Journal of Physics D: Applied Physics

Optically driven conductivity and magnetoresistance in a manganite-based tunnel structure

To cite this article: N V Volkov *et al* 2009 *J. Phys. D: Appl. Phys.* **42** 205009

IOP Publishing JOURNAL OF PHYSICS D: APPLIED PHYSICS

J. Phys. D: Appl. Phys. **42** (2009) 205009 (4pp) doi:10.1088/0022-3727/42/20/205009

Optically driven conductivity and magnetoresistance in a manganite-based tunnel structure

N V Volkov[1,2], C G Lee[3], P D Kim[1], E V Eremin[1,4] and G S Patrin[1,2]

[1] Kirensky Institute of Physics, Russian Academy of Science, Siberian Branch, Krasnoyarsk 660036, Russia
[2] Institute of Engineering Physics and Radio Electronics, Siberian Federal University, Krasnoyarsk 660041, Russia
[3] Changwon National University, School of Nano and Advanced Materials Engineering, Changwon, Gyeongnam 641-773, Korea
[4] Institute of Space Technology, Siberian State Aerospace University, Krasnoyarsk 660014, Russia

E-mail: volk@iph.krasn.ru

Received 7 July 2009, in final form 8 September 2009
Published 2 October 2009
Online at stacks.iop.org/JPhysD/42/205009

Abstract
In the multilayer structure, $La_{0.7}Sr_{0.3}MnO_3$/depleted manganite layer/MnSi, the photovoltaic effect has been discovered. The depleted manganite layer in the structure is dielectric and serves as a potential barrier between the ferromagnetic conducting $La_{0.7}Sr_{0.3}MnO_3$ and MnSi layers by the formation of a magnetic tunnel junction. The photoinduced changes in the transport properties of the magnetic tunnel structure have been observed in the current-in-plane geometry. The changes are reversible and saturate at radiation power densities over 30 mW cm^{-2}. The photovoltaic effect has a threshold character: it reveals only at $h\nu > 1.17$ eV. Most likely, the effect of optical radiation is related to the formation of electron–hole pairs due to interband absorption of light in the dielectric layer. A photocurrent through the tunnel junctions separating the conducting layers causes a redistribution of the current channels between the conducting layers, which influences the conductivity and the magnetoresistance of the structure.

1. Introduction

The phenomenon of spin-polarized electron transport in magnetic tunnel structures consisting of two ferromagnetic (FM) conducting electrodes separated by a thin dielectric layer manifests itself in two ways. Its first manifestation is spin-dependent tunnelling resulting in the tunnel magnetoresistance (TMR) effect [1]. The second one is the spin-torque effect, i.e. the occurrence of the moment exerted by the polarized electron current on the magnetic moment of a magnet [2–4]. This effect makes it possible to control magnetization of the FM electrodes by the transport current. Both TMR and spin-torque effects are promising for applications in spintronic devices, such as magnetic sensors, magnetic random access memory [5], microwave oscillators [6] and detectors [7]. The crucial question to answer is how the effects of the spin-polarized transport in the magnetic tunnel structures will work under the combined action of the external factors. The study of a response of the system to such an action could enlighten the details of the interrelation between the polarized electron current and magnetic subsystem of the tunnel structure and, thus, help to implement principally new spintronic devices. Surprisingly, so far no data on this problem have been reported in the literature. The aim of this study is to investigate the effect of optical radiation on current-in-plane-measured resistance and magnetoresistance (MR) of the manganite-based magnetic tunnel junction.

2. Experimental details

A tunnel structure was prepared by pulse laser sputtering onto SiO_2 (0 0 1) substrates using $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) and Si targets. Under the chosen technological conditions [8, 9], the structure shown in the top inset of figure 1 was

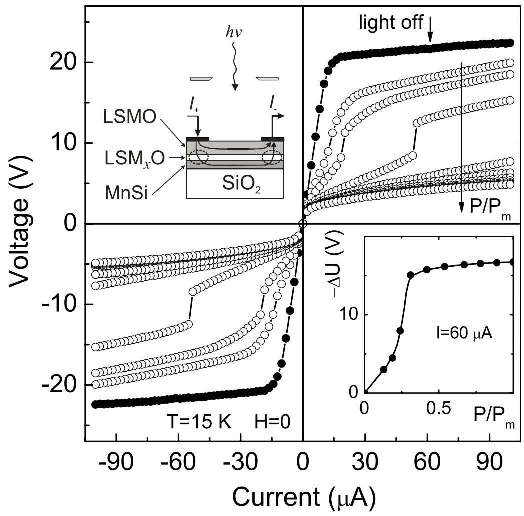

Figure 1. V–I curves of the structure for different power densities of optical radiation (980 nm) at 15 K without a magnetic field; $P/P_m = 0.13$, 019, 0.24, 0.31, 0.42, 0.54, 0.67, 0.78, 0.89 and 1; $P_m = 60$ mW cm^{-2}. The top inset schematically illustrates the tunnel structure and photovoltaic measurement geometry; the arrow curves show the possible current channels. The bottom inset shows the dependences of the photovoltaic effect on power density.

