Letter

Binary information propagation in circular magnetic nanodot arrays using strain induced magnetic anisotropy

M Salehi-Fashami, M Al-Rashid, Wei-Yang Sun, P Nordeen, S Bandyopadhyay, A C Chavez, G P Carman and J Atulasimha

1 Department of Physics and Astronomy, Univ. of Delaware, Newark, DE 19716, USA
2 Department of Mechanical and Nuclear Engineering, Virginia Commonwealth Univ., Richmond, VA 23284, USA
3 Department of Electrical and Computer Engineering, Virginia Commonwealth Univ., Richmond, VA 23284, USA
4 Department of Mechanical and Aerospace Engineering, Univ. of California, Los Angeles, CA 90095, USA
5 Equal contribution.

E-mail: jatulasimha@vcu.edu

Received 3 June 2016, revised 6 July 2016
Accepted for publication 18 July 2016
Published 22 September 2016

Abstract

Nanomagnetic logic has emerged as a potential replacement for traditional Complementary Metal Oxide Semiconductor (CMOS) based logic because of superior energy-efficiency (Salahuddin and Datta 2007 Appl. Phys. Lett. 90 093503, Cowburn and Welland 2000 Science 287 1466–68). One implementation of nanomagnetic logic employs shape-anisotropic (e.g. elliptical) ferromagnets (with two stable magnetization orientations) as binary switches that rely on dipole–dipole interaction to communicate binary information (Cowburn and Welland 2000 Science 287 1466–68, Csaba et al 2002 IEEE Trans. Nanotechnol. 1 209–13, Carlton et al 2008 Nano Lett. 8 4173–8, Atulasimha and Bandyopadhyay 2010 Appl. Phys. Lett. 97 173105, Roy et al 2011 Appl. Phys. Lett. 99 063108, Fashami et al 2011 Nanotechnology 22 155201, Tiercelin et al 2011 Appl. Phys. Lett. 99, Alam et al 2010 IEEE Trans. Nanotechnol. 9 348–51 and Bhowmik et al 2013 Nat. Nanotechnol. 9 59–63). Normally, circular nanomagnets are incompatible with this approach since they lack distinct stable in-plane magnetization orientations to encode bits. However, circular magnetoelastic nanomagnets can be made bi-stable with a voltage induced anisotropic strain, which provides two significant advantages for nanomagnetic logic applications. First, the shape-anisotropy energy barrier is eliminated which reduces the amount of energy required to reorient the magnetization. Second, the in-plane size can be reduced (~20 nm) which was previously not possible due to thermal stability issues. In circular magnetoelastic nanomagnets, a voltage induced strain stabilizes the magnetization even at this size overcoming the thermal stability issue. In this paper, we analytically demonstrate the feasibility of a binary ‘logic wire’ implemented with an array of circular nanomagnets that are clocked with voltage-induced strain applied by an underlying piezoelectric substrate. This leads to an energy-efficient logic paradigm orders of magnitude superior to existing CMOS-based logic that is scalable to dimensions substantially smaller than those for existing nanomagnetic logic approaches. The analytical approach is validated with experimental measurements.
conducted on dipole coupled Nickel (Ni) nanodots fabricated on a PMN-PT (Lead Magnesium Niobate-Lead Titanate) sample.

Online supplementary data available from stacks.iop.org/NANO/27/43LT01/nmedia

Keywords: straintronics, LLG, nanomagnetic logic, multiferroics

(Some figures may appear in colour only in the online journal)

1. Introduction

Strain control of the magnetic state of a magnetoelastic material has been explored experimentally in a number of material systems [11–15] but experimental studies on single domain nanomagnets have been pursued only recently [16, 17]. Among these single domain studies, few have focused on logic operations. Several theoretical papers have established that strain clocked nanomagnetic memory and logic employing single-domain nanomagnets is energy efficient [5–8] and require as little as ∼1 aJ/bit of energy to switch. This provides the motivation to study strain-clocked logic and memory (also known as “straintronics”) since the total energy required to switch a nanomagnet with strain is 2–3 orders of magnitude less than that required for switching current complementary metal oxide semiconductor devices [18] and 4–5 orders of magnitude less than for nanomagnets clocked with a current-generated magnetic field [9] or spin transfer torque [19]. Other energy-efficient methods of clocking nanomagnets include the use of Spin Hall Effect [10] and spin–orbit torque [20].

