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Magnetic tunnel structures: Transport properties controlled by bias, magnetic field, and microwave and optical radiation

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ABSTRACT

Different phenomena that give rise to a spin-polarized current in some systems with magnetic tunnel junctions are considered. In a manganite-based magnetic tunnel structure in CIP geometry, the effect of current-channel switching was observed, which causes bias-driven magnetoresistance, rf rectification, and the photoelectric effect. The second system under study, ferromagnetic/insulator/semiconductor, exhibits the features of the transport properties in CIP geometry that are also related to the current-channel switching effect. The described properties can be controlled by a bias, a magnetic field, and optical radiation. At last, the third system under consideration is a cooperative assembly of magnetic tunnel junctions. This system exhibits tunnel magnetoresistance and the magnetic-field-driven microwave detection effect.

1. Introduction

Recent studies have shown that a spin degree of freedom of charge carriers manifests itself most strikingly and sometimes unexpectedly in nano-sized magnetic and hybrid structures [1,2]. Spin transport and manipulation by spins in nanostructures have formed a novel trend in physics of condensed matter, known currently as spintronics. This field of investigations involves both fundamental physics of spin-dependent phenomena and applications based on controlling an electron spin.

Among the most attractive spin-dependent phenomena in the magnetic nanostructures is the spin dynamics induced by a spin-polarized current. This phenomenon is related to a so-called spin transfer torque effect through which electron spins may influence orientation of magnetization, causing reversal of the latter or stable high-frequency precession [3]. This precession serves as a source of microwaves whose frequency can be controlled by a current and a magnetic field.

The spin transfer torque is responsible also for the inverse effect, i.e., generation of a dc voltage on a magnetic tunnel junction under the action of microwaves [4]. This rectification effect, which can be successfully driven by a magnetic field and a current, originates from the interplay between the spin-polarized current and the spin dynamics in magnetic nanostructures. Thus, magnetic tunnel and hybrid structures exhibit a variety of the spin-dependent physical phenomena. In this study, we consider some spin-dependent phenomena in the magnetic tunnel structures of different types. From our point of view, these phenomena, still insufficiently presented in the literature, have a considerable potential for application. First of all, it concerns a specific response of the magnetic tunnel structures to the effect of microwave and optical radiation. The transport properties of the tunnel structures were studied using unconventional current-in-plane (CIP) geometry, which was suggested, first, by D. Worledge and P.L. Trouilloud [5]. We also discuss the spin-dependent phenomena in a cooperative system of the magnetic tunnel junctions.

2. Magnetic tunnel structures in current-in-plane geometry

The first system to consider is the manganite-based magnetic tunnel structure $La_{0.7}Sr_{0.3}MnO_3$ (100 nm)/manganite depleted layer (5 nm)/MnSi (10 nm) in unconventional CIP geometry [6]. Here, the depleted layer is an insulator; therefore, it forms a potential barrier between the $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) ferromagnetic electrodes with T_C=250 K and MnSi with T_C=30 K. Fig. 1a demonstrates the geometry used in measurements. An equivalent electrical scheme of the structure for the CIP geometry is shown in Fig. 1b.

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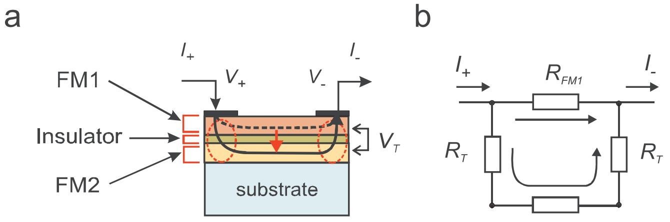

Fig. 1. (a) Magnetic tunnel junction in CIP geometry; FM1 and FM2 are the ferromagnetic LSMO and MnSi layers and an insulator is the depleted manganite layer; the arrows indicate current channels. (b) Equivalent electrical scheme.

