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Magnetic Field Dependent Tunneling Magnetoresistance through a Quantum Well between Ferromagnetic Contacts

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***Abstract*—Spin-charge correlated dynamics is currently of great interest, because it allows to control the electric current and to obtain the large experimentally observed magnetic field dependent responses suitable for various practical applications. Resonant trap-assisted tunneling in heterostructures with ferromagnetic contacts explains the signal magnitude in three-terminal spin-injection experiments by the "spin blockade": An electron cannot escape into the ferromagnetic contact, while the Coulomb blockade prevents a second electron to occupy the trap thus blocking the current. In the magnetic field the electron spin precesses and can escape into the contact, when the spin is parallel to the magnetization, and by this means the "spin blockade" is lifted. However, the non-trivial magnetoresistance can also be achieved without the Coulomb blockade. We investigate the magnetoresistance due to resonant tunneling through a quantum well separated from the two non-collinear ferromagnetic contacts by tunneling barriers. The linear part of the magnetoresistance is suitable for magnetic field sensing.**

***Keywords*—Spin, resonant tunneling, Green's function, tunneling magnetoresistance, magnetic field sensor**

I. INTRODUCTION

The sustainable increase in performance of integrated circuits is continuously supported by the miniaturization of their electronic components and interconnects. The state-of-the art 14nm technology, recently adopted by the semiconductor industry, allows the manufacturing of multi-gate three-dimensional transistors [1]. Although single devices with gate lengths as short as a few nanometers have been demonstrated [2], fabrication, control, and integration difficulties, high costs combined with variability and reliability issues are gradually bringing CMOS scaling to an end.

The principle of the MOSFET operation is fundamentally based on the charge of an electron interacting with an electrostatic field. Another intrinsic electron characteristic, the electron spin, attracts at present much attention as a possible candidate for complementing or even replacing the charge degree of freedom in future electronic devices [3]. The electron spin is characterized by two projections on an axis and could be potentially used in digital information processing. It also takes an amazingly small amount of energy to invert the spin orientation. The key advantages of all spin-based computing advertised in the literature are zero static power, small device count, and low supply voltage [4].

In order to realize a spin field-effect transistor exploiting the electron spin, efficient and all electrical spin injection/detection, propagation, and spin manipulation must be realized. Although the Datta-Das spin field-effect transistor (SpinFET) was proposed more than 25 years ago [5], its successful realization was achieved only recently [6]. The key ingredients allowing the SpinFET demonstration were specially designed quantum point semiconductor contacts with strong spin-orbit interaction enabling an efficient spin injection. The strong gate voltage dependent spin-orbit interaction in the channel made of a III-V semiconductor is used to perform a purely electrical spin manipulation. However, gate voltage dependent resistance oscillations due to the spin precession were observed at temperatures around or below 1K, which was most probably due to a reduction of the spin polarization in the quantum dot contacts [6].

In complement to III-V semiconductor based SpinFET [6], a silicon based room temperature SpinMOSFET with high on/off spin signal ratio was recently demonstrated [7]. Silicon is perfectly suited for spin-driven applications due to its weak spin-orbit interaction and long spin lifetime [8,9]. This is important, because the non-equilibrium spin density injected in a semiconductor is not a conserved quantity. Indeed, while spin diffuses, it gradually relaxes to its equilibrium zero value in a non-magnetic semiconductor. Spin can propagate 350μm through a silicon wafer at 77K [10] and the spin diffusion length is around 200nm at room temperature [8]. In a confined electron structure the spin lifetime and the spin diffusion length is shorter due to the additional spin relaxation at the interfaces [11], however, uniaxial stress along <110> reduces the spin relaxation efficiently [10]. This is due to the fact that stress lifts the degeneracy between the equivalent valleys completely [12], thus suppressing the most efficient spin-flip processes caused by intervalley scattering.

