Book of Abstracts

International Symposium on Integrated Magnetics 2025
iSIM 2025

January 12–13, 2025

New Orleans, USA

International Symposium on Integrated Magnetics 2025 (iSIM 2025)
January 12–13, 2025, New Orleans, USA
Book of Abstracts
https://theisim.org/

Web site

Contents

List of supporters and sponsors

The iSIM 2025 is financially sponsored and supported by the IEEE Magnetics Society.

Platinum sponsor

The IEEE Magnetics Society (https://ieeemagnetics.org/) is the leading international professional organization for magnetism and for related professionals. It promotes the advancement of science, technology, applications and training in magnetism. There are 2100 members and 45 chapters throughout the world (22 Americas, 9 Europe and 14 Asia). The Magnetics Society sponsors major conferences including Intermag, MMM, and Joint MMM/Intermag, organizes summer schools, and publishes the IEEE Transactions on Magnetics, IEEE Magnetics Letters, Special Magnetics Section in the IEEE eXplorer, and the Society Newsletter. Each of four Distinguished Lectures deliver 40-50 talks every year. Women in Magnetism (WiM), Young Professionals (YP) and Students in Magnetism (SiM) are getting more active in recent years. Please visit the Society Web for details, and join it!

The iSIM 2025 is financially supported by the industry sponsors

Gold sponsors

ANALOG DEVICES

AHEAD OF WHAT'S POSSIBLE™

Analog Devices, Inc. (ADI) is a global semiconductor leader that bridges the physical and digital worlds to enable breakthroughs at the Intelligent Edge. ADI combines analog, digital, and software technologies into solutions that help drive advancements in digitized factories, mobility, and digital healthcare, combat climate change, and reliably connect humans and the world. With revenue of more than $9 billion in FY24 and approximately 24,000 people globally, ADI ensures today's innovators stay Ahead of What's Possible. Learn more at www.analog.com and on LinkedIn and Twitter (X).

BOSCH

Bosch Sensortec GmbH, a fully owned subsidiary of Robert Bosch GmbH, develops and markets a wide portfolio of microelectromechanical systems (MEMS) sensors and solutions tailored for smartphones, tablets, wearables and hearables, AR/VR devices, drones, robots, smart home and IoT (Internet of Things) applications. The product portfolio includes 3-axis accelerometers, gyroscopes and magnetometers, integrated 6- and 9-axis sensors, smart sensors, barometric pressure sensors, humidity sensors, gas sensors, optical microsystems and comprehensive software. Since its foundation in 2005, Bosch Sensortec has emerged as the MEMS technology leader in the markets it addresses. Bosch has been both a pioneer and one of the leading providers in the MEMS sensor segment since 1995 and has, to date, sold more than 20 billion MEMS sensors.

Futek Furnace

Management owned and Yokohama based Futek Furnace has been developing, manufacturing and selling thermal processing equipment via an international dealer network for over 40 years. Their current thermal processing equipment line-up includes a broad range of magnetic annealing ovens that are integral to a variety of thin film applications including the development and production of non-volatile memory, sensors and thin film heads.

MULTi DiMENSiON
Sensing the Future

MultiDimension Technology is a leading supplier of magnetic sensors specializing in Tunneling Magnetoresistance (TMR) technology. The company offers high-quality TMR magnetic sensors and system solutions for industrial, consumer and automotive sensor applications. MDT has corporate headquarters in Zhangjiagang Free Trade Zone, Jiangsu, China, with subsidiaries located in San Jose, CA, USA, Tokyo, Japan, and Beijing, Shanghai, Shenzhen, Chengdu, Ningbo in China. MDT owns a unique portfolio of intellectual properties and state-of-the-art manufacturing facilities that support volume production of high-performance, low-power and low-cost sensors to satisfy the most demanding customer needs. Led by its founding team of elite experts and veterans in magnetic sensor technology and engineering services, MDT is committed to creating added values to its customers and ensuring their success.

As a leading global company of innovative semiconductor production equipment, Tokyo Electron (TEL) engages in development, manufacturing, and sales in a wide range of product fields. All of TEL's semiconductor production equipment product lines maintain high market shares in their respective global segments. TEL provides outstanding products and services to customers through a global network in the U.S., Europe, and Asia.

Silver sponsors

The evico magnetics GmbH was founded in 2006 as spin-off of the Leibniz Institut for Solid State and Materials Research (IFW) Dresden. The main products are: (i) Advanced magneto-optical wide-field Kerr microscope systems for the visualization of magnetic domains and magnetization processes in all kinds of magnetic materials. The Kerr microscopes also serve as magneto-optical magnetometers for the sensitive and local measurement of hysteresis loops by MOKE magnetometry. (ii) High Pressure Milling Vials with a gas temperature monitoring system for the synthesis of magnetic powders and hydrogen storage materials. See www.evicomagnetics.com for information.

Hprobe is a global leader in testing solutions for MRAM, advanced memories, and magnetic sensors. Its cutting-edge magnetic field generators produce high-intensity fields with extremely fast amplitude and angular sweep rates. These systems integrated into wafer-level testing equipment are ideal for mass production and R&D applications. By ensuring reliability, performance, and scalability, Hprobe drives the advancement of memory technologies and magnetic sensors across consumer electronics, automotive, and industrial sectors.

Texas Instruments (www.ti.com) is a global semiconductor company that designs, manufactures, tests and sells analog and embedded processing chips. Our approximately 80,000 products help over 100,000 customers efficiently manage power, accurately sense and transmit data and provide the core control or processing in their designs, going into markets such as industrial, automotive, personal electronics, communications equipment and enterprise systems. Our passion to create a better world by making electronics more affordable through semiconductors is alive today as each generation of innovation builds upon the last to make our technology smaller, more efficient, more reliable and more affordable – opening new markets and making it possible for semiconductors to go into electronics everywhere.

General information

Organizing Committee

General Chair: Dr. Dok Won Lee,
Texas Instruments, USA

Program Chair: Prof. Jeffrey McCord,
Kiel University, Europe

Vice Program Chair: Prof. Shin Yabukami,
Tohoku University, Asia

Treasurer: Prof. Amal El-Ghazaly,
Cornell University, USA

Publications & Publicity Chair: Prof. Runwei Li,
Ningbo Institute of Material Technology & Engineering, Asia

Web Admin: Dr. Oleksandr Pylypovskyi,
Helmholtz-Zentrum Dresden-Rossendorf e.V., Europe

iSIM Advisory Board

- Prof. Masahiro Yamaguchi,
  Tohoku University, Asia
- Prof. Nian Sun,
  Northeastern University, USA
- Dr. Denys Makarov,
  Helmholtz-Zentrum Dresden-Rossendorf e.V., Europe

Topics

1. Sensing
   Tunneling magnetoresistive (TMR) sensors, Magnetoelectric sensors, Giant magnetoimpedance sensors, Other magnetoresistive sensors

2. Integrated circuits for magnetics
   Power supply on chip (PwrSoP), Power supply in package (PwrSiP), Magnetics for advanced packaging, Communication circuits, etc

3. Disruptive technologies
   Flexible magnetoelectronics, Eco-sustainable magnetics, Quantum sensing, Machine learning for integrated magnetics

Venue

The conference will be held at the Hyatt Regency New Orleans, 601 Loyola Avenue, New Orleans, Louisiana 70113, USA.

Google map
https://maps.app.goo.gl/rk2R9CmFJceCw8mt9

Schedule

Sunday, January 12		
8:00	Welcome Reception/Arrival/Coffee and Pastries	
8:30	Opening Remarks *Dok Won Lee (iSIM) &* *Ron Goldfarb (IEEE Magnetics Society)*	

Session 1.1: RF Devices

Session chair: Masahiro Yamaguchi

8:45	RF Magnetoelectrics – Materials and Microsystems *N. X. Sun*	P. 15
9:10	Magnetic Field Sensors Based on Surface Acoustic Wave Devices *E. Quandt*	P. 16
09:35	Magneto-Acoustic Resonators for Microwave Applications *T. Nan*	P. 17
10:00	High-Frequency-Carrier Type Thin-Film Magnetic Sensor with Slit-Patterned CoNbZr *L. Tonthat*	P. 18
10:25	**Coffee Break**	

Session 1.2: Magnetic Wires and Films

Session chair: Shin Yabukami

11:15	Integrating Magnetic Nanowires and Magneto-Optical Garnets *B. J. H. Stadler*	P. 19
11:40	Simple and Rapid Controlling Method of Magnetic Anisotropy and Its Application to Thin-film Magnetoimpedance Element *H. Kikuchi*	P. 20

12:05	SMART Actuators Based on Heusler Glass-Coated Microwires with GMI Sensing Ability *R. Varga*	P. 21
12:30	Design Considerations for Microfluxgate *P. Ripka*	P. 22
12:55	**Lunch**	

Session 1.3: XMR and MTJ I

Session chair: Jeffrey McCord

14:30	A Monolithically Integrated Three Axis TMR Magnetometer *P. Mather*	P. 23
14:55	TEL PVD Technology for MTJ (Magnetic Tunnel Junction) *C. M. Park*	P. 24
15:20	Design and Application Prospects of Low-Noise TMR Sensors for picoTesla Magnetic Field Detection *J. Liu*	P. 25
15:45	Challenges in Wafer Level Testing of TMR Sensors *L. Lebrun*	P. 26
16:10	**Coffee Break**	
16:10	**Poster session**	
18:00	**Walk to dinner** Banquet address: Galatoire's Restaurant 209 Bourbon St New Orleans, LA 70130 https://maps.app.goo.gl/UH889nqy2cwQBLqp8 Dress code: suit jackets required; no jeans	

Monday, January 13

8:00	Welcome Reception/Coffee and Pastries

Session 2.1: XMR and MTJ II

Session chair: Denys Makarov

8:30	3D Magnetic Field Sensing with Offset Reduction Enabled by Spin-Orbit Torque *D. Suess*	P. 27
8:55	Read Out of a Powerless Rotation Counter Based on a GMR Nanowire *J. Schmitt*	P. 28
9:20	Reliability of Probabilistic Ising Machines based on Magnetic Tunnel Junctions *E. Raimondo*	P. 29
9:45	Magnetic Tunnel and Josephson Junctions Formed from 2D Materials *S. S. P. Parkin*	P. 30

10:10	**Coffee Break**

Session 2.2: Interdisciplinary

Session chair: Amal El-Ghazaly

11:00	Spintronics in the AI Age *L. Klein*	P. 31
11:25	Micromagnetic Stimulation and Spintronics Sensing in Brain Research and Biomedical Applications *J. P. Wang*	P. 32
11:50	MagnetoElectric NanoParticles for Precision Biomedical Applications *E. Zhang*	P. 33

12:15	**Awards Ceremony & Closing remarks**

List of posters

Invited talks

RF Magnetoelectrics - Materials and Microsystems

Nian Xiang Sun*

[1]*Department of Electrical and Computer Engineering, Northeastern University, Boston, MA, 02115, USA*
**Corresponding: n.sun@northeastern.edu*

The coexistence of electric polarization and magnetization in multiferroic materials provides great opportunities for realizing magnetoelectric coupling, including electric field control of magnetism, or vice versa, through a strain-mediated magnetoelectric coupling in layered magnetic/ferroelectric multiferroic heterostructures. Strong magnetoelectric coupling has been the enabling factor for different multiferroic devices, which, however, has been elusive, particularly at RF/microwave frequencies. In this presentation, I will cover the most recent progress on new RF magnetoelectric materials and microsystems [1-8]. Specifically, we will introduce magnetoelectric materials and their applications in different devices, focusing on ultracompact magnetoelectric mechanical antennas, which are immune from ground plane effect with ultra-compact size, self-biased operation, excellent impedance matching, ground plane immunity, etc. These magnetodielectric and magnetoelectric antennas show great promise for applications in compact, lightweight, and power-efficient sensors, antennas, and tunable components for radars, communication systems, biomedical devices, IoT, etc.