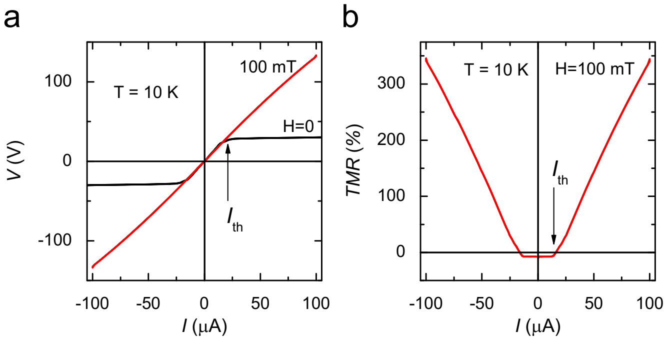

Fig. 2. (a) V–I curves for $H=0$ and for an applied magnetic field of 100 mT at $T=10$ K. (b) Dependence of the magnetoresistance (TMR) on bias current I through the structure.

The top and bottom conducting layers in the structure are separated by a potential barrier preventing current passage in the bottom layer. When I applied to the structure is small, the current flows mainly in the top layer, i.e., in the manganite film (initial linear portion of the V–I characteristic). An increase in I leads to the occurrence of bias voltage V_T on the tunnel junctions under the current contacts and, consequently, a decrease in junction resistance R_T. At a certain value of current I_{th}, R_T becomes lower than resistance R_{FM1} of the top layer, so the current starts flowing mainly in the bottom layer, whose resistance R_{FM2} is small as compared to R_{FM1} ($R_{FM2} \ll R_{FM1}$). One should expect a sharp change in the V–I characteristic of the structure.

The described scenario was observed in full in the structure under study [6]. The V–I characteristics of the structure have the initial, almost linear portion corresponding to the case when the current flows mainly through the top layer of the structure. At some threshold current I_{th}, the slope of the dependences sharply changes (Fig. 2, dependence for $H=0$). This is caused by current channel switching between the layers of the structure (at $I > I_{th}$, the current flows mainly through the bottom layer with higher conductivity).

Approximation of the V–I characteristics in accordance with the equivalent scheme (Fig. 1b) yields satisfactory results [7]. For tunnel current I_T the Simmons formula was used [8] and the current through the upper layer was described according to the Ohm's law.

The measurements of the V–I characteristics showed that the effect of the magnetic field is more pronounced at $T < 30$ K and for $I > I_{th}$ (Fig. 2a). At $T=10$ K in a magnetic field of 100 mT, the V–I characteristic, initially strongly nonlinear, becomes nearly linear. This is due to an increase in R_T at parallel orientation of magnetizations M_M and M_S of the ferromagnetic layers LSMO and MnSi, respectively, in a magnetic field; R_T becomes higher than R_{FM1}, the current channels switch, and the current starts flowing mainly in the top layer, even at $I > I_{th}$. This scenario causes the tunnel magnetoresistance ($TMR=(R(H)-R(0))/R(0)$) effect whose value depends on a bias current applied to the structure (Fig. 2b).

Considering the dependence of I_T on relative orientation of M_M and M_S, we should suggest that, in our case, the ferromagnets are of different types: LSMO is a MASC (majority spin carriers) ferromagnet, where spins of the carriers are mainly parallel to the direction of magnetization. MnSi should be attributed to a MISC (minority spin carriers) type, where spins are mainly antiparallel to magnetization, which is confirmed by the DOS calculation [9]. Only for a tunnel junction with one MISC and one MASC ferromagnetic electrode, R_T will be higher at parallel orientation of the electrodes (in a magnetic field) than at the antiparallel one (magnetic field is zero), i.e., the magnetoresistance is positive ($TMR > 0$) [10].

Now let us consider the effect of microwave radiation on the transport properties of the magnetic tunnel structure under study. As before, we used planar geometry when a current flows parallel to the interfaces. During the measurements, the structure was placed inside a microwave cavity (TE_{102} mode, $f=10$ GHz) in a nodal position of the maximum rf magnetic field. The rf magnetic field h_{ac} was maintained along the structure plane; static in-plane magnetic field H was also applied perpendicular to h_{ac}. At such a configuration, the microwave magnetic field induces microwave current I_{ac} in the tunnel structure.

