ELECTRO-MECHANICAL-MAGNETIC COUPLING IN MULTIFERROIC HETEROSTRUCTURES: PHASE-FIELD MODELING AND DEVICE APPLICATIONS

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Summary We theoretically study the electro-mechanical-magnetic coupling, also known as the converse magnetoelectric effect, in layered magnetic/ferroelectric heterostructures. We obtain electric-voltage induced changes in both the macroscopic magnetization and magnetic domain structures. Based on phase-field simulations, we proposed a new device concept for a Strain-Mediated Magnetoresistive Random Access Memory (SM-RAM). The proposed nanoscale SM-RAM device can achieve ultrahigh storage capacity, ultralow power dissipation, and room-temperature high-speed operation simultaneously, thus offering a potentially significant improvement over existing MRAM technologies or existing device concepts.

Background and Objective

The electro-mechanical-magnetic coupling, i.e., the converse magnetoelectric (ME) effect, has attracted continually increasing research interests in recent years, due to its promising application potential in novel ME devices. It is usually considered as a combination of the electro-mechanical and the magnetoelastic couplings in magnetic/ferroelectric layered heteostructures, mediated by elastic strains. The aim of this study is to present an applicable high-performance device prototype utilizing such strain-driven converse ME effect. The proposed device can function as low-power, high-density magnetic random access memory (MRAM) operating at ultralow voltage at room temperature.

Brief results summary

Both the device working and design principles were illustrated using phase-field simulations. An in-depth quantitative analysis of the device performance, including size scaling, power dissipation and writing speed, was performed. The present device proposal can simultaneously achieve ultrahigh storage capacity, ultralow power dissipation, and room-temperature high-speed operation, thus shows overall superiority over all existing or emerging MRAM technologies (please see the attached Table 1 below) [1].

Table 1| Comparison between the proposed memory device prototype (denoted as SM-RAM, i.e., Strain-Mediated Magnetoresistive Random Access Memory) with several other room-temperature nonvolatile memory technologies. FeRAM and STT-RAM indicate the Ferroelectric random access memory and Spin-transfer-torque random access memory, respectively.

	Flash-NAND	FeRAM	MRAM	STT-RAM	SM-RAM
Storage capacity	>1 Gb	>10 Mb	1-10 Mb	32 Mb	»1 Gb
Write time	1 ms	10 ns	20 ns	3-10 ns	<10 ns
Read time	50 ns	45 ns	10 ns	10 ns	10 ns
Write Energy (pJ/bit)	>0.01	0.005	70	0.1	1.6×10^{-4}

Selected Figures

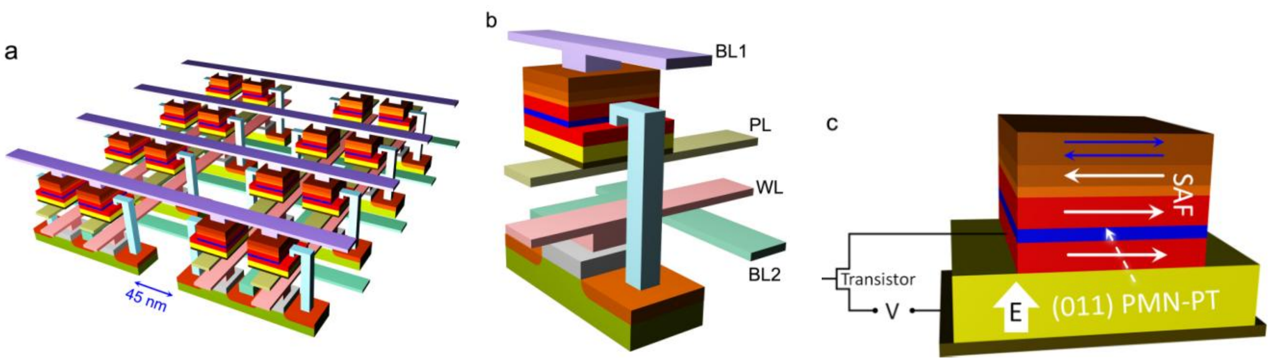

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Figure 1 | a, Array design of the SM-RAM device built on planar complementary metal-oxide-semiconductor (CMOS) platforms. **b**, Architecture of the 1-T(transistor)/1-magnetoresistive(MR) memory unit cell. **c**, Schematic of the basic building block, where a spin-valve or magnetic tunnel junction is integrated onto a PMN-PT layer, upon the application of a perpendicular voltage bias controlled by the transistor. The device resistance change results from the electric-voltage induced in-plane 90° magnetization rotation in the square-shaped free layer.

