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A SPIN CURRENT DETECTING DEVICE WORKING IN THE DRIFT-DIFFUSION AND DEGENERATE REGIMES

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ABSTRACT

A semiconductor-based device working in the spin drift-diffusion regime and for probing the injected or generated spin current was considered. The electric field effects on spin transport were analysed. A drift-diffusion equation for spin density was derived and contributions to the spin current were examined. By referring to the techniques of the spin current injection and generation, expressions for the spin current and spin-induced transverse Hall voltage arising from the injected or generated spin-polarized current were deriv ed. The spin current and Hall voltage in dependences of the external electric field and temperature in the degenerate regime were studied. The device operated on the basis of with no external magnetic fields gives a voltage probe of the spin-induced Hall effect. Finally, a way of enhancing the spin current was explored.

Keywords: Spin transport; spin drift-diffusion; spin-dependent Hall effect; semiconductor

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INTRODUCTION

The basic study dedicated to spintronics is to understand the interaction between the particle spin and its solid-state environments in order to make useful devices based on the spin degree of freedom. However, for the successful incorporation of spins into the currently existing semiconductor technology, one has to resolve technical issues such as efficient spin generation/injection, transport (control and manipulation) of spins and finally, the detection of spins, or spin current [1]. From the fundamental point of view, spintronics includes the investigation of spin transport as well as of spin dynamics and spin relaxation in technologically advanced and efficient solid-state materials.

Recent interest has, however, been motivated by successful examples of metallic (metal-based) spintronic devices, such as read heads for hard disc drives and magnetoresistive random access memory, based on ferromagnetic metals in which, as first suggested by Mott [2], the electrical current is carried by independent majority and minority spin channels. On the other hand, the first semiconductor spintronic (active) device was suggested by Datta and Das in 1990 [3], where they proposed an electronic analogue of an electro-optical modulator, that was later termed "spin field effect transistor" (spin-FET), in a two-dimensional electron gas contacted with two ferromagnetic electrodes: one as a source for the injection of spin polarized electrons (because magnetic materials are natural sources of spin polarized electrons) and the other as an analyser (detector) for electron-spin polarization. Since then, their proposal of a spin-FET, so-called

Datta-Das spin-FET, has been believed to be the most promising and led to an intense focus on realizing the semiconductor-based spintronic devices. However, due to the experimental difficulties in the efficient spin injection for a successful detection, the Datta-Das spin-FET is yet to be implemented in an efficient way.

In the fundamental research, there is a renewed interest to study spin-dependent transport (or spin transport) and spin dynamics in various semiconductors or electronic materials to explore the fundamental properties of different solid-state systems. In addition, recent advances in materials fabrication made it possible to introduce nonequilibrium spin in a novel class of systems including ferromagnetic semiconductors, diluted magnetic semiconductors (nonmagnetic semiconductors containing small amount of magnetic ions, like Mn, to be magnetic, e.g. Ga1-xMnxAs), superconductors, both metallic and semiconducting carbon nanotubes, crystalline MgO [4,5] and, most recently, organic semiconductors [6]. Although different types of semiconductor devices have recently been proposed [7,8], the actual advantages of these devices as compared to the conventional electronic devices have not yet been clearly established.

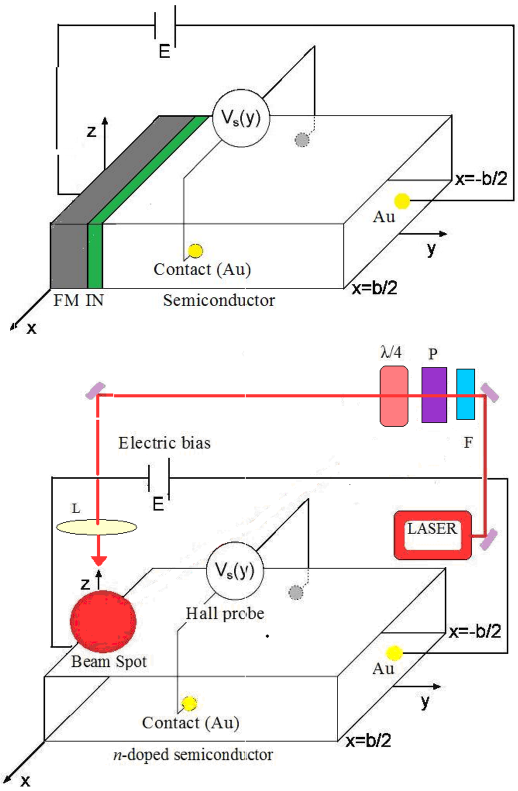

Figure 1. (Top view) Electrical spin current injection from a ferromagnet (FM) to *n*-doped semiconductor through an insulating layer (IN). (Bottom view) Optical spin current generation by a circularly polarized light from a laser (F: Neutral density filter; P: Polarizer; λ/4: Quarter wave-plate; L: Lens; and E: Electric bias field). A quarter wave-plate converts the laser light to a circularly polarized light. Spin current j_s is detected as a transverse voltage $V_s \sim E_{sH}$.

