Voltage probe of the optically oriented electron spin relaxation

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We report here a study of the voltage probe of the electron spin relaxation in zinc-blende semiconductors. Electron spins oriented by a circularly polarized light are dragged by an electric field in transparent devices formed on gallium arsenide. The observed spin polarization-dependent voltage signal (which is a measure of the spin relaxation) is found to decrease about exponentially with the applied electric field. When the spin-oriented electrons are dragged with a high field, a significant decrease in the spin polarization is observed due to an increase in the spin precession frequency of the hot electrons. It is also found that the signal rationally decreases with increasing crystal temperature. The results are discussed based on the Dyakonov–Perel spin relaxation mechanism.

Keywords: Dyakonov–Perel spin relaxation, spin polarization, voltage probe, zinc-blende semiconductor.

SPIN electronics or spintronics is a rapidly growing field of research aimed at realizing new high-performance semiconductor (spintronic) devices that take advantage of the electron spin as well as of its charge[1–3]. It is generally expected that addition of the spin degree of freedom in information processing will extend the functionality of conventional devices (electronic devices) and allow the development of novel electronic devices (spintronic devices), which can hold promise of, for example, reduced power consumption, faster operation, smaller size and nonvolatility.

Conventional electronic devices rely exclusively on the electronic charge. The idea to use the spin property of electrons in conventional devices has drawn a lot of attention recently, motivated by the observations of long spin lifetime (τ_s) or spin diffusion length (δ_s) ($\delta_s = 2$ μm obtained by optical[4] and $\delta_s = 1.7$ μm by electrical measurements[5]) in semiconductors. However, one of the important requirements necessary in developing semiconductor spintronic devices is the detection of spin current (or spin relaxation) in a semiconductor[3]. For a reliable detection, the efficient transport (without spin-flipping or spin relaxation, or the loss of spin polarization) of spin-polarized carriers through a semiconductor over reasonable distances that are comparable to the device dimensions is required. This is because if spin relaxes too fast, the distance travelled by an electron without losing its spin state will be too short to perform any practical purpose or operation.

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The detection of spin current in semiconductors has been obtained mostly by optical methods[1,6]. These include: (i) measurement of the differential transmission using a pump-probe technique (single-photon[7] or multiphoton[8] pumping), with the same and oppositely circularly polarized pulses; (ii) optical Kerr rotation microscopy[4]; (iii) time-resolved circularly polarized photoluminescence or electroluminescence measurement[9]; (iv) optical Hanle effect (depolarization of the photoluminescence in a magnetic field perpendicular to the spin) measurement[10], and, most recently, (v) optical spin Hall effect (SHE) measurement[11]. The electrical detection of SHE (or the spin current in the SHE) still remains a challenge due to the difficulties associated with the absence of the Hall voltage[3].

However, an electrical method (voltage probe) of detecting spin current or spin relaxation in semiconductors is desirable for possible device applications. Electrical detection of spin current in semiconductors has recently been reported[12–14]. For example, Lou *et al.*[12] detected spin transport in a lateral ferromagnetic metal–gallium arsenide (GaAs) semiconductor device in the presence of an external magnetic field at low temperatures. In an earlier study[13], we had detected spin current in GaAs at both low and room temperatures by circularly polarized light excitation via the photo-induced anomalous Hall effect (AHE), and in the absence of the external magnetic field. As no external magnetic field was used, the observed effect was the pure AHE, i.e. without any contribution of the ordinary Hall effect. Here we show the voltage probe of the electron spin relaxation and find that the spin relaxation strongly depends on the applied electric field and crystal temperature.

Device samples were fabricated on moderately ($n = 1 \times 10^{16}$ cm^{-3}) silicon-doped (n-type) 1-μm bulk GaAs. Transparent Au(100 nm)/Ge(40 nm)/Pd(10 nm) contacts, with Pd layers adjacent to GaAs, were deposited on the substrates using an e-beam evaporator with a base pressure of $\sim 5 \times 10^{-8}$ torr. The contact metallization was annealed at 180°C for 1 h to achieve transparent contacts. A gold wire was bonded to the centre of each of the four contacts. Details of the contact formation mechanism have been reported elsewhere[15]. The sample (placed in a cryostat for low-temperature measurements) was optically excited (with excitation energy of ~4 mW) by circularly polarized picosecond pulses from a mode-locked Ti : sapphire laser with a repetition rate of 76 MHz. The polarization of the pulsed beam was modulated using a photoelastic modulator (PEM) at lock-in reference frequency of 42 kHz. The excitation photon energy was tuned ($\lambda \approx 0.8$ μm) slightly above the band gap of GaAs. A neutral density wheel (NDW) was used to vary the optical power level. The laser beam was focused on to a ~8 μm (FWHM) spot at the surface of the sample with a lens. A lock-in amplifier coupled to a computer was used for measuring the spin polarization-dependent voltage signal in the Hall geometry (Figure 1).

