Antiferromagnetic Piezospintronics

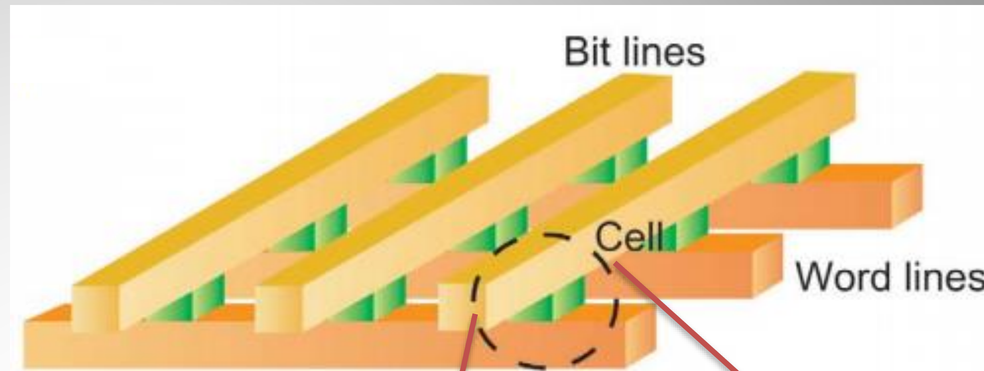
Zhiqi Liu

School of Materials Science & Engineering, Beihang University, Beijing, China

Data Storage for Our Digital Era

Feng, Yan & Liu, Adv. Electron. Mater. **5**, 1800466 (2019)

Current-Driven Information Writing



Write-head: coil with current

Read-head: GMR sensor

0 **1**

MRAM

Area：60 x 60 nm^2

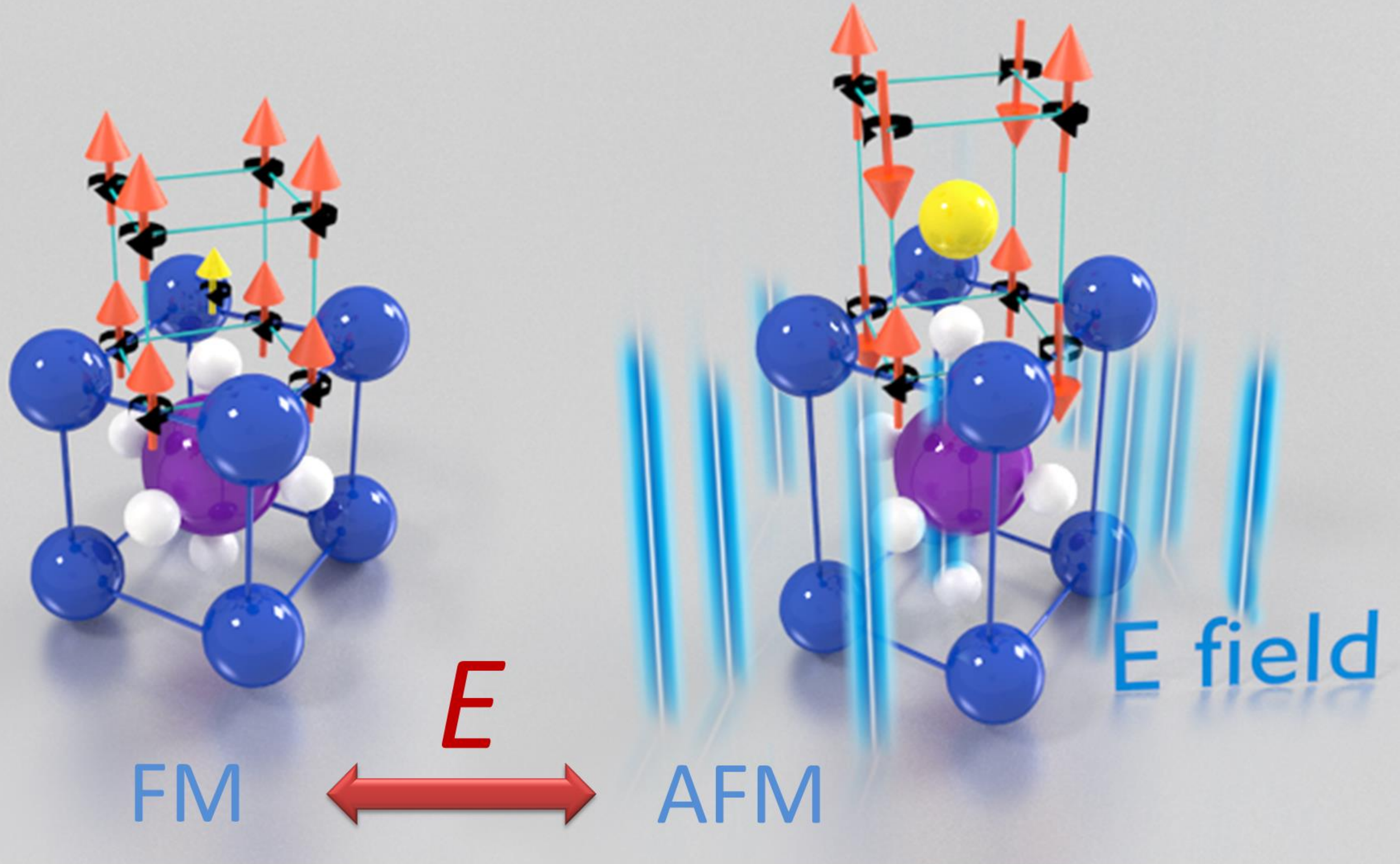
NiFe
MgO
Co
MnFe

MRAM：100 pJ/bit (10^{-10})
STT-MRAM: 1 pJ/bit (10^{-12})

Joule heating: I^2Rt

Electricity for Data Storage

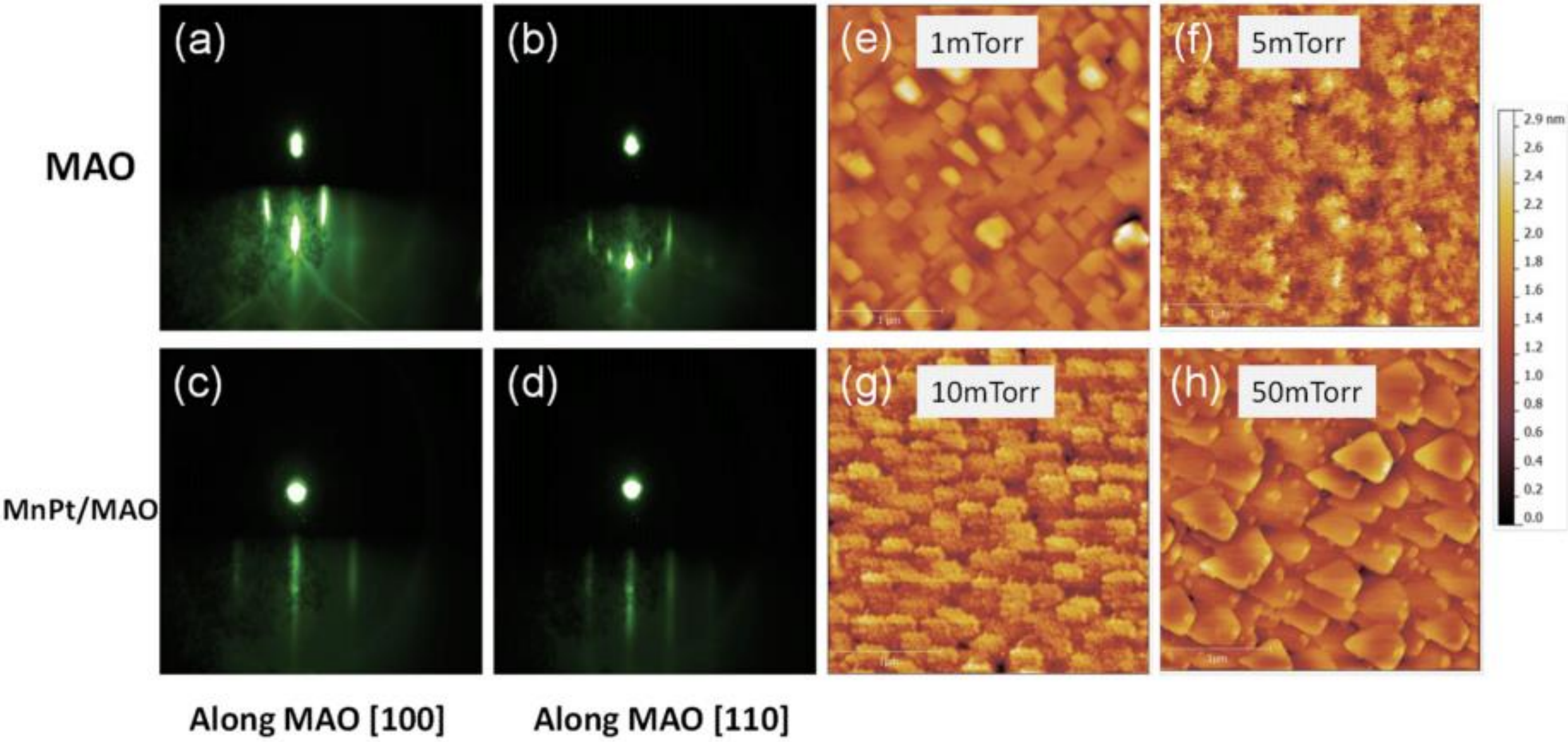
Alternative Approach – Electric-Field Control via FM/FE Heterostructures



Challenges of Epitaxy of Metal Films on Ferroelectric Oxides

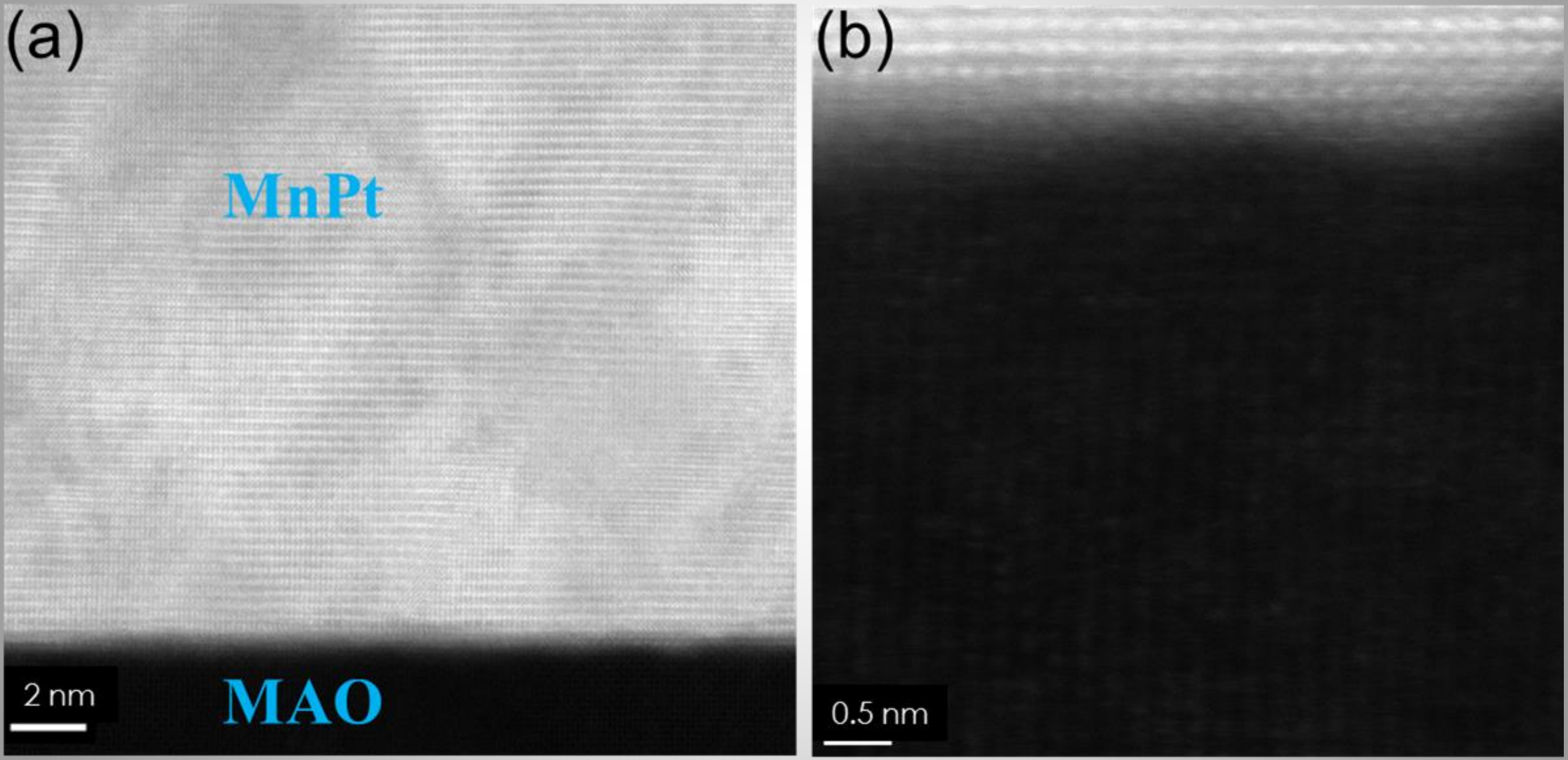
- 1. Epitaxy – high temperature
- 2. Chemical reaction
- 3. Wetting issue
- 4. Lattice mismatch

Epitaxial Growth of MnPt



RHEED & AFM

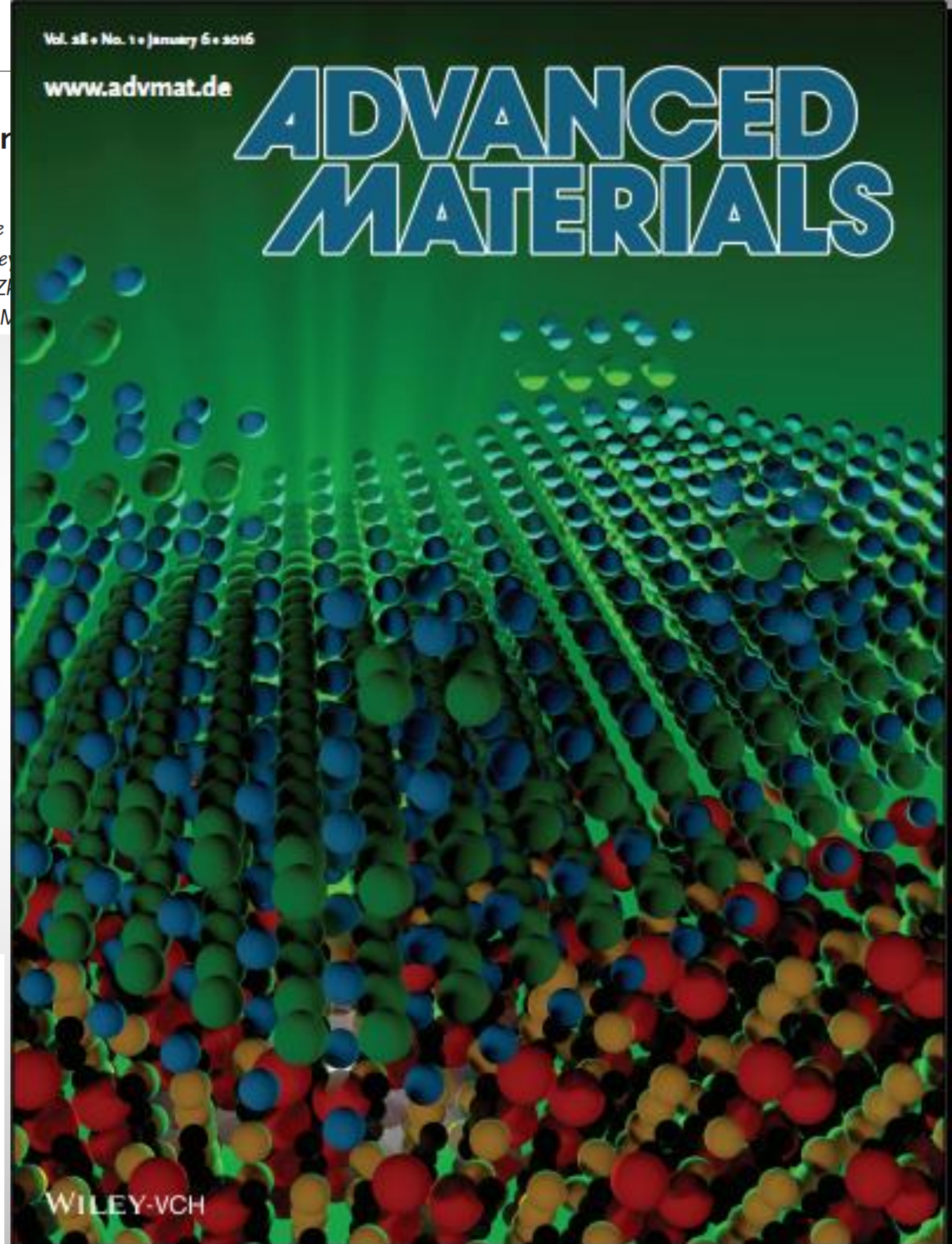
Epitaxial Growth of Intermetallic Films on Oxides – MnPt on $MgAl_2O_4$



Liu *et al*. Adv. Mater. **28**, 118 (2016)

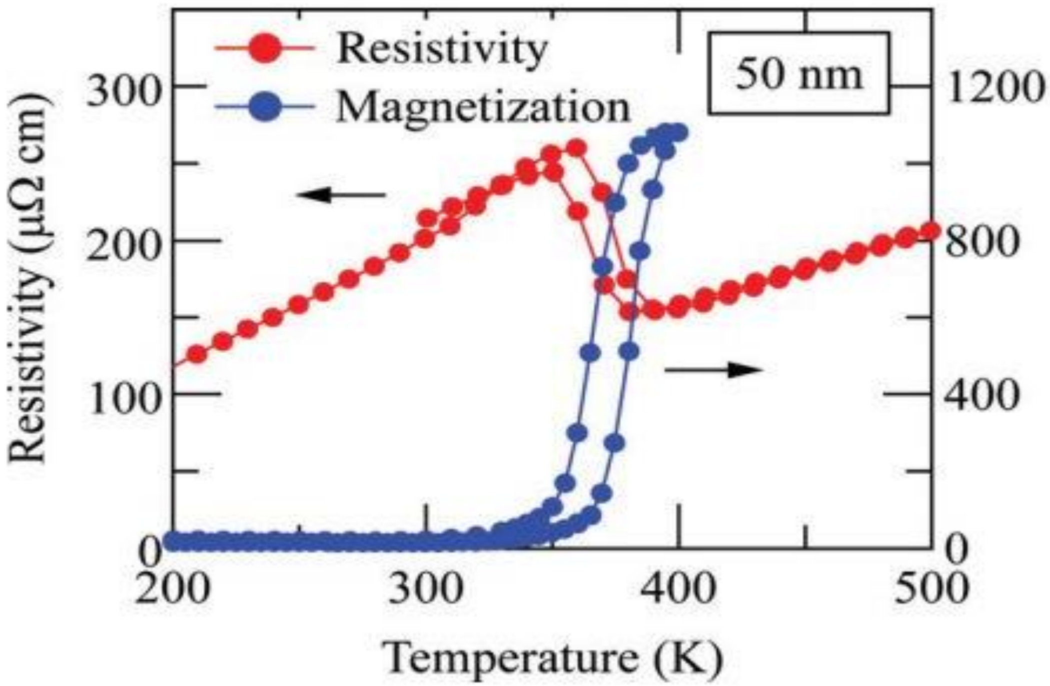

ADVANCED MATERIALS
www.advmat.de
COMMUNICATION
Epitaxial Growth of Intermetallic MnPt Films or
and Large Exchange Bias
Zhiqi Liu,* Michael D. Biegalski, Shang-Lin Hsu, Shunli Shang, Cassie
Li Li, Lisha Fan, Tricia L. Meyer, Anthony T. Wong, John A. Nichols, De
Long You, Zuhuang Chen, Kai Wang, Kevin Wang, Thomas Z. Ward, Z
Ho Nyung Lee, Athena S. Sefat, Valeria Lauter, Zi-Kui Liu, and Hans M