Here, in the present investigation, we consider a semiconductor device, as depicted in Figure 1, and study the transverse spin transport based on the spin-induced Hall effect. A diffusion equation in the drift-diffusion regime for the spin density is derived, and the effect of an external electric field on the injected or generated spin-polarized current is demonstrated. An expression for the transverse Hall field probing the spin current in the device also derived and studied.

MATERIALS AND METHODS

Charge and Spin Transports

We study the transports of charge and spin, with the inclusion of spin relaxation, in semiconductors. The continuity relation that takes into account spin relaxation is

$$\frac{\partial}{\partial t} n_\alpha(\vec{r},t) = \frac{1}{e}\vec{\nabla}.\vec{j}_\alpha(\vec{r}) + \frac{n_{-\alpha}(\vec{r},t) - n_\alpha(\vec{r},t)}{\tau_{s,\alpha}} \tag{1}$$

where α is the spin index (α ≡ ↑, -α ≡ ↓) and $n(\vec{r},t)$, $\vec{j}(\vec{r})$ and τ_s denote respectively carrier density, current density and spin relaxation time. Assuming that there is no space charge and that the material is homogeneous, the expression for the current density of a spin species, including the drift and diffusion contributions, can be written as

$$\vec{j}_\alpha(\vec{r}) = \sigma_\alpha \vec{E} + eC_{d,\alpha}\vec{\nabla} n_\alpha(\vec{r},t) \ , \tag{2}$$

with $\sigma_\alpha = en_\alpha\mu_\alpha$, where μ_α, σ_α and $C_{d,\alpha}$ are the mobility, Drude conductivity and diffusion coefficient for carriers with spin α. We assume that the transport is unipolar (e.g. *n*-doped semiconductor) so that the recombination process can be neglected. Applying the local charge neutrality constraint ($n_\alpha + n_{-\alpha} = 0$) carefully, we obtain

$$\frac{\partial s(\vec{r},t)}{\partial t} = \mu\vec{E}.\vec{\nabla} s(\vec{r},t) + C_{d,\alpha}\nabla^2 s(\vec{r},t) - \frac{s(\vec{r},t)}{\tau_s} \ , \tag{3}$$

where the spin density *s* is defined as $s(\vec{r}) = n_\alpha(\vec{r}) - n_{-\alpha}(\vec{r})$. Here it is assumed that the mobility and diffusion coefficient are equal for spin-up and spin-down carriers and the Mathiessen's rule $1/\tau_s = 1/\tau_{s,\alpha} + 1/\tau_{s,\alpha}$ is valid. Equation (3) now becomes in the steady-state

$$\nabla^2 s(\vec{r}) + \frac{\mu}{C_d}\vec{E}.\vec{\nabla} s(\vec{r}) = \frac{s(\vec{r})}{C_d\tau_s} \ . \tag{4}$$

The above equation is homogeneous and includes the electric field effects in the second term. This drift-diffusion-type equation has recently been used widely to model spin-dependent charge transport or spin transport in semiconductors [9]. In spin transport studies of semiconductors in the diffusive regime, the spin polarization is usually assumed to obey the same usual diffusion equation for the electrochemical potential as in metals [10-13], where there are no electric field effects and the spin polarization decays exponentially on a length scale of the intrinsic spin diffusion length, $\delta_s = \sqrt{C_d\tau_s}$, from the injection point as $\nabla^2\Delta\varphi(\vec{r}) = \Delta\varphi(\vec{r})/(C_d\tau_s)$, where $\Delta\varphi(\vec{r}) = \varphi_\alpha(\vec{r}) - \varphi_{-\alpha}(\vec{r})$ is the splitting of the electrochemical potentials $\varphi_\alpha(\varphi_{-\alpha})$ of up-spin (down-spin) carriers owing to the imbalance of carrier densities in the $\pm\alpha$ spin bands. In semiconductors, in contrast to metals, the field remains partially unscreened. Therefore, it is necessary to study the spin transport in the drift-diffusion regime.

