Spintronic microwave and THz detectors: state-of-the art and future!

Prof. Giovanni Finocchio

University of Messina (UNIME) - Italy

2 June 2021 – SPICE

Funding Agencies

Ministero degli Affari Esteri e della Cooperazione Internazionale

agenzia spaziale italiana

unime siNano

MARIS

Peta Spin

www.petaspin.com

MIUR

Ministero dell'Istruzione, dell'Università e della Ricerca

H.F.R.I.
Hellenic Foundation for Research & Innovation

COST Action MAGNETOFON

Ultrafast opto-magneto-electronics for non-dissipative information technology

COST is supported by the EU Framework Programme Horizon 2020

cost
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

DEMUR
INDUSTRIAL ROBOTS

Spintronic diodes

Type of response
Resonant
Non-resonant - Broadband - Multimodes
Low-frequency

Regime of behavior
Passive
Active

Frequency response
MHz (ferromagnets)
GHz (ferromagnets)
THz (antiferromagnets)

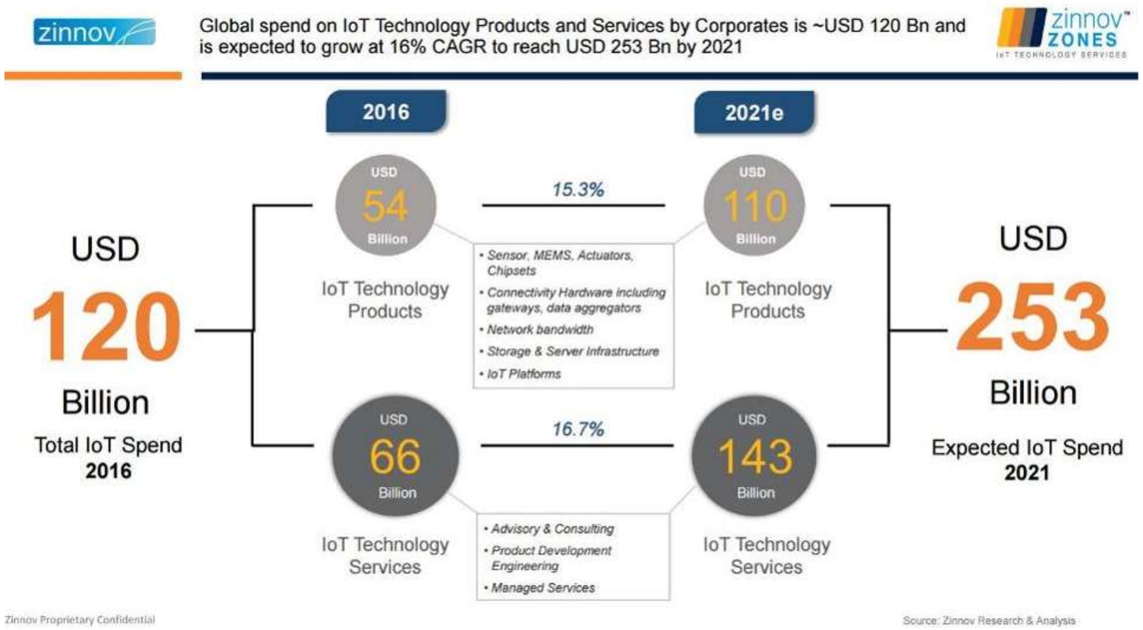
Perspectives on spintronic diodes

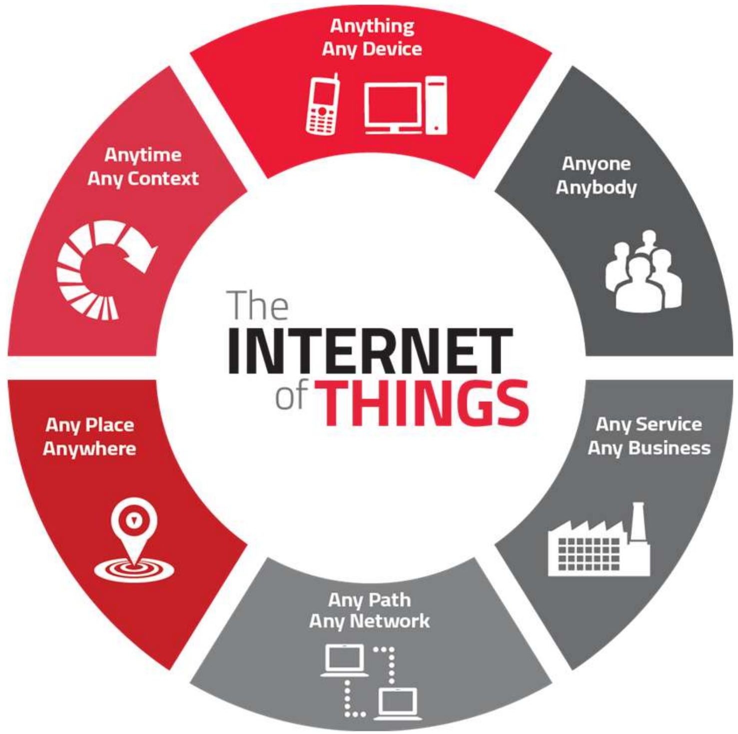
Cite as: Appl. Phys. Lett. **118**, 160502 (2021); doi: 10.1063/5.0048947
Submitted: 28 February 2021 · Accepted: 8 April 2021 ·
Published Online: 22 April 2021

G. Finocchio,[1,a)] R. Tomasello,[2] B. Fang,[3] A. Giordano,[1] V. Puliafito,[4] M. Carpentieri,[5] and Z. Zeng[6]

Motivation

The **Internet of Things** (IoT) is a compelling platform connecting various sensors around us to the Internet, providing great opportunities for the realization of smart living.





- *The market doubled in 5 years.*
- The development of products for IoT will be a key challenge:

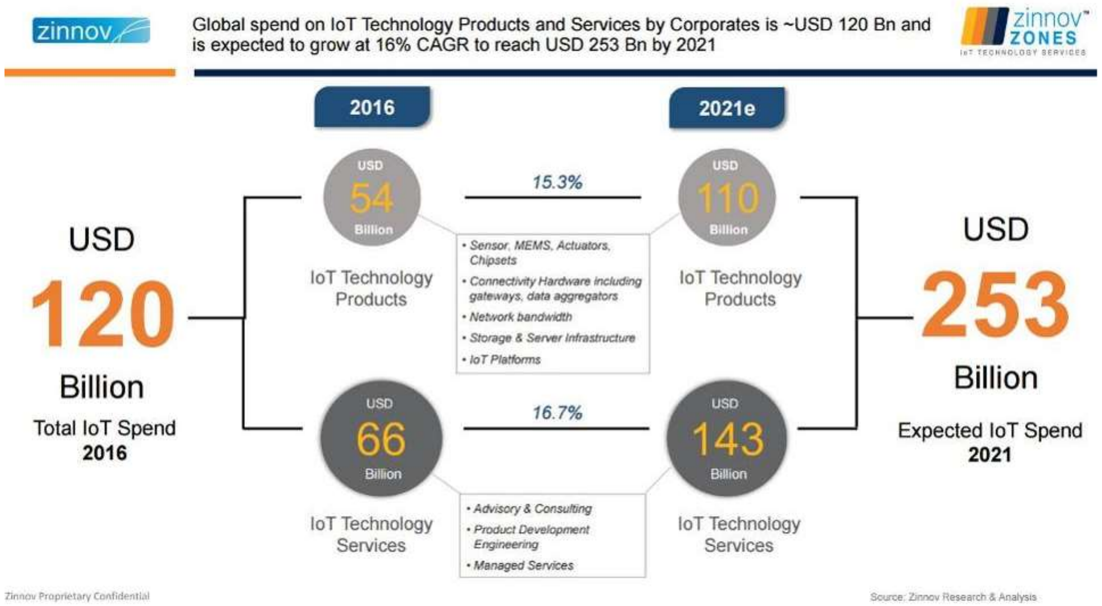
❑**cost as low as possible**
❑**low energy consumption**
❑**nanoscale size**
❑**high performance**

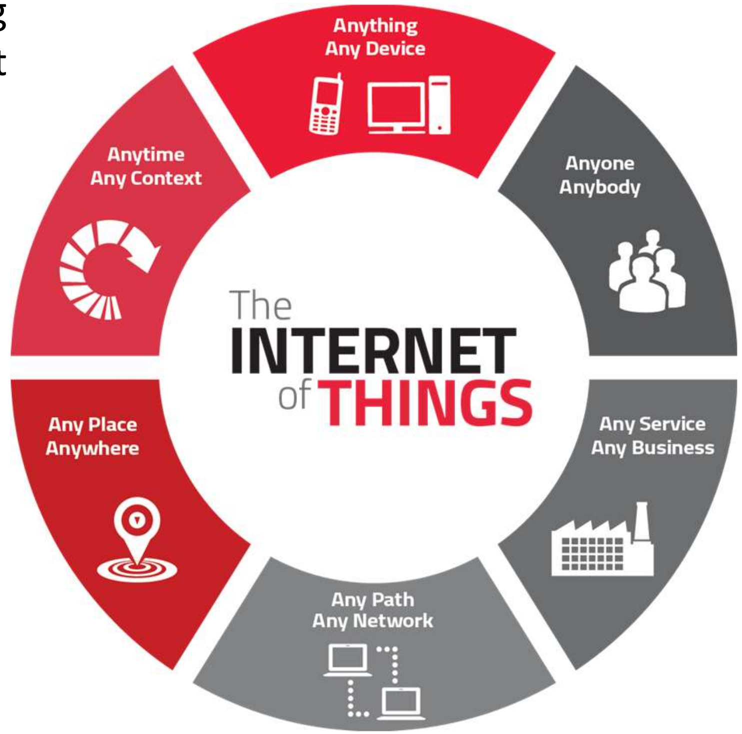
USD >1000 billion by 2027

Digital Twin

Motivation

The **Internet of Things** (IoT) is a compelling platform connecting various sensors around us to the Internet, providing great opportunities for the realization of smart living.





- *The market double in 5 years.*
- The development of products for IoT will be a key challenge:

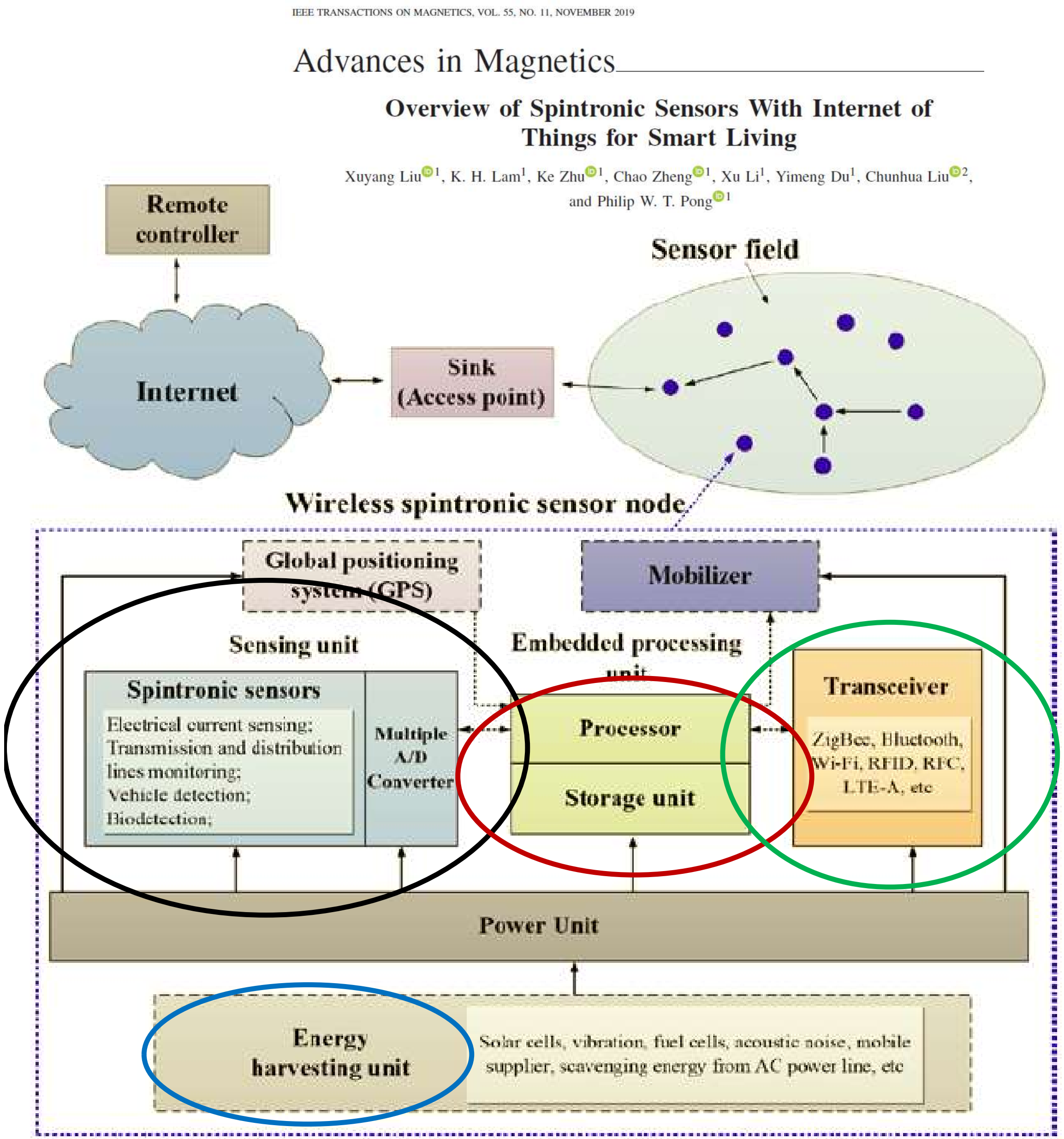
❑**cost as low as possible**
❑**low energy consumption**
❑**nanoscale size**
❑**high performance**

- *A path to face this challenge…*

❑**Spintronics,** successful stories for sensors (i.e. GMR/TMR hard disk read heads, automotive…), memory (STT-MRAM), etc..

❑**low energy consumption**
❑**nanoscale size**
❑**high performance**
❑**The cost is expected to reduce thank to the STT-MRAMs**

Motivation

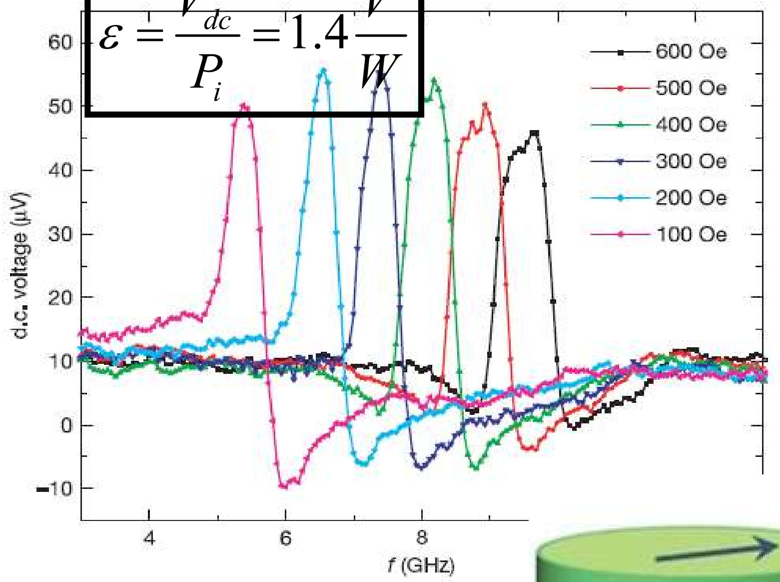


- ❑ Sensors
- ❑ Computing
- ❑ STT-MRAM
- ❑ Oscillators
- ❑ Detectors
- ❑ Spintronic energy harvesters

Resonant spintronic diode

A.A. Tulapurkar, *et al*, *Nature* **438**, 339 (2005).

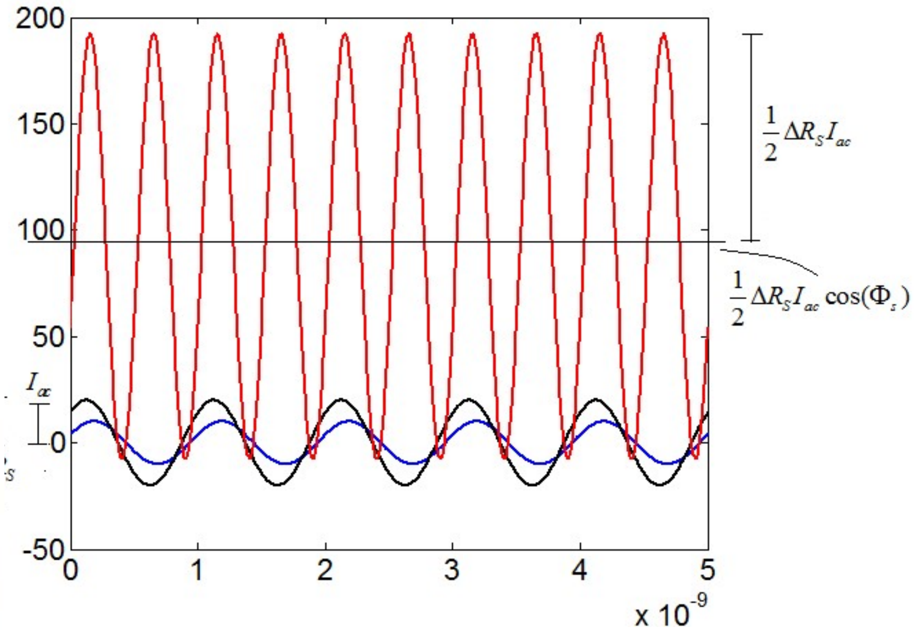
$$\varepsilon = \frac{V_{dc}}{P_i} = 1.4\frac{V}{W}$$



Microwave Current

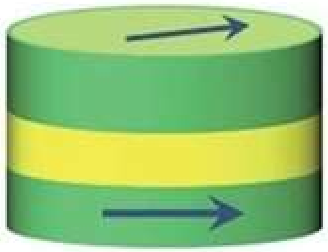
- Diode effect

$$V_{\rm dc} = \frac{1}{2} I_{ac}\Delta R_{\rm s}\cos(\Phi_s)$$



$$i_{ac} = I_{ac}\sin(\omega t + \varphi_{\rm I})$$

$$R(t) = \Delta R_S \sin(\omega t + \varphi_R)$$



$$v = \Delta R_S I_{ac}\sin(\omega t + \varphi_{\rm I})\sin(\omega t + \varphi_R)$$

$$v = \frac{1}{2}\Delta R_S I_{ac}\left(\cos(\varphi_{\rm I} - \varphi_R) - \cos(2\omega t + \varphi_{\rm I} + \varphi_R)\right)$$

$$\Phi_s = \varphi_{\rm I} - \varphi_R$$

$$v = \frac{1}{2}\Delta R_S I_{ac}\cos(\Phi_s)\left(1 - \cos(2\omega t + 2\varphi_R)\right) + \frac{1}{2}\Delta R_S I_{ac}\sin(\Phi_s)\sin(2\omega t + 2\varphi_R)$$

Resonant spintronic diode

Used for the characterization of the damping-like and field-like torques in MTJ

ARTICLES

Measurement of the spin-transfer-torque vector in magnetic tunnel junctions

JACK C. SANKEY[1], YONG-TAO CUI[1], JONATHAN Z. SUN[2], JOHN C. SLONCZEWSKI[2]*, ROBERT A. BUHRMAN[1] AND DANIEL C. RALPH[1]†
[1]Cornell University, Ithaca, New York 14853, USA
[2]IBM T. J. Watson Research Center, Yorktown Heights, New York 10598, USA
*IBM RSM Emeritus
†e-mail: ralph@ccmr.cornell.edu

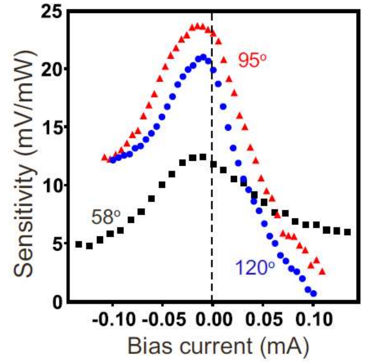
The detection sensitivity was too low for practical application in microwave detectors.

