

# Chapter 27

## Two-Dimensional Spin-FET Transistor

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### 27.1 Introduction

The electrons are not only characterized by their electrical charge but also by their spin magnetic moment. Up to the late 1990s, the electronics had virtually ignored the electron spin (except Pauli's law that two electrons cannot be in the same energy state with equal spin orientation). Since then, spin electronics, or magneto-electronics [1], has grown increasingly and rapidly. In this section, we will see how it is possible to introduce the concepts of magneto-electronic components in a semiconductor. An immediate benefit of this approach is a much reduced switching voltage. Spin-orbit (SO) interactions in technologically important semiconductors are typically weak and weakly sensitive to external potentials [2]. As a result, a large swing in the gate potential (few volts) is often required to turn a short channel spin-polarized field effect transistor (spin-FET) of the traditional type on or off [1]. That results in considerable dynamic energy dissipation during switching. In contrast, our strategy is to modulate transmission resonances (Ramsauer and Fano-type resonances) that occur in the channel of traditional spin-FETs [3, 4] with a gate potential. Since the resonance widths (in energy) are very small, a few millivolts change in the gate potential can take the device from on-resonance to off-resonance and switch it on or off. This approach results in a very small switching voltage (a few millivolts instead of the few volts required in traditional spin-FETs) resulting in much reduced dynamic energy dissipation [4].

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## 27.2 Spintronic

The spin electronics, or “spintronics” [2] is a new research theme has been booming since the late 1980s. The first structures studied in this area are made of ferromagnetic metal multilayers, separated by insulators or “tunnels” or by nonmagnetic metal films. Their operating principles are related to a property of ferromagnetic metals on the spin of electrons: They inject or collect preferentially carriers whose spin is polarized along the direction of their magnetic moment. Such devices are already used industrially as magnetic field sensors for read heads of hard disks or are expected to be soon in the case of magnetic random access memory.

During the past 4 years, groups working in the field of semiconductor components were also interested in properties related to the spin of the electron [5]. Indeed, recent studies have shown that it is possible to act on the spin of charge carriers and use this quantity to modify the electrical and optical structures in semiconductors.

### 27.2.1 Spintronics in Semiconductors (*Spin-FET*)

In semiconductors, the control of the spin of the carriers, in addition to their charges, may give rise to a new generation of electronic devices [6]. This idea was born of a new concept device that can benefit from the manipulation of spin to create a new feature. It is the case of the Datta and Das transistor, whose its structure will be briefly described [7].

This concept was proposed in 1990 and named spin-FET “rotation spin transistor.” This device looks at first sight like the classical field-effect transistor, as illustrated in Fig. 27.1, and has a current source, a drain, and a channel with a conductance controllable via a gate voltage  $V_g$ ; however, comparison stops there. The spin transistor is based on spin-selective contacts, that is to say the capability of injecting or collecting a given spin orientation. The injection and the collection of spin-polarized current is carried by ferromagnetic electrodes (Fe, for example).

To modulate the drain current, Datta and Das proposed to control the rotation of the “bundle” of spin in the channel using the SO Rashba coupling to be a function of the voltage applied to the gate [3]. The drain current reaches a maximum value when the spin orientation is parallel to the magnetization of the electrodes and injection manifold. It reaches a minimum value when they are opposed. This concept also implies a transistor-coherent transmission, i.e., without loss of spin between the injector (source) and collector (drain). Under this proposal, the channel where the propagation of spin takes place must be a two-dimensional electron gas system (2 DEG) to take advantage of the high mobility allowing a coherent propagation. This 2-DEG channel can be obtained in a transistor structure with modulation doping (MODFET)-type InGaAs/InAlAs [8].

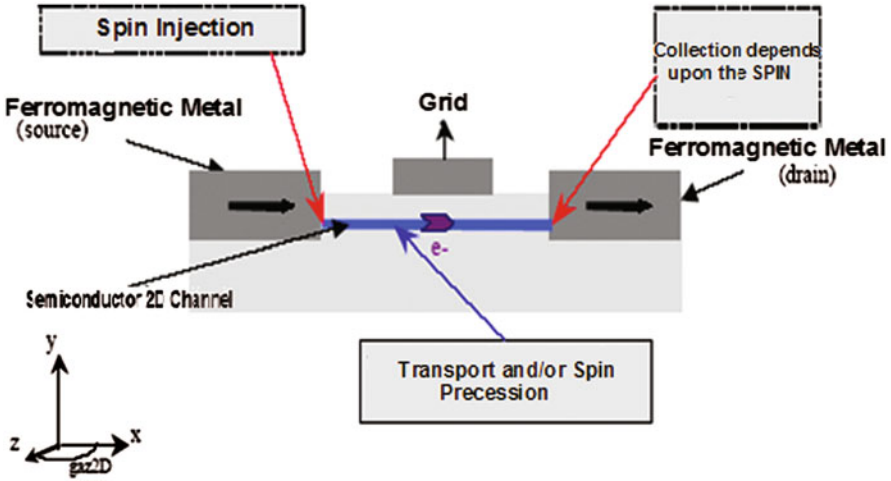


Fig. 27.1 Schematic diagram of the transistor with spin precession (spin-FET)