Spin Current Injection/Generation

A spin current detection device, with an injection/generation scheme, sketched in Figure 1, is considered. The injection (generation) is called for the electrical (optical) case, as shown in the figure top (bottom). The electrical spin injection can be obtained from a ferromagnet to a semiconductor through an insulating or metal oxide (e.g. Al_2O_3) layer. Optical spin generation, on the other hand, can be obtained by pumping the semiconductor sample by a circularly polarized light (produced using a quarter wave-plate or photo-elastic modulator) from a laser. Pumping with a left (right) circularly polarized light of both heavy-hole (hh) and light-hole (lh) transitions in unstrained bulk semiconductor yields an initial spin polarization of 50%, since the inter-band transition dipole matrix elements of the hh transition are three times stronger than those of the lh transitions. Optical pumping with left (right) generates spins along the direction antiparallel (parallel) to the direction of the light propagation, i.e. spins along +*z* (-*z*) [14]. The continuous spin imbalance is injected from the left of the device at $y = 0$. As detailed below, the spin polarization axis is taken to be *z* (optical left circularly polarized case). Take $\vec{E} = -E\hat{y}$ and consider *x* to be the transverse direction, with slab boundaries at $x = -b/2$ and $x = b/2$.

A spin-polarized carrier population produced in this way will be distributed symmetrically in *k*-space in materials with zinc-blende symmetry and, consequently, there can be no net electrical current without a dc-bias field, even though each individual carrier may be generated initially with a large momentum when the material is excited well above the band gap. Optically generated spin-polarized carrier populations are dragged by the external electric field to create a spin-polarized electrical current or spin current [14]. The longitudinal charge current of such a system, obtained either electrical or optical, is spin-polarized, i.e. the current of spin-up (α) electrons (j_α) is not equal to the spin-down current ($j_{-\alpha}$), although both species of electrons move in the same direction, which gives a non-zero spin current (j_s) flowing in the transverse direction:

$$j_s(\vec{r}) = j_\alpha(\vec{r}) - j_{-\alpha}(\vec{r}), \tag{5}$$

where $\vec{j}(\vec{r}) = \vec{j}_\alpha(\vec{r}) + \vec{j}_{-\alpha}(\vec{r}) = e(n_\alpha + n_{-\alpha})\mu\vec{E} = en\mu\vec{E}$ is the total longitudinal charge current, and as there is an imbalance of spins of the electrons carrying the current ($j_\alpha(\vec{r}) \neq j_{-\alpha}(\vec{r})$), the current is called spin-polarized current. For an equal population of spin carriers, the charge current does no matter, i.e. is the same, but the spin current is zero.

Spin Current And Its Detection

Once injected into (generated in) a semiconductor, electrons experience spin-dependent interactions with impurities and excitations/ phonons, which cause spin relaxation. While the total current is conserved when the carrier electrons propagate through the device, the spin density/ polarization decreases as the distance from the point of injection increases and the length scale associated with this decrease is governed by the effective spin diffusion length, which can be obtained from the solution of Equation (4) for *y*>0. The general solution for the variation in only positive *y*-direction is found as $s(y) = A\exp(-y/\Delta_s)$, where A is a constant of integration to be determined by the initial conditions and $(\Delta_s)^{-1} = -\chi + \sqrt{\chi^2 + 1/\delta_s^2}$ with $\chi = \mu E / 2C_d$. If the spin density at the injection point ($y = 0$) is s_0, then $A = s_0$ and the expression for the spin density becomes $s(y) = s_0\exp(-y/\Delta_s)$, which gives the spin density distribution along the positive *y*-direction. The quantity Δ_s is the effective spin diffusion/ decay length, i.e. the distance over which the carriers move within the spin lifetime τ_s in the downstream direction. In the absence of the electric field, Δ_s is equal to the intrinsic spin diffusion length, δ_s. As can be seen, the spin transport distance in semiconductors can be increased by introducing an external electric field. It will, however, be shown that an extension of the spin diffusion length in this way does not translate to a significant increase in spin current owing to the competing effect of field on diffusion.

The spin current as a function of charge current and spin density/polarization can be obtained from Eqs. (2) and (5) as

$$\vec{j}_s(\vec{r}) = \vec{j}_\alpha(\vec{r}) - \vec{j}_{-\alpha}(\vec{r}) = e(\mu\vec{E} + C_d\vec{\nabla})s(\vec{r}) = en(\mu\vec{E} + C_d\vec{\nabla})p(\vec{r}) \ , \tag{6}$$

where the density of spin polarization in terms of carrier densities of spin up and spin down is defined as $p(\vec{r}) = (n_\alpha - n_{-\alpha})/(n_\alpha + n_{-\alpha}) = s(\vec{r})/n$. The expression for the spin current (y-dependent) in terms of the density spin polarization becomes

$$\vec{j}_s(y) = s_0(e\mu\vec{E} - eC_d / \Delta_s\hat{y})\exp(-y/\Delta_s = s_0(\vec{j} + \vec{j}_d)\exp(-y/\Delta_s) \tag{7}$$