In a semiconductor, if the longitudinal current 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 skew-scattering and side jump in the presence of spin–orbit (SO) interaction[16]. This means that the SO coupling in a nonmagnetic semiconductor produces a left–right asymmetric scattering of the carriers for a fixed spin orientation. This leads to both spin[17] and charge[18] accumulation in the transverse direction of the sample. When the photo-induced spin-polarized carriers are dragged by an external bias in a sample, an optically spin-induced transverse voltage (V_S) is observed. V_S is proportional to the spin current or spin relaxation, and is a measure of the net charge accumulation on the transverse edges of the sample for the generated spin-polarized carriers. The origin of V_S is similar to the AHE[13], which has been known for a long time in ferromagnetic metals and in the presence of an external magnetic field. As the optically induced hole spin relaxation is extremely fast, its polarization is effectively zero and can be neglected.

Bias-field dependence of V_S for different crystal temperatures (T_C) is shown in Figure 2. The inset shows typical scans for a sample for $E = 2.1$ kV cm^{-1} at two different crystal temperatures, 300 K (lower) and 120 K (upper). The voltage signal decreases about exponentially with increasing strength of E. This exponential dependence can be seen from the following expression for the spin polarization-dependent transverse electric field[19] derived from the spin drift–diffusion model[20]:

$$E_S = \frac{\sigma_S}{(\sigma_D^2 - \sigma_S^2)}(j + j_{dif})p_0 \exp\{-(-\zeta + \sqrt{\zeta^2 + 1/\delta_S^2})y\}, \quad (1)$$

where $\zeta = \mu E/(2D_c)$ is the field parameter, D_c the diffusion coefficient, $j = ne\mu E$ the drift current and $j_{dif} = neD_c/\Lambda_S$ the diffusion current.

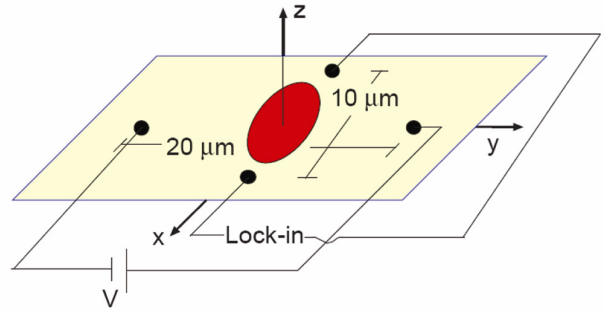

Figure 1. A scheme of the experimental set-up along with an illustration of the geometry of the sample device. The red round area at the centre ($x = 0$, $y = 0$, $z = 0$) of the sample shows the light beam spot. The direction of the circularly polarized light propagation from the photo-elastic modulator is along $-z$. The generation of spins is along $-z(z)$ for right (left) circularly polarized light σ^+ (σ^-).

$$\Lambda_S = \frac{1}{-\zeta + \sqrt{\zeta^2 + 1/\delta_S^2}}, \quad (2)$$

is the spin diffusion length in the presence of the applied electric field, σ_D the Drude conductivity, σ_S the anomalous Hall conductivity, $p(y) = p_0\exp(-y/\Lambda_S)$ the density of spin polarization in the steady state and p_0 the initial density of spin polarization (i.e. p at the point of spin generation, $y = 0$). As can be seen from eq. (1), the transverse field E_S has two current contributions (spin drift and spin diffusion currents) to the total spin current. When E is very large ($\zeta \sim 1/\delta_S$), $1/\Lambda_S \approx 0$ and the diffusion current is zero, so that only the drift current contributes to E_S.

The crystal temperature dependence of V_S is shown in Figure 3. The fit to the experimental data is obtained by a nonlinear regression. As can be seen, V_S varies rationally

$$V_S = \frac{a + T_C}{b + cT_C}, \quad (3)$$

where $a = 67.7412$, $b = 110.3371$ and $c = 2.6506$. The spin polarization-dependent voltage signal increases with decreasing temperature, consistent with the studies by Sanada *et al.*[21]. These authors studied spin relaxation of photo-oriented electrons during transport in GaAs at low temperatures by the time-resolved photoluminescence polarization measurements. They showed that the polarization under drift increased with decreasing crystal temperature. The result is also consistent with the time-resolved Faraday rotation measurements for the spin lifetime τ_S (ref. 4).

