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Response of a manganite-based magnetic tunnel structure to microwave radiation

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Abstract

We demonstrate that a magnetic tunnel structure irradiated by microwaves can generate a typical voltage signal due to the rectification effect. We performed measurements in current-in-plane geometry when a current flows parallel to the interfaces in the structure. The value of the microwave-induced voltage strongly depends on the bias current and can be driven by a magnetic field. The rectification effect is discussed both in classical terms of nonlinearity of the current–voltage characteristics and within the mechanism involving the interplay between the spin-polarized current and the magnetization dynamics in the magnetic tunnel structure.

(Some figures may appear in colour only in the online journal)

1. Introduction

Studies of the spin-polarized transport in magnetic nanostructures have led to the discovery of a number of intriguing phenomena, from giant magnetoresistance to current-driven magnetization dynamics [1–3]. The latter has been a subject of intensive investigations [4–8], since the interplay between the spin-polarized current and spin dynamics is promising for applications in microwave signal processing [9]. Physical grounds of this interplay are related, first of all, to the spin transfer torque effect [10]. The spin transfer torque induced by a dc current injected into a magnetoresistive nanostructure gives rise to precession of magnetization of the layer and, as a consequence, to generation of microwaves. A phenomenon, which, in some aspects, is inverse to this effect, is the generation of a dc voltage on the magnetoresistive nanostructures upon passage of the microwave current [9, 11]. Thus, a magnetic nanostructure can work both as a current-driven microwave oscillator and as a microwave detector with magnetic-field-driven sensitivity.

In this study, we investigate the detection effect in a magnetic tunnel structure. Let us start with a brief discussion of the results obtained earlier in this field. The study of Tulapurkar *et al* [11] was apparently the first one where the authors showed that in magnetic tunnel structures a fundamentally new microwave radiation detection mechanism can be implemented, which is based on the interplay between the spin-dependent electron transport and the spin dynamics. As was shown there, a small microwave current applied to a nano-sized magnetic tunnel contact simultaneously with a constant magnetic field can generate a dc voltage if the current frequency coincides with the eigenfrequency of spin oscillations of a free ferromagnetic (FM) electrode of the structure. Under certain conditions, the coupling between tunnel magnetoresistance and the spin transfer torque effect in magnetic tunnel junctions may cause negative differential resistance; in this case, the magnetic tunnel junctions will be able to serve as amplifiers [9].

In the considered case, resonance precession was induced by a microwave current, which was then detected. This mechanism can be implemented under certain conditions; in particular, characteristic dimensions of the tunnel structure should be of nano-scale. At the same time, another situation is possible when precession of magnetization of a free layer is induced by a microwave field, as at the ordinary FM resonance, and the same microwave field induces a microwave current through the structure [12]. Here, the essence of the mechanism of detection of the microwave current is the same, i.e. it is the interrelation between the spin-polarized current and the spin dynamics in a magnetic tunnel contact. A fundamental point is that the strict requirements on dimensions of the tunnel contact are eliminated. The mechanisms of electrical detection of the FM resonance were described in detail in [13].

In this paper, we report the rectification effect observed for the first time in a manganite-based magnetic tunnel structure using the geometry when a current flows parallel to the interfaces between different layers. Previously, using this current-in-plane (CIP) geometry, we showed that peculiarities of the transport properties in such a structure are caused by current channel switching between different layers and that the switching process can be controlled by a bias current, a magnetic field and optical radiation [14–16].

2. Experimental

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. The chosen technological conditions [14] allowed obtaining the structure shown in figure 1(*a*): the bottom layer (∼10 nm) is manganese monosilicide MnSi, the top layer (∼100 nm) is an LSMO film, and the interface between them (∼5 nm) is a manganite layer depleted in manganese ($LSM_\delta O$). The latter is a nonmagnetic 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; conductivity of the film is typical of the $La_{0.7}Sr_{0.3}MnO_3$ composition but with significant tunnel contribution at low temperatures related to the film microstructure. MnSi is characterized by metal conductivity and undergoes the transition to the FM state at a temperature of 30 K.

