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Quantum spin polarization effect in multi-nanolayer structures

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ABSTRACT

We studied the spin-polarized state transport in Fe–SnO_2–Ag and Fe–BeO–Ag three-nanolayer sandwich structures. The exchange-resonance spectra of these sandwich structures are quite specific and different from those observed earlier in other three-nanolayer structures. The presently recorded spectra comprise a set of discrete lines, their width increasing with the sample temperature and also with the Ag layer thickness, for both samples. The linewidth dependences on temperature and Ag layer thickness were studied in detail. The effect of thickness of the intermediate nanolayers of SnO_2 and BeO on the linewidth was also explored. To explain the observed line broadening effects, we proposed and developed the spin-orbit (SO) coupling mechanism of the electron spin relaxation. In the frameworks of this mechanism, we assumed that the electron spin of a bonding electron in one of the layers of the sandwich system is coupled by SO interaction with the other layers. We found that the change in phonon densities affects the linewidths of the exchange resonance spectra. We estimated the values of the model parameters from the analysis of the experimental data. To that end, we continue further development of our earlier theoretical model, using it to interpret the current experimental results, including *ab initio* calculations of the electronic structure. The exchange resonance spectra were simulated using phenomenological model, where the anisotropy of the *g*-factor was introduced. We performed *ab initio* simulations of the exchange resonance spectra and their linewidths, using Gaussian-2000 and a homemade FORTRAN code.

1. Introduction

The magnetic properties of different materials are used in information processing, system control, data storage, *etc.* Ferromagnetic properties of ferromagnetic materials (Fe, Fe_3O_4, *etc.*) are the base of information storage [1,2]. An important step in this area had been the discovery in 1988 of the GMR effect [3,4]. Further progress in this area may come from other types of magnetic structures that manipulate both spin and charge of an electron [5,6]. Recently, a technology using the electronic spin has emerged called spintronics [7]. Such technology may be used in more exotic information-processing systems [8–11]. The SFET and the spin qubit are examples of spintronic structures [12,13].

Conventional ferromagnetic materials are sometimes incompatible with the existing semiconductor technology. In this case, spin injection efficiency is typically very low [14]. Dilute magnetic semiconductors may offer a solution to this problem [11–13]. Optical methods for spin injection, detection, and manipulation were also discussed [14–18].

It was expected that merging of electronics, photonics, and magnetic fields can create new spin-based multifunctional structures such as SFET [19], spin-LED [20], and spin-RTD [21]. Optical switches operating at terahertz frequencies and other devices for quantum computations and quantum communications have also been discussed [22,23]. Thus, if it were possible to understand and control the spin degree of freedom in semiconductors, semiconductor heterostructures and ferromagnetics, the potential for high-performance spin-based electronics would be excellent.

Different designs of spintronic structures were widely discussed earlier [24–29]. The GMR, FElT, FETT and DNV phenomena were also discussed quite extensively [24–29]. The existing GMR model describes the experimental results quite well [26]. Both FElT [27] and FETT [28] models describe the electron transport in a given spin-polarized state from one material to another, induced by an external electric field [27,28]. In the frameworks of the DNV model, the interaction of the non-bonding electrons of a nitrogen atom with the non-bonding zone in diamond is analyzed [29]. Here, the coupling should be strong, because the energy gap between the respective

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Abbreviations: ERS, exchange resonance spectrum; GMR, giant magneto-resistance; SFET, spin field effect transistor; LED, light-emitting diode; RTD, resonant tunneling device; DNV, diamond nitrogen vacancy; FElT, field electronic transport; FETT, field electronic tunneling transport; QSPSF, quantum spin-polarized state filter; AFM, atomic force microscopy; XRD, X-ray diffraction

