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Spin injection in a semiconductor through a space-charge layer

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ABSTRACT

The electron spin properties provided by semiconductors are of immense interest because of their potential for future spin-driven microelectronic devices. Modern charge-based electronics is dominated by silicon, and understanding the details of spin propagation in silicon structures is key for novel spin-based device applications. We performed simulations on electron spin transport in an n-doped silicon bar with spin-dependent conductivity. Special attention is paid to the investigation of a possible spin injection enhancement through an interface space-charge layer. We found substantial spin transport differences between the spin injection behavior through an accumulation and a depletion layer. However, in both cases the spin current density can not be significantly higher than the spin current density at charge neutrality. Thus, the maximum spin current in the bulk is determined by its value at the charge neutrality condition - provided the spin polarization at the interface as well as the charge current are fixed.

1. Introduction

The tremendous increase of computational power of integrated circuits is supported by the continuing miniaturization of semiconductor devices' feature size. However, with scaling approaching its fundamental limits the semiconductor industry is facing the necessity for new engineering solutions and innovative techniques to improve MOSFET performance. Spin-based electronics (spintronics) is a promising successor technology which facilitates the use of spin as a degree of freedom to reduce the device power consumption [1,2]. Moreover, the spintronic devices are expected to be faster and more compact.

Silicon, the main material of microelectronics, possesses several properties attractive for spintronics [3]: it is composed of nuclei with predominantly zero spin and it is characterized by weak spin–orbit interaction, which should result in a low relaxation rate accompanied by a longer spin lifetime as compared to other semiconductors. Since silicon technology is well established, it will help bringing silicon spin-driven devices to the market. Spin transfer in silicon over long distances has been demonstrated experimentally [4], and a large number of devices utilizing spin has already been proposed [5].

Regardless of the indisputable advantage in realizing spin injection, detection, and the spin transport in silicon at ambient temperature, several difficulties not explained within the theories are pending. One of them is an unrealistically high amplitude of the voltage signal corresponding to the spin accumulation in silicon obtained within the three-terminal spin injection/detection scheme [3]. Recently, an explanation based on the assumption that the resonant tunneling magnetoresistance effect and not the spin accumulation causes the electrically dependent spin signal in local three-terminal detection experiments, was proposed [6,7]. It remains to be seen, if the theory is able to explain all the data including the spin injection experiments through a single graphene layer, where the amplitude of the signal is consistent with the spin accumulation in silicon [8]. Alternatively, an evidence that a proper account of space-charge effects at the interface may boost the spin injection signal by an order of magnitude was presented [9].

In this paper we investigate the influence of the space-charge effects to boost spin injection in semiconductors. Considering charge accumulation and depletion at the spin injection boundary, we observe major differences in the spin current behavior. The existence of the upper threshold spin current under high spin accumulation [10] is confirmed. We demonstrate that the threshold spin current in the bulk is determined by the spin current value injected at the charge neutrality condition under the assumption that the spin polarization and the charge current are fixed. We show that in accumulation the ratio of the spin density s to the charge concentration n, or the spin polarization $P = s/n$, remains

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practically unchanged due to the narrow accumulation layer. Therefore, the spin and the spin current densities decay fast through the accumulation layer determined by the decrease of the charge concentration from its high value at the interface to the equilibrium value determined by the bulk donor concentration. The spin current in the bulk is determined by the spin polarization and the charge current density at the end of the accumulation layer, where the charge neutrality condition is fulfilled. In depletion, however, the situation can be more complex. In the case when the spin diffusion is against the electric field, the spin current remains constant through the depletion region. But, due to the large influx of the minority spins into the depletion layer the spin polarization decreases drastically which causes a significant reduction of the spin current in the bulk as compared to that at the charge neutrality condition. Thus, in both cases of spin transport through the depletion and accumulation region the spin current density cannot be significantly higher than the spin current density at the charge neutrality condition, the value of which is determined by the spin polarization at the interface and the value of the electric field.

We begin with a short review of the spin and charge drift–diffusion equations in the next section. In contrast to the highly nonlinear set of equations describing the transport in the language of chemical potentials [10] suitable for metals, we use the employed equations to describe the transport properties in semiconductors [11,12]. Due to its importance, the solution at the charge neutrality condition is presented next. The system of equations for the electrostatic potential, charge density, spin density, and currents are solved numerically to investigate the spin injection in depletion and accumulation. The boundary conditions used to introduce the non-equilibrium charge density at the interface and thus a nonzero total charge in the system distinguish our approach from the one employed in [12]. The analytical solution at the charge-neutrality condition is used in order to validate the numerical solution. Finally, a discussion of the numerical results is presented.