obtained: the bottom layer (∼5 nm) is manganese monosilicide MnSi, the top layer (∼500 nm) is a LSMO film and the interface (∼5 nm) is a manganite layer depleted in manganese ($LSM_\delta O$). The latter is a non-magnetic dielectric serving as a potential barrier between the conducting electrodes MnSi and LSMO. The manganite film undergoes a transition to the FM state at a temperature of about 300 K; the conductivity of the film is typical of the $La_{0.7}Sr_{0.3}MnO_3$ composition but with a significant tunnel contribution at low temperatures related to the film microstructure. MnSi is characterized by metal conductivity and undergoes a transition to the FM state at a temperature of 30 K [10]. The transport properties of the structure were studied in the current-in-plane (CIP) geometry with a precise Keithley-2400 current/voltage Sourcemeter. Ohmic contacts were formed on top of the structure of size 2×4 mm^2 with the use of two-component silver epoxy. The distance between the contacts was 2 mm. The experimental geometry is illustrated in figure 1 (top inset). The resistance was measured in the constant-current mode and the voltage–current (V–I) characteristics were taken in the current scanning regime. The magnetic field was applied in the plane of the structure. The optical effect was provided by a semiconductor laser (980 nm). The spectral dependence of the photoresponse was studied using an incandescent lamp and a monochromator.

3. Results and discussion

The effect of optical radiation on the transport properties of the structure is observed over the entire temperature range 5–250 K and is most pronounced at temperatures below 30 K. The changes in the V–I characteristics induced by light in the absence of a magnetic field are shown in figure 1. Here we should recall which factors determine the non-linearity of the V–I characteristic unusual for the CIP geometry (light-off curve in figure 1) [8, 9]. The top and bottom conducting layers of the structure are separated by the potential barrier preventing current passage in the bottom layer. When the applied current I is small, it is carried mainly by the top layer, i.e. by the manganite film (initial linear portion of the V–I characteristic). The increase in I leads to the occurrence of bias voltage V_b on the tunnel junctions under the current contacts and, consequently, a decrease in junction resistance R_T. Above a certain value I_{th}, at which the sharp kink in the V–I curve is observed, R_T becomes lower than resistance R_M of the top layer, so the current starts flowing mainly on the bottom MnSi layer whose resistance R_S is small as compared with R_M. At $I > I_{th}$, the V–I characteristic becomes nearly linear again; however, the slope of the curve at $I > I_{th}$ is much smaller than that of its initial portion.

The photoinduced changes in the transport properties are reversible and tend to saturation. The strongest changes in the V–I characteristic are observed at radiation power densities $P < 20$ mW cm^{-2} and nearly stop at $P > 30$ mW cm^{-2}. The bottom inset of figure 1 shows the change in voltage ΔU at a constant current as a function of power density of optical radiation. The resulting V–I characteristic obtained at $P_m = 60$ mW cm^{-2} is similar to the characteristic taken in the absence of radiation. At the same time, under the action of radiation, current I_{th} is smaller and the V–I characteristic at $I > I_{th}$ is considerably lower than that without radiation, which corresponds to a decrease in V on the structure contacts. For the P values at which the photoresponse is not yet saturated, the V–I characteristics are more complex. The sharp jump in V at some I value is noteworthy. As P increases, this feature is revealed more clearly and the current at which it is observed also grows. However, at $P > 20$ mW cm^{-2} for the used I values this feature disappears.

As we established previously [8, 9], at $T < 30$ K in a magnetic field the V–I characteristic changes principally. Already at $H \sim 1$ kOe the dependence becomes nearly linear (light-off curve in figure 2). This is related to the increase in R_T at parallel orientation of magnetizations of the FM layers in the magnetic field; R_T becomes higher than R_M, the current channels switch and the current starts flowing mainly on the top layer even at $I > I_{th}$. This scenario causes the MR effect whose value depends on the bias current applied to the structure. Concerning the influence of optical radiation, the largest changes in the transport properties are observed below $P \sim 20$ mW cm^{-2} (top inset of figure 2); then, the effect reaches saturation, similar to the case when the magnetic field is absent. As P increases, the V–I characteristic gradually transforms, taking the form similar to those of the dependences obtained without the magnetic field; only minor quantitative difference is observed. The bottom inset of figure 2 demonstrates the effect of optical radiation on MR. One can see that with an increase in radiation power the MR effect is suppressed.