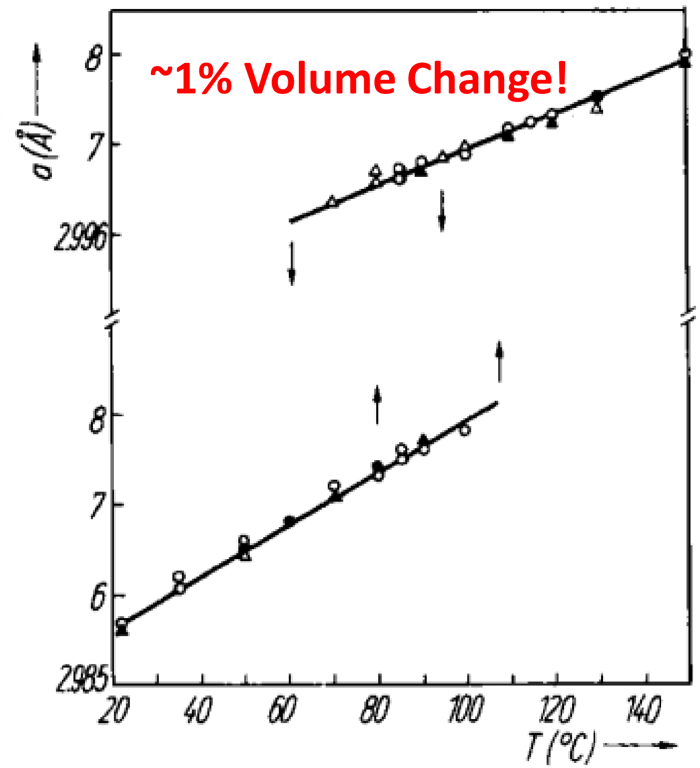
Capable of Integrating Intermetallic Alloys on Oxides with *In-Situ* Monitoring



On page 118, Z. Q. Liu, H. M. Christen, and co-workers demonstrate epitaxial growth of intermetallic MnPt on oxides, promising for magnetoelectric applications. In high-quality films, large exchange coupling between this antiferromagnet and a ferromagnetic layer is observed. In contrast, Mn/Pt antisites result in ferromagnetism, despite the robustness of the antiferromagnetism in bulk MnPt. Image credit: Changjian Li, NUS.

FeRh





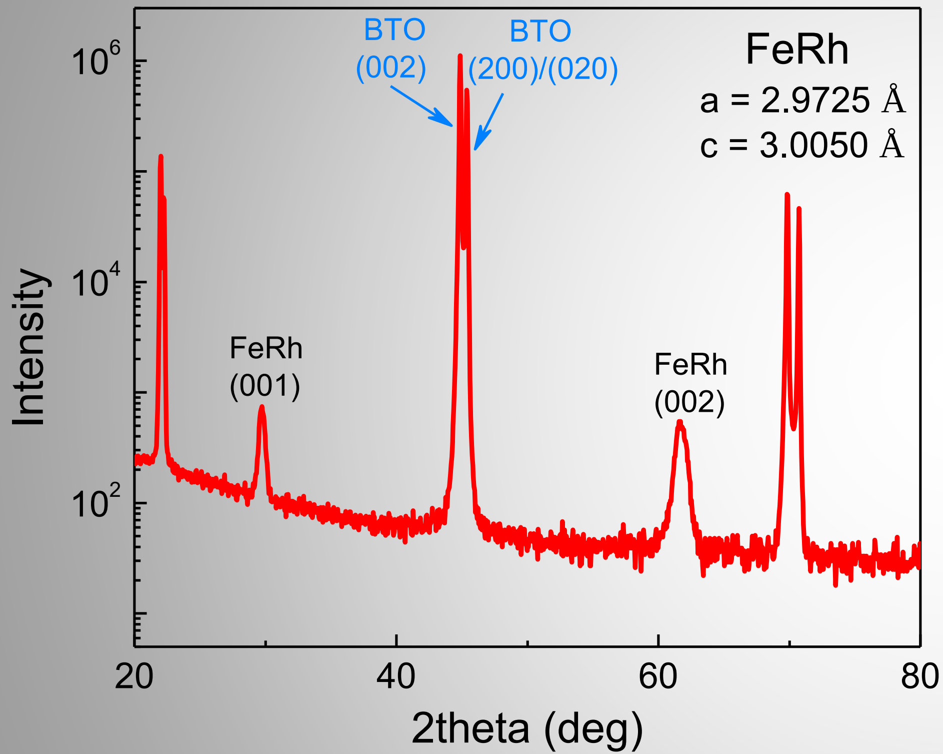
Electrical ⟷ **Magnetic** ⟷ **Structural**

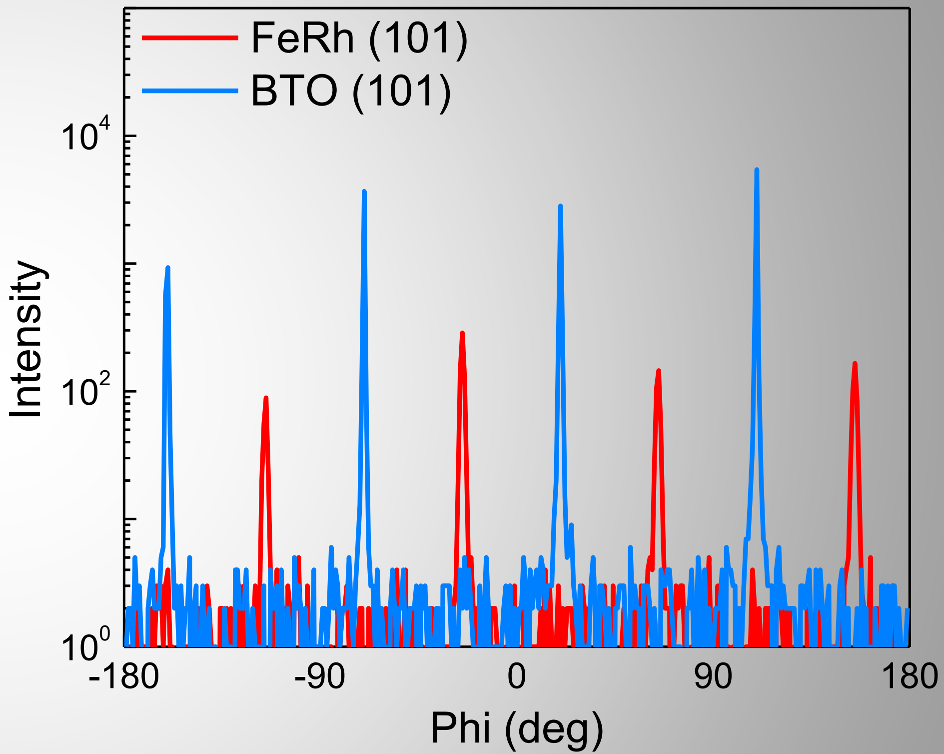
M. Fallot & R. Hocart, Rev. Sci. 77, 498 (1939)