2. Model

The spin drift–diffusion model is successfully used to describe the classical transport of charge carriers and their spins in a semiconductor. The expression for up (down)-spin current, $J_{\uparrow(\downarrow)}$, can be written as [11]:

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

where D is the electron diffusion coefficient, μ is the electron mobility, E denotes the electric field, and e is the absolute charge of an electron. The up (down)-spin concentration is expressed as $n_\uparrow(n_\downarrow)$. The electron concentration is thus represented as $n = n_\uparrow + n_\downarrow$ and the spin density $s = n_\uparrow - n_\downarrow$. The electron (spin) current is defined as [11] $J_n(J_s) = J_\uparrow \pm J_\downarrow$.

The steady-state continuity equation for the up (down)-spin electrons including the spin scattering reveals [11]:

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

where $\tau_s = \frac{\tau}{2}$ is the spin relaxation time. The Poisson equation, defining the electric field, reads:

$$\nabla \cdot E = -e\frac{n_\uparrow + n_\downarrow - N_D}{\epsilon_{Si}}, \tag{3}$$

where ϵ_{Si} is the electric permittivity of silicon and N_D is the doping concentration. We denote V_{th} as the thermal voltage: $V_{th} = \frac{K_BT}{q}$, where K_B is the Boltzmann constant, T the temperature ($T = 300$ K), $q = e$. The intrinsic spin diffusion length is defined as $L = \sqrt{D\tau_s}$ and the diffusion coefficient D is related to the mobility by the Einstein relation $D = \mu V_{th}$. The charge current and the spin currents are:

$$J_n = en\mu E + eD\frac{dn}{dx}, \tag{4}$$

$$J_s = es\mu E + eD\frac{ds}{dx}. \tag{5}$$

The spin density affirms:

$$\frac{d^2s}{dx^2} + \left(\frac{1}{V_{th}}\right)\frac{d(sE)}{dx} - \frac{s}{L^2} = 0, \tag{6}$$

where both s and E are position dependent. The spin drift–diffusion equation must be solved self-consistently with the Poisson and charge transport equation.

2.1. Spin injection at charge neutrality

Eq. (6) as well as the charge drift–diffusion equation and the Poisson equation must be supplemented with appropriate boundary conditions. We consider charge and spin transport through a bar of length W. We assume that the spin density is zero at the right interface while the charge concentration is equal to N_D:

$$s(x = W) = n_\uparrow^W - n_\downarrow^W = 0,$$
$$n(x = W) = n_\uparrow^W + n_\downarrow^W = N_D.$$

Here, $n^w_{\uparrow(\downarrow)}$ is the up (down)-spin concentration at the right contact.

At the left boundary the spin value is kept constant:

$$s(x = 0) = s^0 = n_\uparrow^0 - n_\downarrow^0. \tag{7}$$

Here, $n^0_{\uparrow(\downarrow)}$ is the up (down)-spin concentration at the spin injection point. The electron concentration n^0 at the interface is defined by:

$$n(x = 0) = n_\uparrow^0 + n_\downarrow^0 = n^0. \tag{8}$$

These boundary conditions are different from the von Neumann boundary conditions used in [10] and allow to describe the spin current not only for an accumulation layer but also for a depletion layer. The set of the boundary conditions must be supplemented by defining the electrostatic potential difference U_c between the left and right boundary of the semiconductor bar, which defines the electrostatic field obtained by the Poisson equation.

By this, the same spin density value s^0 at the interface can be provided for different n^0. Therefore, the total charge at the interface n^0 offers an additional degree of freedom and allows to study the influence of the space-charge layer at the interface on the efficiency of the spin injection and transport in a semiconductor. If we affix $n^0 = N_D$, the charge neutrality at the interface (and as a consequence throughout the whole sample) is preserved. In this case, the electric field E will be constant throughout the bar and the expression for the electron charge current (4) is $J_c = eN_D\mu E$, where E is defined by the applied voltage and W as $E = U_c/W$. The general solution for the spin density is [11,10]:

$$s = A_1 \exp\left(\frac{-x}{L_d}\right) + A_2 \exp\left(\frac{x}{L_u}\right). \tag{9}$$

The constants A_1 and A_2 are defined by the boundary conditions. Here, the electric field dependent up (down)-spin diffusion length is given by:

$$L_u(L_d) = \frac{1}{\pm\frac{|eE|}{2K_BT} + \sqrt{\left(\frac{eE}{2K_BT}\right)^2 + \frac{1}{L^2}}}. \tag{10}$$

Therefore, $L_u(L_d)$ monotonically decreases (increases) with the applied electric field and its direction.