### 27.3 Quantum Wire Model

#### 27.3.1 Drain Current Variations

The expression of the drain current in a spin-FET in our model is given by the following equation:

$$I_D = q \frac{E_y}{V_C} \mu(E_y) E_x \frac{1 + P_0 \cos(E_y L / V_R)}{1 + P_0}, \tag{27.1}$$

where the parameter  $V_C$ , equal to  $q / (2\epsilon_0 \epsilon_{SC} W)$ , is uniform to the voltage. It may be noted that the term  $E_y / V_C$  in this expression represents the density in the grid controlled by accumulated electrons in the channel. The parameter  $\mu$  denotes the electron mobility and thus  $\mu E_x$  represents the speed of electrons. The mobility  $\mu$  varies with the intensity of confinement in the channel. It means with the field  $E_y$ , the ratio  $(1 + P_0 \cos(E_y L / V_R)) / (1 + P_0)$  reflects the analysis of spin at the drain. This ratio varies periodically, with period  $E_{y0} = 2\pi V_R / L$ . Its amplitude depends on the spin polarization  $P_0$ . We initially consider the mobility constant and we study the derivative  $g$  of  $I_D / \mu$  function of  $E_y$ :

$$g(u) = \frac{q E_x}{V_C} \frac{1 + P_0(\cos(u) - u \sin(u))}{1 + P_0}, \tag{27.2}$$

where  $u$  is a dimensionless parameter equal to  $E_y L / V_R$ ; except in  $V_C$ , the function  $g(u)$  does not depend on parameters characterizing the quantum wire transistor. The variations of  $g$  give the information on the transconductance of the spin-FET.

## 27.4 Quantum Two-Dimensional Model

In the ideal situation where spin (or its projection along a direction) is conserved, spin current is simply defined as the difference between the currents of electrons in the two spin states. This concept has served well in early studies of spin-dependent transport effects in metals.

### 27.4.1 Theoretical Approach

In semiconductor spintronic structures, where spin is carried by electrons and/or holes, the spin dynamics is controlled by magnetic interactions. Some of these are surveyed below.

#### 27.4.1.1 Interaction with an External Magnetic Field

An external magnetic field  $\vec{B}$  exerts a torque on a magnetic dipole and the magnetic potential energy is given by the Zeeman term

$$U = \frac{g^* \mu_B}{2} \vec{\sigma} \cdot \vec{B}, \quad (27.3)$$

where  $g^*$  is the effective g-factor and  $\vec{\sigma}$  represents a vector of the Pauli spin matrices, used in the quantum-mechanical treatment of spin  $\frac{1}{2}$  (see [9]). The interaction (3) leads to the spin precession around the external magnetic field. This interaction is important in all systems where a magnetic field is present. Moreover, fluctuations of  $\vec{B}$  could lead to noise contributing to spin relaxation.

#### 27.4.1.2 SO Interaction

The SO interaction arises as a result of the magnetic moment of the spin coupling to its orbital degree of freedom. It is actually a relativistic effect, which was first found in the emission spectra of hydrogen. An electron moving in an electric field sees, in its rest frame, an effective magnetic field. This field, which is dependent on the orbital motion of the electron, interacts with the electron's magnetic moment.

The Hamiltonian describing SO interaction, derived from the four-component Dirac equation, has the form

$$H_{SO} = \frac{\hbar^2}{4m^2c^2} (\vec{\nabla} \times V) \cdot \vec{\sigma}, \quad (27.4)$$

where  $m$  is the free electron mass,  $\vec{p}$  is the momentum operator, and  $\vec{\nabla}$  is the gradient of the potential energy, proportional to the electric field acting on the electron. When

dealing with crystal structures, the SO interaction, Eq. 27.4, accounts for symmetry properties of materials. Here, we emphasize two specific mechanisms that are considered to be important for spintronics applications. The Dresselhaus SO interaction [1] appears as a result of the asymmetry present in certain crystal lattices, e.g., the zinc blende structures. For a 2DEG in semiconductor heterostructures with an appropriate growth geometry, the Dresselhaus SO interaction is of the form

$$H_D = \frac{\beta}{\hbar}(\sigma_x p_x - \sigma_z p_z). \quad (27.5)$$

Here,  $\beta$  is the coupling constant.

The Rashba SO interaction [3] arises due to the asymmetry associated with the confinement potential and is of interest because of the ability to electrically control the strength of this interaction. The latter is utilized, for instance, in the Datta–Das spin transistor [7, 10]. The Hamiltonian for the Rashba interaction is written [3] as

$$H_R = \frac{\alpha}{\hbar}(\sigma_x p_z - \sigma_z p_x), \quad (27.6)$$

where  $\alpha$  is the coupling constant. Other possible sources of SO interactions are nonmagnetic impurities, phonons [14], sample inhomogeneity, surfaces, and interfaces. In some situations, these could play a role in spin transport and spin relaxation dynamics.