J. S. Kouvel & C. C. Hartelius, J. Appl. Phys. 33, 1343 (1962)

L. Zsodos, Phys. Stat. Sol. 20, K25 (1967)

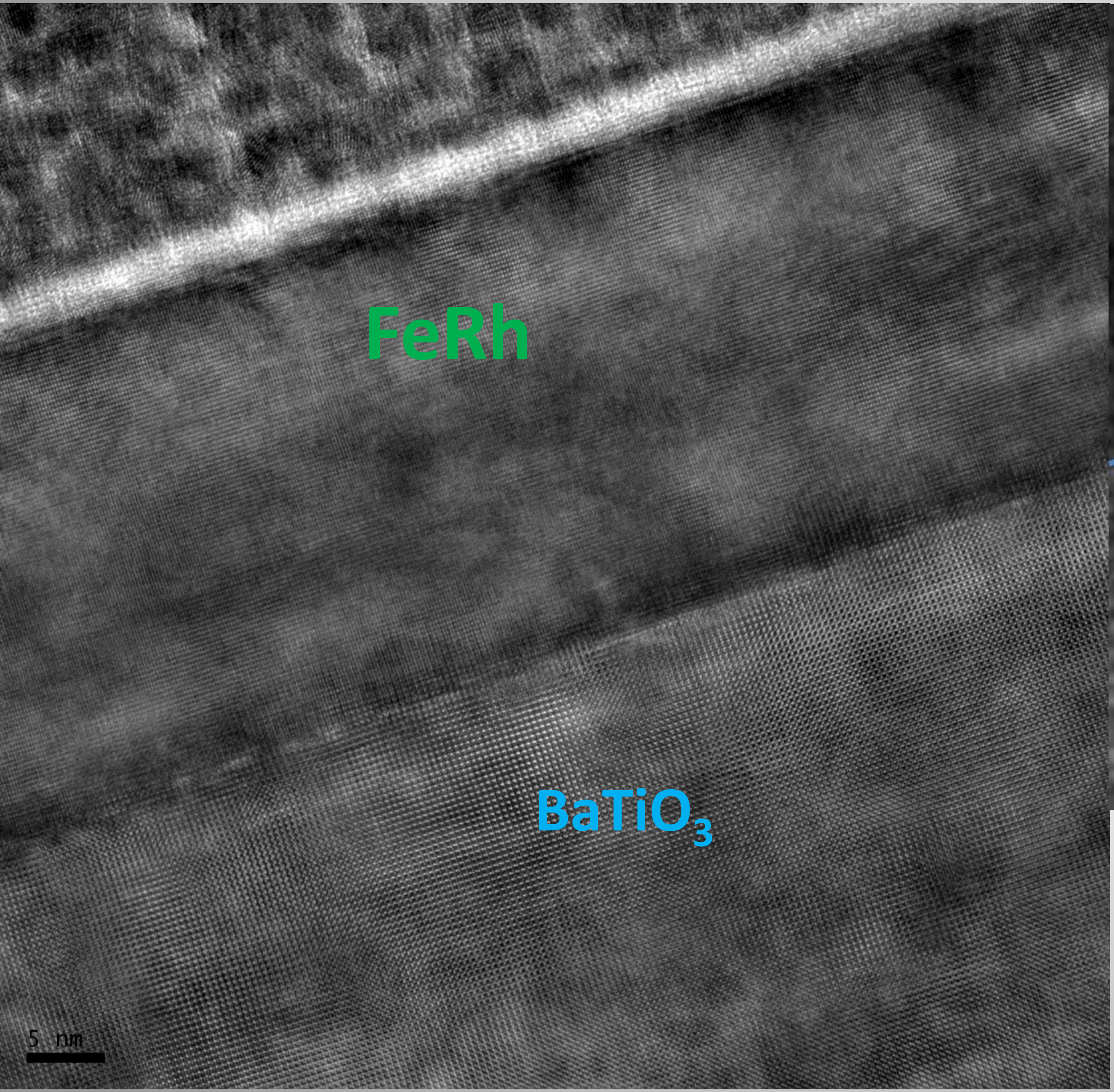
Structural Characterization

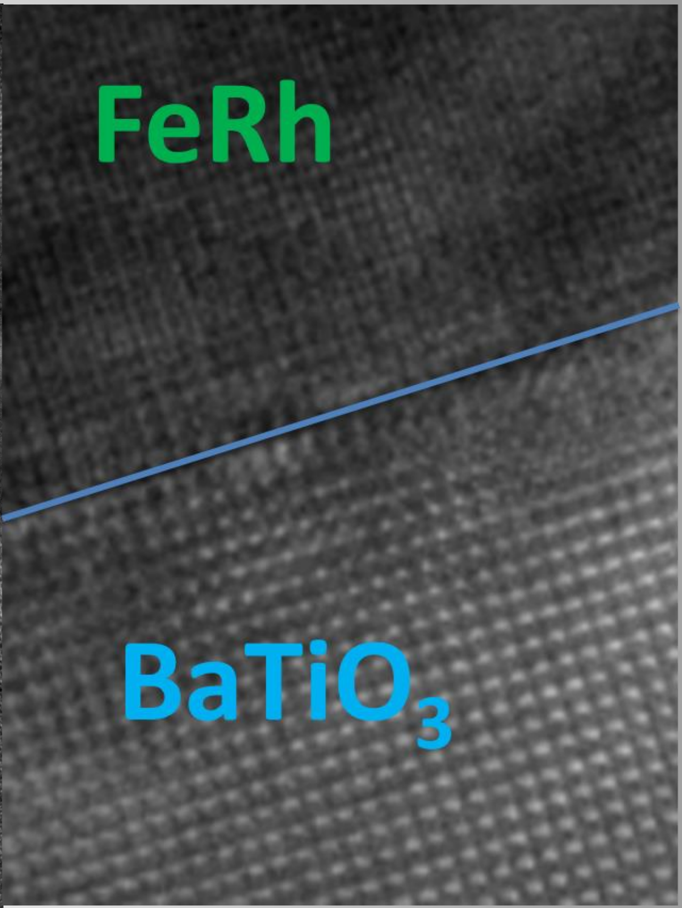




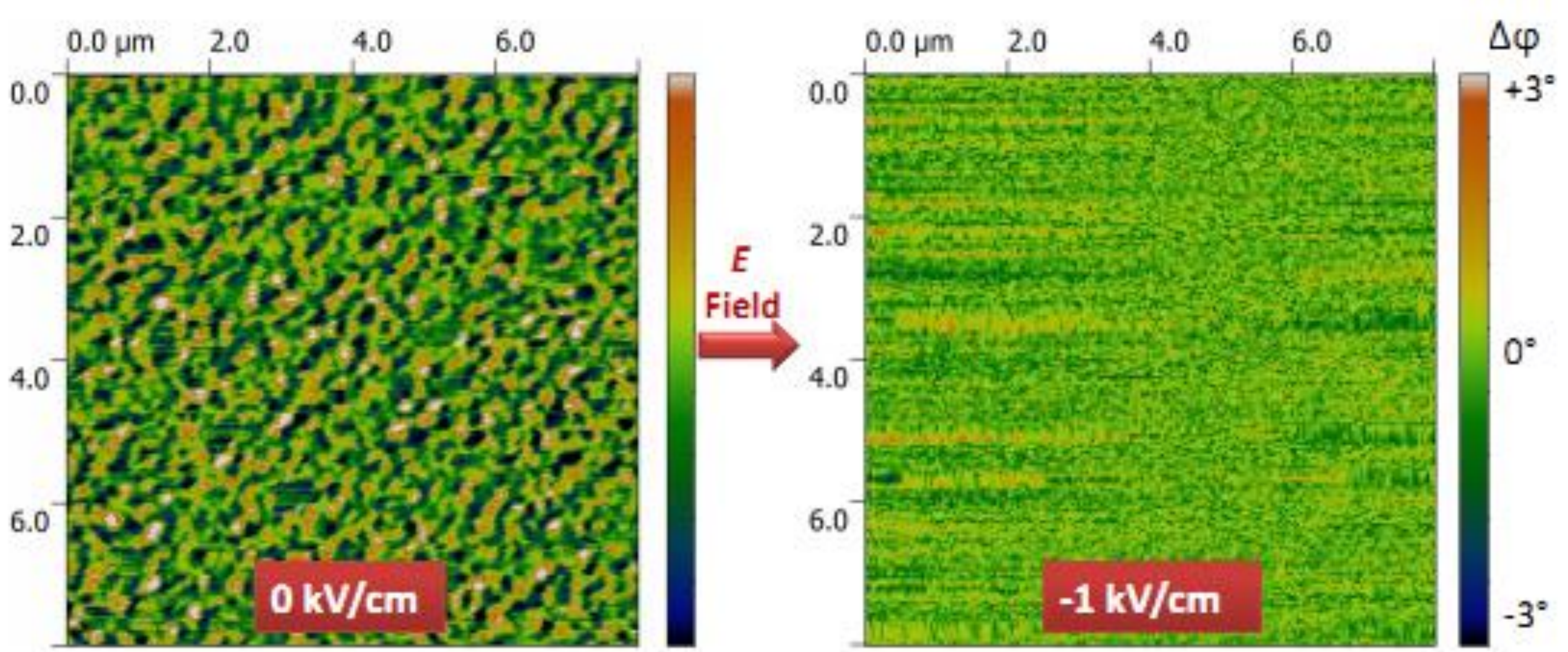
Epitaxy of FeRh on $BaTiO_3$

Cross-Section TEM



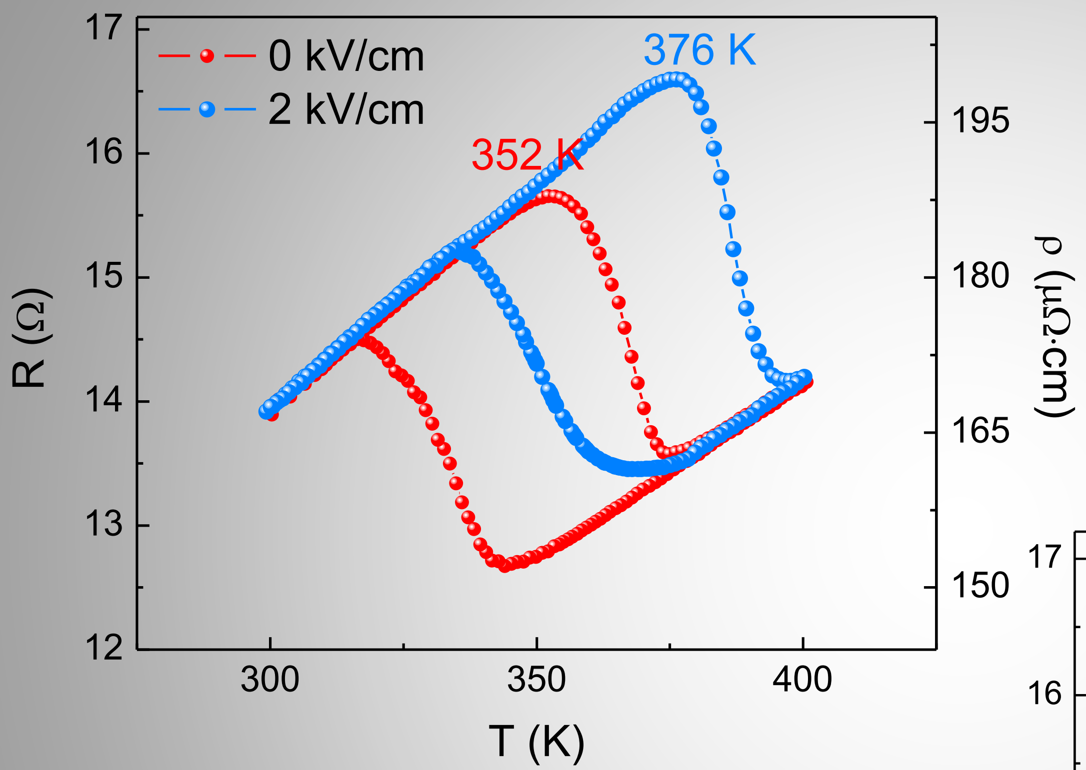


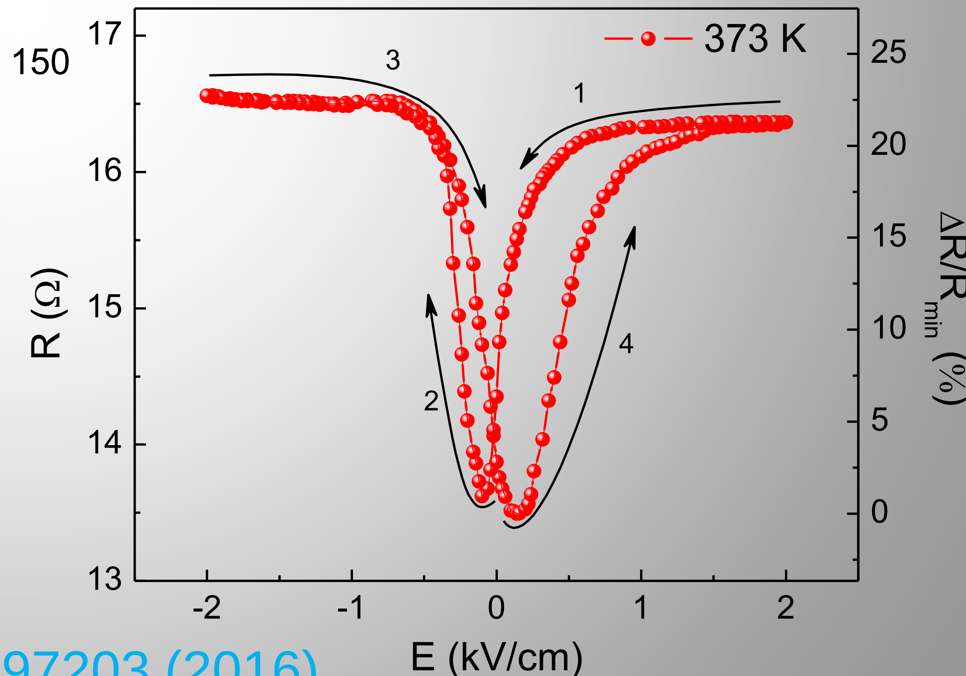
MFM Imaging of Magnetic Phase Transition



Liu *et al*., Phys. Rev. Lett. **116**, 097203 (2016)

Giant Electroresistance in a Metal





Liu *et al.*, Phys. Rev. Lett. **116**, 097203 (2016)

Polarization Switching Energy for 1 Bit

Saturation polarization

Switching voltage

Cell area

$$E_{Switching} = 1/2 P_s V S = 12.5\ \mu C/cm^2 \times 0.83\ kV/cm \times 100\ nm \times 100\ nm \times 100\ nm \approx 10^{-17}\ J/bit$$

5 orders of magnitude lower than STT-MRAM (10^{-12} J/bit)!

7 orders of magnitude lower than MRAM (100 pJ/bit)!

Antiferromagnetic Spintronics

Advantages of Antiferromagnets

- **1. Zero stray field**
  - **Insensitive to external magnetic fields**
  - **Higher packing density for memory devices**

- **2. Due to the canting of AFM spins, the intrinsic spin dynamics is very fast**
  - **Zero field AFM resonance frequency: THz**

Pioneering Theory

PHYSICAL REVIEW B **73**, 214426 (2006)

Theory of spin torques and giant magnetoresistance in antiferromagnetic metals

A. S. Núñez,* R. A. Duine,† Paul Haney,‡ and A. H. MacDonald§
Department of Physics, The University of Texas at Austin, 1 University Station C1600, Austin, Texas 78712-0264, USA

(Received 26 April 2006; published 14 June 2006)

Spintronics in ferromagnetic metals is built on a complementary set of phenomena in which magnetic configurations influence transport coefficients and transport currents alter magnetic configurations. Here, we propose that corresponding effects occur in circuits containing antiferromagnetic metals. The critical current for order parameter orientation switching can be smaller in the antiferromagnetic case because of the absence of shape anisot
discuss possibl

DOI: 10.1103/P

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Phil. Trans. R. Soc. A (2011) **369**, 3098–3114
doi:10.1098/rsta.2011.0014

REVIEW

Antiferromagnetic metal spintronics

BY A. H. MACDONALD[1,2,3] AND M. TSOI[1,2,3,*]

[1] *Department of Physics,* [2] *Center for Nano- and Molecular Science and Technology, and* [3] *Texas Materials Institute, The University of Texas at Austin, Austin, TX 78712, USA*

Pioneering Experiments

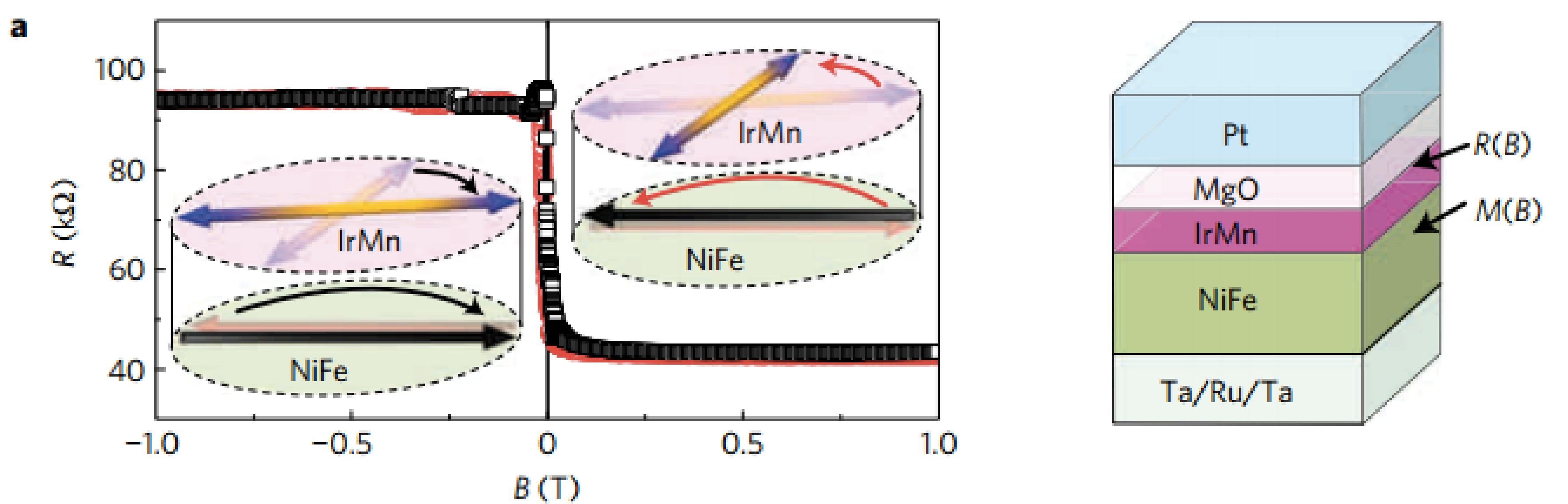
nature materials

LETTERS

PUBLISHED ONLINE: 13 MARCH 2011 | DOI: 10.1038/NMAT2983

A spin-valve-like magnetoresistance of an antiferromagnet-based tunnel junction

B. G. Park[1]*, J. Wunderlich[1,2], X. Martí[3], V. Holý[3], Y. Kurosaki[4], M. Yamada[4], H. Yamamoto[4], A. Nishide[4], J. Hayakawa[4], H. Takahashi[1,4], A. B. Shick[5] and T. Jungwirth[2,6]*



AFM Memory Assisted by Heating

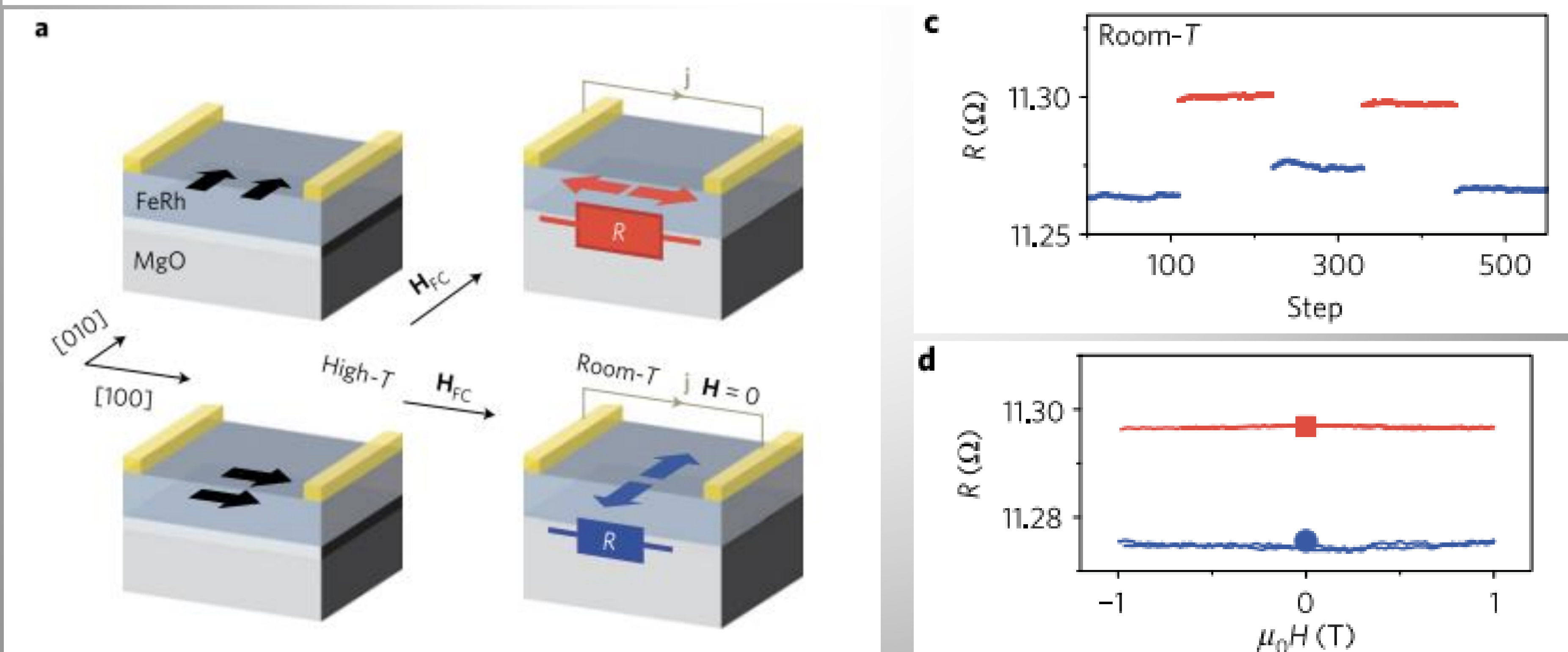
nature materials

ARTICLES

PUBLISHED ONLINE: 26 JANUARY 2014 | DOI: 10.1038/NMAT3861

Room-temperature antiferromagnetic memory resistor

X. Marti[1,2,3]*, I. Fina[4,5], C. Frontera[4], Jian Liu[6], P. Wadley[3,7], Q. He[8], R. J. Paull[1], J. D. Clarkson[1], J. Kudrnovský[9], I. Turek[2,10], J. Kuneš[3], D. Yi[6], J-H. Chu[6], C. T. Nelson[11], L. You[12], E. Arenholz[8], S. Salahuddin[12], J. Fontcuberta[4], T. Jungwirth[3,7] and R. Ramesh[1,6]

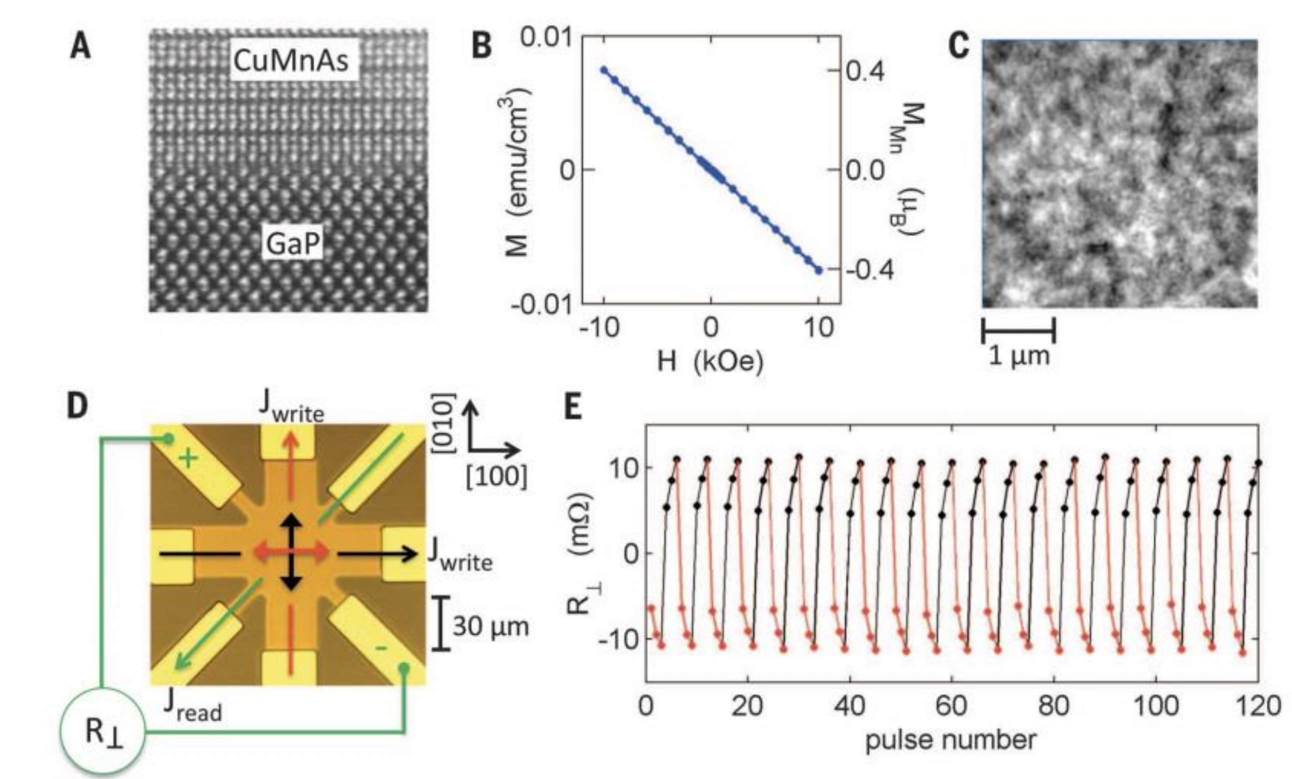


AFM Memory via Spin-Orbit Torque

SPINTRONICS

Electrical switching of an antiferromagnet

P. Wadley,[1*†] B. Howells,[1*] J. Železný,[2,3] C. Andrews,[1] V. Hills,[1] R. P. Campion,[1] V. Novák,[2] K. Olejník,[2] F. Maccherozzi,[4] S. S. Dhesi,[4] S. Y. Martin,[5] T. Wagner,[5,6] J. Wunderlich,[2,5] F. Freimuth,[7] Y. Mokrousov,[7] J. Kuneš,[8] J. S. Chauhan,[1] M. J. Grzybowski,[1,9] A. W. Rushforth,[1] K. W. Edmonds,[1] B. L. Gallagher,[1] T. Jungwirth[2,1]



Anomalous Hall Effect (AHE) in Antiferromagnets

Mechanisms of the AHE

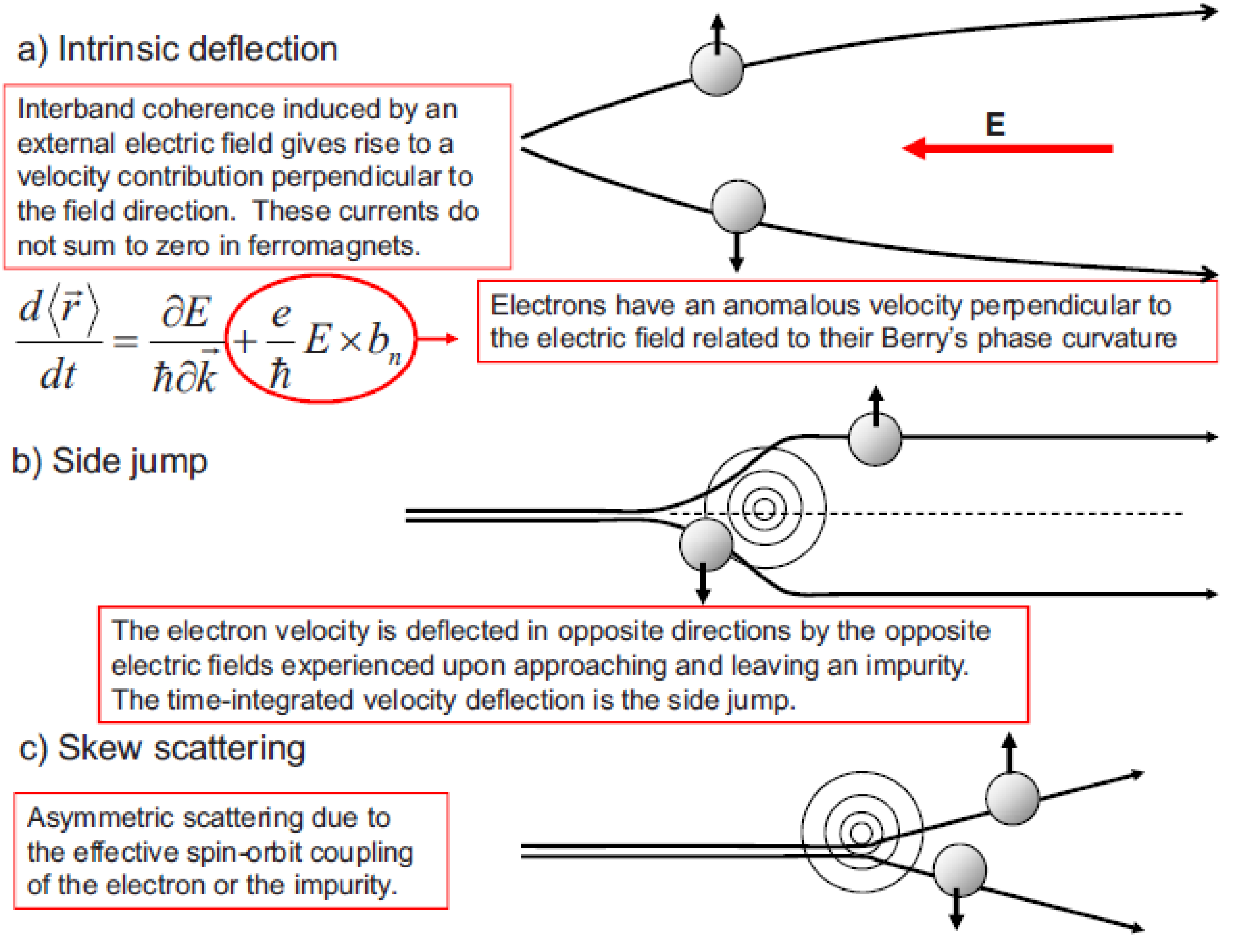


FIG. 3. (Color online) Illustration of the three main mechanisms that can give rise to an AHE. In any real material all of these mechanisms act to influence electron motion.