JOURNAL OF APPLIED PHYSICS **106**, 053905 (2009)

Sensitivity of spin-torque diodes for frequency-tunable resonant microwave detection

C. Wang,[1] Y.-T. Cui,[1] J. Z. Sun,[2] J. A. Katine,[3] R. A. Buhrman,[1] and D. C. Ralph[1,a)]
[1]*Cornell University, Ithaca, New York 14853, USA*
[2]*IBM T. J. Watson Research Center, Yorktown Heights, New York 10598, USA*
[3]*Hitachi Global Storage Technologies, San Jose Res. Ctr., San Jose, California 95135, USA*

(Received 5 May 2009; accepted 8 July 2009; published online 4 September 2009)



Milestones

Interfacial perpendicular anisotropy (IPA)

Voltage controlled magnetocrystalline anisotropy (VCMA)

Resonant spintronic diode

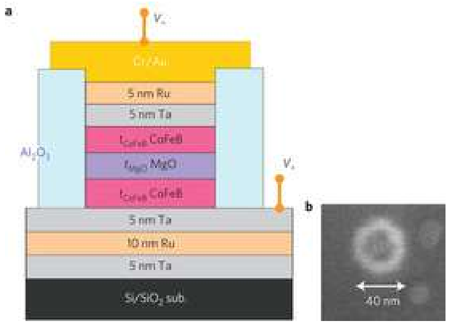
nature materials

LETTERS

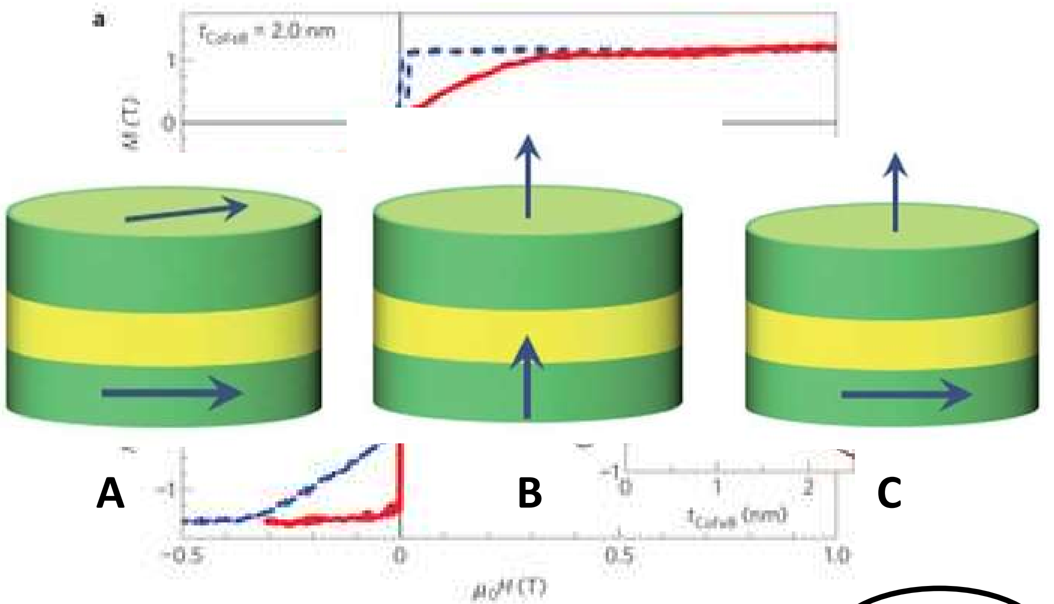
PUBLISHED ONLINE: 11 JULY 2010 | DOI: 10.1038/NMAT2804

A perpendicular-anisotropy CoFeB–MgO magnetic tunnel junction

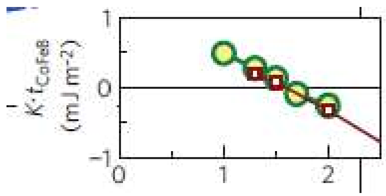
S. Ikeda[1,2*], K. Miura[1,2,3], H. Yamamoto[1,2,3], K. Mizunuma[2], H. D. Gan[1], M. Endo[2], S. Kanai[2], J. Hayakawa[3], F. Matsukura[1,2] and H. Ohno[1,2*]



Electrostatic interaction MgO/CoFeB → surface perpendicular anisotropy



The easy axis depends on the **thickness of the CoFeB**



$$\mathbf{H}_{eff} = \mathbf{H}_{ext} + \mathbf{H}_{exch} + \mathbf{H}_{ani} + \mathbf{H}_{M} + \mathbf{H}_{TH} + \mathbf{H}_{IPA}$$

Resonant spintronic diode

Type of response	Regime of behavior	Frequency response
Resonant	Passive	GHz (ferromagnets)

The detection in passive diodes can be improved with the additional support of the

- VCMA

$$\varepsilon < 500 \frac{V}{W}$$

PRL 108, 197203 (2012) PHYSICAL REVIEW LETTERS week ending 11 MAY 2012

Voltage-Induced Ferromagnetic Resonance in Magnetic Tunnel Junctions

Jian Zhu,[1] J. A. Katine,[2] Graham E. Rowlands,[1] Yu-Jin Chen,[1] Zheng Duan,[1] Juan G. Alzate,[3] Pramey Upadhyaya,[3] Juergen Langer,[4] Pedram Khalili Amiri,[3] Kang L. Wang,[3] and Ilya N. Krivorotov[1]

$$V_{\mathrm{dc}} = \frac{1}{2} I_{\mathrm{ac}} \Delta R_{\mathrm{s}} \cos(\Phi_{\mathrm{s}})$$

Peta Spin

Resonant spintronic diode

Type of response	Regime of behavior	Frequency response
Resonant	Active	GHz (ferromagnets)

$$V_{dc} = \frac{1}{2} I_{ac} \Delta R_s \cos(\Phi_s) + I_{dc} \Delta R_{dc} (I_{ac})$$

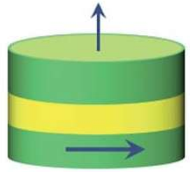
Nonlinear rectification effect

Injection locking (zero field operation and room temperature)

- Auto-oscillator
- An ac input with a frequency close to the one of the auto-oscillator

Resonant spintronic diode

nature COMMUNICATIONS

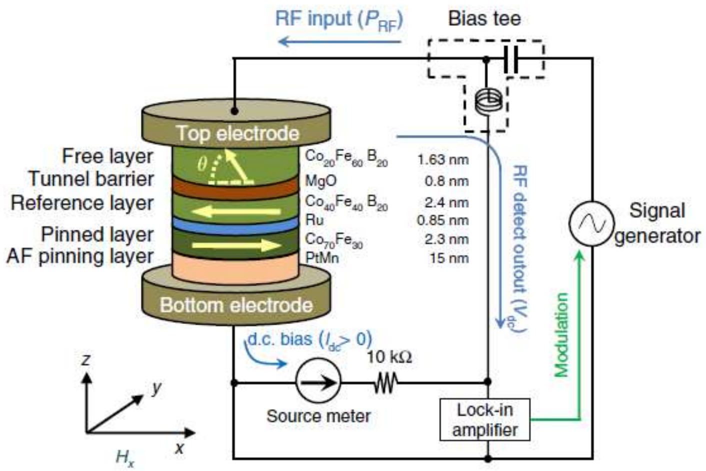


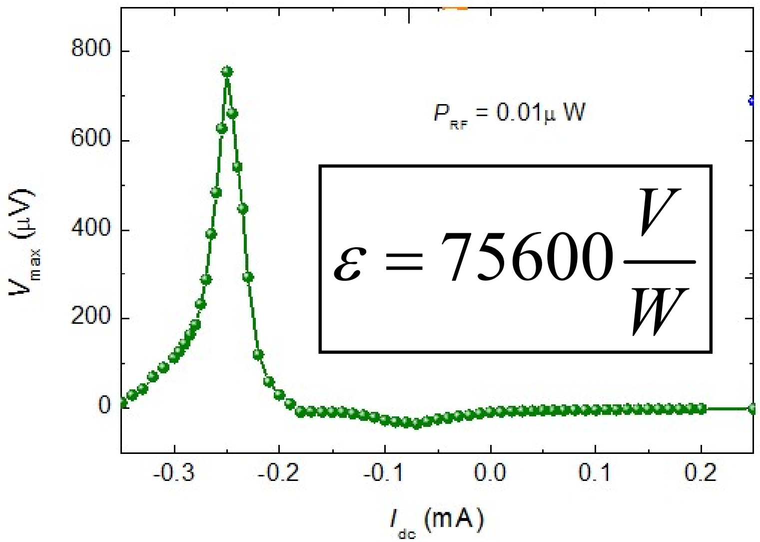
ARTICLE

Received 15 Oct 2015 | Accepted 7 Mar 2016 | Published 7 Apr 2016 DOI: 10.1038/ncomms11259 OPEN

Giant spin-torque diode sensitivity in the absence of bias magnetic field

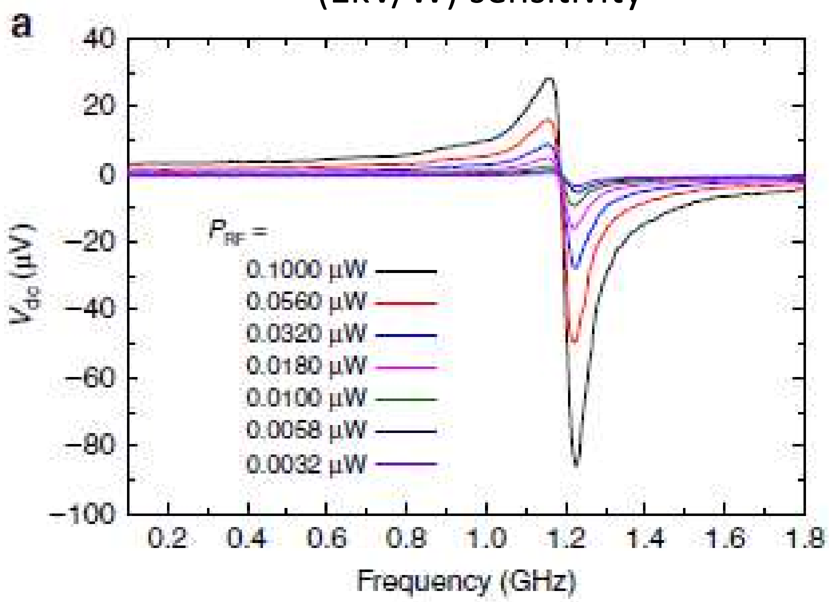
Bin Fang[1], Mario Carpentieri[2], Xiaojie Hao[3], Hongwen Jiang[3], Jordan A. Katine[4], Ilya N. Krivorotov[5], Berthold Ocker[6], Juergen Langer[6], Kang L. Wang[7], Baoshun Zhang[1], Bruno Azzerboni[8], Pedram Khalili Amiri[7], Giovanni Finocchio[9] & Zhongming Zeng[1]





Injection locking

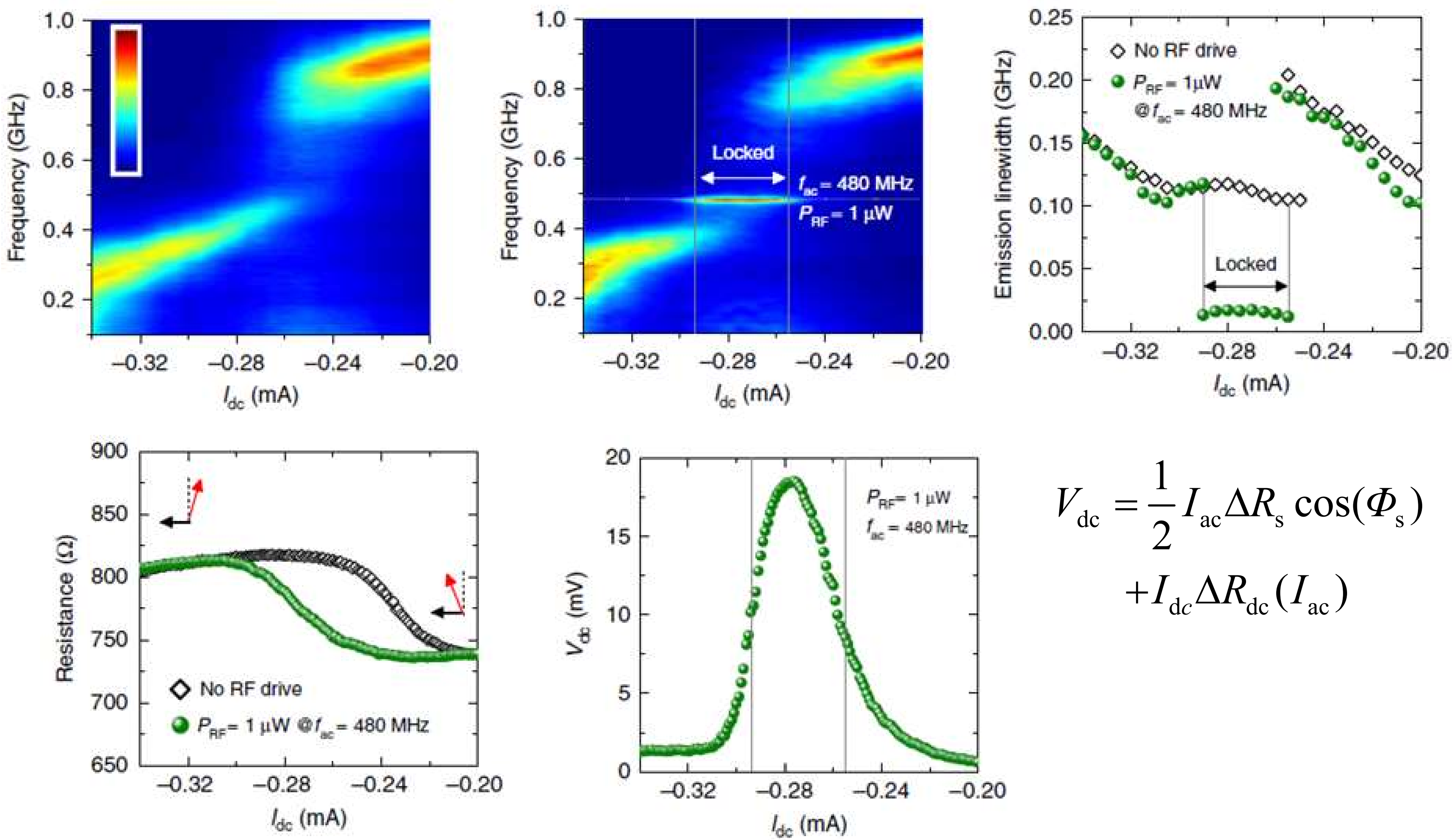
passive "**Resonant Type**" (1kV/W) sensitivity



PetaSpin

Resonant spintronic diode

Self oscillation I_D (I_{AC}=0) | **Injection locking $I_D + I_{AC}$**



$$V_{dc} = \frac{1}{2} I_{ac} \Delta R_s \cos(\Phi_s) + I_{dc} \Delta R_{dc}(I_{ac})$$

Resonant spintronic diode

Type of response	Regime of behavior	Frequency response
Resonant	Active	GHz (ferromagnets)

$$V_{\mathrm{dc}} = \frac{1}{2} I_{\mathrm{ac}} \Delta R_{\mathrm{s}} \cos(\Phi_{\mathrm{s}}) + I_{\mathrm{dc}} \Delta R_{\mathrm{dc}} (I_{\mathrm{ac}})$$

Nonlinear rectification effect

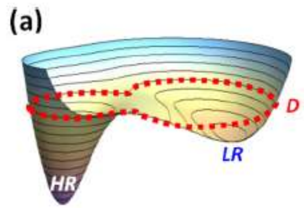
Nonadiabatic stochastic resonance (field and low temperature)

$$\varepsilon = 25000 \frac{V}{W}$$

APPLIED PHYSICS LETTERS **103**, 082402 (2013)

Nonlinear ferromagnetic resonance induced by spin torque in nanoscale magnetic tunnel junctions

X. Cheng,[1,2] J. A. Katine,[2] G. E. Rowlands,[1] and I. N. Krivorotov[1]
[1]Department of Physics and Astronomy, University of California, Irvine, California 92697, USA
[2]HGST, San Jose, California 95135, USA



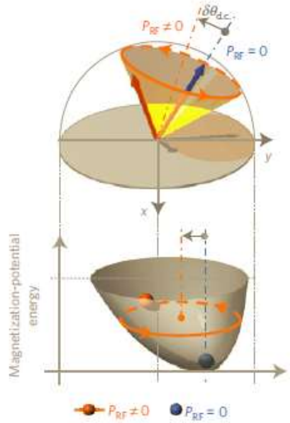
Nonlinear resonance (field and room temperature)

$$\varepsilon = 12000 \frac{V}{W}$$

nature materials | ARTICLES
PUBLISHED ONLINE: 20 OCTOBER 2013 | DOI:10.1038/NMAT3778

Highly sensitive nanoscale spin-torque diode

S. Miwa[1†], S. Ishibashi[1,2†], H. Tomita[1], T. Nozaki[1,2], E. Tamura[1], K. Ando[1], N. Mizuochi[1], T. Saruya[2‡], H. Kubota[2], K. Yakushiji[2], T. Taniguchi[2], H. Imamura[2], A. Fukushima[2], S. Yuasa[2] and Y. Suzuki[1,2*]



First demonstration that spintronic diodes overcome the thermodynamic limit of Schottky diodes

Resonant spintronic diode

Type of response	Regime of behavior	Frequency response
Resonant	Active	GHz (ferromagnets)

$$V_{\mathrm{dc}} = \frac{1}{2} I_{\mathrm{ac}} \Delta R_{\mathrm{s}} \cos(\Phi_{\mathrm{s}}) + I_{\mathrm{dc}} \Delta R_{\mathrm{dc}}(I_{\mathrm{ac}})$$

Nonlinear rectification effect

Vortex core expulsion (field and room temperature)

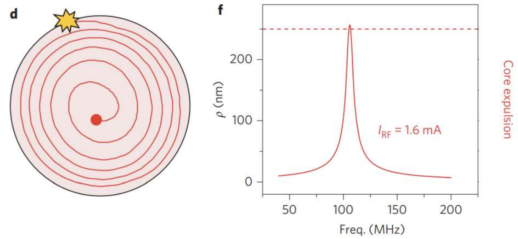
$$\varepsilon = 40 \frac{kV}{W}$$

nature nanotechnology — ARTICLES

PUBLISHED ONLINE: 4 JANUARY 2016 | DOI: 10.1038/NNANO.2015.295

Spin-torque resonant expulsion of the vortex core for an efficient radiofrequency detection scheme

A. S. Jenkins[1], R. Lebrun[1], E. Grimaldi[1], S. Tsunegi[1,2], P. Bortolotti[1], H. Kubota[2], K. Yakushiji[2], A. Fukushima[2], G. de Loubens[3], O. Klein[3†], S. Yuasa[2] and V. Cros[1*]



Spin bolometer and injection locking (field and room temperature)

$$\varepsilon = 4 \frac{MV}{W}$$

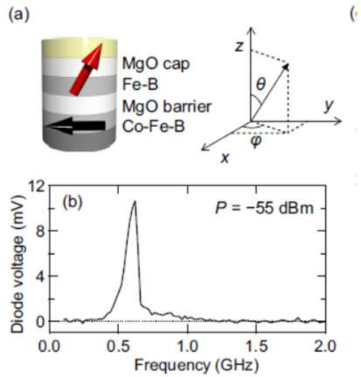
nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-020-20631-0 OPEN

Uncooled sub-GHz spin bolometer driven by auto-oscillation

Minori Goto[1,2], Yuma Yamada[1], Atsushi Shimura[3], Tsuyoshi Suzuki[3], Naomichi Degawa[3], Takekazu Yamane[3], Susumu Aoki[3], Junichiro Urabe[3], Shinji Hara[3], Hikaru Nomura[1,2] & Yoshishige Suzuki[1,2]



$$V_{\mathrm{dc}} = \frac{1}{2} I_{\mathrm{ac}} \Delta R_{\mathrm{s}} \cos(\Phi_{\mathrm{s}}) + (I_{\mathrm{dc}} + I_{th}) \Delta R_{\mathrm{dc}}(I_{\mathrm{ac}})$$

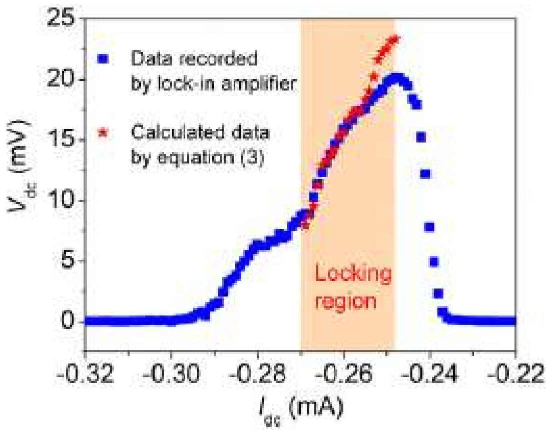
Resonant spintronic diode

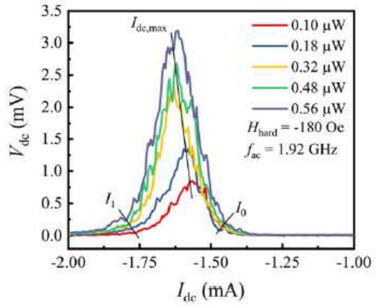
Injection locked spintronic diodes – ReLU-like activation function

