Spin Injection in Silicon: The Role of Screening Effects

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Spin injection in silicon and other semiconductors by purely electrical means is paramount for building spintronic devices. One of the methods is to inject spins from a ferromagnetic electrode. Recently, a robust spin injection from a ferromagnetic metal contact into a semiconductor has been performed at room temperature [1]. However, the magnitude of the spin accumulation signal obtained with the three-terminal measurement setup is several orders of magnitude larger than that predicted by the theory [1]. Recently, evidence that accounting for the space charge effects at the interface may boost the spin injection by an order of magnitude was presented [2]. However, when the charge accumulation is created only at the semiconductor side of the interface, the spin current increases only close to the interface, while at a distance of about the Debye screening length away the value of the spin current is similar to the one at the charge neutrality condition [3]. A possible source of this discrepancy is that the ferromagnetic contact was not considered. Here we include the ferromagnetic contact and investigate the influence of the space charge effects at the interface on the spin injection in a semiconductor.

We consider an *n*-doped (10^{16} cm^{-3}) semiconductor brought in contact to a ferromagnet. To avoid the impedance mismatch problem we assume the ferromagnet to be also a semiconductor doped to a concentration, which is a factor K of the value in the semiconductor. When the charge current flows through the interface, the spin accumulation in the semiconductor appears. We solve the spin and charge transport equations self-consistently to investigate the spin injection efficiency as functions of the charge current and the doping ratio K. The density of states for the spin-up and the spin-down electrons is equal to the density of states in the semiconductor multiplied by $(1\pm P)$, where P is the spin polarization in the ferromagnet.

First, we consider the case K=1. Because the doping is equal on both sides of the interface, the space charge effects can be disregarded. We compare our simulation results to the analytical expressions [4] generalized to account for the ferromagnetic semiconductor. Results for the spin density and the spin current injection efficiency (spin current normalized to charge current) at the interface are shown in Fig.1 and Fig.2, correspondingly. The good agreement confirms our assumption that the space charge effects are irrelevant in this case.

Next, we modify the doping in the ferromagnet by changing the ratio K. For K>1 the spin density develops a sharp dip at the ferromagnetic side followed by a sharp peak in the semiconductor (Fig.3). These features are the results of the charge depletion/accumulation at the ferromagnetic/ nonmagnetic interface, which result in the formation of the potential profile with a barrier for electrons (Fig.4). For this reason the sharp increase of the spin current density (Fig.5) happens only within the space charge layer. However, when the spin and spin current injection efficiency are computed at the screening length away from the interface, a slight decrease is seen as K increases (Fig.6). Therefore, the inclusion of the space charge effects at the junction between the ferromagnet and nonmagnetic material does not result in the spin injection efficiency increase.

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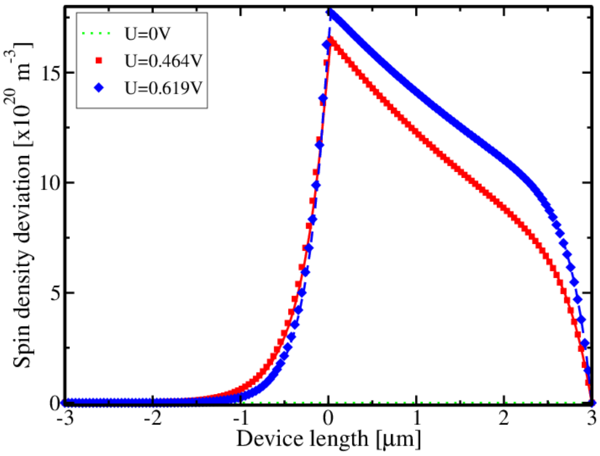

Fig. **1**. Spin accumulation at *K*=1 where voltage (U) is used as a parameter. Lines: theory. P=0.2.

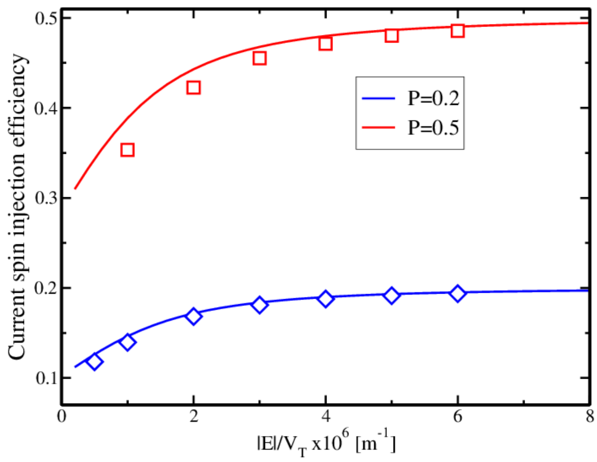

Fig. 2. Spin current injection efficiency (*K*=1) as a function of the electric field. $V_T = kT/q$ - thermal voltage. Lines: theory.

