.

Magnetoelectric tuning of the inverse spin-Hall effect

José M. Vargas, Javier E. Gómez, Luis Avilés-Félix, and Alejandro Butera

Citation: AIP Advances **7**, 055911 (2017); doi: 10.1063/1.4973845
View online: http://dx.doi.org/10.1063/1.4973845
View Table of Contents: http://aip.scitation.org/toc/adv/7/5
Published by the American Institute of Physics

AIP ADVANCES **7**, 055911 (2017)

Magnetoelectric tuning of the inverse spin-Hall effect

José M. Vargas, Javier E. Gómez, Luis Avilés-Félix, and Alejandro Butera
Centro Atómico Bariloche (CNEA), Instituto Balseiro (U. N. Cuyo), and Conicet, 8400 Bariloche, Río Negro, Argentina

(Presented 3 November 2016; received 15 September 2016; accepted 23 October 2016; published online 9 January 2017)

We demonstrate in this article that the magnetoelectric (ME) mechanism can be exploited to control the spin current emitted in a spin pumping experiment using moderate electric fields. Spin currents were generated at the interface of a ferromagnet/metal bilayer by driving the system to the ferromagnetic resonance condition at X-Band (9.78 GHz) with an incident power of 200 mW. The ME structure, a thin (20 nm) FePt film grown on top of a polished 011-cut single crystal lead magnesium niobate-lead titanate (PMN-PT) slab, was prepared by dc magnetron sputtering. The PMN-PT/FePt was operated in the L-T mode (longitudinal magnetized-transverse polarized). This hybrid composite showed a large ME coefficient of 140 Oe cm/kV, allowing to easily tune the ferromagnetic resonance condition with electric field strengths below 4 kV/cm. A thin layer of Pt (10 nm) was grown on top of the PMN-PT/FePt structure and was used to generate and detect the spin current by taking advantage of its large spin-orbit coupling that produces a measurable signal via the inverse spin-Hall effect. These results proved an alternative way to tune the magnetic field at which the spin current is established and consequently the inverse spin-Hall effect signal, which can promote advances in hybrid spintronic devices. [http://dx.doi.org/10.1063/1.4973845]

The generation, manipulation, and detection of a spin current, a flow of electron spins in a solid, is a subject of rapidly growing interest in the field of spintronic.[1–3] In this context the inverse spin-Hall effect (ISHE), which originates in the strong spin-orbit coupling of some heavy metals, deflects the trajectory of the electrons conforming the spin current preferable to one end of the sample generating a measurable ISHE voltage. Thus, the ISHE signal offers a way for a direct detection of a spin current.

In this work we present a novel method to control and tune the ISHE signal by applying electric fields (E-fields), making use of the magnetoelectric coupling effect.

The sample was grown on the polished side of a lead magnesium niobate-lead titanate (011) single crystal with a nominal thickness of 0.05 cm. PMN-PT is a ferroelectric material which exhibits a giant strain controllable with electric fields. In particular, (011)-cut PMN-PT single crystals display large anisotropic in-plane piezoelectric coefficients with a negative d_{31} around -1200 pC N^{-1} and a positive d_{32} of ~400 pC N^{-1}.[4]

We sputtered 50 nm of Ag on the unpolished side as the bottom electrode. On the polished side of the crystal we deposited two thin films consisting of 20 nm of FePt covered by 10 nm of Pt, with lateral size of approximately 4 mm × 1 mm. A sketch of the sample is depicted in Fig. 1, where also is shown the orientation of the PMN-PT crystallographic axes with respect to the coordinate system chosen to analyze the experiments.

FePt equiatomic alloy thin films usually grow in a metastable chemically disordered fcc phase (called A1), which presents a saturation magnetization similar to that of the ordered L10 phase (M_s ~ 1100 emu/cm^3), but has considerably smaller magnetocrystalline anisotropy and coercive fields.[5] As a consequence the A1 phase presents a dominant easy plane shape anisotropy and in contrast to the ordered L10 phase, has a well defined magnetic resonance absorption line. Additionally,