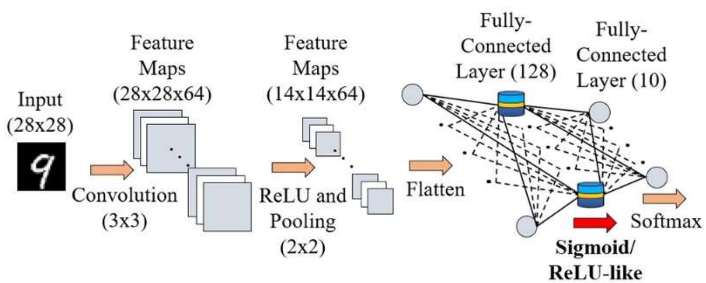
Sparse neuromorphic computing based on spin-torque diodes

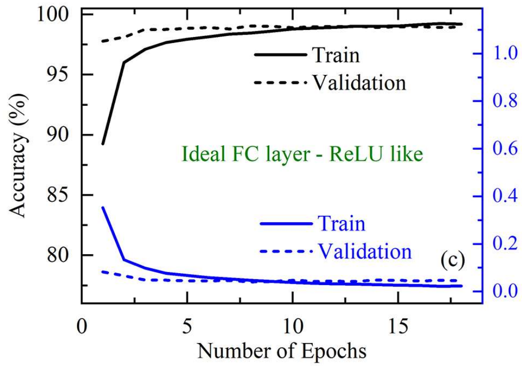
Cite as: Appl. Phys. Lett. 114, 192402 (2019); doi: 10.1063/1.5090566
Submitted: 29 January 2019 · Accepted: 24 April 2019 ·
Published Online: 13 May 2019

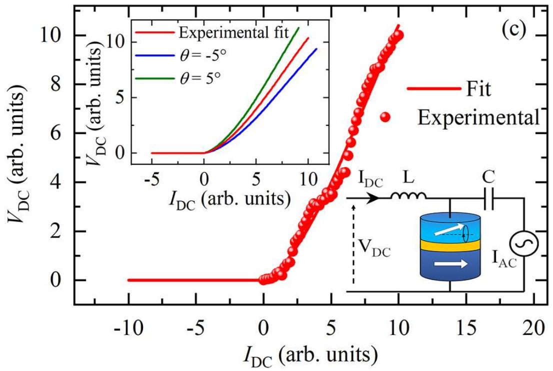
Jialin Cai,[1,2] Like Zhang,[1,2] Bin Fang,[1] Wenxing Lv,[1,2] Baoshun Zhang,[1,2] Giovanni Finocchio,[3] Rui Xiong,[4] Shiheng Liang,[5] and Zhongming Zeng[1,2,a)]

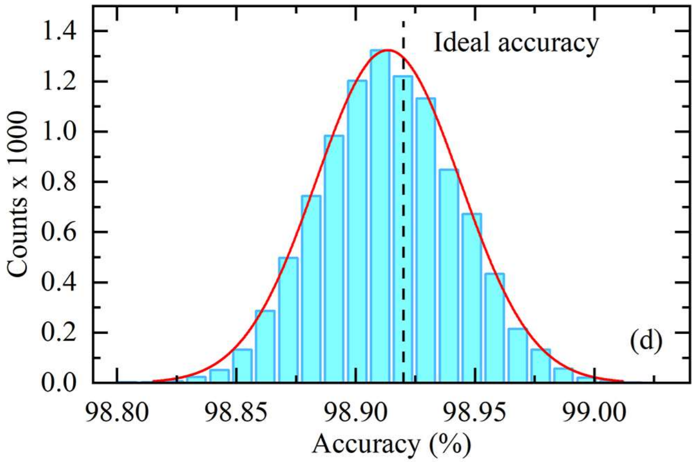








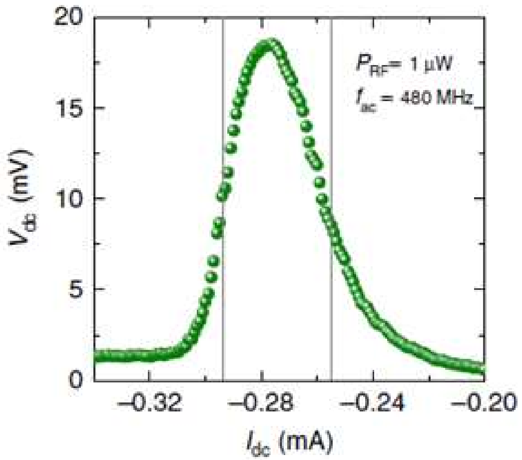


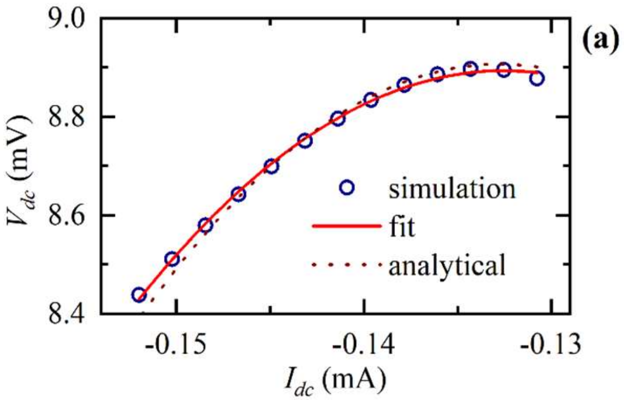


Raimondo, et al
submitted for publication.

Resonant spintronic diode

Injection locked spintronic diodes - Degree of Rectification

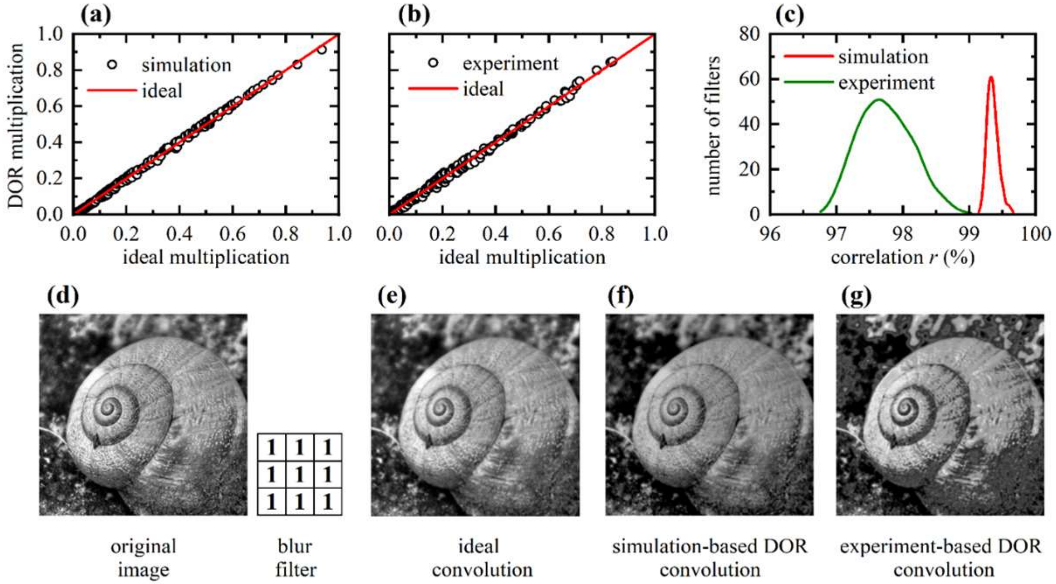


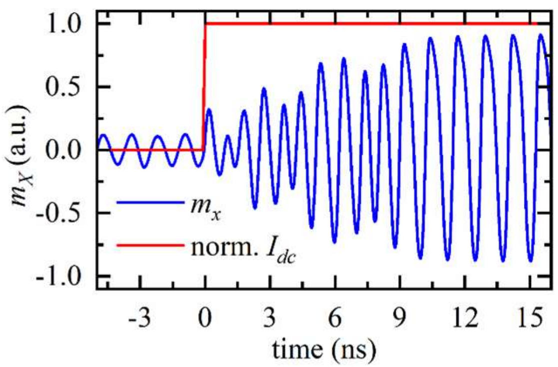


(b)

Parabolic DOR: $V_{dc}(I_{dc}) = \mathbf{a}I_{dc}^2 + \mathbf{b}I_{dc} + \mathbf{c}$		
Parameters	**Fit**	**Analytical**
a (mV/mA^2)	-1.225×10^3	-1.397×10^3
b (mV/mA)	−325	−371
c (mV)	−12.6	−15.7

$$FG = \frac{P(F-G) - P(F) - P(-G) + c}{-2a}$$





Mazza, et al
submitted for publication.

Resonant spintronic diode

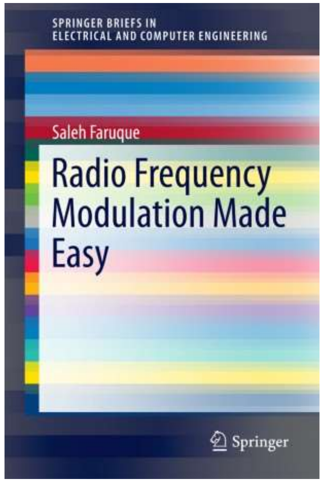
Spintronic diodes as receivers for demodulation of Frequency-shift keying!

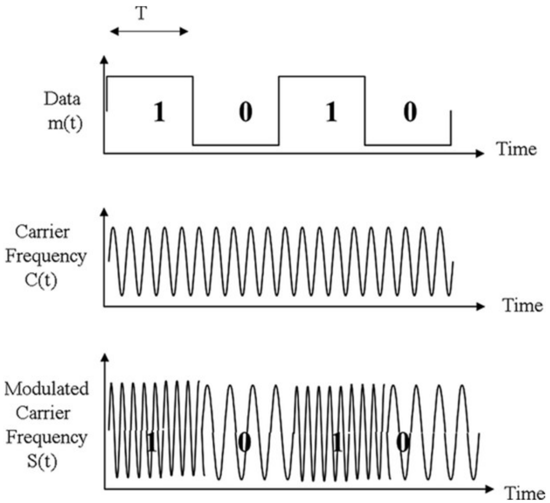
Dual-band microwave detector based on magnetic tunnel junctions

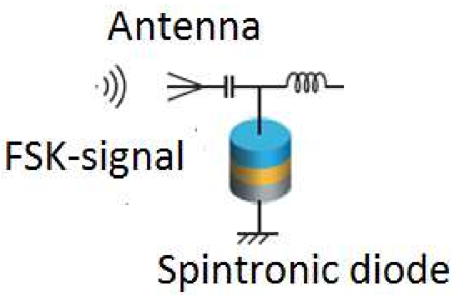
Cite as: Appl. Phys. Lett. 117, 072409 (2020); doi: 10.1063/5.0014881
Submitted: 22 May 2020 · Accepted: 7 August 2020 ·
Published Online: 21 August 2020

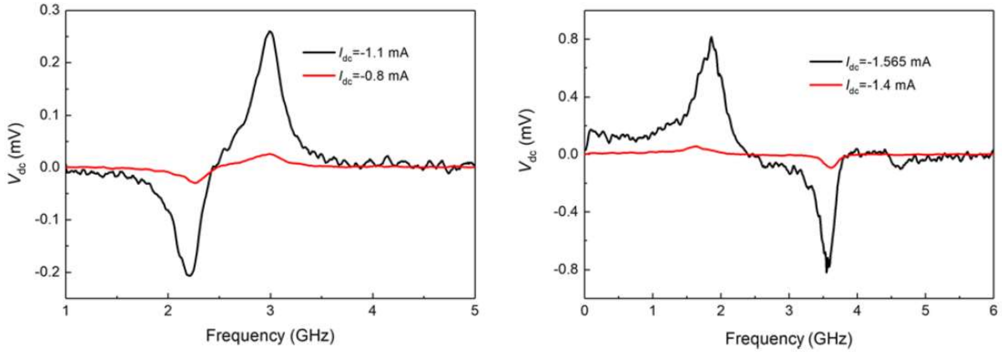
View Online | Export Citation | CrossMark

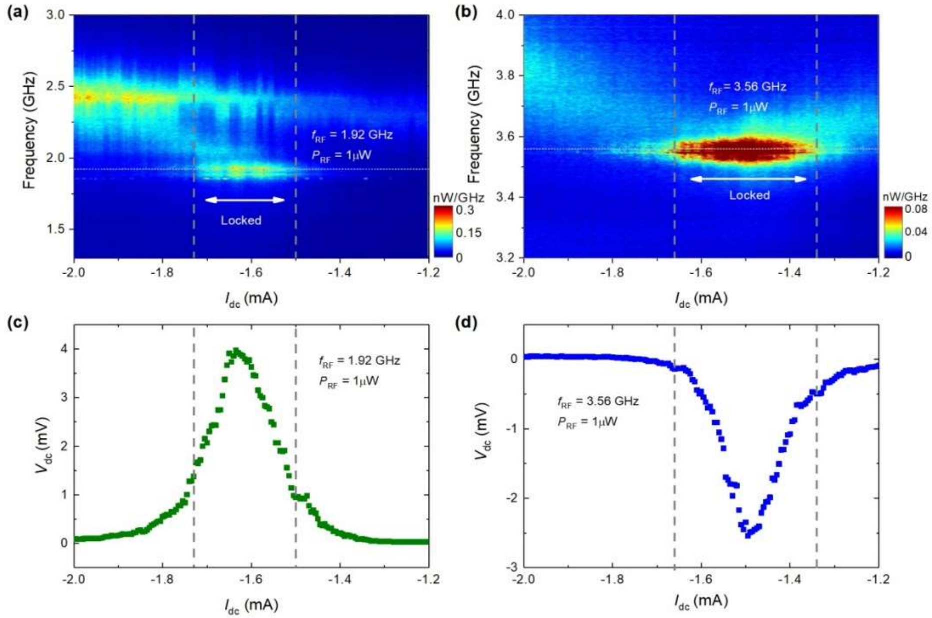
Like Zhang,[1,2] Jialin Cai,[1] Bin Fang,[1] Baoshun Zhang,[1,2] Lifeng Bian,[1,2] Mario Carpentieri,[3]
Giovanni Finocchio,[4,a)] and Zhongming Zeng[1,2,a)]







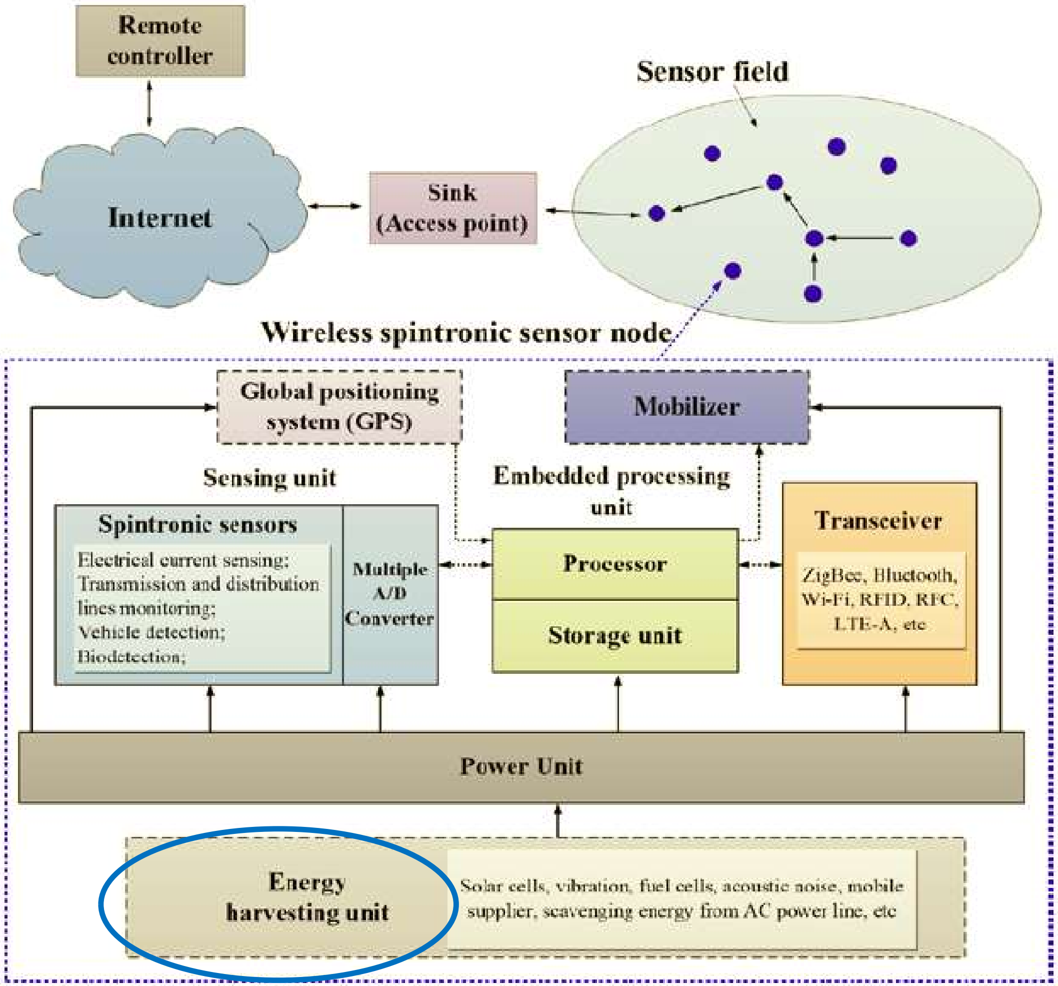




Peta Spin

Motivation

Type of response	Regime of behavior	Frequency response
Broadband	Passive	GHz



- Spintronic energy harvesters

IEEE TRANSACTIONS ON MAGNETICS, VOL. 55, NO. 11, NOVEMBER 2019

Advances in Magnetics

Overview of Spintronic Sensors With Internet of Things for Smart Living

Xuyang Liu[1], K. H. Lam[1], Ke Zhu[1], Chao Zheng[1], Xu Li[1], Yimeng Du[1], Chunhua Liu[2], and Philip W. T. Pong[1]

Motivation – Energy Harvesting

Thermal Power

nature materials

Spin caloritronics

Gerrit E. W. Bauer[1,2*], Eiji Saitoh[1,3] and Bart J. van Wees[4]

