Optically induced Hall effect in semiconductors

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Abstract: We describe an experiment which investigates the effect of a longitudinal electric field on the spin-polarized carriers generated by a circularly polarized light in semiconductors. Our experiment observes the effect as a Hall voltage resulting from nonequilibrium magnetization induced by the spin-carrier electrons accumulating at the transverse boundaries of the sample as a result of asymmetries in scattering for spin-up and spin-down electrons in the presence of spin-orbit interaction. It is found that the effect depends on the longitudinal electric field and doping density as well as on temperature. The results are presented by discussing the dominant spin relaxation mechanisms in semiconductors.

1. Introduction

The anomalous Hall effect (AHE) [1] and the most recently optically observed (predicted a long time ago [2]) spin Hall effect (SHE) [3] are the two types of spin-dependent Hall effects. The proper understanding of the spin-dependent Hall effects, that is of that part of the transverse resistance which depends on the magnetization, is still a challenging problem. However, it has been generally recognized that the spin-orbit (SO) interaction is responsible for the effects, and due to this interaction, electrons with their spin polarization parallel to the magnetization axis will be deflected at right angles to the directions of the longitudinal electric current and of the magnetization while electrons with antiparallel spin polarization will be deflected in the opposite direction via the skew-scattering (SS) [4] and side-jump (SJ) [5]. Thus, if the two spin species or spin populations (spin-up and spin-down) are unequal, there appears a net current in the transverse direction.

In the ordinary Hall effect (HE), the Lorentz force (F) causes a charge imbalance by deflecting like-charge carriers towards one boundary of the sample, creating a voltage transverse to the applied electric and magnetic fields (Fig. 1(a)). The AHE is the result of spin-dependent deflection of carrier (spin-polarized) motion, which produces a Hall voltage proportional to the spin polarization, or the magnetization, and spin accumulation at the transverse boundaries. In the AHE, the SO interaction plays the role of the force, so-called SO coupling force (FSO), that deflects like-spin carriers to one boundary and opposite spins to the other boundary, which causes a spin imbalance as well as a charge imbalance and results in a Hall voltage and a spin accumulation (Fig. 1 (b)). In the SHE, the FSO deflects like-spin carriers in the presence of the magnetization, which causes only the spin imbalance [because the spin-up (j↑) and spin-down (j↓) currents contain an equal number of charge carriers, i.e. j↑ = j↓] and results in no Hall voltage but spin accumulation on the transverse boundaries (Fig.
1(c)). The difficulties associated with the absence of the Hall voltage in SHE make it a challenging problem for the electrical detection which is very desirable for spintronic device applications.

![Diagram of Hall effect](image)

**Fig. 1.** (a) Hall effect in the presence of a magnetic field, $B$ (Hall voltage but no spin accumulation), (b) anomalous Hall effect (Hall voltage as well as spin accumulation) and (c) spin Hall effect (no Hall voltage but spin accumulation). In the anomalous Hall effect and spin Hall effect, carriers with same charge but opposite spin are deflected (in the presence of the magnetization, $m$) by the spin-orbit coupling to opposite sides.

Although AHE in magnetic materials with the application of magnetic fields has been observed for a long time since its discovery in 1880 by Hall [1], AHE has attracted recently much attention because of its close theoretical connection to SHE and because of the rapidly growing interest in spintronics, particularly, spin-dependent transport phenomena, or spin transport in general [6]. In addition, AHE has been used in demonstrating the existence of a ferromagnetic state in several semimagnetic or diluted magnetic semiconductors while searching for materials for possible applications in spintronics.

While the HE results from the Lorentz force, AHE is due to the SO coupling in the presence of spin polarization. In a ferromagnetic material, the presence of the spontaneous magnetization leads to AHE. For a nonmagnetic semiconductor, there is no spontaneous magnetization, so one needs to apply a strong magnetic field to polarize the carriers. However, if one can generate (or inject into) a spin-polarized current ($j^\uparrow \neq j^\downarrow$) in a semiconductor such that it can be sustained on the required length or time scale, one could observe the AHE. In the presence of the generated or injected spin-polarised currents, the nonmagnetic semiconductor could behave more like a ferromagnet as far as, or as long as, the transport is concerned. Furthermore, since AHE often persists above the ferromagnetic Curie temperature, an analogous AHE should be observable in a paramagnetic system in which the charge carriers are spin polarized by an external magnetic field or by other methods, for instance, optically since circularly polarized light breaks time-reversal symmetry and could lead to AHE [7].
In this work, we experimentally observe a photo-induced Hall-type charge and spin transport in \( n \)-doped nonmagnetic semiconductor GaAs. Our paper describes an experiment which electrically investigates the effect, as a Hall voltage, of a longitudinal electric field on the spin-polarized carriers induced by a circularly polarized light [8]. Since the photo-generated hole spins relaxation is extremely fast [9], the experiment observes only the effect resulting from spin-polarized electrons (not holes) accumulating at the transverse boundaries of the sample as a result of left-right asymmetries in scattering for spin-up and spin-down electrons in the presence of SO interaction. It is found that the effect depends on the longitudinal electric field and doping density as well as on temperature. The results obtained from the experiment are discussed in details.