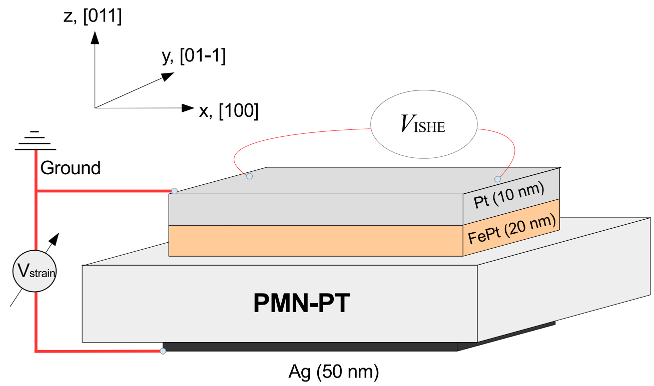

FIG. 1. Sketch of the sample consisting of an FePt(20 nm)/Pt(10 nm) bilayer grown on a (011) PMN-PT single crystal slab with a bottom 50 nm Ag electrode. The crystallographic axes of the PMN-PT slab relative to the coordinate reference system are also shown.

FePt alloy displays potentially interesting magnetostrictive properties,[6] making it ideal to be used as a test-bed magnetostrictive film in spin pumping investigations.

Spin pumping through the metallic interface was induced by driving the FePt layer to the ferromagnetic resonance (FMR) condition. The experiment was performed at room temperature in a commercial Bruker ESP300 spectrometer at a microwave frequency of 9.78 GHz (X-band, TE_{102} rectangular cavity), the external magnetic field was applied along the *y* direction and the microwave field along the *x* axis (see Fig. 1). The ISHE signal was acquired by measuring the voltage between the edges of the sample as described in a previously published work.[7]

Due to the hysteretic behavior of the PMN-PT substrate, it is necessary to follow a systematic protocol for the application of the *E*-field in order to get repetitive and reliable results. Before starting the measurements, the PMN-PT was cycled by applying alternatively electric fields of ±4 kV/cm. Then, $E = -4$ kV/cm was used as the starting point for the experiments.

Figure 2 shows the typical Lorentzian line shape of the ISHE signal taken at 2.6 kV/cm. The FMR absorption spectrum presents a derivative Lorentzian line shape due to the modulation field used for the detection (inset of Fig. 2). The ISHE signal has a maximum voltage, V_{ISHE}, occurring at H_{ISHE} coincident with the FMR resonance field position.

The application of an *E*-field between the electrodes produces a strain on the PMN-PT which in turn causes a mechanical deformation of the magnetostrictive FePt/Pt bilayer, generating a *E*-field tunable magnetic anisotropy. Considering the crystal orientation and the sign of the piezoelectric coefficients of the PMN-PT a positive strain along the *y* direction and a negative deformation along the *x* direction are expected.

The induced anisotropy enables to control the field position H_{ISHE}, at which the ISHE signal is established; and this anisotropy can be modified by varying the strain (that is dependent on the applied voltage). The variation of H_{ISHE} as a function of the *E*-field is shown in Fig. 3, the ascending and descending branches were acquired by following the *E*-field sweeping protocol mentioned before. A non-reversible butterfly-like hysteretic curve is observed, that follows closely the *E*-field induced strain in the ferroelectric crystal.[8] The sharp twist in each curve at $E \sim \pm 1$ kV/cm matches with the expected value of the PMN-PT electric coercive field which is required for a reorientation of the electric polarization domains. The inset of the Fig. 3 shows selected ISHE signals obtained in the ascending branch at different *E*-fields where it is clearly observed that H_{ISHE} can be controlled by the external field. Additionally, it shows that the intensity and the line shape do not change significantly when the *E*-field is varied.

The Smit-Beljers formalism is generally used to obtain the dispersion relation in ferromagnetic materials.[9] It relates the microwave excitation frequency with the magnetic and anisotropy fields. Using the effective shape anisotropy field (H_{eff}) and the magnetoelastic field defined as $H_1 = \frac{3\lambda}{M}\Delta\sigma$, the dispersion relation can be approximated by[10]