NATURE MATERIALS | VOL 11 | MAY 2012

Wireless Power

Electromagnetic Energy harvesting

Motivation – Energy Harvesting

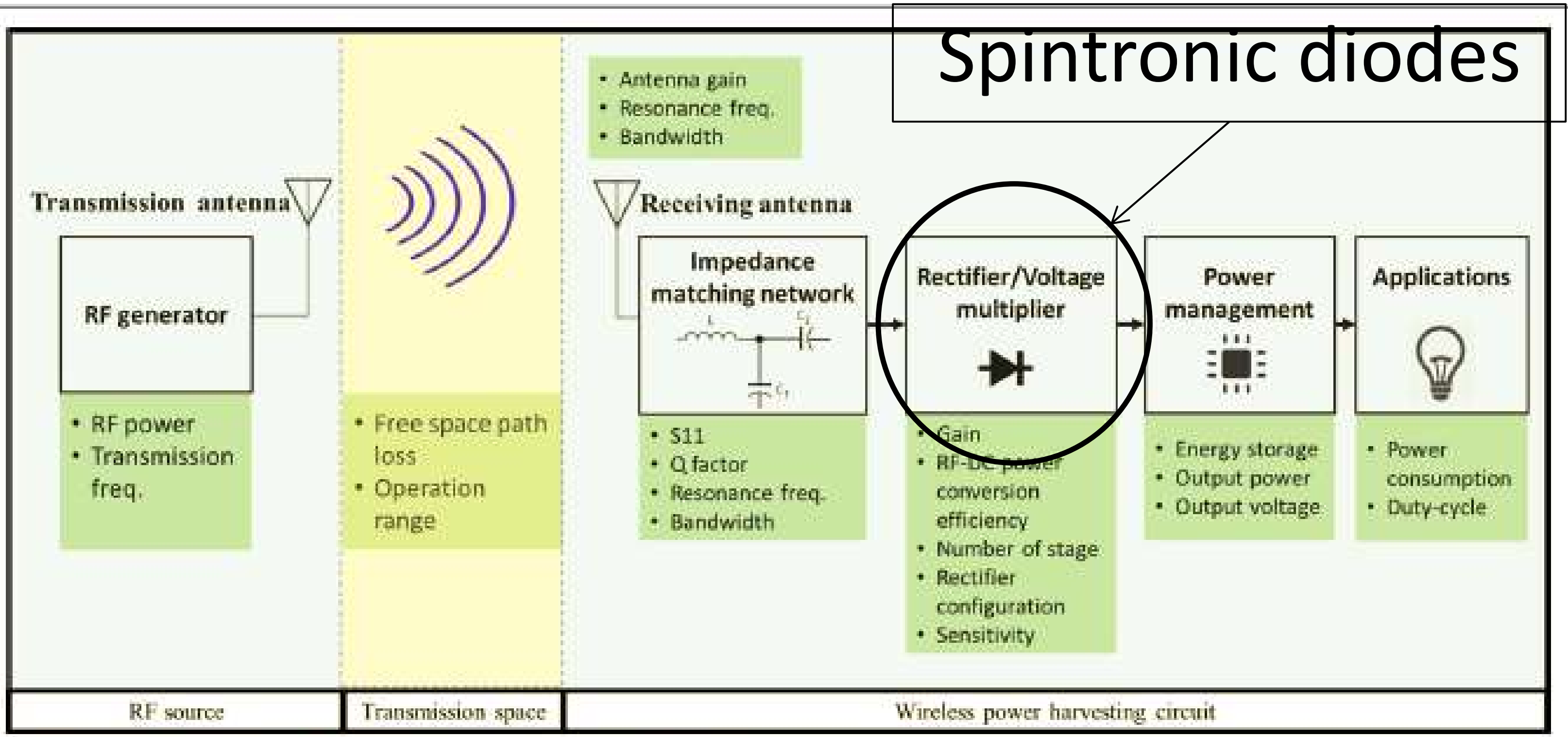


Fig. 1 Conceptual block diagram of an RF power harvesting system

Tran et al. *Micro and Nano Syst Lett* (2017) 5:14
DOI 10.1186/s40486-017-0051-0

Micro and Nano Systems Letters

REVIEW Open Access

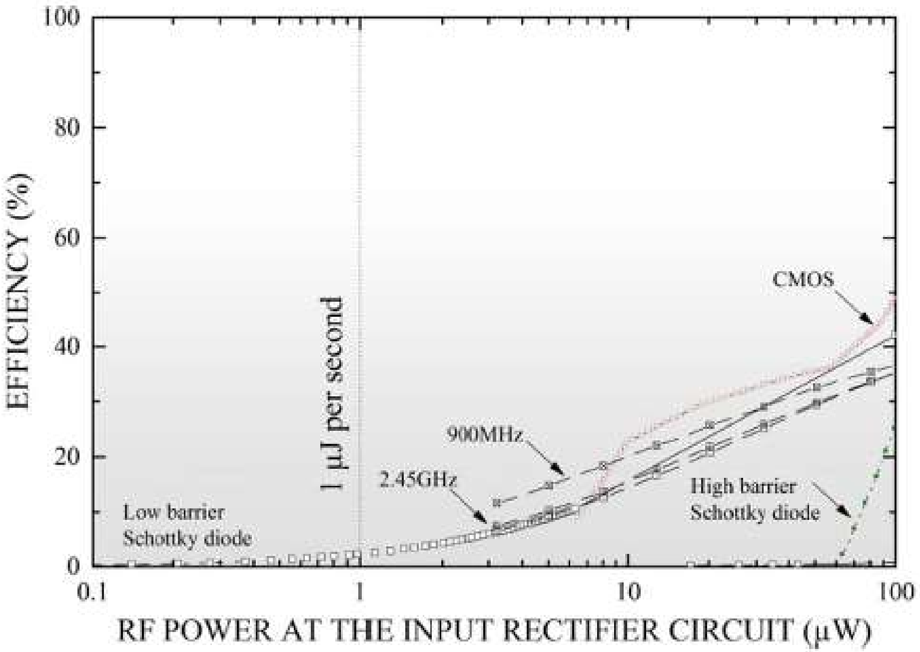
RF power harvesting: a review on designing methodologies and applications

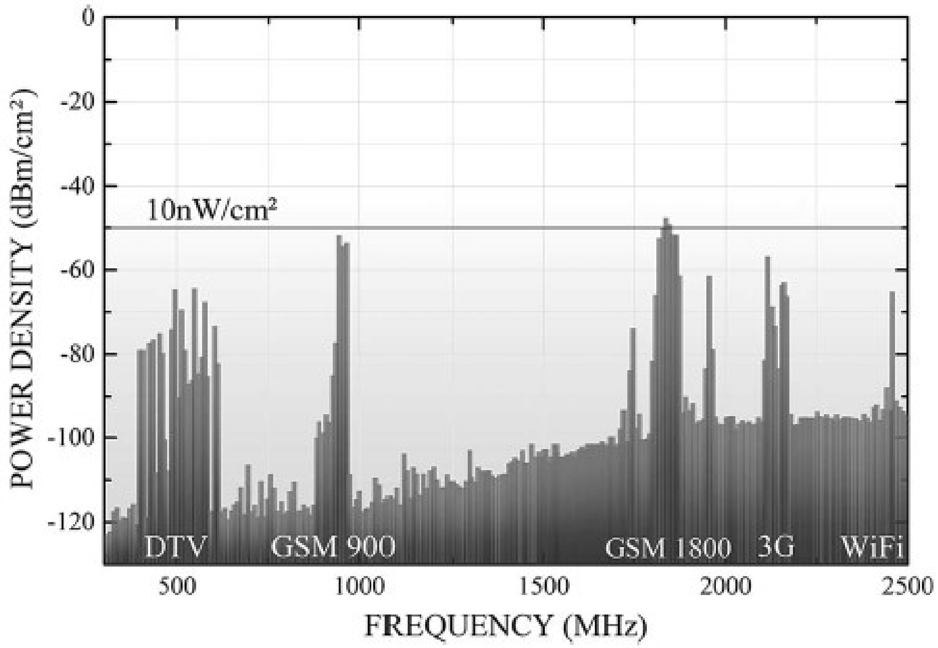
Le-Giang Tran[1], Hyouk-Kyu Cha[2] and Woo-Tae Park[1,3*]

Motivation – Energy Harvesting

Hemour and Wu: Radio-Frequency Rectifier for Electromagnetic Energy Harvesting

Vol. 102, No. 11, November 2014 | Proceedings of the IEEE





The efficiency goes down for input power below 100 uW.

Low barrier Schottky diodes can be used for power below 10 uW.

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 62, NO. 4, APRIL 2014

Towards Low-Power High-Efficiency RF and Microwave Energy Harvesting

Simon Hemour, *Member, IEEE*, Yangping Zhao, *Student Member, IEEE*, Carlos Henrique Petzl Lorenz, Dimitri Houssameddine, Yongsheng Gui, Can-Ming Hu, and Ke Wu, *Fellow, IEEE*

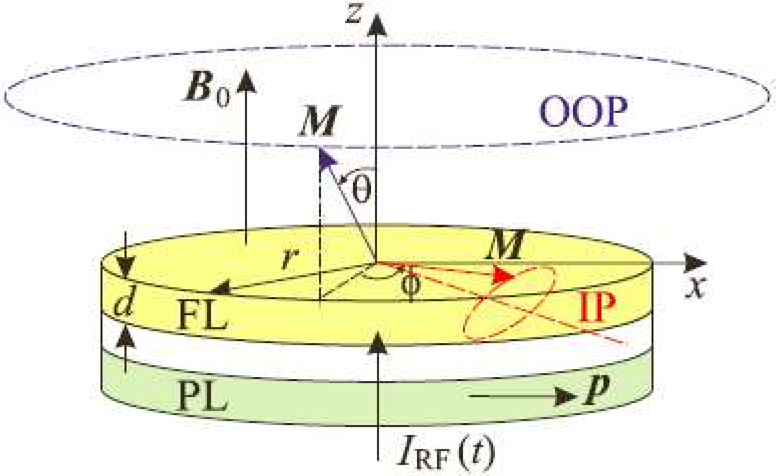
MTJ (spin diode effect) can be a direction towards nW electromagnetic energy harvesting

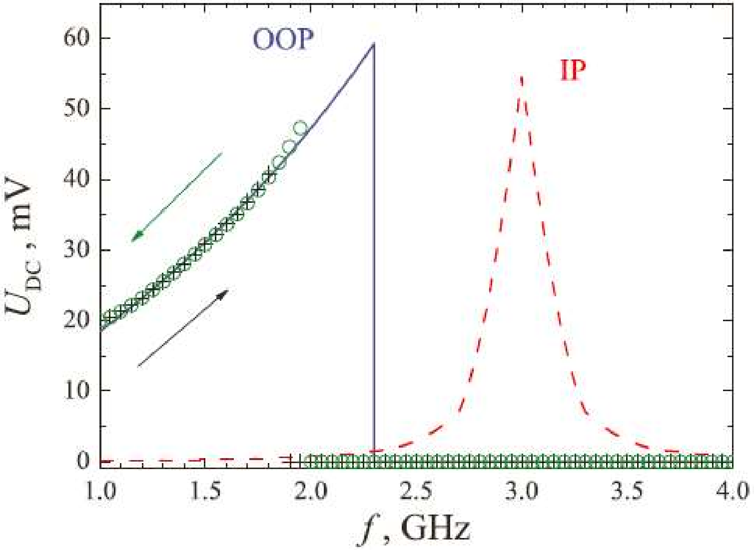
Broadband Spintronic diode

JOURNAL OF APPLIED PHYSICS **111**, 123904 (2012)

Spin-torque microwave detector with out-of-plane precessing magnetic moment

O. V. Prokopenko,[1,a)] I. N. Krivorotov,[2] E. Bankowski,[3] T. Meitzler,[3] S. Jaroch,[4] V. S. Tiberkevich,[4] and A. N. Slavin[4]





Tilted Easy axis induced by the IPA

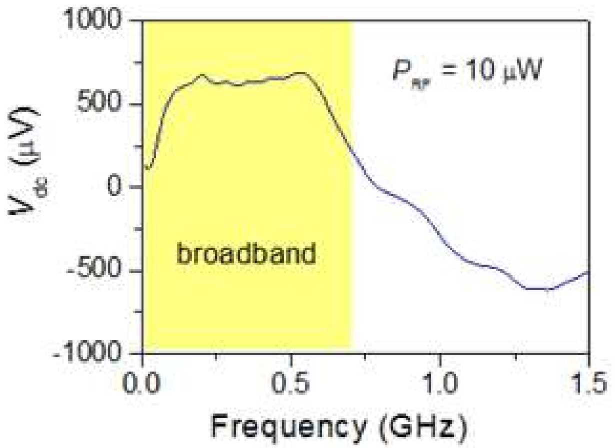
Broadband Spintronic diode

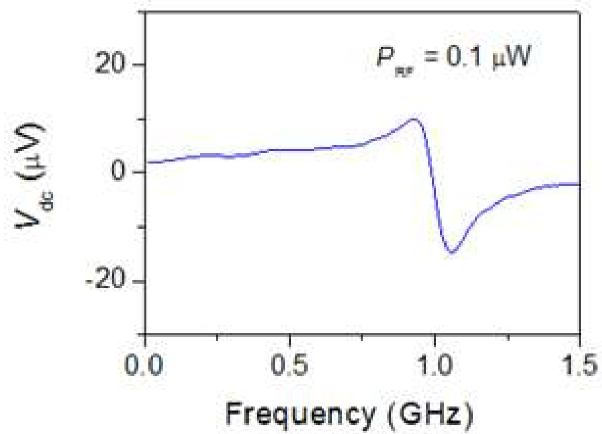
Type of response	Regime of behavior	Frequency response
Broadband	Passive	MHz-GHz

PHYSICAL REVIEW APPLIED 11, 014022 (2019)

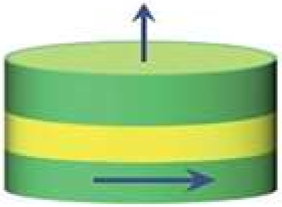
Experimental Demonstration of Spintronic Broadband Microwave Detectors and Their Capability for Powering Nanodevices

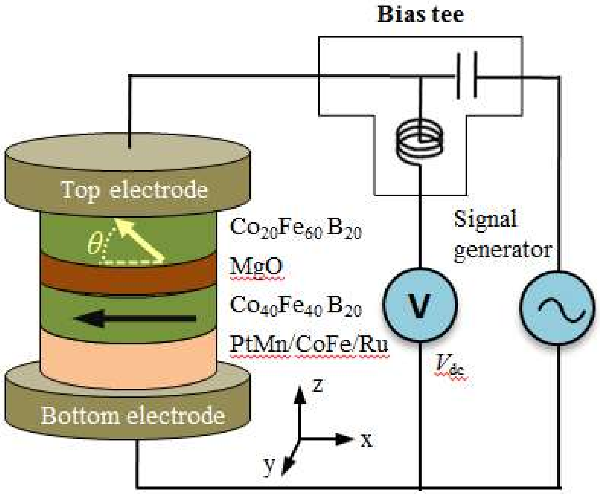
Bin Fang,[1] Mario Carpentieri,[2] Steven Louis,[3] Vasyl Tiberkevich,[4] Andrei Slavin,[4] Ilya N. Krivorotov,[5] Riccardo Tomasello,[6] Anna Giordano,[7] Hongwen Jiang,[8] Jialin Cai,[1] Yaming Fan,[1] Zehong Zhang,[1] Baoshun Zhang,[1] Jordan A. Katine,[9] Kang L. Wang,[10] Pedram Khalili Amiri,[10,11] Giovanni Finocchio,[7,*] and Zhongming Zeng[1]

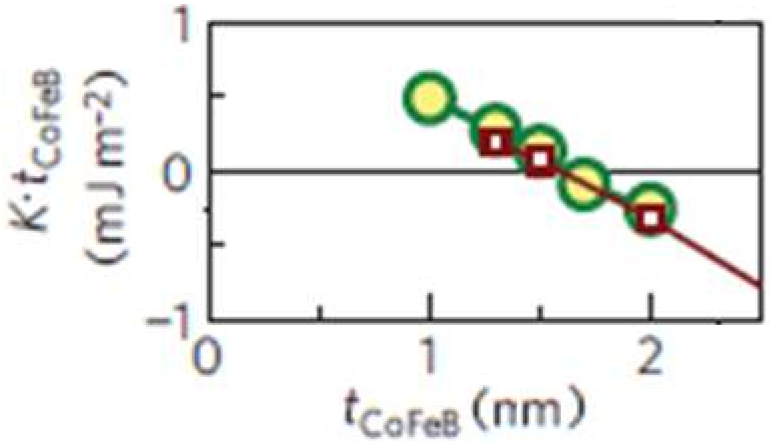




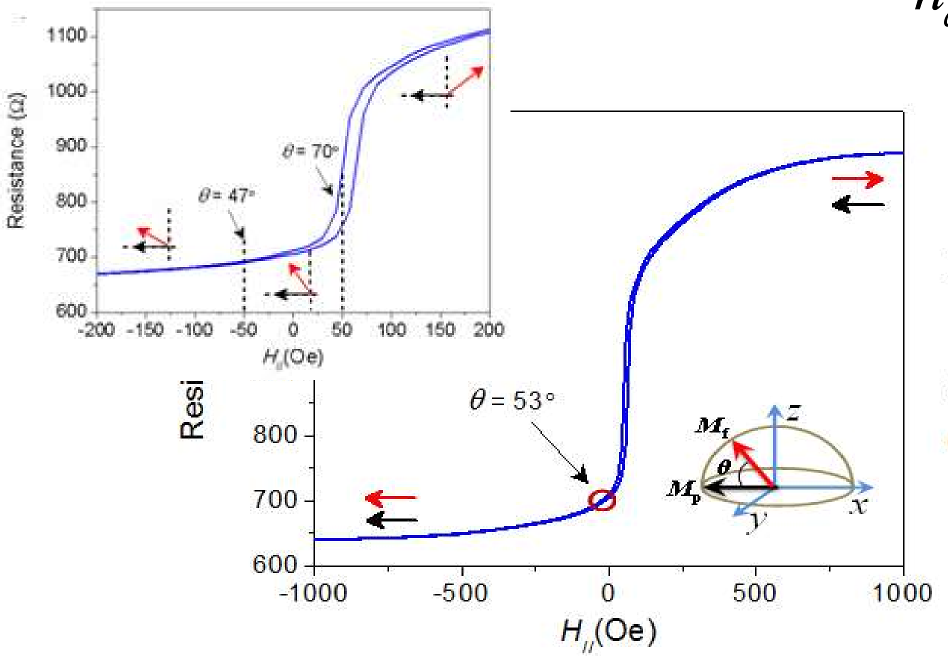
Broadband Spintronic diode

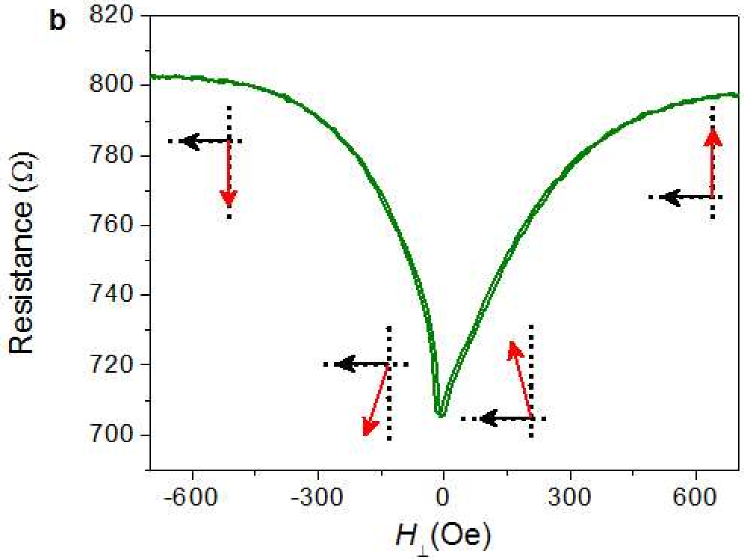




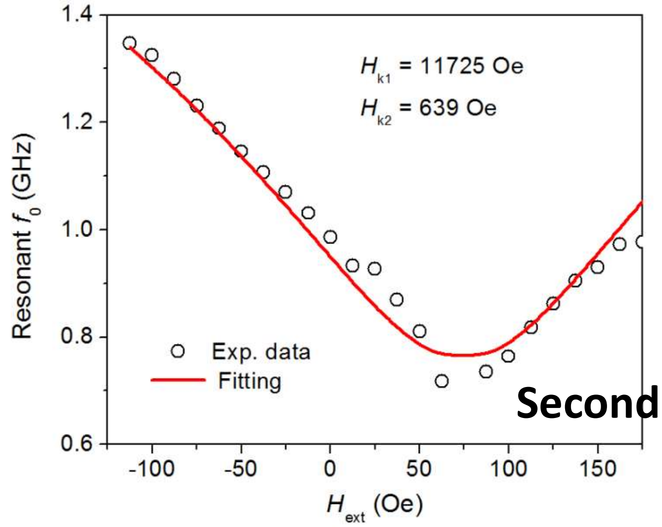


$$h_{ani-z} = \frac{2K_1 m_z + 4K_2 m_z (1 - m_z^2)}{\mu_0 M_S^2}$$





Broadband Spintronic diode

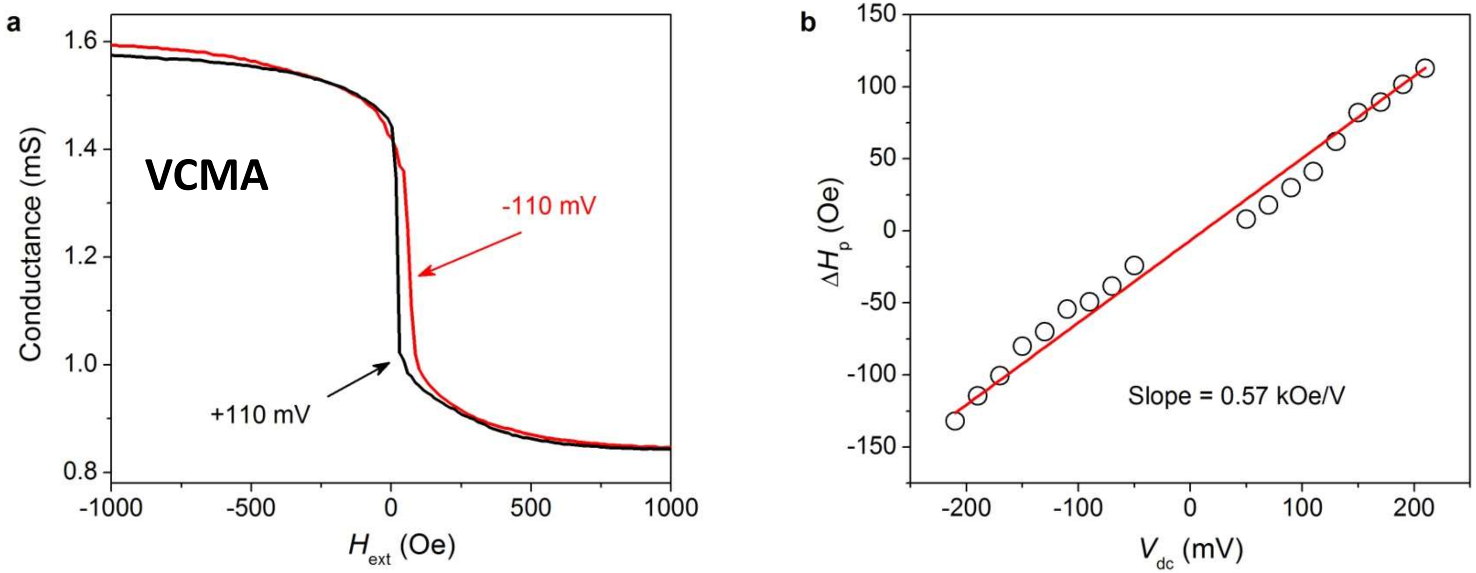


Second order anisotropy contribution in perpendicular magnetic tunnel junctions

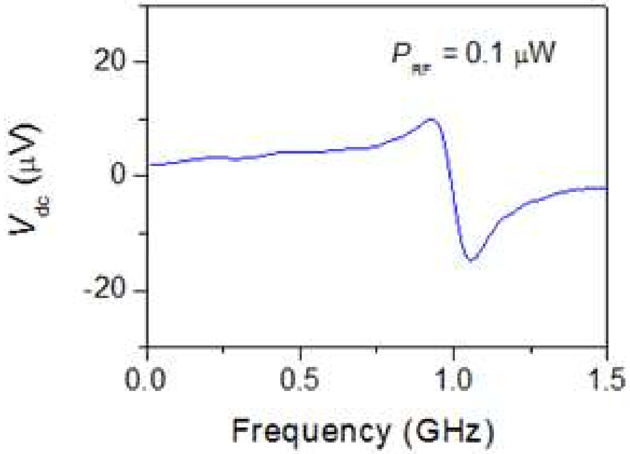
A. A. Timopheev[1,2,3], R. Sousa[1,2,3], M. Chshiev[1,2,3], H. T. Nguyen[1,2,3] & B. Dieny[1,2,3]

