This is an electronic reprint of the original article.

This reprint may differ from the original in pagination and typographic detail.

Zietek, Slawomir; Ogrodnik, Piotr; Skowronski, Witold; Stobiecki, Feliks; van Dijken, Sebastiaan; Barnas, Jozef; Stobiecki, Tomasz

Electric-field tunable spin diode FMR in patterned PMN-PT/NiFe structures

Published in:
Applied Physics Letters

DOI:
[10.1063/1.4961124](https://doi.org/10.1063/1.4961124)

Published: 15/08/2016

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:

Zietek, S., Ogrodnik, P., Skowronski, W., Stobiecki, F., van Dijken, S., Barnas, J., & Stobiecki, T. (2016). Electric-field tunable spin diode FMR in patterned PMN-PT/NiFe structures. *Applied Physics Letters*, 109(7), [072406]. <https://doi.org/10.1063/1.4961124>

Electric-field tunable spin diode FMR in patterned PMN-PT/NiFe structures

Slawomir Ziętek, Piotr Ogrodnik, Witold Skowroński, Feliks Stobiecki, Sebastiaan van Dijken, Józef Barnaś, and Tomasz Stobiecki

Citation: [Applied Physics Letters](#) **109**, 072406 (2016); doi: 10.1063/1.4961124

View online: <http://dx.doi.org/10.1063/1.4961124>

View Table of Contents: <http://scitation.aip.org/content/aip/journal/apl/109/7?ver=pdfcov>

Published by the [AIP Publishing](#)

Articles you may be interested in

[High-resolution electron microscopy in spin pumping NiFe/Pt interfaces](#)

J. Appl. Phys. **117**, 17D910 (2015); 10.1063/1.4914126

[The role of the non-magnetic material in spin pumping and magnetization dynamics in NiFe and CoFeB multilayer systems](#)

J. Appl. Phys. **117**, 163901 (2015); 10.1063/1.4918909

[Resonance magnetoelectric effects in a layered composite under magnetic and electrical excitations](#)

J. Appl. Phys. **112**, 014103 (2012); 10.1063/1.4733466

[Low moment NiCr radio frequency magnetic films for multiferroic heterostructures with strong magnetoelectric coupling](#)

J. Appl. Phys. **111**, 103915 (2012); 10.1063/1.4722344

[Nonuniform demagnetizing field and magnetization in element of patterned NiFe films](#)

J. Appl. Phys. **93**, 7598 (2003); 10.1063/1.1555313

A promotional banner for Applied Physics Reviews. On the left is a small image of the journal cover for 'Applied Physics Reviews', which features a diagram of a device structure. The main part of the banner has a blue background with a molecular structure. The text 'NEW Special Topic Sections' is prominently displayed in white. Below this, on an orange background, it says 'NOW ONLINE' in yellow, followed by 'Lithium Niobate Properties and Applications: Reviews of Emerging Trends' in white. The AIP Applied Physics Reviews logo is in the bottom right corner.

NEW Special Topic Sections

NOW ONLINE
Lithium Niobate Properties and Applications:
Reviews of Emerging Trends

AIP Applied Physics Reviews

Electric-field tunable spin diode FMR in patterned PMN-PT/NiFe structures

Slawomir Ziętek,^{1,a)} Piotr Ogródnik,^{1,2,b)} Witold Skowroński,¹ Feliks Stobiecki,³ Sebastiaan van Dijken,⁴ Józef Barnaś,^{5,3} and Tomasz Stobiecki¹

¹AGH University of Science and Technology, Department of Electronics, Al. Mickiewicza 30, 30-059 Kraków, Poland

²Faculty of Physics, Warsaw University of Technology, ul. Koszykowa 75, 00-662 Warszawa, Poland

³Institute of Molecular Physics, Polish Academy of Sciences, ul. Smoluchowskiego 17, 60-179 Poznań, Poland

⁴NanoSpin, Department of Applied Physics, Aalto University School of Science, P.O. Box 15100, FI-00076 Aalto, Finland