In contrast to SpinFETs, the weak spin-orbit interaction in a SpinMOSFET does not allow the spin manipulation in the channel by the gate voltage efficiently. Therefore, the only advantage of adding the electron spin to nanoscale CMOS technology is to exploit the current dependence on the relative orientation of the magnetizations of ferromagnetic source and drain, which paves the path towards reprogrammable non-volatile logic [13].

The dependence of the resistance on the magnetic field and relative magnetization orientation of the ferromagnetic electrodes in sandwich structures is a phenomenon used in many practical applications. In fact, the giant magnetoresistance, the tunneling magnetoresistance, and the transport phenomena due to the spin dependent charge currents, have revolutionized the way the information is stored and recovered from modern non-volatile magnetic memory devices, like hard drives and spin-transfer torque MRAM. The large magnetic field dependent responses observed recently in organic light-emitting diodes are explained by the correlated spin-charge dynamics: The magnetic field aligns spins on the adjacent sites, which, due to the prohibition for electrons with the same spin to occupy the same site, forbids hopping in the organic conductor and thus influences the lighting properties [14]. Magnetic field dependent spin correlated trap assisted tunneling was recently claimed responsible for the unusually large amplitudes of signals in experiments on three-terminal electrical spin injection into non-magnetic semiconductors [15]. The explanation is based on the fact that the electron with its spin anti-aligned to the ferromagnetic contact magnetization has a smaller probability to escape from the trap due to the much smaller density of states for this spin projection in the contact. The electron stays longer on the trap and, because of the Coulomb blockade, prevents another electron entering the trap, which suppresses the current. The magnetic field perpendicular to the magnetization eases the spin-down induced blockade by making the spin on the trap precess. This creates a non-zero average projection along the contact magnetization, thus facilitating the electron to escape the trap, which removes the spin-induced blockade and enables current flow.

The Coulomb blockade is not a necessary ingredient to achieve the dependence of the resonant tunneling resistance on the magnetic field. A special design of the structure with a resonant level positioned just below the spin-down band in the contact allows only the spin-up electrons to tunnel [16]. This effectively produces a 100% spin polarized current leading to a large TMR ratio, but only at small voltages and temperatures, when inelastic processes can be neglected. The resonant tunneling phenomenon was claimed to be responsible for several important phenomena [17] like the large tunneling magnetoresistance at small voltages as well as a possible enhancement of the spin-transfer torque.

II. Method

In a recent work [18] it was demonstrated that even in the absence of the Coulomb blockade and the resonant filtering the tunneling current through a resonant level is a non-trivial function of the angle between the magnetic field and the magnetization orientation, and the magnetic field strength. The quantum mechanical coupling between the spin-up and spin-down levels at the trap through a ferromagnetic electrode is responsible for the level broadening depending on the spin projection and the magnetic field angle. In quantum wells the Coulomb blockade is not important at room temperature. Here, we consider the tunneling transport through a quantum well between two ferromagnetic contacts with arbitrary magnetization orientations (Fig.1). Our goal is to determine the tunneling magnetoresistance at a finite bias voltage as a function of the magnetic field for several relative magnetization orientations of the non-collinear ferromagnetic contacts.

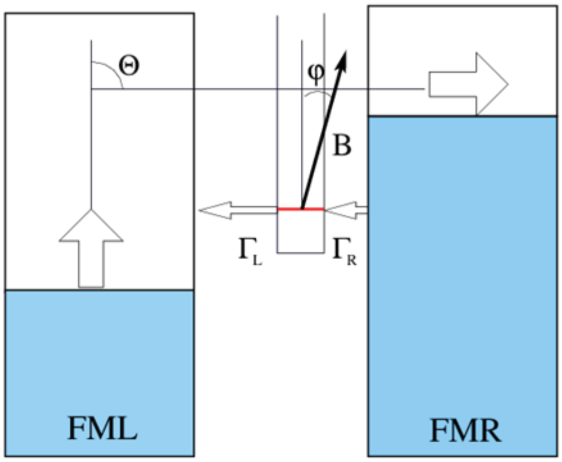

Fig. 1. The quantum well is positioned between the two ferromagnetic non-collinear electrodes. ΓL and ΓR are the tunneling rates and B is the magnetic field.