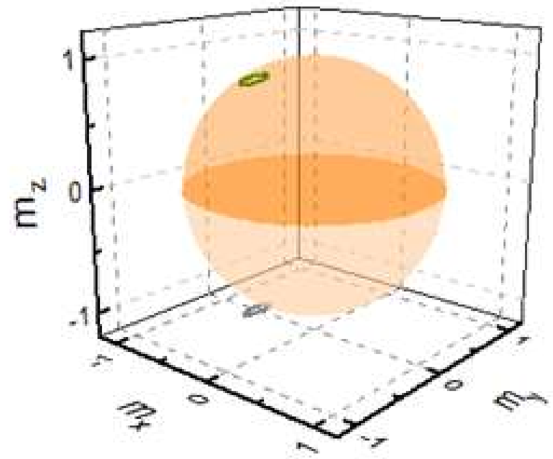
SCIENTIFIC REPORTS | 6:26877 | DOI: 10.1038/srep26877

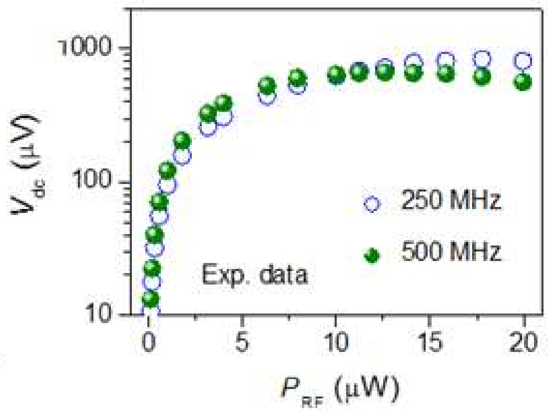
Second order anisotropy

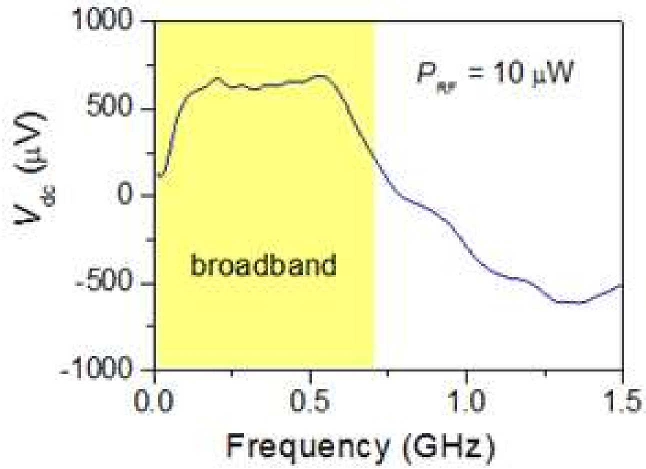


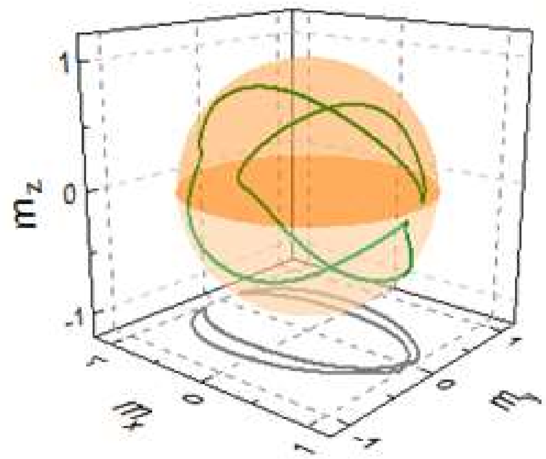
Broadband Spintronic diode

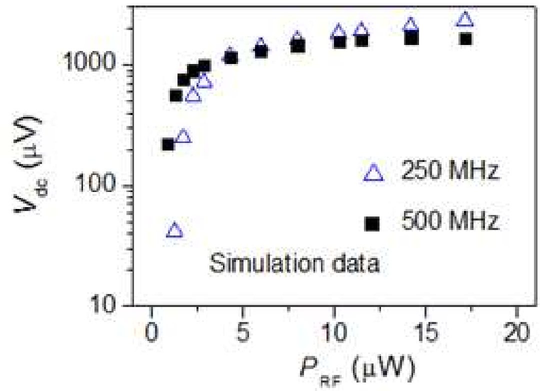


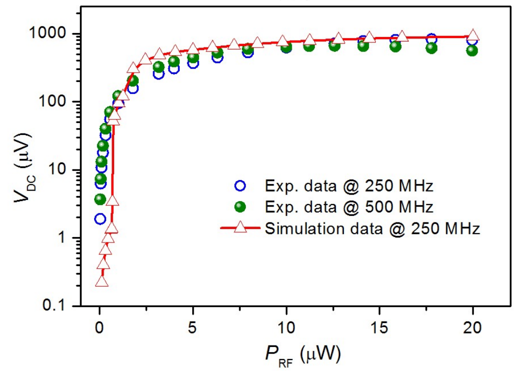










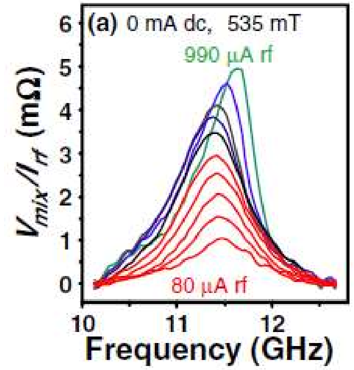


Broadband Spintronic diode

PRL 96, 227601 (2006) PHYSICAL REVIEW LETTERS week ending 9 JUNE 2006

Spin-Transfer-Driven Ferromagnetic Resonance of Individual Nanomagnets

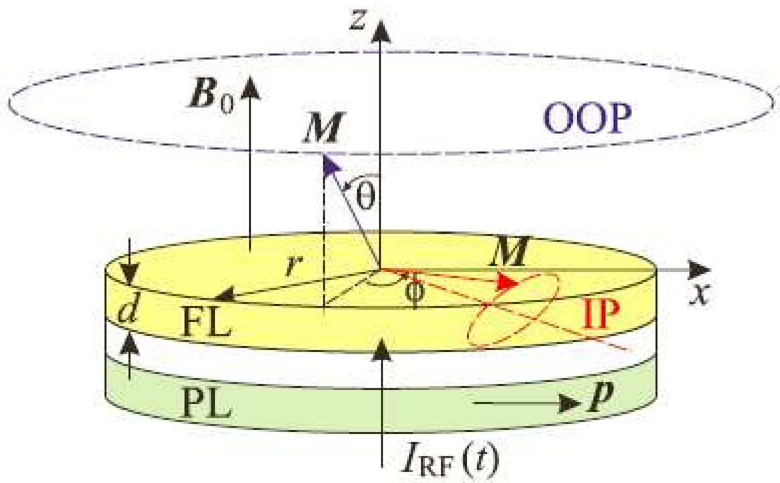
J. C. Sankey, P. M. Braganca, A. G. F. Garcia, I. N. Krivorotov, R. A. Buhrman, and D. C. Ralph
Cornell University, Ithaca, New York 14853, USA
(Received 4 February 2006; published 5 June 2006)

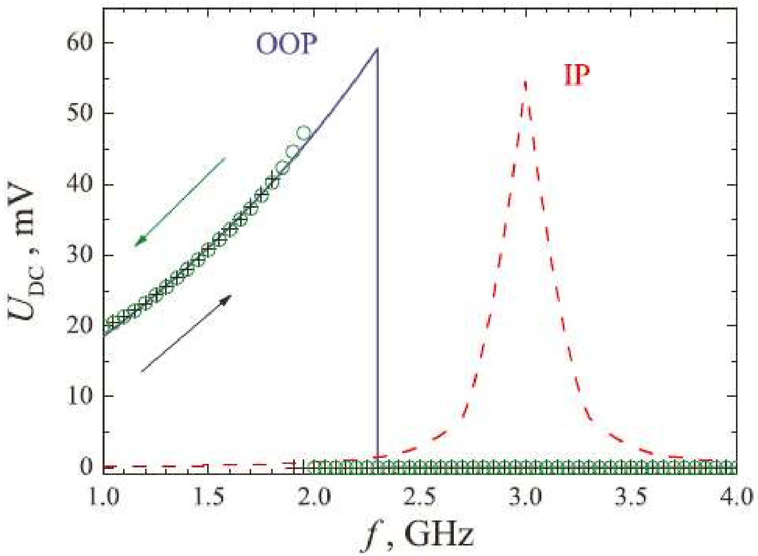


JOURNAL OF APPLIED PHYSICS 111, 123904 (2012)

Spin-torque microwave detector with out-of-plane precessing magnetic moment

O. V. Prokopenko,[1,a)] I. N. Krivorotov,[2] E. Bankowski,[3] T. Meitzler,[3] S. Jaroch,[4] V. S. Tiberkevich,[4] and A. N. Slavin[4]



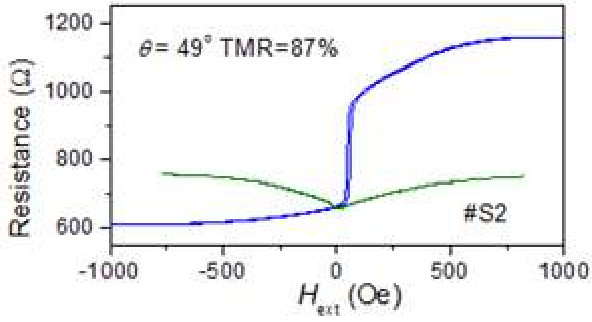


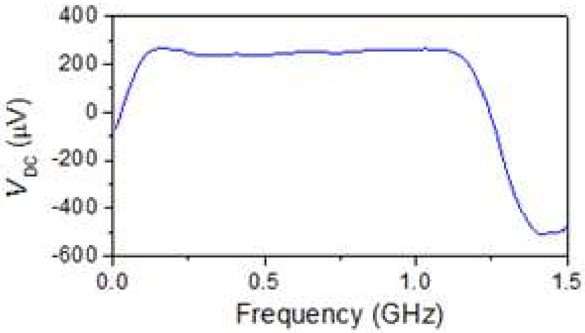
Tilted Easy axis induced by the IPA

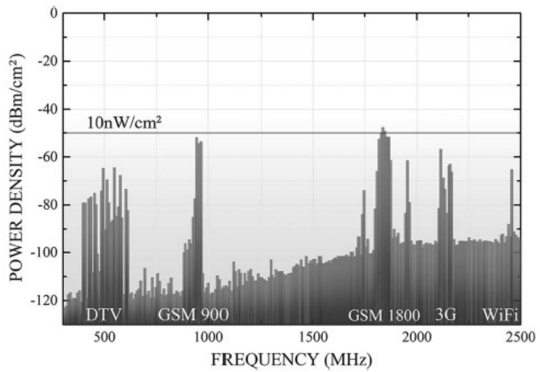
Detection voltage almost independent of the input frequency within the broadband response

