Voltage-controlled skyrmion Hall angle in Ferromagnetic/Piezoelectric devices

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Introduction

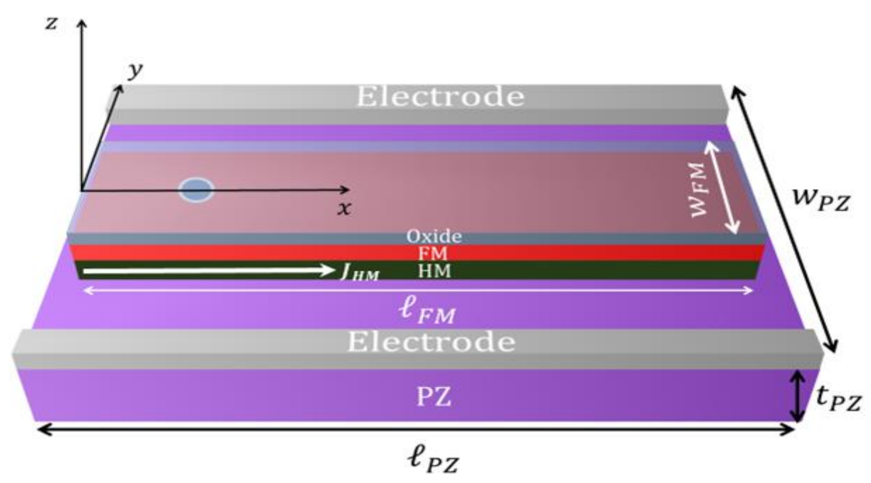

Fig.1: Sketch of the studied device consisting of a Piezoelectric/Heavy Metal/Ferromagnet/Oxide multilayer.

Considered as new information carriers magnetic Skyrmions held a particular interest in the last decade. They were used to design several spintronic devices, among them the skyrmion racetrack memory inspired from the famous Domain-wall racetrack memory designed by S.Parking et al in 2008 [1] took a particular interest and was considered as one of the most promising applications. However, moving skyrmions in a straight way in the track is not so simple. Due to their topological nature they move in a tilted path, this was related to the skyrmion Hall effect [2].

In this work, we propose a route for versatile control of the skyrmion trajectory and suppression of the skyrmion Hall effect in an artificial multiferroic structure. Using both electromechanical and micro-magnetic simulation we investigate the piezoelectric response and the control of the current-driven skyrmion motion in a PZT-4/Pt/CoFeB/MgO multilayer system shown in Fig.1 [3].

Simulation

Electro-mechanical simulation

We first study the piezoelectric response of our device using electro-mechanical simulation based on COMSOL Multiphysics[4]. The elastic strain in the electromechanical model reads

$$\boldsymbol{\varepsilon} = \boldsymbol{d} \times \boldsymbol{E} \quad (1)$$

Where $\boldsymbol{d}$ is the dielectric matrix and $\boldsymbol{E}$ is the electric field.

Micro-magnetic simulation

Once characterized the elastic strain profile in our device we resort to micromagnetic simulation to study its effect on the current-driven skyrmion motion, We solve numerically LLG equation including the contribution of the magneto-elastic field given by

$$\boldsymbol{H}_{mel} = \frac{1}{\mu_0 M_s} \sigma_{ij} \frac{\delta \varepsilon_{ij}^{m}}{\delta \boldsymbol{m}} \quad (2)$$

Where σ_{ij} is the elastic stress, ε_{ij}^{m} is the magnetic strain tensor and $\boldsymbol{m}(r,t) = \frac{\boldsymbol{M}(r,t)}{M_s}$ is the normalized magnetization. Micromagnetic simulations are run using an in-home modified version of Mumax^3 [5].

Analytical Model

For a better understanding of our findings we used Thiele's model[6]. Using simple calculation Thiele's equation could be reduced to the skyrmion velocities along the longitudinal and the transversal directions

$$V_x = \frac{\alpha D F_{SHE} + G F_{el}}{\alpha^2 D^2 + G^2} \ (3) \quad \text{and} \quad V_y = \frac{-G F_{SHE} + \alpha D F_{el}}{\alpha^2 D^2 + G^2} \ (4)$$

Where F_{SHE} is the force due to the spin-orbit torque and F_{el} is the force due to the strain induced by the PZ layer.

To compensate the skyrmion Hall effect we found analytically that a condition should be fulfilled in terms of the strain and the applied current density

$$\frac{\partial \varepsilon_{yy}}{\partial y} = \frac{2\pi\, \eta\, G\, \hbar\, \theta_{SH}}{3\alpha D |e| \Delta\, \lambda_s t_{FM} (C_{11} + C_{12})} J_{HM} \quad (5)$$

Where J_{HM} is the charge current flowing in the HM layer.

