SPIN HALL EFFECT OF LIGHT IN A SEMICONDUCTOR

BY JEAN-MICHEL MÉNARD, ADAM E. MATTACCHIONE, MARKUS BETZ AND HENRY M. VAN DRIEL

Jean-Michel Ménard <jmenard@physics.utoronto.ca>, Adam E. Mattacchione, Markus Betz, and Henry M. van Driel, Department of Physics and Institute for Optical Sciences, University of Toronto, Toronto, ON, M5S 1A7

Jean-Michel Ménard received 2nd prize in the 2009 CAP Best Student Oral Presentation Competition

Snell's law and the Fresnel equations are well known expressions that describe the reflection and transmission of plane-wave light at an optical interface. However, any realistic light beam is spatially limited and is therefore composed of a sum of plane-waves propagating in slightly different directions. Thus when a beam is incident on a sample, the resulting spread of incident angles at the optical interface is responsible for surprising optical phenomena including the Goos-Hänchen effect, an angular deviation in the law of specular reflection and, the subject of this article, the spin Hall effect of light (SHEL). Predicted by Fedorov[1] and first observed by Imbert[2], the SHEL is a transverse displacement of the circular components (or spin components) of a non-normally incident beam at an optical interface. This effect is the optical analogue of the electrical spin Hall effect that gives rise to the separation of carriers of opposite spin flowing through a semiconductor. Recently, theoretical work[3-5] and preliminary experimental demonstrations[5-6] of the SHEL have described polarization changes experienced by a light beam at an interface as a function of the incident angle of the light and for a variety of beam geometries and/or material structures. Yet, every experimental technique proposed up to now to observe the SHEL only considered interfaces between transparent media and always observed the shift of the circular components in the far field. The experimental technique we present[7] utilizes an ultrafast pump-probe configuration and takes advantage of absorption in a semiconductor to observe the SHEL *in situ*. A linearly polarized femtosecond pump pulse tightly focused onto an optically thin GaAs specimen is shown to generate electron spin ensembles of spin up (↑) and spin down (↓) orientation laterally shifted in opposite direction from the center of the incident beam. This SHEL induced separation is directly revealed by scanning a time-delayed probe beam across the excitation region in the semiconductor. For a p-polarized pump beam at an angle of incidence of 55°, we observe a separation up to 200nm between the circular components of the pump beam at the interface due to the SHEL.

A schematic rendition of the pump and probe beam configuration is shown in Figure 1. The 820 nm (1.50 eV) 100 fs pulses are obtained from a mode-locked Ti:sapphire laser of 76 MHz repetition rate. A spatial filter is used to ensure good quality of the beam profile. The pulses are split so that pump pulses of 3.5 mW average power are focused onto the sample using an aspheric lens with a numerical aperture of NA = 0.16. Linearly polarized probe pulses with << 1 mW average power are focused with an aspheric lens (numerical aperture NA = 0.25) at normal incidence on the sample and a piezo transducer allows for transverse scanning of the probe focus across the excitation spot. The sample is an 800 nm thick [100]-oriented GaAs layer (band gap energy = 1.42 eV at 295 K) mounted on a glass substrate. The probe light transmitted through the GaAs is collimated with a large aperture lens (NA = 0.3) and passed through a quarter wave plate. A Wollaston prism in combination with two photodiodes serves as a polarization bridge to extract the transmitted intensity $T_{\pm}$ of the circular components (σ^{+} and σ^{-}) of the probe beam as well as their change in transmission $\Delta T_{\pm}$ induced by the pump.

To obtain a relatively large SHEL shift, the pump pulses are p-polarized and impinge on the sample at an angle of incidence of θ_i = 55°, which is the largest deflection allowed by our experimental configuration. A close up of the beam geometry at the sample interface is shown in Figure 2. For optical excitation of zincblende semiconductors, such as GaAs, with photon energy just above the band gap, a right circularly polarized beam generates a density of ↓ electrons which is three times the density of ↑ electrons, and vice-versa for left circularly polarized light. This ratio corresponds to a degree of optical spin injection of 50% determined by the selection rules governing optical transitions from heavy or light hole states to conduction band states. As a result, the spatially shifted circular components of the pump beam generate slightly separated opposite spin populations creating an imprint of the SHEL acting on the light directly at the interface. To image this inhomogeneous spin distribution, a probe beam is tightly focused on the sample

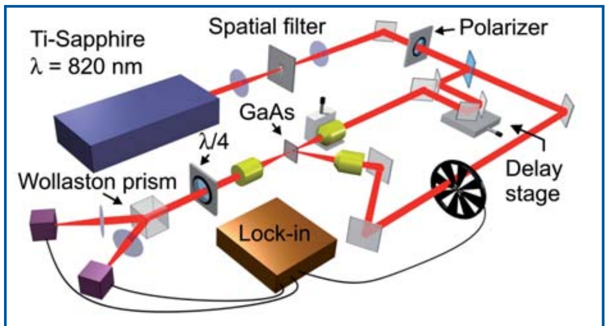

Fig. 1. Experimental geometry used in observing the SHEL via absorption in GaAs.

SUMMARY

We use an ultrafast technique to observe the spin Hall effect of light in situ at an air-semiconductor interface by taking advantage of spin injection in the material.

and scanned across the excitation region. The increase in the overall probe transmission is linearly proportional to the density of carriers in the semiconductor because of state filling: the fermionic carriers fill up available states in the semiconductor bands and therefore prevent some of the probe light from being absorbed and consequently promoting additional carriers at these specific spin and energy states. The preferential interaction between a circular polarization and its respective electron spin population results in a difference in transmission between the σ^+ and σ^- of the probe components, known as a circular dichroism. Using a linearly polarized probe beam and some polarization optics, the circular dichroism can be spatially resolved to quantitatively measure the SHEL. Finally, the probe pulse is delayed by 2 ps from the pump pulse to avoid nonlinear interactions. This time delay is also long enough to allow for carrier thermalization and relaxation of the spin of the holes but short compared to the carrier recombination and spin relaxation time of the electrons.

