Spin transport and precession in semiconductors in the drift-diffusion regime

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Abstract. We present a theoretical analysis of spin transport in semiconductors in the drift-diffusive regime. We investigated spatial distributions of spin polarization and spin current under electrical injection and in presence of magnetic field. Numerical evaluations made for silicon highlight its strong potential for spintronic applications: the electron spin length at room temperature can spread over several microns and a rather weak magnetic field (of the order of 10 mT) can strongly modify the injected spin distribution in the structure.

1. Introduction
Spintronics have received considerable attention last decades thanks to its innovative potential applications in many fields such opto- and nanoelectronic engineering, quantum computation and data storage. It promises a reduction in energy consumption, high-speed operation and easy device integration. With recent advances in various nanofabrication techniques \cite{1,4}, much work has been devoted to spintronics taking aim at the elaboration of reliable devices such as Magnetic Random Access Memories (MRAMs).

The approach of spintronics involves the intrinsic angular momentum of conduction electrons (spins) as an additional degree of freedom to generate new functionalities of devices \cite{5-10}. In those lines, Datta and Das proposed a device in which spin polarized electrons are electrically injected from a ferromagnetic material into a semiconductor, drift along the device without losing their spin orientation, and are finally collected by the same kind of ferromagnetic material/semiconductor junction \cite{11}. One can manipulate the electrons spin for information processing by applying some perturbation such as an external magnetic field or another equivalent effect (Rashba effect for example). By virtue of its operating principle, such device is commonly called "spin transistor". Thus, the key challenges for the spin transistor achievement lie in the following points: spin injection from ferromagnetic metals to semiconductors, spin transport in semiconductors, spin processing, and spin detection.

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Spin injection from a ferromagnetic material into a semiconductor is not a trivial issue. The Schottky barrier formed by the metal-semiconductor contact prevents the injection of electrons from the metal into the conduction band of the semiconductor. To overcome this issue, the insertion of a thin insulating layer between the ferromagnetic metal and the semiconductor was put forward in order to unpin the electrochemical potential at the ferromagnetic metal/semiconductor interface [12,13]. In these structures, the spin-polarized electrons get through this insulating layer by tunneling. Moreover, the insulating layer could act as a physical barrier against the metal diffusion in the semiconductor, preventing then the formation of an interfacial dead layer able to lead up to spin depolarization. The introduction of a tunnel barrier helps to resolve the mismatch between the conductivities of the two materials, which strongly affects the current polarization in ferromagnetic metal/normal metal junctions [14]. The use of tunneling barrier paved the way for successful electrical spin injection into semiconductors [15-17], stimulating then many studies on the elaboration of nanoscaled thin oxide layers [18-21].

Spin transport and processing rely heavily on the spin length, namely the distance along which polarized electrons can travel without losing their spin orientation. The spin length depends on the semiconductor material, or more precisely on the spin relaxation time in it. As a matter of fact, the spin length limits the size of spintronic devices; it must exceed the distance between the spin injector and the spin detector in case of the spin transistor.

In the present paper, we focus on theoretical analysis of room temperature (RT) spin transport and spin processing by external magnetic field in semiconductors in pure drift-diffusion regime. The numerical evaluations made in the framework of the developed model for silicon highlights a high potential in spintronics of this fundamental material of modern microelectronics.

2. Analysis of spin transport and precession

We assume that, through the ferromagnetic/insulator/semiconductor junction, we inject in semiconductor unequal electrical current densities \( J_+ \) and \( J_- \) of electrons with spin-up and spin-down orientations respectively, and whose sum corresponds to the total current density \( J \). These densities give rise to the current polarization \( P_J \) as given by the following equation:

\[
P_J = \frac{J_+ - J_-}{J_+ + J_-} = \frac{\Delta J}{J}
\]

It’s essential to understand what is meant by the injected current densities \( J_+ \) and \( J_- \): Despite the fact that they refer to electrons current densities, these quantities are positive and correspond to modulus of spin-up and spin-down electrons current densities vectors \( \vec{J}_+ \) and \( \vec{J}_- \) that are oriented from the injector toward the detector.