In logic and memory applications, nanomagnets are typically designed with high magnetic anisotropy (either shape or perpendicular magnetic anisotropy) energy barriers \( \Delta U \geq 50 k_B T \), where \( k_B \) is the Boltzmann constant and \( T = 300 \text{ K} \). This energy barrier is required for two reasons: first, the anisotropy produces two distinct stable magnetization orientations to encode the binary logic bits ‘0’ and ‘1’. Second, the energy barrier prevents the magnetization from randomly flipping between the two stable states in the presence of thermal noise (the probability of spontaneous flipping is \( e^{-\Delta U/k_B T} \)). If \( \Delta U \geq 50 k_B T \), we can expect the mean time between static bit errors due to spontaneous flipping \( (\tau_\text{e}e^{\Delta U/hT}) \) to be greater than 150 years, where the inverse attempt frequency \( \tau_\text{e} \) is typically \( 10^{-12} \) to \( 10^{-9} \) s [21, 22]). The latter feature makes nanomagnetic logic ‘non-volatile’ and now the same device can be used as both ‘logic’ and ‘memory’.

However, some nanomagnetic elements in a device that implements non-volatile logic can remain volatile. Specifically, only the nanomagnets storing the output bits need to be non-volatile and require a thermal energy barrier \( \Delta U \geq 50 k_B T \) between the degenerate ‘0’ and ‘1’ states at room temperature. The other nanomagnetic elements in the logic devices merely carry out logic operations rather than store bits of information and thus may be volatile. Therefore, these other nanomagnets can be small, super-paramagnetic, and circular. Recent experimental studies have shown that anisotropy created by different methods can transform super-paramagnetic nanoparticles at room temperature to single domain non-volatile ferromagnets [23–25]. Specifically, it has been recently demonstrated that Ni nanoparticles can be switched between a super-paramagnetic state and a single-domain ferromagnetic state at room temperature by application of a voltage induced biaxial strain that changes the magnetic anisotropy [25]. This provides two distinct advantages. First, it lowers the amount of energy required to propagate the information along the chain to the final non-volatile bit. Second, the size of these elements can be made ultra-small to increase processing density. This results in an extremely energy efficient nanomagnetic logic device that is scalable to smaller feature sizes.

A critical component of dipole-coupled nanomagnetic logic systems is a ‘binary wire’ that propagates a logic bit unidirectionally from one end of the wire to the other [2–5, 7–10]. In this paper, we theoretically simulate a binary wire implemented with a linear array of dipole-coupled circular nanomagnets subjected to room-temperature thermal noise. In this simulation, voltage induced Bennett clocking [28] of the nanomagnets is achieved with strain produced by an underlying piezoelectric thin film deposited onto a silicon substrate as shown in figure 1. Here voltage is applied to electrode pairs to overcome the substrate clamping issues imposed on a thin film piezoelectric (~500 nm or less) as proposed by Cui et al [26] to generate a bi-axial strain that is transferred to the nanomagnet. (Supplementary material section A1 describes the in-plane magnetic anisotropy created by applying a voltage induced strain that turns a circular ferromagnet into a bistable nanomagnet element.) By sequentially applying a voltage, propagation of the information encoded in the magnetic moments of the nanomagnets is achieved. Further, the ability to induce bistability with magnetic anisotropy induced by strain in dipole coupled circular Ni nanodots of 100 nanometer diameter deposited on a PMN-PT substrate is experimentally demonstrated. We note that these experiments use global clocking as the tests are performed on a bulk PMN-PT substrate rather than thin film PZT. The reason why a global scheme was used is because the fabrication and testing of the device shown in figure 1 is difficult and involves several steps of electron beam lithography for patterning the nanostructures and electrodes followed by experimental verification of the operation of the device with Scanning Electron Microscopy with Polarization Analysis or Time Resolved Photoemission Electron Microscopy. The primary testing method, Magneto-Optic Kerr Effect (MOKE), is not capable of resolving the magnetization of individual nanodots. Therefore, a critical first step would be to
thermodynamic fields and stress was simulated using the Landau–Lifshitz–Gilbert (LLG) equation [29–31] in the presence of room temperature thermal noise under single domain approximation. The Ni nanodots are 100 nm in diameter and the proposed paradigm aims for further downscaling. Cowburn et al [32] has shown that supermalloy (Ni80Fe14Mo3) circular nanodots of ~100 nm diameter act as single domain. So, the macrospin assumption is very likely valid in the range of dimensions for which the study is intended. The LLG equation for the ith magnet in the array can be written as:

\[
\frac{d\vec{M}_i(t)}{dt} = -\gamma \vec{M}_i(t) \times \vec{H}^\text{eff}_i(t) - \frac{\alpha}{M_s} [\vec{M}_i(t) \times (\vec{M}_i(t) \times \vec{H}^\text{eff}_i(t))],
\]

