

Spin blockade at semiconductor/ferromagnet junctions

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We study theoretically extraction of spin-polarized electrons at nonmagnetic semiconductor/ferromagnet junctions. The outflow of majority-spin electrons from the semiconductor into the ferromagnet leaves a cloud of minority-spin electrons in the semiconductor region near the junction, forming a local spin-dipole configuration at the semiconductor/ferromagnet interface. This minority-spin cloud can limit the majority-spin current through the junction, creating a pronounced spin blockade at a critical current. We calculate the critical spin-blockade current in both planar and cylindrical geometries and discuss possible experimental tests of our predictions.

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The use of electron spins in semiconductors and their dynamics across semiconductor/ferromagnet (S/F) interfaces shows great promise for device applications.¹⁻⁴ Most of the theoretical and experimental attention, so far, has been focused primarily on mechanisms of spin injection from the ferromagnet to the semiconductor, spin transport, and spin relaxation in semiconductors.⁵⁻¹⁶ However, it is believed that a functional spintronic device⁴ would involve not only injection of spin-polarized electrons from the ferromagnet to the semiconductor, but also the reverse process: the *extraction* of spin-polarized electrons from the semiconductor to the ferromagnet. Despite the apparent similarity with the injection process and recent experimental and theoretical progress in this area,¹⁷⁻²² the physics of spin extraction has not been fully explored yet.

The main experimental breakthrough in this field is the discovery^{17,18} and observation^{19,20} of the ferromagnetic proximity effect in several systems. In these experiments, a spontaneous electron-spin polarization of several percent in magnitude has been generated optically and electronically in the vicinity of the interface in the semiconductor region. An interesting finding is that the direction of spontaneous spin polarization can be parallel or antiparallel to the magnetization of the ferromagnet. These experiments have been explained using scattering theory²¹ and its extension.²² According to this theory, spontaneous spin polarization near the interface appears because spin-up and spin-down electrons have different probabilities of entering into (or of being reflected from) the ferromagnet.

In this Brief Report, we consider spin extraction from a nonmagnetic semiconductor with a nondegenerate electron gas into a ferromagnet in the regime when the degree of spin polarization near the interface is high (close to 100%). We show that the most important feature of this regime is that the cloud of spin polarization of minority spins limits the majority-spin current through the junction via a spin blockade when a critical current is reached. We discuss this phenomenon at both planar S/F interfaces and at an interface between a semiconductor and a ferromagnet of cylindrical shape. The latter case is relevant for scanning tunneling microscopy (STM) experiments with ferromagnetic tips. We show that the spin blockade of the current is more important in materials with long spin-relaxation times. Therefore, this phenomenon is fundamentally relevant for the design of fu-

ture spintronic devices and can be readily verified experimentally.

Let us start by discussing the planar S/F interface. Figure 1 shows the system under investigation, consisting of a junction between a ferromagnetic material and a *n*-doped nonmagnetic semiconductor. We assume that a bias is applied to the system in such a way that the electron flow is directed from the nonmagnetic semiconductor into the ferromagnet. The electrons incoming from the bulk of the semiconductor are spin unpolarized. Let us start by considering a perfect ferromagnet, such as a ferromagnetic half-metal. The latter accepts only (say) spin-up electrons at the junction. Therefore a cloud of spin-down electrons (which cannot enter into the ferromagnet without undergoing spin reversal) must form in the semiconductor side in proximity to the junction (see Fig. 1). It is obvious that the cloud of spin-down electrons increases with current. The spin blockade occurs then at a certain current magnitude when the semiconductor region near the junction becomes completely depleted of electrons having the same direction of spins as the majority-spin electrons in the ferromagnet.