The structure exhibits the effect of rectification of I_{ac}, but at $T < 30$ K the value of detected voltage V_{dc} depends on H (Fig. 3a). Bias current I_{dc} through the structure strongly affects V_{dc} and its behavior in a magnetic field. The maximum value of V_{dc} corresponds to I_{dc}, for which the maximal nonlinearity is observed in the V–I characteristics (Fig. 3b). Upon detuning of the I_{dc} in the regions where the V–I characteristics are more smooth, V_{dc} decreases and at zero bias no rectification effect is observed. It is apparently nonlinearity of the V–I characteristics that determines the detection properties of the structure under study. The magnetic-field dependence of the effect appears due to modification of the V–I characteristics in the applied magnetic field. Thus, we believe that, in our case, the same mechanism as in the case of classical (nonmagnetic) tunnel junctions works. At the same time, we should note that it is the magnetic-field dependence of the resistance of the magnetic tunnel transitions that is the origin of the change in the V–I characteristics (as was discussed above).

Electromagnetic radiation in the optical range also affects the transport properties of the investigated structure in the CIP geometry [11]. The photoinduced changes in the transport properties are reversible and tend to saturation with increasing radiation power density P (Fig. 4). This suggests that the observed changes are not related to trivial heating due to radiation absorption. This suggestion is confirmed by a measured spectral dependence of the photoelectric effect. The spectral dependence has a threshold character, as the photoinduced changes are observed at the photon energies $(h\nu)_{th} > 1.17$ eV.

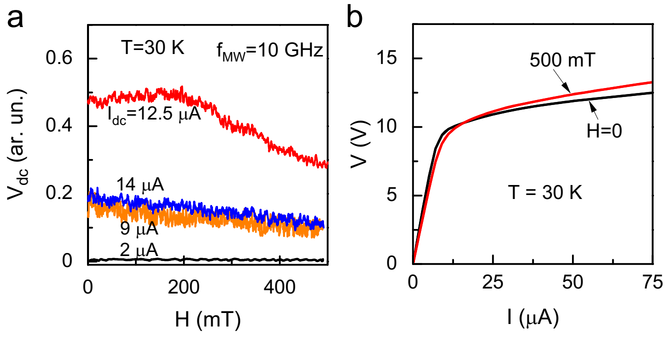

Fig. 3. (a) Detected dc voltage V_{dc} as a function of the magnetic field measured for different bias current at $T=30$ K. (b) V–I characteristic for $H=0$ and in a field of 500 mT at $T=30$ K.

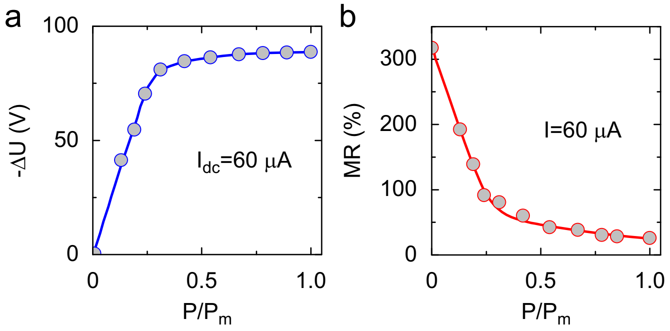

Fig. 4. (a) Photoinduced change in a voltage ΔU on the structure and (b) magnetoresistance versus power density of optical radiation P; $P_m = 60$ mW/cm^2.

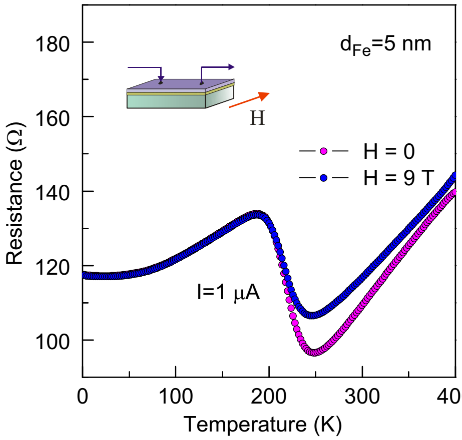

Fig. 5. Temperature dependences of resistance of the continuous-film structure at $H=0$ and $H=9$ T; the bias current is $I=1$ μA. Inset: the geometry of the experiment.

The analysis of the experimental results allows us to conclude that here interband light absorption in the dielectric layer occurs. The light with energy $h\nu$ higher than dielectric band gap E_g generates electron-hole pairs in the dielectric layer. Photogenerated carriers contribute to the total current through the tunnel junctions, thus controlling current channel switching between the top and bottom layers of the structure. Under the action of radiation, the V–I characteristics strongly change. Rapid saturation with increasing P and some peculiarities of the photoelectric effect can be attributed to the features of generation and recombination of photoelectrons and photoholes in the tunnel structure.