⁵Faculty of Physics, Adam Mickiewicz University, ul. Umultowska 85, 61-614 Poznań, Poland

(Received 20 May 2016; accepted 4 August 2016; published online 18 August 2016)

Dynamic properties of NiFe thin films on PMN-PT piezoelectric substrate are investigated using the spin-diode method. Ferromagnetic resonance (FMR) spectra of microstrips with varying width are measured as a function of magnetic field and frequency. The FMR frequency is shown to depend on the electric field applied across the substrate, which induces strain in the NiFe layer. Electric field tunability of up to 100 MHz per 1 kV/cm is achieved. An analytical model based on total energy minimization and the Landau-Lifshitz-Gilbert equation, taking into account the magnetostriction effect, is used to explain the measured dynamics. Based on this model, conditions for optimal electric-field tunable spin diode FMR in patterned NiFe/PMN-PT structures are derived.

Published by AIP Publishing. [<http://dx.doi.org/10.1063/1.4961124>]

Electric field control of magnetism at room temperature can lead to the development of efficient and low-power memories,^{1–3} magnetic field sensors,⁴ voltage-tunable microwave filters,⁵ and oscillators.⁶ Application of multiferroic materials can additionally lead to the design of new electronic devices in which both the electron spin and charge are affected by an external electric field. Voltage control of magnetic anisotropy (VCMA) in multiferroics can be realized by strain transfer from a ferroelectric or piezoelectric layer to a ferromagnetic film, as the deformation of the ferromagnet changes the magnetoelastic anisotropy *via* inverse magnetostriction.^{7–23}

Recently, the influence of electric-field induced strain on magnetic anisotropy has been demonstrated in a variety of unpatterned and patterned multiferroic heterostructures including BaTiO₃/FM,^{7–10} PMN-PT/FM,^{11–18} and PZN-PT/FM^{18–23} with FM = Ni,^{9,11,14} NiFe,²¹ NiCo,²⁰ Co,¹⁷ CoFe,^{7,8} CoFeB,^{15,16,23} Fe,¹⁰ FeGaB,^{19,22} and Fe₃O₄.¹⁸ Electric-field tuning of ferromagnetic resonance (FMR) has also been studied. In most reports, strong tuning of FMR in continuous ferromagnetic films on piezoelectric substrates is inferred from microwave cavity or vector network analyzer FMR measurements.^{15,18–23}

In this letter, we experimentally study electric-field tuning of FMR in patterned Ni₈₀Fe₂₀ microstrips on PMN-PT substrates using a spin diode (SD) measurement technique. Patterning of the ferromagnetic film is anticipated to introduce a magnetostatic shape anisotropy, which competes with the magnetoelastic anisotropy that is induced via transfer of piezoelectric strain. To systematically study this effect, we consider NiFe microstrips of different widths. An analytical model for electric-field tunable microwave signals in confined

ferromagnetic geometries is also presented. Using this model, we derive a phase diagram of the FMR frequency shift as a function of microstrip width and magnetic field strength.

On a polished PMN-PT (0.72Pb(Mg_{1/3}Nb_{2/3})O₃–0.28PbTiO₃) (011)-oriented piezoelectric substrate, a 20 nm thick layer of Ni₈₀Fe₂₀ was deposited using magnetron sputtering. The bottom side of the crystal was covered by a 5 nm Ti/50 nm Au layer, in order to apply high voltage perpendicular to the piezoelectric substrate. Afterwards, NiFe microstrips of 1.5, 2.6, 6.7 μm width and 90 μm length along the [01-1] direction of the PMN-PT crystal were fabricated using electron beam lithography and ion-beam etching. The sample was vacuum annealed at 330 °C in an in-plane magnetic field to increase the anisotropic magnetoresistance (AMR) ratio. The dc resistance of the respective strips was 842 Ω, 576 Ω, and 201.5 Ω.