The observed photovoltaic effect is not related to trivial heating of the structure by optical radiation. This is explained by the character of the induced changes as (1) the behaviour of the V–I characteristics upon radiation cannot be explained by

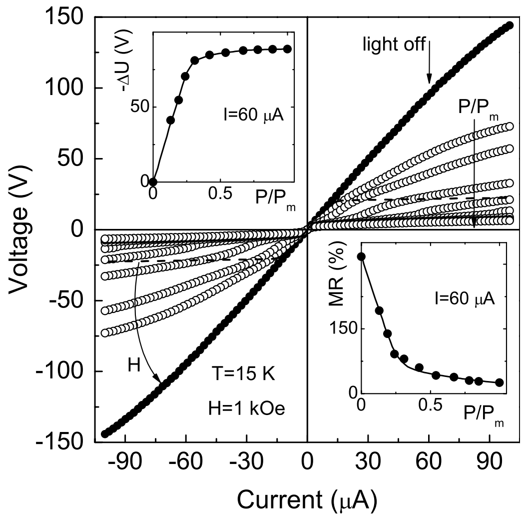

Figure 2. V–I curves of the structure for different power densities of optical radiation (980 nm) at 15 K and $H = 1$ kOe; P/P_m and P_m are the same as in figure 1; dashed curve is a dependence for $H = 0$ and $P = 0$. The top inset shows the dependences of the photovoltaic effect on power density. The bottom inset shows the dependence of the MR on power density.

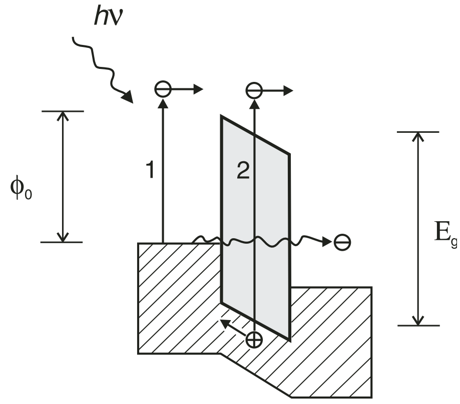

Figure 3. Schematic band diagram of the tunnel junctions in the structure and two possible mechanisms of the photovoltaic effect: (1) photoemission of the electrons from the metal electrode; (2) generation of the electron–hole pair due to the interband absorption in the dielectric layer.

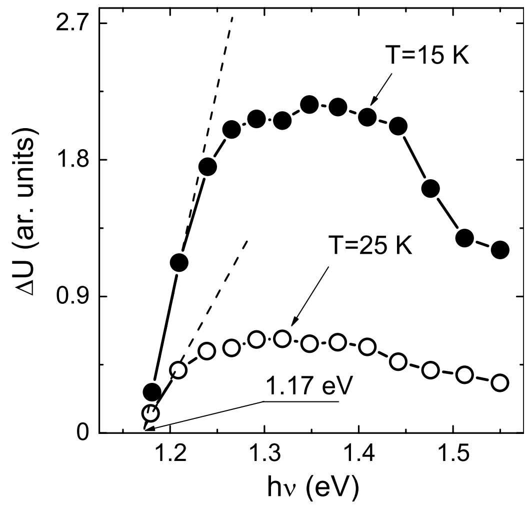

Figure 4. Dependences of the photovoltaic effect on photon energy $h\nu$ at 15 and 25 K.

the effect of heating only; (2) saturation of the effect should not be reached upon heating the structure; and (3) the obtained temperature dependences of the resistance of the structure for different radiation powers unambiguously evidence a non-thermal character of the photoinduced changes.

Since all the fundamental features of the V–I characteristic and the MR effect of the structure in the CIP geometry are determined by the magnetic tunnel junctions separating the top and bottom conducting layers, the effect of light is, most likely, related to the processes occurring at the potential barrier of the structure. The study carried out on classical (non-magnetic) tunnel junctions [11] suggested the following two most probable mechanisms: (1) The light absorbed by the metal electrodes of the tunnel structure excites electrons up to levels sufficiently high to overcome the potential barrier (figure 3). The threshold determining the start of this process known as photoemission is the barrier height ϕ_0 counted from the Fermi level in a metal. (2) The light with energy $h\nu$ higher than the dielectric bandgap E_g can generate electron–hole pairs in the dielectric forming the potential barrier (figure 3). The photogenerated carriers can contribute to the total current through the tunnel junction.