We consider a quantum well separated by the tunnel barriers from the two ferromagnetic contacts. We assume that the well is sufficiently narrow that only one subband is located between the contacts' Fermi levels and is responsible for the resonant tunneling. The magnetic field lifts the degeneracy between the subbands for spin-up and spin-down. In the absence of the Coulomb repulsion between the up/down subbands the current I through the structure is determined by the following expression [19]:

$$I = \frac{e}{h}\int dE\,[S_L(E) - S_R(E)]\mathrm{Tr}(G^a\Gamma_R G^r\Gamma_L) \qquad (1)$$

e is the electron charge and h is the Plank constant. Because the confinement quantizes only the perpendicular motion in the well, while the in-plane motion is free, the supply functions $S_{L(R)}(E)$ from the left(right) contacts obtained by the integration of the in-plane momenta are entering in (1).

$$S_{L(R)}(E) = \frac{mT}{2\pi\hbar^2}\ln\left(1+\exp\left(\frac{\mu \pm \frac{U}{2} - E}{T}\right)\right) \qquad (2)$$

T, E and μ are the temperature, energy, and chemical potential, respectively. m is the effective mass, and U is the applied voltage. The advanced and retarded Green's functions G^a, G^r are the matrices defined by (3).

$$G^{r,a} = \left(E - M \pm \frac{i}{2}(\Gamma_R + \Gamma_L)\right)^{-1} \qquad (3)$$

$$M = \frac{\Delta}{2}\begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$

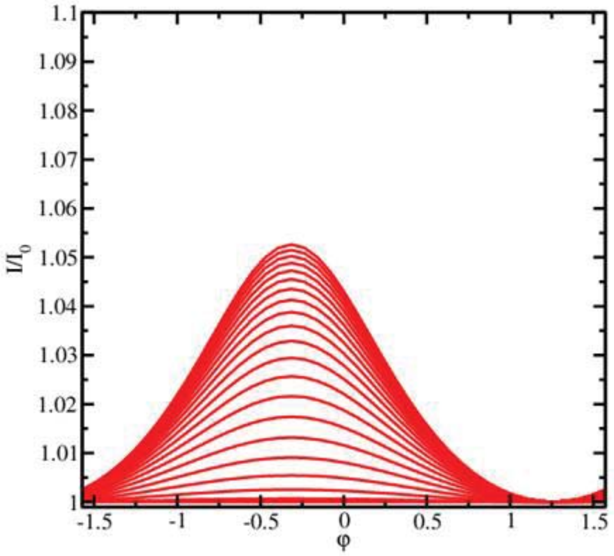

Fig. 2. Normalized current as a function of the angle between the magnetic field and the magnetization for several magnetic field values. The current increases with B increased. The angle between the contact magnetizations is Θ=-π/5.

$$\Gamma_{L,R} = \gamma_{L,R}\begin{pmatrix} 1 + p_{1,2}\cos\Theta_{1,2} & p_{1,2}e^{-i\varsigma_{1,2}}\sin\Theta_{1,2} \\ p_{1,2}e^{i\varsigma_{1,2}}\sin\Theta_{1,2} & 1 - p_{1,2}\cos\Theta_{1,2} \end{pmatrix} \quad (4)$$

$p_{1,2}$ is the spin polarization at the ferromagnetic contacts, $\Delta = \frac{\hbar eB}{mc}$ is the Zeeman splitting in the magnetic field B, and $\varsigma_{1,2}$ and $\Theta_{1,2}$ are the azimutal and polar angles defining the magnetization orientation relative to the OZ axis along the magnetic field.