A radio frequency (rf) current of amplitude I , flowing through the NiFe strips deposited on the PMN-PT substrate, generates a time-dependent spin transfer torque (STT) and Oersted field. These effects lead to magnetization dynamics and, because of AMR, resistance oscillations. Mixing of the oscillating current and resistance generates a dc SD voltage V_{dc} . The amplitude of this signal is proportional to the real part δR of the complex amplitude of the resistance change,^{24–26} $V_{dc} = \frac{1}{2} I \delta R$. The AMR effect is given by $R = R_{\perp} + \Delta R \cos^2 \theta_M$, where $\Delta R = R_{\parallel} - R_{\perp}$ and $R_{\perp}$ ($R_{\parallel}$) denote the resistance of the strip when the magnetization is perpendicular (parallel) to the current. The change in resistance due to a small change in the angle θ_M between magnetic moment and current is thus given by $\delta R = 2\Delta R \sin \theta_M \cos \theta_M \delta \theta_M$. From this, one finds $V_{dc} = I \Delta R \sin \theta_M \cos \theta_M \delta \theta_M$. We note that $\delta \theta_M$ represents the real part of the complex angular changes.

As mentioned above, the magnetization dynamics responsible for the V_{dc} signal is driven by the uncompensated Oersted field and by the STT effect. Even for a single-layer

^{a)}Electronic mail: zietek@agh.edu.pl

^{b)}Electronic mail: piotrogr@if.pw.edu.pl

ferromagnetic strip, an uncompensated Oersted field can be induced, since electron scattering processes at both interfaces are generally different. The STT, on the other hand, may appear due to some inhomogeneities of the magnetization distribution within the permalloy strip.²⁵ Small changes of the angle θ_M can be derived from the Landau-Lifshitz-Gilbert (LLG) equation for a unit vector along the magnetization $\vec{m} = \vec{M}/M$

$$\frac{\partial \vec{m}(\vec{r})}{\partial t} - \alpha \vec{m}(\vec{r}) \times \frac{\partial \vec{m}(\vec{r})}{\partial t} = \vec{\Gamma}, \quad (1)$$

where α is a damping constant (of the order of 10^{-3}) and

$$\vec{\Gamma} = -\gamma \vec{m}(\vec{r}) \times \nabla_{\vec{M}} \mathcal{U}(\vec{r}) - (\vec{u}(\vec{r}) \cdot \nabla) \vec{m}(\vec{r}) \quad (2)$$

is a torque acting on the magnetic moment $\vec{m}$, with γ being the gyromagnetic ratio. The second term in Eq. (2) corresponds to the STT effect. Its amplitude, $\vec{u}(\vec{r})$, is proportional to the magnitude of the rf current density $\vec{j}$ and its spin polarization P , i.e., $\vec{u}(\vec{r}) \propto \vec{j}P$.²⁷ We have omitted here the non-adiabatic term in STT, as its amplitude is usually much smaller than that of the adiabatic term.²⁸ The averaged magnetic energy $U = \langle \mathcal{U}(\vec{r}) \rangle$ includes the shape anisotropy, Zeeman-like terms due to static and dynamic (Oersted) magnetic fields, as well as terms related to the stress due to the deformation of the PMN-PT substrate under external electric field. Bias voltage applied to the PMN-PT (011) oriented substrate generates a tensile and compressive stress along the [01-1] and [100] directions, respectively. Both stresses enhance the magnetic anisotropy along the strips. The energy U can be written as

$$U = -\vec{M} \cdot \vec{H}_d - \vec{M} \cdot \vec{H} - \frac{3}{2} \lambda \sigma_{[01-1]}(E) \cos^2 \theta_M - \left[K_{[100]} + \frac{3}{2} \lambda \sigma_{[100]}(E) \right] \sin^2 \theta_M \sin^2 \phi - \vec{M} \cdot \vec{H}_{Oe[100,011]}, \quad (3)$$