The spin-induced Hall effect, derived from the concept of the anomalous Hall effect (AHE), has recently been proposed to be a useful tool for electrically detecting spin currents in paramagnetic materials [7]. However, in the derivation, he assumed that the charge and spin transport are diffusive, i.e. by neglecting the electric field effect, in the semiconductor. It was predicted that, if a spin-polarized current is present in a semiconductor, a spin-dependent transverse Hall-like electric field can be generated by spin-orbit (SO) coupling without an external magnetic field [2]. This is similar to the electrical current induced spin-polarization [4]. To see this transverse field in the drift-diffusion and different electron-statistical regimes, we start with the following expression for the current density, obtained from the approximate form of the Boltzmann equation for the relaxation time of each spin species in magnetic metals by inserting the distribution function as a sum of equilibrium and nonequilibrium distributions and including a spin-dependent anomalous velocity contribution $\vec{\omega}_{s,\alpha}(\vec{v})$ to account for the SO scattering in the definition of the current

$$\vec{j}_\alpha(\vec{r}) = (2\pi)^{-3}\int d^3\vec{v} f_\alpha(\vec{r},\vec{v})\{\vec{v} + \vec{\omega}_{s,\alpha}(\vec{v})\}:$$

$$\vec{j}_\alpha(\vec{r}) = \sigma_\alpha\vec{E}_\alpha(\vec{r}) + \sigma_{s,\alpha}\vec{E}_\alpha(\vec{r}) \times \alpha \ , \tag{8}$$

where $\vec{\omega}_{s,\alpha}(\vec{v}) = \eta\vec{v} \times \alpha$, $\eta = m\zeta / \tau_\alpha$, ζ is the SO coupling constant and $\sigma_{s,\alpha}$ is the spin-dependent Hall conductivity. Although Equation (8) is derived for magnetic metals, it is also valid for nonmagnetic materials when the longitudinal current is spin-polarized. The transverse open-circuit condition requires that the current for each spin channel must vanish at the boundaries. Taking the longitudinal and transverse components of the current density in the y- and x-directions for two spin channels from Equation (8) and using the transverse open-circuit boundary condition, we obtain, after a simple algebra with $\sigma_\alpha = \sigma_{-\alpha} = \sigma$ and $\sigma_{s,\alpha} = \sigma_{s,-\alpha} = \sigma_s$, an expression for the spin-induced transverse Hall field (E_{sH}):

$$E_{sH}(y) = -\frac{s_0\sigma}{(\sigma^2 - \sigma_s^2)}[e\mu E + eC_d / \Delta_s]\exp(-y/\Delta_s). \tag{9}$$

As known from the literature [15], this field originates from the induced non-equilibrium magnetization and consists of contributions from a left-right asymmetry skew-scattering of the spin-polarized charge carriers and a side-jump that the charge carriers undergo at each and after some scattering events.

For the spin and charge accumulating at the boundaries, a distance *b* apart, of the device sample, the transverse Hall voltage $V_s(y)$ is thus obtained as

$$V_s(y) = E_s(y)b = -\frac{b\sigma p_0}{(\sigma^2 - \sigma_s^2)}[en\mu E + enC_d / \Delta_s]\exp(-y/\Delta_s) \qquad (10)$$

where $(\Delta_s)^{-1} = -(\mu E/2C_d) + \sqrt{(\mu E/2C_d)^2 + 1/\delta_s^2}$ and $p_0 = p(y = o)$ is the initial spin polarization. It should be noted here that although the maximum optically polarization for a unstrain bulk sample is expected to be 50% in theory, the maximum experimentally observed to be ~40% [16]. However, the initial polarization obtained by electrical methods is much below than that and varies with the properties of the contact materials and semiconductor host and with the processes used for the injection [17].

RESULTS AND DISCUSSION

Spin Current And Spin-Induced Hall Field

The transverse Hall field E_{sH}, derived in Equation (9) or Hall voltage V_s in Equation (10) is the spin-induced Hall effect owing to spin polarization of the generated longitudinal current. The injected spin current is the source of this Hall current, and E_{sH} or V_s can be a measure of the spin generation or spin current in the device. Equation (10) shows that the device can detect spin current through the measurement of the spin-induced Hall effect. We calculate the spin current and Hall field as a function of electric field temperature (using the Einstein relation: $e\beta C_d = \mu$ for C_d) for a micrometer-sized Hall bar. In the calculation of Hall field, we used the reported values of the Hall and spin Hall conductivities, and the intrinsic spin diffusion length [1,18,19]. For the later one, we used an average value obtained from the optical and electrical measurements [1,19].