3. Hybrid structure with a tunnel barrier in current-in-plane geometry

The hybrid multilayer nanostructures consisting of magnetic elements and nonmagnetic semiconductor layers combine a huge potential of conventional semiconductor electronics and advantages of magnetic materials whose transport properties can be controlled via spin states of electrons. The study of the hybrid structure Fe (5 nm)/SiO$_2$ (1.5 nm)/p-Si (substrate) shows that, similar to the case of magnetic tunnel junctions, features of its transport properties in CIP geometry are related to the effect of current channel switching [12].

The temperature dependences of resistance R for the structure with the continuous Fe film are shown in Fig. 5. The main feature in the R behavior is a sharp jump at 250–200 K. This feature is attributed to current channel switching between the semiconductor substrate and the iron film. At high temperatures ($T > 250$ K), resistance of the Fe/SiO$_2$/p-Si transition is lower than that of the ferromagnetic film and the current flows mainly in the semiconductor substrate. Below 250 K, resistance of the transition starts rapidly growing; at 200 K, the current path in the upper iron film becomes more favorable, since R of the iron film appears lower than the transition resistance.

We studied also a simplest lateral device: two electrodes separated by a gap of 20 μm were formed from a continuous iron film. The experimental results obtained for the gap-film structure is an additional argument for the scenario at which current channel switching occurs between the semiconductor substrate and the Fe film in the continuous-film structure. As one could expect, the behavior of resistance of the gap-film structure at $T > 250$ K repeats qualitatively that of the continuous-film structure (Fig. 6). However, below 250 K, R starts continuously growing, which is caused by the absence of the Ohmic contact between Fe electrodes on the structure surface.

The planar geometry in which we studied the transport properties of the gap-film structure suggests that the current path lies through the Fe/SiO$_2$/p-Si junctions and the p-Si semiconductor substrate volume. The SiO$_2$ layer forms a potential barrier and, consequently, the tunnel transition separates the upper Fe film and the semiconductor substrate in the structure. Nevertheless, the role of principal is played by a Schottky barrier formed near the SiO$_2$/p-Si interface. Its resistance strongly depends on temperature and bias current; these dependences determine the transport properties of the gap-film and continuous-film structures. In the latter case, redistribution of the current between the iron film and the semiconductor substrate occurs with varying resistance of the Schottky barrier at the SiO$_2$/p-Si interface.

The V–I characteristics and temperature dependences of R for the gap-film and continuous-film structures which were calculated using the general expression for the current via the metal/insulator/semiconductor junction reproduce all the features of the experimental results well.

Regarding the effect of the magnetic field, noticeable positive magnetoresistance MR for both types of the structures is observed only at high temperatures ($T > 200$ K), i.e., before the sharp growth of resistance of the Fe/SiO$_2$/p-Si transition. Below 250 K, MR rapidly decreases. Typical field dependences of R are given in Fig. 7.

To explain the observed magnetoresistive properties, we may address to the theory [13], where positive magnetoresistance is implemented in a weakly disordered medium with regard to the

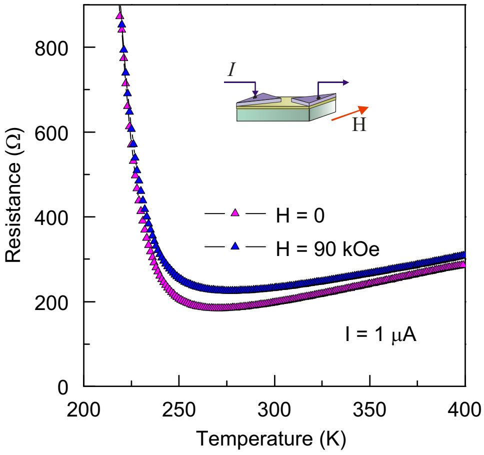

Fig. 6. Temperature dependences of resistance of the gap-film structure at $H=0$ and $H=9$ T; the bias current is $I=1$ μA. Inset: the geometry of the experiment.