Further, the carrier spin polarization \( P \) is characterized by the respective concentrations, \( n_+ \) and \( n_- \), of electrons with spin-up and spin-down orientations:

\[
P = \frac{n_+ - n_-}{n_+ + n_-} = \frac{\Delta n}{n}
\]

Where \( n \) is the total carrier concentration.

In this theoretical study, we consider that injected current densities \( \vec{J}_+ \) and \( \vec{J}_- \) as well as the electrical field into the semiconductor \( \vec{E} \) are oriented toward the y-axis as shown in figure 1.
2.1. Drift-diffusion spin transport

Assuming that the semiconductor material is free of magnetic impurities, the mobility \( \mu \) and the diffusion coefficient \( D \) of carriers are spin-independent and the difference in conductivities of electron gases with spin-up and spin-down orientations is given only by the difference in their concentrations. Thus, for n-type semiconductors, the spin transport is driven by the standard drift-diffusion and continuity equations for electrons with spin-up and spin-down orientations \([22,23]\) as following:

\[
\bar{J}_\pm = \sigma_\pm E + qD \cdot \bar{v}_n \tag{3}
\]

\[
\frac{\partial n_\pm}{\partial t} = -\left( \frac{1}{q} \nabla \bar{J}_\pm - \frac{n_\pm + n}{2\tau_s} \right) \tag{4}
\]

Where \( \sigma_\pm \) and \( \sigma_\pm \) stand for respective conductivities of spin-up and spin-down polarized electrons, \( q \) represents the elementary charge \( (q = +1.6 \times 10^{-19} \text{ C}) \) and \( \tau_s \) is the spin relaxation time.

In the case of weak injection, \( n \) could be regarded as constant everywhere in the semiconductor \( (\bar{v}_n = 0) \), and the diffusion contribution to the total current is insignificant. This approximation is consistent if we assume that the semiconductor doping is homogenous and no local excitation leading to carriers’ gradient is applied. Thus, in the stationary state \( (\frac{\partial n}{\partial t} = \frac{\partial^2 (\Delta n)}{\partial t^2} = 0) \), the previous equations lead to the following one-dimensional equations:

\[
D \frac{\partial^2 (\Delta n)}{\partial y^2} - \frac{J}{q n} \frac{\partial (\Delta n)}{\partial y} - \frac{\Delta n}{\tau_s} = 0 \tag{5}
\]
Equation (5) is equivalent to the drift-diffusion equation obtained in [22,23]. The latter usually involves the electric field inside the semiconductor, which is a quantity difficult to measure. Therefore, we prefer to characterize the electron motion in semiconductor by the total current density \(J\), since it is easily measurable in experiment. Solutions of equations (5) and (6) are explicit and provide the stationary distributions of differences between spin-up and spin-down populations’ concentrations \(\Delta n\) and current densities \(\Delta J\) as following:

\[
\Delta n = A_1 \exp\left(-\frac{y}{l_s}\right) + A_2 \exp\left(\frac{y}{l_s}\right)
\]

\(7\)

\[
\Delta J = C_1 \exp\left(-\frac{y}{l_s}\right) + C_2 \exp\left(\frac{y}{l_s}\right)
\]

\(8\)

Where \(A_1, A_2, C_1\) and \(C_2\) are constants depending on boundary conditions, and \(l_s\) and \(l_b\) are characteristic spin lengths given by the expression:

\[
l_{s,0} = \sqrt{D l_s} \left[\sqrt{\gamma^2 + 1} - \gamma\right]
\]

\(9\)

The dimensionless quantity \(\gamma\) is defined by the expression:

\[
\gamma = \frac{J}{2qn} \left(\frac{\tau_s}{D}\right)^{1/2}
\]

\(10\)

From a physical point of view, the parameter \(\gamma\) is related to the ratio of electron drift velocity \(v_{\text{drift}} = \frac{J}{qn}\) and electron spin diffusion velocity \(v_{\text{diff}} = \left(\frac{D}{\tau_s}\right)^{1/2}\), or the ratio of electron drift length \(l_{\text{drift}} = v_{\text{drift}} \cdot \tau_s\) and the spin diffusion length \(l_{\text{diff}} = v_{\text{diff}} \cdot \tau_s\) as following:

\[
\gamma = \frac{v_{\text{drift}}}{2 \cdot v_{\text{diff}}} = \frac{l_{\text{drift}}}{2 \cdot l_{\text{diff}}}
\]

\(11\)

The lengths \(l_{\text{drift}}\) and \(l_{\text{diff}}\) correspond respectively to the distances over which the spin can drift and diffuse during the relaxation time \(\tau_s\).

