Phase-field modeling on the elastically coupled magnetic and ferroelectric domains

T.N. Yang[1], J.M. Hu[1], C.W. Nan[2], and L.Q. Chen[1,2]

[1]*Department of Materials Science and Engineering, the Pennsylvania State University, University Park, Pennsylvania 16802*

[2]*Department of Materials Science and Engineering, Tsinghua University, Beijing 100084, China*

The scaling law for ferroics[1,2] indicates that the domain width of magnets and ferroelectrics become comparable only when the thickness of ferroelectrics is much larger. Indeed, it has been recently demonstrated in multiferroic layered heterostructures with magnetic thin films directly grown on ferroelectric (FE) $BaTiO_3$ substrates[3-7] that the domains in an as-grown magnetic thin film have not only the same width but also a surprising collinear alignment with the contacted FE domains. This further enables a precise control over the magnetic domain wall motion by electrically driving its elastically coupled FE domain wall[8,9]. Such one-to-one match between magnetic and FE domains offers new opportunities for the creation of periodic magnetic domain patterns used for magnonic devices, and particularly, the low-power spintronic devices based on electro-strain-driven magnetic domain orientation or domain wall propagation.

In the present work, a phase-field model is developed to study the dynamics of such local elastic coupling between magnetic and FE domains in multiferroic heterostructures. Taking a CoFe film grown on a $BaTiO_3$ single crystal substrate as an example, we simulate the evolution of both types of domains upon applying an electric field, including field-driven changes in domain morphology and domain wall velocity.

Ferroelectric stripe domains are directly imprinted onto the overlaying magnetic domains through elastic coupling in the as-grown multiferroic heterostructure. By driving the elastically coupled ferroelectric domains with a vertical AC electric field, repeated writing and erasure of the magnetic stripe domains are achieved. An alternating occurrence of coherent local magnetization rotation and magnetic domain wall motion coupled to ferroelectric domain walls is observed during an electric field loop. Studies on the dynamics of electric-field manipulation of magnetic domain evolution reveal closely coupled domain wall motions of magnetic and ferroelectric domain walls with almost identical velocities.

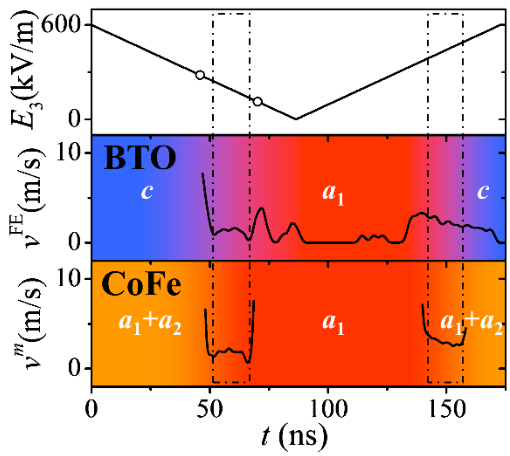

FIG. 1. Time sequence of the applied vertical electric field E and the resultant velocity of FE (v^{FE}) and magnetic (v^m) domain wall motion, in FE a_1/c domain and mixed a_1 and a_1/a_2 magnetic domain configurations, respectively. The background colors indicate the dominant FE or magnetic domains at different stages.

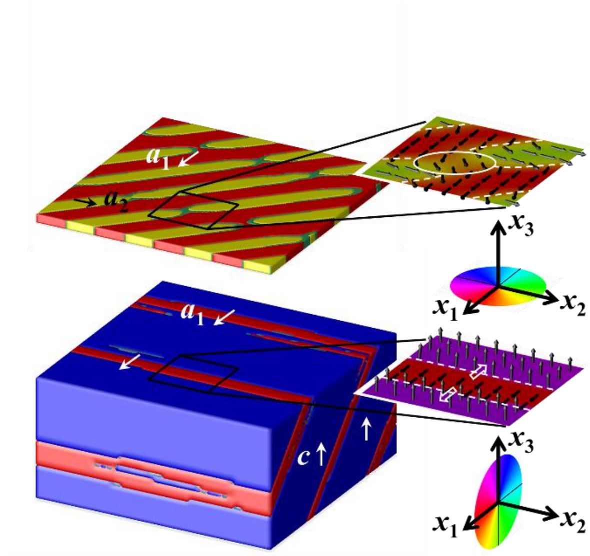

FIG. 2. Magnetic and FE domain structures at E_3=280 kV/m in a downhill electric-field cycle. (Right column) close-up vector plots of the polarization and magnetization configuration within the selected areas; the white dashed lines and the hollow arrows indicate the domain wall and the direction of the domain wall motion, respectively.

References

[1] A. Schilling, T. B. Adams, R. M. Bowman, J. M. Gregg, G. Catalan, and J. F. Scott, Phys. Rev. B **74,** 024115 (2006).
[2] G. Catalan, J. F. Scott, A. Schilling, and J. M. Gregg, J. Phys.: Condens. Matter **19,** 022201 (2007).
[3] T. H. E. Lahtinen, J. O. Tuomi, and S. van Dijken, Adv. Mater. **23,** 3187-3191 (2011).
[4] R. V. Chopdekar, V. K. Malik, A. Fraile Rodríguez, L. Le Guyader, Y. Takamura, A. Scholl, D. Stender, C. W. Schneider, C. Bernhard, F. Nolting, and L. J. Heyderman, Phys. Rev. B **86,** 014408 (2012).
[5] R. Streubel, D. Köhler, R. Schäfer, and L. M. Eng, Phys. Rev. B **87,** 054410 (2013).
[6] S. Geprägs, M. Opel, S. T. B. Goennenwein, and R. Gross, Phys. Rev. B **86,** 134432 (2012).
[7] K. J. A. Franke, D. L. González, S. J. Hämäläinen, and S. van Dijken, Phys. Rev. Lett. **112**, 017201 (2014).
[8] K. J. A. Franke, T. H. E. Lahtinen, and S. van Dijken, Phys. Rev. B **85,** 094423 (2012).
[9] H. T. Chen, Y. Ni, and A. K. Soh, J. Appl. Phys. **113,** 134102 (2013).