References

[1] B. Luo, et al. Magnetoelectric microelectromechanical and nanoelectromechanical systems for the IoT, Nature Reviews Electrical Engineering, 1, 317-334 (2024).
[2] X. Liang, et al. Mechanically driven solidly mounted resonator-based nanoelectromechanical systems magnetoelectric antennas, Advanced Engineering Materials, 2300425 (2023).
[3] C Dong, et al., Thin film magnetoelectric sensors toward biomagnetism: materials, devices, and applications, Advanced Electronic Materials 8 (6), 2200013 (2022).
[4] M. Zaeimbashi, et al, Ultra-compact dual-band smart NEMS magnetoelectric antennas for simultaneous wireless energy harvesting and magnetic field sensing, Nature Comm. 12, 3141 (2021).
[5] C. Dong, et al. A Portable Very Low Frequency (VLF) Communication System Based on Acoustically Actuated Magnetoelectric Antennas, IEEE Antennas and Wireless Propagation Letters 19 (3), 398-402 (2020).
[6] M. Zeimbashi, et al., NanoNeuroRFID: A wireless implantable device based on magnetoelectric antennas, IEEE J-ERM, 3, 206 (2019).
[7] C. Dong, et al. Characterization of magnetomechanical properties in FeGaB thin films, Applied Physics Letters 113 (26), 262401 (2018).
[8] T. Nan, et al. Acoustically actuated ultra-compact NEMS magnetoelectric antennas, Nature Comm. 8, 296 (2017).

Magnetic Field Sensors Based on Surface Acoustic Wave Devices

F. Weisheit, D. Meyners, E. Quandt

Department of Material Science, Kiel University, Kiel, Germany
eq@tf.uni-kiel.de

Surface acoustic wave sensors have proven to be very promising components for detecting and quantifying various physical quantities. Love wave sensors, as a special type of surface acoustic wave (SAW) sensors, use horizontal shear waves that are confined in a guiding layer on the surface of the sensor, thereby increasing the surface sensitivity for the quantities to be measured at this surface. The principle of the magnetic field sensor is based on the change of the elastic properties of magnetostrictive materials in magnetic fields, the so-called ΔE effect. The Love wave SAW sensor utilizes surface acoustic waves guided by a fused silica layer with an exchange-biased multilayer on top. The velocity of these waves follows the change of the shear modulus induced by the magnetostriction according to the applied magnetic field. The SAW sensor is operated in a delay line configuration and translates the magnetic field into a corresponding phase shift [1].

These magnetostrictive sensors based on SAW delay lines show great potential as sensors for low-frequency and extremely weak magnetic fields, such as those found in biomagnetic applications. While these sensors provide sufficient frequency bandwidth for most applications, their limit of detection is limited by the low-frequency noise generated by the magnetostrictive layers. This noise is closely related to the activity of domain walls, which is caused by the stress exerted by the sound waves propagating through the film [2]. One successful method of reducing domain walls is to couple the ferromagnetic material to an antiferromagnetic material via their interface, thus inducing a unidirectional exchange bias. In addition, an antiparallel bias of two consecutive exchange bias stacks achieves a stray field closure and thus prevents the formation of magnetic edge domains. This antiparallel alignment of the multilayer magnetization provides a single-domain state throughout the entire film and results in a reduction of magnetic phase noise with LODs of only 28 pT/Hz$^{1/2}$ at 10 Hz and 10 pT/Hz$^{1/2}$ at 100 Hz [3].

The frequency at which the sensor operates plays a crucial role in this sensor principle. In my presentation, I will therefore discuss the frequency-dependent properties of Love wave SAW sensors in a range from 100 MHz to 750 MHz and show how frequency affects sensitivity, phase noise and thus LOD.

References

[1] Kittmann, A.; Durdaut, P.; Zabel, S.; Reermann, J.;, Schmalz, J.; Spetzler, B.; Meyners, D.; Sun, N.X.; McCord, J.; Gerken, M.; Schmidt, G.; Höft, M.; Knöchel, R.; Faupel, F.; Quandt, E.: Wide Band Low Noise Love Wave Magnetic Field Sensor System, Scientific Reports (2018), 8:278, DOI: 10.1038/s41598-017-18441-4.

[2] Müller, C.; Durdaut, P.; Holländer, R. B.; Kittmann, A.; Schell, V.; Meyners, D.; Höft, M.; Quandt, E.; McCord, J.: Imaging of Love Waves and Their Interaction with Magnetic Domain Walls in Magnetoelectric Magnetic Field Sensors, Advanced Electronic Materials 8 (2022), 2200033, DOI:10.1002/aelm.202200033.

[3] Schell, V.; Spetzler, E.; Wolff, N.; Bumke, L.; Kienle, L.; McCord, J.; Quandt, E.; Meyners, D.: Exchange biased surface acoustic wave magnetic field sensors, Scientific Reports 13 (2023), 8446, https://doi.org/10.1038/s41598-023-35525-6.

Magneto-Acoustic Resonators for Microwave Applications

Tianxiang Nan[1*]

[1]*School of Integrated Circuits, Tsinghua University, Beijing, China*
**Corresponding author: nantianxiang@mail.tsinghua.edu.cn*

Surface Acoustic Wave (SAW) devices, essential for microwave applications, convert electrical signals to acoustic waves and back, harnessing these waves traveling along the substrate surface to achieve frequency resonances. The integration of magnetic materials introduces magneto-acoustic coupling, broadening the application of SAW in tunable microwave, magnetic field sensing, and the dynamic control of spin textures. In this talk, I will introduce our recent progress in magneto-acoustic resonators. We propose a magneto-acoustic waveguide structure, where acoustic energy is significantly concentrated in the magnetostrictive layer with low acoustic velocity, amplifying the delta-E effect and its influence on SAW propagation. Our findings reveal a robust correlation between tunability and the magnetic layer's thickness, consistent with our simulation. Additionally, by utilizing magneto-acoustic waveguide structure, we also demonstrate a SAW actuated magnetoelectric antenna with enhanced performance. Lastly, the presentation will cover our work on the manipulation of Néel-type skyrmions via horizontal acoustic waves, demonstrating their potential directional motion driven by SAW.

High-frequency-carrier Type Thin-film Magnetic Sensor with Slit-Patterned CoNbZr

Loi Tonthat[1*], Ryota Suzuki[1], Shin Yabukami[1,2]

[1]*Graduate school of Engineering, Tohoku University, Sendai 980-8579, Japan*
[2]*Graduate school of Biomedical Engineering, Tohoku University, Sendai 980-8579, Japan*
**Corresponding.ton.that.loi.e8@tohoku.ac.jp*

In recent years, magnetic field sensors have seen growing use in biological diagnostics and nondestructive testing, with a focus on enhancing sensitivity. Traditional sensors like SQUIDs and optical pumping offer high sensitivity but require complex setups, limiting practicality. In contrast, room-temperature sensors such as magnetoimpedance (MI), giant magnetoimpedance (GMI), fluxgate, and tunnel magnetoresistance (TMR) sensors, particularly in the GHz range, are simpler and more practical. However, there has been limited focus on optimizing sensitivity through impedance matching. In our previous study, we developed a high-frequency thin-film magnetic sensor to detect magnetic near fields in wireless power systems, overcoming limitations of loop antennas [1]. To enhance performance, we introduced narrow slits into the magnetic thin film, optimizing impedance matching and current flow. The sensor (Fig. 1) features a straight coplanar structure (19.8 mm length) on a CoNbZr thin film with slit widths from 6 to 50 µm. The CoNbZr film (1 mm × 18.2 mm) was RF-sputtered onto a 1 mm glass substrate, and a Cu meander coplanar circuit (300 µm wide, 50 µm gap, 1 µm thick) was formed using lift-off on a 3 µm SrTiO thin film, with a 0.2 µm Cr intermediate layer. The CoNbZr film was annealed to induce magnetic anisotropy by rotational (350°C, 1.5 hours, 0.3 T) and static (340°C, 1 hour, 0.3 T) magnetic field. Sensors with different slit widths were characterized using S_{21} and S_{11} measurements (300 kHz–8 GHz). The sensitivities of the sensors were evaluated by producing the maximum gradient respect DC bias field applied and the amplitude of S_{21} which is proportional to the carrier signal strength at the maximum gradient. Sensor sensitivity peaked at a slit width of 10 µm, showing improved S_{21} amplitude and impedance matching, with near-target impedance of 50 Ω.

References

[1] L. Tonthat, et al., “Thin Film Magnetic Sensor for Magnetic Near-Field Measurement in Wireless Power Transfer System”, *IEEJ Trans Elec Electron Eng*, vol. 19, pp.1763-1769, 2024.

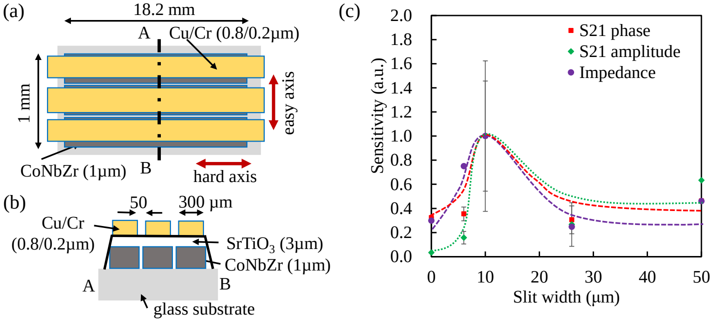

Fig. 1. High-frequency-driven thin-film magnetic sensor with narrow slits. (a) Schematic view of sensor element (b) top view (c) normalized amplitude, phase, and impedance sensitivities as a function of slit width.

Integrating Magnetic Nanowires and Magneto-Optical Garnets

B. J. H. Stadler*[1,2], A. Harpel[2], P-H. Liu[1], R. Kolisnyk[1], J. Um[1], K. Srinivasan[1], Y. Chen[1], R. F. Franklin[1]

[1]Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis MN 55455, USA
[2] Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis MN 55455, USA
**stadler@umn.edu*

In the broad sense, integrated circuits (ICs) include many applications, for example high frequency ICs and photonic ICs (PICs). We have developed two novel material families for advanced packaging and PIC communication circuits, namely magnetic nanowires and magneto-optical garnets, onto Si and SOI platforms.

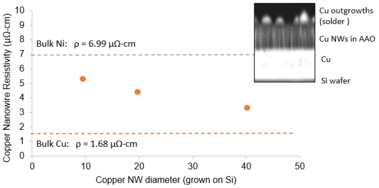

Fig. 1. Resistivity of Cu nanowires (NWs) on Si, down to 10nm diameter. [inset: SEM of NWs]

For high frequency packaging, metallic nanowires (NWs) can be incorporated into interposers as nanometer scale vias. Copper NWs can be monolithically integrated on Si substrates using aluminum films that are anodized to produce a nanoporous oxide. Metals are then electrodeposited into the nanopores. Fig. 1 shows that the resistivity of these "nanoscale vias" is comparable to bulk, even with diameters as small as 10nm. In addition, magnetic materials can be electrodeposited instead of copper, which introduces opportunities for integrated inductors. Also, magnetic NWs can be heated for nanoscale ball grid arrays, or ferromagnetic resonance (FMR) enables a new form of reconfigurable security that we can FMR-ID.

