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Spin injection and diffusion in silicon based devices from a space charge layer

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We have performed simulations on electron spin transport in an n-doped silicon bar with spin-dependent conductivity with or without the presence of an external electric field. We further consider three cases like charge neutrality, charge accumulation, and charge depletion at one boundary and found substantial differences in the spin transport behavior. The criteria determining the maximum spin current are investigated. The physical reason behind the transport behavior is explained. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4856056]

I. INTRODUCTION

The scaling of CMOS devices will reach fundamental limits in the near future, which necessitates the development of new technologies in semiconductor industry. Spin-based electronics (spintronics) is a promising successor technology which facilitates the spin as a degree of freedom and reduces the device power consumption.[1] Silicon, due to its long spin lifetime and well established processes and technology, is an ideal material for spintronics.[2] In order to design and fabricate high-performance spintronics devices, a comprehensive understanding of spin transport and injection properties of semiconductors is required. An evidence that an introduction of space charge effects at the interface boosts the spin injection by an order of magnitude was recently presented.[3] In this paper, we are able to reproduce the analytical solution of the classical spin drift-diffusion model without the presence of a space-charge at the boundary under arbitrary external electric field.[4] Additionally, our research is not restricted to charge neutrality and simulations are carried out considering charge accumulation and depletion at a boundary. We also find the existence of an upper threshold spin current, as already predicted,[5] under high spin accumulation. We compare this with the spin current under charge neutrality but varied spin polarization at the same boundary. The role of extra charge and screening are also discussed in this paper.

II. MODEL AND SIMULATION SETUP

A. Mathematical equations

A common transport model for spin drift-diffusion is considered. The up(down)-spin electron density contributes to the device current as[4]

$$J_{n_{\uparrow(\downarrow)}} = q\, n_{\uparrow(\downarrow)} \mu E + q D \nabla n_{\uparrow(\downarrow)}, \tag{1}$$

D is the electron diffusion coefficient, μ is the electron mobility (these parameters are assumed to be constant for up(down)-spin electrons), E denotes the electric field. μ ($1400\,\mathrm{cm^2V^{-1}s^{-1}}$) is kept invariant with electric field, and carrier concentration over the simulation domain. q is the elementary charge. The up (down)-spin concentration is described as $n_\uparrow(n_\downarrow)$. The electron concentration is thus defined as $n = n_\uparrow + n_\downarrow$ and the spin density $s = n_\uparrow - n_\downarrow$. We further define the spin polarization as $SP = \frac{s}{n}$. The charge (spin) current is described as $J_c(J_s) = J_{n_\uparrow} + (-)J_{n_\downarrow}$. The steady-state continuity equation for the up(down)-spin electrons including the spin scattering (τ denotes the spin relaxation time) reads[4]

$$\nabla \cdot J_{n\uparrow(\downarrow)} = \pm q \left(\frac{n_\uparrow - n_\downarrow}{\tau} \right). \tag{2}$$

The Poisson equation, coupled with the continuity equations, reads $\nabla \cdot E = -\frac{\rho}{\epsilon}$, where ρ denotes the charge density and ϵ is the electric permittivity of silicon.

The intrinsic spin diffusion length is known as $L = \sqrt{D\tau}$. Simulations are performed by the finite volume method (FVM) (Ref. 6) for a $3\,\mu$m n-silicon bar with $L = 1\,\mu$m having a doping concentration of $N_D = 10^{16}\,\mathrm{cm^{-3}}$. The voltage ($U$) is always applied opposite to the spin injection boundary.

B. Analytical solution

When charge neutrality (implying $n_\uparrow + n_\downarrow = N_D$) is considered at the boundaries, the general solution of the continuity equations for the spin density gives[4]

$$s = A_1 \exp\left(\frac{-x}{L_1}\right) + A_2 \exp\left(\frac{x}{L_2}\right), \tag{3}$$

$\lambda_1 = \frac{1}{L_1}$ and $\lambda_2 = \frac{1}{L_2}$ are the roots of the quadratic equation $\lambda^2 + \frac{\lambda \mu E}{D} - \frac{1}{L^2} = 0$. The constants A_1, A_2 are defined by the boundary conditions. The constants L_1, L_2 are given by

$$L_1(L_2) = \frac{1}{\mp \frac{|0.5E|}{V_{th}} + \sqrt{\left(\frac{|0.5E|}{V_{th}}\right)^2 + \frac{1}{L^2}}}, \tag{4}$$