where $\vec{H}_d = -\hat{N}\vec{M}$ is the demagnetizing field calculated based on the analytical formulas for demagnetization factors,²⁹ $\vec{H}$ is the external magnetic field, and $K_{[100]}$ is the uniaxial magnetocrystalline anisotropy that is induced during magnetic-field annealing. The coordinate system with defined angles describing orientation of the magnetization (θ_M) and magnetic field (θ_H) with respect to the crystallographic axes of the PMN-PT crystal is shown in Fig. 1(a). The easy axis in our sample is transverse to the strip long axis, i.e., along the [100] direction. In turn, $\vec{H}_{Oe[100,011]}$ in Eq. (3) denotes the time-dependent Oersted field components in the [100] or [011] directions. Because its amplitudes are constant within the sample, the Oersted field may be written as a gradient with respect to $\vec{M}$ of the energy term $-\vec{M} \cdot \vec{H}_{Oe[100,011]}$. Finally, λ in Eq. (3) is the magnetostriction constant. The electric field-dependent stress $\sigma(E)$ acting on permalloy in the [100] and [01-1] directions can be calculated from the relation between the strain of the PMN-PT substrate and the applied electric field, $\epsilon_i = d_{ji}E_j$, where ϵ_i denotes the strain of the PMN-PT along the i direction ($i = (Y, Z) \equiv [100], [01-1]$), d_{ji} is a matrix of piezoelectric constants, and E_j is the electric

FIG. 1. (a) Model geometry: The rf current is flowing along the z direction, θ_H is the angle of the external magnetic field and θ_M and ϕ denote the polar and azimuthal angles of the magnetization direction. (b) Experimental setup for SD effect measurements with external voltage applied to the PMN-PT piezoelectric crystal to electrically strain the NiFe microstrips.

field applied in the j direction ($j = X \equiv [011]$). Since the electric field is applied perpendicularly to the substrate (in [011] direction), the only strains that influence the permalloy microstrip are those in [100] and [01-1] directions. In particular, the relation between the strain within PMN-PT and stress transmitted to permalloy can be written as¹³

$$\sigma_{[01-1]}(E) = \frac{Y(d_{31} + \nu d_{32})}{(1 - \nu^2)} E_{[011]}, \quad (4a)$$

$$\sigma_{[100]}(E) = \frac{Y(d_{32} + \nu d_{31})}{(1 - \nu^2)} E_{[011]}, \quad (4b)$$

where $Y = 200$ GPa is the Young's modulus, and $\nu = 0.3$ is Poisson's ratio of NiFe.³⁰ From the above equations, one can see that stresses in both in-plane directions ([100] and [01-1]) of permalloy may be different. Thus, depending on their signs, they can induce either easy or hard magnetization axes along the [100] or [01-1] directions of the NiFe microstrips. In our case, d_{33} equals $1740 \pm 91 \frac{pC}{N}$ (discussed in experimental part), which agrees well with the data reported by Shanthi *et al.* in Ref. 31 for a PMN-PT crystal. Based on this, we assume the remaining piezoelectric coefficients: $d_{31} \equiv d_{[011][01-1]} = 723 \pm 20 \frac{pC}{N}$ and $d_{32} \equiv d_{[011][100]} = -1761 \pm 13 \frac{pC}{N}$. As a consequence, the strain-induced easy magnetization axis is aligned along the [01-1] direction, which is parallel to the magnetostatic shape anisotropy of the microstrip.

From the LLG equation, one finds $\delta\theta_M$ as a function of the driving frequency f . The solution has a general resonance-curve form²⁶

$$\delta\theta_M = \frac{\cos \Psi [A\sigma f^2 + B(f^2 - f_0^2)] + \sin \Psi [A f(f^2 - f_0^2) - B\sigma f]}{(f^2 - f_0^2)^2 + \sigma^2 f^2}, \quad (5)$$

where A and B describe the amplitudes of the symmetric and antisymmetric contributions to the V_{dc} signal, while f_0 denotes the resonance frequency given by

$$f_0 = \frac{1}{2\pi M_s \sin \theta_M} \sqrt{\frac{1}{(1 + \alpha^2)} \left(\frac{\partial^2 U}{\partial \phi^2} \frac{\partial^2 U}{\partial \theta_M^2} - \left[\frac{\partial^2 U}{\partial \phi \partial \theta_M} \right]^2 \right)}, \quad (6)$$

with the partial derivatives calculated at the stationary angles (θ_M, ϕ) determined by minimum magnetic energy (Eq. (3)) in the absence of rf current. Because of the lack of dc

current, the resonance frequency does not depend on the STT- and Oersted-field-related terms. On the other hand, the resonance frequency implicitly depends on the applied electric field due to the presence of static electric-field related energy terms.