(1)

where \(\gamma\) is the gyromagnetic ratio, \(\alpha\) is the Gilbert damping constant in the nanomagnet and \(\vec{H}^\text{eff}_i(t)\) is the effective magnetic field acting on the magnetization vector of the ith nanomagnet. The effective field incorporates the effect of stress, dipole coupling from neighbors, and random thermal noise and can be expressed as:

\[
\vec{H}^\text{eff}_i(t) = -\frac{1}{\mu_0 \Omega} \partial U_i(t) - \frac{1}{\mu_0 M_s} \Delta_{ij} U_i(t) + \vec{H}_\text{thermal}(t),
\]

(2)

where \(\Omega\) is the volume of the nanomagnet, \(U_i(t)\) is the magnetic field acting on the magnetization owing to thermal noise and \(\Delta_{ij} U_i(t)\) is its total potential energy at the instant of time \(t\).

In an array of dipole-coupled closely spaced nanomagnets in the \(x-y\) plane as shown in figure 1(b), the total potential energy of each nanomagnet is:

\[
U_i(t) = E_{\text{dipole}} + E_{\text{shape-anisotropy}} + E_{\text{stress-anisotropy}}
\]

\[
= \frac{\mu_0 M_s^2 \Omega}{4\pi R^3} \sum_{j=1}^{N_d^{\text{int}}} [-2m_{x,i} m_{x,j} + m_{y,i} m_{y,j} + m_{z,i} m_{z,j}]
\]

\[
+ \Omega \left( \frac{M_s^2 \rho_i}{2} \left[ N_{d,xx} m_{x,i}^2(t) + N_{d,yy} m_{y,i}^2(t) \right] + \left[ N_{d,zz} m_z^2(t) \right] - \frac{3}{2} \lambda_s \sigma_i(t) m_y^2(t) \right),
\]

(3)

where \(R\) is the distance between the nearest neighbor nanomagnets and \(N_{d,kk}\) is the demagnetization factor in the \(k\) direction. Calculation of the demagnetization factors is discussed in the supplementary section. The reduced magnetization \(\vec{m}\) can be defined as

\[
\vec{m} = \frac{\vec{M}}{M_s}; \quad m_x^2 + m_y^2 + m_z^2 = 1.
\]

In equation (3), the first term represents the dipole–dipole interaction energy \(E_{\text{dipole}}\) between nearest neighbor magnets. The second term, \(E_{\text{shape-anisotropy}}\), denotes the shape anisotropy energy due to the circular cylinder shape (although \(N_{d,xx} = N_{d,yy}\) because the magnets have circular cross-section, \(N_{d,zz}\) is different from \(N_{d,xx}\) or \(N_{d,yy}\) and the magnetization dynamics is significantly affected by out-of-
plane excursions of the magnetization). The third term represents stress anisotropy energy caused by a uniaxial stress ($\tau$) along the $y$-direction that is developed in the magnetostrictive layer when strain is transferred to it from the bottom piezoelectric layer which is strained by the application of voltage as shown in figure 1.

The effect of thermal perturbation is modeled with a random field ($\vec{H}_\text{thermal}(t)$) with statistical properties described below:

$$\vec{H}_\text{thermal}(t) = \frac{2K_0 T_\Omega}{\gamma \mu_0 M_0 \Delta t} \vec{G}(t),$$

where $\vec{G}(t)$ is a Gaussian random distribution with mean of 0 and variance of 1 in each Cartesian coordinate axis; $\Delta t = 1$ (ps) is the time step used in simulating the switching trajectories and it is inversely proportional to the attempt frequency with which thermal noise disrupts magnetization.