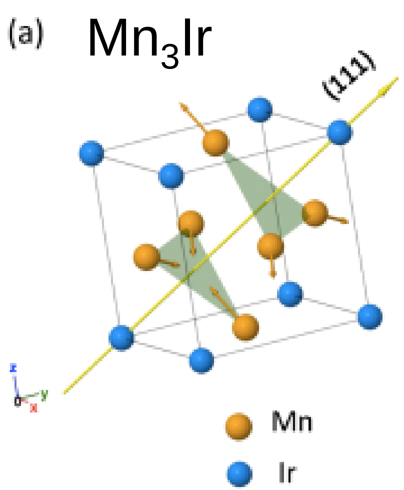
Breakthrough in the AHE

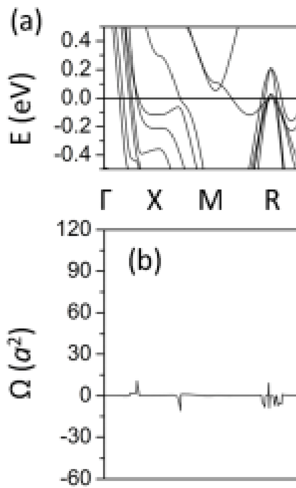
PRL **112**, 017205 (2014) PHYSICAL REVIEW LETTERS week ending 10 JANUARY 2014

Anomalous Hall Effect Arising from Noncollinear Antiferromagnetism

Hua Chen, Qian Niu, and A. H. MacDonald
Department of Physics, University of Texas at Austin, Austin, Texas 78712, USA
(Received 3 October 2013; published 10 January 2014)

As established in the very early work of Edwin Hall, ferromagnetic conductors have an anomalous Hall conductivity contribution that cannot be attributed to Lorentz forces and therefore survives in the absence of a magnetic field. These anomalous Hall conductivities are normally assumed to be proportional to magnetization. We use symmetry arguments and first-principles electronic structure calculations to counter this assumption and to predict that Mn_3Ir, a high-temperature antiferromagnet that is commonly employed in spin-valve devices, has a large anomalous Hall conductivity.





epl A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS December 2014
EPL, **108** (2014) 67001 www.epljournal.org
doi: 10.1209/0295-5075/108/67001

Non-collinear antiferromagnets and the anomalous Hall effect

J. Kübler[1] and C. Felser[2]

[1] *Institut für Festkörperphysik, Technische Universität Darmstadt - D-64289 Darmstadt, Germany*
[2] *Max Planck Institute for Chemical Physics of Solids - D-01187 Dresden, Germany*

received 10 November 2014; accepted 2 December 2014
published online 10 December 2014

PACS 73.43.Cd – Theory and modeling
PACS 75.50.Ee – Antiferromagnetics
PACS 75.70.Tj – Spin-orbit effects

Abstract – The anomalous Hall effect is investigated theoretically by employing density functional calculations for the non-collinear antiferromagnetic order of the hexagonal compounds Mn_3Ge and Mn_3Sn using various planar triangular magnetic configurations as well as unexpected non-planar configurations. The former give rise to anomalous Hall conductivities (AHC) that are found to be

Breakthrough in the AHE

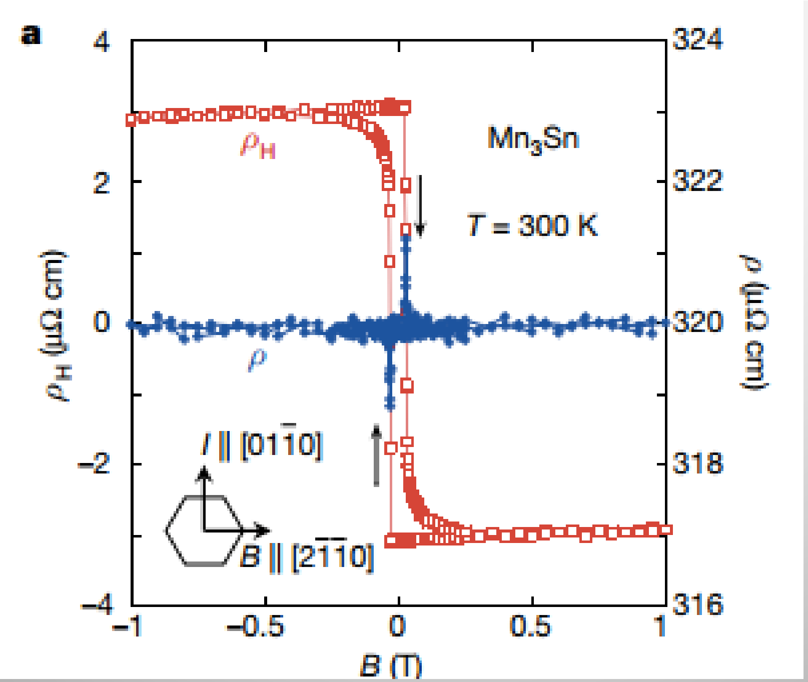
LETTER

doi:10.1038/nature15723

Large anomalous Hall effect in a non-collinear antiferromagnet at room temperature

Satoru Nakatsuji[1,2], Naoki Kiyohara[1] & Tomoya Higo[1]

Mn_3Sn



AHE in Non-Ferromagnetic Systems

- **Non-collinear antiferromagnets (Mn_3Ir, Mn_3Sn, Mn_3Ge, etc)**
  - **Spin-structure-induced non-vanishing Berry Curvature**

  Chen *et al*., Phys. Rev. Lett. **112**, 017205 (2014); Nakatsuji *et al*., Nature **527**, 212 (2015)

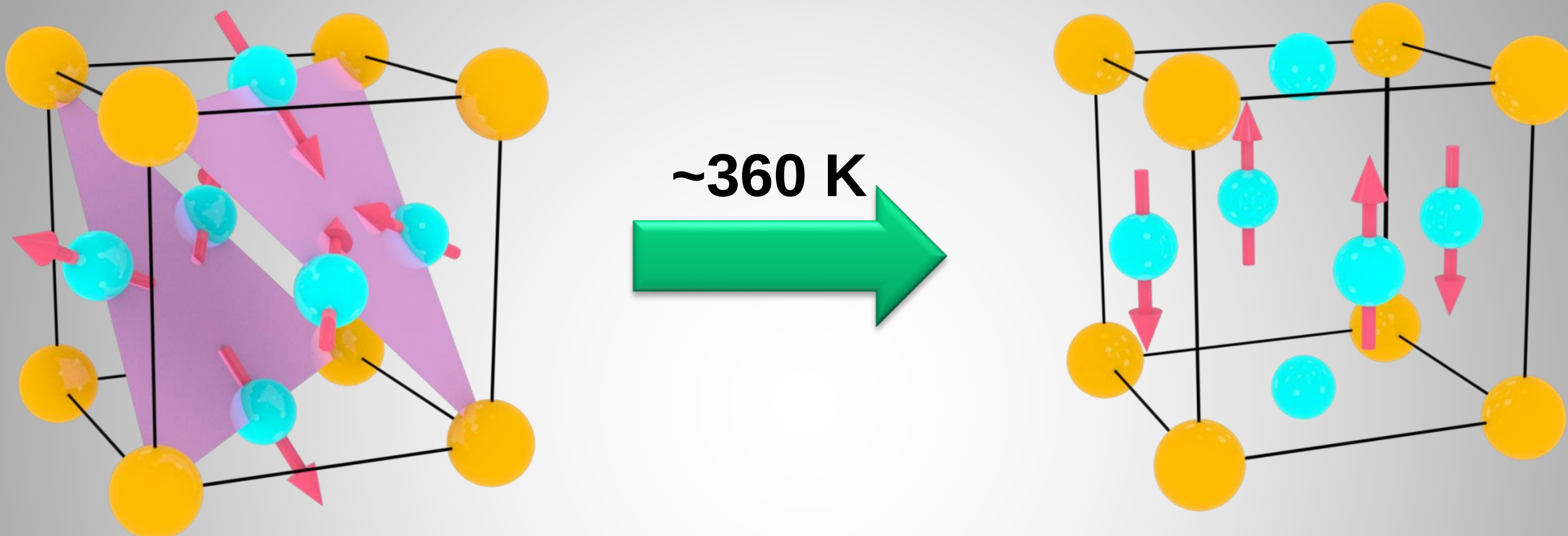
- **Non-magnetic two-dimensional materials (WTe_2, $MoTe_2$, etc)**
  - **Berry-curvature dipole induced by inversion symmetry breaking**
  - **Second-order nonlinear AHE**

  Sodemann & Fu, Phys. Rev. Lett. **115**, 216806 (2015); Zhang *et al*., 2D Mater. **5**, 044001 (2018); Kang *et al*., Nat. Mater. **18**, 324 (2019); Ma *et al*., Nature **565**, 337 (2019)

- **Non-magnetic two-dimensional electron gas (MgZnO/ZnO heterostructure, etc)**
  - **Skew scattering of electrons from paramagnetic centers**

  Maryyenko *et al*., Nat. Commun. **8**, 14777 (2017)

First-Order AFM Magnetic Transition

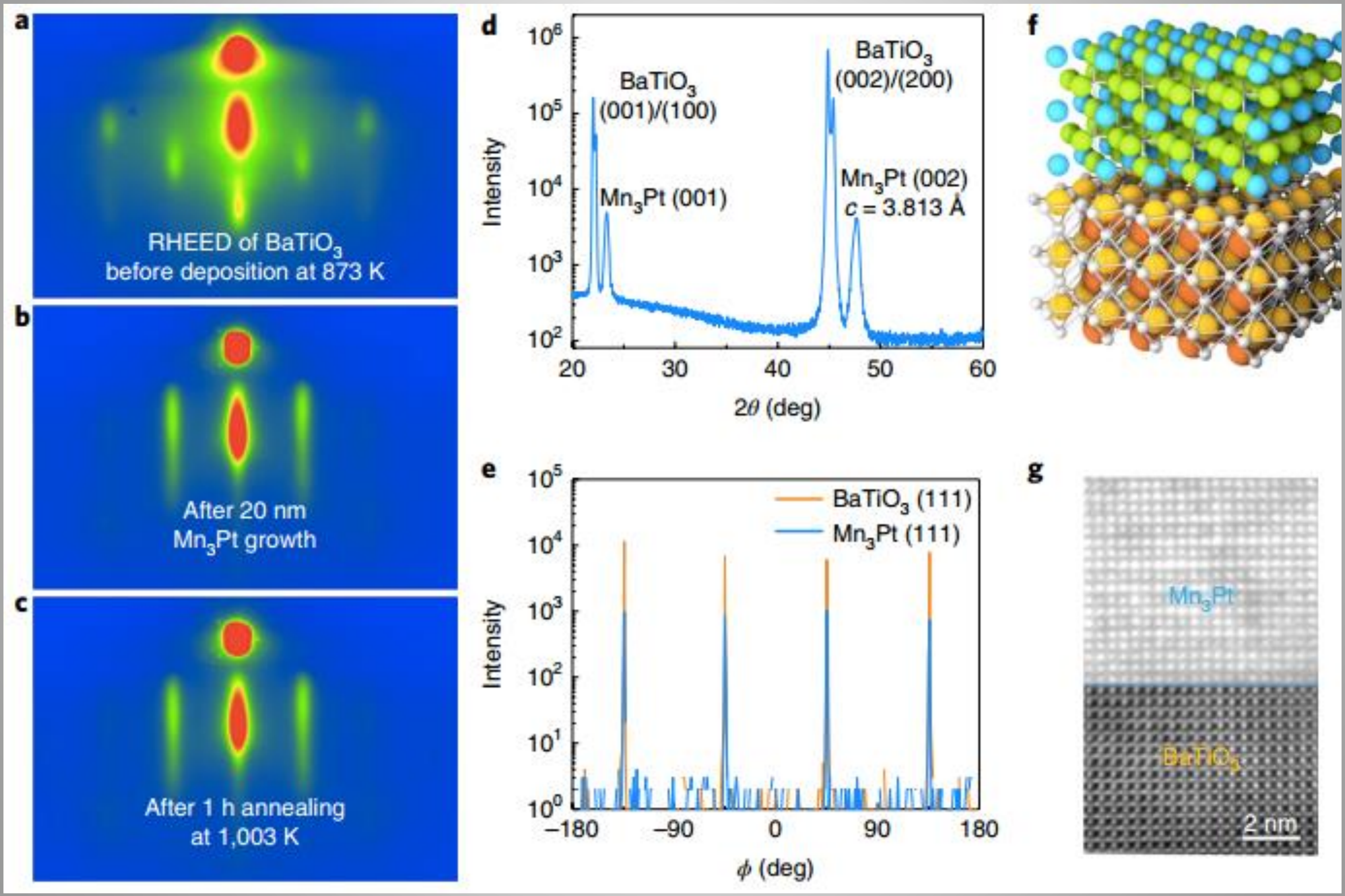


PHYSICAL REVIEW VOLUME 171, NUMBER 2 10 JULY 1968

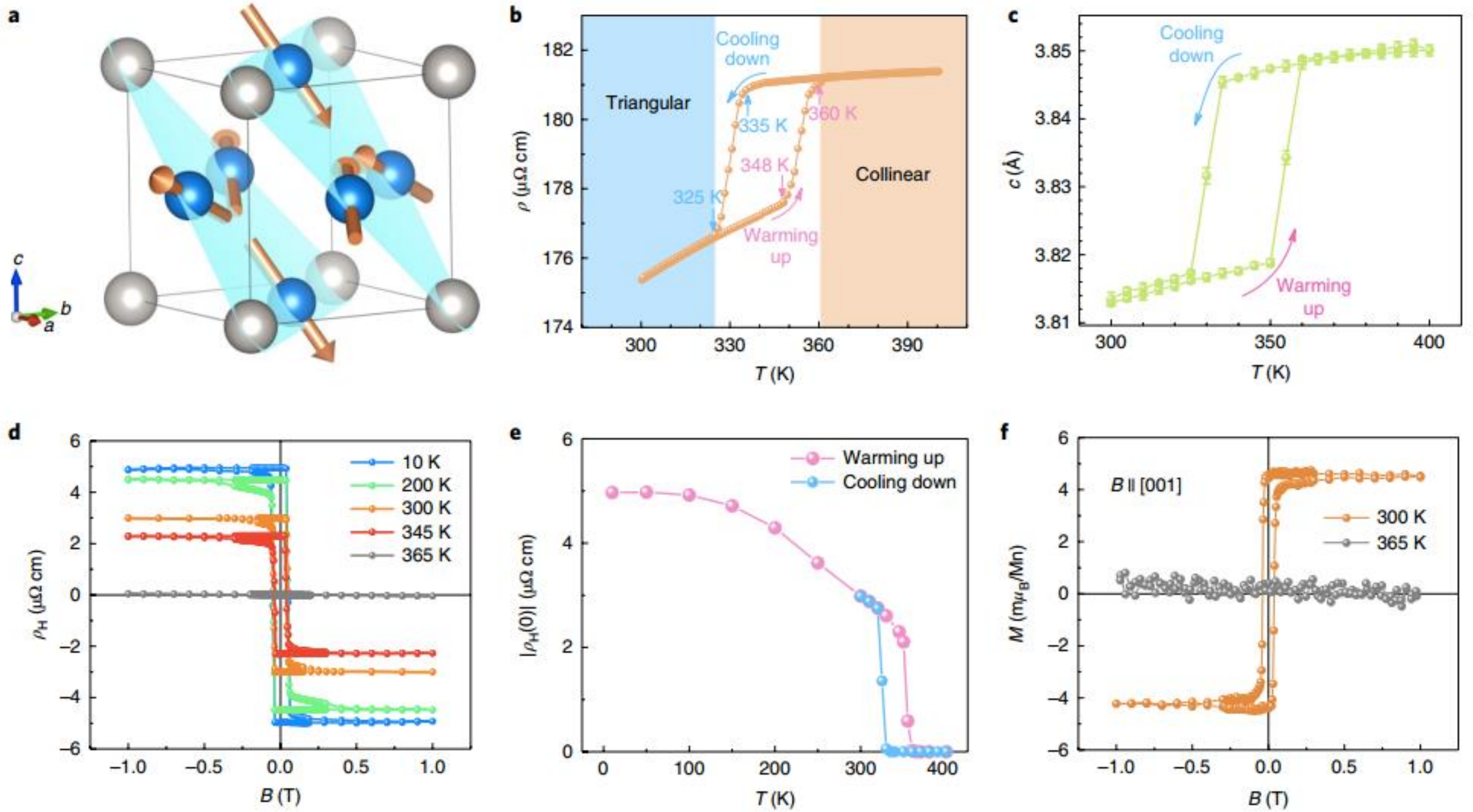
Magnetic Structures and Exchange Interactions in the Mn–Pt System