We now analyse the electron-statistical regime to which our transport processes belong. To do this, we define the degenerate (DG) and nondegenerate (NDG) regimes as $DG : \gamma \geq 1$ and $NDG : \gamma \leq 1$, where $\gamma = \beta^{-1}E_F$, $\beta^{-1} = k_B T$ is the thermal energy and $\in_F = \hbar^2 k_F^2 / 2m^*$ is the Fermi energy ($m^* = 0.076\, m_0$ for GaAs, where m^* is the electron effective mass and m_0 is the free electron mass). In Figure 2, we plot γ as a function of carrier density for various temperatures, where the intermediate or degenerate-nondegenerate crossover regime ($\gamma \approx 1$) is shown. As can be seen, the processes within our density and temperature limits are in the degenerate regime.

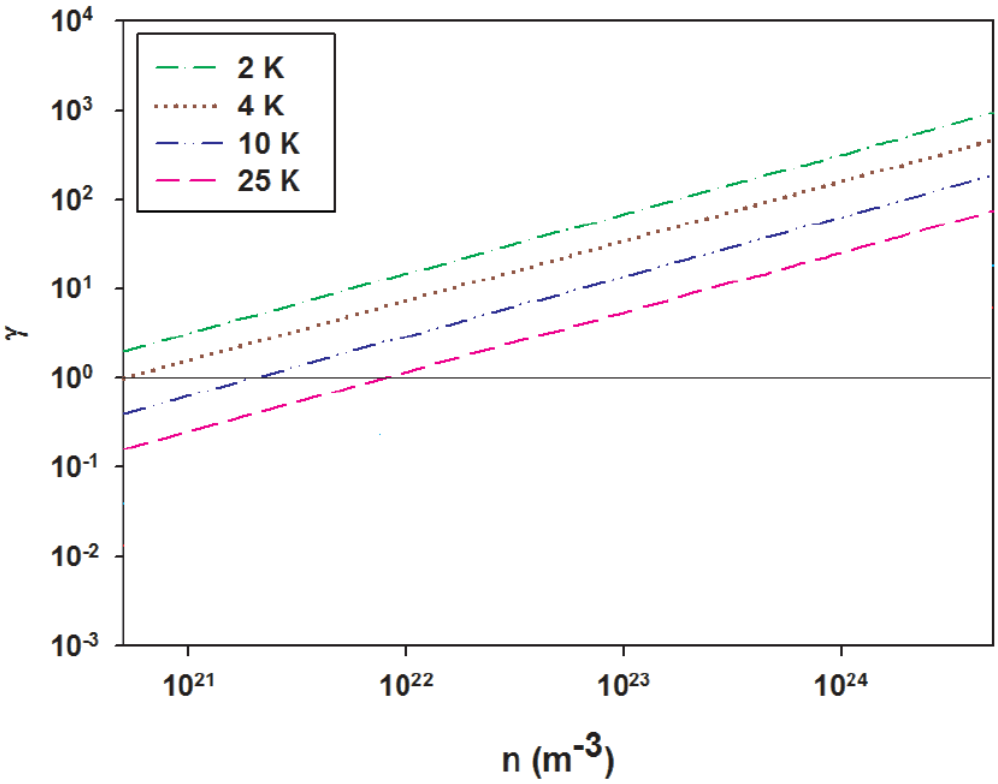

Figure 2. Plot of γ as a function of carrier density for various temperatures. The degenerate-nondegenerate crossover is indicated by a black solid line.

