THE SPIN-DRIVEN ELECTRICAL CURRENTS

BY C.-M. HU AND W.-K. GE

The current which we use every day is mostly produced by electrical generators, which are based on the principle of the Faraday's dynamo [1] demonstrated by Michael Faraday in 1831. The Faraday's dynamo, in which a steady current was produced by a copper disk revolving in the magnetic field as sketched in Fig. 1a, revealed beautifully the effect of magneto-electric induction, which was pivotal in the establishment of the field theory of electromagnetism. It tells us that electrical and magnetic phenomena are macroscopically connected. From the microscopic point of view, the Faraday's dynamo is based solely on the charge property of the electrons. The magnetic field imposes the Lorentz force on the charges, which deflects the electrons and converts energy from mechanical motion to a current of electricity. Trends toward device miniaturization have led to the transformation of the macroscopic electromagnetism phenomena into the microscopic spintronics topics. By utilizing the interplay between spins and charges, a single device component may perform multi tasks impossible otherwise. One of the new trends in the field of spintronics is to generate electric currents via spin effects. The *spin rectification* and the *spin photo-galvanic effect,* which we review in this article, are two specific mechanisms that have been deployed for this purpose recently. They expand our view of how to produce an electrical current and may open new avenues for tailoring the magnetoelectric response.

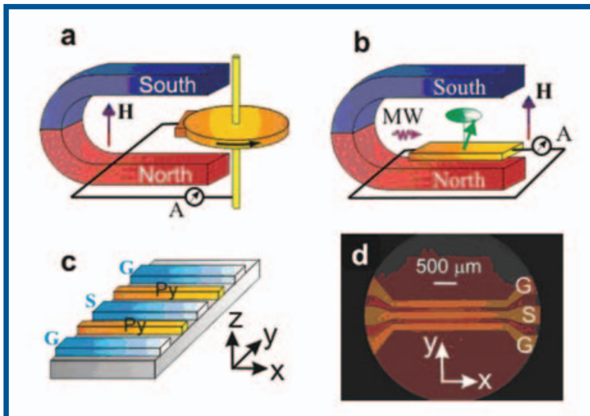

Fig. 1 **Faraday's dynamo & the spin dynamo** (adapted from Ref. 2). **a)** Faraday's dynamo, with a copper disk revolving in a d.c. magnetic field, converts energy from rotation to a current of electricity; **b)** Spin dynamo, with a ferromagnetic strip in a d.c. magnetic field, converts energy from spin precession to a bipolar current of electricity; **c)** Diagram of the spin dynamo structure with Py strips placed in slots between the ground (G) and signal (S) lines of a coplanar waveguide, which are deposited on top of a GaAs substrate; **d)** Top view micrograph of a coplanar waveguide with two inserted Py strips.

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THE SPIN RECTIFICATION EFFECT

In fact, even in the Faraday's dynamo, the magnetic field also acts on the spins of the electrons by placing a torque on the magnetic moment. This gives rise to the Larmor precession. Larmor precession is of broad interest and has been studied in a variety of materials. In metals, it gives rise to the electron spin resonance (ESR) via which physicists measure the electron g-factor. In magnetic materials, it causes the ferromagnetic resonance (FMR) and spin waves (SW) which determinate the recording speed of magnetic storage devices. Doctors use Larmor procession of nuclei spins to get the magnetic resonance image (MRI) of patients. In the quantum mechanic picture, Larmor procession corresponds to the magnetic dipole transitions between spin split energy levels. Applying a magnetic field of about 1 Tesla, the splitting energy of a free electron spin is typically at the order of µeV. The Larmor precession can therefore be driven by electromagnetic waves at radio frequency (RF) or microwaves.

SUMMARY

Currents are used to be generated via the charge property of the electrons, but the electrons can also be shuttled around by their spin. In the field of spintronics, the search is on for driving electrical currents via spin effects in a variety of materials.