3. Discussion of simulation results

Here we study information propagation without stress and then with sequential application of stress to show how the latter is necessary to propagate information in circular nanomagnets. Prior to time $t = 0$, voltage is absent and the first ‘input’ elliptical nanomagnet’s magnetization points at 90° (in the upward direction) while the other nanomagnets’ magnetization are assumed to point at 0° (to the right). A sequential voltage is applied, starting at $t = 0$ with 1 ns delay onto each consecutive nanomagnet starting with the second element. The voltage induces ∼250 ppm compressive strain (we assume a very conservative value, instead of ~1000 ppm used in Cui et al [26] and Wu et al [33]) that can be generated in each circular nanomagnet producing an anisotropy favoring alignment with the $y$-axis shown in figure 1. The voltage induced anisotropy due to a compressive strain is caused by the negative magnetostrictive properties of Ni.

Figure 2(d) shows the in-plane magnetization dynamics that result from the application of a sequential voltage to the elements. For these results, a voltage is applied at $t = 0$ to the second element, at $t = 1$ ns to the third element, and at $t = 2$ ns to the fourth element. As can be seen, the second nanomagnet in the chain rotates toward −90° after the application of the voltage at $t = 0$ and begins oscillations around −90° after about 0.5 ns. This deterministic rotation, i.e. counter-clockwise as contrasted with clockwise, is caused by the dipole–dipole interaction present with the adjacent elliptical nanomagnet. Here it is important to point out that the motion of this circular nanomagnetic also influences its neighbor; the third element rotates partially between $t = 0$ and $t = 1$ ns. At $t = 1$ ns, a voltage is applied to the third element producing a rotation/stabilization toward the 90° direction. The periodic oscillations in this element about this equilibrium point occurs at approximately $t = 1.3$ ns or within 0.3 ns of the voltage applied. Here it is again important to point out that the motion of this circular nanomagnet also influences its neighbor, the fourth element which also rotates partially before a voltage is applied to it. The application of this voltage (at $t = 2$ ns) stabilizes the fourth element with an orientation at −90°. These results show that a chain of many nanomagnets can be clocked sequentially with a voltage to propagate logic along this chain.

The results in figure 2(d) demonstrate that a voltage produces sufficient compressive strain to each nanomagnet to significantly lower the energy of the ‘up’ and ‘down’ states (ϕ = 90°, −90°). This essentially promotes anti-ferromagnetic ordering of magnetizations in the alternating ‘up’ and ‘down’ states. This anti-ferromagnetic order is the result of inter-magnet dipole coupling and the voltage induced stress anisotropy that make this configuration energetically more favorable than the magnetizations pointing horizontally. Furthermore, the results show that information can successfully be transferred along a chain of circular nanomagnets at the rate of 1 bit/nanosecond between two neighboring nanomagnets.
The numerical simulations assume that two mechanisms dominate the magnetization reorientation. These two effects are (1) dipole coupling between nanomagnets and (2) stress induced magnetic anisotropy through the magnetoelastic effect. To demonstrate that these are the two dominant mechanisms, a series of experiments were designed to establish the dipole effect and stress induced uniaxial magnetic anisotropy in the same chain of nanomagnets. These effects can be quantified by measuring the averaged M-H curves of an ensemble of nanomagnets and focusing on a large pitch array, a small pitch array (dipole coupled) without stress, and a small pitch array subjected to stress. By measuring the remanence changes along select directions, specific conclusions can be drawn about the relative magnitudes and the ability to control dipole coupling in the proposed logic device supporting the analytical conclusions. These results are discussed below.

4. Experimental methods

To experimentally demonstrate the effects of dipole field and strain induced magnetic anisotropy on the arrays of circular nanomagnets, arrays of circular Ni nanomagnets have been deposited on a PMN-PT substrate and MOKE measurements have been performed without and with applied strain.

4.1. Fabrication of the nanodots

Planar electrodes are first deposited on the PMN-PT’s top (50 nm Pt) and bottom (50 nm Au) surfaces. The nanostructure arrays are subsequently patterned on the Pt electrodes using a double layer of polymethylmethacrylate resist (PMMA 950 K A2) and liftoff-assisting copolymer (EL6 MMA). Electron beam writing was performed using a charge dose of 700 C cm⁻². The resist pattern was developed using a solution of 1:3 MIBK to IPA (methyl isobutyl ketone and isopropyl alcohol, respectively). Prior to depositing the Ni nanostructures, the PMN-PT was poled with a 0.8 MV m⁻¹ electric field. After poling, 5 nm Ti followed by 12 nm Ni (adhesion and ferromagnetic layers) were deposited by e-beam evaporation. This was followed by 12 h of room-temperature lift-off using n-methyl-2-pyrrolidone solvent. The resulting two nanostructure arrays each had a 500 nm pitch along the y-direction, but varied in pitch along the x-direction.
x-direction. Specifically, the pitches along the x-direction were 250 nm and 150 nm for array 1 and 2 respectively.