E. Krén, G. Kádár, L. Pál, J. Sólyom, P. Szabó, and T. Tarnóczi

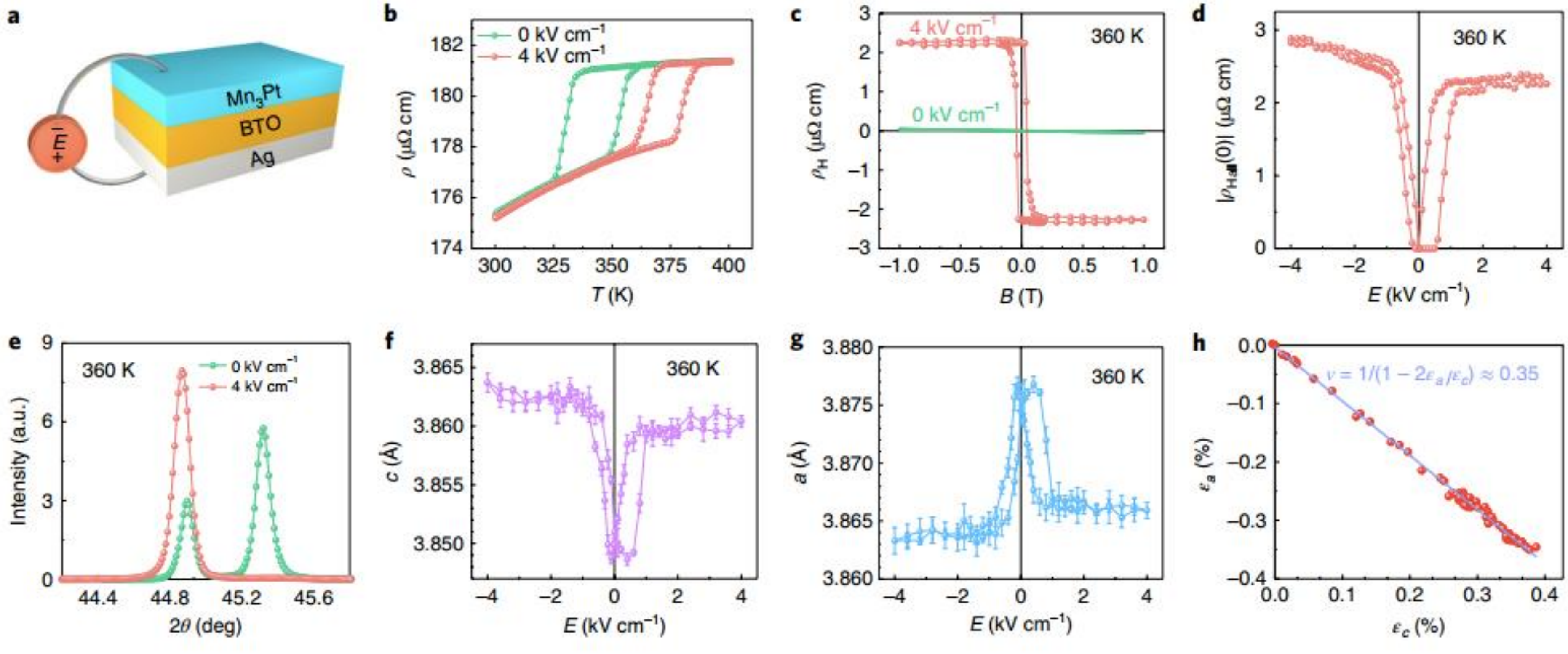
Growth - Mn_3Pt



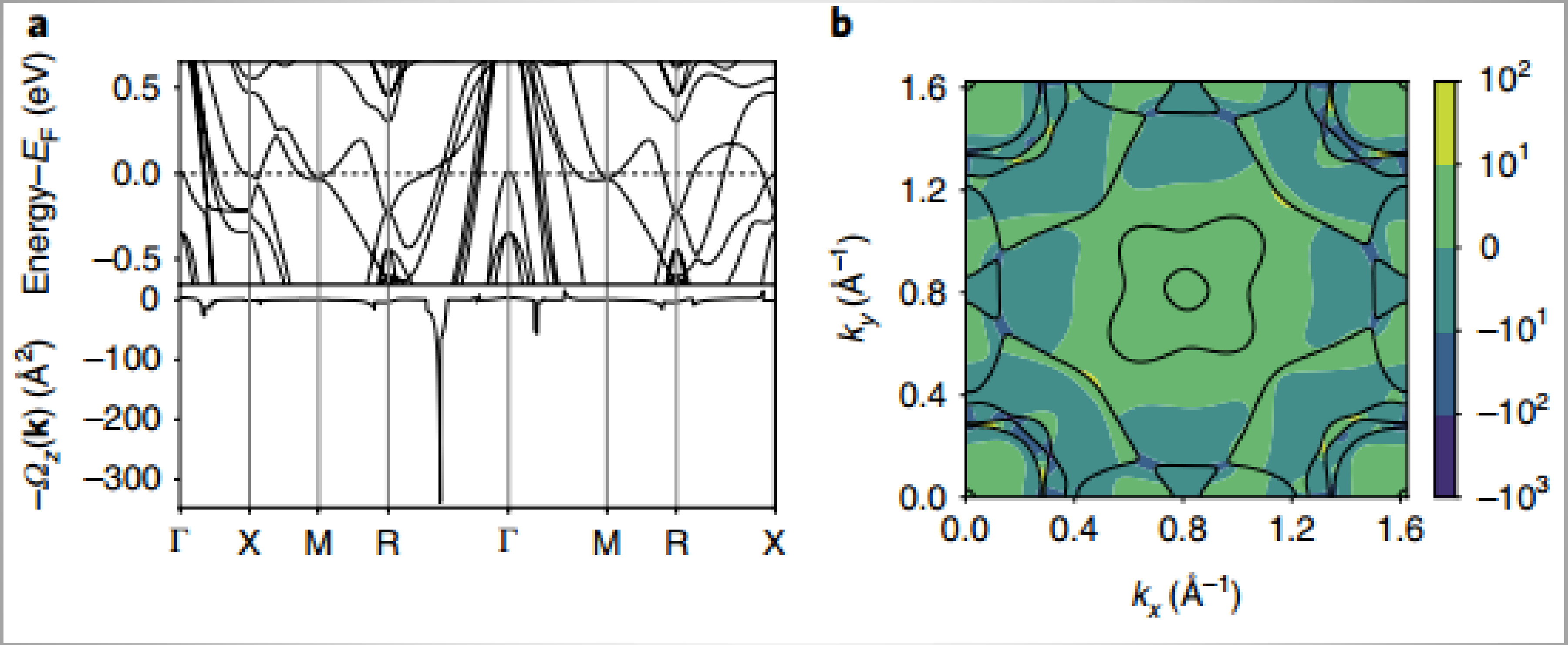
Characterization



Electrical Switching



Theory – Anomalous Hall Conductivity of Strained Mn_3Pt



Calculated: $\sigma_H = 81\,\Omega^{-1}\,\mathrm{cm}^{-1}$

$|\sigma_H| = |\rho_H|/\rho^2$

experimental value of $74.2\,\Omega^{-1}\,\mathrm{cm}^{-1}$

Liu *et al*., Nat. Electron. **1**, 172 (2018)

Towards Low Energy-Consuming AFM Spintronic Devices

KIT, Germany

news & views

ANTIFERROMAGNETIC SPINTRONICS

Electrical switching of the anomalous Hall effect

The anomalous Hall effect in an antiferromagnet can be switched on and off using an electric field to alter the strain in the material.

Christoph Sürgers

tuning of the crystalline lattice. Writing in *Nature Electronics*, Zhiqi Liu and colleagues show that the AHE in antiferromagnetic Mn_3Pt thin films can be switched on and off at above room temperature by varying the strain in the film[5]. This is achieved by applying a voltage to a piezoelectric substrate beneath the Mn_3Pt layer.

The researchers — who are based at Beihang University, Colorado State University, the University of Texas at Austin, Oak Ridge National Laboratory, Nanyang Technological University, and Trinity College Dublin — epitaxially grew Mn_3Pt

The manipulation of magnetism using an electric field is of particular interest in the development of spintronic devices as it is expected to yield devices that require a lower switching power than those based on current-induced magnetization switching[6]. The work of Liu and colleagues demonstrates electric-field control of the AHE in a non-collinear antiferromagnet and is thus an important step in the development of antiferromagnetic spintronics.

NATURE ELECTRONICS | VOL 1 | MARCH 2018 | 154–155 | www.nature.com/natureelectronics nature physics

Research Highlight | Published: 06 April 2018

SPINTRONICS

Turn it off and on again

David Abergel

Nature Physics **14**, 328 (2018) | Download Citation

Nat. Electon. **1**, 172–177 (2018)

Ferromagnetic materials exhibit an anomalous Hall effect, a current-driven transverse voltage that arises without the need for an external magnetic field. In principle, the effect could be used for data processing and storage, if it weren't for the fact that ferromagnetism is so robust — the 'off' switch being somewhat difficult to locate. But now, Zhiqi Liu and co-workers have demonstrated that the non-collinear antiferromagnet Mn_3Pt also exhibits an anomalous Hall effect, and the magnetic order is fragile enough that it can be destroyed by applying a small strain.

The authors made a device by stacking a thin film of Mn_3Pt on top of a piezoelectric layer. Applying an electric field made the piezo layer expand, which in turn generated strain in the Mn_3Pt and caused the magnetic phase transition. The electric field could thus be used as an external control to turn the anomalous Hall effect on and off, providing an all-electronic method of writing and reading a bit.

Highlighted by Nature Physics

Highlighted by Science

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SHARE

MAGNETISM

Manipulating an antiferromagnet

Jelena Stajic
+ See all authors and affiliations

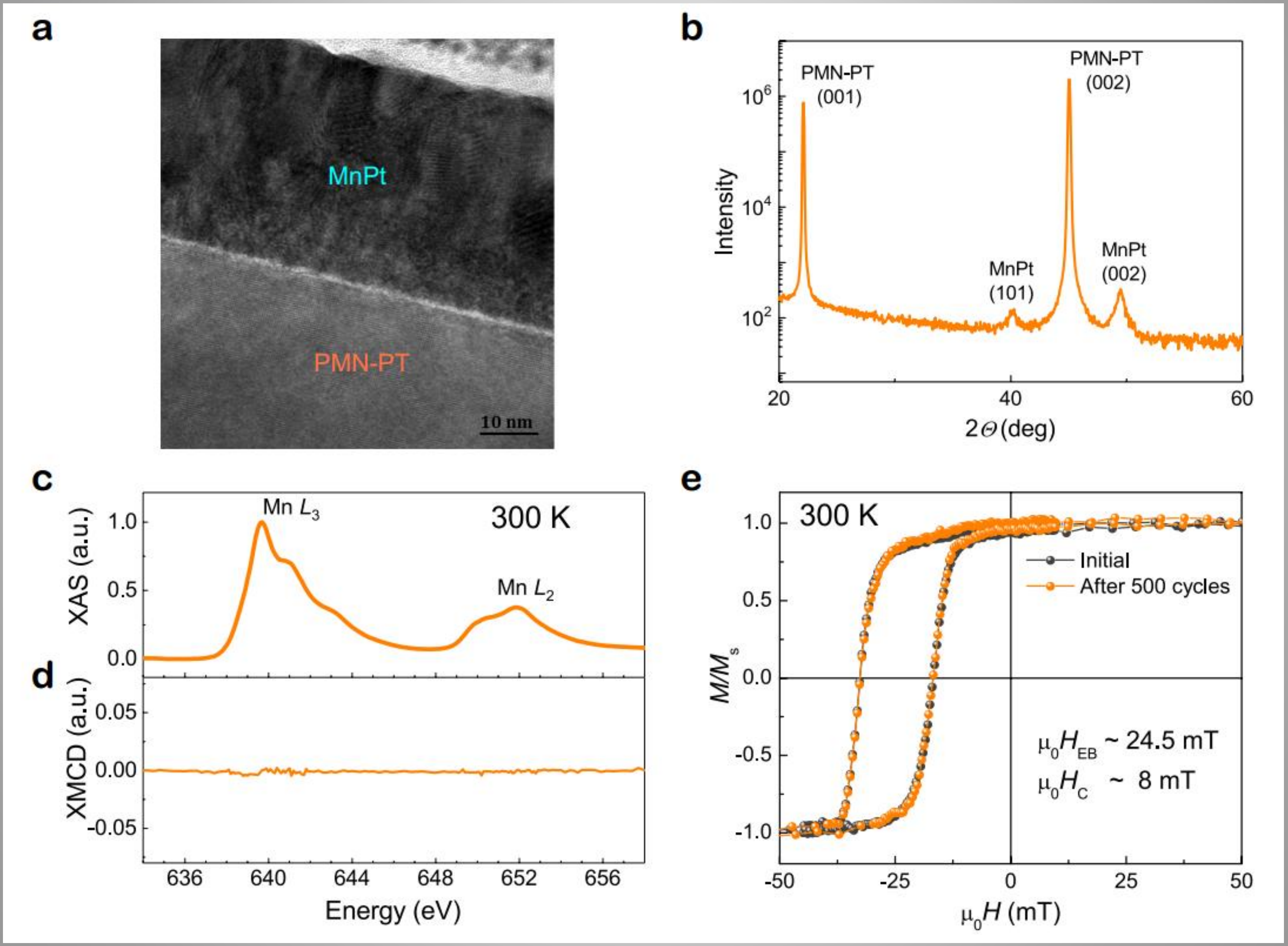
Science 20 Apr 2018:
Vol. 360, Issue 6386, pp. 281-282
DOI: 10.1126/science.360.6386.281-e

Article Info & Metrics eLetters PDF

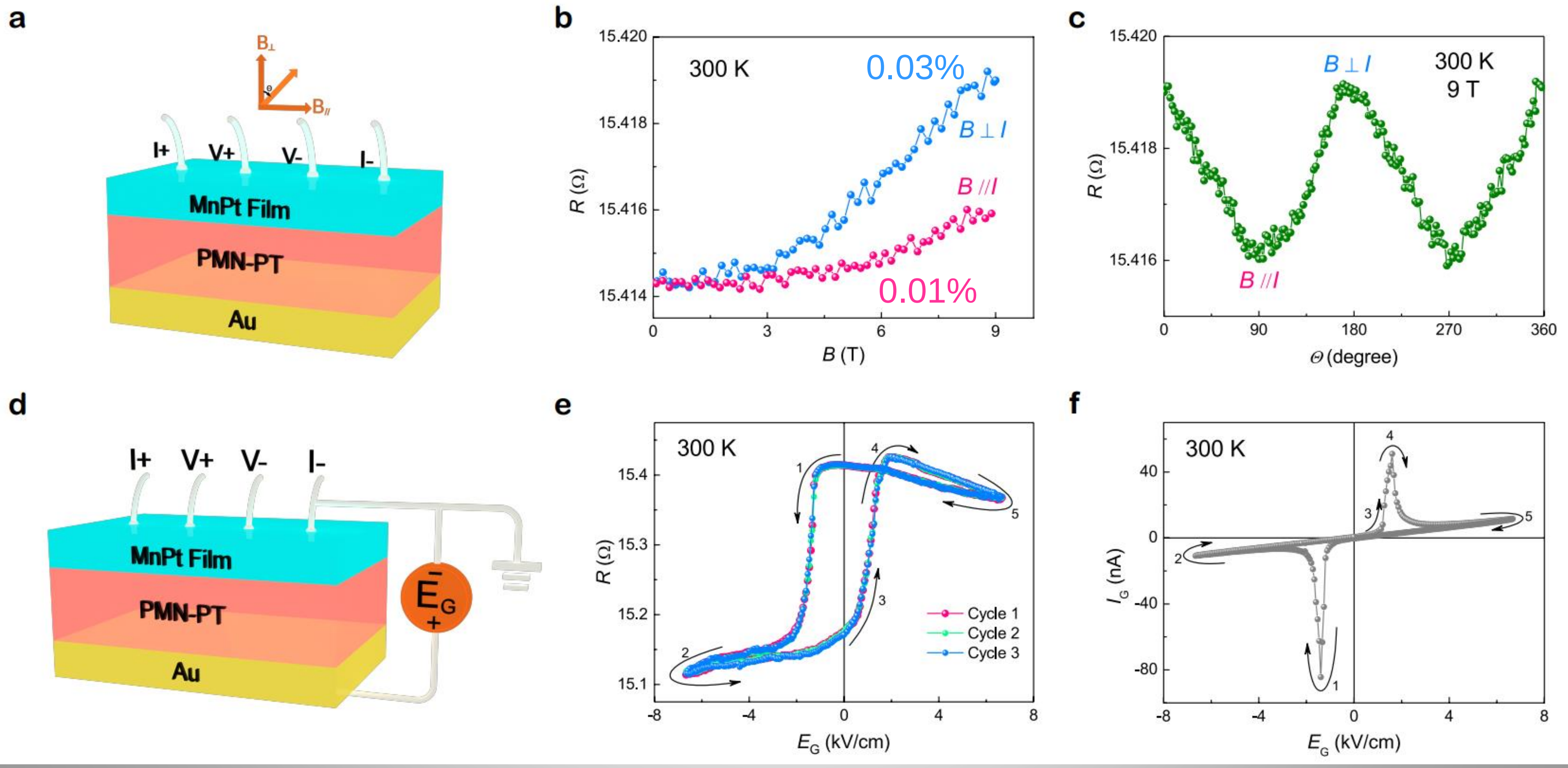
Magnetic materials are routinely used in electronic devices, and the ability to change their magnetic state using electric fields is highly desirable. Most devices use ferromagnets—materials in which individual atomic spins all point in one direction—but there are important advantages to developing analogous devices with antiferromagnetic (AFM) materials. Liu *et al.* made thin films of the AFM $MnPt_3$, a material that transitions from a noncollinear to a collinear AFM state a bit above room temperature. The thin films were grown on a ferroelectric substrate; applying an electric field to the substrate near the transition temperature changed the strain in the $MnPt_3$ film, which in turn caused the film to change its spin structure from collinear to noncollinear.

Nat. Electron. **1**, 172 (2018).