$$\left(\frac{\omega}{\gamma}\right)^2 \sim (H + H_1)(H + H_{eff}), \tag{1}$$

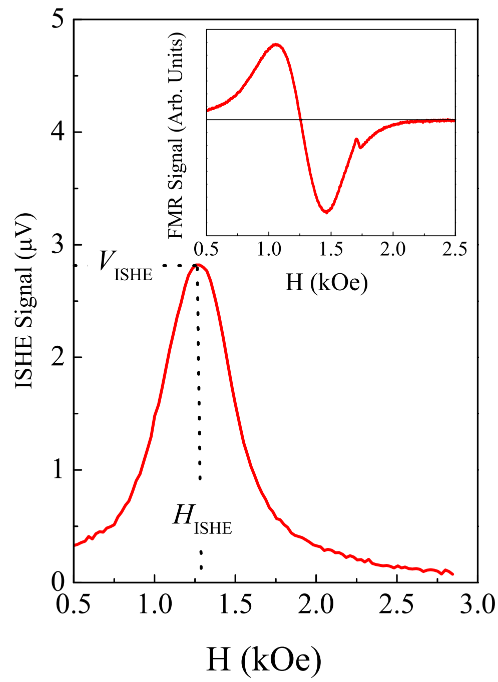

FIG. 2. ISHE signal as a function of magnetic field, obtained for $E = 2.6$ kV/cm. The inset shows the ferromagnetic resonance absorption derivative for the same applied electric field.

where $\omega/2\pi$ is the microwave excitation frequency, $\gamma = g\mu_B/\hbar$ is the gyromagnetic ratio, λ is the saturation magnetostriction coefficient of FePt, and $\Delta\sigma$ is the difference between the stress components along the two in plane PMN-PT crystal axis, $\Delta\sigma = (\sigma_y - \sigma_x)$.[10]

Equation 1 shows that the effective magnetoelastic field H_1 can be associated to the changes in the magnetic field position at which V_{ISHE} occurs. From the experimental results, the total variation of H_1 in the spanned range of E-fields is $\Delta H \sim 500$ Oe. Considering an average slope in the ascending and descending branches of Fig. 2 we can estimate a ME coefficient of ~140 Oe cm/kV. This coefficient indicates how efficiently the ISHE signal can be tuned by the external E-field.

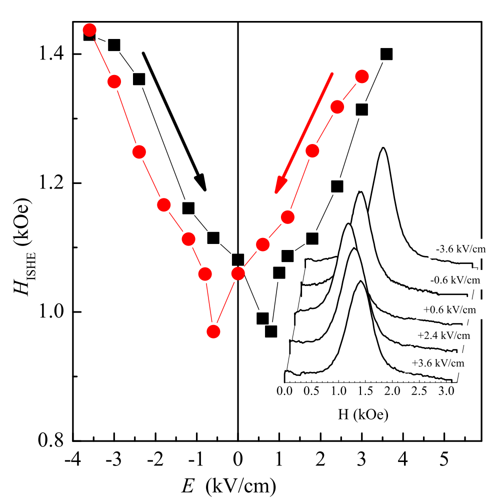

FIG. 3. Variation of the magnetic field where the maximum ISHE signal is observed as a function of E for the PMN-PT/FePt/Pt system. The inset shows typical ISHE curves for different electric fields.

When FePt layer is not strained, Eq. 1 reduces to the well known in plane dispersion relation of a single ferromagnetic film. In such a case it is expected to obtain a resonance field position dominated by the effective shape anisotropy. In this investigation, the resonance field position obtained in the vicinity of E=0 is coincident with values obtained in previous works on samples of FePt grown on 100 oriented Si wafers, where a resonance field between 900-1100 Oe was measured.[6,11]

In order to analyze V_{ISHE} as a function of the E-field, it is necessary to explore the effect of the magnetoelastic anisotropy fields on the spin current pumped during the FMR experiment. The magnetization precessing in the ferromagnetic film loses angular momentum generating an interfacial (FePt/Pt) spin current that propagates diffusively across the thickness of the Pt film and vanishes exponentially at the opposite interface (Pt/air). The ISHE signal comes from the ability of the Pt layer to convert this spin current into a measurable voltage.