Larmor precession of spins was used to be believed as independent from the charge degree of the electrons and hence played little role in today's electronics. Now a team at the University of Manitoba, Canada, Gui *et al*. has found that Larmor precession can produce d.c. electrical current [2]. Their experiment was performed on a spin dynamo (Fig. 1b) based on a permalloy (Py) microstripe with the dimension of 2.45 mm × 20 µm × 137 nm. The Py microstripe was placed between the ground and signal stripe lines of a coplanar waveguide (Fig. 1c and d), via which the microwaves were fed to the Py sample. By sweeping the magnetic field at a fixed microwave frequency, a d.c. current was measured when the resonant condition for FMR was satisfied. The team found an intriguing

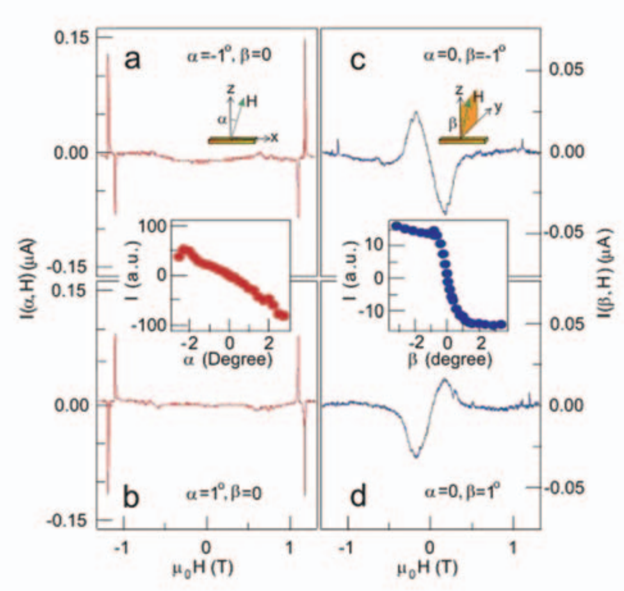

Fig. 2 **Bipolar symmetry** (adapted from Ref. 2). Bipolar d.c. currents measured as a function of the magnetic field H applied with angles a) $\alpha = -1°$, $\beta = 0$, b) $\alpha = 1°$, $\beta = 0$, c) $\alpha = 0$, $\beta = -1°$, and d) $\alpha = 0$, $\beta = 1°$. The microwave frequency is fixed at 5.4 GHz. Insets summarize the angular dependence of the maximum current.

bipolar behaviour, i.e., the direction of the current flow depends on the applied field configuration (Fig 2). The observed bipolar symmetry sheds light on the underlying mechanism of the spin rectification effect.

The spin rectification effect [2] can be understood by using the well-known example of the optical rectification, which occurs in nonlinear media with large second order susceptibility. Here the optical response to the product of time-dependent electric fields $e_0 \cos(\omega t)$ is governed by the trigonometric relation: $\cos(\omega_1 t)\cdot\cos(\omega_2 t) = \{\cos[(\omega_1-\omega_2)t] + \cos[(\omega_1+\omega_2)t]\}/2$. If the frequencies $\omega_1 = \omega_2$, the terms with difference and sum frequencies causes optical rectification and second harmonic generation, respectively. Similar nonlinear dynamic response to the product of RF electric and magnetic fields is the origin of the spin rectification effect. The effect is strongest when the spin precession is at resonance with the RF magnetic field. Microscopically, the spin rectification effect has the similar origin as the anisotropic magnetoresistance and extraordinary Hall effect, which couple static electrical and magnetic response of the magnetic materials.

With the demonstration of current driven by Larmor precession, a new aspect is expected to emerge in the spintronics: rectifying RF magnetic field via spin dynamics. This could yield entirely new device paradigms, such as sensors for telecommunication or antenna for medical applications utilizing MRI.

An even more remarkable characteristic expected for the spin rectification effect is electrical detection of spin excitations [3] in nano-structured magnets. Understanding spin excitations in nanomagnets are not only pivotal for describing nanomagnetism, but also essential for designing high-speed recording devices with high-density. Conventional techniques such as FMR absorption and Brillion light scattering are facing their sensitivity limits when the sample size keeps shrinking. Using the electrical detection techniques based on the spin rectification effect, the Manitoba group has established a comprehensive picture for spin excitations in Py microstripe [3], which include magnetostatic modes, standing spin waves, and a special dipole-exchange mode, all quantized due to the finite size effect. They determined precisely the boundary condition for the quantized spin excitations, which has been a long controversial topic.

