**Introduction**

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.Parkin 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/PbCoFeB/MgO multilayer system shown in Fig.1 [3].

**Simulation**

**Electro-mechanical simulation**

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

\[ e = d \times E \]  

(1)

Where \( d \) is the dielectric matrix and \( E \) 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

\[ H_{me} = \frac{1}{\mu_0 M_s} \sigma_{ij} E_{ij} \]  

(2)

Where \( \sigma_{ij} \) is the elastic stress, \( E_{ij} \) is the magnetic strain tensor and \( m(r,t) = \frac{M(r,t)}{M_s} \) is the normalized magnetization. Micromagnetic simulations are run using an in-home modified version of Mumax3 [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

\[ V_x = \frac{a D E_{SO} + a D E_{el}}{d^2 + \zeta^2} \]  

(3)

\[ V_y = -\frac{a D E_{SH} + a D E_{el}}{d^2 + \zeta^2} \]  

(4)

Where \( E_{SO} \) is the force due to the spin-orbit torque and \( E_{el} \) 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

\[ \frac{d e_{yy}}{dy} = \frac{2 \pi \eta \eta \theta_{SO}}{3 a D \epsilon |a \lambda_{FM} (C_{12} + C_{12}) |} J_{HM} \]  

(5)

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

**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 nanostr. (c) Elastic strain \( (\epsilon_{yy}) \) 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 \( w_{PZ} = 1 \) \( \mu \)m. (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/m² and different strain gradients. In the legend, “s” stands for “strain gradient”, \( s = \frac{d e_{yy}}{dy} \) (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.

**References**