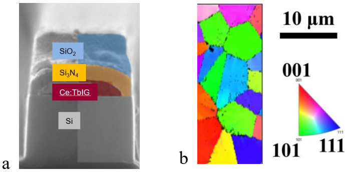

Fig. 2- a) Cross section of Si waveguide with Ce:TbIG cladding for a magnet-free isolator. b) Single phase garnet is low loss, high gyrotropy.

For photonic circuits, magneto-optical garnets can be used to control the polarization of light. The magnetization of a garnet cladding on Si waveguides (Fig. 2) is set by shape anisotropy occurs along the waveguide, so the garnet gyrotropy causes the propagating transverse-electric (TE) or -magnetic (TE) modes to experience nonreciprocal mode conversion (NRMC). It is important to note that index of refraction is isotropic, which means grain boundaries do not scatter light. Although a somewhat high temperature anneal is needed to crystallize garnet on Si, recent studies show that garnet can be transfer printed off a silicon growth wafer onto a PIC.

References

[1] Harpel, Allison, Joseph Um, Aditya Dave, Yali Zhang, Nikita Mahjabeen, Yicong Chen, Rashaunda Henderson, Rhonda Franklin, and Bethanie JH Stadler. "Vertically Integrated Nanowires on Si Wafers and into Circuits." *IEEE Transactions on Magnetics* (2022)..

[2] Um, Jospeh, Bethanie Stadler, Rhonda Franklin, Yali Zhang, Rashaundra Henderson, "*Adhesion Layer for Forming Nanowires in Anodic Aluminum Oxide."* Awarded U.S. Patent Application on Sept 24, 2024. **US-12100879-B2**.

[3] J Srinivasan, Karthik, Cui Zhang, Prabesh Dulal, Cosmin Radu, Thomas E. Gage, David C. Hutchings, and Bethanie JH Stadler. "High-Gyrotropy Seedlayer-Free Ce: TbIG for Monolithic Laser-Matched SOI Optical Isolators." *ACS Photonics* 6, no. 10 (2019): 2455-2461.

[4] Stadler, Bethanie Joyce Hills, Karthik Srinivasan, "*Push-Pull Non-Reciprocal Phase Shifting"* Awarded US Patent on August 6, 2024. **US-12055756-B2**

Simple and Rapid Controlling Method of Magnetic Anisotropy and Its Application to Thin-film Magnetoimpedance Element

H. Kikuchi[1*], A. Ueno[1], K. Sato[1]

[1]*Faculty of Science and Engineering, Iwate University, 4-3-5 Ueda, Morioka 020-8551, Japan*
**Corresponding.hkiku@iwate-u.ac.jp*

Control of magnetic anisotropy is often crucial for enhancing the performance of thin-film magnetic devices. Magnetic anisotropy can be induced during film deposition or adjusted through field annealing post-deposition. However, field annealing typically requires larger equipment, including systems capable of generating strong magnetic fields and heating in a vacuum. To simplify this process, we have proposed a more straightforward method that combines Joule heating with the application of magnetic fields via permanent magnets [1]. We have demonstrated the feasibility of controlling anisotropy using this method and have achieved distinct anisotropy control on the same substrate by applying it to thin-film magnetoimpedance elements [1, 2]. In this study, we focus on more localized anisotropy control and its reversibility, aiming to advance the control of anisotropy for high-sensitivity, high-functionality sensors. We also discuss the optimization of experimental conditions and the selection of applicable materials when applying this method to thin-film magnetoimpedance elements.

Figures 1 and 2 show the domain structures observed via MOKE and the magnetoimpedance characteristics of a thin-film element composed of three 0.5-mm segments connected in series. In this experiment, only the center segment was heated while a magnetic field parallel to the element width was applied. The heating was performed with a current of 120 mA for 1 minute, and the impedance was measured at a frequency of 1 GHz. Before heating, the easy axes in all segments were aligned parallel to the length direction. However, after heating, only the domain in the middle segment realigned along the width direction, indicating that anisotropy was modified solely in the heated region. This is further confirmed by the impedance profiles: the impedance of the center segment (“m”) differs from those of the outer segments (“b” and “u”) even though all segments showed same characteristics before heating. In addition, the reversibility of the method—specifically, the realignment along the length direction—and the time required for control and temperature distribution will be discussed.

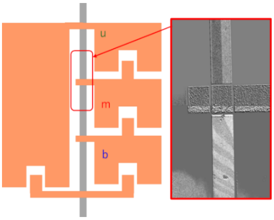

Fig. 1. Domain structures after Joule heating locally. Only segment of “m” was heated with 120mA, 1min. in the air.

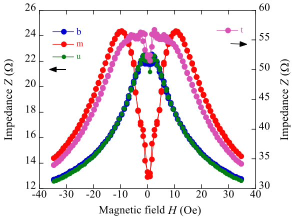

Fig. 2. Applied field dependence on impedance for each segment (“u”, “m”, “b”) and total impedance (“t”) after heating at 1 GHz.

References

[1] H. Kikuchi, A. Ueno, M. Tanii, “Controlling the magnetoimpedance property of thin-film elements using Joule heating,” IEEE. Trans. Magn. vol, 58, #2000905, 2022.

[2] H. Kikuchi, A. Ueno, M. Tanii, “Realization of Different Anisotropy Direction for Thin-film Magnetoimpedance Elements on the Same Substrate,” IEEE. Trans. Magn. vol, 59, No. 11, # 2500405, 2023.

SMART Actuators Based on Heusler Glass-Coated Microwires With GMI Sensing Ability

L. Nulandaya[1,2], L.Frolova[2], M. Hennel[2], P. Sarkar[2], T. Ryba[3], O. Milkovic[1], O. Heczko[4], R.Varga[1,3*]

[1]Institute of Experimental Physics, Slovak Academy of Sciences, 040 01 Kosice, Slovakia
[2]CPM-TIP, UPJS, Park Angelinum 9, 040 01 Kosice, Slovakia
[3] RVmagnetics a.s., Nemcovej 30, 040 01Kosice, Slovakia
[4] Institute of Physics, Czech Academy of Sciences, Na Slovance 2, 18221 Prague, Czech Republic
**varga@rvmagnetics.com*

Glass-coated microwires have shown to be successfully employed like a sensor of magnetic field, temperature, mechanical stress, using their unique magnetic properties – Giant MagnetoImpedance or magnetic bistability [1]. Naturally, the idea to use their special shape and easy and replicable production process to develop microwire-based actuators.

Heusler alloys are ideal candidates for design of actuators as they show wide variety of physical effect that can be easily tuned by chemical composition [2]. One of the best candidates for shape memory, or magnetocaloric effect-based application is Ni-Mn-Ga, which shows one of the most pronounced strains induced by magnetic field [3]. On the other hand, transition in Ni-Mn-Ga alloy is extremely sensitive to chemical composition and even negligible compositional variation results in change of shape memory or magnetocaloric effect. On the other hand, Ni-Fe-Ga alloy can be produced in a very repeatable way.

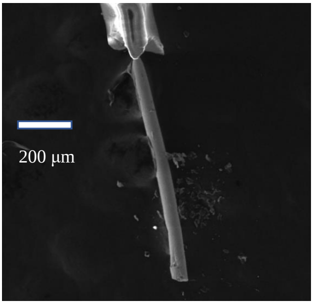

Fig. 1. SEM photo of glass-coated microwire

In the given contribution, we show the Ni-Fe-Ga glass-coated microwire produced by Taylor-Ulitovski method that allows for repeatable production of large volume of materials. They offer easy adjustment the chemical composition to the desired transition temperature within wide temperature range [4]. Most of the microwires show monocrystalline structure along their entire length with the possibility to orient the crystalline axis along the wire axis. As a result, they are able of repetitive (over 1 000 000 times) and high shape memory effect (strain over 20 %) without the change of their crystal structure.

Their wire-shape results in the well-defined easy axis being parallel to the wire axis in austenite form and out of the wire axis for martensite phase. This result in strong variation of initial permeability (over 1600 %) as well as GMI effect accompanied with the phase transformation. Such behavior makes Ni-Fe-Ga microwire SMART actuator with sensing properties.

References

[1] M. Vazquez, “Advanced magnetic microwires,” in “Handbook of Magnetism and Advanced Magnetic Materials,” H. Kronmuller, S.S.P. Parkin (Eds.),Wiley, Chichester, England, 2007, p. 2193.
[2] T. Graf, C. Felser, S. S. P. Parkin, “Simple rules for the understanding of Heusler compounds,” Progress in Solid State Chemistry, vol. 39, p. 1, 2011.
[3] O. Heczko, A. Sozinov, K. Ullakko, ”Giant field-induced reversible strain in magnetic shape memory NiMnGa alloy,” IEEE Trans. Magn., vol.36, p.3266, 2000.
[4] M. Hennel, L. Galdun, R. Varga, “Analysis of magnetocaloric effect in Ni_2FeGa-based glass-coated microwires,” J. Magn. Magn. Mater., vol.560, art.No.169646, 2022.

Design Considerations for Microfluxgate

P. Ripka [*], J. Maier, M. Mirzaei

Faculty of Electrical Engineeting, Czech Technical University, Prague, 166 27 Czech Republic
**ripka@fel.cvut.cz*

Microfluxgates are cheaper than classical wire-wound macrofluxgates and they allow to integrate electronics on the same chip. They have similar noise as magnetoresistors, their main advantage is low temperature offset drift (5 nT/K for DRV425 with 2 mT range, 20 nT/K for HMC1001 with 0,2 mT range).

Fluxgate type

All published microfluxgate are of the parallel type, working in 2nd harmonic mode (or more even harmonics). Orthogonal fluxgates operating in the fundamental mode may consume less power and have lower noise. Their weak point is offset stability [1]

Core shape

Microfluxgate usually use double-bar cores [2] or racetrack [3]. While double-bar has lower demagnetization and thus higher sensitivity, racetrack requires less excitation power and/or has better offset stability.

Core material

Low-magnetostriction, low-coercivity, low saturation induction are usual requirements. FeNi permalloys or Co-based amorphous materials are usually used. The cores are manufactured by sputtering or electrodeposition, or by etching from the amorphous tape. Ideal thickness is several micrometers: it depends on required minimum demagnetization and also on the excitation frequency.

Coil technology and geometry

Flat coils have poor coupling to the core and if made in CMOS technology they have high resistance. Electrodeposited solenoids are much better, but still have higher resistance than wirewound coils.

Excitation

Excitation frequency is limited by eddy currents in the core, causing unsaturated region in the central part. This causes perming and may be the source of the offset jumps. The waveform is usually squarewave, shorter pulses are often used to save energy.

Output signal processing

most of the fluxgates use voltage output, but for integrated fluxgate current output is attractive option, as the sensitivity is inversely proportional to the number of turns [1]. However, the pickup coil resistance of integrated fluxgate is high, causing that the real sensitivity is lower. Another possibility is to use flux output by integrating the voltage output. This decreases the frequency bandwidth of the output signal - in microfluxgate this is usually done by output tuning. Tuning is standard for macro fluxgate, but usually inefficient for microfluxgate because the quality factor is low due to the high winding resistance.