The magnetoelastic anisotropy field modifies the ISHE signal, and a mathematical solution at the resonance condition can be approached as:[10]

$$J_s^0 \propto \frac{H_{\mathrm{ISHE}} + H_{\mathrm{eff}} + \frac{3\lambda}{M}\sigma_y}{\left(2H_{\mathrm{ISHE}} + H_{\mathrm{eff}} + H_1 + \frac{3\lambda}{M}\sigma_y\right)^2}. \tag{2}$$

By considering that the linewidth of the ISHE signal is not significantly changed when the E-field is varied and because the shape anisotropy field is much larger than the other fields, the variation of the magnetoelastic fields produced by the external voltage is predicted to generate very small changes in J_s^0 (see Eq. 2). This is in good agreement with the experimental result showing that the value of V_{ISHE} is weakly dependent on E as can be observed in the inset of Fig. 3. It is important to note that if the protocol is not followed some variations on the linewidth are observed and the magnitude of V_{ISHE} is not constant when the E-field is varied. Another point to be considered is the influence of the strain on the spin-orbit coupling, that in turns should change the spin-Hall angle parameter of the Pt layer. As the V_{ISHE} intensity remains relatively constant while the E-field is changed such an effect was neglected in this article but represents an open topic to be studied in future investigations.

In summary, we have shown that an E-field can be used to modify the magnetic field position at which the spin pumping phenomenon occurs in a magnetoelectric structure (PMN-PT/FePt/Pt) and consequently the possibility of an E-field control of the ISHE signal. We show that this magnetoelectric composite possesses a large ME coupling of 140 Oe cm/kV that allows to tune the observed ISHE signal in a relatively large magnetic field range. These results can promote substantial advances in hybrid ME/spintronic devices.

This work was supported in part by Conicet under Grant No. PIP 112-201101-00482, ANPCyT Grants No. PICT 2013-2363 and PICT 2013-0401, and U. N. Cuyo Grant No. 06/C421, all from Argentina.

[1] F. J. Jedema, A. T. Filip, and B. J. van Wees, Nature **410**, 345 (2001).
[2] Y. Kajiwara, K. Harii, S. Takahashi, J. Ohe, K. Uchida, M. Mizuguchi, H. Umezawa, H. Kawai, K. Ando, K. Takanashi *et al.*, Nature **464**, 262 (2010).
[3] C. Hahn, G. de Loubens, O. Klein, M. Viret, V. V. Naletov, and J. Ben Youssef, Phys. Rev. B **87**, 174417 (2013).
[4] P. Han, W. Yan, J. Tian, X. Huang, and H. Pan, Appl. Phys. Lett. **86**, 052902 (2005); I. A. Ivan, M. Rakotondrabe, J. Agnus, R. Bourquin, N. Chaillet, P. Lutz, J. C. Poncot, R. Duffait, and O. Bauer, Rev. Adv. Mater. Sci. **24**, 1 (2010).
[5] H. Kanazawa, G. Lauhoff, and T. Suzuki, J. Appl. Phys. **87**, 6143 (2000); E. Sallica Leva, R. C. Valente, F. Martínez Tabares, M. Vásquez Mansilla, S. Roshdestwensky, and A. Butera, Phys. Rev. B **82**, 144410 (2010).
[6] N. R. Álvarez, J. E. Gómez, A. E. Moya Riffo, M. A. Vicente Álvarez, and A. Butera, J. Appl. Phys. **119**, 083906 (2016); N. Álvarez, G. Alejandro, J. Gómez, E. Goovaerts, and A. Butera, J. Phys. D: Appl. Phys. **46**, 505001 (2013); V. Mansilla, J. Gómez, and A. Butera, IEEE Trans. Magn. **44**, 2883 (2008).
[7] J. E. Gómez, M. Guillén, A. Butera, and N. P. Albaugh, Rev. Sci. Instrum. **87**, 024705 (2016).
[8] Z. Zhou, S. Zhao, Y. Gao, X. Wang, T. Nan, N. X. Sun, X. Yang, and M. Liu, Sci. Rep **6**, 20450 (2016).
[9] J. Smit and H. G. Beljers, Philips Res. Rep. **10**, 113 (1955).
[10] J. E. Gómez, J. M. Vargas, L. Avilés-Félix, and A. Butera, Appl. Phys. Lett. **108**, 242413 (2016).
[11] N. R. Álvarez, M. E. Vázquez Montalbetti, J. E. Gómez, A. E. Moya Riffo, M. A. Vicente Álvarez, E. Goovaerts, and A. Butera, J. Phys. D: Appl. Phys. **48**, 405003 (2015).