V_S is also seen to decrease with E for all temperatures. The decay of V_S with E might be due to the enhanced

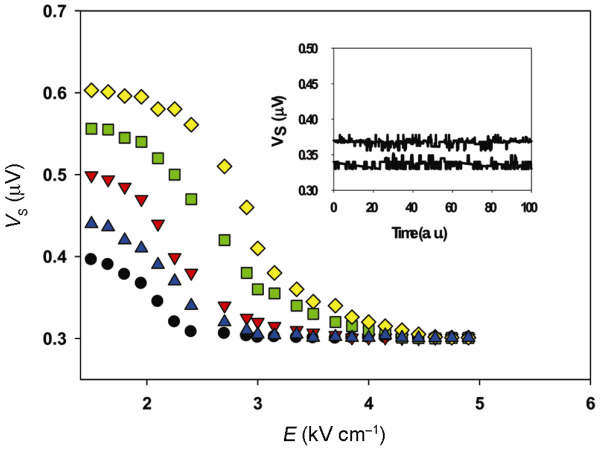

Figure 2. Bias-field dependence of the voltage signal for different crystal temperatures (circle, 300 K; triangle up, 120 K; triangle down, 40 K; square, 12 K, and diamond, 4 K). (Inset) Typical scans for a sample for $E = 2.1$ kV cm^{-1} at two different crystal temperatures, 300 K (lower) and 120 K (upper).

electron spin relaxation at higher electric fields. 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 was observed. Increasing E leads to larger charge and spin accumulation near the sample boundaries, but polarization decreases because of shorter τ_S for larger E. The suppression of τ_S with increasing E implies that spin decay increases with E, consistent with other observations[1]. From the variation of V_S, it has been revealed that polarization suppresses exponentially.

The observed spin depolarization is considerably enhanced due to the enhanced spin relaxation as a result of increase of the electron temperature (T_e). As expected, electron spin at lower temperatures (compared to that at higher temperatures) disappears at higher fields. Our field-dependences agree with those of the transport experiment reported by Hägele *et al.*[22], who showed that the photo-oriented spins could travel without losing their initial spin orientation as long as E was below 1 kV cm^{-1} and the spin relaxation rate increased rapidly with E, and the polarization disappeared at ~3.5 kV cm^{-1}. The photo-electron spins were generated with a much higher optical power (10 mW) in their study[22].

The origin of field-dependent efficient electron spin relaxation in n-type GaAs has been discussed based on the Dyakonov–Perel (DP) spin relaxation mechanism[18]. The DP mechanism is due to SO coupling in semiconductors lacking inversion symmetry. In III–V semiconductors, 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 ↑ and ↓ spin 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 of ↑(↓). The resulting energy difference, for electrons with the same wave vector $\vec{k}$ but different spin states, plays

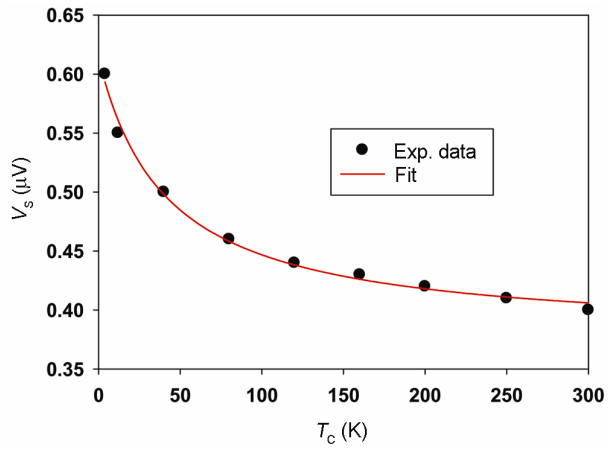

Figure 3. Crystal temperature dependence of the voltage signal at field $E = \sim 1$ kV cm^{-1}. Red solid line is a rational fit made by eq. (3) to the experimentally obtained data.