References

[1] P. Ripka, “Magnetic sensors and magnetometers”, 2nd edition, Artech House, 2021.
[2] M. F. Snoeij, V. Schaffer, S. Udayashankar et al., “Integrated Fluxgate Magnetometer for Use in Isolated Current Sensing,” IEEE Journal of Solid-State Circuits, vol. 51, no. 7, pp. 1684-1694
[4] J. Maier, P. Ripka, P. Chen: CMOS-based Micro-fluxgate with Racetrack Core and Solenoid Coils, Sensors and Actuators A 379 (2024) 115886

A Monolithically Integrated Three Axis TMR Magnetometer

P. Mather[1]; Bosch Sensortec TMR Team[1,2]
[1]Robert Bosch LLC, 960 W. Elliot Rd. Tempe, AZ 85284
[1]Bosch Sensortec, GmbH, Gerhard-Kindler-Straße 9, 72127 Reutlingen, Germany

The rapidly expanding field of magnetic sensors touches upon our everyday lives in myriad ways. Magnetic sensors ensure our safety through detection of wheel speed rotation in antilock braking systems, and by enabling precise and reliable measurement of steering wheel angular position. They improve the efficiencies of electrical power delivered to high current electrical motors and generated in solar arrays. Magnetic sensors are an integral part of the sensing system suite forming the intuitive human - machine interface present in game controllers, cell phones, and virtual and augmented reality devices.

The recent acceleration in magnetometry arose from the virtuous cycle of an expanding application field ushered in by innovations and technological advancements, which lead to new market opportunities. Reducing noise and power consumption while simultaneously delivering higher accuracy requires a shift away from the prior generations of Hall and Anisotropic Magneto Resistance technologies and incorporation of novel designs and process technologies. Tunneling Magneto Resistance (TMR) technology is showing the highest growth rate among the magnetic sensing technologies as it affords new degrees of freedom in transducer design: decoupling magnetic and electrical performances and allowing independent control of each. Adjustable device impedance allows a fully optimized read path to be tailored for the Application Specific Integrated Circuitry (ASIC). Simultaneously, the high output signal of the technology can be utilized to both extend the sensing field range and the signal strength. The transducer – ASIC system can be designed in concert to achieve lower total sensing power while enhancing performance, enabling a wealth of power sensitive applications for mobile devices as well as Internet of Things (IoT) applications**,** such as parking space and industrial monitoring**.**

Similarly, the drive to smaller form factors opens up unique mounting locations and assembly solutions, such as brushless DC motor rotor sensing and countless other space sensitive positioning applications. A compact magnetometer that is monolithically integrated with CMOS, offering the flexibility of in plane and out of plane field sensitivity, can be tuned to address these applications.

Essential elements of a high-performance wafer level chip scale three axis monolithically integrated TMR magnetometer will be described. The TMR layers and interconnects are deposited directly on top of a mixed signal CMOS process technology. A high throughput lot-level wafer batch processing step is performed to create two orthogonal pinned reference layer directions for orthogonal in plane response directions. Integrated flux guides steer the out of plane magnetic field into the in plane sense elements allowing detection of the magnetic fields in all three directions with no additional thickness added to the overall chip height. [1]

With global leadership in the motion sensing marketplace, achieved through pioneering technology developments across a wide portfolio of MEMS sensors, Bosch produces over 1.5 billion MEMS sensors each year. Bosch Sensortec is a wholly owned subsidiary which develops products tuned to the consumer electronics market. Bosch Sensortec has been the world leading supplier of electronic compass modules and is developing the next generation of magnetic sensing solutions.

Reference

[1] https://www.bosch-sensortec.com/products/motion-sensors/magnetometers/bmm350/

TEL PVD Technology for MTJ (Magnetic Tunnel Junction)

Chang-Man Park, Ph. D.

Sr. Director,
Marketing Support Div. Tokyo Electron U.S. Holdings Inc.

The rapid advancements in spintronics have led to the development of promising memory technologies like STT-MRAM, HDD and TMR magnetic sensors. These devices offer significant advantages over traditional solutions, including higher speed & accuracy, lower power consumption, and greater thermal stability.

However, the successful integration of STT-MRAM, HDD and xMR into various applications requires overcoming several challenges, particularly in physical vapor deposition (PVD). This presentation will discuss the critical role of TEL PVD tools in achieving the desired properties of these spintronic devices.

Key requirements for PVD tools include:

- **High-quality MTJ deposition:** Achieving consistent RA, high TMR ratio, and optimal magnetic properties.
- **Flexibility:** The ability to deposit stacks for both in-plane and perpendicular MTJs with varying RA to accommodate future technological advancements.
- **High throughput and consistency:** Ensuring uniform deposition across wafers and maintaining tool performance over extended periods to enable high-volume manufacturing.

This presentation will present the latest results on MTJ film properties deposited using TEL PVD tools, as well as discuss the potential of low-wide range MgO i/p-MTJ characteristics for near-future applications.

Design and Application Prospects of Low-Noise TMR Sensors for picoTesla Magnetic Field Detection

Mingfeng Liu, Kuohai Zheng, Jinfeng Liu*

MultiDimension Technology Co., Ltd., Zhangjiagang, Jiangsu 215634, China
**jinfeng.liu@dowayusa.com*

This paper presents recent advancements in low-noise Tunneling Magnetoresistance (TMR) sensors and their application in detecting weak magnetic fields with picoTesla-level resolution. TMR sensors are emerging as a key component in next-generation high-performance magnetic sensors, thanks to their high sensitivity, low noise, broad frequency response, and low power consumption. Advances in low-field detection have expanded their applications across consumer electronics, renewable energy, biomedicine, industrial sensor systems, and more. A major challenge in weak-field detection has been the relatively high 1/f noise at low frequencies, limiting practical applications that require picoTesla-level resolution. We present the results of our long-term research integrating MultiDimension Technology's TMR9xxx series, which features a noise level of 150pT/√Hz @ 1Hz, with advanced signal conditioning circuits to reduce the noise floor to 10pT/√Hz @ 1Hz. We demonstrate the efficacy of several prototypes and commercial products in medical applications, including magnetic cardiography (MCG) and MRI object screening, as well as in other industrial applications.

Challenges in wafer level testing of TMR sensors

Siamak SALIMY, Steven Lequeux, Gilles Zahnd, Brice Blanc, Antoine Chavent, Laurent Lebrun

Hprobe SA, 4 Rue Joliot Curie, 38320 Eybens, France
siamak.salimy@hprobe.com

Wafer-level testing of Tunnel Magneto Resistive (TMR) sensors poses significant challenges due to their high sensitivity and precision requirements. Controlling uniform multi axial magnetic fields with controlled strength and angle across the wafer, accurately measuring low resistance, and managing thermal effects are critical hurdles. Magnetic interference from probing chamber and testing equipment further complicates the process. Additionally, proper sensor alignment with the applied magnetic fields and required accuracy and repeatability of excitation field add complexity. These challenges affect test accuracy, production yield, and cost-efficiency, making it extremely challenging to balance precision with throughput in high-volume manufacturing environments.

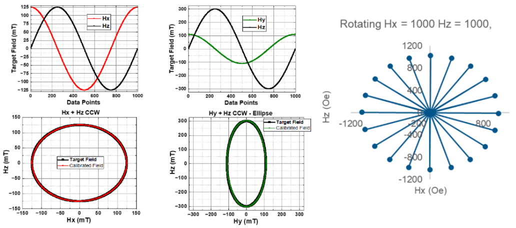

Fig. 1. Illustration of angular and strength resolved magnetic excitation for TMR sensor wafer level test.

TMR sensors are based on Magnetic Tunnel Junctions, which consist of two ferromagnetic layers separated by a thin insulating barrier. The relative magnetization of these two layers affects the device's resistance. TMR sensors usually consist of a network of magnetic tunnel junctions connected to a Wheatstone bridge, which transduces the magnetic field into an output voltage. These sensors can operate in either linear mode (low field, typically below 100mT) or saturation mode (high field, typically above 100mT). During wafer-level testing, an external magnetic field is applied and controlled, varying in amplitude and/or angle depending on the application. For 1D sensors, excitation is applied along a single axis, while multi-directional magnetic excitation is required for angular 2D or 3D sensors, including fields in the wafer plane or perpendicular to it.

To meet wafer test throughput requirements in high-volume manufacturing, magnetic field settling time or sweep frequency is maximize to achieve the highest throughput, which is inversely proportional with the cost of test. However, the speed requirement causes coupling effects with metal parts (such as the chuck stage), resulting in eddy currents and parasitic fields around the wafer that impact the accuracy and repeatability of measurements.

This presentation will introduce our current development to address these challenges. It includes the demonstration of a new magnetic instrument that exceeds the current state of the art, designed specifically for testing TMR sensors. The instrument features a high-dynamic 3D magnetic generator and advanced alignment, calibration, monitoring, and compensation protocols, all integrated with a probe card and wafer prober.

References

[1] E. Monteblanco et al., “Normalization and Correction Factors for Magnetic Tunnel Junction Sensor, Performances Comparison,” IEEE SENSORS JOURNAL, VOL. 21, NO. 14, JULY 15, 2021.

[2] C. Baraduc, M. Chshiev, B. Dieny, “Spintronic Phenomena: Giant Magnetoresistance, Tunnel Magnetoresistance and Spin Transfer Torque,” Giant Magnetoresistance (GMR) Sensors From Basis to State-of-the-Art Applications, pp.1-30, Smart Sensors, Measurement and Instrumentation 6, Springer edition.

3D Magnetic Field Sensing with Offset Reduction Enabled by Spin-Orbit Torque

Dieter Suess[1,*], Sabri Koraltan,[1, 2], Sebastian Zeilinger[1], Rahul Gupta,[3] Reshma Peremadathil Pradeep,[4] Fabian Kammerbauer,[3] Klemens Prügl,[5] Michael Kirsch,[5] Bernd Aichner,[1] Krystina Davidkova,[1] Florian Bruckner,[1] Santiago Helbig,[1] Claas Abert,[1]Andrada Oana Mandru,[4] Gerhard Jakob,[3] Hans Josef Hug,[4] Mathias Kläui,[3] Armin Satz[6]

[1]Faculty of Physics, University of Vienna, Vienna, Austria
[2]Vienna Doctoral School in Physics, University of Vienna, Vienna, Austria
[3]Institute of Physics, Johannes Gutenberg University Mainz, 55099 Mainz, Germany
[4]Empa, Dübendorf CH-8600, Switzerland
[5]Infineon Technologies AG, Regensburg, Germany
[6]Infineon Technologies AG, Villach, Austria
*dieter.suess@univie.ac.at

Magnetic field sensors are essential in our modern-day society, utilized in various applications including automobiles, mobile phones, and robotics. In this talk, I will discuss our work on magnetic field sensors that exploit spin orbit torque (SOT) to detect all three components of an external field with a single device. Initially, the focus will be on sensors where the signal is derived from the anomalous Hall effect. We demonstrate that active offset compensation for all three components is feasible through the SOT effect and a spinning current method applied to the anomalous Hall effect sensors. The SOT effect is induced by a spin-polarized current generated in a heavy metal (HM) layer via an electrical current, which then exerts a torque on a ferromagnetic (FM) layer positioned above the HM layer. This interaction modulates the magnetization of the free layer, enabling an offset-compensated sensor signal. Our results include various free layer designs aimed at achieving sensors with distinct linear regimes. One design utilizes a CoFeB free layer coupled with MgO, where the perpendicular anisotropy at the CoFeB/MgO interface compensates for shape anisotropy, resulting in sensors with linear ranges around 1 mT—ideal for detecting very low field strengths.