In the case of a semi-infinite semiconductor extended along positive y-axis \((A_2 = C_2 = 0)\), carrier spin and current polarizations decrease exponentially with a decay rate given by the characteristic spin length \(l_s\). Thus, the found expression yields the electrons spin polarization \(P\):

\[
P = \left(\frac{\Delta n}{n}\right)_{0} \exp\left(-\frac{y}{l_s}\right)
\]

\(12\)

Where \((\Delta n)_{0}\) corresponds to the difference between spin-up and spin-down concentrations at injection \((\Delta n)_{0} = \Delta n(y=0))\).

In the case of silicon, the RT spin length \(l_s\) is presented in figure 2 as a function of total current density of injected electrons \(J\). The used value for \(\tau_s\) is \(10^8\) s and it corresponds to that measured, at
ambient, for low-doped n-type silicon (in the range of $7 \times 10^{14}$ cm$^{-3}$ to $8 \times 10^{16}$ cm$^{-3}$) by electron spin resonance experiments [24]. According to this figure, one can notice that, for weak injected current ($\gamma \ll 1$), the $l_s$ value tends to the classical spin diffusion length $l_{\text{diff}}$ which is about 5.5 $\mu$m (for $J = 0$ in figure 2). This result is consistent with experimental measurements showing that the spin can diffuse in silicon over several microns at ambient [7,8], and represents an excellent prospect since the typical feature sizes of silicon integrated circuits are ranging from several microns down to hundreds of nanometers. In addition, the spin length increases with stronger injected current ($\gamma \gg 1$) and tends to the asymptotic value of the spin drift length $l_{\text{drift}} = (\tau_s / q n) J$. This situation is equivalent to that described in [23] for strong electrical field into the semiconductor.

It should be emphasized that the electron spin polarization $P$ and electron current polarization $P_J$ do not have the same behavior. Taking into account the fact that the difference of conductivities between spin-up and spin-down electrons depends on the concentrations difference, the relationship between these polarizations is obtained according to equation (6):

$$P_J = P - \frac{D}{v_{\text{dop}}} \frac{\partial (P)}{\partial y}$$  \hspace{1cm} (13)

Figure 3 shows distributions inside the semiconductor of spin and current polarizations, in the case of low-doped n-type silicon, for different injected current densities. The curves of figure 3 are obtained when normalizing the current density to that of injection: $P_J (\gamma = 0) = 1$.

The left graph of figure 3, corresponding to a donor concentration of $10^{16}$ cm$^{-3}$, shows that spin and current polarizations increase with injected current since the latter increases the distance over which
electrons can travel with weak spin attenuation. Indeed, apart from the concentrations difference between spin-up and spin-down electrons, the observed difference between $P$ and $P_j$ depends also on the difference of velocities of the two polarized electron populations. The figure 3, shows the distributions of electron polarizations under the weak injection hypothesis ($n$ remaining constant over semiconductor) and for low donor doping concentrations (in the range corresponding to $\tau_s = 10^{-8}$ s as considered above). As shown in this graph, concentrations of spin-up ($n_+$) and spin-down ($n_-$) electrons are different at injection from the ferromagnetic metal and tend to even out because of spin relaxation ($P(y \to \infty) = 0$). From data of the figure 3, we can see the influence of the diffusion on differences between spin-up and spin-down currents and concentrations: After injection of spin-polarized electrons, the diffusion tends to enhance the current of majority-injected spins regarding the minority one, in contrast to the difference in concentrations, which is reduced.

Figure 3. RT distributions of spin polarizations (in solid lines) and normalized current polarizations (in dashed lines) in n-doped silicon for different injected current densities ($10^5$ A.m$^{-2}$, $10^6$ A.m$^{-2}$, and $10^7$ A.m$^{-2}$) at $n = 10^{16}$ cm$^{-3}$ (left graph) and for different concentrations ($10^{15}$ cm$^{-3}$, $10^{16}$ cm$^{-3}$, and $5\times10^{16}$ cm$^{-3}$) at $J = 10^6$ A.m$^{-2}$ (right graph). Spin relaxation time is $10^{-8}$ s.