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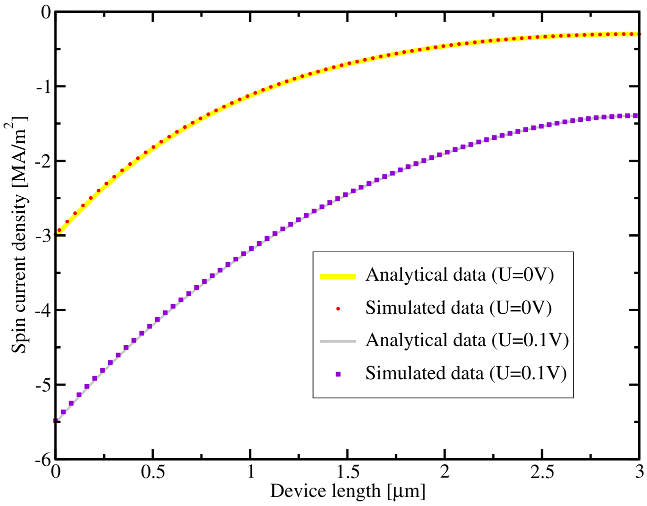

FIG. 1. Comparison of the spin current density between the simulated and the analytical data under charge neutrality. A spin polarization of 0.5 at the left boundary and an applied voltage U of $0V$ and $0.1V$ are assumed.

V_{th} is the thermal voltage. A good agreement between the simulated results and the analytical expression for the spin current density is obtained (Fig. 1).

III. RESULTS

When the presence of space charge at a boundary is scrutinized, Dirichlet boundary conditions of zero spin density (right boundary) and

$$\begin{bmatrix} n_\uparrow \\ n_\downarrow \end{bmatrix} = N_D \begin{bmatrix} \exp\left(\frac{\mu_{Chem}}{V_{th}}\right) \\ 0 \end{bmatrix}, \quad (5)$$

(left boundary) are assumed for the simulations (hence $SP = 1$ at the injection boundary). μ_{Chem} describes the chemical potential.[5] The injection ($\mu_{Chem} > 0$) or the release ($\mu_{Chem} < 0$) of charge always causes a non-zero charge current in the device even at the absence of an external electric

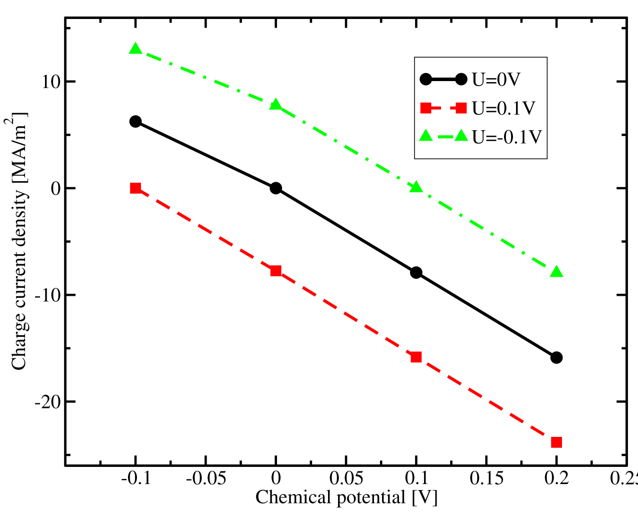

FIG. 2. The variation of the charge current density as a function of chemical potential and external voltage (U) as parameter. The boundary is given by Eq. (5).