2. Device fabrication and measurements

Investigated samples were fabricated on \( n \)-doped (with various doping densities) GaAs. Prior to contact deposition, the substrates were cleaned using conventional organic solvents. The native surface oxide was then removed using HCl:H\(_2\)O (1:1 vol.) followed by a de-ionized water rinse and blown dry with nitrogen before loading the substrates in the evaporation chamber. Au/Ge/Pd contacts were deposited on the substrates, with Pd layers adjacent to the GaAs substrates, using an e-beam evaporator with a base pressure of \(~5 \times 10^{-8} \text{ Torr}\). The contact metallization was annealed in a tube furnace in flowing nitrogen at temperature 180 °C for 1 h to achieve reliable or transparent contacts with low contact resistance. The specific contact resistivity was assessed using transmission line model and was found to be \(~10^6 \text{ Ω cm}^2\), which confirms that the device contains ohmic contacts. Gold wires were bonded from the sample-holder to the contact pads. Experiments were performed at various sample temperatures from low (3 K) to room temperature (300 K) by placing the samples in a cryostat. For optical excitation, a mode-locked Ti:sapphire laser which generates ps pulses at 76 MHz repetition rate was used. The excitation photon energy was tuned at \( \lambda \approx 800 \text{ nm} \), i.e. slightly above the energy bandgap of GaAs. A neutral density wheel was used to vary the optical power level. The average power on the sample was \(~5 \text{ mW} \). The polarization of the optical beam was modulated using a photo-elastic modulator at a lock-in reference frequency of 42 kHz. The laser beam was focused to a \(~90 \mu \text{m} \) (FWHM) spot of the sample with a lens. Care was taken not to illuminate any of the electrical contacts to avoid the generation of any artefacts. For this purpose (i.e. to check that the beam hits the sample on the desired location), a microscope was used. The lens was designed for minimum spherical aberrations. The spot size was measured by knife-edge scans and the spatial (or the sequence focus) profile of the pulse was found to be Gaussian. The laser beam was found to be stable at the power level we used. A regulated electric power supply was used as a bias source. The signal was measured by a lock-in amplifier coupled to a computer. A schema of the experimental set-up is shown in Fig. 2.

Fig. 2. A schema of the experimental set-up along with an illustration of the geometry of the sample.
3. Results and discussion
We observed a Hall-type effect in a nonmagnetic semiconductor without the application of an external magnetic field, but in the presence of a circularly polarized light. The circularly polarized light created a spin-polarized longitudinal current. If the longitudinal current in a nonmagnetic semiconductor is spin-polarized, e.g. current carriers contain more spin-up electrons than spin-down electrons, there would be more electrons scattered to the right than to the left via SS and SJ in the presence of the SO interaction. This leads to both spin and charge accumulations in the transverse direction of the sample. When the photo-induced spin-polarized electrons are dragged by an external bias in a sample, a light-induced Hall voltage ($V_{\text{LH}}$) proportional to the net spins or spin-polarized current is observed. The $V_{\text{LH}}$ is a measure of the net charge accumulation on the transverse boundaries of the sample for the generated spin-polarized electrons. The origin of the $V_{\text{LH}}$ is similar to the AHE, or the extraordinary Hall effect, in ferromagnetic materials in the presence of magnetic fields.

The results obtained from the experiments are presented in Figs. 3-5. In Fig. 3, we plot $V_{\text{LH}}$ as a function $E$ for a sample at sample temperature $T=300$ K, where an average of the data taken from several experiments for a field strength was calculated. As can be seen, $V_{\text{LH}}$ increases quickly to a maximum value and remains almost constant, and then suppresses almost exponentially. Above 150 mV $\mu$m$^{-1}$, $V_{\text{LH}}$ was found to be decayed, and it disappeared very quickly after 180 mV $\mu$m$^{-1}$. The decay of $V_{\text{LH}}$ with $E$ might be due to the enhanced electron spin relaxation at higher current densities.