2.2. Magnetic field-induced spin precession
We investigated injected electrons spin behavior and distribution when an external magnetic field is applied perpendicularly to the spin orientation. For this purpose, we introduce the mean spin vector of injected electrons defined as: $\bar{S} = \sum s_i/n$, where $s_i$ are spins of individual electrons.

Without magnetic field, the mean spin is given by the spin polarization as following:

$$S = \frac{\|\bar{S}\|}{n} = \frac{1}{n} \left[ n_+ \left( \frac{1}{2} \right) + n_- \left( -\frac{1}{2} \right) \right] \frac{P}{2}$$

(14)

In the presence of a magnetic field $\bar{B}$ non collinear to the injected spin orientation ($\bar{B} \times \bar{S} \neq \bar{0}$), the coupling between $\bar{B}$ and $\bar{S}$ leads to the precession of injected spins around $\bar{B}$ with the Larmor
frequency $\tilde{\Omega} = \frac{g \mu_B B}{\hbar}$, where $g$, $\mu_B$ and $\hbar$ stand respectively for the $g$ factor of conduction electrons, the Bohr magneton, and the reduced Planck constant. Moreover, applying an external magnetic field induces Lorentz forces that can modify the orbital motion of electrons. In the case of weak magnetic fields, we can assume that the contribution of Lorentz forces has a weak influence to be taken into account. Thus, inserting the coupling term in equation (5) leads to the following equation:

$$D \frac{\partial^2 \langle \mathbf{S} \rangle}{\partial y^2} - \frac{q n}{\tau_s} \frac{\partial \langle \mathbf{S} \rangle}{\partial y} - \frac{1}{\tau_s} \mathbf{S} + \frac{g \mu_B B}{\hbar} \mathbf{S} \times \mathbf{S} = 0$$

(15)

Different orientations of magnetic field and injected spins are possible. However, in the case of the planar structure presented in figure 1, a rather weak in-plane magnetic field can perturb the magnetization of the ferromagnetic layer, for example by changing the orientation of magnetization from x- to y-orientation in the case of a magnetic field along the y-direction. To put magnetization perpendicular to the layer is much more difficult, a magnetic field stronger than 1 Tesla is needed. Therefore, the orientation of $\mathbf{B}$ parallel to z-axis is preferable: it can induce a rapid Larmor precession of spins inside the semiconductor without noticeable variation of magnetization in the ferromagnetic layer.

By resolving equation (15) in the case of a semi-infinite semiconductor [25] under an external magnetic field along the z-direction, we find the general expressions of the spin components $S_x$ and $S_y$ as following:

$$\begin{align*}
S_x &= \frac{\langle \Delta n \rangle_0}{2n} \exp \left( -\frac{y}{l_s} \right) \cos \left( \frac{y}{l_s} \right) \\
S_y &= \frac{\langle \Delta n \rangle_0}{2n} \exp \left( -\frac{y}{l_s} \right) \sin \left( \frac{y}{l_s} \right)
\end{align*}$$

(16)

Where the spin characteristic attenuation length $l_s$ and rotation length $l_r$ are described by the following expressions:

$$l_s = \frac{l_{\text{diff}}}{\left[ (y^2 + 1)^2 + \left( \frac{\tau_s \Omega}{y^2 + 1} \right)^2 \right]^{1/4}} \cos \left[ \frac{1}{2} \arctan \left( \frac{\tau_s \Omega}{y^2 + 1} \right) \right] - y$$

(17)

$$l_r = \frac{l_{\text{diff}}}{\left[ (y^2 + 1)^2 + \left( \frac{\tau_s \Omega}{y^2 + 1} \right)^2 \right]^{1/4}} \sin \left[ \frac{1}{2} \arctan \left( \frac{\tau_s \Omega}{y^2 + 1} \right) \right]$$

(18)

Figure 4 illustrates schematically the precession of spin vector along the semiconductor channel in the case of an external magnetic field oriented along the z-axis. The determined solutions reduce, for zero magnetic field, to the only x-component of spin ($l_s \rightarrow 0$ and $l_r \rightarrow \infty$) corresponding to pure drift-diffusive transport as described by equations (12) and (14).
According to equations (17) and (18), the characteristic decay length $l_A$ and spatial period $l_R$ depend on the applied magnetic field and the injected electron current. Figures 5 and 6 plot RT attenuation and oscillation lengths in n-silicon (with a dopant concentration of $10^{16}$ cm$^{-3}$) as functions of magnetic field and electrons injected density.