Electrical currents/voltages generated from spin excitations have also been recently demonstrated on magnetic multilayers [4,5], and studied using magnetic bilayers [6]. The fast pace of the research efforts in this direction promises an exciting time ahead for bringing photonic, spintronics, and electronics together.

THE SPIN PHOTO-GALVANIC EFFECT

Photogalvanic effects (PGE) are due neither to inhomogeneity of optical excitation of electron-hole pairs, as in the Dember effect, nor to inhomogeneity of the sample, as in the conventional photovoltaic effect in *p-n* junctions. The fundamental physical reason for the PGE studied here is essentially due to spin-orbit coupling of semiconductors with either (or both) bulk inversion asymmetry (BIA) and structure inversion asymmetry (SIA), it is therefore commonly referred as spin photogalvanic effect (SGE) [7,8].

A system with BIA has the Dresselhaus spin-orbit interaction, and that with SIA has the Rashba spin-orbit interaction. The linear terms in the Hamiltonian of the Dresselhaus model leads to a modification of the dispersion curves of the electron systems in the structure. In the following, we will concentrate on a Rashba system which has a linear term in the Hamiltonian as $H_{SO} = \alpha\vec{\sigma}\cdot(\vec{z}\times\vec{k}_{//}) = \alpha\vec{k}_{//}\cdot(\vec{\sigma}\times\vec{z})$, where α is the Rashba coefficient, σ the Pauli matrix, z the unit vector along the [001] direction, and $k_{//}$ the in-plane momentum. The dispersion curve of such a system is shown in Figure 3 where the first electron level (e1) and the heavy hole level (hh1) are shown. Also shown in the figure are the optical transitions obeying energy, momentum as well as angular momentum (spin) conservation. A σ_+ light excitation brings +1 angular momentum into the semiconductor system, thereby leading to a transition from the -3/2 hole state to the -1/2 electron state only. Due to the linear term in the Hamiltonian, the dispersion curve is spin split, separating the two curves corresponding to spin 1/2 and -1/2 for electrons and 3/2 and -3/2 for holes. The separation is simply proportional to the Rashba coefficient, α. As α is different for electrons and holes, the two allowed absorption transitions shown in the figure will result in electrons with unbalanced momentum, and thus a current.

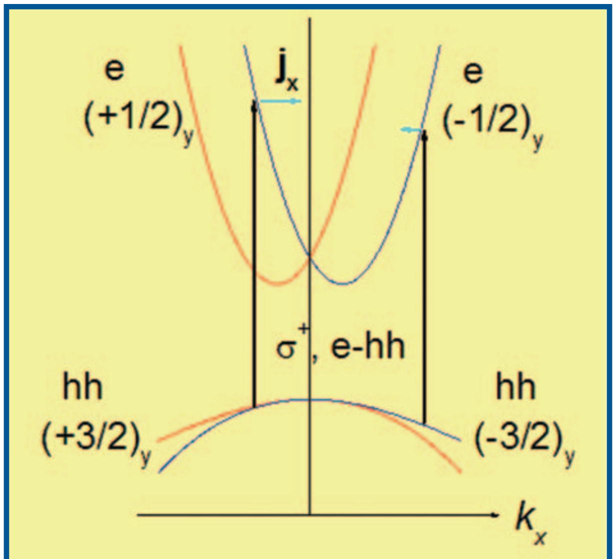

Fig. 3 **Circularly polarized light excitation** in a Rashba system.