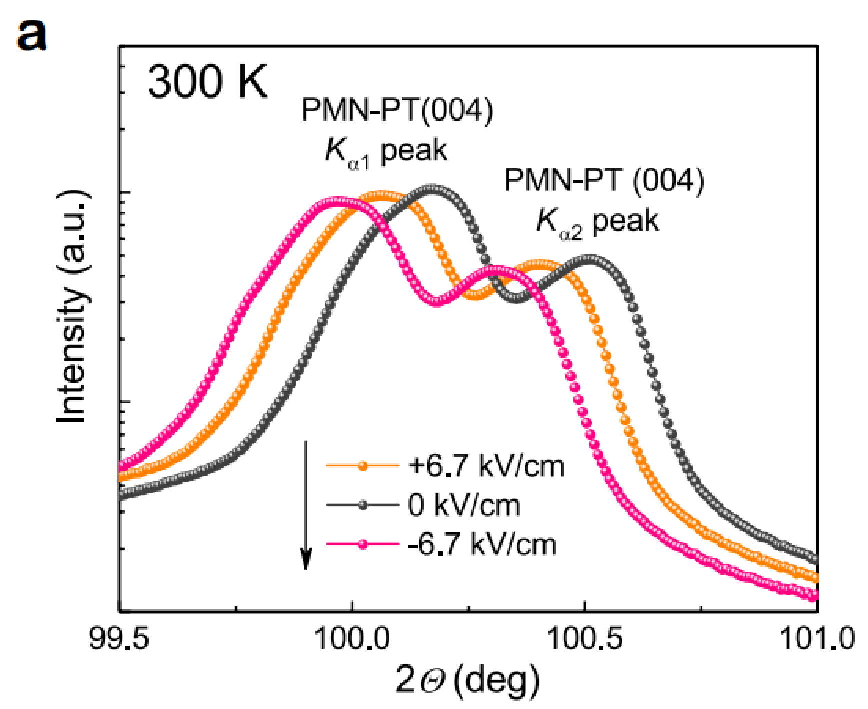
AFM MnPt (T_N ~ 975 K)



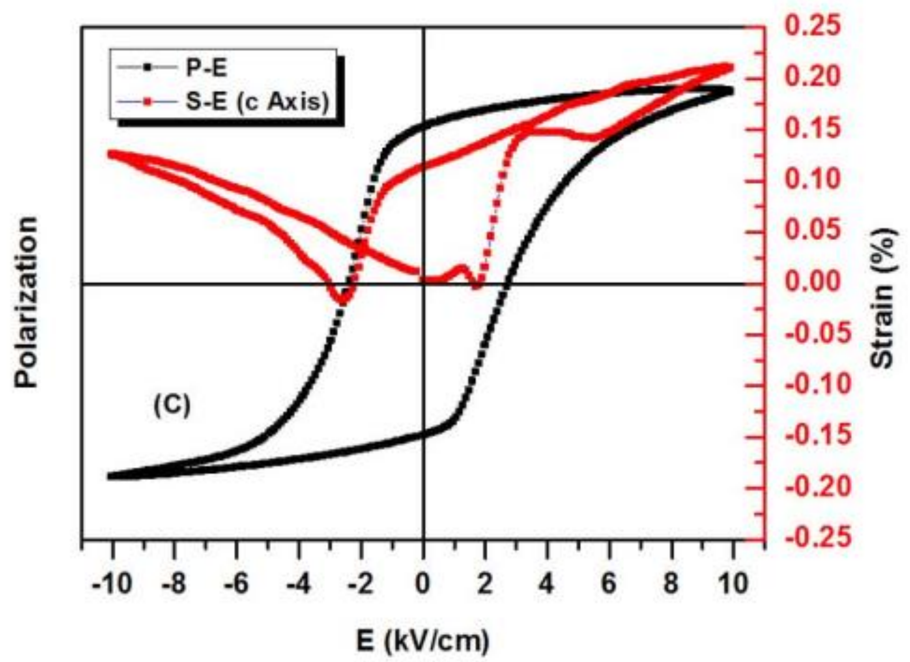
Responses to *B* & *E*



Asymmetric Strain



Strain



SCIENTIFIC REPORTS | 5 : 8905 | DOI: 10.1038/srep08905

Asymmetric Strain in (001)-Oriented PMN-PT

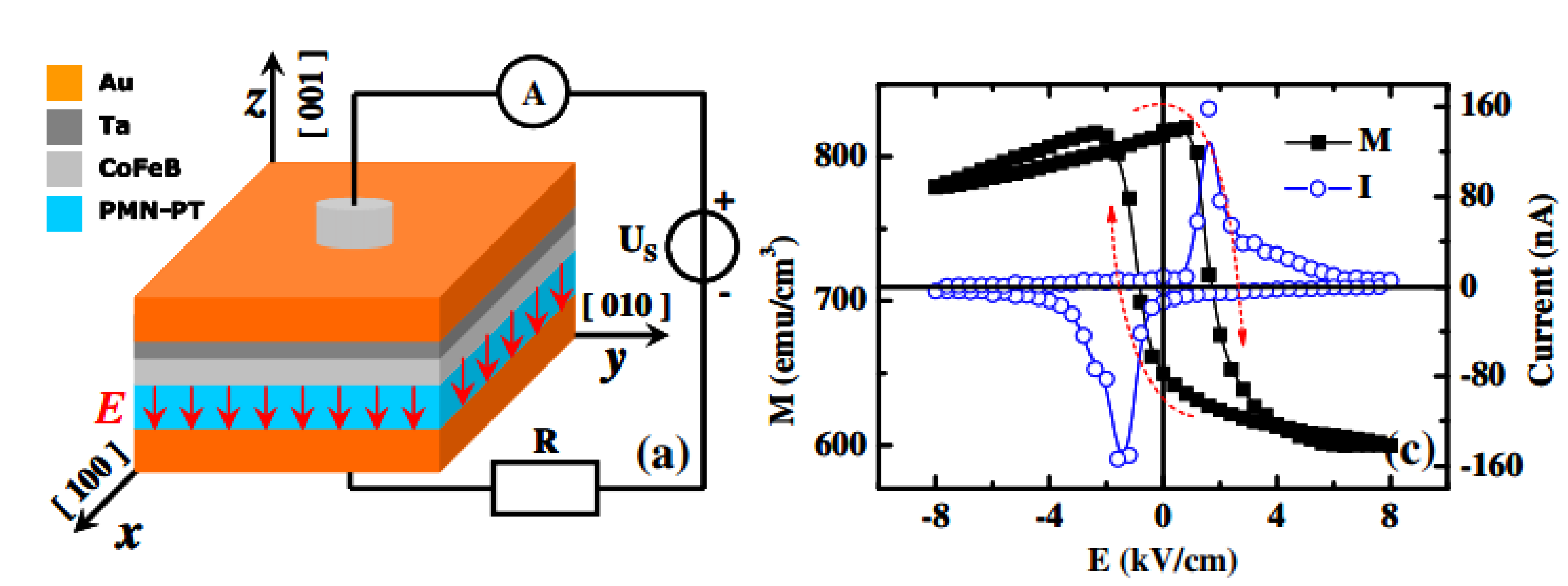
PRL **108,** 137203 (2012) PHYSICAL REVIEW LETTERS week ending 30 MARCH 2012

Electric-Field Control of Nonvolatile Magnetization in $Co_{40}Fe_{40}B_{20}/Pb(Mg_{1/3}Nb_{2/3})_{0.7}Ti_{0.3}O_3$ Structure at Room Temperature

S. Zhang,[1] Y. G. Zhao,[1,*] P. S. Li,[1] J. J. Yang,[1] S. Rizwan,[2] J. X. Zhang,[3,8] J. Seidel,[3] T. L. Qu,[1,3] Y. J. Yang,[4] Z. L. Luo,[4] Q. He,[3] T. Zou,[2] Q. P. Chen,[1] J. W. Wang,[1] L. F. Yang,[1] Y. Sun,[2] Y. Z. Wu,[6] X. Xiao,[6] X. F. Jin,[6] J. Huang,[7] C. Gao,[4,5] X. F. Han,[2] and R. Ramesh[3]

[1]*Department of Physics and State Key Laboratory of Low-Dimensional Quantum Physics, Tsinghua University, Beijing 100084, China*
[2]*Beijing National Laboratory for Condensed Matter Physics, Chinese Academy of Sciences, Beijing 100190, China*
[3]*Department of Materials Science and Engineering, University of California, Berkeley, California 94720, USA*
[4]*National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei, Anhui 230026, China*
[5]*Department of Materials Science and Engineering, University of Science and Technology of China, Hefei, Anhui 230026, China*

Strain



Electrostatic Doping?

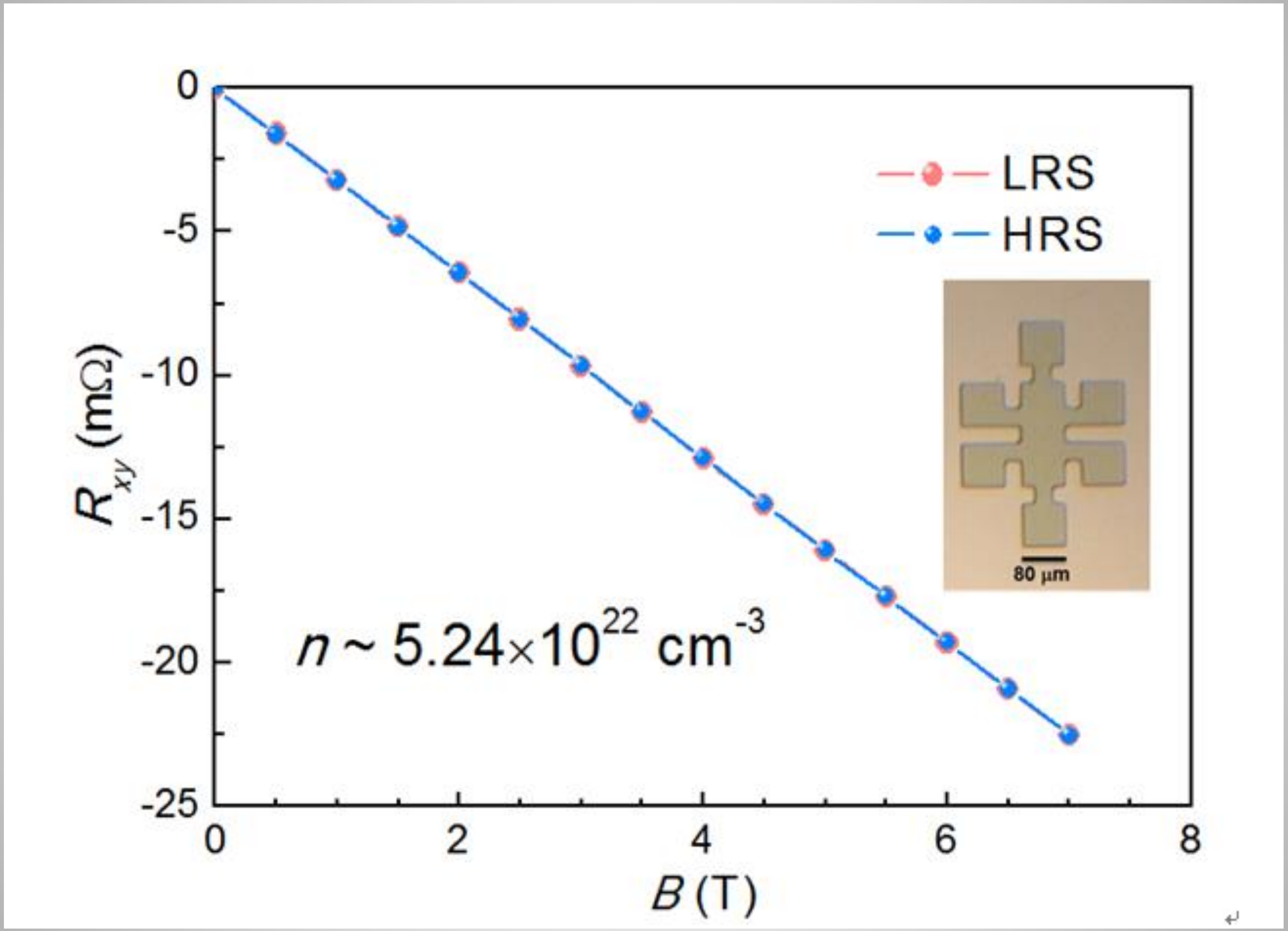
The Thomas-Fermi screening length in the semiclassical model can be expressed as $\lambda_{TF} = (2\varepsilon_0\varepsilon_r E_F/3ne^2)^{1/2}$,

$$E_F = (\hbar^2/2m_e)(3\pi^2 n)^{2/3}$$

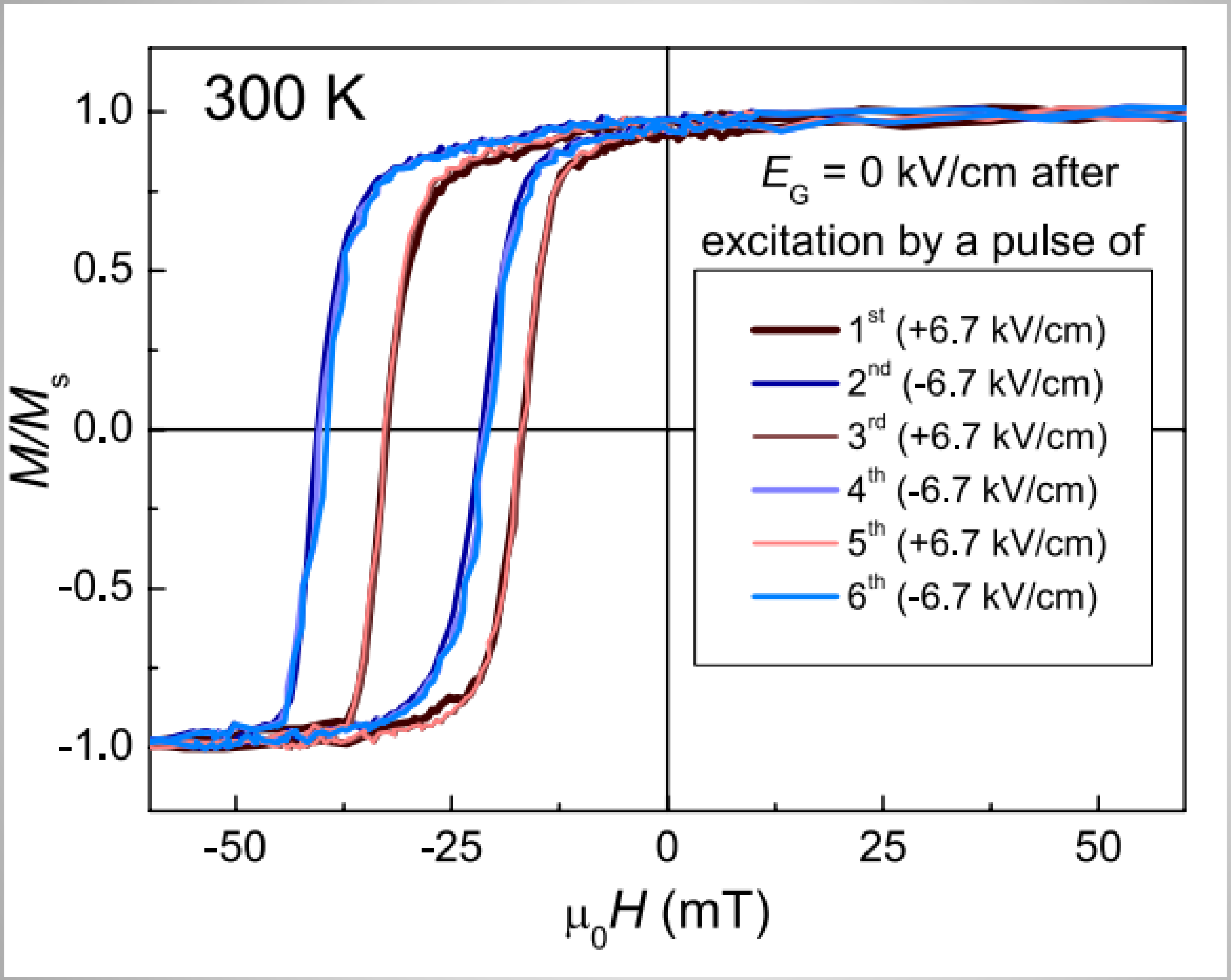
$$\lambda_{TF} \sim n^{-1/6} \sim 2\ \text{Å}$$

Liu *et al.*, Phys. Rev. Lett. **116**, 097203 (2016)