![Field dependence of $V_{\text{LH}}$ for a sample with $n=1 \times 10^{22}$ m$^{-3}$ at sample temperature $T=300$ K. An average of the data taken from several experiments for a field-strength was calculated. The resulting high temperature ($T_e$) of the field-drifting electrons together with the momentum relaxation ($\tau_p$) leads to enhanced DP spin relaxation ($1/(\tau_s)_{DP} \sim T_e^3 \tau_p$).](image)

As seen from Fig. 3, $V_{\text{LH}}$ and thus polarization, or spin lifetimes ($\tau_s$), is preserved during transport in $n$-doped GaAs in moderate electric fields, which is very important for implementing spin-sensitive or spintronic new device ideas. Although the spin for moderate electric field is preserved, the spin relaxation rate becomes considerably larger for higher fields. When the electrons were injected with a high $E$, a significant reduction in the spin relaxation is observed. Increasing $E$ leads to larger charge and spin accumulations near sample boundaries, but polarization saturates because of shorter $\tau_s$ for larger $E$. The suppression of $\tau_s$ with increasing $E$ from saturation implies that spin decay increases with...
$E$ is consistent with other observations\textsuperscript{[10,11]}. The decay of polarization was found to be exponential (Fig. 3) and the fields (for all the samples) at which spin relaxation or depolarization occurs was found to be within a moderate range. A similar feature can be seen in a theoretical investigation based on a spin drift-diffusion model\textsuperscript{[12]}, where it was shown that a significant increase in the spin current could not be achieved by increasing the field owing to the competing effect of field on diffusion because the spin drift and spin diffusion currents contribute additively to the spin current and because the spin diffusion current decreases with the field while the spin drift current increases.

As found, the photo-generated spin can travel without losing their initial orientation as long as their field is below a threshold value. Above the threshold, spin depolarization is considerably enhanced due to the enhanced spin relaxation as a result of increase of the electron temperature ($T_e$). Our results agree with those of the field-dependent spin transport experiment by D. Hägele et al.\textsuperscript{[13]}. These authors studied spin relaxation of photo-generated electrons during drift transport in GaAs at low temperatures by photoluminescence measurements. They found almost complete conservation of the orientation of the electron spin during transport in GaAs over a distance as long as 4 $\mu$m, but fields up to a couple of hundreds mV $\mu$m$^{-1}$.

The results obtained by us are also in good agreement with those of the spin transport experiments\textsuperscript{[14]}, similar to one employed in Ref. 13. They showed that the photo-generated spins could travel without losing their initial spin orientation as long as $E$ was below 100 mV $\mu$m$^{-1}$ and the spin relaxation rate increased rapidly with $E$, and polarization disappeared at $\sim$350 mV $\mu$m$^{-1}$. It is noted here that the photo-generated spins in their study were generated with a higher optical power.

The origin of the field-dependent efficient electron spin relaxation is discussed based on the D’yakonov–Perel (DP) spin relaxation mechanism\textsuperscript{[2]}. The DP mechanism is due to SO coupling in semiconductors lacking inversion symmetry. In III-V semiconductors, such as GaAs, the degeneracy in the conduction band is lifted for $\vec{k} \neq 0$ due to the absence of inversion symmetry. Without inversion symmetry the momentum states of spin-up ($\uparrow$) and spin-down ($\downarrow$) electrons are not degenerate, i.e. $E_{\vec{k}\uparrow} \neq E_{\vec{k}\downarrow}$, where $E_{\vec{k}\uparrow}(E_{\vec{k}\downarrow})$ is the momentum-dependent electron energy with spin $\uparrow(\downarrow)$. The resulting energy difference, for electrons with the same $\vec{k}$ but different spin states, plays the role of an intrinsic $\vec{k}$-dependent magnetic field\textsuperscript{[15]}, $\vec{h}(\vec{k}) =\alpha h^2(2emE_g)^{-1/2}[k_y(k_y^2-k_x^2)\hat{x} + c.p.]$, where $\alpha$ is a dimensionless, material-specific parameter which gives the magnitude of the SO splitting and is approximately given by $\alpha = 4\eta(m/m_e)/\sqrt{3-\eta}$ (where $\eta = \Delta/(E_g + \Delta$), $E_g$ is the bandgap, $\Delta$ is the SO splitting of the valence band, $m$ is the electron’s effective mass and $m_e$ is a constant close in magnitude to free electron mass $m_0$) induced by the presence of the Dresselhaus\textsuperscript{[16]} SO interaction in a zinc-blende structure, acting on the spin with its magnitude and orientation depending on $\vec{k}$ and results in spin precession (spin relaxation) with intrinsic Larmor frequency $\Omega_s(\vec{k})=(e/m)\vec{h}(\vec{k})$ during the time between collisions.

The corresponding Hamiltonian term (DP Hamiltonian) describing the precession of electrons in the conduction band is $H_{SO}(\vec{k}) = (\hbar/2)\hat{\vec{\sigma}}\cdot\Omega_s(\vec{k})$, where $\hat{\vec{\sigma}}$ is the vector of Pauli spin matrices. In a quantum well, for example, both the bulk and structural inversion asymmetries are present. So the DP term is composed of the Dresselhaus\textsuperscript{[16]} and Rashba\textsuperscript{[17]} terms.

