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Quantum filter of spin polarized states: Metal–dielectric–ferromagnetic/semiconductor device

Vladimir I. Makarov [a,*], Igor Khmelinskii [b]

[a] Department of Physics, University of Puerto Rico, Rio Piedras, PO Box 23343, San Juan, PR 00931-3343, USA
[b] Universidade do Algarve, FCT, DQF, and CIQA, Faro P8005-139, Portugal

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ABSTRACT

Recently we proposed a model for the Quantum Spin-Polarized State Filter (QSPSF). The magnetic moments are transported selectively in this model, detached from the electric charge carriers. Thus, transfer of a spin-polarized state between two conductors was predicted in a system of two levels coupled by exchange interaction. The strength of the exchange interaction between the two conductive layers depends on the thickness of the dielectric layer separating them. External magnetic fields modulate spin-polarized state transfer, due to Zeeman level shift. Therefore, a linearly growing magnetic field generates a series of current peaks in a nearby coil. Thus, our spin-state filter should contain as least three nanolayers: (1) conductive or ferromagnetic; (2) dielectric; and (3) conductive or semiconductive. The spectrum of spin-polarized states generated by the filter device consists of a series of resonance peaks. In a simple case the number of lines equals S, the total spin angular momentum of discrete states in one of the coupled nanolayers. Presently we report spin-polarized state transport in metal–dielectric–ferromagnetic (MDF) and metal–dielectric–semiconductor (MDS) three-layer sandwich devices. The exchange-resonance spectra in such devices are quite specific, differing also from spectra observed earlier in other three-layer devices. The theoretical model is used to interpret the available experimental results. A detailed ab initio analysis of the magnetic-field dependence of the output magnetic moment averaged over the surface of the device was carried out. The model predicts the resonance structure of the signal, although at its present accuracy it cannot predict the positions of the spectral peaks.

1. Introduction

We start with introducing the abbreviations: ERS, exchange resonance spectrum; MDF, metal–dielectric–ferromagnetic; MDS, metal–dielectric–semiconductor; GMR, giant magneto-resistance; SFET, spin field effect transistor; Spin-LED, light-emitting diode; Spin RTD, resonant tunneling device; DNV, diamond nitrogen vacancy; FET, field electronic transport; FETT, field electronic tunneling transport.

Magnetic devices are widely used in information processing and storage. In particular, magnetism in metals has been the backbone of information storage for years [1,2]. A key event in this area had been the discovery in 1988 [3] of the GMR effect, where the resistance of a thin-film ferromagnetic/nonmagnetic layer is strongly magnetic-field dependent. This effect is now at the heart of almost every modern computer hard drive [4]. Further advances in this area may come from other types of magnetic devices that manipulate both spin and charge of an electron [5,6]. Recently, a technology using the electronic spin has emerged called spintronics (spin-transport electronics or spin-based electronics), where it is not the electron charge but the electron spin that carries information, envisioning a new generation of devices combining standard microelectronics with spin-dependent effects that arise from the interaction between the spin of the carrier and the magnetic properties of the material [7]. This technology may lead to more exotic information devices, capable of a wide variety of functionalities [8–11].

Two notable examples of spintronic devices are the SFET and the spin qubit [12,13]. In the SFET, the drain and source of a conventional FET transistor are ferromagnetic. If the two ferromagnetic electrodes are aligned, a spin-polarized current will behave like a normal FET current. If the ferromagnetic electrodes are anti-aligned, the SFET will be shut off. This could be done dynamically, allowing microprocessors to reconfigure hardware during runtime. In a spin qubit, the electron spin is used as a quantum bit, i.e. a bit that can exist as a superposition of a pure “0” and a pure “1” logical values. Electron spins are natural qubits, because every electron spin-state is always a superposition

* Corresponding author. Tel.: +1 787 529 2010; fax: +1 787 756 7717.
E-mail address: vmvimakarov@gmail.com (V.I. Makarov).

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of the spin-up and spin-down states. A major hindrance in practical implementation of such devices is that they require efficient spin-polarized carrier injection and transport.

Conventional ferromagnetic metals are often incompatible with existing semiconductor technology. Moreover, spin injection efficiency is often very low due to resistivity differences and formation of Schottky barriers [14]. Dilute magnetic semiconductors may offer a solution to this problem; these are alloys where a stoichiometric fraction of the constituent atoms have been used, with well-defined magnetic properties (e.g., paramagnetic, antiferromagnetic, ferromagnetic) that conventional semiconductors do not have [11–13]. Potentially they may be used as means to inject electrons in a well-defined spin state and to control spin properties in non-magnetic semiconducting layers adjacent to magnetic transition-metal atoms.

Major experimental and theoretical challenges of spintronics include optimization of electron spin lifetimes, detection of spin coherence in nanoscale structures, transport of spin-polarized carriers across relevant length scales and heterointerfaces, and manipulation of both electron and nuclear spins on sufficiently fast time scales. Recent experiments suggest that the storage time of quantum information encoded in electron spins may be extended through their strong interplay with nuclear spins in the solid state. Moreover, optical methods for spin injection, detection, and manipulation have been discussed that exploit the ability to precisely engineer the coupling between electron spins and optical photons [11,14,17].