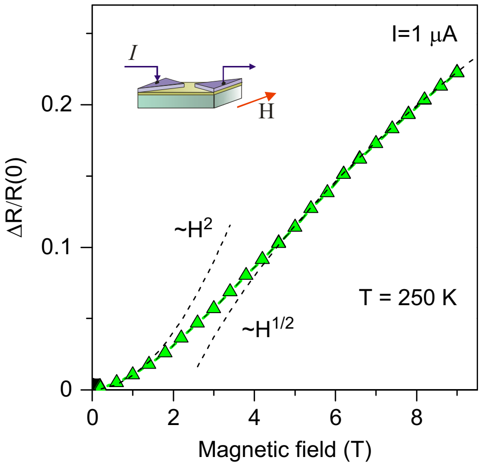

Fig. 7. Field dependence of magnetoresistance of the gap-film structure at $T=250$ K; dashed lines are approximations of the dependences by $H^2$and $\sqrt{H}$.

electron interaction. A silicon crystal (substrate) doped with boron can be considered as a medium where carriers have random potentials, which is formed by random distribution of impurities over a crystal volume. This theory predicts the $\sqrt{H}$ dependence within the strong-field limit, the H^2 dependence in weak fields, and the crossover point near $H=k_BT/g\mu_B$ ($\sim$2.2 T at $T=300$ K). This is consistent with the experimental magnetic-field dependences of resistance.

4. Cooperative system of magnetic tunnel junctions

The third system under study is a granular manganite material that represents a cooperative assembly of the magnetic tunnel junctions. This system exhibits a great value of magnetoresistance and the magnetic-field-driven microwave detection effect [14,15]. The magnetoresistance and rectification effects in the granular manganite sample are caused by a ramified network of the magnetic tunnel junctions, which are formed by ferromagnetic conducting grains with insulator boundaries. Magnetoresistance originates from the spin-dependent tunnel current between the grains, while the rectification effect is based on the interplay between the spin-polarized current through the tunnel junctions and magnetic resonance induced inside the grains forming the junctions.

Typical dependences of detected voltage V_{dc} on magnetic field are shown in Fig. 8. The dependences measured at different microwave frequencies from 8 to 12 GHz represent a broad peak resembling an absorption line.

With an increase in microwave radiation frequency, the peak broadens, its intensity decreases, and its position shifts toward stronger magnetic fields, as could be expected for a magnetic resonance absorption line. The latter suggests that, indeed, the nature of the rectification effect is related to the magnetic dynamics in the tunnel junctions of the system.

Briefly, the essence of the mechanism is the following: a microwave magnetic field induces microwave current I_{ac} through the tunnel junctions and, on the other hand, precession of magnetization in the FM grains. At specified conditions, for two grains forming a junction, magnetization of one grain is fixed but that of the other processes with a magnetic resonance frequency.

Since the resistance of the magnetic tunnel structure depends on relative orientation of magnetization of the ferromagnetic electrodes, the temporal dependence of the resistance appears for the current flowing through the junction. This gives rise to the diode effect and, consequently, to rectification of the microwave current in the magnetic tunnel junction. It is clear that a rectified voltage on the sample is a total response of a set of the tunnel junctions formed in a granular system.

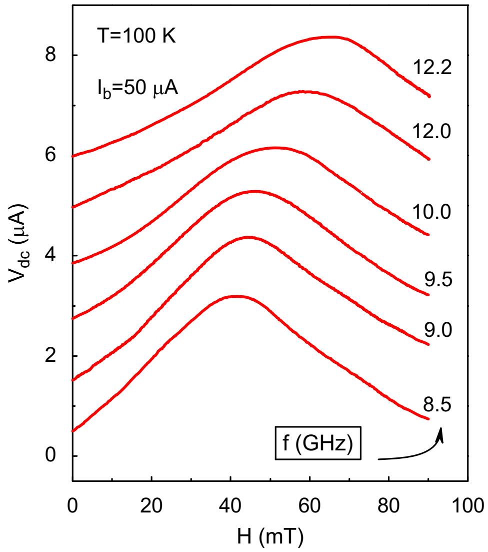

Fig. 8. Detected dc voltage as a function of a magnetic field in granular $La_{0.7}Ca_{0.3}MnO_3$.

5. Summary

In this paper, we reported some novel phenomena observed in several systems with the magnetic tunnel junction. All these phenomena are determined by the features of the spin-polarized transport in magnetic nanostructures. We believe that these examples convincingly show that the potential of the magnetic tunnel structures is not completely exhausted and they will bring many new interesting discoveries both for fundamental physics and spintronics applications.

Acknowledgments

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