4.2. MOKE measurement

Magnetization measurements are made using longitudinal MOKE, where the sample’s plane is parallel to the applied field. Magnetization measurements via MOKE are limited to the area covered by the incident laser. Since the laser spot size (2 mm) exceeds the array length (1 mm), measurement of the paramagnetic response of the underlying Pt electrode is also included. However, the ferromagnetic response of the Ni nanodots is much stronger than the paramagnetic response of Pt. For this reason, the paramagnetic contribution can be ignored and the acquired data represents an average magnetic response of the nanodot array. The sample is held in place between the poles of the electromagnet using custom holders made of brass clips and PCB board. M-H curves are measured in both planar directions (i.e., x and y) and with an electric field of 0.6 MV m\(^{-1}\) applied. An electric field of 0.6 MV m\(^{-1}\) produces anisotropic in-plane strain [33]; specifically the strains are \(\varepsilon_x = 1000 \mu \varepsilon\) and \(\varepsilon_y = -3000 \mu \varepsilon\). Each published M-H curve consists of up to 500 hysteresis loops sampled per orientation and electric field in order to reduce error.

5. Discussion of experimental results

Two different samples were tested consisting of Nickel circular (100 nm) nanodot arrays patterned on a 10 mm \(\times\) 10 mm \(\times\) 0.5 mm single crystal (011) PMN-PT substrate sourced from TRS Technologies, Inc., USA. The arrays are 1 \(\times\) 1 mm and isolated from each other with a 2 mm separation as shown in figure 3(a). The [100] in-plane crystallographic axis of the PMN-PT substrate is aligned with the sample’s y-direction while the [011] in-plane crystallographic axis is aligned with the x-direction. The nanodot pitch along the y-direction is 500 nm for all arrays while the nanodot pitch along the x-direction is 250 nm and 150 nm for arrays 1 and 2, respectively.

Figure 3(b) shows M-H curves for the 250 nm spacing measured along both x- and y-directions without an electric field. The M versus H curves for both x- and y-directions are similar indicating an isotropic in-plane magnetization response. All the nanodots are circular, and thus shape does not introduce any magnetic anisotropy. Furthermore, since the measurement shows an absence of in-plane magnetic anisotropy, one concludes that the spacing between nanodots is sufficiently large to eliminate any dipole coupling. Specifically, 250 nm spacing is sufficiently large that the dipole−dipole coupling range is trivial for these circular Ni
nanodots. We calculate that the effective field due to this coupling is \( \sim 6 \text{ Oe} \) even if both nearest neighbors are included.

Figure 3(c) shows M–H loops measured along both x- and y-directions for the 150 nm spaced array without an electric field. When contrasting these measurements to those of figure 3(b) for the 250 nm spaced array, distinct similarities and differences are noted. First, there is a similarity in the \( M_r \) values measured in the x-direction, in particular they are approximately 0.8. Second, there is a dissimilarity in the \( M_r \) values measured in the y-direction; specifically the \( M_r \) for the 150 nm array is 0.5 while for the 250 nm array it is 0.8. The results for the 150 nm spacing clearly shows the presence of dipole–dipole coupling. Specifically dipole–dipole coupling along the y-direction should produce magneto-alignment reducing the measured \( M_r \) values along the y-direction. Figure 3(d) shows M–H curves for the 150 nm spaced array with a 0.6 MV m\(^{-1}\) electric field applied. The results show a distinct change in the M–H curves with the applied electric field as contrasted with the results without an electric field shown in figure 3(c). Specifically, without an electric field, the remnant magnetization in the x-direction is 0.8, but when a field is applied, the remanence decreases to approximately 0.5. The remanence decreases as the easy axis is now being established along an axis perpendicular to the x-axis array. This causes the easy magnetization direction to rotate toward the y-axis and away from the x-axis, in spite of the dipole coupling. A change in \( M_r \) occurs for the y-direction as well. However, the remanence increases from 0.5 to about 0.8 with an applied electric field. The remanence increase in the y-direction is surprising given the dipole coupling favors an anti-parallel state in the y-direction. However, for this configuration, the stress induced magnetic anisotropy is sufficiently large to mask the dipole effect and ensure that the nanomagnet’s magnetization remains along the y-direction even after the magnetic field is withdrawn. This result clearly confirms that the magnetic easy axis of the nanomagnet is established along the y-direction when an electric field is applied. This change is attributed to the voltage induced magnetoelastic effect. Since Ni is negatively magnetostrictive, the magnetoelastic response of the nanostructures causes the magnetization to favor alignment with the axis of compression implying that the chain is magnetically harder. We also established that the magnetoelastic energy is sufficiently larger than the dipole–dipole coupling that favors anti-parallel alignment in the y-direction and parallel alignment in the x-direction.