It is anticipated that merging of electronics, photonics, and magnetic fields will ultimately lead to new spin-based multifunctional devices such as SFET [18], spin-LED (light-emitting diode) [19], spin RTD (resonant tunneling device) [20], optical switches operating at terahertz frequencies [21], modulators, encoders, decoders, and quantum bits for quantum computation and communication [22]. If we can understand and control the spin degree of freedom in semiconductors, semiconductor heterostructures, and ferromagnetics, the potential for high-performance spin-based electronics will be excellent.

There are many studies that analyze and discuss different models of spintronic devices [23–28]. The most famous and popular are GMR [23–25], FET [26], FETT [27] and DNV [28] models. The GMR model is well-developed [23–25] and describes the experimental results quite well [25]. Both FET [26] and FETT [27] models describe transport of electron in a given spin-polarized state from one material to another. Such transport is induced by an external electric field [26,27]. The DNV model describes interaction of unbounded electrons of a nitrogen atom with the unbounded zone in diamond [28]. Since the energy gap between the respective electronic states is small, their mutual coupling should be strong, resulting in high transition probability [28,11]. The optical spin polarization effect has also been discussed by several authors [29,30].

Analysis of spin-polarized state dynamics using novel theoretical approaches is a fundamental problem in spintronics. The Quantum Spin Polarized State Filter (QSPSF) device described earlier [31–34] allows to transfer spin-polarized states between nanolayers of different nature and measure values of g-factor difference between nanolayers and the relaxation parameters of the spin-polarized states. This earlier developed modeling approach assumes transfer of spin-polarized states between different nanolayers. Simple explanations for the preparation of spin-polarized states in ferromagnetics, conductors and semiconductors were analyzed. A phenomenological model of spin-polarized state transfer was proposed and discussed. Experimental measurements of the exchange-resonance spectra in three-layer sandwich structures were carried out. The presently discussed MDF and MDS structures produce distinct spectra, differing from those obtained earlier for other nanolayer sandwich structures [31–34]. These spectra are analyzed and interpreted using the earlier and presently developed theoretical models.

2. Experimental

The experimental setup used in the current studies has already been described [31,32]. It was built around a home-made nanosandwich device. This device included a ferrite needle (1) (TPS&TPSA, Power Electronics Technology), with the needle tip 50 μm in diameter was made of a stainless-steel capillary filled by ferrite powder suspended in glycerol, and the body 1 mm in diameter. The saturation field and the frequency band for the ferrite are 11–13 kG and $\nu_{H,0} = (1–15) \times 10^8$ Hz, respectively. The transmission of the ferrite at frequencies $\nu_H > \nu_{H,0}$ is described by

$$\vartheta(\nu_H) = \vartheta(\nu_{H,0}) e^{-((\nu_H - \nu_{H,0})/\nu_{H,0})} \quad (1)$$

A spiral coil of copper wire (0.3 mm wire diameter, 10 turns) was wound on the needle body. The needle tip touched the surface of a Si substrate at the (1 0 0) plane. The opposite surface of the Si substrate, equally (1 0 0), was covered by a sandwich structure. The three-layer sandwich structure included layers of different physical/chemical nature. A partial cross-section of a Si substrate (commercial product, 0.15 mm thickness) was shown earlier [1,2]. Charge sputtering was used to deposit metals, and laser vapor deposition to deposit dielectrics and semiconductors. The layer thickness was controlled by transmission electron microscopy (TEM) on cross-cut samples, prepared using heavy-ion milling.

A second ferrite item (TPS&TPSA, Power Electronics Technology), with the input surface 10 mm in diameter and the body 1 mm in diameter, contacted the output metal surface by way of a magnetic contact provided by ferrite powder suspended in glycerol (1:1 w/w) (TPS&TPSA, Power Electronics Technology, 25 μm average particle diameter). Copper wire, 0.3 mm in diameter, was wound on the body of the item (10 turns). Note that the same high-frequency ferrite material was used everywhere, rated for up to 100 MHz applications. The entire assembly with the nanosandwich sample was placed into a liquid nitrogen bath ($T \approx 77$ K), to reduce noise.

A home-made current generator, with the electronic circuit shown in Fig. 1(b), was controlled via an I/O data acquisition board (PCI- 6034E DAQ, National Instruments), which was programmed in the LABVIEW environment and run on a Dell PC. The generator fed pulsed output currents of up to 10 A into the input coil. The pulse shape was programmed to reproduce the linear function:

$$I_2(t) = \begin{cases} 0, & 0 \le t < t_0 \\ I_0 \times (t - t_0), & t_0 \le t < t_0 + \tau \\ 0 & t_0 + \tau \le t \end{cases} \quad (2)$$

where I_0, t_0 and τ (pulse amplitude, start time and duration) were chosen to obtain the required magnetic field sweep rate. The output coil was connected to a digital oscilloscope (LeCroy; WaveSurfer 432), which collected and averaged the output signal. The I/O DAQ board generated an analog signal, controlling the current generator, and a rectangular TTL pulse 100 ns in duration, triggering the oscilloscope with its rising edge, 100 ns before the start of the analog control signal sweep.

Low-temperature measurements were carried out at 5.3 K using a closed-cycle liquid He cryostat (ARS; model CS202*E-DMX-1AL).

3. Results and discussion

We recorded exchange-resonance spectra for three sets of three-layer sandwich devices, one set with metal–dielectric–ferromagnetic