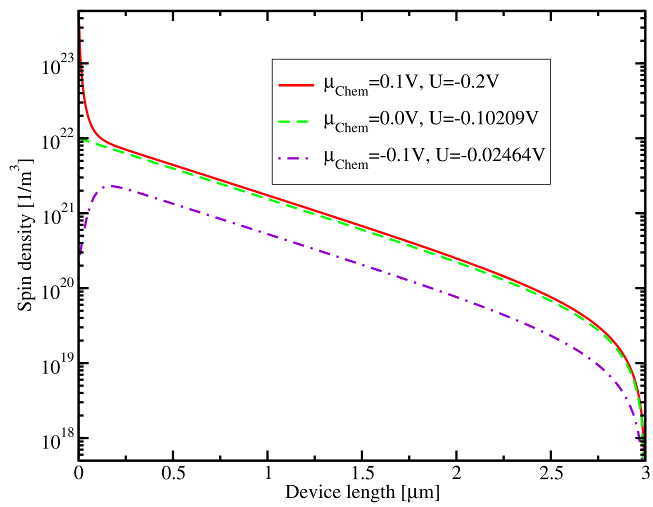

FIG. 3. Variation of the spin density with the boundary conditions given by Eq. (5). The charge current density is kept fixed ($7.9\,\mathrm{MA/m^2}$) by adjusting the voltage (U). It is evident that the spin density drops strongly during the depletion at interface and the bulk.

field. This charge current can be compensated by applying an external voltage, given by the equation,

$$U_c = -V_{th} \ln\left(\frac{n_\uparrow^0 + n_\downarrow^0}{N_D}\right), \quad (6)$$

$n_\uparrow^0(n_\downarrow^0)$ denotes the up(down)-spin electron concentration at the spin injection boundary. A considerable spin and charge accumulation (depletion) can thereby be introduced and the spin current can diffuse out of this region. This spin current can be tuned by varying the chemical potential.

The dependence of the charge current on the chemical potential at varied electric field is depicted in Fig. 2. The variations of the charge current with μ_{Chem}, when the device moves from accumulation to deep depletion, is caused by nonlinear effects in charge screening. Additional tuning of the voltage is done to sustain a fixed charge current (zero or non-zero). We observe a significant decrease of the spin density (Fig. 3) and the carrier concentration (Fig. 4) during the

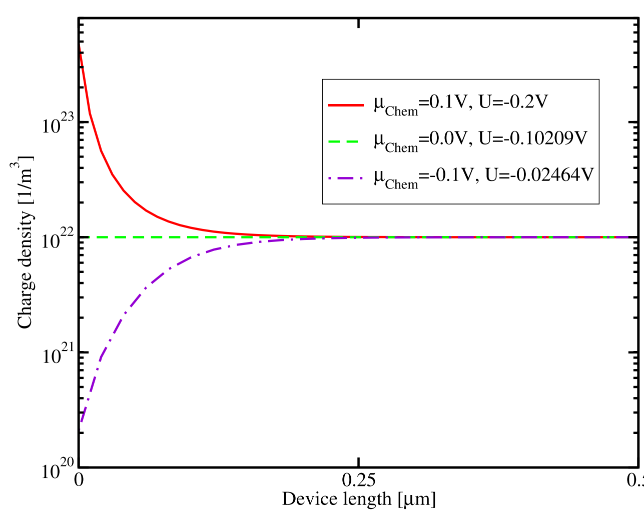

FIG. 4. Electron concentration assuming the same conditions as in Fig. 3.

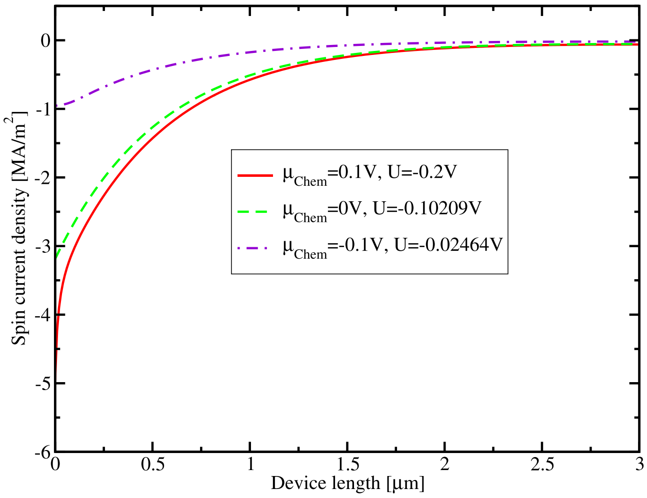

FIG. 5. Spin current density assuming the same conditions as in Fig. 3.