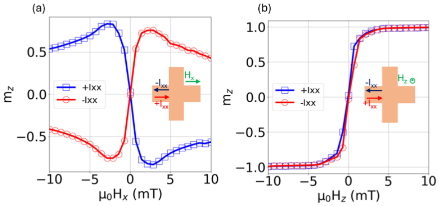

Fig. 1. m_z component of the magnetization (blue for positive currents, red for negative currents) for different current direction and external field direction, for a total current of I = 2.7mA

The response of the m_z magnetization for H_x fields for positive and negative currents is shown in Fig. 1a. Since, for positive and negative currents the damping like SOT under H_x fields reverse the orientation in z-direction the transfer curve for these two polarities have opposite. The sensor signal is the difference of these two signals.

The H_z field can be measured since it tilts out the magnetization due to the Zeeman field. Here, the slope of the transfer curve has the same sign for the two current polarities as shown in Fig 1b. Hence, the H_z field can be determined by the sum of the two signals. The offset cancelation is obtained for H_z field by a spin current technique.

In order to increase the linear regime we use in another design [W/CoFeB/MgO] multilayers [1] which allows linear regimes above 20 mT.

References

[1] Koraltan, Sabri, et al. "Skyrmionic device for three dimensional magnetic field sensing enabled by spin-orbit torques." arXiv preprint arXiv:2403.16725 (2024).

Read Out of a Powerless Rotation Counter Based on a GMR Nanowire

J. Schmitt[1*], G. Cosgrave[2]

[1] *Analog Devices, Industrial and Automation BU, Munich, 80807, Germany*
[2] *Analog Devices, Industrial and Automation BU, V94RT99, Limerick, Ireland*
*Jochen.Schmitt@analog.com

A first-generation multi-turn sensor (ADMT4000) based on a GMR nanowire will be released in October 2024 by Analog Devices (ADI). The GMR stack used for the sensing element is made of a state-of-the-art spinvalve using an artificial antiferromagnet. The nanowire created from the GMR film is only a few hundred nanometers wide and formed to a spiral (see Figure 1). A wider area called a domain wall generator is located at one end of the spiral. To increase shape anisotropy, the free-layer thickness is relatively high compared to other applications. Such an arrangement is reported in the scientific literature [1, 2, 3] for a few years but is now developed as a freely available product for customers.

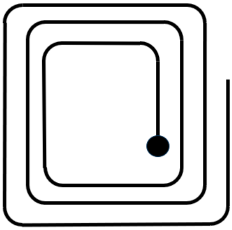

Figure 1 magnetic open loop spiral with domain wall generator.

The new sensor has a counting range of 46 turns. To achieve this, the spiral needs to have 46 windings. For economic reasons the sensor and ASIC are needed to be on separate die. The sensing area is about 10 times smaller than the ASIC die and a monolithic integration would Multiply the manufacturing yield loss. This caused the problem of needing numerous contacts between the dies. On each winding there are four areas where the resistance of the nanowire needs be measured to locate the domain wall position. These are the horizontal and vertical portions referring to Figure 1. This requires a large number of contacts between the electrical readout circuit and the sensor. In a monolithic integration such numerous contacts are relatively easy to implement. But for a two-die solution the number of contacts 368 (46 windings x 4 resistors x 2 contacts per resistor) would not be manageable.

There were multiple solutions to reduce the number of contacts needed to read out the sensors. It will be shown how contacts could be reduced to 28 bond-bads using a matrix approach and a guarding principle to read out the sensor (see Figure 2). This allows each of the 184 resistors to be measured. Turn count is then inferred from the state sequence of the resistors.

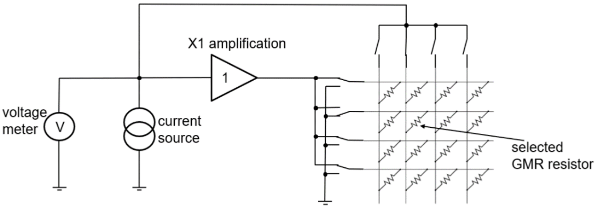

Figure 2 simplified matrix resistor readout circuit.

References

[1] R. Mattheis, M. Diegen, U. Hübner, and E. Halder, Multiturn Counter Using the Movement and Storage of 180 Magnetic Domain Walls, IEEE Trans. Mag. 42, 3297 (2006)
[2] B. Borie, A. Kehlberger, J. Wahrhusen, H. Grimm, and M. Kläui, Geometrical Dependence of Domain-Wall Propagation and Nucleation Fields in Magnetic-Domain-Wall Sensors, Phys. Rev. Applied 8, 024017 (2017).
[3] Marco Diegel, Sacha Glathe, Roland Mattheis, Manfred Scherzinger, and Ernst Halder, A new four bit magnetic domain wall based multiturn counter, IEEE Trans. Magn. 45, 3792 (2009).

Reliability of Probabilistic Ising Machines based on Magnetic Tunnel Junctions

E. Raimondo[1,2], Y. Shao[3], A. Grimaldi[2], M. Chiappini[1], P. K. Amiri[3], G. Finocchio[2*]

[1]Istituto Nazionale di Geofisica e Vulcanologia, Rome, 00143, Italy
[2]Department of Mathematical and Computer Sciences, Physical Sciences and Earth Sciences, University of Messina, Messina, 98166, Italy
[3]Department of Electrical and Computer Engineering, Northwestern University, Evanston, IL, 60208, USA
**gfinocchio@unime.it*

The development of hardware-based unconventional computing paradigms is an active research topic focused on reducing energy consumption and area occupancy of the system, while preserving flexibility in control. Magnetic tunnel junctions (MTJs), key components in spintronic devices, address many of these requirements by offering low power consumption, nanoscale size, high operational frequency (up to GHz), high tunability and compatibility with CMOS technology [1]. This work proposes an MTJ-based probabilistic Ising machine (PIM), a hardware-friendly system for solving combinatorial optimization problems (COPs) [2] by searching the ground state of the Ising Hamiltonian. In PIMs, the Ising spin is represented by the probabilistic bit (p-bit) − a tunable, bistable stochastic unit exhibiting sigmoidal behavior, which can be naturally implemented using MTJs [3]. The hardware implementation of the PIM inherently introduces device-to-device variations. Experimental data show that these variations are mainly reflected in a slight changes in the slope (α) of the p-bit's sigmoidal curve.

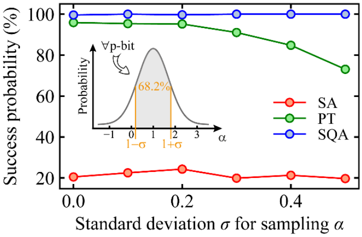

Fig. 1. Success probability as a function of variability of the p-bits, for a Max-SAT instance, using SA (red), PT (green), and SQA (blue).

To emulate this nonideal behavior, we assign a different α value to each p-bit, sampled from a Gaussian distribution with a mean of one and a standard deviation of σ (see inset in Fig. 1). We evaluate the success probability of solving a Max-SAT instance (a well-known COP problem) as the variability σ increases. Figure 1 compare the performance of three popular energy minimization algorithms: simulated annealing (SA), parallel tempering (PT) and simulated quantum annealing (SQA), using 1000 replicas of the system. The results reveal that SQA consistently outperforms both SA and PT, demonstrating a remarkable robustness to device variability. This highlights the potential to mitigate nonideal hardware behavior at the algorithmic level through a co-designed hybrid PIM.

Acknowledgments: This work was supported by Project No. 101070287 — SWAN-on-chip — HORIZON-CL4-2021-DIGITAL-EMERGING-01, the projects PRIN 2020LWPKH7, PRIN_20225YF2S4, PRIN20222N9A73, PON Capitale Umano (CIR_00030), funded by the Italian Ministry of University and Research (MUR), and by the PETASPIN association (www.petaspin.com).

References

[1] V. K. Joshi et al., "From MTJ Device to Hybrid CMOS/MTJ Circuits: A Review", in IEEE Access, vol. 8, pp. 194105-194146, (2020)
[2] N. Mohseni et al., "Ising machines as hardware solvers of combinatorial optimization problems", Nat Rev Phys, vol. 4, pp. 363–379, (2022).
[3] G. Finocchio et al., "The Promise of Spintronics for Unconventional Computing", J. Magn. Magn. Mater., vol 521, 167506 (2021).

Magnetic Tunnel and Josephson junctions formed from 2D materials

Stuart S.P. Parkin*

Max Planck Institute of Micostructure Physics, Halle (Saale) 06120, Germany
**stuart.parkin@mpi-halle.mpg.de*

van der Waals layers for spintronic phenomena are highly interesting. We discuss all-antiferromagnetic tunnel junctions that are formed from bilayers of the van der Waals antiferromagnetic CrSBr that are twisted at angles ranging between 0 and 90 degrees. Each CrSBr layer is ferromagnetic with a strong in-plane magnetic anisotropy that results from its low symmetry. In the bulk the interlayer coupling between the CrSBr ferromagnetic layers is antiferromagnetic (AF) but twisting diminishes this interaction considerably so that we show that a device formed from two AF bilayers exhibits two non-volatile states in zero magnetic field with a giant tunnelling magnetoresistance exceeding ~700%. Nevertheless, each bilayer thus has no net magnetization, a necessity for applications where stray magnetic fields otherwise result in interactions within and between nanoscopic magnets. We show from theoretical modelling that the origin of the tunnelling magnetoresistance is via the accumulated k-dependent transmission through the individual semiconducting CrSrBr layers which depends on the twist angle [1].

We also discuss superconducting proximity effects in non-superconducting van der Waals layers from adjacent superconducting van der Waals layers [2, 3]. We show that vertical Josephson junctions formed from WTe_2 show a Josephson Diode effect with a large non-reciprocity in the critical supercurrent when a small magnetic field is applied perpendicular to the supercurrent within the plane of the WTe_2 flake [4]. The diode effect strongly depends on the orientation of the magnetic field within the plane of the WTe_2 with respect to the crystal structure of the WTe_2. These results clearly indicate that the Josephson diode effect has an intrinsic origin. Such an effect could have important applications as a novel magnetic field detector at cryogenic temperatures, for example, to "read" magnetic domain walls in a cryogenic racetrack memory*.

* Funded through an European Research Council Advanced Grant "SUPERMINT" (2022-2027).

References

[1] Y. Chen *et al.*, "Twist-assisted all-antiferromagnetic tunnel junction in the atomic limit," Nature, vol. 632, pp. 1045-1051, 2024.
[2] B. Pal *et al.*, "Josephson diode effect from Cooper pair momentum in a topological semimetal," Nat. Phys., vol. 18, pp. 1228-1233, 2022.
[3] P. K. Sivakumar *et al.*, "Long-range Phase Coherence and Second Order φ_0-Josephson Effect in a Dirac Semimetal 1T-$PtTe_2$ " Comm. Phys., 2024.
[4] J.-K. Kim *et al.*, "Intrinsic supercurrent non-reciprocity coupled to the crystal structure of a van der Waals Josephson barrier," Nat. Commun., vol. 15, p. 1120, 2024.

Spintronics in the AI age

Lior Klein*

Department of Physics, Institute of Nanotechnology and Advanced Materials, Bar-Ilan University, Ramat-Gan 5290002, Israel
**kleinl@biu.ac.il*

The rapid advancements in artificial intelligence (AI), coupled with significant investments, seem to promise a continued surge in its applications. However, the expansion in AI use may be slowed down since the current computing hardware imposes critical limitations, particularly for edge computing. To address these challenges, neuromorphic computing systems—especially those leveraging in-memory analogue computation—are emerging as a promising solution. Among these, spintronic systems based on magnetic tunnel junction (MTJ) crossbars have garnered increasing attention. Yet, conventional MTJs are limited to only two resistance states, restricting their potential.