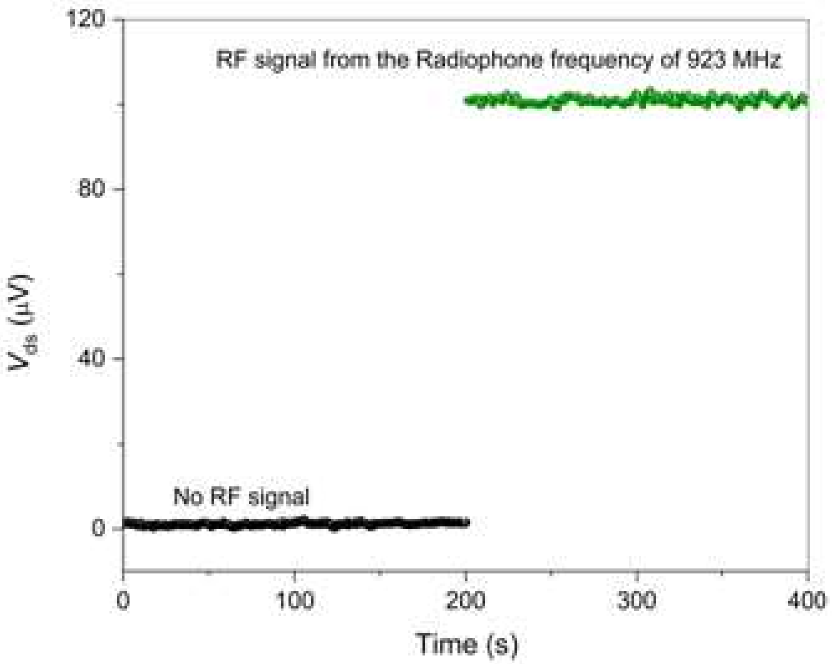
Peta Spin

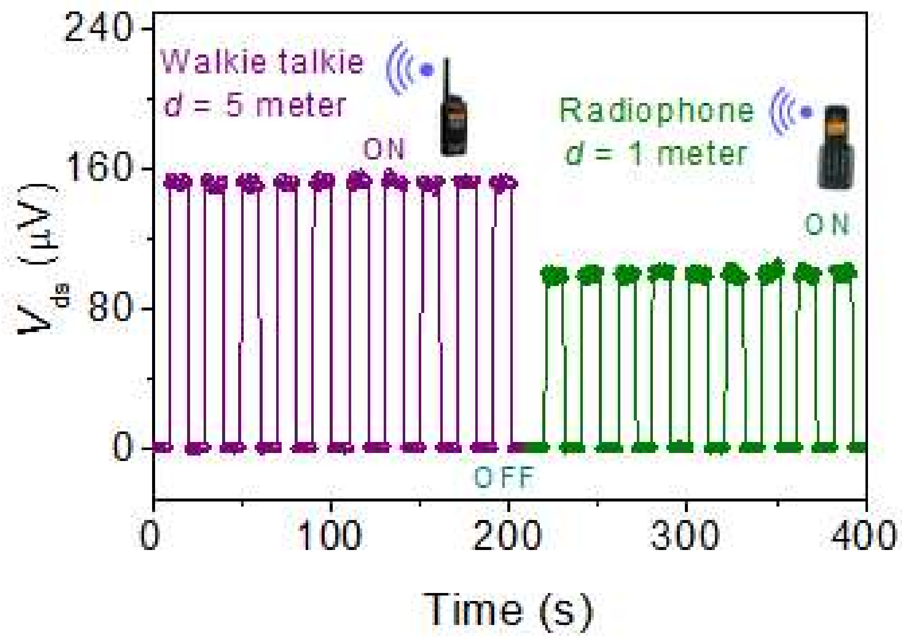
Broadband Spintronic diode











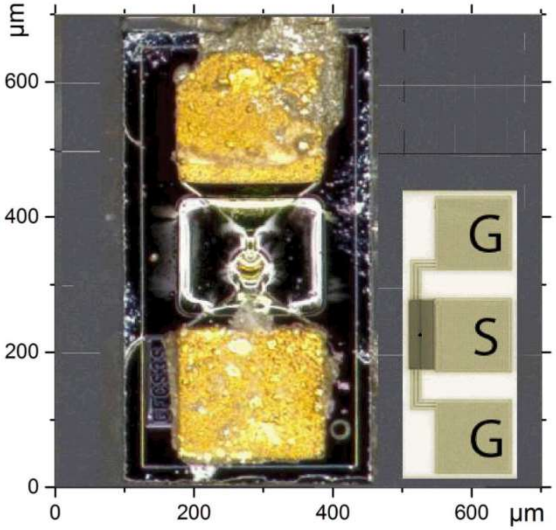
$$V \approx V_1 + V_2$$

Broadband Spintronic diode

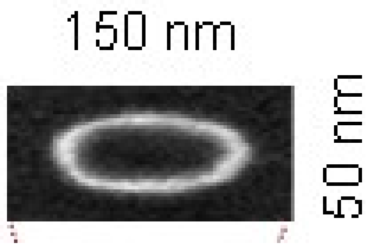
SKYWORKS

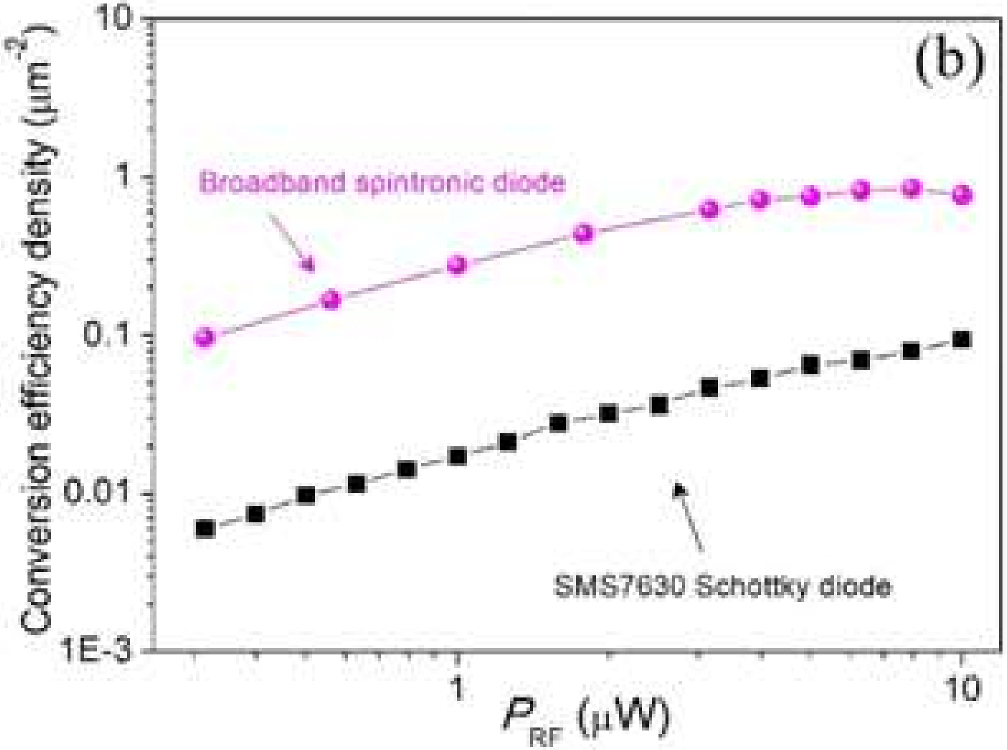
DATA SHEET

SMS7630-061: Surface Mount, 0201 Zero Bias Silicon Schottky Detector Diode



$$\eta = \frac{P_{dc}}{P_i}$$





Schottky diode Area > 10 um^2

Spintronic diode Area < 0.1 um^2

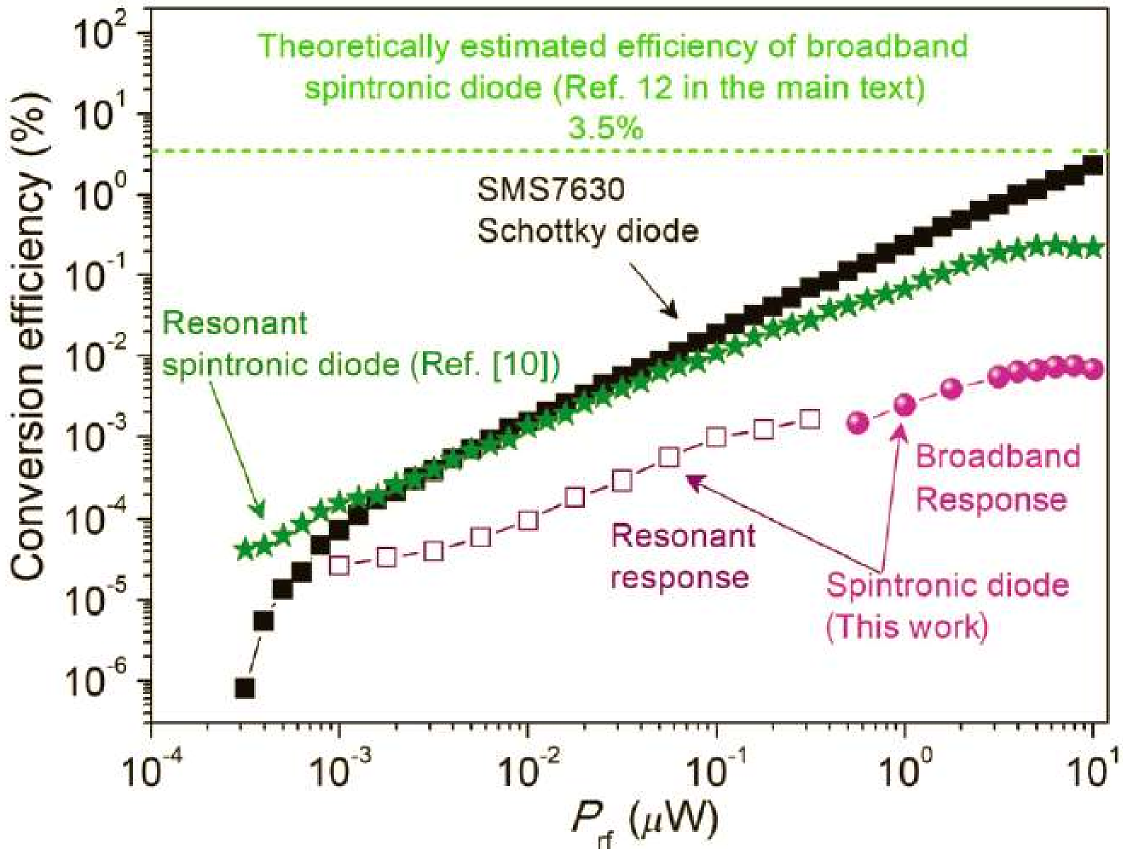
Broadband Spintronic diode

$$\eta = \frac{P_{dc}}{P_i}$$

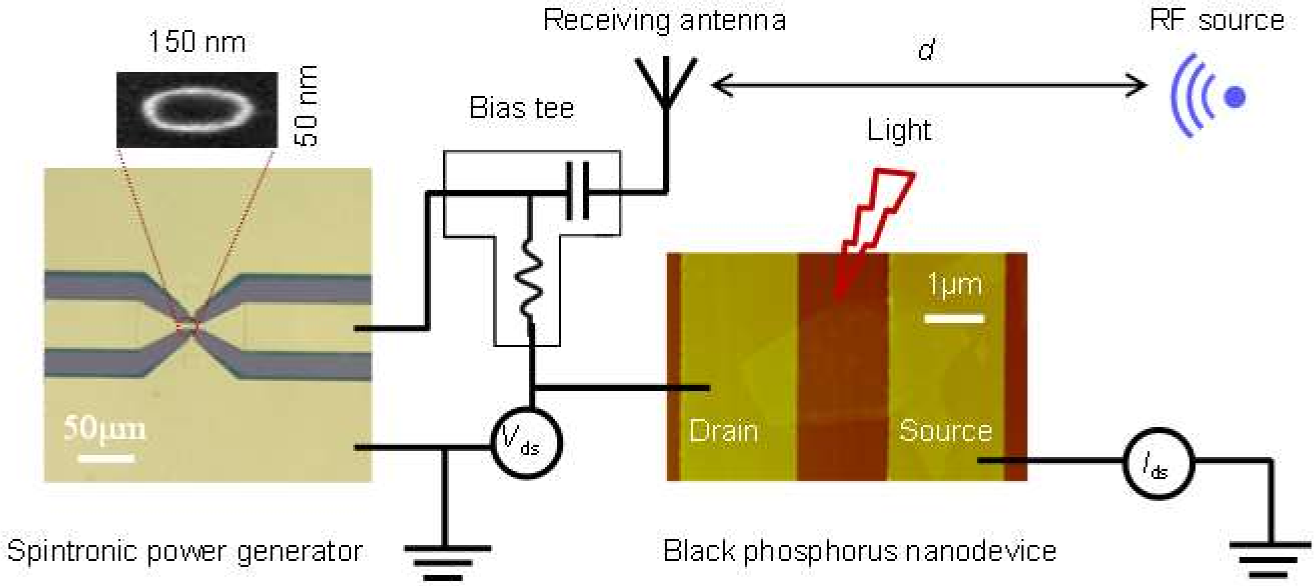
PHYSICAL REVIEW APPLIED 11, 014022 (2019)

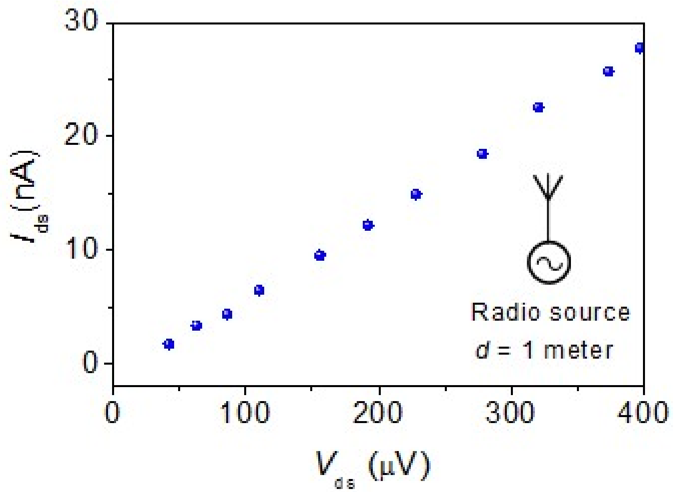
Experimental Demonstration of Spintronic Broadband Microwave Detectors and Their Capability for Powering Nanodevices

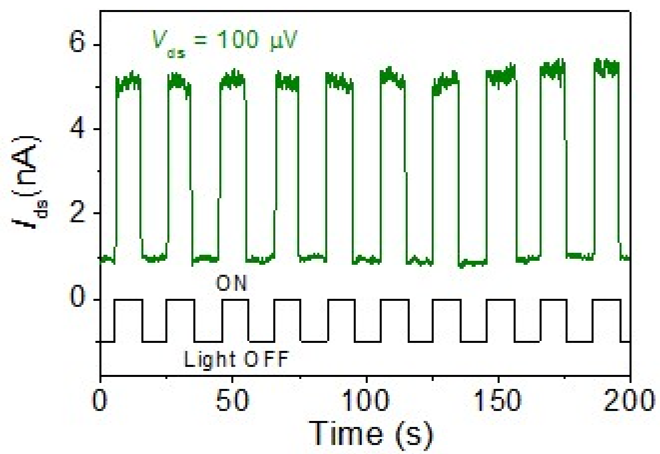
Bin Fang,[1] Mario Carpentieri,[2] Steven Louis,[3] Vasyl Tiberkevich,[4] Andrei Slavin,[4] Ilya N. Krivorotov,[5] Riccardo Tomasello,[6] Anna Giordano,[7] Hongwen Jiang,[8] Jialin Cai,[1] Yaming Fan,[1] Zehong Zhang,[1] Baoshun Zhang,[1] Jordan A. Katine,[9] Kang L. Wang,[10] Pedram Khalili Amiri,[10,11] Giovanni Finocchio,[7,*] and Zhongming Zeng[1]



Broadband Spintronic diode







Broadband Spintronic diode

Theranostics 2018, Vol. 8, Issue 4 1005

IVYSPRING INTERNATIONAL PUBLISHER

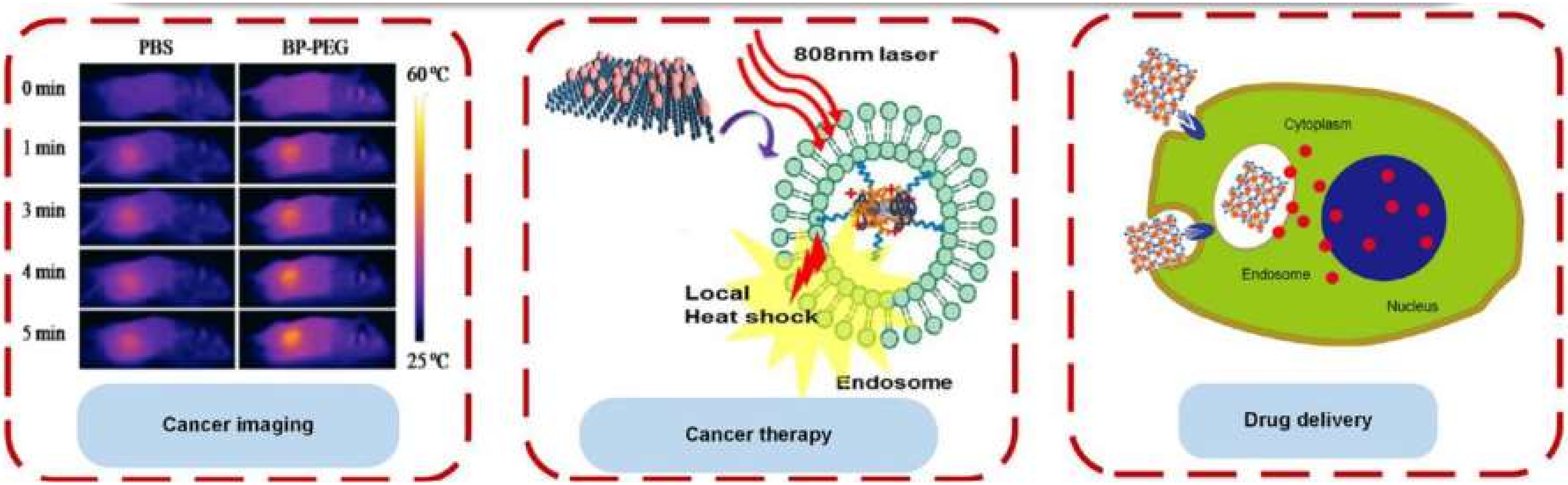
Theranostics

2018; 8(4): 1005-1026. doi: 10.7150/thno.22573

Review

Black Phosphorus and its Biomedical Applications

Jane Ru Choi[1*], Kar Wey Yong[2*], Jean Yu Choi[3], Azadeh Nilghaz[1], Yang Lin[4], Jie Xu[4], Xiaonan Lu[1]



Peta Spin

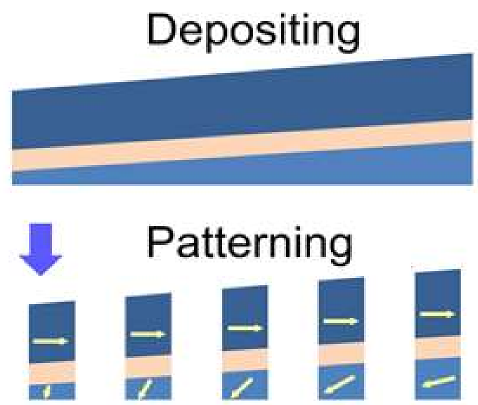
Broadband Spintronic diode

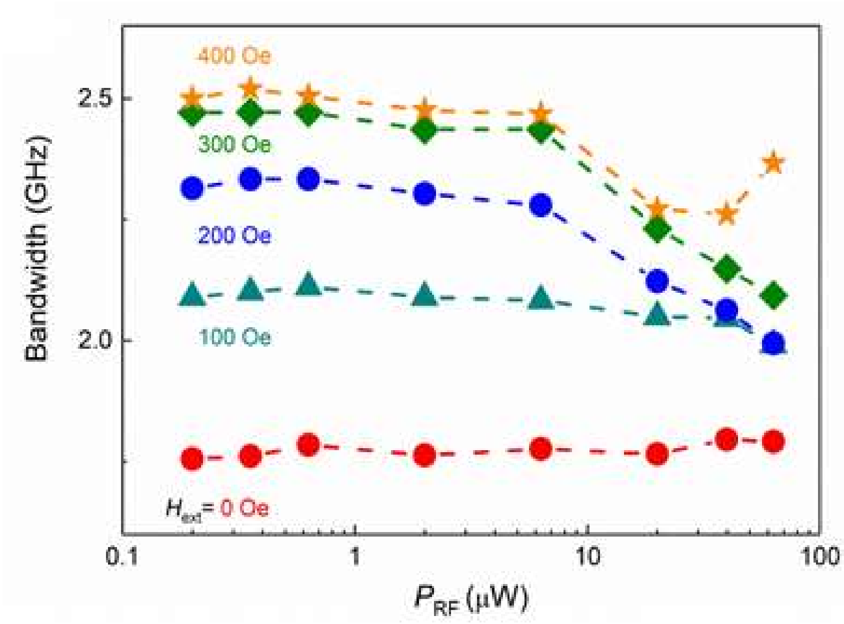
Optimization of broadband detectors

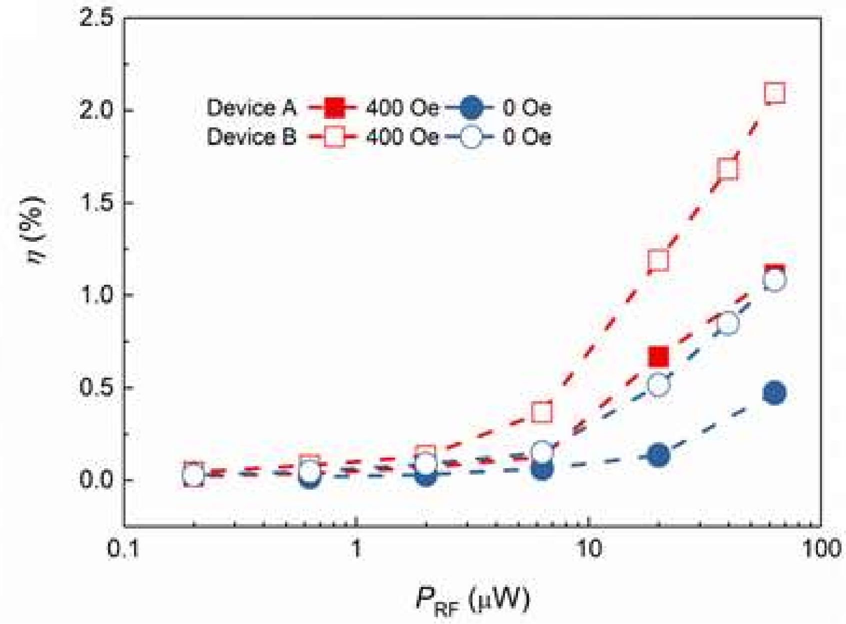
ACS APPLIED MATERIALS & INTERFACES
Research Article
Cite This: ACS Appl. Mater. Interfaces 2019, 11, 29382−29387
www.acsami.org

Enhanced Broad-band Radio Frequency Detection in Nanoscale Magnetic Tunnel Junction by Interface Engineering

Like Zhang,[†,‡] Bin Fang,[†] Jialin Cai,[†,‡] Weican Wu,[†] Baoshun Zhang,[†,‡] Bochong Wang,[§] Pedram Khalili Amiri,[∥] Giovanni Finocchio,[⊥] and Zhongming Zeng[*,†,‡]

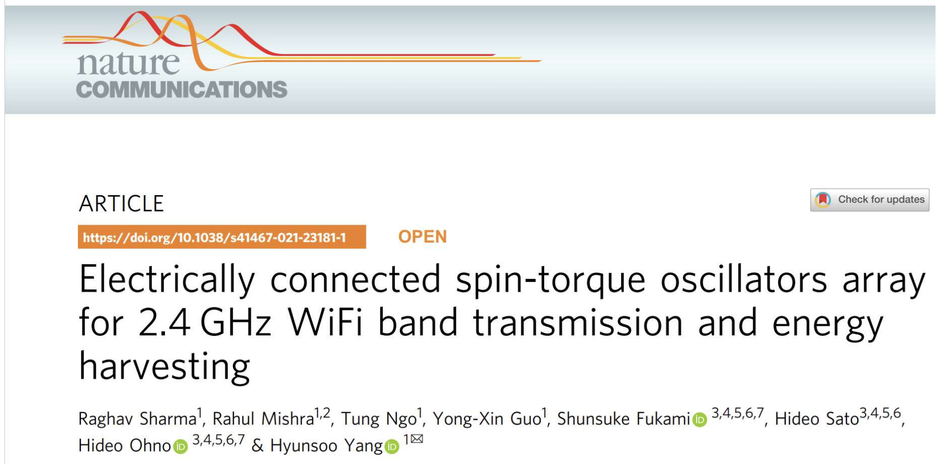






Broadband Spintronic diode

Injection locked spintronic diodes – Array configuration


nature COMMUNICATIONS

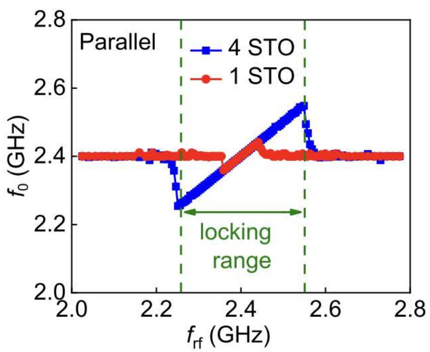
ARTICLE

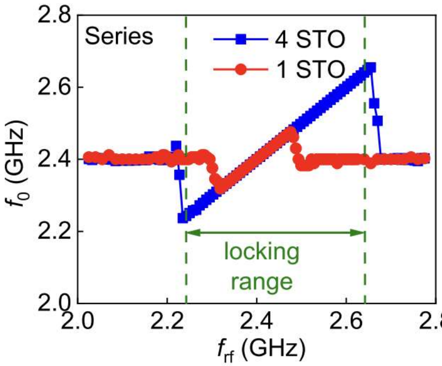
Check for updates

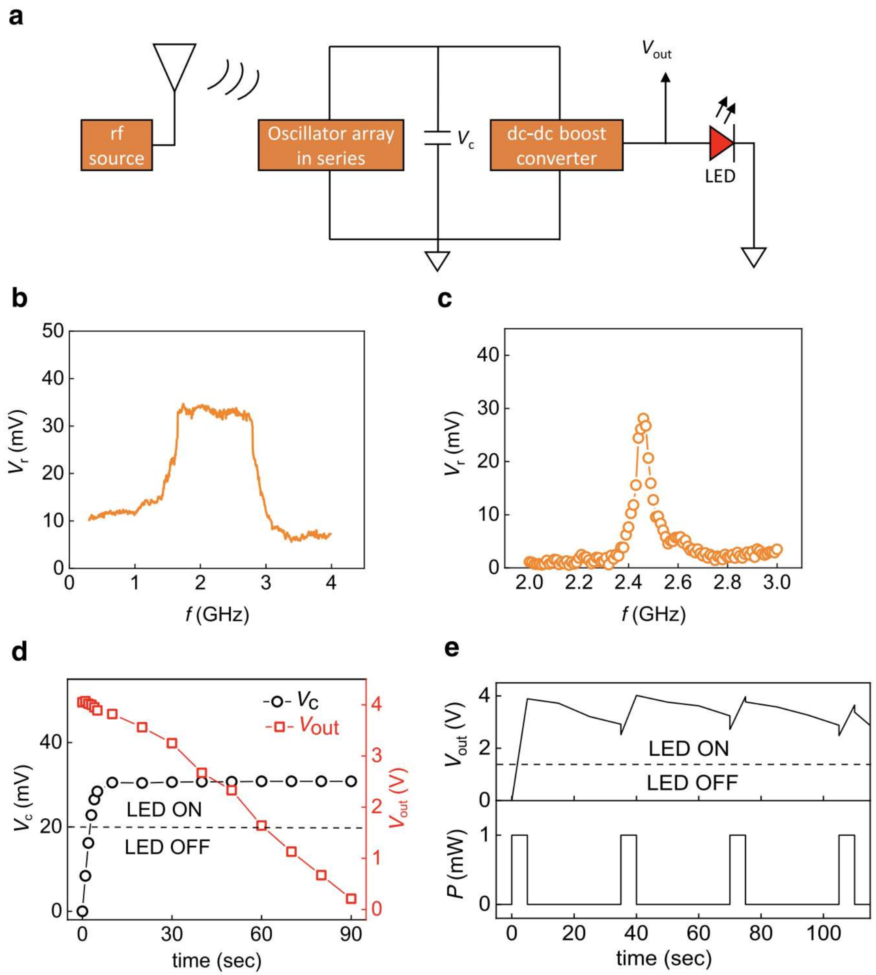
https://doi.org/10.1038/s41467-021-23181-1 OPEN