The increased electron momentum at higher electric fields brings about a stronger $\vec{h}(\vec{k})$ and consequently, the electron precession frequency $\Omega_s(\vec{k})$ becomes higher. The intrinsic magnetic field depends on the underlying material, on the geometry of the device, and on $\vec{k}$. Momentum-dependent spin procession described by the DP Hamiltonian, together with momentum scattering characterized
by momentum relaxation time ($\tau_p(E_k)$) leads to the DP spin relaxation. Since the magnitude and the
direction of $\vec{k}$ changes in an uncontrolled way due to electron scattering with the environment, this
process contributes to (DP) spin relaxation given by $1/(\tau_s)_{DP} = \gamma(\alpha / \hbar)^2 E_k^3/ (E_g) \tau_p (E_k)$ [15], where
$E_k = k_B T_e$ and $\gamma$ is a dimensionless factor that ranges from 0.8 to 2.7 depending on the dominant
momentum relaxation process.

During transport in the electric field, electrons are accelerated to higher velocities at higher fields,
where $T_e$ increases sharply due to the energy-independent nature of the dominant energy relaxation
process via the longitudinal polar optical phonon scattering [15]. The resulting high $T_e$ leads to
enhanced DP spin relaxation ($1/(\tau_s)_{DP} \sim T_e^3 \tau_p$) because they have large kinetic energy between
successive collisions.

The $V_{\text{LH}}$ decreases rapidly with $E$, which is consistent with the results of the Monte Carlo
simulation performed by Barry et al. [18]. They have shown that for relatively low fields up to 100
mV $\mu m^{-1}$ a substantial amount of spin polarization is preserved for several microns at room
temperature and the DP spin relaxation rate increased rapidly for fields higher than 150 mV $\mu m^{-1}$ and
became infinite for $E$ higher than 250 mV $\mu m^{-1}$. For GaAs, the Elliot-Yafet spin relaxation is less
effective due to the large $E_g$ and low scattering rate [6]. For $n$-doped materials, as holes are rapidly
recombined with electrons due to the presence of a large number of electrons, spin relaxation due to
the Bir-Aronov-Pikus mechanism is usually blocked [6]. The spin relaxation in $n$-doped GaAs is
therefore dominated by the DP mechanism.

Fig. 4 shows the doping-density dependence of the signal, where $V_{\text{LH}}$ is plotted as a function of $n$.
As seen, an enhancement of $V_{\text{LH}}$ with increasing doping is observed. The introduction of $n$-type
dopants in semiconductors increases $\tau_s$, because the electronic spin polarization in these systems
survives for longer times. Studies of spin precession in $n$-GaAs reveal that moderately $n$-doping yields
significantly extended $\tau_s$ [11,19].

![Fig. 4. Doping-density dependence of $V_{\text{LH}}$.](image-url)
As known from the literature [6], the spin-dependent Hall effects originate from a variety of mechanisms and consists of the contribution due to an asymmetric SS of charge carriers, the contribution due to a SJ that the charge carriers undergo at each scattering event and the contribution not related to scattering (but arising as a result of the band structure), i.e. the intrinsic contribution [7]. As they originate from the same mechanisms, the same physics underlies both AHE and SHE. For the less-doped sample, the spin-dependent Hall conductivity is low because of the higher compensation ratio [20], and the SJ contribution dominates the effect. Although the SJ contribution is independent of $\tau_s$, SS contribution will grow with $\tau_s$, resulting in a higher contribution to the effect for higher $n$ [21], but would be cut off when $\tau_s$ becomes comparable to $\Delta^{-1}$ at the Fermi level due to the $k^2$-Dresselhaus term in the DP expression. For the higher-doped samples, SS increases with $n$, agreeing with the theoretical predictions performed in Refs. [22,23].

![Fig. 5. Temperature dependence of $V_{LH}$ for a sample.](image)

The dependence of the Hall signal on temperature is shown in Fig. 5. As can be seen, $V_{LH}$ increases with decreasing temperature, in consistence with the studies by others [14]. These authors studied spin relaxation of photo-generated electrons during transport in GaAs at low temperatures by the time-resolved and photoluminescence polarization measurements. They showed that the polarization under drift increased with decreasing temperature. The result is also consistent with the time-resolved Faraday rotation experimental findings for the $\tau_s$ measurements [10,11].

4. Conclusions
We experimentally studied the circularly polarized light-induced Hall effect in n-doped GaAs at temperatures ranging from 3 K to 300 K. Our experiment investigated the effect of a longitudinal electric field on the optically spin-polarized electrons accumulating at the transverse boundaries of the sample via the measurements of $V_{LH}$. It was found that the effect depends on the longitudinal electric field and doping density as well as on temperature. The results obtained from the investigation were discussed based on the dominant spin relaxation mechanisms for the semiconductor.

References