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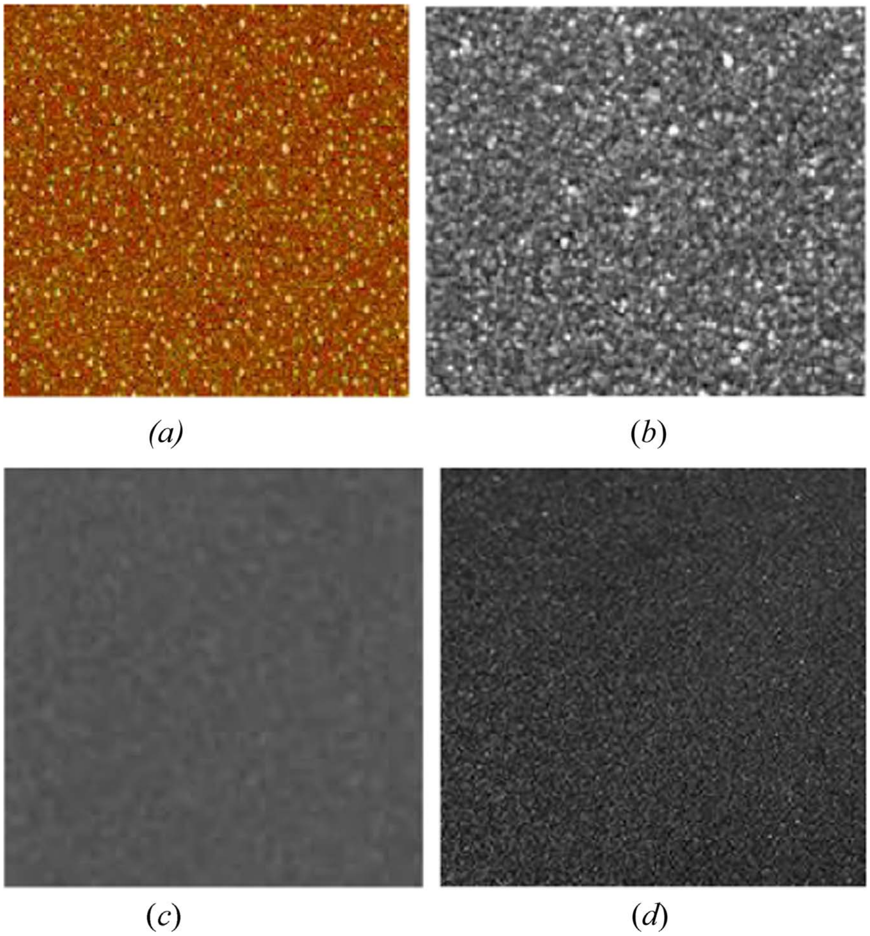

Fig. 1. AFM images of the nanolayers: (a) Fe, 7.3 nm thick, (b) SnO_2, 6.1 nm, (c) BeO, 7.8 nm, and (d) Ag, 7.9 nm. The frame size of the images is 20×20 nm^2.

electronic states is small, which also leads to high transition probability between the states [29,30]. Several authors also discussed the optical spin polarization effect [31,32].

The development of new experimental and theoretical approaches to the investigation of spin-polarized state dynamics is a fundamental problem of spintronics. The QSPSF device described earlier involving different multi-nanolayer structures [33–40] allows to transfer spin-polarized states between nanolayers of different physical and chemical nature, and measure the values of the Δg difference between g-factors of nanolayers of the studied sandwich structure, the relaxation parameters of the spin-polarized states, the energy gap between the interacting spin states in the absence of an external magnetic field and the total spin of the interacting spin states. The earlier developed modeling approach explored the spin-polarized state transfer between different nanolayers. We analyzed simple explanations for the preparation of spin-polarized states in ferromagnetics, conductors and semiconductors, proposing and discussing a phenomenological model of spin-polarized state transfer. We reported experimental measurements of the exchange-resonance spectra in three-layer sandwich structures [33–40]. We also reported detailed *ab initio* analysis of the exchange resonance occurring between different nanolayers in a multi-nanolayer system [36–40]. We assumed that the spin-polarized state transfer in caused by spin anticrossing, with the spin states in different nanolayers coupled by the exchange interaction and shifted past each other by an external magnetic field [38–40]. These earlier developed experimental and theoretical approaches were also used in the present study.

The presently discussed S1 (Fe-SnO_2-Ag) and S2 (Fe-BeO-Ag) sandwich structures produce distinct spin-anticrossing spectra, differing from those obtained earlier for other nanosandwich structures [33–40]. We analyze and interpret these spectra using the previously developed theoretical models with major modifications [33–40], and some new models. An important progress in the theoretic description was achieved by employing anisotropic g-factors, which we approximated by axial tensors. We also determined the components of the Δg tensor, comparing the present results with the earlier reported [33–40] theoretical analysis that employed an unstructured vacuum in place of an insulator nanolayer. The present models properly describe the recorded exchange resonance spectra and their temperature dependence, producing the model parameter values. The linewidth dependence on temperature and Ag layer thickness was studied in detail. We also explored the effect of thickness of the intermediate nanolayer of SnO_2 and BeO on the linewidth. To explain the observed line broadening effects, we proposed and developed the spin-orbit (SO) coupling mechanism for the electron spin relaxation. In the frameworks of this mechanism, we assumed that the electron spin of the bonding electrons in a nanolayer is coupled by SO interaction to the other nanolayers. We found that the changes in the phonon density, caused by varying temperature and layer thickness, affect the linewidth in the exchange resonance spectra. We obtained the values of the model parameters from the analysis of the experimental data, comparing the present and the earlier reported modeling approach.

2. Experimental

The experimental setup used in the current studies has already been described [33–40]. 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 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