Electrically connected spin-torque oscillators array for 2.4 GHz WiFi band transmission and energy harvesting

Raghav Sharma[1], Rahul Mishra[1,2], Tung Ngo[1], Yong-Xin Guo[1], Shunsuke Fukami[3,4,5,6,7], Hideo Sato[3,4,5,6], Hideo Ohno[3,4,5,6,7] & Hyunsoo Yang[1✉]







Peta Spin

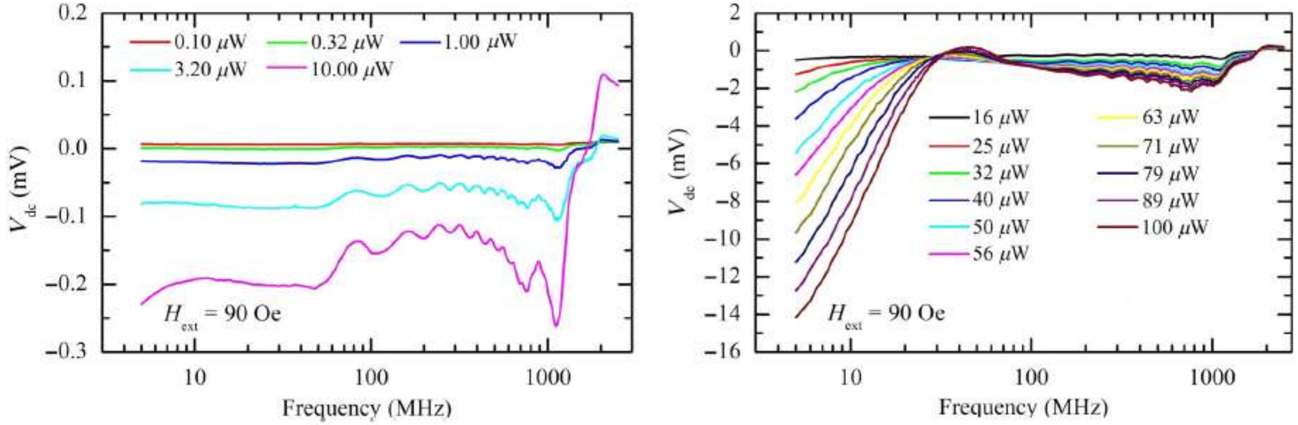
Broadband Spintronic diode

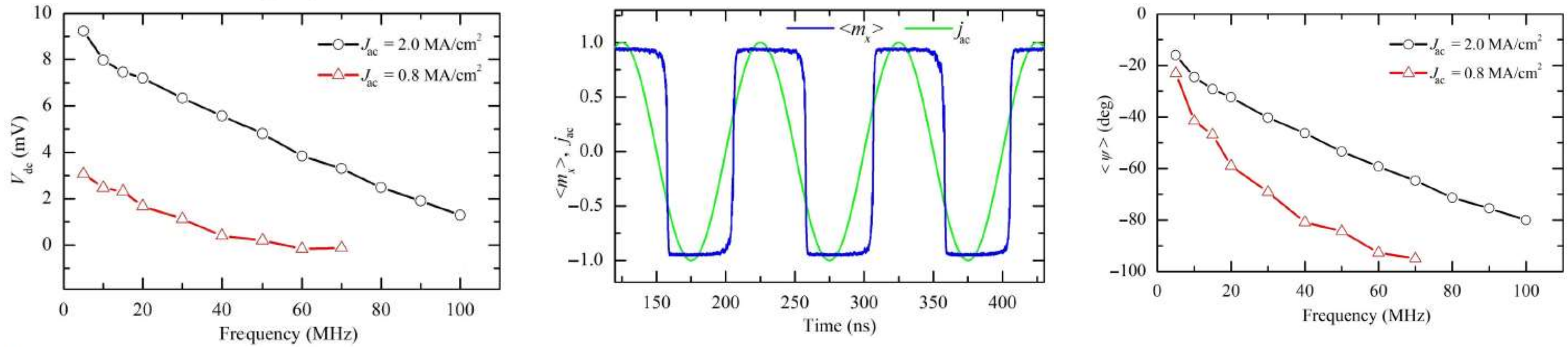
Type of response	Regime of behavior	Frequency response
Low-frequency tail	Passive	MHz

PHYSICAL REVIEW APPLIED **14**, 024043 (2020)

Low-Frequency Nonresonant Rectification in Spin Diodes

R. Tomasello,[1,*] B. Fang,[2,§] P. Artemchuk,[3,4] M. Carpentieri,[5] L. Fasano,[6] A. Giordano,[7] O.V. Prokopenko,[3] Z.M. Zeng,[2,†] and G. Finocchio[7,‡]





Peta Spin

THz Detectors

Progress in Quantum Electronics 34 (2010) 278–347

ELSEVIER

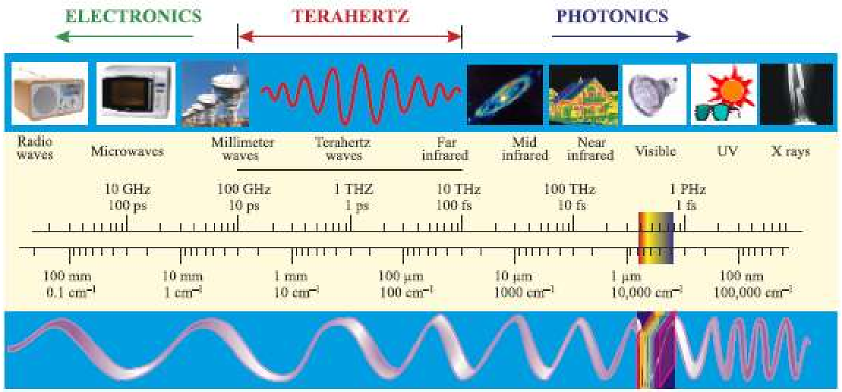
Progress in Quantum Electronics

Review

THz detectors

F. Sizov[a,*], A. Rogalski[b]

- ❑ Incoherent detection systems which allow only signal amplitude detection.
- ❑ Coherent detection systems, which allow detecting not only the amplitude of the signal, but also its phase.



- ❑ Photon detectors.
- ❑ Thermal detectors.

OPTO-ELECTRONICS REVIEW 19(3), 346–404, 2011

DOI: 10.2478/s11772-011-0033-3

Terahertz detectors and focal plane arrays

A. ROGALSKI[1] and F. SIZOV[2]

Letter | Vol. 43, No. 8 / 15 April 2018 / Optics Letters 1647

Graphene-based broadband terahertz detector integrated with a square-spiral antenna

WANLONG GUO,[1,2,3] LIN WANG,[1,*] XIAOSHUANG CHEN,[1,4] CHANGLONG LIU,[1] WEIWEI TANG,[1] CHENG GUO,[1] JIN WANG,[1] AND WEI LU[1]

Table 1. Comparison of the Performance and Efficiency of this Work and the Earlier Works About Graphene Based Terahertz Detectors

Materials Device Architecture	Spectral Range (Terahertz)	NEP (nW/Hz$^{0.5}$)	Responsivity (V/W)	References
Monolayer Graphene Square-Spiral Antenna	0.08 ~ 0.12, 0.14, 0.3	0.35	28	This Letter
Bilayer Graphene FET	0.29 ~ 0.38	2	1.2	[6]
Graphene FET on Flexible Substrate	0.487	3	2	[26]
Monolayer Graphene FET	0.3	30	0.15	[15]
Monolayer Graphene Asymmetrical Electrodes	1.9	1.7	4.9	[8]
Monolayer Graphene Split Gating	0.4	0.13	74	[21]

- ❑ Graphene based THz detectors.
- ❑ THz detectors with metamaterials.
- ❑ AFM –based THz detectors.

Review | Trends in Food Science & Technology 85 (2019) 241–251

State-of-the-art in terahertz sensing for food and water security – A comprehensive review

Aifeng Ren[a,b], Adnan Zahid[a], Dou Fan[b], Xiaodong Yang[b], Muhammad Ali Imran[a], Akram Alomainy[c], Qammer H. Abbasi[a,*]

Detection of water content in living plant leaves: The first application of THz imaging and sensing for detecting the water content is to monitor and evaluate the moisture level of plant leaves, which can provide the valuable information to farmers and scientists regarding plant drought stress and irrigation management. In (Qu, Nie, Lin, Cai, &

Peta Spin

THz Detectors

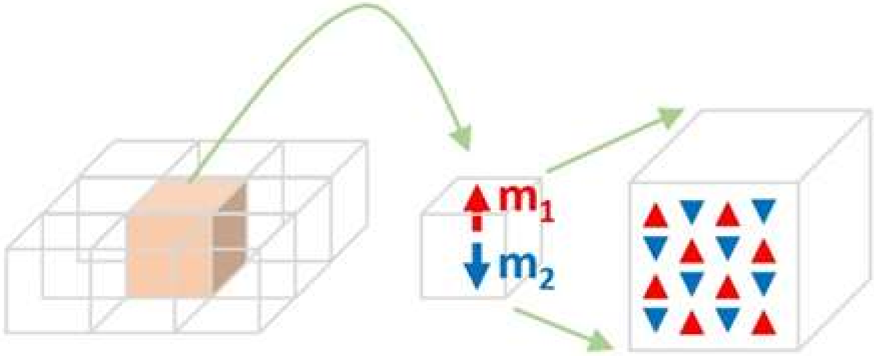
Type of response	Regime of behavior	Frequency response
Resonant	Passive/Passive	THz

Theoretical predictions

Main motivations:

- ❑ **Resonant**
- ❑ **Tuneable electrically**
- ❑ **Compact size**

Micromagnetics

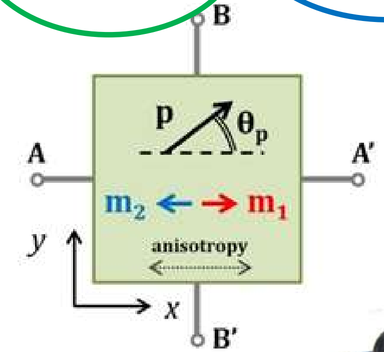


$$\begin{cases} \mathbf{h}_{\text{eff-1}} = \mathbf{h}_{\text{exch-1}} + \mathbf{h}_{\text{ani-1}} + \mathbf{h}_{\text{demag-1}} \\ \mathbf{h}_{\text{eff-2}} = \mathbf{h}_{\text{exch-2}} + \mathbf{h}_{\text{ani-2}} + \mathbf{h}_{\text{demag-2}} \end{cases}$$

$$\begin{cases} \mathbf{h}_{\text{exch-1}} = \lambda_{\text{AFM}} \mathbf{m}_2 + \alpha_{\text{exch-FM}} \nabla^2 \mathbf{m}_1 + \alpha_{\text{exch-AFM}} \nabla^2 \mathbf{m}_2 \\ \mathbf{h}_{\text{exch-2}} = \lambda_{\text{AFM}} \mathbf{m}_1 + \alpha_{\text{exch-FM}} \nabla^2 \mathbf{m}_2 + \alpha_{\text{exch-AFM}} \nabla^2 \mathbf{m}_1 \end{cases}$$

$$\begin{cases} \dfrac{d\mathbf{m}_1}{d\tau} = -(\mathbf{m}_1 \times \mathbf{h}_{\text{eff-1}}) + \alpha \mathbf{m}_1 \times \dfrac{d\mathbf{m}_1}{d\tau} + d_J (\mathbf{m}_1 \times \mathbf{m}_1 \times \mathbf{p}) \\ \dfrac{d\mathbf{m}_2}{d\tau} = -(\mathbf{m}_2 \times \mathbf{h}_{\text{eff-2}}) + \alpha \mathbf{m}_2 \times \dfrac{d\mathbf{m}_2}{d\tau} + d_J (\mathbf{m}_2 \times \mathbf{m}_2 \times \mathbf{p}) \end{cases}$$

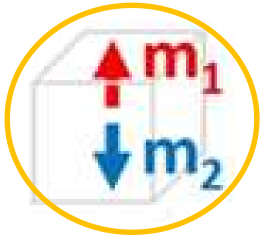
$$d_J = \frac{g\mu_B}{2\gamma_0 e M_S^2}$$



PRL 117, 017202 (2016) PHYSICAL REVIEW LETTERS week ending 1 JULY 2016

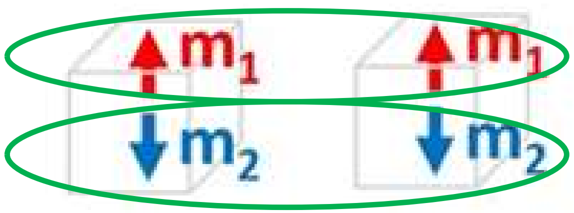
High Antiferromagnetic Domain Wall Velocity Induced by Néel Spin-Orbit Torques

O. Gomonay,[1,2,*] T. Jungwirth,[3,4] and J. Sinova[1,3]



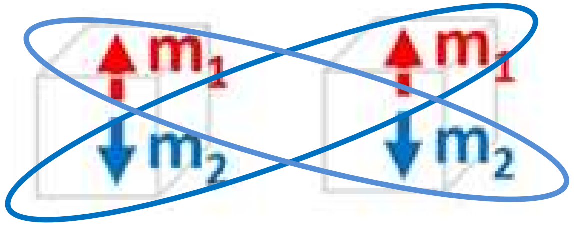
λ_{AFM}

J-1 J



$\alpha_{\text{exch-FM}}$

J-1 J



$\alpha_{\text{exch-AFM}}$

THz Detectors

Homogeneous intersublattice exchange constant A_0=5.0 pJ/m

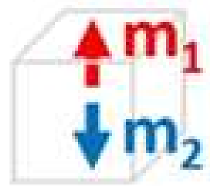
Atomic lattice constant a=0.5nm ➔ A_0/a^2=20MJ/m^3 (high hom. interlattice exch.)

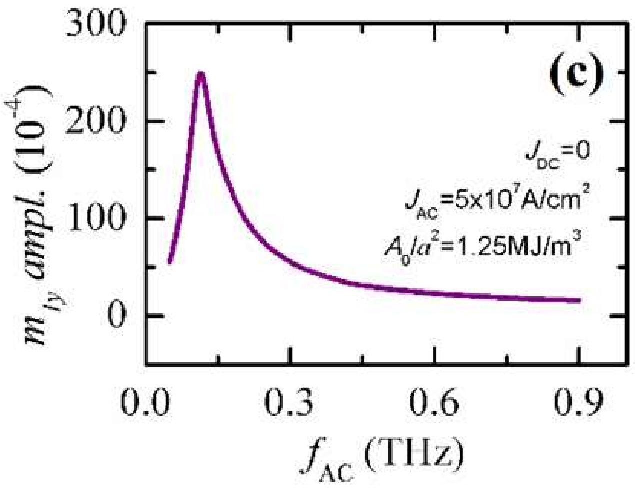
Atomic lattice constant a=1.0nm ➔ A_0/a^2=5MJ/m^3

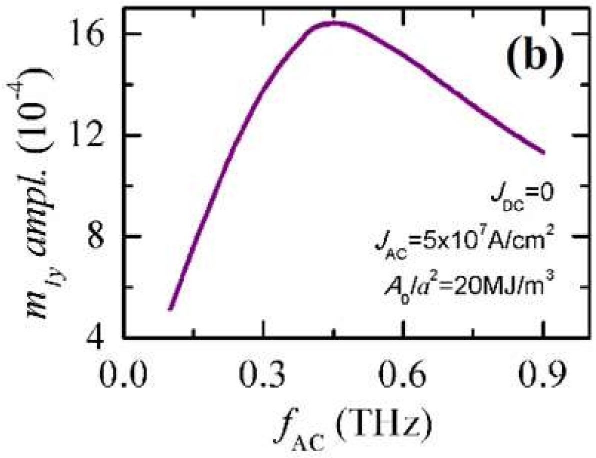
Atomic lattice constant a=2.0nm ➔ A_0/a^2=1.25MJ/m^3 (low hom. interlattice exch.)

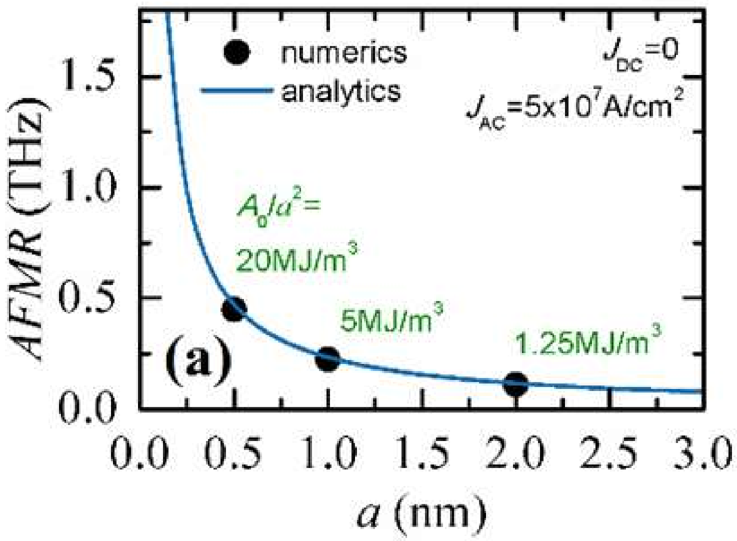
$$H_{ani} = 2K_U/M_s$$

$$H_{ex} = \frac{4A_{AFM}}{a^2 M_s}$$









$$f_{AFMR} = \frac{\gamma_0}{2\pi}\sqrt{2H_{ex}H_{ani}}$$

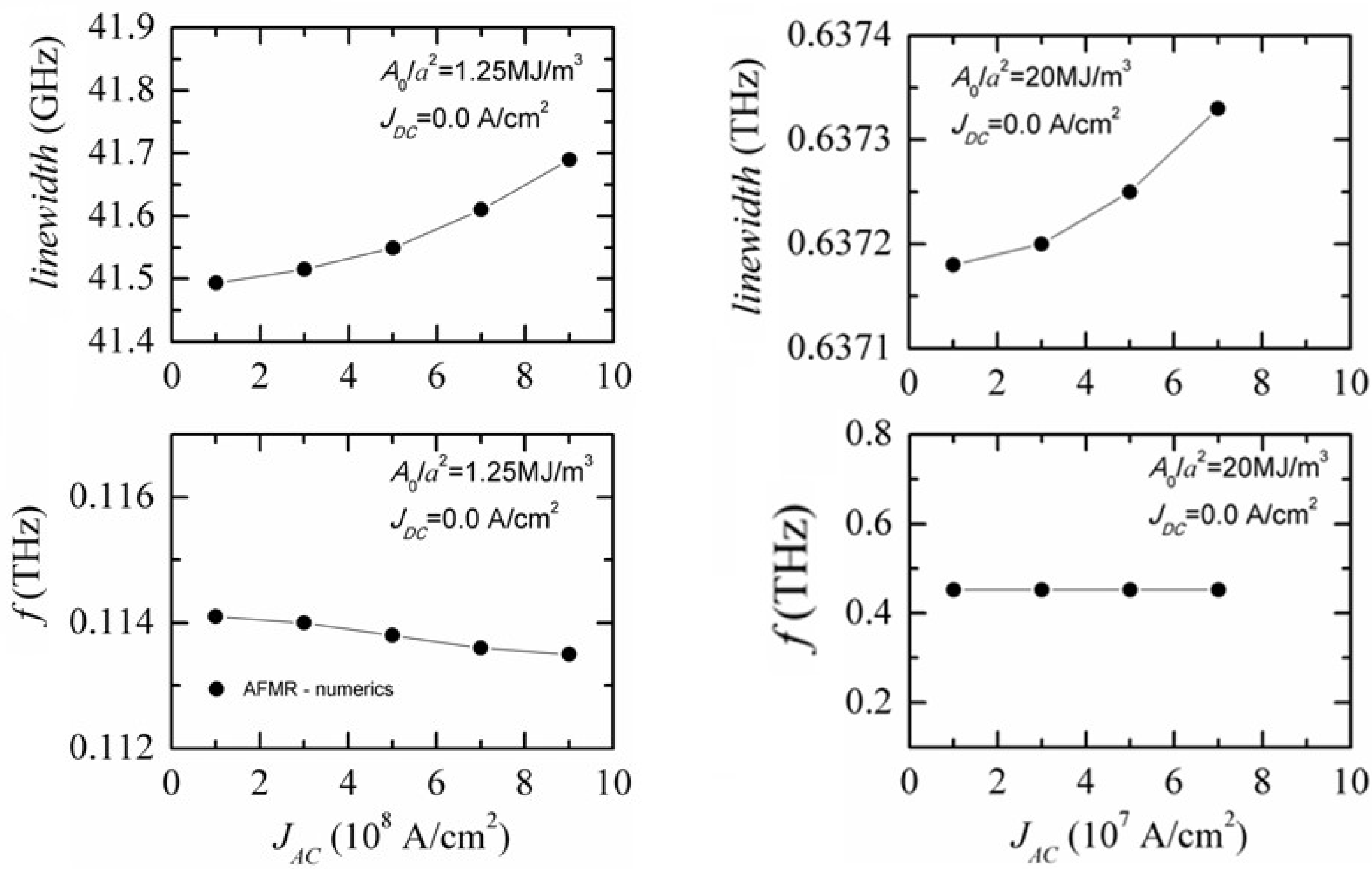
Numerical results agree with the analytical model:

Resonant frequency and **linewidth** as a function of the input current amplitude.