Geometry of the experiment chosen to study the detection properties of the magnetic tunnel structure is shown in figure 1(*a*). Similar to our previous study on the transport properties, we used the planar geometry with a current flowing parallel to the interfaces of the structure. Rectified voltage V_{dc} was measured between contact pads formed at the top layer of the structure. During the measurements, the structure was placed inside a microwave cavity in a nodal position of minimum rf electric field and maximum rf magnetic field (figure 1(*b*)). The rectangular microwave cavity was tuned at 10 GHz in the TE_{102} mode. The rf magnetic field h_{ac} was maintained parallel to the structure plane, and the in-plane static magnetic field H was applied perpendicular to h_{ac}.

In this configuration, the microwave magnetic field induces, on the one hand, microwave current I_{ac} and, on the other hand, precession of magnetization in the layers of the FM structure, when field H satisfies the resonance conditions. The electric circuit used in V_{dc} measurements (figure 1(*c*)) allows applying dc bias current I_{dc} to the structure. To measure only the radiation-induced dc voltage across the sample and to reduce noise, microwave radiation was chopped at 1 kHz and the dc signal proportional to V_{dc} was recorded using a lock-in amplifier. All the measurements of the microwave detection effect were performed in a helium cryostat in the temperature range from 4.2 to 300 K at an applied field of 0–10 kOe.

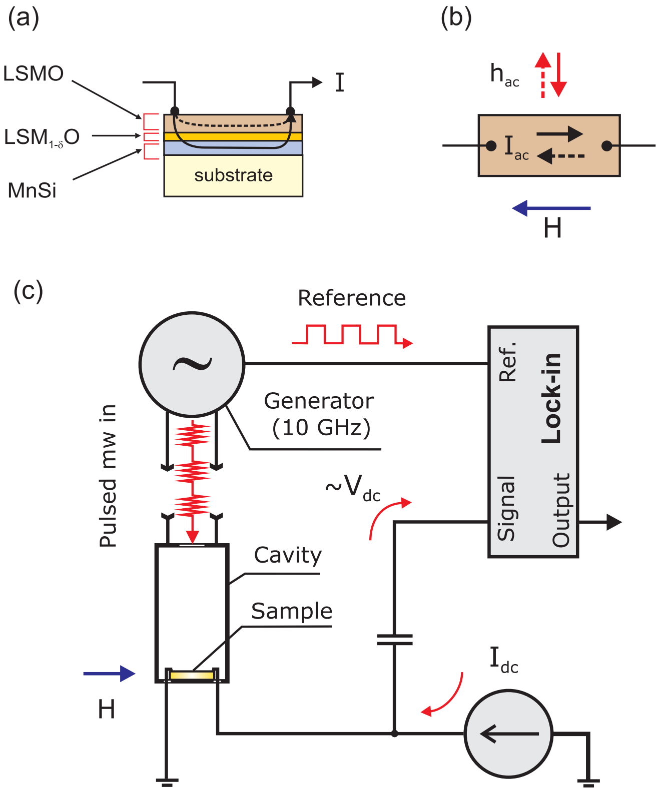

Figure 1. (*a*) Tunnel structure. The arrow curves show possible current channels in CIP geometry. (*b*) Top view of the sample; H is the static magnetic field; h_{ac} and I_{ac} are the microwave magnetic field and the rf current pattern, respectively. (*c*) Circuit for measuring the microwave detection effect.

3. Results and discussion

Before considering the obtained results, we should emphasize once again that we were interested, first of all, in the magnetically driven microwave detection effect involving both the spin-polarized current and the magnetization dynamics in a magnetic tunnel structure. The mechanism of this effect is easy to explain considering that the resistance of the magnetic tunnel junction depends on the mutual orientation of magnetization of the FM layers $\vec{m}_1$ and $\vec{m}_2$ of the structure:

$$R_T = R_{\uparrow\uparrow} + 1/2(R_{\uparrow\downarrow} - R_{\uparrow\uparrow})(1 - \vec{m}_1\vec{m}_2),$$