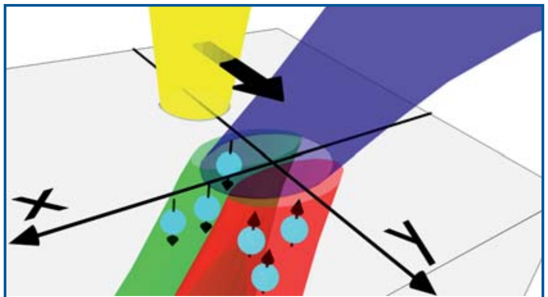

Fig. 2 Close up of the experimental geometry at the sample interface where the circular components of the non-normally incident pump beam (blue) in the x-z plane experience a transverse displacement in the y-direction.

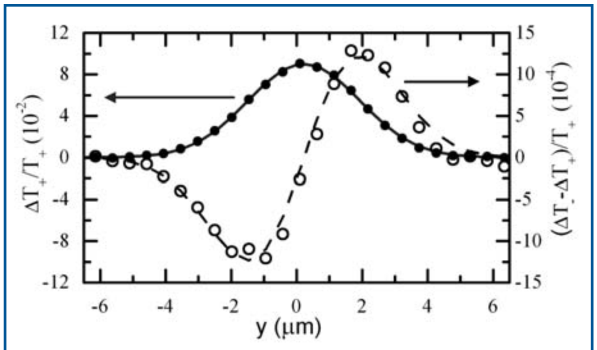

Fig. 3 Measured normalized change in transmission (solid dots) of the σ^+ polarized component of the probe beam as it is scanned along the y-direction across the excitation region. Also shown (open dots) is the differential transmission for the circularly polarized components. The curves are fits based on a Gaussian function (solid), and the difference between two spatially displaced Gaussian functions (dashed).

Figure 3 shows a typical pump induced change in the transmission of the probe beam as it is scanned along the excitation region in the direction of the separation between the spin populations. The data obtained by measuring the transmission change induced in one of the probe circular component ($\Delta T_+/T_+$) is well represented by a Gaussian function with a width (FWHM) of 4.2 ± 0.5 μm, consistent with the spatial convolution of the focused pump and probe spot sizes. Since the SHEL shift is more than an order of magnitude smaller than the spot size of our beams, this measurement alone does not directly reveal the separation between the spin populations. However by subtracting the transmission change measured for both probe components ($[\Delta T_- - \Delta T_+] / T_+$), we obtain a pronounced dispersive-like curve with a zero crossing at y = 0. These results are indicative of ↑ electrons being preferentially generated for y < 0, while ↓ electrons are centered at y > 0. The spatial displacement d between the centers of these opposite spin populations is obtained in two steps. First we fit the difference between two spatially separated Gaussian signals corresponding in amplitude and waist to the signal $\Delta T_+/T_+$, with the separation as the only fitting parameter until it fits the differential curve in Fig. 3. Then, this separation is scaled by the probe efficiency to distinguish from pump induced ↑ and ↓ electron populations which directly relies on the degree of optical spin injection. The conversion factor experimentally measured using a circularly polarized pump beam corresponds to 0.18, lower than the theoretical maximum of 0.25 (50% x 50%), likely due to spin relaxation and many body effects. Our experimental result therefore indicates an actual SHEL-induced separation of d = 205±30 nm in agreement with the theoretical prediction (175 nm) corresponding to our experimental parameters.

In summary, using a pump-probe technique we have demonstrated an *in situ* method of quantitatively analyzing the SHEL directly at the interface between a transparent medium and a semiconductor via the transfer of spin angular momentum from the light beam to the electrons. This opens up the possibility of observing SHEL effects in a wide class of materials.

We gratefully acknowledge J.E. Sipe and A.L. Smirl for useful discussions and NSERC for financial support.

REFERENCE

1. F.I. Fedorov, "K Teorii Polnogo Otrazheniya", Dokl. Akad. Nauk SSSR **105**, 465 (1955).
2. C. Imbert, "Calculation and Experimental Proof of the Transverse Shift Induced by Total Internal Reflection of a Circularly Polarized Light Beam," *Phys. Rev. D* **5**, 787 (1972).
3. K.Y. Bliokh and Y.P. Bliokh, "Conservation of angular momentum, transverse shift, and spin Hall effect in reflection and refraction of an electromagnetic wave packet," *Phys. Rev. Lett.* **96**, 073903 (2006).
4. A. Aiello and J.P Woerdman, "Role of beam propagation in Goos–Hänchen and Imbert–Fedorov shifts," *Opt. Lett*. **33**, 1437 (2008).
5. O. Hosten and P. Kwiat, "Observation of the Spin Hall Effect of Light via Weak Measurements," *Science* **319**, 787 (2008).
6. F. Pillon, G. Herve, and S. Girard, "Experimental Observation of the Imbert-Fedorov Transverse Displacement after a Single Total Reflection," *Appl. Optics* **43**, 1863 (2004).
7. J.-M. Menard, A.E. Mattacchione, M. Betz, and H.M. van Driel, "Imaging the Spin Hall Effect of Light Inside Semiconductors via Absorption", *Optics Letters* **34**, 2312 (2009).