References

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Results

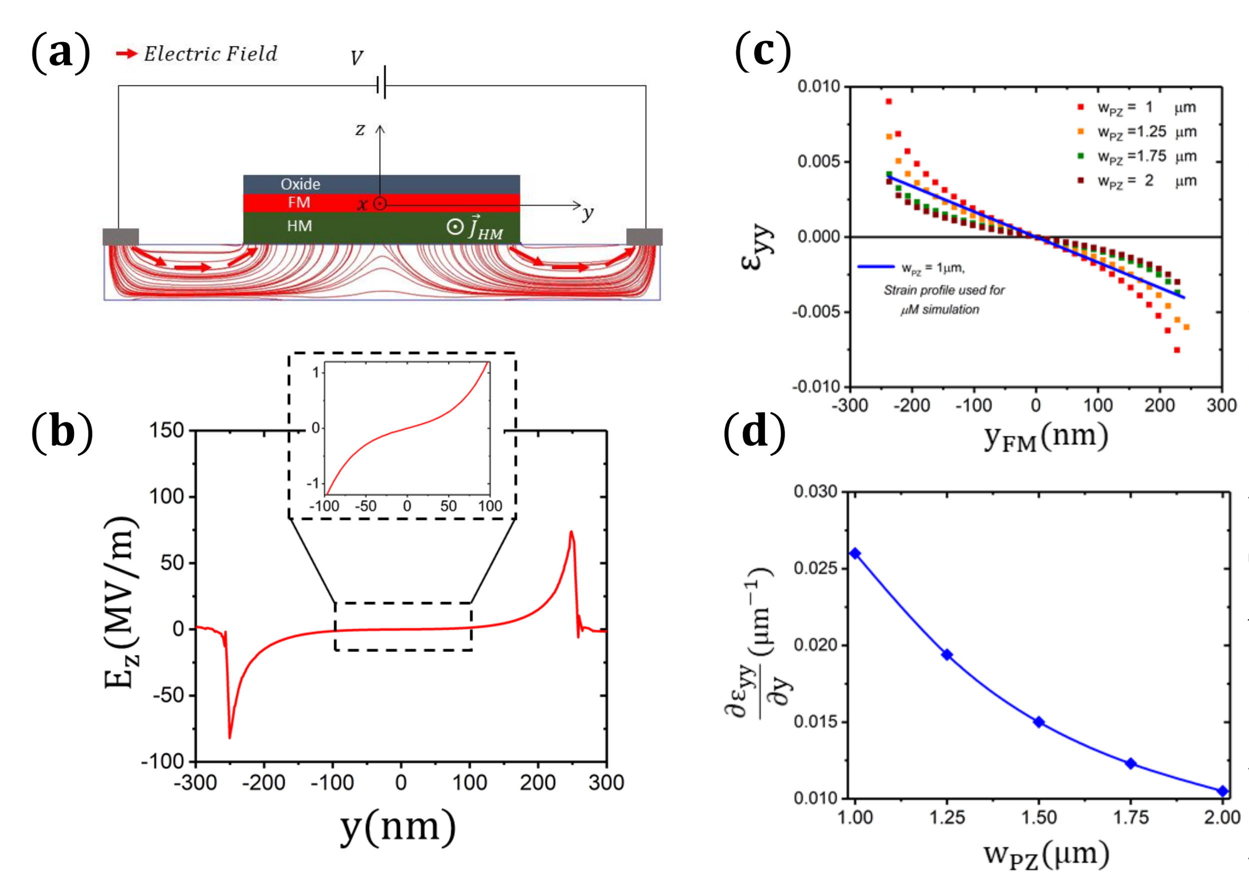

Fig.2:(a) Device cross section showing the electric field lines in the PZ substrate. (b) Profile of the vertical component E_z along the PZ/HM interface. The inset zooms out the profile in the central region of the nanostrip. (c) Elastic strain (ε_{yy}) profile transferred to the FM layer across the central region for different PZ layer widths. The blue line represents a linear profile obtained by extrapolating the slope at the origin (y=0) for $w_{PZ} = 1$ µm. (d) Strain gradient in the center of the FM (y=0) for different PZ layer widths w_{PZ}. A voltage V=10 V between the electrodes is applied in all cases.