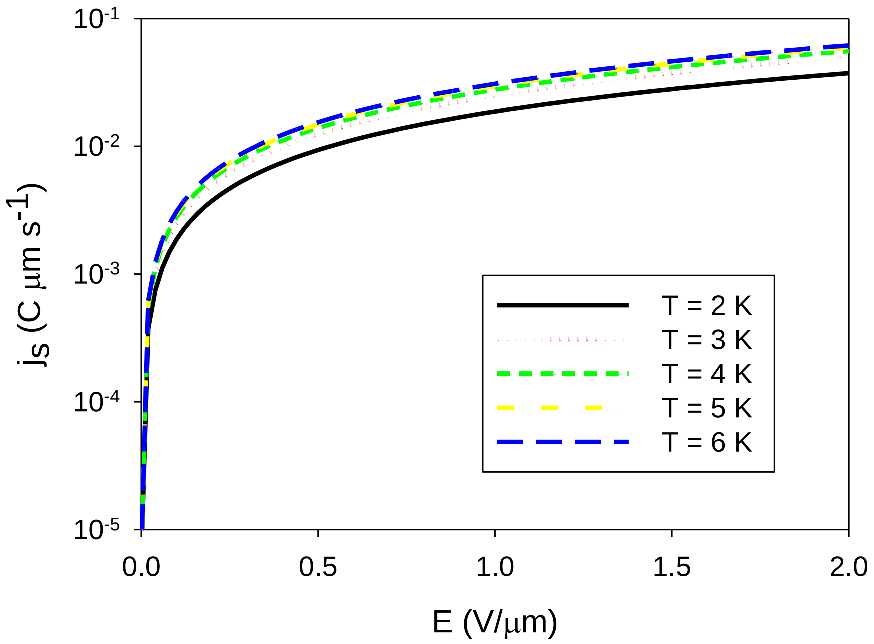

Figure 3. Spin current (normalized by n_0) as a function of electric field for different temperature. The value of the mobility μ=2300 cm^2 V^{-1} s^{-1}, characteristic of $1x10^{18}$ cm^{-3} Si-doped GaAs [1].

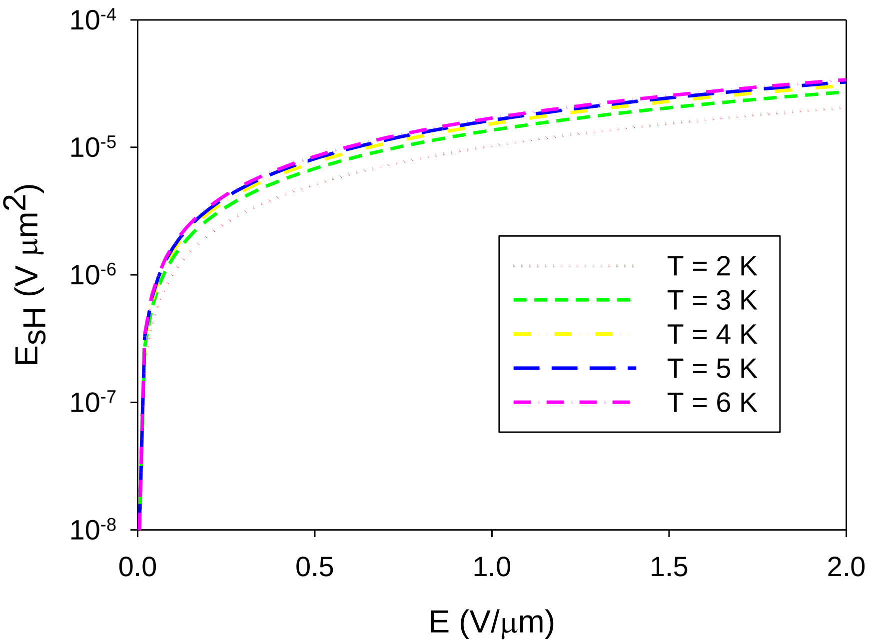

Figure 4. Spin-induced Hall field as a function of electric field for different temperatures. In the calculation, σ =30 $(\Omega cm)^{-1}$ and σ_{sH} =5x10^{-3} $(\Omega cm)^{-1}$ are taken from [18].

The calculated spin current and spin-induced Hall field in dependences of longitudinal electric field and temperature are shown in Figs. 3 and 4. As can be seen, both spin current and Hall field increase with increasing the strength of longitudinal electric field and temperature in the degenerate regime. However, as expected, both the spin current and spin-induced Hall field at higher external electric-field is found to be saturated. It should be noted that the spin current or transverse Hall field has two current contributions: one is the drift current $j = ec\mu E$ and another is the diffusion current $j_d = ecC_d / \Delta_s$, and both currents contributing additively to the total current ($j + j_d$) in the down stream direction since they are in the same direction along y. As can be seen, the diffusion current decreases with E while the drift current increases. When E is very large, $1/\Delta_s \approx 0$, and the diffusion current is zero, so that only the drift current contributes to the spin current and hence to the transverse field. It is important to note that in order for the diffusion contribution become significant, the electric field must therefore be very weak. However, due to the drift-diffusion competing effect, an increase of spin current with increasing E is a problem, as pictured in Figure 5, where the drift current j and diffusion current j_d are reduced by the term neC_d (primes denote their reduction).