For our analysis of this phenomenon, the detailed structure of the interface is not very important. We therefore solve spin transport equations for the semiconductor region only. The calculations are performed at a fixed current through the structure. Using the current as the external control parameter, rather than the applied voltage, is more convenient because the current is constant throughout the electric circuit that contains the sample. On the other hand, if we use the voltage as the external control parameter, we have to take into account voltage drops in different parts of the circuit, such as, for example, at the Schottky barrier between metal and semi-

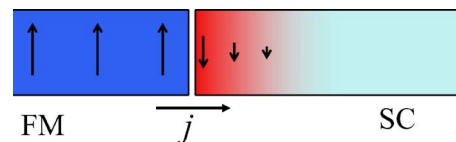


FIG. 1. (Color online) Schematic of spin-polarization distribution in the biased semiconductor/ferromagnet junction. The flow of spin-up electrons from the semiconductor (SC) into the ferromagnet (FM) results in higher concentration of spin-down electrons near the junction.

conductor. The junction with the ferromagnet is then taken into account through the boundary condition on current components and by neglecting space-charge effects. The critical current is found from the condition of zero spin-up density at the junction.

Our theory is based on the two-component drift-diffusion model.⁵ The system of drift-diffusion equations consists of the continuity equations for spin-up and spin-down electrons and the equations for the current:

$$e \frac{\partial n_{\uparrow(\downarrow)}}{\partial t} = \text{div} \vec{j}_{\uparrow(\downarrow)} + \frac{e}{2\tau_{sf}} (n_{\downarrow(\uparrow)} - n_{\uparrow(\downarrow)}), \quad (1)$$

$$\vec{j}_{\uparrow(\downarrow)} = \sigma_{\uparrow(\downarrow)} \vec{E} + eD \nabla n_{\uparrow(\downarrow)}, \quad (2)$$

where $-e$ is the electron charge, $n_{\uparrow(\downarrow)}$ is the density of spin-up (spin-down) electrons, $\sigma_{\uparrow(\downarrow)} = en_{\uparrow(\downarrow)}\mu$ is the spin-up (spin-down) conductivity, and the mobility μ is defined via $\vec{v}_{drift} = \mu\vec{E}$. The spin-relaxation time is labeled with τ_{sf} , and the diffusion constant with D . It is assumed that the total electron density in the semiconductor is constant, i.e., $n_{\uparrow}(x) + n_{\downarrow}(x) = N_0$. Correspondingly, the electric field is homogeneous and coupled to the total current density as $j = e\mu N_0 E_0$.

By substituting Eq. (2) into Eq. (1), we obtain two coupled equations for the density of spin-up and spin-down electrons:

$$\frac{\partial n_{\uparrow(\downarrow)}}{\partial t} = D \frac{\partial^2 n_{\uparrow(\downarrow)}}{\partial x^2} + \mu E_0 \frac{\partial n_{\uparrow(\downarrow)}}{\partial x} + \frac{n_{\downarrow(\uparrow)} - n_{\uparrow(\downarrow)}}{2\tau_{sf}}. \quad (3)$$

A steady-state solution of Eq. (3) can be written in the form

$$n_{\uparrow} = \frac{N_0}{2} - Ae^{-\alpha x}, \quad (4)$$

$$n_{\downarrow} = \frac{N_0}{2} + Ae^{-\alpha x}, \quad (5)$$

where A and α are constants to be determined. By substituting Eqs. (4) and (5) into Eq. (3), we obtain a quadratic equation for α . The positive solution of this equation is

$$\alpha = \frac{\mu E_0 + \sqrt{\mu^2 E_0^2 + 4 \frac{D}{\tau_{sf}}}}{2D}, \quad (6)$$

which is the inverse of the upstream spin-diffusion length defined in Ref. 5.

The constant A can be found from the boundary conditions imposed on the current. We consider the case when current is unpolarized at $x \rightarrow \infty$ and fully polarized at $x=0$:

$$j_{\uparrow}(x \rightarrow \infty) = j_{\downarrow}(x \rightarrow \infty) = j/2, \quad (7)$$

$$j_{\uparrow}(x=0) = j, \quad (8)$$

$$j_{\downarrow}(x=0) = 0. \quad (9)$$

It can be easily seen that the solutions (4) and (5) with a positive α automatically satisfies Eq. (7). From Eqs. (8) and (9), we find

$$A = \frac{N_0}{\sqrt{1 + 4 \frac{D}{\tau_{sf}\mu^2 E_0^2} - 1}}. \quad (10)$$

We notice from Eq. (10) that A is a monotonically increasing function of the current. Physically, the constant A is the deviation of the spin-up (and spin-down) electron density from its equilibrium level at the junction. Since the maximum possible spin polarization can only be 100%, the maximum possible value of A is $N_0/2$. It follows from Eq. (10) that the critical current density corresponding to $A=N_0/2$ is