where $R_{\uparrow\uparrow}$ and $R_{\uparrow\downarrow}$ are the resistances of the junction at parallel and antiparallel orientations of magnetization, respectively. If, under the action of microwave radiation, the magnetic resonance conditions, i.e. a certain ratio between microwave radiation frequency f_{mw} and the external magnetic field H, are satisfied for one of the layers of the structure, magnetization of this layer starts precessing. This makes the resistance time-dependent: $R_T = R(t)$. Since the alternating current in the structure is induced by microwave radiation and has the same frequency, the resistance of the structure will be different for positive and negative polarities of the current. It is this fact that causes the diode effect and, consequently, rectification of the alternating current in a diode structure. The voltage $V(t) = I(t)R(t)$ will contain the term that involves mixing between I_{ac} and $\Delta R(t) = R_{\uparrow\uparrow} - R_{\uparrow\downarrow}$; therefore, the rectified voltage will be obtained by averaging $V_{dc} = \langle I(t)R(t)\rangle_T$ over a period of time.

We should remember, however, that the classical nonmagnetic tunnel contact also possesses the detection properties under the action of external fields with frequencies up to the visible optical range [17–20]. If the electromagnetic field energy quantum is lower than the potential barrier height, then the prevailing mechanism of the interaction between the tunnel contact and radiation is adiabatic modulation of the Fermi level in one metal electrode relative to the other. This modulation caused by the fields inside the potential barrier leads to modulation of the effective voltage on a contact. The total voltage on contacts can be presented as $V(t) = V_b + \nu(t)\cos(f_{mw}t)$, where V_b is the bias voltage on the tunnel structure and $\nu(t)$ is the voltage induced on the structure by the external electromagnetic field. The current rectified on the tunnel structure is determined by averaging the current $I(t) = V(t)/R$ (R is the resistance of the tunnel structure) over the period: $I_{rec} = (2\pi)^{-1}\int_{-\pi}^{\pi} I(t)\,d(\omega t)$. Obviously, the nonzero detecting voltage may occur only in the presence of bias voltage V_b or at the nonsymmetrical current–voltage characteristic (CVC). Here, the effect of the magnetic field may be expected only if the latter changes, by some means, the CVC of the structure.

Our CIP-geometry study of the LSMO/LSM$_\delta$O/MnSi magnetic tunnel structure showed that the latter exhibits the effect of detection of microwave radiation. However, while at $T > 30$ K the detected voltage is independent of the magnetic field, below 30 K we observe such a dependence. Figure 2(*a*) demonstrates rectified voltage V_{dc} as a function of the external magnetic field near 30 K, the maximum signal is 20 μV at a bias of 12.5 μA. The value of the voltage and the character of the dependence strongly depend on the bias current via the structure. It is noteworthy that the maximum value of the effect and the strongest changes in the magnetic field correspond to a certain value of bias current I_{dc} at which the CVC is the most nonlinear (figure 2(*b*)). Upon detuning of I_{dc} to the region of smoother CVC portions, the value of the detection effect decreases; at zero bias, there is no detection effect. It is apparently the nonlinearity of the CVC that determines the detection properties of the structure under investigation. As for the dependence on the magnetic field, it occurs due to CVC variation in the field: the higher the field, the smoother is the dependence, linear in the limit. As a consequence, the value of the detection effect decreases with increasing field. Thus, in this case the detection mechanism is the same as in the classical tunnel contacts, although just the magnetic-field dependence of resistance of the magnetic tunnel junction determines the CVC variation [14, 15]. The above results were obtained at temperatures near $T = 30$ K corresponding to the transition of the bottom conducting layer of the structure to the FM state (the top, manganite layer becomes FM at much higher temperatures, $T_c \sim 300$ K). This fact determines a relatively weak magnetic-field dependence of the CVC of the structure.