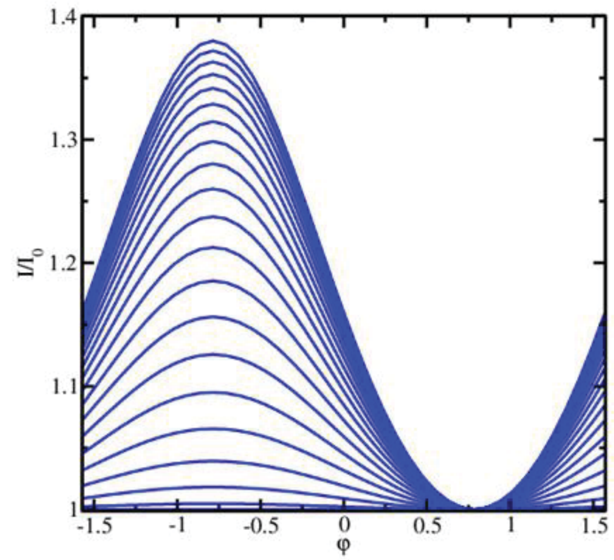

Fig. 3. Normalized current as a function of the angle between the magnetic field and the magnetization for several magnetic field values. The current increases with B increased. The angle between the contact magnetizations is Θ=-π/2.

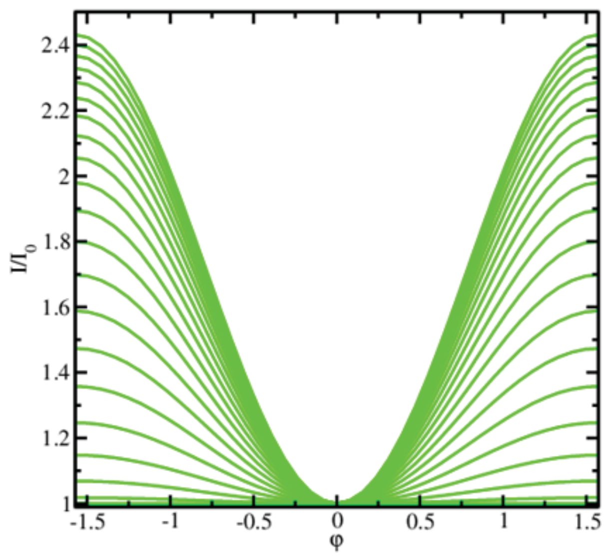

Fig. 4. Normalized current (as in Fig.2 and Fig.3) for antiparallel contact orientation Θ=π .

III. RESULTS

We consider the system sketched in Fig.1 ($\varsigma_{1,2} = 0$, $\Theta = \Theta_1 - \Theta_2, \varphi = -\Theta_1$). The Figs.2, 3, and 4 show the current through the system as a function of the magnetic field direction φ in-plane with both magnetizations for values of the Zeeman splitting from 0 to 4γ stepped with 0.2γ. The angles between the electrodes' magnetizations are fixed at $\Theta = -\frac{\pi}{5}, -\frac{\pi}{2}, \pi$, correspondingly. Furthermore, we choose $\gamma = \gamma_R = \gamma_L$, μ=0, $p_{1,2} = 0.8$, T=300K, U=1/3T. The amplitude of the current has a pronounced dependence on the external magnetic field