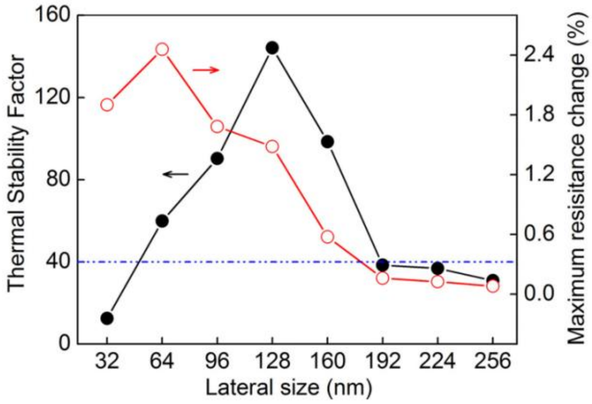

Figure 2| Lateral size (i.e., the length and width of the free layer in Fig. 1c) dependence of the device thermal stability and the maximum electric-voltage induced resistance change. The dashed line shows the minimum thermal stability requirements for reliable data retention of the SM-RAM device. The optimum lateral size range of our device is estimated to be around 64~160 nm. The thickness of the Ni free layer is set as 5 nm.

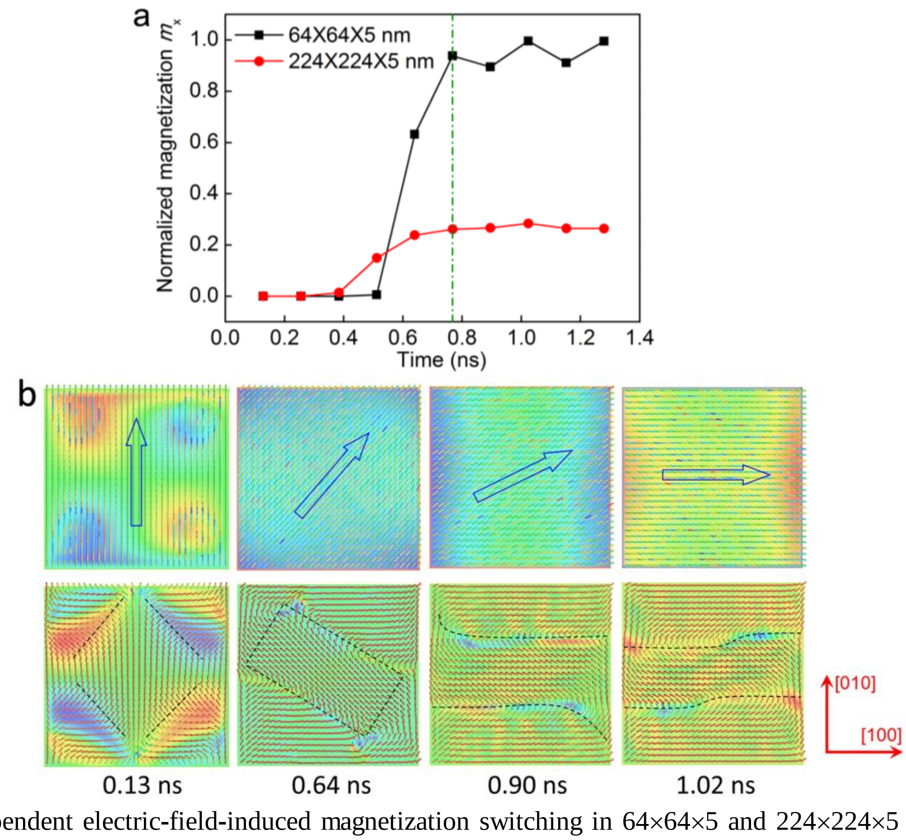

Figure 3| a, Time-dependent electric-field-induced magnetization switching in 64×64×5 and 224×224×5 nm^3 Ni free layers, where the magnetic vectors rotate from the initial [010] direction (m_x=0) to its orthogonal in-plane [100] direction (m_x=1). m_x denote the normalized magnetization in the [100] direction. **b**, Snapshots of the magnetization vector diagrams in 64×64×5 (the first row) and 224×224×5 nm^3 (the second row) Ni free layers at t=0.13, 0.64, 0.90 and 1.02 ns. The arrows and the dashed curves are the eye guides for the coherent magnetization rotation and domain-wall motion processes in single-domain 64×64×5 and multi-domain 224×224×5 Ni films, respectively.

References

[1] Hu J.-M., Li Z, Chen L.-Q. & Nan C. W.: High-density magnetoresistive random access memory operating at ultralow voltage at room temperature. *Nat. Commun.* **2**:553, 2011.