6. Conclusion

The simulations and the experiments together demonstrate the feasibility of using circular magnetostrictive nanomagnets clocked with strain to propagate information. We have further estimated that information can be transmitted along a circular nanomagnet chain clocked with stress with high reliability (error < 10\(^{-6}\) m, see supplementary material section B) provided there are no defects that pin the magnetization in such magnets. It can also be extremely low energy ~1\( \text{aJ/bit} \) (see supplementary material, section C), provided it is implemented on thin film PZT unlike the bulk PMN-PT used in this study. More importantly, this could provide a path to the ultimate scaling of nanomagnetic devices to implement Boolean operation and propagate logic at lateral dimensions below 20 nm, along with very little energy dissipation. This paradigm will be both scalable and extremely energy-efficient provided lithographic variations, misalignments and imperfections can be controlled at these scales.

Acknowledgments

JA, MSF and MA acknowledges support from NSF CAREER grant CCF-1253370. WYS, PN, ACC and GPC were supported in part by FAME, one of six centers of STARNet, a Semiconductor Research Corporation program sponsored by MARCO and DARPA.

References

[1] Salahuddin S and Datta S 2007 Interacting systems for self-correcting low power switching Appl. Phys. Lett. 90 093503
[2] Cowburn R P and Welland M E 2000 Room temperature magnetic quantum cellular automata Science 287 1466-8
[3] Csaba G, Imre A, Bernstein G H, Porod W and Metlushko V 2002 Nanocomputing by field-coupled nanomagnets IEEE Trans. Nanotechnol. 1 209–13
[4] Carlton D B, Emley N C, Tuchfeld E and Bokor J 2008 Simulation studies of nanomagnet-based logic architecture Nano Lett. 8 4173–8
[5] Atulasimha J and Bandyopadhyay S 2010 Bennett clocking of nanomagnetic logic using multiferroic single-domain nanomagnets Appl. Phys. Lett. 97 173105
[6] Roy K, Bandyopadhyay S and Atulasimha J 2011 Hybrid spintronics and spintronics: a magnetic technology for ultra low energy computing and signal processing Appl. Phys. Lett. 99 063108
[7] Salehi Fashami M, Roy K, Atulasimha J and Bandyopadhyay S 2011 Magnetization dynamics, Bennett clocking and associated energy dissipation in multiferroic logic Nanotechnology 22 155201
[8] Tiercelin N, Dusch Y, Klimov A, Giordano S, Preobrazhensky V and Pernod P 2011 Room temperature magnetoelectric memory cell using stress-mediated magnetoelectric switching in nanostructured multilayers Appl. Phys. Lett. 99 192507
[9] Alam M T, Siddiq M J, Bernstein G H, Niemier M, Porod W and Hu X S 2010 On-chip clocking for nanomagnet logic devices IEEE Trans. Nanotechnol. 9 348–51
[10] Bhowmik D, You L and Salahuddin S 2013 Spin Hall effect clocking of nanomagnetic logic without a magnetic field Nat. Nanotechnol. 9 59–63
[11] Britlinger T, Lim S-H, Baloch K H, Alexander P, Qi Y, Barry J, Mehgalalis J, Salamanca-Riba L, Takeuchi I and Cumings J 2010 In situ observation of reversible nanomagnetic switching induced by electric fields Nano Lett. 10 1219–23
[12] Li P, Chen A, Li D, Zhao Y, Zhang S, Yang L, Liu Y, Zhu M, Zhang H and Han X 2014 Electric field manipulation of magnetization rotation and tunneling magneto-resistance of
magnetic tunnel junctions at room temperature Adv. Mater. 26 4320–5