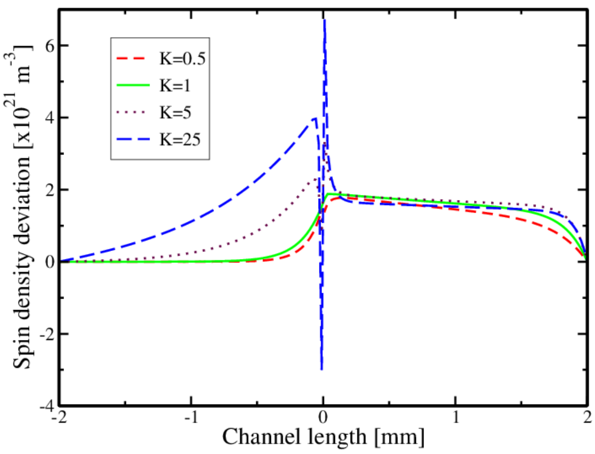

Fig. 3. Spin density accumulation under applied voltage 620mV, *P*=0.2. K is used as a parameter.

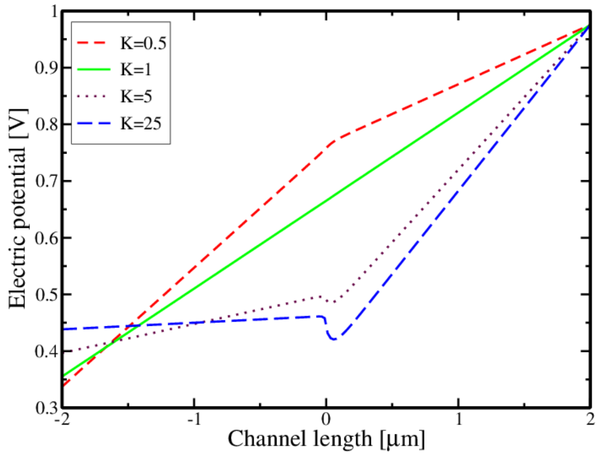

Fig. 4. Electric potential dependence at different doping, under similar conditions as in Fig 3.

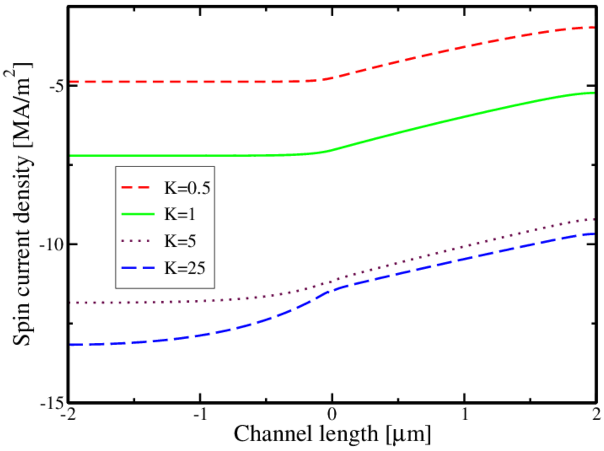

Fig. 5. Spin current through the interface, for different doping concentrations (Fig. 3) in the ferromagnetic semiconductor.

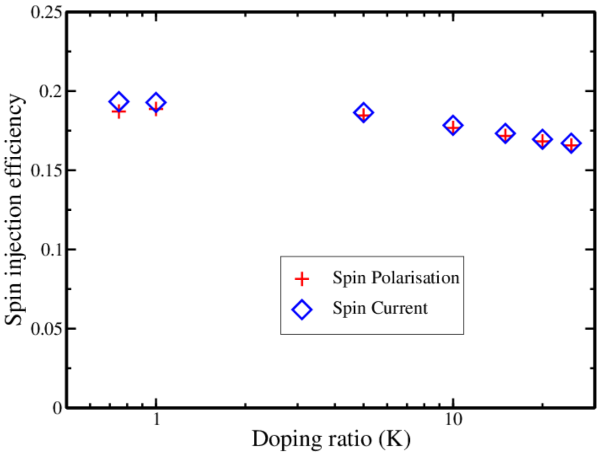

Fig. 6. Spin and spin current injection efficiency, *P*=0.2. The applied voltage is 620mV, and the channel length is 4 µm.