In this talk, I will present a novel approach adopted by the EU-funded consortium MultiSpin.AI (https://multispinai.eu), which aims to dramatically enhance the speed and energy efficiency of spintronic neuromorphic hardware by using MTJs capable of supporting at least four resistance states.

Micromagnetic Stimulation and Spintronics Sensing in Brain Research and Biomedical Applications

Jian-Ping Wang[1*]

[1]*Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN, 55455, USA*
**Corresponding.jpwang@umn.edu*

The radically smaller and more precise implantable stimulators, sensors, and magnetic field and electrical current-delivering devices and systems have been developed and used to both treat brain disorders and understand the nervous system, particularly signal transmission within the neural network. Recently the knowledge gained in magnetism and spintronics are being used to not only develop more medical treatments but also advance the development of brain-computer interfaces, neuromorphic computing, and ultra low-power information processing technologies. I believe that the technological progress in magnetism and spintronics may ultimately help to uncover the physical and biological mechanisms of memory and consciousness.

In this talk, opportunities and challenges of magnetism and spintronics in brain research and related biomedical applications will be reviewed and discussed. I will then report recent magnetic biomedical brain-related research work: 1) micromagnetic neural stimulation; 2) spintronic neural sensing. First, the designing, fabrication, and testing of two micromagnetic implants – the Magnetic Pen (MagPen), a solenoid-shaped single µcoil prototype, and the Magnetic Patch (MagPatch), a rectangular helix-shaped planar µcoil array prototype, is discussed. The efficacy of micromagnetic activation using MagPen has been successfully tested over many rodent models. The MagPatch array was designed and fabricated to study µMS at the single-cell resolution. Second, we used FEM exemplary models and open-source computational libraries and calculated the magnetic fields generated by individual neurons and neuronal networks at micrometer distances. Our results show that the magnetic field generated by a single-neuron action potential can be detected by ultra-high sensitivity sub-pT magnetic field sensors, which opens the door to future in vivo decoding of neuronal activities through neural networks. Third, room temperature, high endurance, small volume and low power make spintronic sensors one of the promising candidates for neural sensing. The recent experimental progress for the spintronic sensors for neural sensing, e.g. Magnetoencephalography (MEG), will be discussed.

By the end of my talk, a NeuroSpin Initiative will be introduced, which is a collaboration of neurologists, neuroscientists, and engineers to develop novel nanomagnetic materials and quantum spintronic devices for investigating and understanding the nervous system.

References

[1] R. Saha, et al, “A review on magnetic and spintronic neurostimulation: challenges and prospects,” Nanotechnology, vol. 33 (2022) 182004.
[2] D. Tonini, et al, “Feasibility study of magnetic sensing for detecting single-neuron action potentials,” Ann. Biomed. Sci. Eng., vol. 6 (2022)019.
[3] D. Tonini, et al, “Magnetic detection of single-neural compound action potential using tunnel magnetoresistive sensors in amphibian sciatic nerve”, 2024, submitted.
[4] R. Saha et al., “Micromagnetic stimulation (µMS) dose-response of the rat sciatic nerve,” Journal of Neural Engineering, vol. 20, (2023) 036022
[5] R. Saha et al., “Micromagnetic Stimulation (µMS) Controls Dopamine Release: An in vivo Study Using WINCS Harmoni,” bioRxiv, (2023) 2023
[6] R. Saha et al., “Planar Microcoil Arrays for in vitro Cellular-Level Micromagnetic Activation of Neurons,” Journal of vacuum Science & Technology B, 42 (2024) 033001.

MagnetoElectric Nanoparticles for Precision Biomedical Applications

E. Zhang[1*], S.Khizroev[2]

[1]*Department of Mechanical and Process Engineering, ETH Zürich, 8092 Zürich, Switzerland*
[2]*Electrical and Computer Engineering, University of Miami, Miami, FL, 33146, USA*
**elzhang@ethz.ch*

Biology is an incredible exercise in the power and versatility of emergent behavior. Following relatively simple rules, complex patterns emerge. One of the building blocks for biological functions comes from the detection and response to electric fields, which modulate events at all length scales. Electric fields dominate protein folding and intramolecular forces, control ion channels and cellular membrane activity, and give rise to cell differentiation, neuron signaling, and muscle activation. It is no wonder then that so many technologies exist to try and manipulate electric fields within the body.

The power of electric fields in biology is also the source of a major engineering challenge. Electric fields interact with too many vital biological processes, so to use them in medical contexts, they must be delivered through precise methods. Traditionally, this has taken the form of implanted wires and power sources. Whether in deep brain stimulation, pacemakers, or pain management, wired stimulators are the most direct way to deliver electrical fields and currents to precise regions of the body. Despite the relatively high effectiveness of such approaches, wired stimulators tend to face a common trifecta of challenges. First, they require invasive surgery for implantation and adjustment. Second, mechanical requirements for implantation are typically mutually exclusive with ideal biomechanical properties for long-term use. And third, fundamental physics and implanted power considerations rapidly increase the complexity of selectively targeting additional spatial regions.

These limitations have driven much effort into developing wireless and minimally invasive alternatives, of which magnetic field mediated methods have seen particular success. This is due to the broad range of bio-compatible magnetic fields and variety of methods to convert non-interacting magnetic fields into biologically relevant electrical, thermal, and chemical gradients. Recently developed magnetoelectric methods[1] have sought to capitalize on progress in composite magnetoelectric materials that directly transduce magnetic fields into hyperlocal electric fields. The key advantages of magnetoelectric approaches are the specificity of spatial response, and the possibility to tailor magnetic, chemical, thermal, and optical responses to the biological environment and needs.

This presentation will cover our most recent research in partnerships with medical researchers across the globe to launch game-changing precision biomedical applications of MagnetoElectric NanoParticles (MENPs)[2]. These applications include bidirectional wireless brain-machine interfaces[3], cancer theragnostic technologies[4], targeted drug delivery, spinal repair microrobots[5], and many others.

References

[1] E. Zhang *et al.*, "Magnetic-field-synchronized wireless modulation of neural activity by magnetoelectric nanoparticles," *Brain Stimulation*, vol. 15, no. 6, pp. 1451–1462, Nov. 2022, doi: 10.1016/j.brs.2022.10.004.
[2] K. Yue, R. Guduru, J. Hong, P. Liang, M. Nair, and S. Khizroev, "Magneto-Electric Nano-Particles for Non-Invasive Brain Stimulation," *PLoS ONE*, vol. 7, no. 9, p. e44040, Sep. 2012, doi: 10.1371/journal.pone.0044040.
[3] E. Zhang *et al.*, "Ab Initio Physics Considerations in the Design of Wireless and Non-Invasive Neural Recording Systems Using Magnetoelectric Nanoparticles," *IEEE Trans. Magn.*, vol. 59, no. 10, pp. 1–5, Oct. 2023, doi: 10.1109/TMAG.2023.3300791.
[4] J. M. Bryant *et al.*, "Nanoparticles use magnetoelectricity to target and eradicate cancer cells," Oct. 15, 2024, *Bioengineering*. doi: 10.1101/2024.10.13.618075.
[5] H. Ye *et al.*, "Magnetoelectric Microrobots for Spinal Cord Injury Regeneration," *bioRxiv*, p. 2024.08.06.606378, Aug. 2024, doi: 10.1101/2024.08.06.606378.

Posters

Determination of the Optimal Magnetic Flux Density and Frequency Applied to a Magnetic Helical Robot to Maximize the Tunneling Performance of Clogged Blood Vessels

Serim Lee[1], Junhyoung Kwon[1], Junchi Sa[1], Gunhee Jang[1*]

[1]*Department of Mechanical Convergence Engineering, Hanyang University, 04763 Seoul, Korea*
**ghjang@hanyang.ac.kr*

Occlusive vascular disease (OVD) such as stroke in brain and myocardial infarction in heart occurs when a blood vessel becomes narrowed or blocked due to accumulated blood clots and lipids. Medical doctors perform an endovascular intervention procedure to treat OVD. It has 3 major problems; 1) inaccurate procedure, 2) long hours of operation, 3) X-ray radiation exposure of the medical personnel. Robotic endovascular intervention, which utilizes a magnetic navigation system (MNS) and magnetic robots, has been introduced to overcome the conventional endovascular intervention [1]. The magnetic helical robot (MHR) is required to be synchronized by external rotating magnetic field to generate maximum tunneling performance through the thrombus [2,3]. However, it is restricted by the limit of a power supply and the increased impedance due to inductance at fast rotating speed. This paper presents a method to determine the optimal magnetic flux density and frequency applied to the MHR in such a way to maximize the tunneling performance by maximizing the rotational kinetic energy of the MHR.

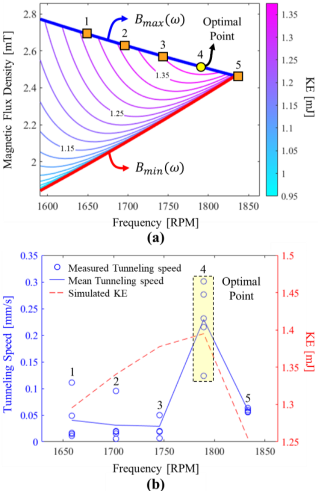

Fig. 1. (a) Rotational kinetic energy of the MHR within the applicable magnetic flux density and frequency (b) Measured tunneling speed of the MHR.

Fig. 1(a) shows the maximum and minimum magnetic flux densities, $B_{max}(\omega)$ and $B_{min}(\omega)$, along the contour lines of the simulated rotational kinetic energy. $B_{max}(\omega)$ is the maximum magnetic flux density that the MNS can generate, and $B_{min}(\omega)$ is the minimum magnetic flux density obtained experimentally to synchronize the rotating motion of the MHR by the applied rotating magnetic field [3]. It shows that the point 4 generates the maximum rotating kinetic energy. Fig. 1(b) shows the measured tunneling speed with artificial blood clot (0.8 wt%, agar) with respect to five operating points as shown in Fig. 1(a). It shows that the tunneling speed of the MHR is maximum when the rotational kinetic energy of the MHR is maximum. This paper will contribute to maximizing the tunneling performance of the MHR in the robotic endovascular intervention.

References

[1] J. Hwang et al., “A review of magnetic actuation systems and magnetically actuated guidewire-and catheter-based microrobots for vascular interventions,” Intelligent Service Robotics, vol. 13, pp. 1-14, Jan. 2020.

[2] P. Chakrabarty and R. P. Paily, "Time-Varying Magnetic Field to Enhance the Navigation of Magnetic Microparticles in a Bifurcated Channel," in IEEE Magnetics Letters, vol. 13, pp. 1-5, Jan. 2022.

[3] J. Kwon, J. Sa, D. Lee and G. Jang, "Enhanced Tunneling Performance of Magnetic Helical Robots Utilizing Pecking Motion Generated by Alternating Rotating Magnetic Field," in IEEE Transactions on Magnetics, vol. 59, no. 11, pp. 1-5, Nov. 2023.

Heating Efficacy of Short Nanowires Produced by Multilayered Template-assisted Electrodeposition

R. Kolisnyk[1*], A. Harpel[2], A. Afful[1], B. Stadler[1,2]

[1]*Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN, 55455, USA*
[2]*Department of Chemical Engineering and Material Science, University of Minnesota, Minneapolis, MN, 55455, USA*
**rkolisny@umn.edu*

Various metallic or oxide nanoparticles are widely used for magnetic hyperthermia and nanowarming of cryopreserved biospecies under an alternating magnetic field. Magnetic nanowires (MNWs) under the same concentration can beneficially contribute to the heating rate due to coupled hysteresis and resistive losses compared to other nanoparticles. One of the limitations is upscaling the production of such particles to meet the demand for high concentration.