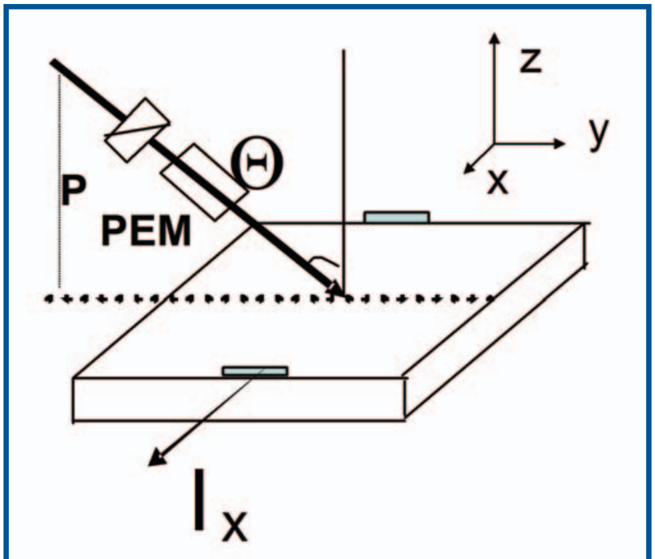

Fig. 4 **Set-up of the CPGE experiment.**

Note that the excitation in the above figure is using a circularly polarized light, so that the effect is named as Circular Photo-Galvanic Effect (CPGE), firstly demonstrated by Ganichev *et al.* [7] using inter-subband excitations. The most effective inter-band excitation induced CPGE was reported by the Hong Kong University of Science and Technology (HKUST) group, *Yang et al.* [8], which is two orders stronger than the similar observation using far-infrared excitation for inter-subband transitions. Based on the Hamiltonian, one can interpret the Rashba coupling as if the momentum (carried by a current) induces an effective magnetic field, or the spin induces an effective momentum. In order to induce a current, in-plane spin polarization is necessary.

In the experiment of *Yang et al.* [8], two samples (named as D and E) studied were $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ 2DEGs grown on semi-insulating (001) InP substrate by molecular beam epitaxy, with the well thickness of 14 nm. The SIA was achieved by δ–doping of only one side of the barrier layer (on top of the well). To enhance the SIA, sample E was grown with a graded indium composition from 0.53 to 0.75 for the quantum well, instead of the uniform indium composition of 0.70 for sample D. The carrier concentration was 1.5 x 10^{12} cm^{-2} and 1.4 x 10^{12} cm^{-2}, and the mobility was 1.1 x 10^5 $cm^2V^{-1}S^{-1}$ and 0.9 x 10^5 $cm^2V^{-1}S^{-1}$ for sample D and E, respectively. The Rashba coefficient for the two samples were measured by beatings of the Shubnikov–de Haas (SdH) oscillations at low fields, and calculated by $\alpha = \frac{\Delta n \hbar^2}{m^*}\sqrt{\frac{\pi}{2(n-\Delta n)}}$ where $\Delta n = |n_\uparrow - n_\downarrow|$ is the carrier concentration difference between the two spin bands, $n = n_\uparrow + n_\downarrow$ is the total carrier concentration, and $m^* = 0.039\ m_0$ is used as the electron effective mass. The calculated value of α is 3.0 x 10^{-12} eVm and 6.3 x 10^{-12} eVm for samples D and E, respectively, indicating that the stronger the inversion asymmetry, the larger the spin-orbital interaction in a system.

The experimental setup for the inter-band transition induced CPGE is schematically shown in Figure 4. Obliquely incident linearly polarized laser beam was transmitted through a photo-elastic modulator (PEM) which yields a periodically oscillating polarization between σ^- and σ^+. The electrodes are made at the $[1\bar{1}0]$ and $[\bar{1}10]$ sample edges to lead the current along the laboratory x-direction. The photocurrent I_x was measured in the unbiased structures at various temperatures via a low-noise current amplifier and a lock-in amplifier. The PEM gives the difference between σ^- and σ^+ polarization but does not present a background current even at normal incidence, the latter is most possibly due to the Damber effect when inter-band excitation was employed. The incident light beam is polarized in the *z-y* plane, with an angle of Θ away from the normal. This oblique incidence is to ensure that the induced electron spin polarization would have a component along the laboratory *y*-direction ([110] orientation of the crystal). By changing angle ϕ between the polarization plane of the incident light and the optical axis of the PEM, one can measure the helicity dependence of the photocurrent, which is the fingerprint of spin photocurrent in distinguishing itself from other photocurrent effects.

Figure 5 (a) and (b) show the dependence of the photocurrent of the two samples on the laser beam polarization represented by angle ϕ, with λ = 880 nm and Θ = 30°. It clearly depicts that when ϕ changes from $-\pi/4$ to $\pi/4$ the current varies from one maximum to the other maximum of opposite directions, in good agreement with the fitting using $\sin 2\phi$ (see the discussion below).