A schematic of the experimental setup for SD measurements of the FMR effect is presented in Fig. 1(b). A microwave signal of 10 dBm was applied to the NiFe microstrip using a rf probe and generator, and the dc voltage produced by mixing of the rf current with resistance oscillations was detected by a dc voltmeter. Experiments with unpatterned PMN-PT/NiFe sample were also conducted as reference. X-ray diffraction (XRD) scans of the (022) PMN-PT reflection were measured in an electric field ranging from 0 to 12 kV/cm (Fig. 2(a)). The electric-field induced piezoelectric strain ϵ that is derived from these measurements is summarized in Fig. 2(b). The slope of the curve, which corresponds to the d_{33} piezoelectric constant, equals $174 \times 10^{-6} \pm 9.1$ cm/kV.

We used the SD effect to characterize voltage-tunable FMR in our patterned PMN-PT/NiFe structures for dc voltages in the range of 0–100 V (0–2 kV/cm). Examples of electric-field tunable FMR spectra are shown in Fig. 3(a). The spectra were measured in a constant magnetic field (20–500 Oe) applied at $\theta_H = 40^\circ$, which corresponds to the angle for which maximum SD voltages have been observed.²⁵ Evolutions of resonance frequency with applied magnetic field strength for three different NiFe strips in an electric field up to 2 kV/cm are shown in Fig. 3(b). The largest voltage-induced shift in FMR frequency (202 MHz) is observed for the widest strip at low magnetic field (21.5 Oe). For more narrow strips and larger magnetic fields, the voltage-induced frequency shifts are smaller. Fig. 3(c) shows the FMR frequency at 36.5 Oe as a function of electric fields for microstrips with different width. The solid lines indicate theoretical model calculations.

To additionally prove the consistency of the derived model, AMR loops on 6.7 μm wide strips were measured (Fig. 4(a)). Theoretical curves (solid lines) were calculated for 0 kV/cm and 4 kV/cm using the same parameters as for the calculated FMR shifts. In the absence of a magnetic field, the magnetization and current density are both aligned along the [01-1] direction. According to the expression for AMR given earlier, the strip's resistance is maximum under these conditions. An applied magnetic field tilts the magnetization away from the [01-1] direction and thus decreases the

FIG. 2. (a) XRD θ - 2θ scans of the (022) reflection of the PMN-PT substrate for electric fields ranging from 0 to 12 kV/cm. (b) Electric field induced relative change of the out-of-plane (011) lattice parameters of the PMN-PT substrate. The red line represents a linear fit.

FIG. 3. (a) Electric-field controlled FMR spectra at constant magnetic fields (in the range of 20–200 Oe) as a function of frequency for NiFe microstrips with a width of 6.7 μm . The resonance curves for 36.5 Oe are magnified in the right panel. (b) Dispersion relations for three microstrips with different width measured at 0 and 2 kV/cm applied electric field. Solid lines represent theoretical predictions calculated using Eq. (6) with $K_{[100]} = 785 \frac{\text{J}}{\text{m}^2}$, $\alpha = 0.007$, $M_s = 0.97$ T (determined from VSM measurements), $\lambda_{\text{NiFe}} = 2.5 \times 10^{-6}$ and demagnetization factors (N_x, N_y, N_z) [width]: (0.992627, 0.006880, 0.000493) [6.7 μm], (0.984052, 0.015521, 0.000427) [2.6 μm], (0.974991, 0.024620, 0.000389) [1.5 μm]. (c) FMR frequency as a function of applied electric field measured for three microstrip widths at 36.5 Oe.

resistance. The sharp peaks that occur at low magnetic fields correspond to a perpendicular alignment of the magnetization and the long axis of the strip. Such a configuration occurs in a very narrow range of magnetic field.

