin-LED with a Co_2FeSi (Fe) injector layer, increasing the magnetic field from zero will lead to an increasing alignment (antialignment) of the spin polarizations in the emitter and detector injector layers relative to each other and hence to an increasing (decreasing) photocurrent in the detector, up to the fields where the magnetizations in the injector layers saturate, namely between 1 and 2 T.

The measured field dependence of the photocurrent in the detector spin-LED is shown in Fig. 3(b) for the cases of using an emitter spin-LED with a Co_2FeSi and Fe injector layer. A comparison of these results at low magnetic fields, shown in Fig. 3(c), clearly demonstrates the predicted behavior of an increased (decreased) photocurrent up to a saturation field of $\sim$1.5 T detected for the aligned (antialigned) spin polarization in the emitter injector layer relative to that of the detector spin-LED. Therefore, the detector spin-LED can be used to "read out" the opposite spin polarizations injected in the emitter spin-LEDs, demonstrating the optical transfer of spin information from one spin-LED to another. The changes in photocurrent by several percent at the saturation fields are greater than expected from direct multiplication of typical spin injection and detection efficiencies as described in Figs. 1 and 2, resulting in less than 1%, potentially due to more favorable optical excitation wavelength and intensity conditions in the communication experiment. A parabolic background behavior can be seen in Fig. 3(b), which originates from the parabolic magnetic field dependence of Zeeman splitting induced spin-alignment in the bare emitter LED structure (no injector layer).[19]

To summarize, we have demonstrated optical transfer of spin information from a spin-LED emitter to a distant spin-LED detector. Based on the magnetic field dependence of the photocurrent in the detector spin-LED, one can distinguish between opposite spin polarizations injected in the emitter spin-LED. If the injector layers of the spin-LEDs display magnetic remanence, the field dependence of the photocurrent may replicate that of conventional spin-valve devices, hence allowing for the possibility for remote sensing applications using optical spin-valves. We believe this work enables further research toward using light as a functional component in future designs of spin-optoelectronic circuits.

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