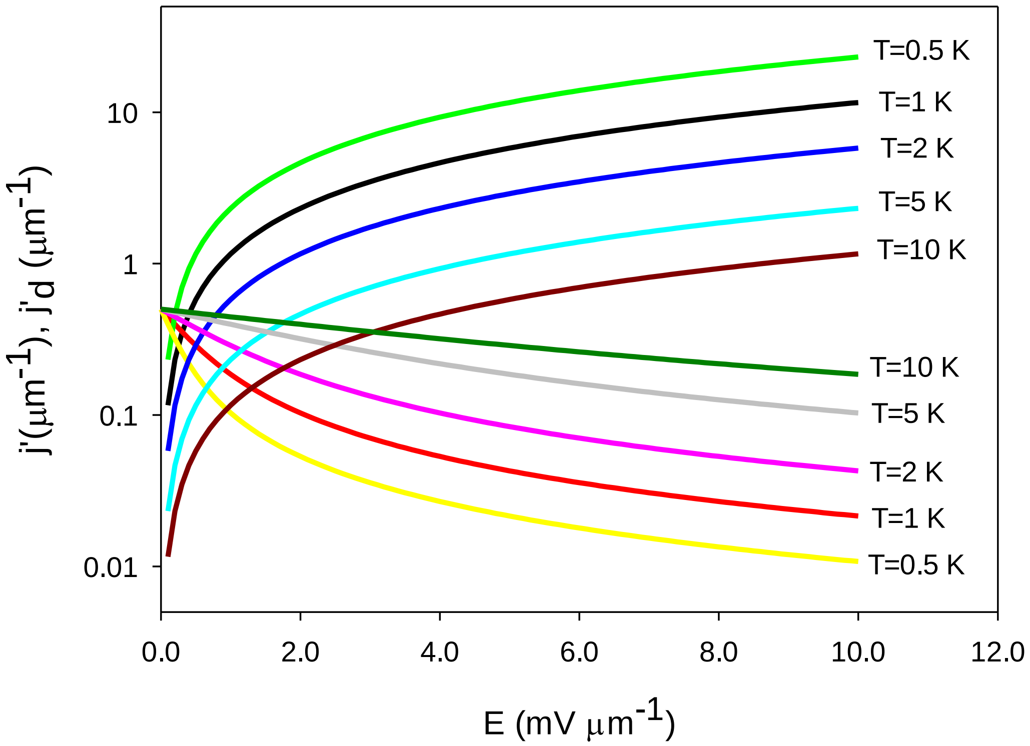

Figure 5. Drift current (diffusion current) increases (decreases) with the electric field at different temperatures. There is a crossover field for a temperature, where the drift current and diffusion current are the same.

How To Increase The Spin Current?

As there is a difficulty in enhancing the spin current by increasing the strength of the electric field, we search for an alternative way. We now consider the relationship between the mobility and the diffusion coefficient. Since the diffusion and mobility of both spin and charge in doped semiconductors are determined by the properties of a single carrier species, one can relate them through the generalized Einstein relation, which for degenerate systems can be approximated [20-21] as $C_d \approx 2\mu/(e\beta)\Im_{1/2}(\gamma)/\Im_{-1/2}(\gamma)$, where $\gamma = \beta(\in_F - \in_{0,-\alpha})$, $\in_{0,-\alpha}$ denotes the bottom-edge energy of the conduction band for the spin $-\alpha$, and $\Im_c(\gamma)$ are the Fermi integrals $\Im_c(\gamma) = 2/\sqrt{\pi}\int_0^\infty z^c[1+\exp(z-\gamma)]^{-1}dz$ with c= ±1/2. When $\gamma >> 1$, which is the case for the highly DG systems, $\Im_c(\gamma) \approx 2/\sqrt{\pi}\gamma^{c+1}/(c+1)$ and the expression for the diffusion coefficient becomes $C_d = (2/3)\mu\gamma/(e\beta) = (2/3)\mu(\in_F - \in_{0,-\alpha})/e$, which shows that $e\beta C_d >> \mu$. The above condition suggests a possible way to enhance the spin current and hence increase the spin-induce Hall voltage. Since for degenerate systems $e\beta C_d >> \mu$, a way to increase the spin current for a given E would be to use the degenerate regime by, for example, lowering the temperature. Increasing C_d in this way would increase the diffusive contribution without any change of the drift contribution. The results are consistent with those obtained in the recent experiments and published in the literature [18,22,23]. However, when $\gamma << -1$, $\Im_c(\gamma) \approx \exp(\gamma)$, which applies to the Maxwell-Boltzmann Statistics of the nondegenerate systems and the above expression for C_d simply gives the well-known Einstein relation $\mu = e\beta C_d$.