Typically, MNWs are synthesized through template-assisted electrodeposition, and their aspect ratio is determined by porous template parameters. It is worth mentioning that for bioapplication nanoparticles' dimensions are limited. Considering this and the industrial approach of a porous template manufacturing process, in the case of short nanowires mass production around 90-95% of template thickness would not be used, which is ineffective. Thus, two cases are available: 1-decreasing template thickness, which has processing restrictions and confined application; 2- filling pores with stacked nanowires. The latter case is discussed further.

Firstly, this study investigates the possibility of upscaling the production of short cobalt, nickel, and iron MNWs synthesized through a standard template-assisted process and the additional introduction of sacrificial copper interlayers. They are subsequently chemically etched, using as oxidizers iron(III) nitrate, ammonium hydroxide, and ammonium chloride of different concentrations, to yield high aspect ratio MNWs. Secondly, it is determined how the synthesis and etching conditions affect MNWs' heating efficacy in terms of reproducibility. While nickel MNWs during the template release process and following copper interlayers etching undergo surface passivation ($\delta_{NiO} \approx 5$nm) and show fairly high repeatability, the iron and cobalt MNWs are sensitive to both successive processes and their repeatability and heating efficiency are highly susceptible to treatment condition (e.g etching agent and its concentration, treatment time).

In conclusion, the potential process of upscaling the synthesis of short nickel, cobalt, and iron nanowires has been studied and the consequent heating application has been discussed.

Scalable Ultra High Sensitivity Soil Moisture Detection Using Photonic Crystal Cavity Array With SIW Technology

Justin Jose[1], Syamlal Sankaran Kunnath[2] , Nikhil Kumar [1]

[1] *Department of Electronics and Communication Engineering, National Institute of Technology, Calicut, India*
2 ISQI, Adam Mickiewicz University, Poznan, Poland
nikhilkumarcs@nitc.ac.in

Soil nutrients and water content are two crucial factors that affect the yield of farming production. Hence, monitoring and measuring the water content and soil type is a critical requirement. Photonic crystals contain regularly repeating regions of high and low refractive index. Light waves will propagate through this structure, or propagation will be forbidden, depending on their wavelength[1].

Researchers have demonstrated that coherent spin wave oscillations can be obtained using magnetic feedback spintronic nano oscillator [2], a magnonic cavity and array of magnonic cavities [3-4] and this can be used for quantum sensing applications [5]. In this paper, we demonstrate the ultra-sensitivity capabilities of photonic crystal cavities can be attained using Substrate Integrated Waveguide (SIW) technology. Here we are proposing a scalable ultra-high sensitive soil moisture sensor, which is based on a two-dimensional photonic crystals cavity array using SIW technology centered on a symmetrical cross-shaped slot as shown in Figure 1a. The cross slots act as a resonator and the photonic crystals surrounding the slots tune the resonance frequency of resonators to increase the mode confinement in the resonator. The resonant modes are in the 2.1 GHz, 5.2 GHz, and 8 GHz bands. The sensor's sensitivity is maximized using this design, which exhibits an enhancement in sensitivity of 1000 times that of a single column of photonic crystal-based SIW [6], which has a frequency shift of the order of GHz. In contrast, in the proposed design, the frequency shift is of the order of MHz.

Figure 1a shows the design structure of the soil moisture sensor’s unit cell, which was designed and simulated using the CST Design studio tool. The structure produces various modes of resonances in the GHz frequency range, these modes are represented by using the Return loss plot (Figure 1b) which is a measure of the signal reflection by the sensor based on the soil composition and water content; Figure 1c shows the absorption plot of Type1 soil. And, Figure 1d compares the Absorption characteristics of three different soil types (Three colors red, green, and blue respectively for Type 1 to Type 3 soil samples) having the characteristics of soil Type 1 (moisture level = 0 %, permittivity = 3, loss = 0.033), Type 2 (moisture level = 5 %, permittivity = 3.9, loss = 0.153) and Type 3 (moisture level = 10 %, permittivity = 5.3, loss = 0.27). The absorption for these different soil types is different, as they have different moisture content values and the corresponding sensitivity values differ. The sensor can also be used to measure soil pH value and thereby estimate the soil nutrient’s concentration, which is valuable information for the yield of crops and for applying the necessary fertilizers. The high-resolution sensor is achieved by creating physical channels in the Substrate Integrated Waveguide cavity. The ability of this sensor to absorb electromagnetic signals to the full extent enables the formation of highly accurate, low-profile radio frequency passive sensors. There is no demand for an external power supply to sense the soil wirelessly. This sensor can monitor the absorption characteristics from a distance by transmitting RF signals. Hence the proposed sensor can be a good choice for remote sensing applications in the farming sector.

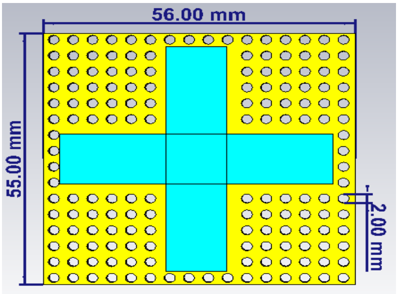

Figure 1a

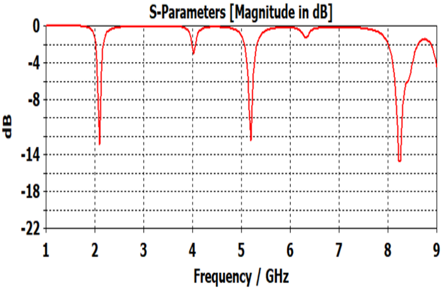

Figure 1b

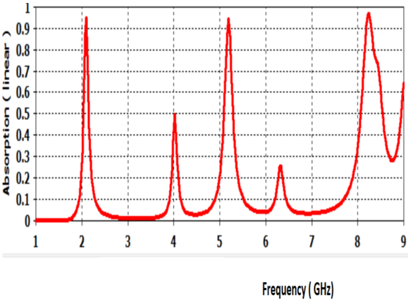

Figure 1c

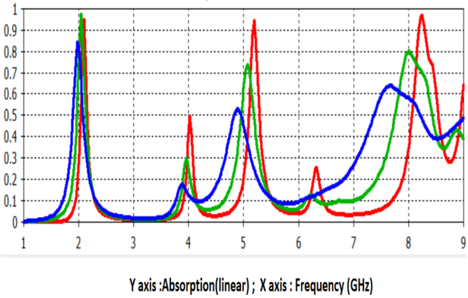

Figure 1d

References

1. Meade, R. D. V., Johnson, S. G., & Winn, J. N. (2008). Photonic crystals: Molding the flow of light.

2. Dinesh Kumar, K. Konishi, Nikhil Kumar, S. Miwa, A. Fukushima, K. Yakushiji, S. Yuasa, H. Kubota, C. V. Tomy, A. Prabhakar, Y. Suzuki & A. Tulapurkar, Coherent microwave generation by spintronic feedback oscillator, Scientific Reports volume 6, Article number: 30747 (2016)

3. N. Kumar, A. Prabhakar, Resonant spin wave excitations in a magnonic crystal cavity, Scientific Reports, 2016/8/1.

4. Nikhil Kumar, Enhanced spin wave coupling between array of spin torque nano oscillators in magnonic crystal cavities, Physica B: Condensed Matter, Volume 645, 15 November 2022, 414248.

5. Nikhil Kumar, Paweł Gruszecki, Mateusz Gołębiewski, Jarosław W Kłos, Maciej Krawczyk, Exciting High-Frequency Short-Wavelength Spin Waves using High Harmonics of a Magnonic Cavity Mode, Advanced Quantum Technologies, 29 March 2024.

6. Amiri, Mehran Abolhasan, Negin Shariati, Justin Lipman, Soil moisture remote sensing using SIW cavity based metamaterial perfect absorber, Scientific Reports, (2021) 11:7153.

Magnetic Hyperthermia Coil and Temperature Distribution Classified Using Machine Learning

A. Kuwahata[1,2*], J. Lazic[1,3], A. Yamazaki[1], T. Kagami[2], Shin Yabukami[1,2]

[1]Graduate school of Engineering, Tohoku University, 6-6-05 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan
[2]Graduate school of Biomedical Engineering, Tohoku University, 6-6-12 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan
[3]School of Electrical Engineering, University of Belgrade, Bulevar kralja Aleksandra 73, 11120 Beograd, Srbija
**akihiro.kuwahata.b1@tohoku.ac.jp*

Magnetic hyperthermia (MH) using magnetic nanoparticles (MNPs) and an alternating magnetic field (AMF) offers a targeted approach to cancer treatment by heating the affected area to the therapeutic range of 43-45°C [1]. However, excessive heating can cause side effects, while insufficient heating fails to eliminate cancer cells. Thus, controlling the temperature distribution, which depends on the magnetic field generated by a coil, is crucial for the treatment's success. The effectiveness of MH relies heavily on precise control of temperature within the tumor, which is largely influenced by the design of the magnetic coil generating the AMF. Traditional coil design methods often involve trial-and-error, a process that can be both time-consuming and inefficient. To overcome this challenge, in this study, we propose a novel approach using convolutional neural networks (CNNs) to recognize coil shapes based on their corresponding temperature distribution patterns for the first time.

Our approach involved generating a comprehensive dataset of magnetic field distributions corresponding to four different coil geometries and their associated temperature distributions (Fig. 1) [2]. Following the CNN training process, the model successfully recognized the coil shapes most likely to produce a given temperature distribution. This capability enables rapid exploration of the design space, facilitating the identification of the optimal coil configuration for specific clinical applications (Fig. 2).

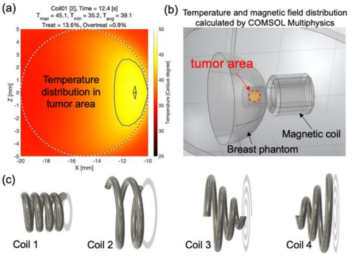

Fig 1. (a) Temperature distribution for magnetic hyperthermia cancer treatment. (b) Breast phantom and magnetic coil. (c) four different coil designs.

The dataset comprises 264 samples, collected using four distinct coil shapes by varying their positions relative to cancer cells. In conjunction with the dataset, we developed a convolutional neural network (CNN) for the task of coil shape classification. Once trained, our model can classify arbitrary temperature distributions to the most probable coil shape responsible for their generation in a matter of seconds. The model achieved an accuracy of 61.61% on the test data. Our findings indicate that different coil shapes produce temperature distributions with distinguishable features, even for relatively small neural networks. This highlights the potential of machine learning in image analysis as a promising approach for optimizing magnetic hyperthermia cancer treatments in the future.

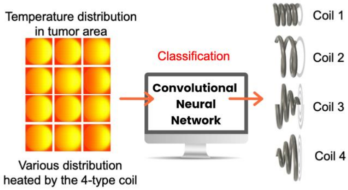

Fig. 2. Classification of magnetic coil using CNN.

References

[1] X. Liu *et al.*, Theranostics **10**, 3793-3815 (2020). https://doi.org/10.7150/thno.40805.
[2] T. Kagami *et al.*, IEEJ TRANS. **19**, 755–758 (2024). https://doi.org/10.1002/tee.24013.