THz Detectors

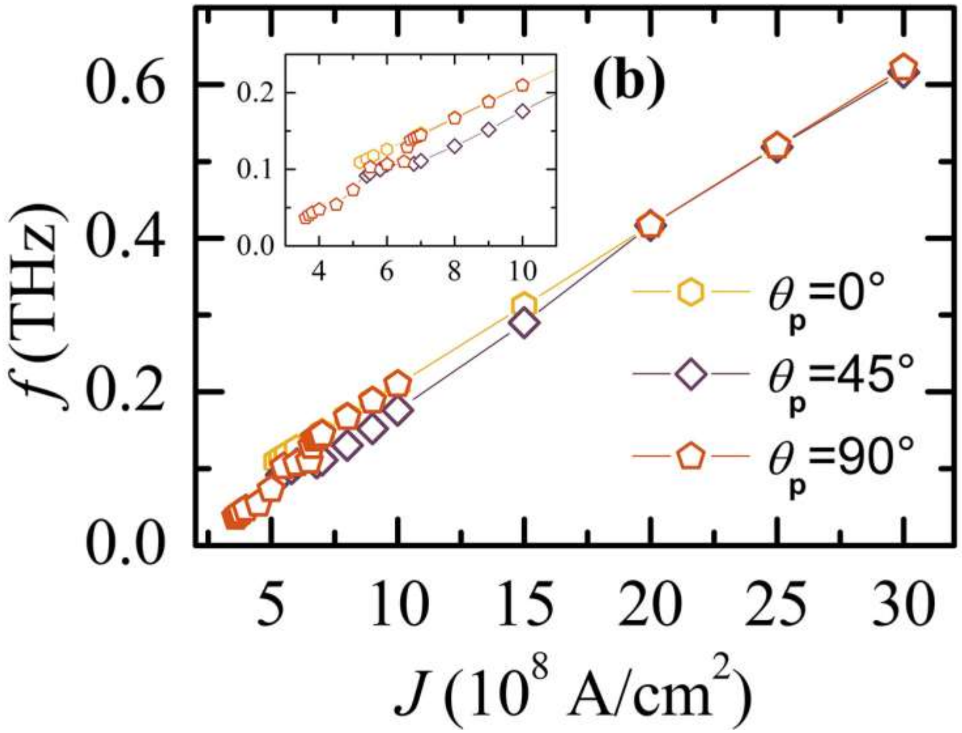
LOW
HOM. INTERSUBLATTICE EXCHANGE

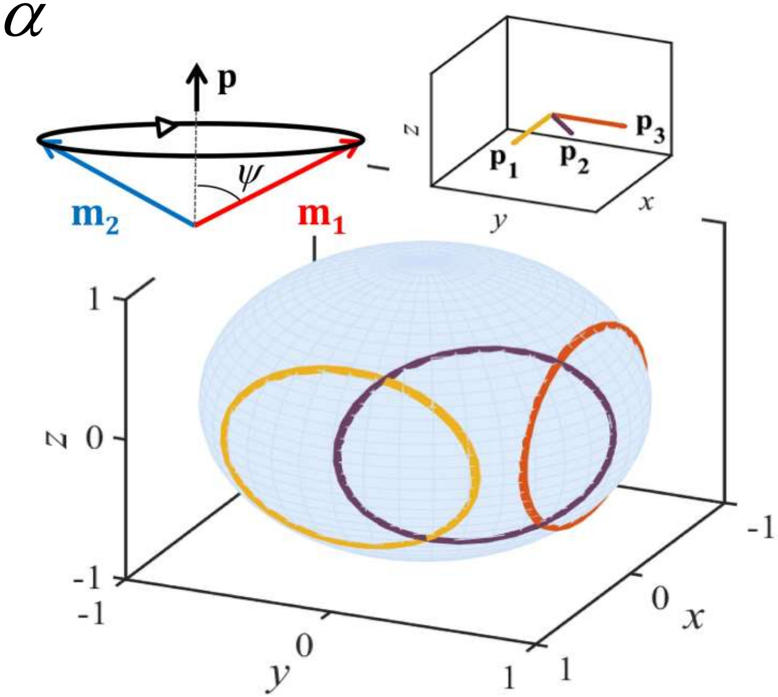
HIGH
HOM. INTERSUBLATTICE EXCHANGE

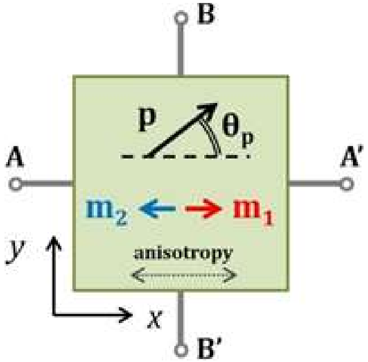


THz Detectors

$$\omega = \frac{\sigma J}{\alpha}$$





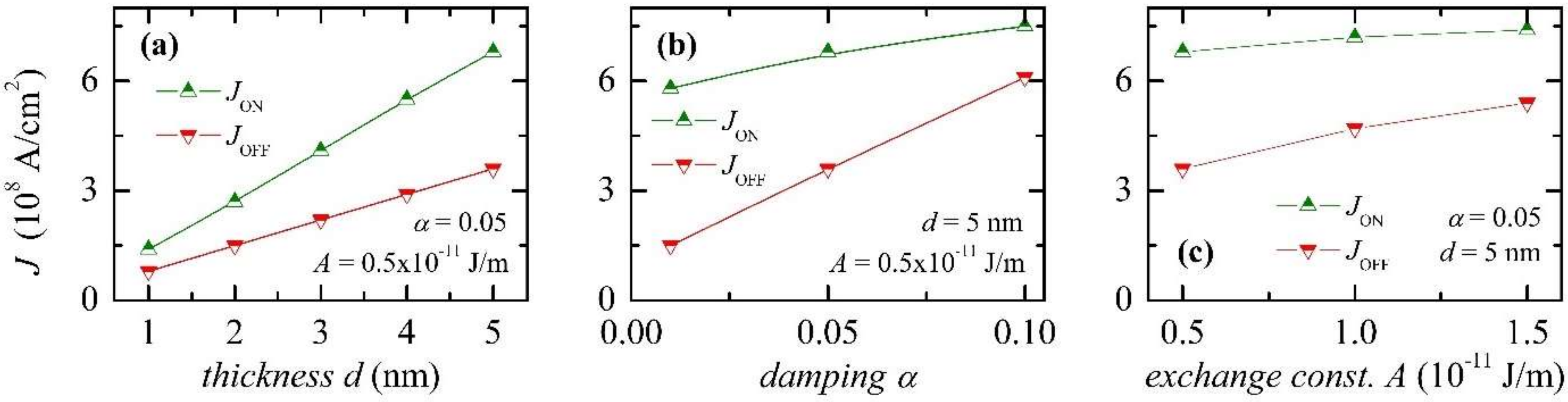


PHYSICAL REVIEW B **99**, 024405 (2019)

Micromagnetic modeling of terahertz oscillations in an antiferromagnetic material driven by the spin Hall effect

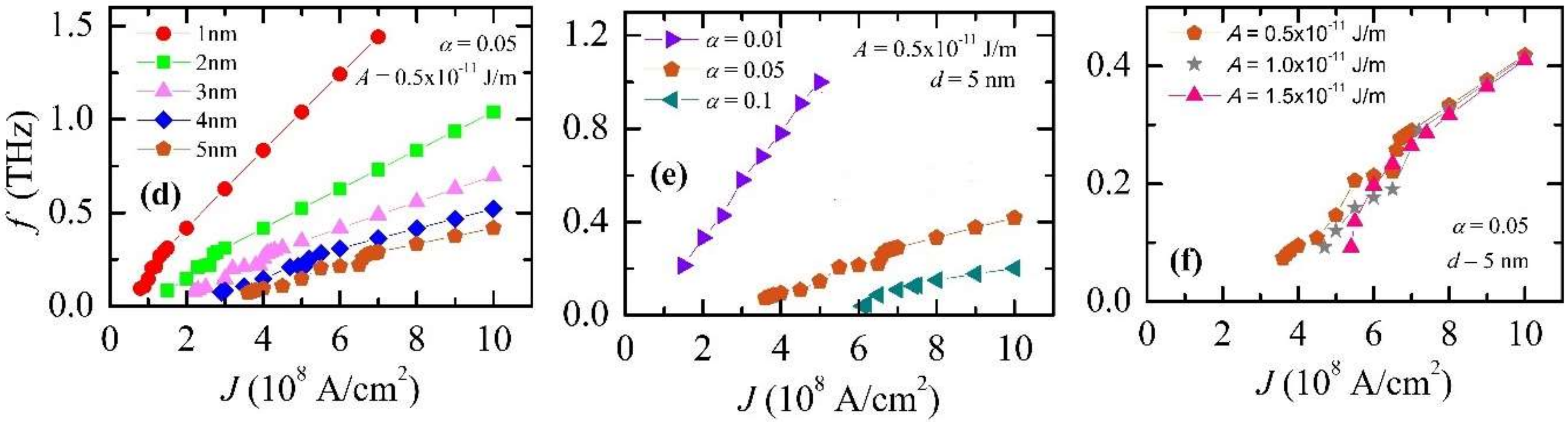
V. Puliafito,[1] R. Khymyn,[2] M. Carpentieri,[3] B. Azzerboni,[1] V. Tiberkevich,[4] A. Slavin,[4] and G. Finocchio[5]

THz Detectors



$$j_1^{\text{th}} = \frac{\omega_e}{2\sigma} \qquad j_2^{\text{th}} = \frac{2\alpha}{\pi\sigma}\sqrt{\omega_{\text{ex}}\omega_e}$$

$$\omega = \frac{\sigma J}{\alpha}$$

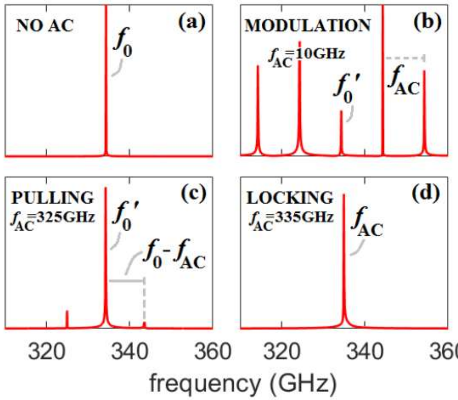


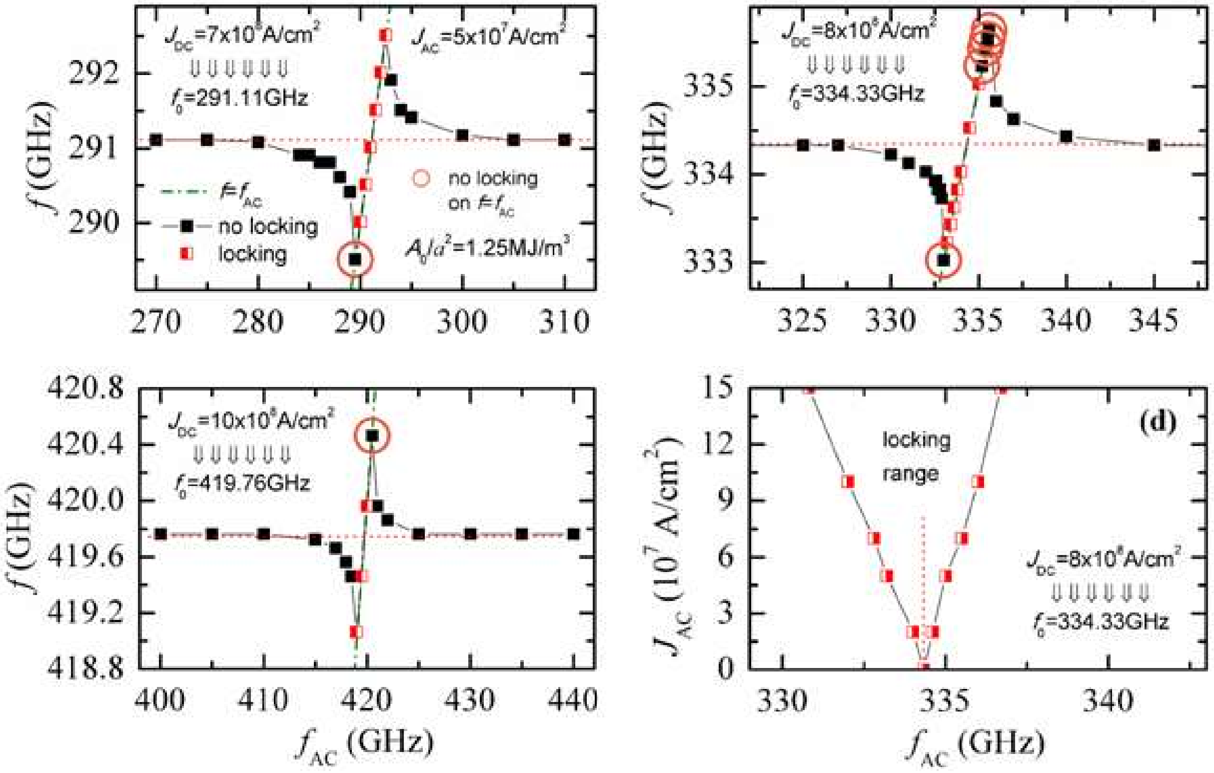
THz detectors

IEEE TRANSACTIONS ON MAGNETICS, VOL. 57, NO. 2, FEBRUARY 2021 4100106

Modulation, Injection Locking, and Pulling in an Antiferromagnetic Spin-Orbit Torque Oscillator

V. Puliafito[1], L. Sanchez-Tejerina[2,3], M. Carpentieri[4], B. Azzerboni[1], and G. Finocchio[3]





- Above-threshold regime
- Locking of the oscillation at the THz signal
- Narrow-band detection
- Quality factor $Q = f/\Delta f$ of about 400

Narrow-band tunable terahertz detector in antiferromagnets via staggered-field and antidamping torques

O. Gomonay,[1] T. Jungwirth,[2,3] and J. Sinova[1,2]

THz Detectors

Appl. Phys. Lett. 117, 222411 (2020); doi: 10.1063/5.0031053

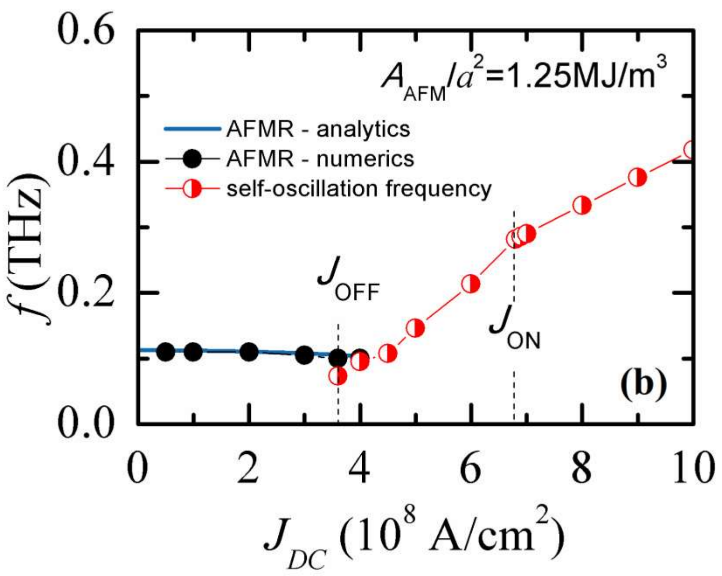
Electrically tunable detector of THz-frequency signals based on an antiferromagnet

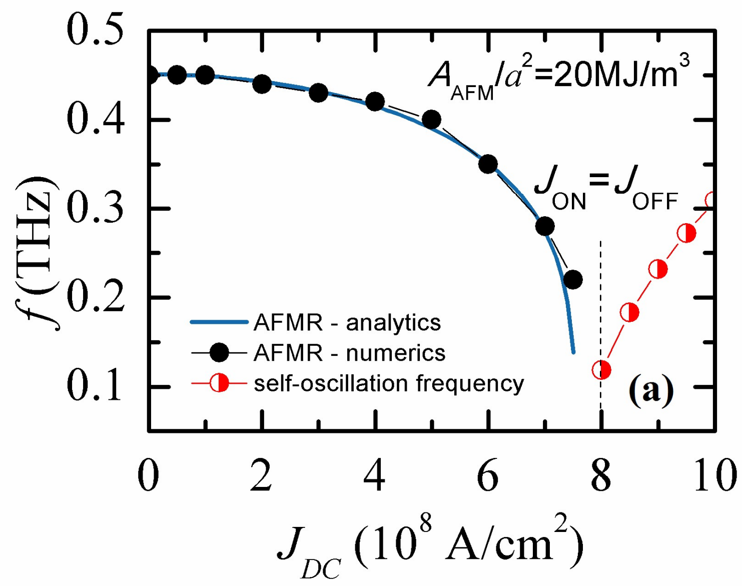
View Online Export Citation CrossMark

A. Safin,[1,2,a)] V. Puliafito,[3] M. Carpentieri,[4] G. Finocchio,[5] S. Nikitov,[1,6,7] P. Stremoukhov,[1,6,8] A. Kirilyuk,[1,8] V. Tyberkevych,[9] and A. Slavin[9]

$$f_{AFMR} = \frac{\gamma_0}{2\pi}\sqrt{2H_{ex}H_{ani}} \quad H_{ex} = \frac{4A_{AFM}}{a^2 M_s}$$

$$\omega_{\mathrm{AFMR}}(\tau) = \gamma\mu_0\sqrt{\sqrt{1-\frac{4\tau^2}{(\gamma\mu_0 H_e)^2}}H_{\mathrm{ex}}H_e}$$



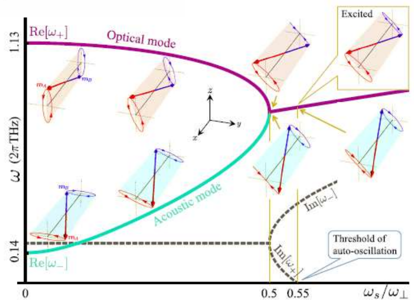


PRL 116, 207603 (2016) PHYSICAL REVIEW LETTERS week ending 20 MAY 2016

Terahertz Antiferromagnetic Spin Hall Nano-Oscillator

Ran Cheng* and Di Xiao
Department of Physics, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA

Arne Brataas
Department of Physics, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway



Peta Spin

Conclusions

- Spintronic diodes based on magnetic tunnel juntions are ready to face the last challenges needed to face before approaching the market!

- Antiferromagnets are very promising for the realization of a resonant, compact (sub-micrometer size) and tuneable THz detector. (Still on the paper but I think in less than 1 year, there will be a proof-of-concept.

Perspectives on spintronic diodes

Cite as: Appl. Phys. Lett. **118**, 160502 (2021); doi: 10.1063/5.0048947
Submitted: 28 February 2021 · Accepted: 8 April 2021 ·
Published Online: 22 April 2021

View Online Export Citation CrossMark

G. Finocchio,[1,a)] R. Tomasello,[2] B. Fang,[3] A. Giordano,[1] V. Puliafito,[4] M. Carpentieri,[5] and Z. Zeng[6]