[13] Chu Y-H et al 2008 Electric-field control of local ferromagnetism using a magnetoelectric multiferroic Nature Mater. 7 478–82

[14] Chang T K, Keller S and Carman G P 2009 Electric-field-induced reversible magnetic single-domain evolution in a magnetoelectric thin film Appl. Phys. Lett. 94 132501

[15] Wu T, Bur A, Wong K, Zhao P, Lynch C S, Amiri P K, Wang K L and Carman G P 2011 Electrical control of reversible and permanent magnetization reorientation for magnetoelectric memory devices Appl. Phys. Lett. 98 262504

[16] D’Souza N, Salehi Fashami M, Bandyopadhyay S and Atulasimha J 2016 Experimental clocking of nanomagnets with strain for ultralow power boolean logic Nano Lett. 16 1069–75

[17] Buzzi M, Chopdekar R V, Hockel J L, Bur A, Wu T, Pilet N, Warnicke P, Carman G P, Heyderman L J and Nolting F 2013 Single domain spin manipulation by electric fields in strain coupled artificial multiferroic nanostructures Phys. Rev. Lett. 111 027204

[18] Datta S, Diep V Q and Behin-Aein B 2014 What constitutes a nanoswitch? A perspective Emerging Nanoelectronic Devices ed An Chen et al (Hoboken, NJ: John Wiley and Sons) pp 15–34

[19] Ralph D C and Siles M D 2008 Spin transfer torques J. Magn. Magn. Mater. 320 1190–216

[20] Yu G et al 2014 Switching of perpendicular magnetization by spin–orbit torques in the absence of external magnetic fields Nat. Nanotechnol. 9 548–54

[21] Brown W F Jr 1963 Thermal fluctuations of a single domain particle J. Appl. Phys. 34 1319–20

[22] Gaunt P 1977 The frequency constant for thermal activation of a ferromagnetic domain wall J. Appl. Phys. 48 3470–4

[23] Cowburn R P 2003 Superparamagnetism and the future of magnetic random access memory J. Appl. Phys. 93 9310–5

[24] Skumryev V, Stoyanov S, Zhang Y, Hadijpanayis G, Givord D and Nogues J 2003 Beating the superparamagnetic limit with exchange bias Nature 423 850–3

[25] Kim H K D, Schelhas L T, Keller S, Hockel J L, Tolbert S H and Carman G P 2013 Magnetoelectric control of superparamagnetism Nano Lett. 13 884–8

[26] Cui J, Hockel J L, Nordeen P K, Pisani D M, Liang C Y, Carman G P and Lynch C S 2013 A method to control magnetism in individual strain-mediated magnetoelectric islands Appl. Phys. Lett. 103 2011–6

[27] Cui J, Hockel J L, Nordeen P K, Pisani D M, Carman G P and Lynch C S 2014 Giant electric-field-induced magnetic anisotropy reorientation with patterned electrodes on a Ni thin film/lead zirconate titanate heterostructure J. Appl. Phys. 115 98–101

[28] Bennett C H 1982 The thermodynamics of computation—a review Int. J. Theor. Phys. 21 905–40

[29] Brown G, Novotny M A and Rikvold P A 2001 Langevin simulation of thermally activated magnetization reversal in nanoscale pillars Phys. Rev. B 64 134422

[30] Gilbert T L 2004 A phenomenological theory of damping in ferromagnetic materials IEEE Trans. Magn. 40 3443–9

[31] Nikonorov D E, Bourianoff G I, Rowlands G and Krivorotov I N 2010 Strategies and tolerances of spin transfer torque switching J. Appl. Phys. 107 113910

[32] Cowburn R P, Koltsos D K, Adeyeye A O, Welland M E and Tricker D M 1999 Single-domain circular nanomagnets Phys. Rev. Lett. 83 1042–5

[33] Wu T, Zhao P, Bao M, Bur A, Hockel J L, Wong K, Mohanchandra K P, Lynch C S and Carman G P 2011 Domain engineered switchable strain states in ferroelectric (011)[Pb(Mg1/3Nb2/3)O3]1−x[PbTiO3]x (PMN-PT, x ≈ 0.32) single crystals J. Appl. Phys. 109 124101