Carrier Density



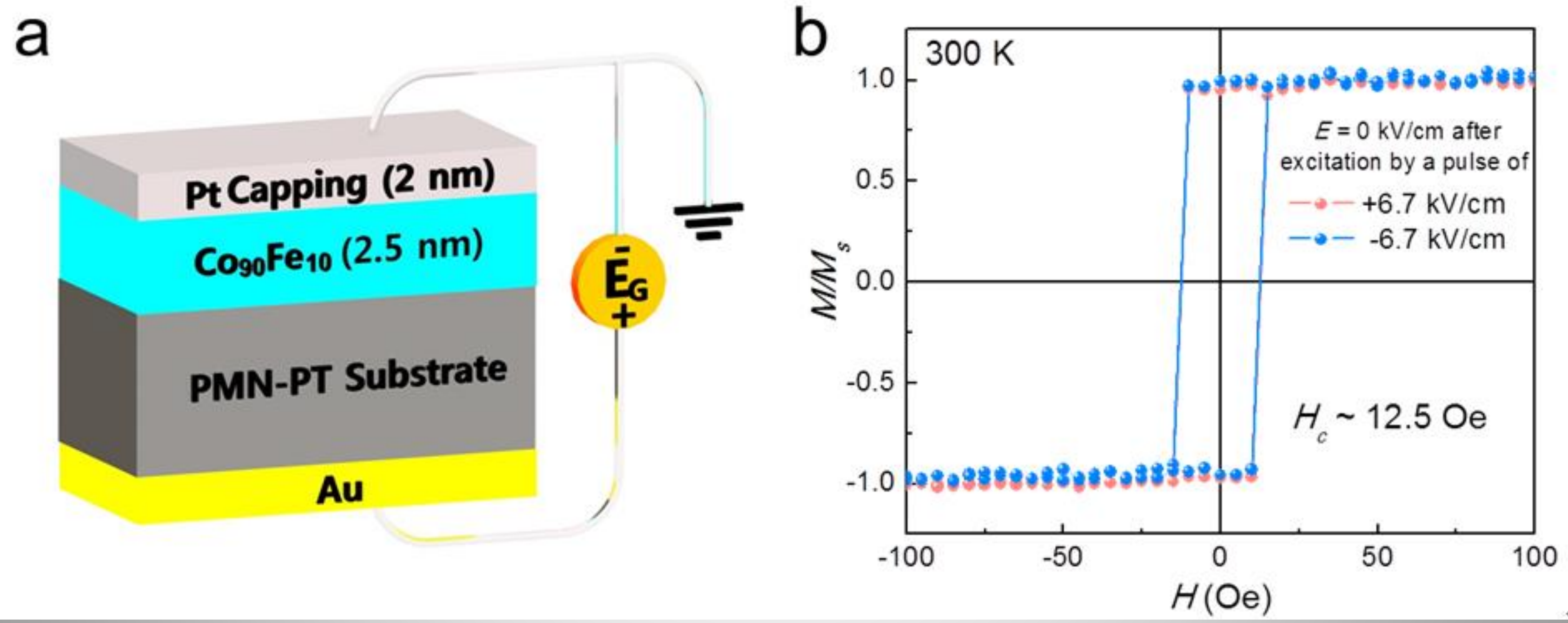
Exchange Bias Modulation



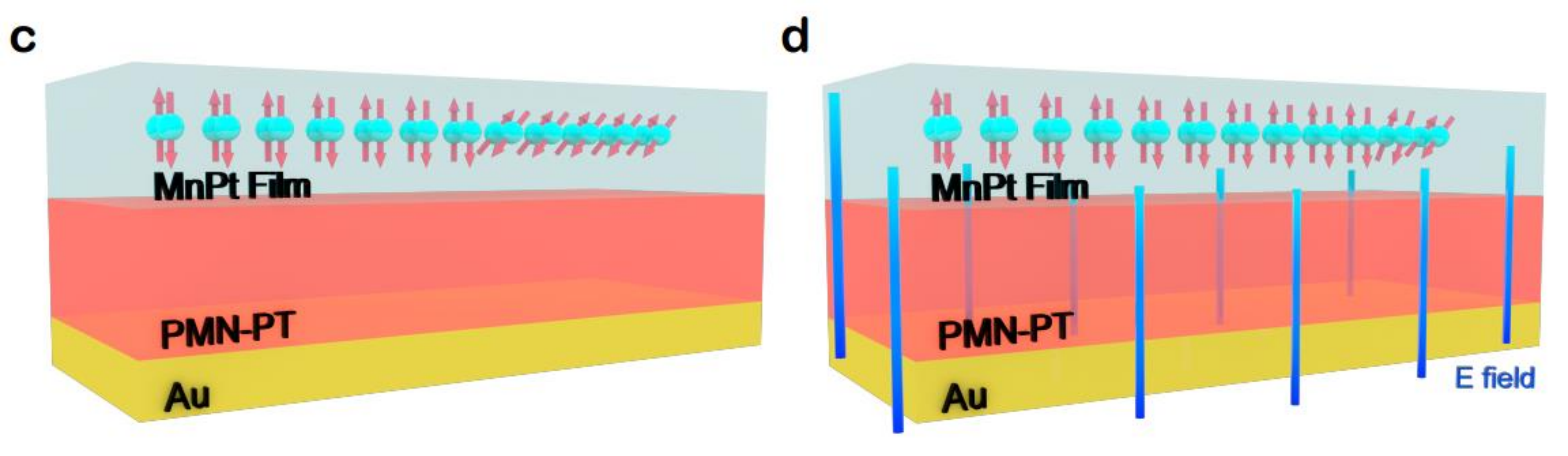
Delta H_{EB} ~ 60 Oe

Delta H_c ~ 14 Oe

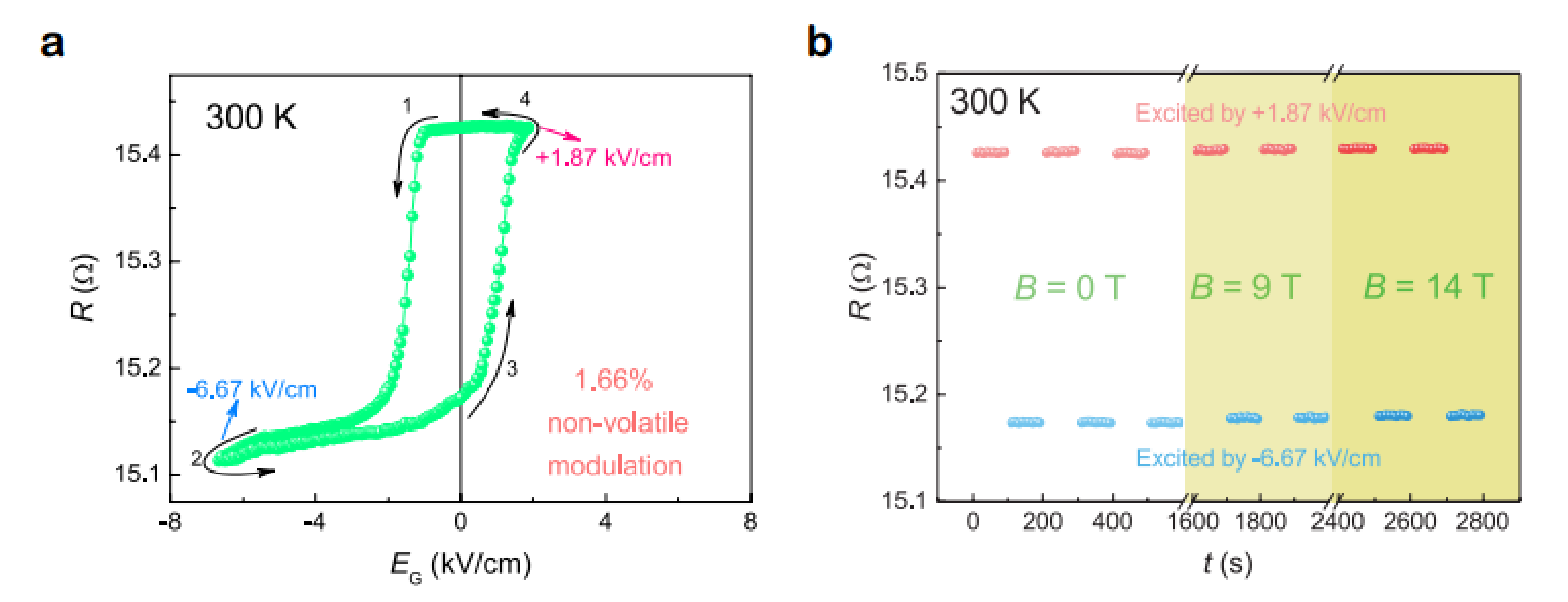
FM Layer Insensitive to Strain



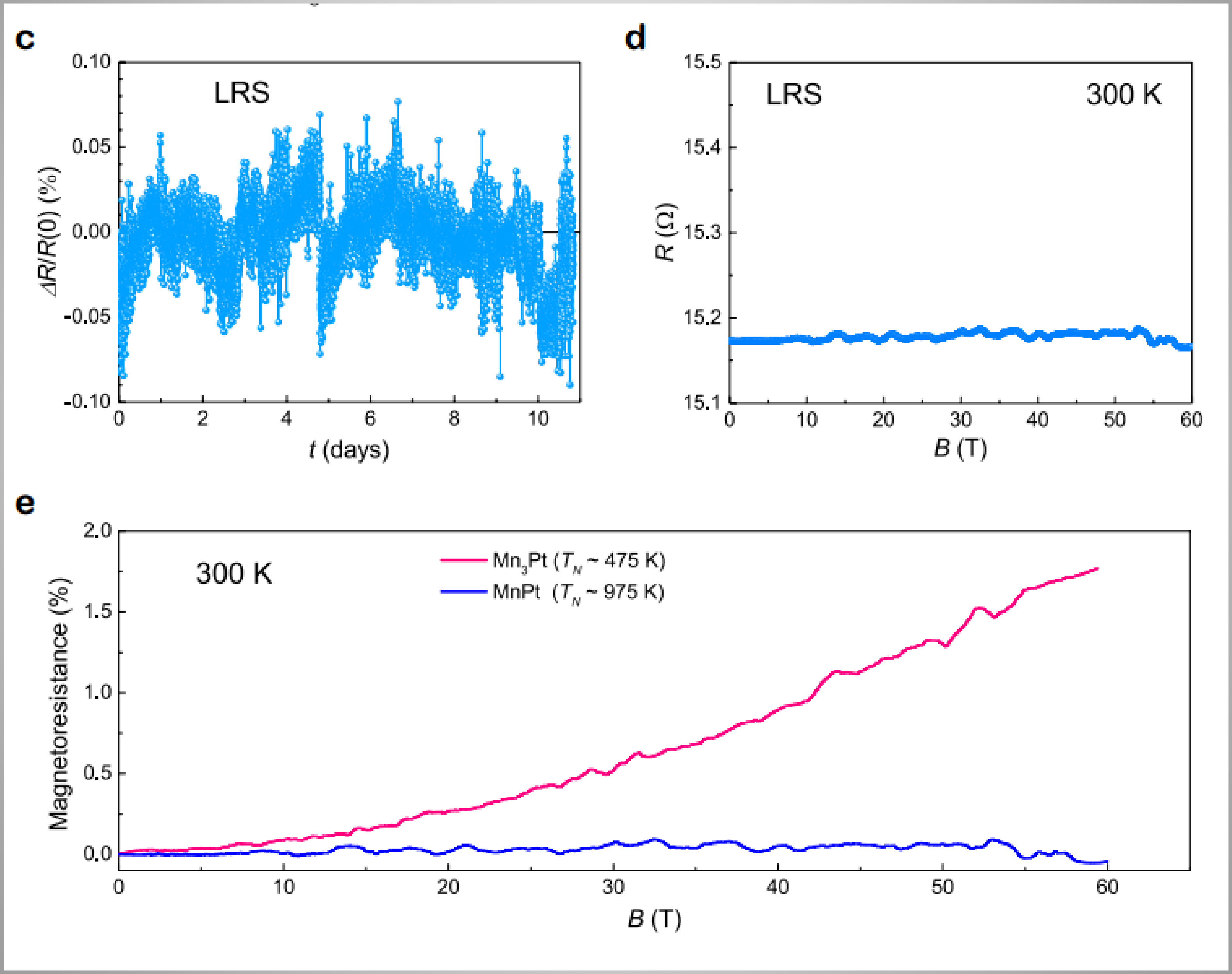
Mechanism – Rotation of AFM Spins in (101)-Oriented Grains



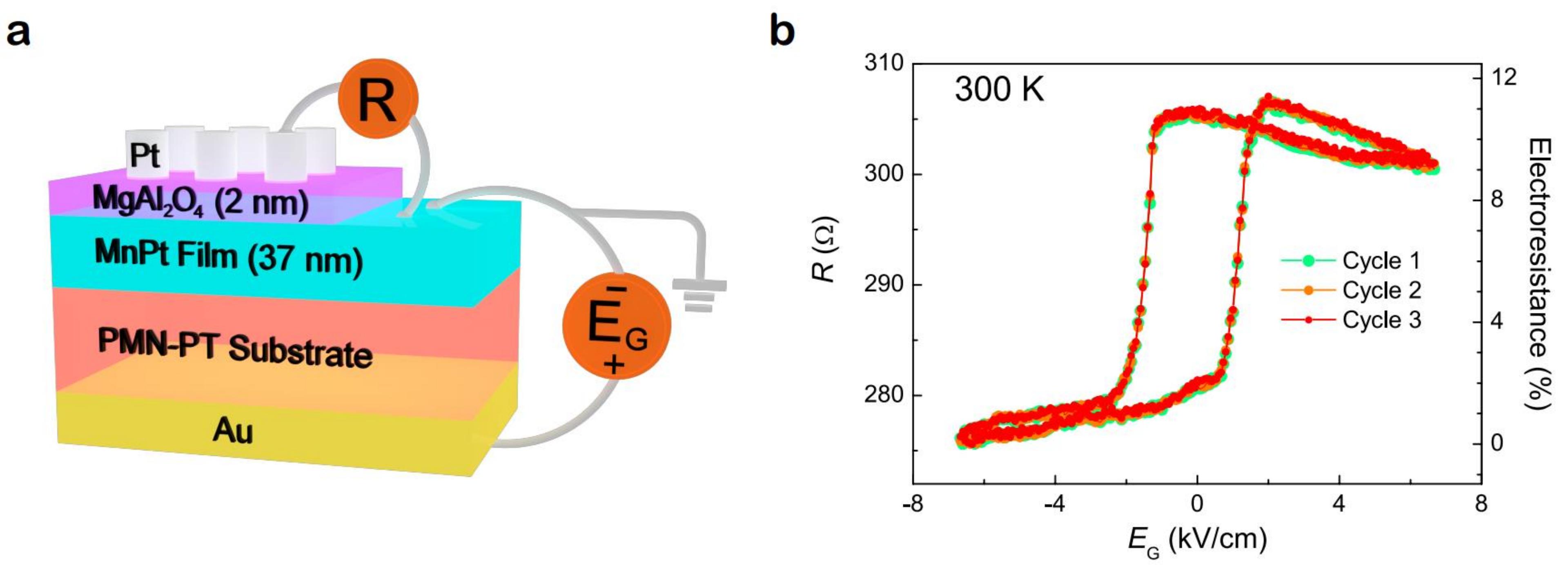
Information Writing under Strong *B*



Data Retention under Ultrahigh *B*



Piezoelectric Strain-Controlled AFM Tunnel Junction



~11.2% resistance modulation at 300 K

Yan *et al*., Nat. Nanotechnol. **14**, 131 (2019)

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SPINTRONICS

Strain controls antiferromagnetism

Jelena Stajic
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Science 08 Feb 2019:
Vol. 363, Issue 6427, pp. 596
DOI: 10.1126/science.363.6427.596-f

Article Info & Metrics eLetters PDF

Antiferromagnetic (AFM) materials—materials in which neighboring spins point in opposite directions—have an important advantage over the better-known ferromagnets: Their properties are much less sensitive to external magnetic fields. This, however, also makes AFM devices trickier to control. Yan *et al.* grew a film of AFM manganese platinum on a piezoelectric substrate. Applying an electric field resulted in strain in the substrate through the inverse piezoelectric effect. This strain in turn altered the magnetic properties of the adjacent AFM film, changing its electrical resistance. Based on this mechanism, the researchers were able to electrically switch the resistance of the film between two values, an operation that was insensitive to magnetic fields up to 60 tesla.

Nat. Nano. 10.1038/s41565-018-0339-0 (2019).

Applied Physics Letters ARTICLE scitation.org/journal/apl

Strain control of the Néel vector in Mn-based antiferromagnets

Cite as: Appl. Phys. Lett. **114**, 142403 (2019); doi: 10.1063/1.5093701
Submitted: 24 February 2019 · Accepted: 19 March 2019 ·
Published Online: 11 April 2019
https://doi.org/10.1063/1.5093701
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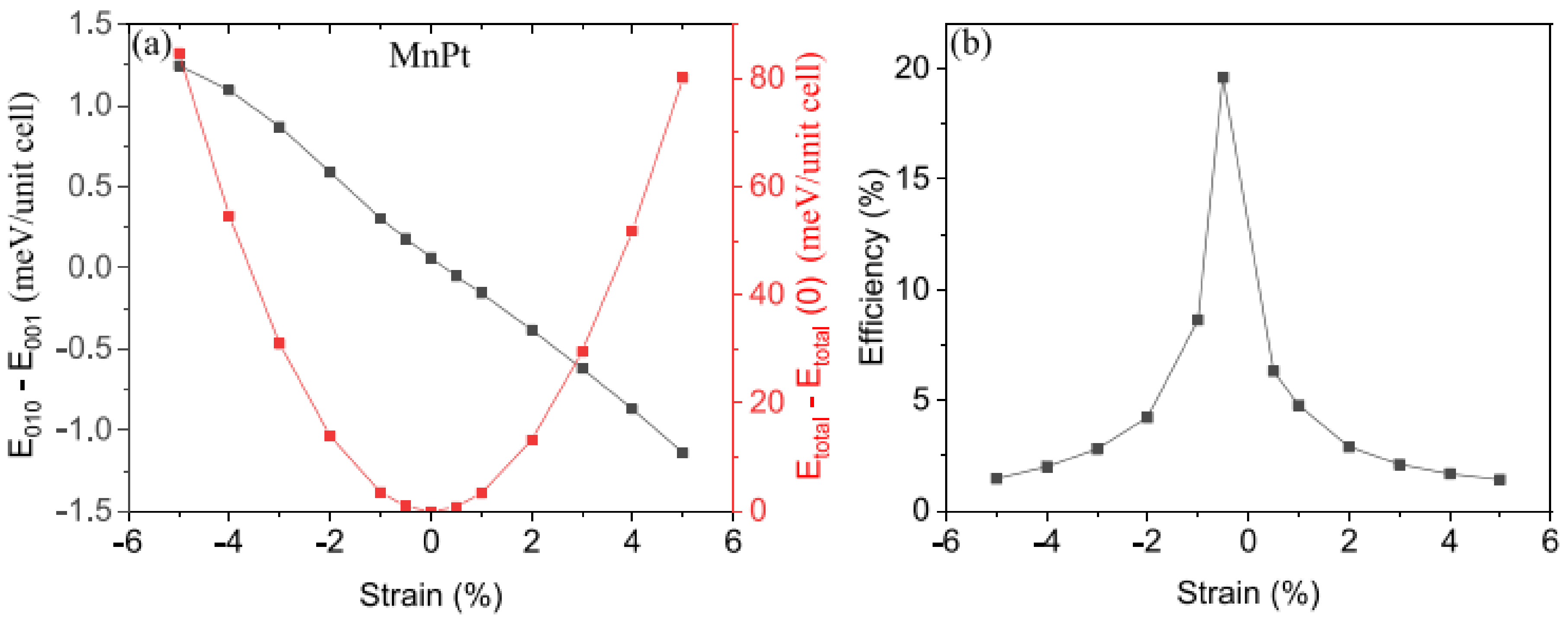
In Jun Park,[1,a)] Taehwan Lee,[2] Protik Das,[1] Bishwajit Debnath,[1] Greg P. Carman,[3] and Roger K. Lake[1,a)]



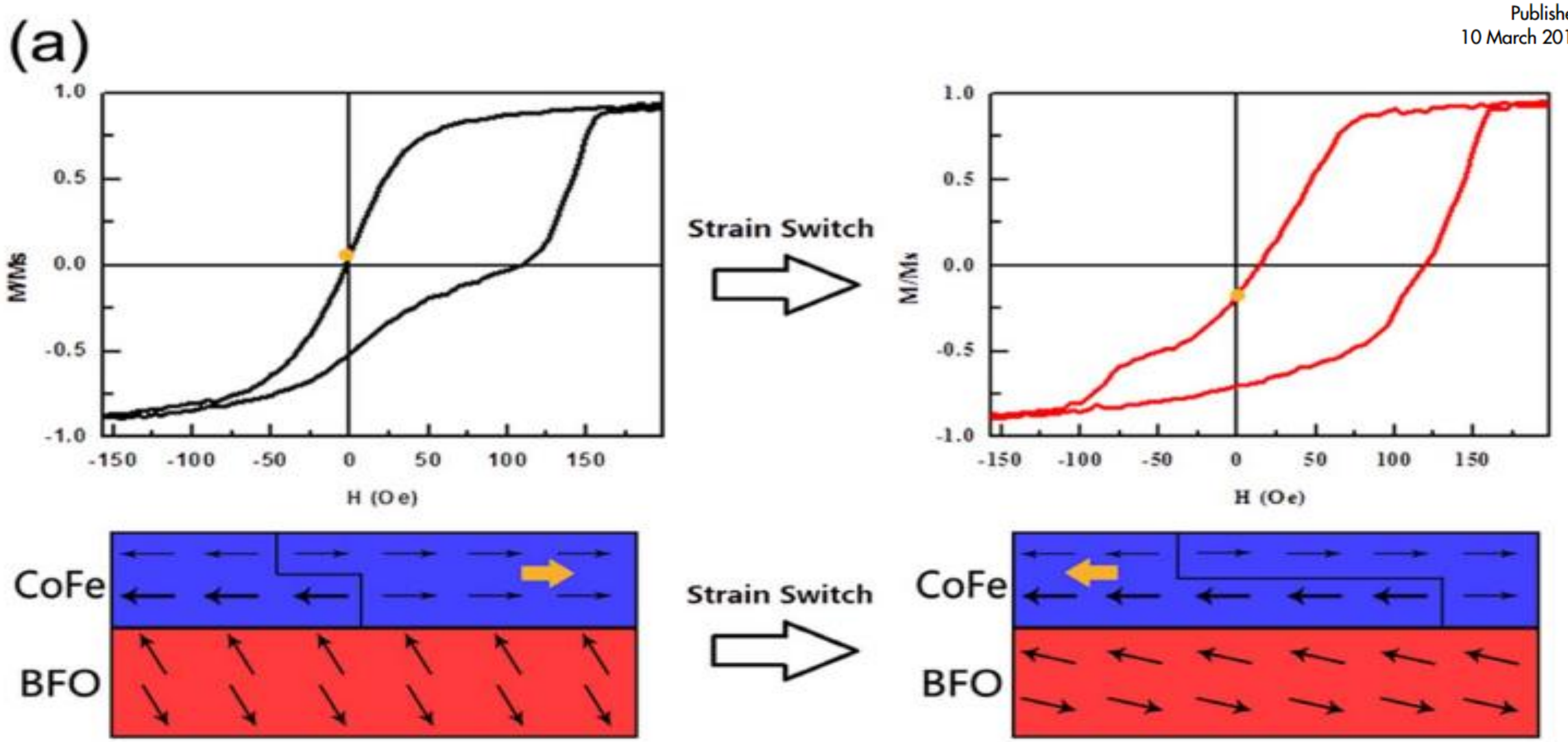
Strain-Controlled Anisotropy in Antiferromagnets