As shown in figure 5, the attenuation length $l_A$ is strongly affected by the quite weak magnetic field (of several mT). This is because the electrons with the spin-up and spin-down orientation progress in semiconductor with different velocities (as seen in the drift-diffusion spin transport), which leads to
the spatial decoherence of spin precessions. For higher magnetic field, the strong contribution of the spin-magnetic field coupling compared to diffusion-drift competing mechanism ($\Omega \gg \frac{j^2}{q\mu D}$) results in the decreasing of the attenuation length. This result is consistent with equation (15) and clearly evidenced in the right graph of figure 5 showing the attenuation length as a function of injected current density for different values of applied magnetic field.

As documented in figure 6, the oscillation length decreases with the applied magnetic field, and is almost the same for the injected current densities of $10^5$ A.m$^{-2}$ and $10^6$ A.m$^{-2}$. This result is very interesting from a practical point of view, since it shows the possibility to manipulate spins of low-doped silicon-based devices with different electrical characteristics (but operating in the above current density range) with the same magnetic field (that could be generated with a current line such in MRAMs). In addition, for weak magnetic field values, the linear trend of the log-log left graph of figure 6 indicates that the oscillation length is rather proportional to the inverse of weak applied magnetic field. Under strong magnetic fields, the spins precess with increasing spatial frequencies, shortening then the spatial period of the spin oscillations.

Moreover, as shown in the right graph of figure 6 for different values of magnetic field, in contrast with the attenuation length, the spatial rotation period $l_R$ is almost independent of the injected electron current density in the weak-injection range, and increases beyond.

Figure 6. Effect of external magnetic field and injected electrons current density on RT oscillation length of the spin for low-doped n-silicon ($n = 10^{16}$ cm$^{-3}$). Spin relaxation time is $10^{-8}$ s.

Figure 7 depicts the spatial distribution of the normalized $S_z$ spin component, in low-doped n-silicon ($n = 10^{16}$ cm$^{-3}$) at room temperature, for different values of applied magnetic field and injected current density.

As we can see in the left graph, under weak magnetic field, the spin oscillation can be clearly observed only for the relatively strong currents densities ($10^7$ A.m$^{-2}$), when the drift current dominates the diffusion one, increasing then the attenuation length (as shown in figure 5). For low current densities ($10^6$ A.m$^{-2}$), the spin oscillation is strongly damped and the effect of external magnetic field is reduced to a considerable reduction of the “effective” diffusion spin length. This effect is very strong and the
external magnetic field of several milli-Tesla can completely depolarize electrons approaching the spin detector, about one micron far from the injector.

Figure 7. RT spatial distributions of the normalized $S_x$ spin component, in low-doped n-type silicon ($n = 10^{16}$ cm$^{-3}$), for different values of transverse external magnetic field (0 T, 10 mT and 50 mT) and for injected current densities of $10^7$ A.m$^{-2}$ (left graph) and $10^6$ A.m$^{-2}$ (right graph). Spin relaxation time is $10^{-8}$ s.

3. Conclusion
We developed a drift-diffusive theoretical model of spin transport and spin precession under an external magnetic field in semiconductors, and we investigated carrier spin and current polarizations of electrons with spin-up and spin-down orientations. The developed analysis was used to make numerical evaluations for relatively low-doped silicon at room temperature. It was found that the spin length in silicon is about several microns at room temperature and increases with the drift current. Furthermore, a rather weak external magnetic field (of several milliTesla) strongly affects spin transport and thus can be used for spin processing in silicon-based spintronic devices.

Apart of being the most used material in semiconductor industry, the silicon is then found to be a promising material for spintronic applications, where the spin transport and the spin manipulation along relatively long and different distances are necessary.

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