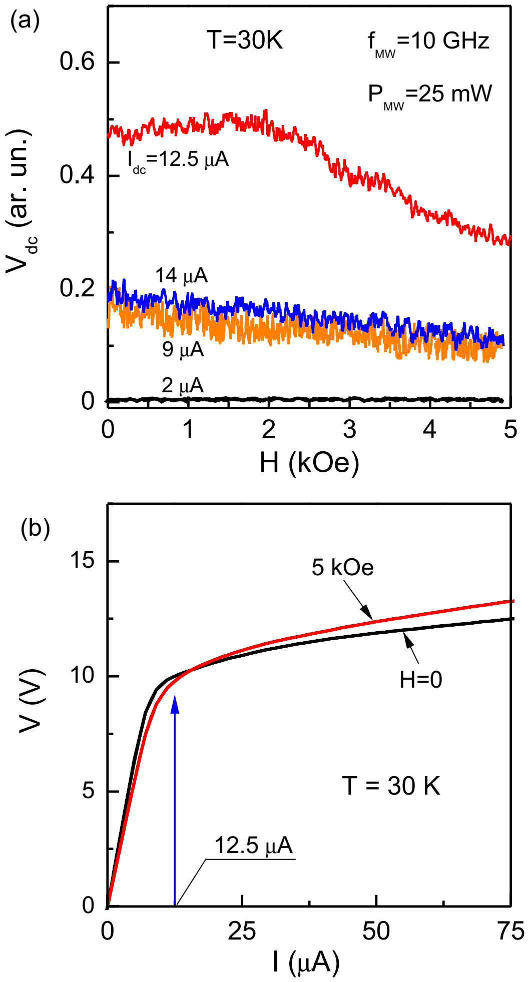

Figure 2. (*a*) Detected dc voltage V_{dc} as a function of the magnetic field at different values of the bias current at a temperature of 30 K. (*b*) Current–voltage characteristic in zero magnetic field and in a field of 5 kOe at a temperature of 30 K.

At low temperatures, the conductivity of the structure changes much strongly in weaker magnetic fields [14]. It can be seen in figure 3(*a*) that at $T = 10$ K the CVC becomes almost linear already in the fields of about 1 kOe. In this case, the initial linear portion is nearly invariable. As we know from the previous studies, this CVC portion corresponds to passage of the current only in the upper layer of the structure, i.e. in the manganite field; therefore, one should not expect the rectification effect in this bias current range. In fact, it can be seen in figure 3(*b*) that there is no detection effect at the initial CVC portion. As the increasing current I_{dc} approaches the nonlinear CVC portion that corresponds to current channel switching from the top to the bottom layer of the structure, the detection properties start occurring. The maximum effect is observed at the bias current $I_{dc} \cong 20\,\mu$V. As one would expect, the effect depends on the magnetic field: with increasing field, the value of the effect decreases and, above $H \sim 1$ kOe, it almost vanishes (figure 3(*c*)). This is quite understandable, since, as was