The small discrepancy in switching fields between the theoretical and experimental results may be caused by thermally activated switching, which are not taken into account in the macrospin model. Apart from the hysteretic region, however, the macrospin model predictions fit the experimental data well.

This allows us to model the frequency shift in an electric field of 2 kV/cm as a function of NiFe strip width and external magnetic field using system parameters that are derived from dynamic and static measurements. The result is shown

FIG. 4. (a) Electric field effect on the $R(H)$ loop measured for $\theta_H = 40^\circ$. The solid lines represent macrospin calculations. (b) Calculated shift of the resonance frequency, Δf , as a function of external magnetic field and strip width.

in Fig. 4(b). The calculated phase diagram can be used to identify the parameter space for which strong electric-field tuning of FMR can be attained in NiFe microstrips on piezoelectric PMN-PT. The results indicate that the largest effects are obtained in wide microstrips at modest external magnetic field. The reduction of strain sensitivity in more narrow strips can be attributed to stronger magnetostatic shape anisotropy, which reduces the effect of the piezostain induced magnetoelastic anisotropy.

To summarize, we have used the spin diode effect to explore the phenomenon of electric-field tuning of FMR in NiFe microstrips on the piezoelectric PMN-PT substrate. Our experimental results indicate that voltage control of FMR spectra is sensitive to the shape of the NiFe microstructures and the applied magnetic field. Electric field tunability of up to 100 MHz per 1 kV/cm was obtained in the widest (6.7 μm) of the investigated strips at low magnetic field (21.5 Oe). The experimental findings are reproduced by an analytical model.

This work was supported by the Polish National Science Center Grant No. Harmonia-UMO-2012/04/M/ST7/00799. S.v.D. acknowledges the financial support from the European Research Council (ERC-2012-StG 307502-E-CONTROL). S.Z. acknowledges the Dean's Grant No. 15.11.230.198.

¹M. Bibes and A. Barthélemy, *Nat. Mater.* **7**, 425 (2008).

²J. Scott, *Nat. Mater.* **6**, 256 (2007).

³Z. Li, J. Wang, Y. Lin, and C. Nan, *Appl. Phys. Lett.* **96**, 162505 (2010).

⁴W. Skowronski, P. Wiśniowski, T. Stobiecki, S. Cardoso, P. P. Freitas, and S. van Dijken, *Appl. Phys. Lett.* **101**, 192401 (2012).

⁵A. Tatarenko, V. Gheevarghese, and G. Srinivasan, *Electron. Lett.* **42**, 540 (2006).

⁶A. Useinov, A. Kalitsov, J. Velez, and N. Kioussis, *Phys. Rev. B* **91**, 094408 (2015).

⁷T. H. Lahtinen, J. O. Tuomi, and S. van Dijken, *Adv. Mater.* **23**, 3187 (2011).

⁸T. H. E. Lahtinen, K. J. A. Franke, and S. van Dijken, *Sci. Rep.* **2**, 258 (2012).

⁹R. Streubel, D. Köhler, R. Schäfer, and L. M. Eng, *Phys. Rev. B* **87**, 054410 (2013).

¹⁰K. J. A. Franke, B. Van de Wiele, Y. Shirahata, S. J. Hämäläinen, T. Taniyama, and S. van Dijken, *Phys. Rev. X* **5**, 011010 (2015).

¹¹M. Buzzi, R. Chopdekar, J. Hockel, A. Bur, T. Wu, N. Pilet, P. Warnicke, G. Carman, L. Heyderman, and F. Nolting, *Phys. Rev. Lett.* **111**, 027204 (2013).

¹²S. Cherepov, P. K. Amiri, J. G. Alzate, K. Wong, M. Lewis, P. Upadhyaya, J. Nath, M. Bao, A. Bur, T. Wu *et al.*, *Appl. Phys. Lett.* **104**, 082403 (2014).

