Nanojunctions as logic operators for the spintronics

S. Bellucci\textsuperscript{1, a} and P. Onorato\textsuperscript{1, 2}

\textsuperscript{1} INFN, Laboratori Nazionali di Frascati, P.O. Box 13, 00044 Frascati, Italy
\textsuperscript{2} Department of Physics “A. Volta”, University of Pavia, via Bassi 6, 27100 Pavia, Italy

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Abstract. We propose two all-electrical nanodevices where the spin properties of an incoming electron are modified by the spin-orbit interaction (SOI), resulting in a transformation of the qubit state carried by the spin. Our proposal is essentially based on nanojunctions made of crossing quantum wires patterned in a two dimensional electron gas where the Rashba SOI is present. We investigate in detail the spin precession of one electron traveling in the proposed nanodevices. The nanojunctions acts as spin filters or ballistic spin rotators whose properties can be varied by tuning the strength of the SOI, by changing the geometry of the junctions. Two different basic mechanism in order to obtain in plane or out of the plane rotations are discussed. We show that, starting from the spin rotators, a large class of unitary transformations can be attained with one or more nanojunctions in series. By choosing appropriate parameters the spin transformations can be made unitary, which corresponds to lossless operators.

1 Introduction

Conventional electronic devices rely on the transport of electrical charge carriers. In recent years, the study of spintronics devices, which utilize the spin rather than the charge of an electron, has been intensified \cite{1, 2} mainly because they are expected to operate at much higher speeds than the conventional ones and have potential applications in quantum computing \cite{3, 5}. Many researchers proposed to use the spin degree of freedom in information processing applications where local states are up and down with respect to certain quantization directions. Moreover the electron spin degree of freedom can also be considered one of the prospective carriers of qubits, the fundamental units in quantum information processing \cite{3}. To realize this aim, however, requires to perform basic spin operations such as the production of spin-polarized carriers \cite{6–8} and the rotation of spin orientation \cite{9, 10}.

Here, we propose two devices able to rely a spin rotation or to produce a spin polarization in the emerging current. We calculate the spin transport properties of two-dimensional nanojunctions, which can be fabricated from, for example, InAlAs/InGaAs based heterostructures \cite{11} or HgTe/HgCdTe quantum wells \cite{12}, where Rashba-type \cite{13} spin-orbit interaction (SOI) is present. The SOI comes from the expansion quadratic in $v/c$ of the Dirac equation \cite{14} and is due to the Pauli coupling between the spin momentum of an electron and a magnetic field, which appears in the rest frame of the electron, due to its motion in the electric field

$$\hat{H}_{SO} = -\frac{\lambda^2_{SO}}{\hbar} m_0 \epsilon \mathbf{r} [\sigma \times \mathbf{p}].$$

(1)

Here $m_0$ the electron mass in vacuum, $\sigma$ are Pauli matrices, $\mathbf{p}$ is the canonical momentum operator, $\mathbf{r}$ is a 3D position vector and $\lambda^2_{SO} = \hbar^2/(2m_0c)^2$. In condensed matter systems $m_0$ and $\lambda_0$ are substituted by their effective values $m^*$ and $\lambda$. The Rashba SOI \cite{15, 16} originates from the macroscopic electric field in a semiconductor quantum well (a potential well along the $z$ direction which is present in semiconductors heterostructures). Due to the band offsets at the interface of two different materials the electrons are confined by forming a two dimensional electron gas (2DEG in the $xy$-plane). Since the asymmetry in quantum well potential that confines the electron gas \cite{17} in some heterostructures the electrons are moving in an effective electric field $E_z$ along $z$ and the Hamiltonian in equation (1) will take the form \cite{18}

$$\hat{H}'_{SO} = \frac{\alpha_R}{\hbar} [x \mathbf{p}_y - y \mathbf{p}_x].$$

(2)

$\alpha_R$, which in vacuum is given by $\lambda^2_{SO} E_z e$, in semiconductor heterostructures takes values typically \cite{19–22} within the range $10^{-11} - 10^{-12}$ eVm while its highest value is close to $10^{-10}$ eVm as reported in references \cite{23, 24}. Even though the Rashba spin splitting is expected to be very small, nonetheless this perturbation can give rise to a sizable modification of a semiconductor band structure \cite{19, 25}. Moreover, it has already been demonstrated in experiments that the strength of this type of SOI can

\footnote{a e-mail: stefano.bellucci@lnf.infn.it}
be controlled by external gate voltages [19,26] in the range of a few volts.