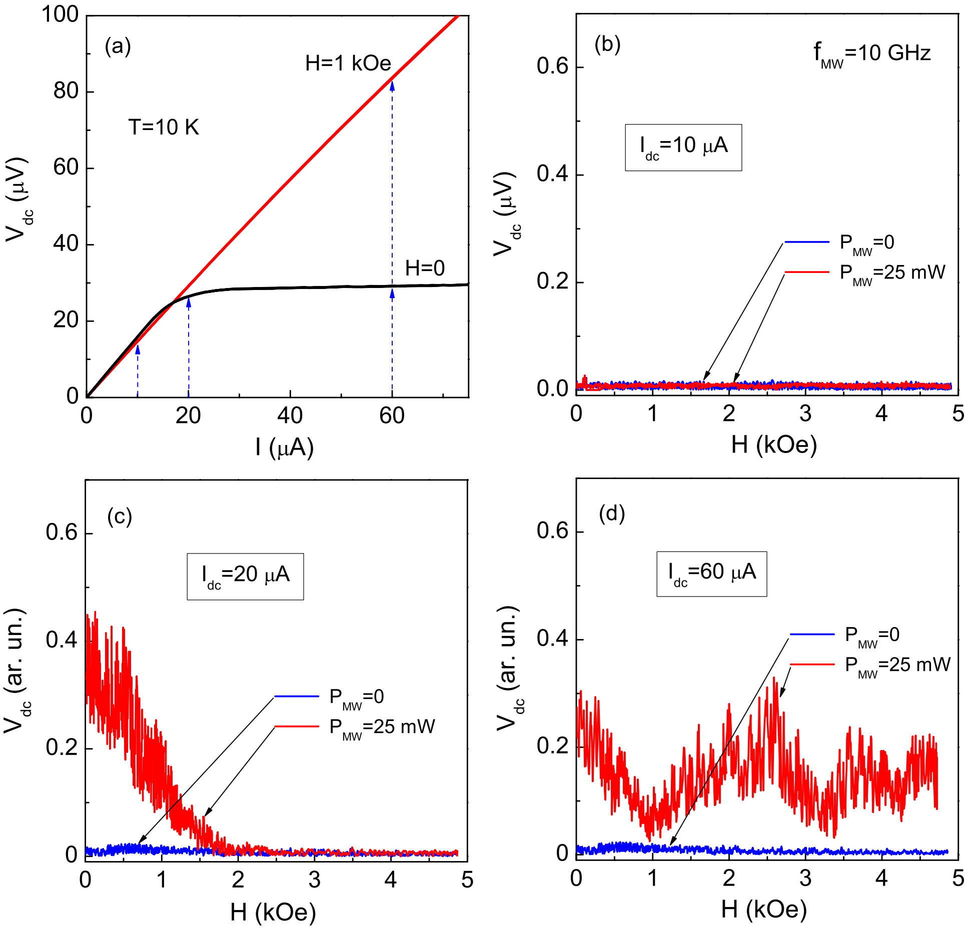

Figure 3. (*a*) Current–voltage characteristic in zero magnetic field and in a field of 5 kOe; the arrows indicate the current–voltage characteristic points corresponding to bias currents I_{dc} of 10, 20 and 60 μA. (*b*) Detected dc voltage V_{dc} as a function of the magnetic field measured at $I_{dc} = 10\,\mu$A. (*c*) $V_{dc}(H)$ at $I_{dc} = 20\,\mu$A. (*d*) $V_{dc}(H)$ at $I_{dc} = 60\,\mu$A. All data are obtained at $T = 10$ K. Microwave radiation power P_{mw} is 25 mW.

already mentioned, in such fields the CVC becomes linear and does not change with a further increase in the field. Note that the detected signal is rather noisy because of a feature of CVC variation in CIP geometry at the change in the magnetic field. The CVC variation is determined by redistribution of the current channels between the top and bottom layers of the structure. Governing elements in the structure that are responsible for this redistribution are the magnetic tunnel junctions under the contact pads. While for the single magnetic tunnel contacts commonly investigated in a standard geometry (current perpendicular to the plane) the contact square is given by physical dimensions, in our case, the contact square is not strictly limited and can be almost randomly changed. The square of the junctions can effectively vary with bias current and magnetic field; this will be determined by inhomogeneity of the layers, quantity of the interfaces, the domain structure of the FM layers, processes of their magnetization, etc. The junction itself will have inhomogeneous properties and each part of the junction will be involved in the detection process at different moments of time, forming a response to microwave radiation.

Despite the fact that magnetic tunnel junctions are involved in the detection effect in the structure under study and there is a pronounced magnetic-field dependence, we may conclude again that here the classical mechanism works, which is caused by CVC nonlinearity. Nevertheless, we do not exclude that, under certain conditions, in the considered structure in CIP geometry a mechanism can be implemented, which is based on the interrelation between the spin-polarized current and the spin dynamics. The evidence for this fact is, for instance, the magnetic-field-dependent detection effect observed at the bias current $I_{dc} = 60\,\mu$A (figure 3(d)). Again, we see a typical decrease in the detected voltage V_{dc} with an increase in the magnetic field up to about 1 kOe. Recall that, at this point, the CVC of the structure becomes smooth (close to linear) and does not vary with a further increase in the field and, considering the classical mechanism of microwave detection proposed above, no response should be observed. Meanwhile, the signal is observed in fields far above 1 kOe; the high noise level can be attributed, as before, to the features related to operation of the magnetic tunnel junctions in CIP geometry. Irregularity of the magnetic-field dependence of V_{dc} in the case of the mechanism related to the magnetic dynamics can be explained by the fact that, at low temperatures, manganites have very wide magnetic resonance lines that present, as a rule, superposition of several absorption lines. At present, it seems difficult to make more definite conclusions on the detection mechanisms implemented at large bias currents. Additional investigations are required, including those on structures of different compositions.