the role of an intrinsic $\vec{k}$-dependent magnetic field, known as effective magnetic field[23]

$$\vec{h}(\vec{k}) = \frac{\alpha\hbar^2}{\sqrt{2em^* E_g}}[k_x(k_y^2 - k_z^2)\hat{x} + k_y(k_z^2 - k_x^2)\hat{y} + k_z(k_x^2 - k_y^2)\hat{z}], \quad (4)$$

where $\hbar$ is the reduced Planck constant (Planck constant divided by 2π) and α a dimensionless, material-specific parameter which gives the magnitude of the SO splitting and is approximately given by

$$\alpha \simeq 4\eta(m^*/m_{cv})/\sqrt{3-\eta}. \quad (5)$$

$\eta = \Delta/(E_g + \Delta)$, E_g is the energy bandgap, Δ the SO splitting of the valence band, m^* the effective mass of the electron and m_{cv} a constant close in magnitude to free electron mass m_0, induced by the presence of the Dresselhaus (due to the bulk inversion asymmetry) SO interaction in a zinc-blende structure, acting on the spin with its magnitude and orientation depending on $\vec{k}$, which results in spin precession with intrinsic Larmor frequency $\Omega_S(\vec{k})$ during the time between collisions, according to the relation

$$d\vec{S}/dt = \Omega_S(\vec{k}) \times \vec{S}, \quad (6)$$

where $\Omega_S(\vec{k}) = (e/m^*)\vec{h}(\vec{k})$ and $\vec{S}$ is the electron spin polarization vector. The corresponding Hamiltonian term (DP Hamiltonian) due to spin–orbital splitting of the conduction band describing the precession of electrons in the conduction band is

$$H_{SO}(\vec{k}) = [H_{SO}(\vec{k})]_D = (\hbar/2)\vec{\sigma} \cdot \Omega_s(\vec{k}), \quad (7)$$

where $\vec{\sigma}$ is the vector of Pauli spin matrices. In a quantum well (QW), for example, the DP Hamiltonian is composed of the Dresselhaus[24] and Rashba terms[25]:

$$H_{SO}(\vec{k}) = [H_{SO}(\vec{k})]_D + [H_{SO}(\vec{k})]_R. \quad (8)$$

The Rashba term appears if the self-consistent potential within a QW is asymmetric along the growth direction and is therefore referred to as structural inversion asymmetry contribution.

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 effective 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 of eq. (7), together with momentum scattering characterized by momentum relaxation time $\tau_p(E_{\vec{k}})$ leads to DP spin relaxation. As the magnitude

and direction of $\vec{k}$ change in an uncontrolled way due to electron scattering with the environment, this process contributes to spin relaxation given by[23]

$$1/\tau_S = \gamma(\alpha/\hbar)^2 \tau_p E_{\vec{k}}^3/E_g, \quad (9)$$

where $f_S = 1/\tau_S$ is the spin relaxation frequency, $E_{\vec{k}} = k_B T_e$ and γ is a dimensionless factor that ranges from 0.8 to 2.7 depending on the dominant momentum relaxation process. For example, for scattering by polar optical/piezoelectric phonons $\gamma \approx 0.8$, while scattering by ionized impurities gives $\gamma \approx 1.5$, and scattering by acoustic phonons gives $\gamma \approx 2.7$ (refs 2 and 23). Equation (9) shows approximately the third-order power dependence of f_S on the electron temperature, i.e. $F_S \sim (k_B T_e)^3$.

The DP spin relaxation in a bulk zinc-blende structure occurs due to the spin precession about $\vec{h}(\vec{k})$ induced by the presence of the Dresselhaus SO interaction expressed in eq. (7). 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[26]. The resulting high T_e leads to enhanced DP spin relaxation $[f_S \sim E_{\vec{k}}^3 \tau_p(E_{\vec{k}})]$, because they have large kinetic energy between successive collisions.

Optically oriented spin relaxation was detected and probed electrically in GaAs at room temperature as well as at low temperatures. The polarization-dependent voltage signal was a measure of the spin relaxation or spin current. It was found that the spin relaxation strongly depends on the applied electric field and crystal temperature. When the electron spins were dragged with a high field, a significant decrease was observed in the spin polarization, and consequently voltage signal, due to an increase in the spin precession frequency of the hot electrons. The spin current was injected optically at the longitudinal terminal (source) and its detection was obtained electrically at the transverse Hall terminal (drain). Further systematic experiments that use controllable parameters, such as gate voltage, will provide us with a clear view of many of the principal criteria required for implementation.

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Received 12 May 2011; revised accepted 11 August 2011