$$j_c = eN_0 \sqrt{\frac{D}{2\tau_{sf}}}. \quad (11)$$

Let us estimate this critical current density. For a GaAs structure with $D=200$ cm²/s, $N_0=10^{15}$ cm⁻³, and $\tau_{sf}=10$ ns, the spin-down cloud extends up to about 14 μ m at $E_0 \rightarrow 0$, and the critical current density for spin blockade calculated using Eq. (11) is $j_c = 1.7 \times 10^{-7}$ A/ μ m². Such current densities are definitely achievable in microstructures. Furthermore, in our calculations, we have used the classical noninteracting diffusion constant D . Typically, due to the spin Coulomb drag effect, the interacting diffusion constant D_s is smaller.¹²

The above analysis can be readily extended to junctions of nonmagnetic semiconductors with ordinary ferromagnets. Let us characterize the level of spin polarization of the current at the junction by a parameter η defined as

$$\eta = \frac{j_{\uparrow}(x=0) - j_{\downarrow}(x=0)}{j}. \quad (12)$$

The limit of fully polarized spin current corresponds to $\eta=1$; fully unpolarized to $\eta=0$. To first approximation, it can be assumed that η does not depend on j , so that the ratio $j_{\uparrow}(x=0)/j_{\downarrow}(x=0)$ is a constant. By repeating the above calculations, we find in this case

$$A = \frac{\eta N_0}{\sqrt{1 + 4 \frac{D}{\tau_{sf}\mu^2 E_0^2} - 1}} \quad (13)$$

and

$$j_c = eN_0 \sqrt{\frac{D}{(\eta^2 + \eta)\tau_{sf}}}. \quad (14)$$

Figure 2 shows that the critical current density increases slowly by decreasing η from 1 to ~ 0.3 . Therefore, the spin-blockade phenomenon is also important in junctions with ordinary ferromagnets.

Let us now consider spin blockade in the case in which the ferromagnet has cylindrical geometry. This analysis is relevant to STM configurations with ferromagnetic tips. A sketch of the experimental setup we have in mind is presented in Fig. 3. Here, spin transport is studied through a

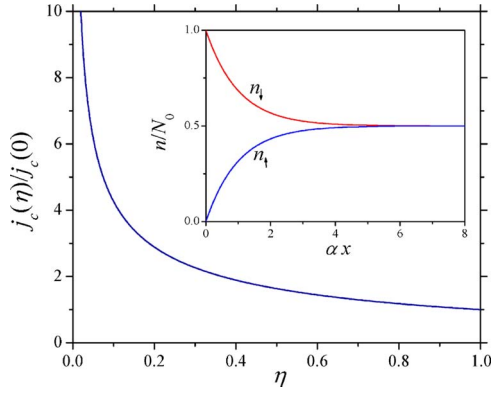


FIG. 2. (Color online) Critical current density for spin blockade as a function of current spin polarization η . Inset: spin-up and spin-down densities at $j=j_c$ as a function of the distance from the junction.

ferromagnetic tip of radius r_1 forming a junction with a two-dimensional (2D) electron system. It is assumed that spin-unpolarized electrons are injected at $r \rightarrow \infty$ and spin-up electrons are extracted at $r=r_1$. From a 2D equation for spin-density imbalance in the polar coordinates, we obtain the following expressions for spin-up and spin-down densities:

$$n_{\uparrow(\downarrow)} = \frac{N_0}{2} \mp Cr^{-\gamma/2} K_{\gamma/2}[\tilde{r}], \quad (15)$$

where the minus sign corresponds to spin-up electrons. Here, C is a constant, $\gamma=J/(2\pi eN_0D)$, J is the total current, $K_m(x)$ is the modified Bessel function of the second kind, and $\tilde{r}=r/\sqrt{D\tau_{sf}}$. From the boundary condition $j_{\downarrow}(r=r_1)=0$, we find

$$C = \frac{N_0 r_1^{\gamma/2}}{\tilde{r}_1 (K_{(\gamma/2)-1}[\tilde{r}_1] + K_{(\gamma/2)+1}[\tilde{r}_1]) - K_{\gamma/2}[\tilde{r}_1]}. \quad (16)$$