Thus many of the proposed spintronic devices are low dimensional nanostructures that work in the presence of the SOI.

Here we propose devices in which the local manipulation of the SOI strength leads to effects which could be used in various practical spintronic applications. We focus on low dimensional electron systems formed by crossing narrow wires patterned in 2DEG where a the Rashba SOI is present For the latter devices in the ballistic (coherent) regime, a one-dimensional model provides appropriate description. The geometries we are considering are reported in Figure 1.

In Section 2 we present the model and the basic bricks of our calculations, in Section 3 we report the main results obtained, while in Section 4 we discuss the feasibility of the proposed devices.

2 Model and theoretical approach

The ballistic one-dimensional wire is a nanometric solid-state device in which the transverse motion is quantized into discrete modes, and the longitudinal motion (along $\xi$ and along $y$ for the wires in Figs. 1C and in 1A respectively) is free. In this case, electrons propagate freely down to a clean narrow pipe and electronic transport with no scattering can occur. Next we assume that the motion perpendicular to the 2DEG (along $z$) and the one along the transverse direction (e.g. $\eta$ and $x$ for the wires in Figs. 1C and in 1A respectively) are quantum mechanically frozen out (i.e. with a mean value $\langle p_y\rangle = \langle p_x\rangle = 0$ in the ground state, for the potential wells in the $z$ or $x$ direction). This approximation can be justified by assuming the Fermi energy of the moving electrons in the wires, $\varepsilon_F$, to be less than $\Delta \sim \hbar^2/(2m^*W^2)$ where $W$ is the effective width of the QW (for a QW of effective width $W \sim 20$ nm, is $\Delta \sim 50$ meV). Moreover the effective width $W$ has to be smaller than the others length parameters ($b, d$, corresponding to the lengths of the crossing wires). Starting from these approximation the Hamiltonian of one electron moving along $y$ (Fig. 1C) becomes

$$\hat{H} = \frac{\hat{p}_y^2}{2m^*} + \frac{\alpha_R}{\hbar} \hat{p}_y \hat{\sigma}_z = \frac{\hat{p}_y^2}{2m^*} + \frac{\hbar^2 k_R \hat{p}_y}{m^*} \hat{\sigma}_z,$$

where $k_R \equiv \frac{m^* \alpha_R}{\hbar^2}$ takes values in the range [18,26] from $10^{-3}$ to $10^{-2}$ nm$^{-1}$. The latter quantity can be written as $k_R = \frac{\pi}{L_{SO}}$, where the spin-precession length, $L_{SO}$ measures the strength of Rashba SOI in terms of a length scale. Typical values are $L_{SO} \sim 400$ nm in InGaAs/InP and 100 nm in HgTe/HgCdTe heterostructures.

The Rashba subbands splitting in the energies is obtained by the diagonalization of equation (3) as

$$\varepsilon_{k,\pm} = \pm \hbar^2 \left( (k \pm k_R)^2 - k_R^2 \right).$$

The $\pm$ sign corresponds to the spin polarization along the $x$ axis i.e. to the spin eigenstate $\chi_s$, (see Appendix A). Hence we can conclude that 4-split channels are present for a fixed Fermi energy, $\varepsilon_F$, corresponding to $\pm p_y$ and $s_x = \pm 1$ with eigenfunctions $\varphi_{\varepsilon_F,s_x} = e^{ik_s(\varepsilon_F)\xi} \chi_{s_x}$. Here $k_s(\varepsilon_F) = sk_R \pm \sqrt{k_R^2 + \frac{2m^*}{\hbar^2} \varepsilon_F}$.

In each of the sectors of the junction, $H$ has eigenvalues in the form $\varphi_{\varepsilon_F,s_n}(\xi) = e^{ik_s(\varepsilon_F)\xi} \chi_{s_n}^r$, where now $(\xi,\eta)$ are two arbitrary orthogonal direction in the 2DEG plane according the lying position of the QW (see Fig. 1C). Thus the wavefunctions $\varphi_{\varepsilon_F,s_n}(\xi)$ in the sectors $(n = 1, ..., 4)$ are build.

In order to study the transport properties of a nanometric device subject to a constant, low bias voltage (linear regime) we could calculate the zero temperature conductance $G$ based on the Landauer formula [27], $G_{pq} = \frac{\sigma}{e^2 T_{pq}}$. The latter formula works in the ballistic transport regime, in which scattering with impurities can be