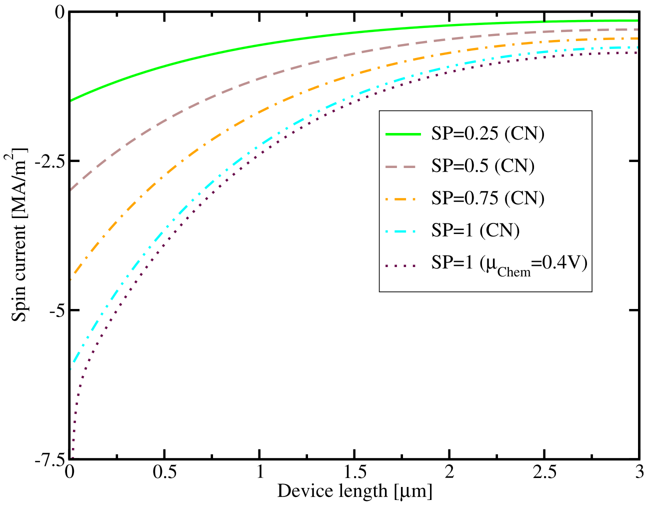

FIG. 6. Spin current density with *SP* (under charge neutrality *CN*). One plot is also shown considering high charge accumulation ($\mu_{Chem} = 0.4$V). The charge current is set zero.

depletion. Lack of carriers causes the spin current to decrease (Fig. 5) drastically under depletion compared to the accumulation regime even though the device charge current is fixed. Under accumulation, the spin current shows an upper threshold[5] (Fig. 5) and strong charge screening within the Debye length (λ_D, typically 41 nm) from the interface is noticed. The amount of spin current leaked from the accumulation region almost does not change in this case, even if the injection is increased.

Furthermore, we vary the spin polarization factor (*SP*) at the left boundary by maintaining the charge neutrality conditions. One can see from Fig. 6 that the spin current reaches its maximum, when *SP* is 1. It is also noticed that, when *SP* is 1, the spin current at λ_D from the interface for charge

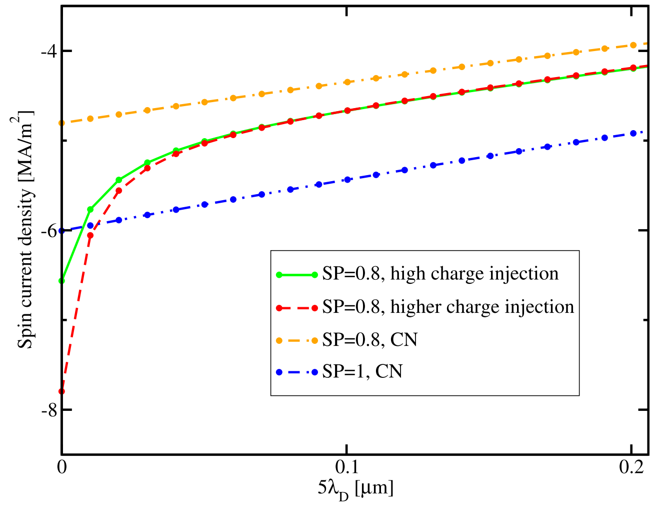

FIG. 7. Spin current density up to 5 times the Debye length λ_D from the left boundary. Both the charge neutrality *CN* and the charge accumulation are considered. Charge current is set zero.

accumulation is the same as for the charge neutral condition at the interface (Fig. 6). In contrast to[3] we find that if $SP < 1$, it is not possible to get a spin current in the bulk as high as for $SP = 1$ with charge neutrality, even under high spin current and charge accumulation at the interface. This may be due to an incompleteness of our model with respect to[3] which ignores the effective magnetic field in the semiconductor. The spin current at a distance about λ_D from the interface in the later case is equal to the interface spin current at charge neutrality provided *SP* is the same (Fig. 7).

IV. CONCLUSION

Spin injection in a semiconductor from a space charge layer is considered. Due to a lack of carriers the spin current in the bulk is reduced, when injected from a depletion layer. Because of screening the spin current injected from an accumulation layer cannot be larger than a certain upper critical current. The value of the critical current is determined by the spin current injected under charge neutrality at the same spin polarization.

ACKNOWLEDGMENTS

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