Unfortunately, in the cylindrical geometry we cannot derive a closed analytical expression for the critical current from the equation $n_{\uparrow}(r_1)=0$. Figure 3 shows a numerical solution of

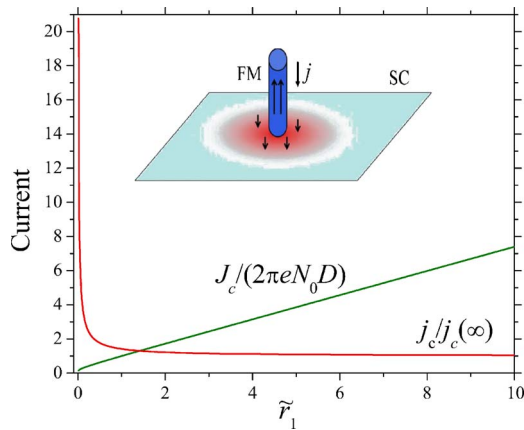


FIG. 3. (Color online) Critical current J_c and the critical current density j_c as a function of the tip radius r_1 . Inset: ferromagnetic tip contacting a system of electrons constrained to two dimensions.

this equation. The total critical current J_c is almost a linear function of r_1 . Such dependence implies a constant critical current density at $\tilde{r}=\tilde{r}_1$ for $\tilde{r}_1 \gg 1$.

We can also see that for large values of r_1 , the critical current density approaches the critical current density of the planar junction. Indeed, using the asymptotic expansion $K_\nu(z) \sim e^{-z} \sqrt{\pi/(2z)}$ for fixed ν and large z , the following asymptotic expression for the critical current density at large r_1 is obtained:

$$j_c \sim \frac{2}{3} e N_0 \sqrt{\frac{D}{\tau_{sf}}}. \quad (17)$$

Taking into account that $2/3 \approx 0.67$ and $1/\sqrt{2} \approx 0.71$, Eqs. (11) and (17) are in very good agreement.

We conclude by discussing the meaning and implications of the spin-blockade critical current in actual experiments. The critical current is the steady-state current that flows through the system when the density of majority spins near the junction becomes equal to zero. Therefore, a further increase of the current through the junction with a fixed level of spin polarization is not possible at all. This implies that in junctions with perfect ferromagnets, further current increase is not allowed. On the other hand, in junctions with nonideal ferromagnets, a current increase may still occur via a decrease of spin polarization η . Therefore, we expect a saturation behavior of current-voltage characteristics in junctions with perfect ferromagnets and a peculiarity (change of the expected behavior) of current-voltage characteristics in junctions with ordinary ferromagnets. Optical means provide an alternative way to test this phenomenon.

Finally, there are several important spin-relaxation mechanisms in semiconductors.^{23,24} One of them is due to the interaction with nuclear spins.²⁴ Due to electron and nuclear spin-flip interactions, nonequilibrium electron-spin polarization results in nuclear polarization.²⁵ A nonequilibrium nuclear-spin polarization has been already observed in S/F junctions.^{17,19} The spin-blockade regime is interesting in this respect because of the high level of local electron spin-polarization, which should result in a strong local nuclear-spin polarization. Using a moving ferromagnetic STM tip, one may thus write a desirable nuclear-spin polarization profile in a semiconductor.²⁶ In addition, due to the very large current densities one can achieve in nanostructures, the predicted spin blockade may have unexpected consequences in molecular spintronics.²⁷

In conclusion, we have predicted that the extraction of spin-polarized electrons from S/F junctions may produce a pronounced spin blockade at a critical current. Only a single junction is required to observe the spin blockade. This is an important phenomenon since it implies that the observation of a current saturation serves as a signature of spin polarization in a semiconductor. This may be of value for such materials as silicon. In a broader perspective, this phenomenon may have far-reaching consequences in the spin control in mesoscopic and nanoscopic devices.

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