If the incidence is in the (*y*,*z*) plane of quantum well structures grown along the principal axis [001], which has a symmetry

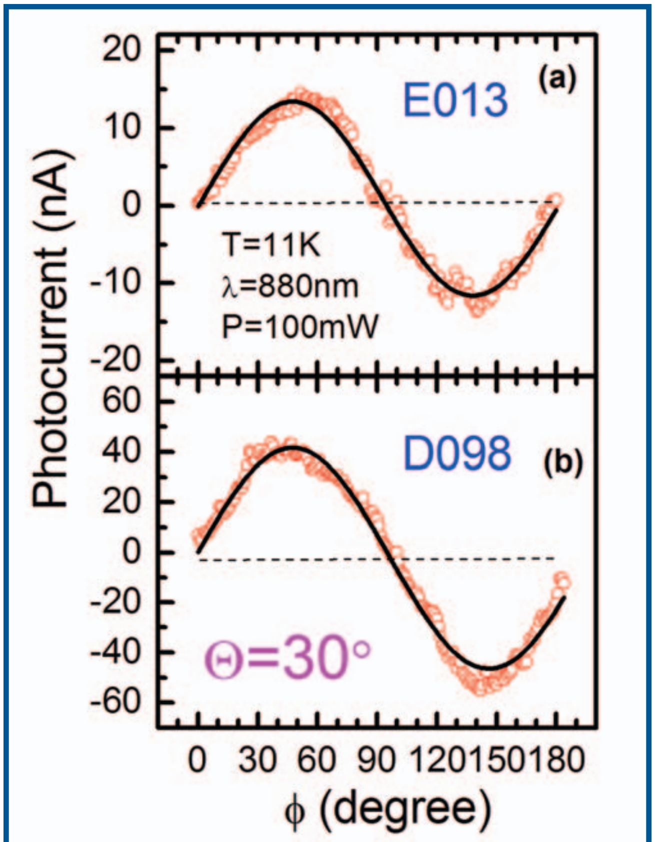

Fig. 5 Helicity dependence of the CPGE current.

C_{2v}, the photocurrent is induced along x direction and can be phenomenologically estimated to be $j_x = \gamma_{xy} t_p t_s \sin\theta E_0^2 P_{circ}$ where γ_{xy} is the pseudotensor component associated with the Rashba coupling coefficient, t_p and t_s are the transmission coefficients following Fresnel's formula for linear p and s polarizations, E_0 is the electric field amplitude in vacuum, θ is the angle of refraction: $\sin\theta = \sin\Theta/\sqrt{\varepsilon^*}$, $\varepsilon^* \sim 13$ is taken as the dielectric constant of the quantum well material. Since $P_{circ} = \frac{I_{\sigma^-} - I_{\sigma^+}}{I_{\sigma^-} + I_{\sigma^+}} = \sin 2\phi$, j_x is expected to be proportional to sin 2ϕ at a fixed incident angle Θ, just as we have observed. The determination of the value of γ_{xy} should give a direct measurement of the Rashba coefficient α. It is noticed from Fig. 5 that the CPGE current for sample E is about three times stronger than that of sample D, similar to their Rashba coefficient ratio revealed by the SdH experiment. It is also found that the inter-band excitation induced spin photocurrent is up to 2 orders stronger than that of the inter-subband transitions in similar experiments. This is believed as resulting from the fact that the inter-band excitation provides much larger spin generation efficiency.

One more important result is that the spin photocurrent can change its direction by changing the laser wavelength. It is understood that CPGE can provide complicated wavelength response [9] due to the different selection rules of heavy hole and light hole if band to band excitation is employed. The spectral dependence of CPGE clearly shows that when the initial state in the excitation is switched from heavy hole to light hole, the CPGE signal also alters its sign.

In summary, in a specially designed Rashba system, i.e. a 2DEG system with asymmetric potential barriers, spin photocurrent clearly demonstrates the coupling of spin and orbit momentum. The spin photocurrent induced by inter-band excitation is found to be with efficiency much larger than the similar effect induced by inter-subband transitions. The spectral dependence of the CPGE has also been investigated to further reveal the spin determined nature of the effect.

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