### 27.4.2 Model

Consider the two-dimensional channel of a spin-FET in the  $x$ - $y$  plane with current flowing in the  $x$ -direction. An electron's wave vector components in the channel are designated as  $k_x$  and  $k_z$ , while the total wave vector is designated as  $kt$ . Note that  $k^2 = k_x^2 + k_z^2$ .

The gate terminal induces an electric field in the  $y$ -direction, which causes Rashba interaction. The Hamiltonian operator describing an electron in the channel is

$$H = \frac{p_x^2 + p_z^2}{2m^*}[\mathbf{I}] + \alpha[V_G](\sigma_x p_z - \sigma_z p_x), \quad (27.7)$$

where the  $p$ -s are the momentum operators, the  $\sigma$ -s are the Pauli spin matrices and  $[\mathbf{I}]$  is the  $2 \times 2$  identity matrix. Since this Hamiltonian is invariant in both  $x$  and  $z$  coordinates, the wave functions in the channel are plane wave states  $e^{i(k_x x + k_z z)}$ . Diagonalization of the Hamiltonian yields the eigenenergies and the eigenspinors in the two spin-split bands in the two-dimensional channel:

$$\begin{aligned} E_d &= \frac{\hbar^2 k^2}{2m^*} + \alpha [V_G] k \quad (\text{lower band}) \\ E_u &= \frac{\hbar^2 k^2}{2m^*} - \alpha [V_G] k \quad (\text{upper band}) \end{aligned} \quad (27.8)$$

and

$$\begin{aligned} [\Psi]_l &= \begin{bmatrix} \sin\theta \\ \cos\theta \end{bmatrix} \quad (\text{lower band}) \\ [\Psi]_u &= \begin{bmatrix} -\cos\theta \\ \sin\theta \end{bmatrix} \quad (\text{upper band}) \end{aligned} \quad (27.9)$$

where  $\theta = (1/2)\arctan(k_z/k_x)$ .

Now if we also assume that the spin injection efficiency at the source is 100 % and the electron for an energy  $E$  have two different waves for  $k_x^{(1)}$  and  $k_x^{(2)}$  (corresponding to the two values of  $k$ ), the corresponding spinor at the drain end will be:

$$\begin{aligned} [\Psi]_{\text{drain}} &= C_1 \begin{bmatrix} \sin\theta \\ \cos\theta \end{bmatrix} e^{i(k_x^{(1)}L + k_zW)} + C_2 \begin{bmatrix} -\cos\theta \\ \sin\theta \end{bmatrix} e^{i(k_x^{(2)}L + k_zW)} \\ &= e^{ik_zW} \begin{bmatrix} \sin\left(\theta + \frac{\pi}{4}\right) \sin\theta e^{ik_x^{(1)}L} + \cos\left(\theta + \pi/4\right) \cos\theta e^{ik_x^{(2)}L} \\ \sin\left(\theta + \frac{\pi}{4}\right) \cos\theta e^{ik_x^{(1)}L} - \cos\left(\theta + \pi/4\right) \sin\theta e^{ik_x^{(2)}L} \end{bmatrix} \end{aligned} \quad (27.10)$$

where  $L$  is the channel length (distance between source and drain contacts) and  $W$  is the transverse displacement of the electron as it traverses the channel.

Then the transmission's factor is given by:

$$|T|^2 = \cos^4\left(\theta + \frac{\pi}{4}\right) \left| 1 + \tan^4\left(\theta + \frac{\pi}{4}\right) e^{i(k_x^{(1)} - k_x^{(2)})L} \right|^2. \quad (27.11)$$

The current density in the channel of the spin-FET (assuming ballistic transport) is given by the Tsu–Esaki formula:

$$J = \frac{q}{W_y} \int_0^\infty \frac{1}{h} dE \int \frac{dk_z}{\pi} |T|^2 [f(E) - F(E + qV_{SD})], \quad (27.12)$$

where  $q$  is the electronic charge,  $W_y$  is the thickness of the channel (in the  $y$ -direction),  $V_{SD}$  is the source-to-drain bias voltage, and  $f(E)$  is the electron occupation probability at energy  $E$  in the contacts. Since the contacts are at local thermodynamic equilibrium, these probabilities are given by the Fermi–Dirac factor.

In the linear regime, the expression of the drain current reduces to

$$J = \frac{q^2 V_{SD}}{W_y} \int_0^\infty \frac{1}{h} dE \int \frac{dk_z}{\pi} |T|^2 \left[ -\frac{\partial f(E)}{\partial E} \right]. \quad (27.13)$$

This yields that the channel conductance  $G$  is

$$G = \frac{I_{SD}}{V_{SD}} = \frac{q^2 W_z}{\pi h} \int_0^\infty dE \int dk_z |T|^2 \left[ -\frac{\partial f(E)}{\partial E} \right]. \quad (27.14)$$

## 27.5 Conclusion

In this work, we studied the transport of two-dimensional spin-polarized in SpinFET, we have established a relation giving the expression of the source–drain current as a function of the parameters of the semiconductor used, and the electric field across the control grid and polarization of injected spins, and then we have calculated the associated transconductance  $G$ . This model is based on semiclassical considerations with the holders of spin injected with ballistic trajectories inside the conduction channel.

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