Both the above-mentioned processes are threshold; i.e. there should be a threshold energy $(h\nu)_{th}$ below which no photovoltaic effects are observed. The spectral dependences of the photoresponse obtained at 15 and 25 K are given in figure 4. It is seen that, indeed, in our case the photovoltaic effect has a threshold character, as the photoinduced changes are observed at photon energies $h\nu > 1.17$ eV. Note that the presence of the threshold is another confirmation of the fact that the photovoltaic effect is not just trivial heating of the structure by optical radiation. The spectral dependences taken at different temperatures show that the value of the photoresponse changes with temperature; however, $(h\nu)_{th}$ remains constant (1.17 eV). This allows one to conclude that here interband light absorption in the dielectric layer occurs. Firstly, as the dielectric layer is a non-magnetic LSMO depleted in manganese, its bandgap width can be estimated using the data for $La_{0.7}Sr_{0.3}MnO_3$ in the paramagnetic state ($E_g \sim 1$ eV) [12]. Secondly, our estimates showed that the average potential barrier ϕ_0 of the tunnel structure under study is much lower than 1 eV and should strongly change at low temperatures due to the shift in chemical potential in the MnSi layer after its transition to the FM state [9]. In addition, the change in the bias voltage applied to the tunnel junction results in the change in the barrier height due to the effect of the image forces [13]. In other words, in the case of photoemission, the value $(h\nu)_{th}$ should strongly change with temperature and bias voltage, which is not observed experimentally.

Note that the photoresponse in the CIP geometry is not directly related to the generation of the photopotential on the tunnel junction as one could expect for a single tunnel contact in the conventional current-perpendicular-to-plane (CPP) geometry. Light favours the increase in current through the tunnel contacts, thus controlling the current channel switching between the top and bottom layers of the structure. The action of light both with and without a magnetic field causes switching from the top low-conducting layer to the bottom high-conducting one already at small bias currents. After such switching, the V–I characteristic branch goes much lower, i.e. corresponds to smaller V values, as compared with the case in the absence of optical radiation. Such a change is graphically revealed in the V–I characteristics at $P > 30\,\mathrm{mW\,cm^{-2}}$ when the photoinduced changes reach saturation. The complexity of the V–I characteristic at smaller P can be attributed to the peculiarities of generation and recombination of photoelectrons and photoholes in different parts of the tunnel structure.

Since the MR effect is determined, in this case, by the resistance of the tunnel junctions separating the structure layers and its dependence on the magnetic field [8, 9] and the photoinduced current through the junction actually bridges this resistance, it is obvious that under the action of radiation the value of the MR effect should drop, which is observed experimentally (bottom inset of figure 2).

4. Conclusions

The effect of optical radiation on the transport and magnetotransport properties of the magnetic tunnel structure $La_{0.7}Sr_{0.3}MnO_3$/depleted manganite layer/MnSi has been discovered. The effect of optical radiation is apparently based on interband light absorption in the dielectric spacer of the tunnel structure with the formation of an electron–hole pair. We believe that the results obtained will be useful for various applications, in particular for the fabrication of novel optically driven spintronic devices.

Acknowledgments

This study was supported by the Russian Foundation for Basic Research (Projects Nos 08-02-00259-a and 08-02-00397-a) and the Division of Physical Sciences of the RAS, Programme ‘Spin-dependent Effects in Solids and Spintronics’ (Project No 2.4.2 of the Siberian Branch of the RAS).

References

[1] Moodera J S and Meservey R H 2004 *Magnetoelectronics* ed M Johnson (Amsterdam: Elsevier)
[2] Slonczewski J C 1996 *J. Magn. Magn. Mater.* **159** L1
[3] Berger L 1996 *Phys. Rev.* B **54** 9353
[4] Zhang S, Levy P M and Fert A 2002 *Phys. Rev. Lett.* **88** 236601
[5] Hirota E, Sakakima H and Inomata K 2002 *Giant Magneto-resistance Devices* (Berlin: Springer)
[6] Fuchs G D, Emley N C, Krivorotov I N, Braganca P M, Ryan E M, Kiselev S I, Sankey J C, Ralph D C and Buhrman R A 2004 *Appl. Phys. Lett.* **85** 1205
[7] Tulapurkar A A, Suzuki Y, Fukushima A, Kubota H, Maehara H, Tsunekawa K, Djayaprawira D D, Watanabe N and Yuasa S 2005 *Nature* **438** 339
[8] Volkov N V, Eremin E V, Tsikalov V S, Patrin G S, Kim P D, Seong-Cho Y, Kim D-H and Chau N 2009 *J. Phys. D: Appl. Phys.* **42** 065005
[9] Volkov N V, Eremin E V, Tsikalov V S, Patrin G S, Kim P D, Seong-Cho Y, Kim D-H and Chau N 2009 *Tech. Phys. Lett.* **35** at press
[10] Ishikawa Y, Shirane G and Tarvin J A 1977 *Phys. Rev.* B **16** 4956
[11] Kao K C and Hwang W 1981 *Electrical Transport in Solids* (Oxford: Pergamon)
[12] Dagotto E, Hotta T and Moreo A 2001 *Phys. Rep.* **344** 1
[13] Simmons J G 1963 *J. Appl. Phys.* **34** 1793