¹³T. Nan, Z. Zhou, M. Liu, X. Yang, Y. Gao, B. A. Assaf, H. Lin, S. Velu, X. Wang, H. Luo, J. Chen, S. Akhtar, E. Hu, R. Rajiv, K. Krishnan, S. Sreedhar, D. Heiman, B. M. Howe, G. J. Brown, and N. X. Sun, *Sci. Rep.* **4**, 3688 (2014).

¹⁴T. Wu, A. Bur, P. Zhao, K. P. Mohanchandra, K. Wong, K. L. Wang, C. S. Lynch, and G. P. Carman, *Appl. Phys. Lett.* **98**, 262504 (2011).

¹⁵M. Liu, B. M. Howe, L. Grazulis, K. Mahalingam, T. Nan, N. X. Sun, and G. J. Brown, *Adv. Mater.* **25**, 4886 (2013).

¹⁶S. Zhang, Y. Zhao, X. Xiao, Y. Wu, S. Rizwan, L. Yang, P. Li, J. Wang, M. Zhu, H. Zhang, X. Jin, and X. Han, *Sci. Rep.* **4**, 3727 (2014).

¹⁷S.-W. Yang, R.-C. Peng, T. Jiang, Y.-K. Liu, L. Feng, J.-J. Wang, L.-Q. Chen, X.-G. Li, and C.-W. Nan, *Adv. Mater.* **26**, 7091 (2014).

¹⁸M. Liu, O. Obi, J. Lou, Y. Chen, Z. Cai, S. Stoute, M. Espanol, M. Lew, X. Situ, K. S. Ziemer *et al.*, *Adv. Funct. Mater.* **19**, 1826 (2009).

¹⁹J. Lou, M. Liu, D. Reed, Y. Ren, and N. X. Sun, *Adv. Mater.* **21**, 4711 (2009).

²⁰M. Liu, S. Li, O. Obi, J. Lou, S. Rand, and N. X. Sun, *Appl. Phys. Lett.* **98**, 222509 (2011).

²¹M. Liu, O. Obi, J. Lou, S. Li, X. Xing, G. Yang, and N. X. Sun, *J. Appl. Phys.* **109**, 07D913 (2011).

²²M. Liu, Z. Zhou, T. Nan, B. M. Howe, G. J. Brown, and N. X. Sun, *Adv. Mater.* **25**, 1435 (2013).

²³S. Li, Q. Xue, J.-G. Duh, H. Du, J. Xu, Y. Wan, Q. Li, and Y. Lü, *Sci. Rep.* **4**, 7393 (2014).

²⁴A. Tulapurkar, Y. Suzuki, A. Fukushima, H. Kubota, H. Maehara, K. Tsunekawa, D. Djayaprawira, N. Watanabe, and S. Yuasa, *Nature* **438**, 339 (2005).

²⁵A. Yamaguchi, H. Miyajima, T. Ono, Y. Suzuki, S. Yuasa, A. Tulapurkar, and Y. Nakatani, *Appl. Phys. Lett.* **90**, 182507 (2007).

²⁶S. Ziętek, P. Ogródnik, M. Frankowski, J. Chęciński, P. Wiśniowski, W. Skowronski, J. Wrona, T. Stobiecki, A. Żywczyk, and J. Barnaś, *Phys. Rev. B* **91**, 014430 (2015).

²⁷A. Yamaguchi, K. Motoi, A. Hirohata, and H. Miyajima, *Phys. Rev. B* **79**, 224409 (2009).

²⁸A. Thiaville and Y. Nakatani, *J. Appl. Phys.* **104**, 093701 (2008).

²⁹A. Aharoni, *J. Appl. Phys.* **83**, 3432 (1998).

³⁰M. Levy, E. Henry, R. Richard, and V. Keppens, *Handbook of Elastic Properties of Solids, Liquids, and Gases*, Elastic Properties of Solids: Biological and Organic Materials, Earth and Marine Sciences Vol. 3 (Academic Press, 2001).

³¹M. Shanthi, L. Lim, K. Rajan, and J. Jin, *Appl. Phys. Lett.* **92**, 142906 (2008).