CONCLUSION

A semiconductor device for the electrical detection of spin current was studied theoretically. The device was designed and sketched, and techniques for injection and generation of spin current were discussed. A drift-diffusion equation for the spin density distribution in the device was derived, and electric field effects on spin transport of injected spin was analysed. In the drift-diffusion regime, expressions for the spin current and spin-induced transverse Hall voltage arising from the injected or generated spin-polarized current were derived. The spin current and Hall voltage as a function of temperature in the degenerate regime were studied. The results were discussed by searching the possible ways of enhancing the effects. The results, however, suggest an electrical or voltage probe of the spin-induced Hall current and thus a process of increasing spin current in semiconductors. In the model device, the spin current was injected at the longitudinal terminals (source) either electrically or optically and its detection was obtained electrically at the transverse Hall terminal (drain). Further systemic theoretical investigations and 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.

REFERENCE

1 Awschalom, D., & Loss, D. 2002. *Semiconductor spintronics and quantum computation*. Springer Science & Business Media.

2 Mott, N. F. 1936. The resistance and thermoelectric properties of the transition metals. *Proceedings of the Royal Society of London. Series A-Mathematical and Physical Sciences*, *156*(888), 368-382.

3 Datta, S., & Das, B. 1990. Electronic analog of the electro-optic modulator. *Applied Physics Letters*, *56*(7), 665-667.

4 Dyakonov, M. I., & Khaetskii, A. V. 2008. Spin hall effect. *Spin physics in semiconductors*, 211-243.

5 Idrish Miah, M. 2008. Semiconductor spintronics and its requirements. *Journal of optoelectronics and advanced materials*, *10*(10), 2487-2493.

6 Xiong, Z. H., Wu, D., Valy Vardeny, Z., & Shi, J. 2004. Giant magnetoresistance in organic spin-valves. *Nature*, *427*(6977), 821-824.

7 Hirsch, J. E. 1999. Spin hall effect. *Physical review letters*, *83*(9), 1834.

8 Miah, M. I. 2008. Drift-diffusion crossover and the intrinsic spin diffusion lengths in semiconductors. *Journal of Applied Physics*, *103*(6).

9 Pershin, Y. V. 2004. Drift–diffusion approach to spin-polarized transport. *Physica E: Low-dimensional Systems and Nanostructures*, *23*(1-2), 226-231.

10 Van Son, P. C., Van Kempen, H., & Wyder, P. 1987. Boundary resistance of the ferromagnetic-nonferromagnetic metal interface. *Physical Review Letters*, *58*(21), 2271.

11 Valet, T., & Fert, A. J. P. R. B. 1993. Theory of the perpendicular magnetoresistance in magnetic multilayers. *Physical Review B*, *48*(10), 7099.

12 Schmidt, G., Ferrand, D., Molenkamp, L. W., Filip, A. T., & Van Wees, B. J. 2000. Fundamental obstacle for electrical spin injection from a ferromagnetic metal into a diffusive semiconductor. *Physical Review B*, *62*(8), R4790.

13 Fert, A., & Jaffres, H. 2001. Conditions for efficient spin injection from a ferromagnetic metal into a semiconductor. *Physical Review B*, *64*(18), 184420.

14 Miah, M. I., Kityk, I. V., & Gray, E. M. 2007. Detection and study of photo-generated spin currents in nonmagnetic semiconductor materials. *Acta materialia*, *55*(18), 6392-6400.
15 Chazalviel, J. N., & Solomon, I. 1972. Experimental evidence of the anomalous Hall effect in a nonmagnetic semiconductor. *Physical Review Letters*, *29*(25), 1676.
16 Miah, M. I. 2011. Optical spin generation/detection and spin transport lifetimes. *Materials Science and Engineering: B*, *176*(3), 252-255.
17 Miah, M. I. 2009. Low-temperature annealed ohmic contacts to Si-doped GaAs and contact formation mechanisms. *Materials Chemistry and Physics*, *113*(2-3), 967-970.
18 Kato, Y. K., Myers, R. C., Gossard, A. C., & Awschalom, D. D. 2004. Observation of the spin Hall effect in semiconductors. *science*, *306*(5703), 1910-1913.
19 Miah, M. I. 2008. Diffusive to drift-diffusion crossover of spin transport in the low-field regime. *Applied Physics Letters*, *92*(9).
20 Shur, M. 1990. *Physics of Semiconductor Devices*. Prentice-Hall, Englewood Cliffs, & New Jersey.
21 Miah, M. I. 2008. Spin drift-diffusion and its crossover in semiconductors. *Spintronics: Materials, Applications and Devices*, 231-244.
22 Miah, M. I. 2007. Observation of the anomalous Hall effect in GaAs. *Journal of Physics D: Applied Physics*, *40*(6), 1659.
23 Dyakonov, M. I. 2007. Magnetoresistance due to edge spin accumulation. *Physical Review Letters*, *99*(12), 126601.