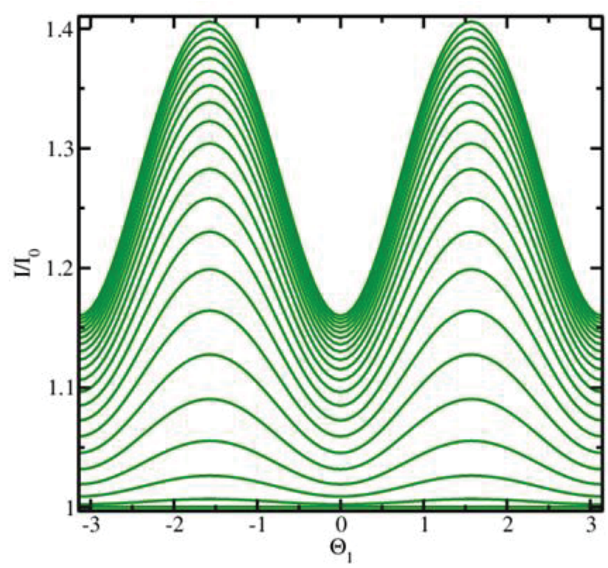

Fig. 5. Normalized current as a function of the angle Θ_1 between the magnetic field (along the OZ axis) and the in-plane magnetization direction of the first contact. The magnetization of the second contact is out-of plane along the OY axis (Θ_2=ς_2=π/2,ς_1=0).

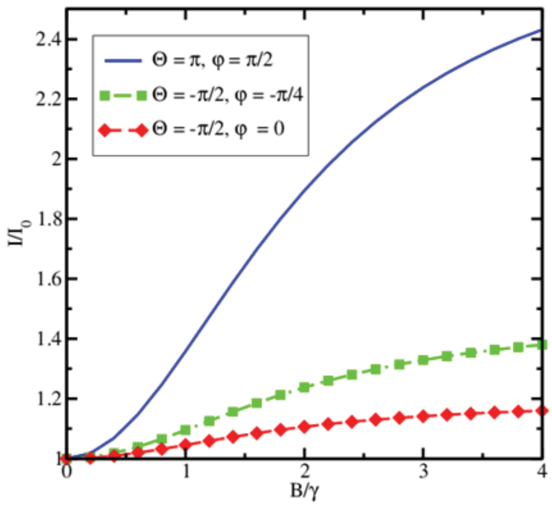

Fig. 6. The dependence of the magnetoresistance on the magnetic field for several angular arrangements. The anti-parallel contact arrangement results in a stronger dependence on the magnetic field orthogonal to the magnetizations.

with its maximum at the magnetic field direction along the vector corresponding to the sum of the magnetizations in the two contacts. This orientation of the magnetic field causes the spin entering the quantum well parallel to the magnetization in the source to precess on the trajectory which passes the direction colinear to the magnetization in the drain. This facilitates the electron to escape from the well, thus, leading to the current increase. The amplitude of the magnetoresistance increases with the angle Θ between the contact magnetizations ranging almost from zero for parallel contacts to its maximum value, when the contacts are anti-parallel. Analogously to a magnetic tunnel junction (MTJ) with anti-parallel ferromagnetic contacts, the current in this case is minimal, provided the external magnetic field is zero. The magnetic field perpendicular to the anti-parallel contact magnetizations forces the spins in the quantum well to precess. This increases the current and brings it closer to its value for parallel contacts. Fig.5 shows the current, when the magnetic field direction Θ_1 is in-plane perpendicular to the second contact ($\Theta_2 = \varsigma_2 = \frac{\pi}{2}, \varsigma_1 = 0$).

The dependence of the magnetoresistance on the magnetic field strength is shown in Fig.6, for several angular arrangements. The linear part of the dependences is suitable for magnetic field sensing. The field magnitude which can be detected is determined by the tunneling rates Γ between the quantum well and the contacts and thus can be engineered. The constant built-in stray field along the favorable direction can be adjusted by placing the well appropriately between the two non-colinear ferromagnetic contacts, the magnetization of which could be fixed by exchange coupling to a ferromagnet.

IV. SUMMARY

We investigated the magnetoresistance due to resonant tunneling through a quantum well separated from two non-collinear ferromagnetic contacts by tunneling barriers. Due to the coupling between the up/down spin subbands through a ferromagnetic contact the magnetoresistance show a dependence on the relative angles between the magnetic field and the magnetization orientations in non-collinear contacts. The linear part of the magnetoresistance dependence is suitable for magnetic field sensing.

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