4. Conclusion

We have investigated the magnetically driven microwave detection effect in an LSMO/LSM$_\delta$O/MnSi magnetic tunnel structure in the CIP geometry. We believe that rectification is caused by nonlinearity of the current–voltage characteristic of the structure, i.e., in this case, the classical mechanism typical of the nonmagnetic tunnel junctions works. As for the magnetic-field dependence of the effect, it is determined by the change in the shape of the current–voltage characteristic in a magnetic field. This change is related to peculiarities of the transport and magnetotransport properties of the magnetic tunnel structure in CIP geometry. The response of the structure to microwaves at low temperatures and large bias currents allow us to assume that the mechanism involving the magnetization dynamics of the FM electrodes and the spin-dependent transport through the structure can also be implemented.

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References

[1] Tsymbal E Y, Mryasov O N and LeClair P R 2004 *J. Phys.: Condens. Matter* **15** R109

[2] Zutic I, Fabian J and Das Sarma S 2004 *Rev. Mod. Phys.* **76** 323

[3] Fert A 2008 *Thin Solid Films* **2–5** 517

[4] Sun J 2003 *Nature* **425** 359

[5] Kaka S, Pufall M R, Rippard W H, Silva T J, Russek S E and Katine J A 2005 *Nature* **437** 389

[6] Pribiag V S, Krivorotov I N, Fuchs G D, Braganca P M, Ozatay O, Sankey J C, Ralph D C and Buhrman R A 2007 *Nature Phys.* **3** 498

[7] Moriyama T, Cao R, Fan X, Xuan G, Nikolic B K, Tserkovnyak Y, Kolodzey J and Xiao J Q 2008 *Phys. Rev. Lett.* **100** 067602

[8] Kajiwara Y *et al* 2010 *Nature* **464** 262

[9] Suzuki Y and Kubota H 2008 *J. Phys. Soc. Japan* **77** 031002

[10] Ralph D C and Stiles M D 2008 *J. Magn. Magn. Mater.* **320** 1190

[11] 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

[12] Fan X, Cao R, Moriyama T, Wang W, Zhang H W and Xiao J Q 2009 *Appl. Phys. Lett.* **95** 122501

[13] Harder M, Cao Z X, Gui Y S, Fan X L and Hu C-M 2011 *Phys. Rev.* B **84** 054423

[14] Volkov N V, Eremin E V, Tsikalov V S, Patrin G S, Kim P D, Yu S-C, Kim D-H and Chau N 2009 *J. Phys. D: Appl. Phys.* **42** 065005

[15] Volkov N V, Eremin E V, Tsikalov V S, Patrin G S, Kim P D, Yu S-C, Kim D-H and Chau N 2009 *Tech. Phys. Lett.* **35** 990

[16] Volkov N V, Lee C G, Kim P D, Eremin E V and Patrin G S 2009 *J. Phys. D: Appl. Phys.* **42** 205009

[17] Faris S M and Gustafson T K 1974 *Appl. Phys. Lett.* **25** 544

[18] Faris S M, Fan B and Gustafson T K 1975 *Appl. Phys. Lett.* **27** 629

[19] Miskovsky N M, Shepherd S J, Cutler P H, Sullivan T E and Lucas A A 1979 *Appl. Phys. Lett.* **35** 560

[20] Van der Heijden R W, Jansen A G M, Stoelinga J H M, Swartjes H M and Wyder P 1980 *Appl. Phys. Lett.* **37** 245