SCIENTIFIC REPORTS

Strain-mediated electric-field control of exchange bias in a $Co_{90}Fe_{10}/BiFeO_3/SrRuO_3$/PMN-PT heterostructure

S. Z. Wu[1], J. Miao[1,3], X. G. Xu[1], W. Yan[2], R. Reeve[3], X. H. Zhang[2] & Y. Jiang[1]

Received
6 November 2014
Accepted
10 February 2015
Published
10 March 2015



Strain-Controlled Anisotropy in Antiferromagnets

JOURNAL OF APPLIED PHYSICS **120**, 143904 (2016)

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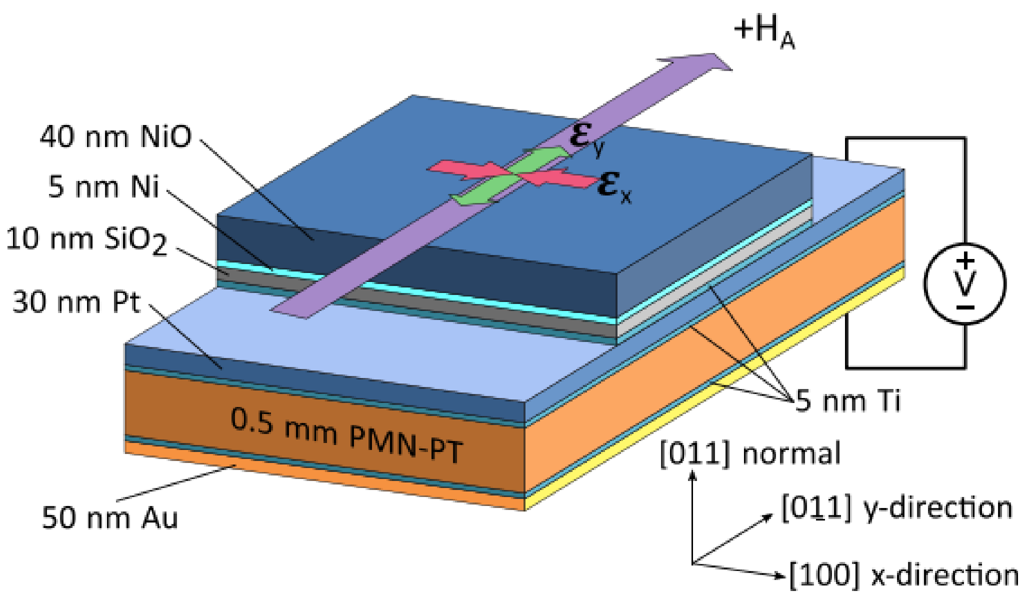
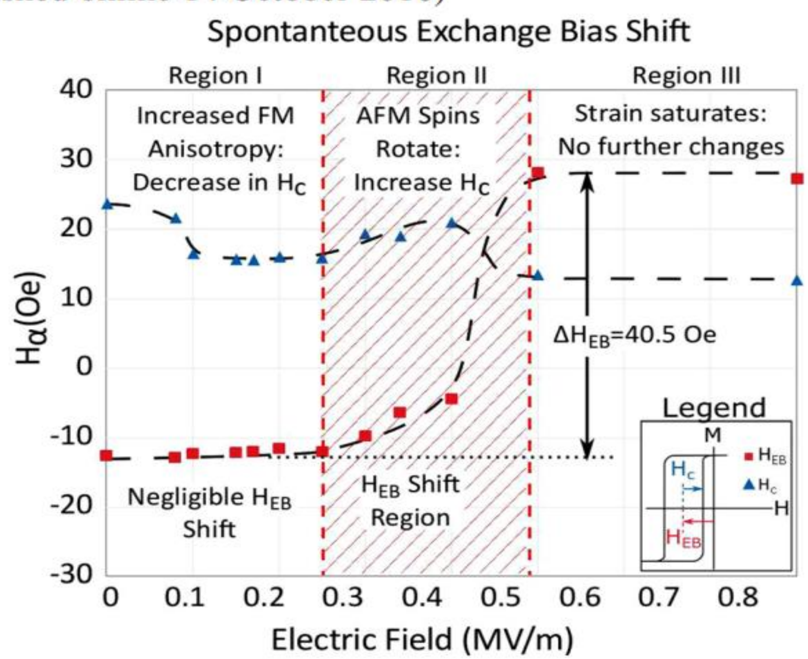
Strain-mediated multiferroic control of spontaneous exchange bias in Ni-NiO heterostructures

John P. Domann,[1,a)] Wei-Yang Sun,[1,a)] Laura T. Schelhas,[2,3] and Greg P. Carman[1,b)]
[1]*Department of Mechanical and Aerospace Engineering, University of California, Los Angeles, California 90095, USA*
[2]*Department of Chemistry and Biochemistry, University of California, Los Angeles, California 90095, USA*
[3]*SLAC National Accelerator Laboratory, Stanford Synchrotron Radiation Lightsource, Menlo Park, California 94025, USA*

(Received 23 August 2016; accepted 29 September 2016; published online 14 October 2016)



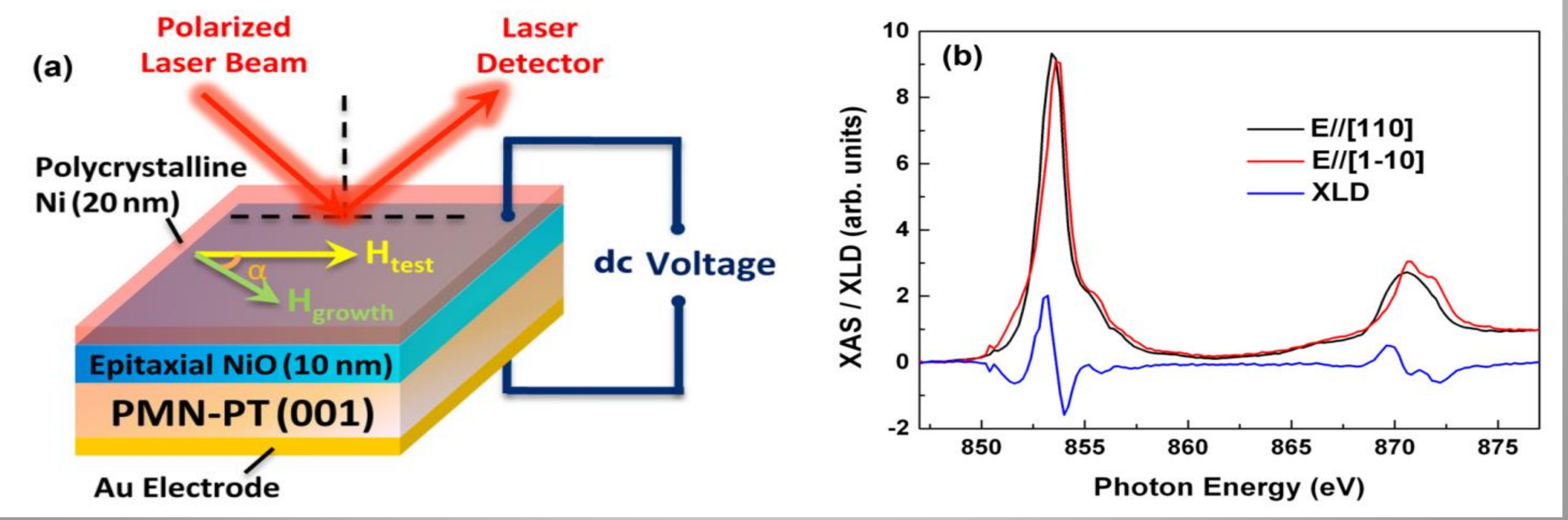


Strain-Controlled Anisotropy in Antiferromagnets

PHYSICAL REVIEW B
covering condensed matter and materials physics

Ferroelectric strain modulation of antiferromagnetic moments in Ni/NiO ferromagnet/antiferromagnet heterostructures

Yu-Jun Zhang, Jia-Hui Chen, Liang-Liang Li, Jing Ma, Ce-Wen Nan, and Yuan-Hua Lin
Phys. Rev. B **95**, 174420 – Published 15 May 2017



Strain-Controlled Anisotropy in Antiferromagnets

Phys. Status Solidi RRL, 1–4 (2017) / **DOI** 10.1002/pssr.201600438

Part of Focus Issue on
Antiferromagnetic Spintronics
Eds.: Jairo Sinova, Tomas Jungwirth, Olena Gomonay

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Manipulation of antiferromagnetic domain distribution in Mn_2Au by ultrahigh magnetic fields and by strain

A. A. Sapozhnik[*,1,2], R. Abrudan[3,4], Yu. Skourski[5], M. Jourdan[1,2], H. Zabel[1,2], M. Kläui[1,2], and H.-J. Elmers[1,2]

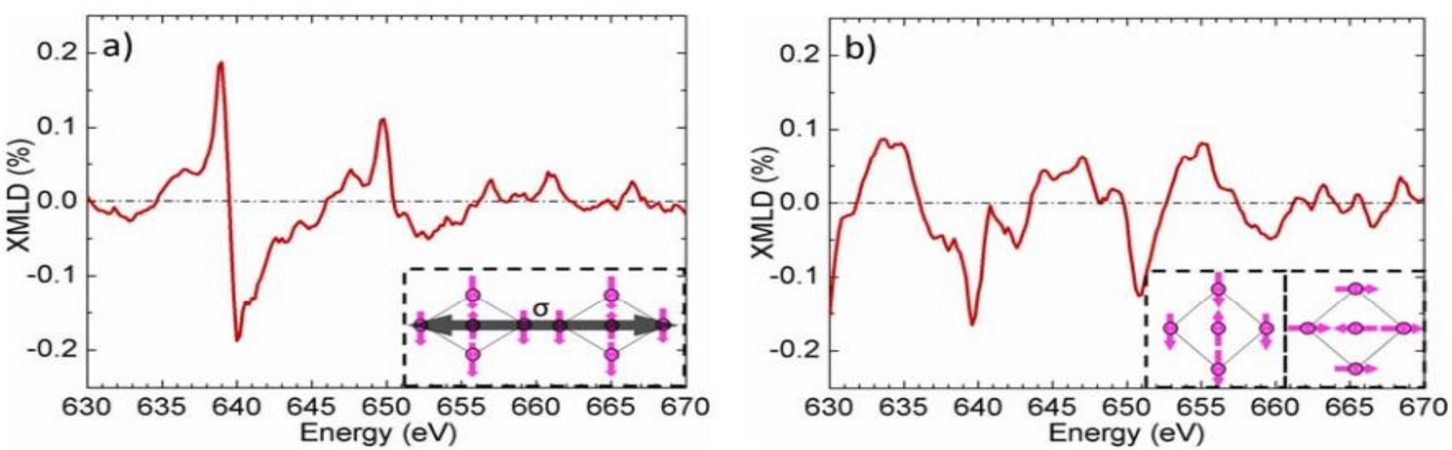


Figure 2 XMLD spectra measured for strained (a) and unstrained (b) Mn_2Au layers. The inset in (a) sketches the magnetization configuration in the strained sample with stress σ (gray arrows) and elongation along [110] with only one remaining Néel vector orientation along $[1\bar{1}0]$. The inset in (b) sketches the magnetization configuration of the unstrained sample with two equivalent AFM domains with Néel vectors along [110] and $[1\bar{1}0]$.

Strain-Controlled Anisotropy in Antiferromagnets

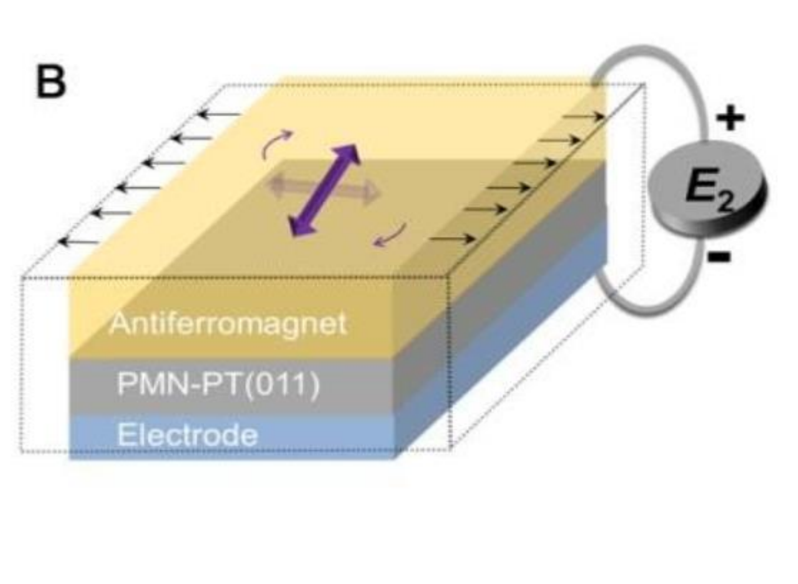
nature materials

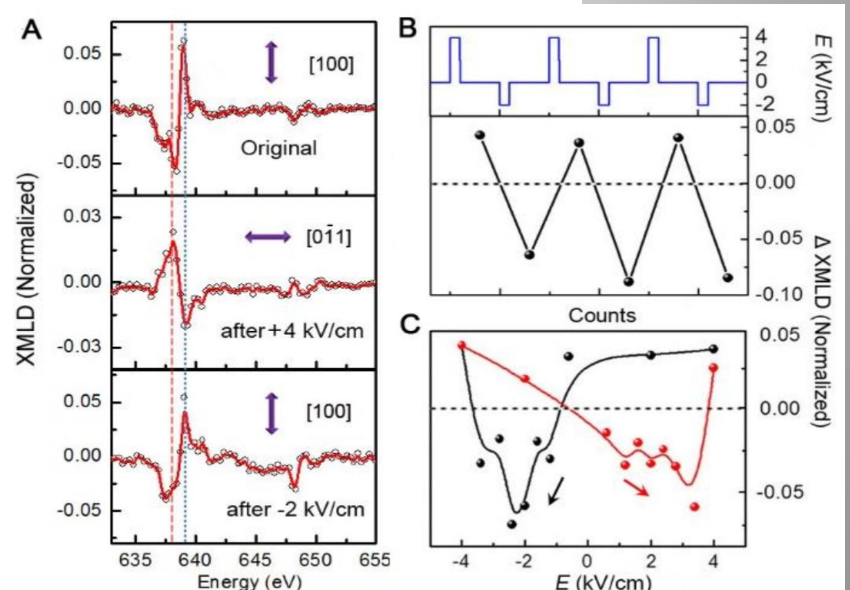
LETTERS

https://doi.org/10.1038/s41563-019-0424-2

Electric field control of Néel spin–orbit torque in an antiferromagnet

Xianzhe Chen[1,5], Xiaofeng Zhou[1,5], Ran Cheng[2,5], Cheng Song[1*], Jia Zhang[3], Yichuan Wu[3], You Ba[4], Haobo Li[4], Yiming Sun[1], Yunfeng You[1], Yonggang Zhao[4] and Feng Pan[1*]





Magnetoelastic Energy induced by Strain

Magnetostriction

Strain

$$E_{\mathrm{Strain}} \sim 3/2\lambda_s\sigma$$

Origins: Long-range magnetic order & Spin-orbit coupling

Although antiferromagnets cannot sense magnetic fields, they can feel strain well like ferromagnets!

PROGRESS REPORT Adv. Electron. Mater. 2019, 5, 1900176

ADVANCED ELECTRONIC MATERIALS
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Spintronics

Antiferromagnetic Piezospintronics

Zhiqi Liu, Zexin Feng, Han Yan, Xiaoning Wang, Xiaorong Zhou, Peixin Qin, Huixin Guo, Ronghai Yu, and Chengbao Jiang*

Antiferromagnets naturally exhibit three obvious advantages over ferromagnets for memory device applications: insensitivity to external magnetic fields, much faster spin dynamics (≈THz), and higher packing density due to the absence of any stray field. Recently, antiferromagnetic spintronics has emerged as a cutting-edge field in the magnetism community. The key mission of this rapidly rising field is to steer the spins or spin axes of antiferromagnets via external stimuli and then realize advanced devices based on their physical property changes. Herein, the state-of-the-art of antiferromagnetic spintronics is presented. Subsequently, the history of ferromagnetic/ferroelectric multiferroic composites is briefly revisited. Finally, an ultralow-power, long-range, and magnetic-field-insensitive approach for harnessing antiferromagnetic spins based on recent experimental progress, i.e., piezoelectric strain control, is introduced. Relevant theoretical and experimental studies have formed an attractive new branch in antiferromagnetic spintronics, which is dubbed "antiferromagnetic piezospintronics."

antiferromagnet involves the antiferromagnetic exchange field H_E as well due to spin canting via $\omega_{AFM} \approx r\sqrt{2H_E H_A} \approx rH_{SF}$, where r is the gyromagnetic ratio of an electron. It can be three orders of magnitude higher than that of ferromagnets $\omega_{FM} \approx rH_A$ (typically GHz) and reaches THz. For example, the study on the laser-induced spin reorientation in antiferromagnetic $TmFeO_3$ in 2004 shows that the antiferromagnetic spins can be manipulated on a timescale of a few picoseconds.[1]

In 2006, Núñes et al. proposed a pioneering theory that spin transfer torques can induce the order parameter orientation switching in antiferromagnetic metals, which is well similar to the ferromagnetic case.[2] However, they pointed out that compared with the ferromagnetic case, the critical current for antiferromag-

Epitaxial VS Piezoelectric Strain

Comparison between Two Types of Strain			
Epitaxial Strain	Static & Irreversible	Quick relaxation from interfaces	Short range (1-30 nm)
Piezoelectric Strain	Dynamic & Reversible	100% in-plane strain mediation via interfaces	Long range (Up to ~um)

Liu *et al*., Adv. Electron. Mater. **5**, 1900176 (2019)

Biegalski *et al*., Appl. Phys. Lett. **96**, 151905 (2010)

Dekker *et al*., Phys. Rev. B **84**, 054463 (2011)

Thank you for your attention!

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