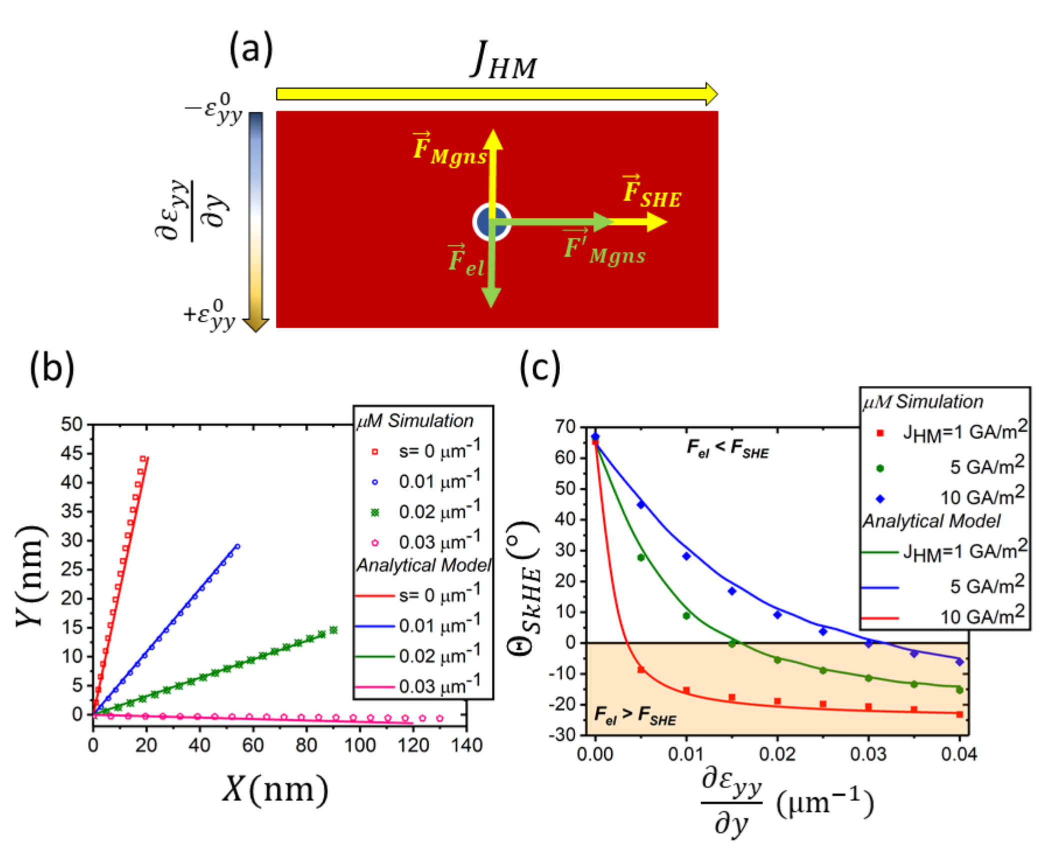

Fig.3: (a) Schematic representation of the force contributions on the skyrmion dynamics. (b) Skyrmion trajectories obtained from micromagnetic simulations (dots) and analytical calculations (lines) for a current density $J_{HM} = 10$ GA/m^2 and different strain gradients. In the legend, "s" stands for "strain gradient", $s \equiv \frac{d\varepsilon_{yy}}{dy}$. (c) Evolution of the skyrmion Hall angle with the strain gradient for different current density values.

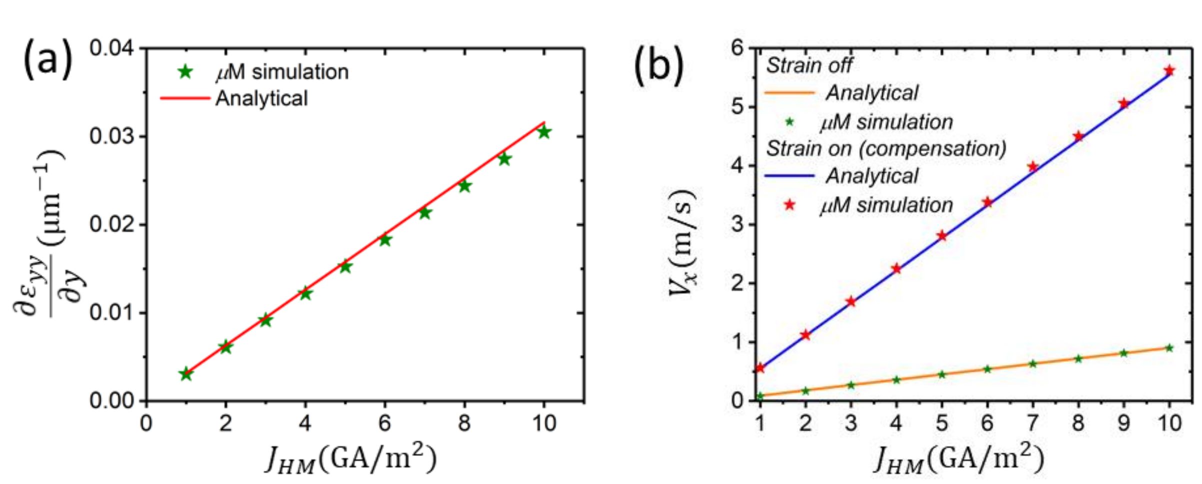

Fig.4: (a) Strain gradient slope required to compensate the skyrmion Hall angle for each current density J_{HM} value. (b) Skyrmion speed versus applied current in the absence of strain and in present of a strain compensating the skyrmion Hall angle.

Conclusions

- ✓ Due to the non uniform electric field created in a PZ/HM/FM/Oxide multilayers a strain gradient will be created between two transversally displayed electrodes.
- ✓ The created strain profile exert a net force on magnetic skyrmions which can move them towards high strain regions.
- ✓ This force is used to control the skyrmion trajectory, to compensate the skyrmion hall angle and to speed up magnetic skyrmion in ferromagnetic nanostrips.

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