Expanding the Field Range of PHE Sensors for Increased Industrial Applicability

Daniel Lahav[1*], Moty Schultz[1], Shai Amrusi[2], Asaf Grosz[2] and Lior Klein[1]

[1] *Department of Physics, Institute of Nanotechnology and Advanced Materials, Bar-Ilan University, Ramat-Gan 52900, Israel*

[2] *Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva 84105, Israel*

*[*daniel.lahav@live.biu.ac.il](mailto:daniel.lahav@live.biu.ac.il)*

A recent comprehensive review of planar Hall effect (PHE) sensors [1] underscores the growing interest in these sensors and identifies numerous opportunities for further enhancements that could broaden their application scope, including in microfluidics and flexible sensor technologies. However, PHE sensors have a notable limitation: they typically operate within a magnetic field range of hundreds of microteslas (μT) [2]. This restriction poses challenges for applications requiring broader field ranges, such as in the automotive industry. To meet the increasing demand for highly sensitive magnetic sensors with larger measuring field range across industrial, scientific, and consumer sectors, it is essential to expand the field range of PHE sensors and evaluate the impact of such an expansion on their equivalent magnetic noise (EMN) [3]. Previous attempts to increase the field range of magnetoresistive sensors included modifications to the ferromagnetic layer and variations in the thicknesses of spacer and capping layers. Here, we achieve an increase of more than an order of magnitude in the field range by manipulating the shape-induced magnetic anisotropy [3]. We present measurements of elliptical PHE sensors with uniaxial magnetic anisotropy ranging from less than mT to more than 10 mT, and show that an EMN of less than 10 nT/√ Hz at 10 Hz is achieved for anisotropy field exceeding 4 mT (Fig.1). Additionally, by measuring the PHE resistance (R_{PHE}) in a field range where the sensor response in linear, descending from a high positive field (R_{PHE}^{+}), and ascending from a low negative field (R_{PHE}^{-}), we show that sensors with larger field range exhibit negligible hysteresis, associated with their effective single magnetic domain behaviour (Fig.2). We discuss the potential industrial applications of PHE sensors with extended field range and compare their performance with other commonly used sensors in similar applications. In addition, we discuss promising routes to further expand the field range while minimizing detrimental effects on resolution.

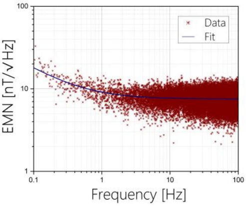

Figure 1: EMN vs. frequency of a PHE sensor with an anisotropy field of 4.2 mT.

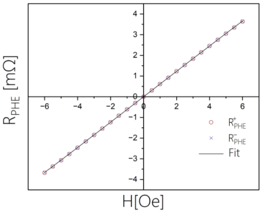

Figure 2: R_{PHE}^{+} and R_{PHE}^{-} vs applied field parallel to the hard axis of the ellipse of a PHE sensor with an anisotropy field of 4.2 mT.

References

[1] A. Elzwawy, H. Pişkin, N. Akdoğan, M. Volmer, G. Reiss, L. Marnitz, A. Moskaltsova, O. Gurel, and J.-M. Schmalhorst, "Current trends in planar hall effect sensors: evolution, optimization, and applications," Journal of Physics D: Applied Physics, vol. 54, no. 35, p. 353002, 2021.

[2] H. Nhalil, T. Givon, P. T. Das, N. Hasidim, V. Mor, M. Schultz, S. Amrusi, L. Klein, and A. Grosz, "Planar hall effect magnetometer with 5 pt resolution," IEEE Sensors Letters, vol. 3, no. 12, pp. 1–4, 2019.

[3] D. Lahav, M. Schultz, S. Amrusi, A. Grosz, and L. Klein, "Planar Hall effect magnetic sensors with extended field range," Sensors, vol. 24, no. 13, 2024.

Multi-Functional Flexible Planar Hall Effect Sensors

Daniel Lahav[1*], Hariharan Nhalil[1], Moty Schultz[1], Shai Amrusi[2], Asaf Grosz[2] and Lior Klein[1]

[1]Department of Physics, Institute of Nanotechnology and Advanced Materials, Bar-Ilan University, Ramat-Gan 52900, Israel

[2]Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva 84105, Israel

**daniel.lahav@live.biu.ac.il*

Magnetic sensors are essential in various technological applications, including navigation, medical diagnostics, industrial automation, consumer electronics, and more. Among magnetoresistive sensors, planar Hall effect (PHE) sensors, in particular, offer significant advantages such as ultra-low equivalent magnetic noise (EMN) in the range of pT/√ Hz, straightforward design, and cost-effectiveness. In previous studies we have presented rigid elliptical PHE sensors with EMN of 24 pT/√ Hz at 50 Hz [1]. Furthermore, by integrating magnetic flux concentrators (MFCs) an EMN of 5 pT/√ Hz at 10 Hz was achieved [2]. Recently, we have reported flexible elliptical PHE sensor (Fig.1) with EMN of ~200 and ~300 pT/√ Hz at 10 Hz, in flat and bent states, respectively [3]. These EMN values represent a major improvement compared to other flexible magnetic field sensors. Here, we report a significant step forward and present a multi-functional flexible PHE sensor, that can be used not only for measuring magnetic fields but also for measuring minute strains. We will present our latest results which indicate that flexible elliptical PHE sensor have the potential of serving as strain gauges with the ability to detect few percents of micro-strain.

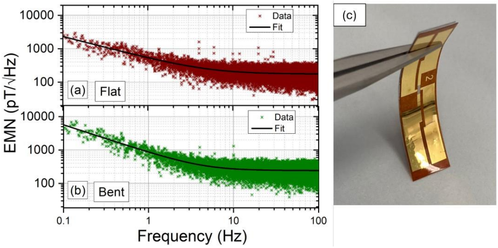

Figure 1: EMN of flexible elliptical PHE sensors vs. frequency in (a) flat and (b) bent states. (c) A photo of a flexible elliptical PHE sensor.

References

[1] H. Nhalil, P. T. Das, M. Schultz, S. Amrusi, A. Grosz, and L. Klein, "Thickness dependence of elliptical planar Hall effect magnetometers," Applied Physics Letters, vol. 117, no. 26, p. 262403,2020.

[2] H. Nhalil, T. Givon, P. T. Das, N. Hasidim, V. Mor, M. Schultz, S. Amrusi, L. Klein, and A. Grosz, "Planar Hall effect magnetometer with 5 pT resolution," IEEE Sensors Letters, vol. 3, no. 12, pp. 1–4, 2019.

[3] H. Nhalil, D. Lahav, M. Schultz, S. Amrusi, A. Grosz, and L. Klein, "Flexible planar Hall effect sensor with sub-200 pT resolution," Applied Physics Letters, vol. 123, p. 024102, 07 2023.

Magnetic Sensor Integrated Circuits for Industrial and Automotive Applications

D. W. Lee[1*]

[1]*Kilby Labs, Texas Instruments, Santa Clara, CA, 95051, USA*
**dok.lee@ti.com*

Semiconductor based magnetic sensors have been widely used in industrial and automotive applications due to their high reliability and low cost. Several figures of merits (FOM) of these magnetic sensors are important for real-world applications and play an important role in their adoption and commercialization. They include magnetic sensitivity, noise, offset, resistance, temperature drift, cost of manufacturing and size.

Silicon-based magnetic sensors can be manufactured in standard CMOS process and monolithically integrated with analog and digital circuitry. Integrated circuitry can be used to improve FOMs and correct the process-related variations. As an example, on-chip circuits have been widely used to correct the offset of the stand-alone Hall-effect sensors [1].

This presentation will discuss the importance of accurate compact models of magnetic sensors for circuit simulations and analytical understanding of the performance drift after the correction.

References

[1] R. Popovic et al., “Future of Magnetic Sensors,” Sensors and Actuators A, vol. 56, pp. 39-55, 1996.

High Data-Rate VLF Magnetoelectric Communications with Single-Side-Band Nonlinear Antenna Modulation

Yisi Liu, Thomas Noochan, Bin Luo, Mark Sun, Nian Sun*

Department of Electrical and Computer Engineering, Northeastern University, Boston, MA, 02115, USA
*n.sun@northeastern.edu

Very Low Frequency (VLF) electromagnetic waves show great potential in underground and underwater communication owing to their strong penetration depth in lossy media like seawater [1]. However, the long wavelength of VLF signals requires antennas large in size and high-power consumption. At the same time, state-of-the-art VLF communication systems suffer from low data rates of ~200 bit/s. Recent research demonstrated that magnetoelectric (ME) antennas leveraging electromechanical resonance(EMR) could reduce VLF antenna size by several orders of magnitude [1-4].

Despite this advancement, the bandwidth and efficiency of VLF ME antennas are limited by relatively low resonance frequencies at VLF. Recently, a double-side-band Nonlinear Antenna Modulation (DSB-NAM) technique with carrier frequency equal to the electromechanical resonance frequency ($f_{carrier} = f_{EMR}$), has been utilized to overcome this limitation, but it suffers from high power consumption and weak signals (Fig. 1, Fig. 2a and b) [1-4]. In this work, we demonstrate a new modulation technique for VLF ME antennas, the single-side-band Nonlinear Antenna Modulation (SSB-NAM), which offers higher signal-to-noise ratio (SNR) with over 10 kb/s data rates, and much stronger modulation output.

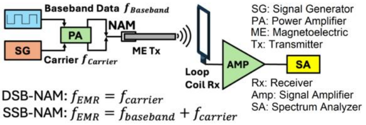

Fig. 1. (a) Schematic of the double-sideband nonlinear antenna modulation (DSB-NAM) and single-sideband nonlinear antenna modulation (SSB-NAM) communication link between magnetoelectric transmitter (ME Tx) and Loop Coil Rx.

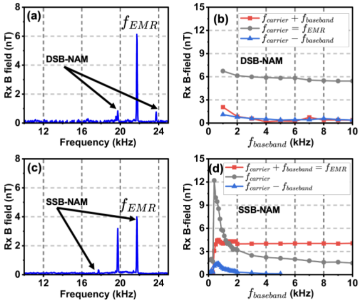

Fig. 2. (a) (b) the spectrum and frequency-dependent modulated signal intensity for DSB-NAM. (c) (d) are for SSB-NAM.

Unlike DSB-NAM [1-4], where the carrier signal frequency is equal to the EMR frequency (f_{EMR}) of VLF ME antennas, the $f_{carrier}$ in SSB-NAM is adjusted with the baseband data frequency ($f_{baseband}$), ensuring that $f_{carrier} + f_{baseband} = f_{EMR}$ (Fig 1, Fig. 2c and d). In both DSB-NAM and SSB-NAM, no mixer is used before feeding the baseband data and carrier signal into ME antennas; instead, the modulation output signal is directly produced due to the intrinsic nonlinearity of ME antennas. The spectrum reveals three peaks at $f_{carrier}-f_{baseband}$, $f_{carrier}$,

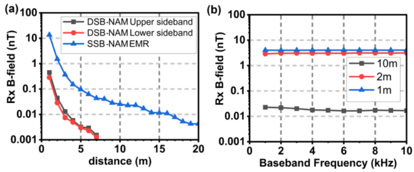

Fig. 3. (a) Long-distance transmission comparison between SSB-NAM and DSB-NAM systems. (b) Magnetic field stability across various baseband frequencies (1–10 kHz) at different distances (1 m, 2 m, and 10 m) using SSB-NAM.

and f_{EMR} (Fig. 2c). Our findings indicate that the modulated output at f_{EMR} remains stable and strong across an f_{baseband} range from 0.5 kHz to 10 kHz, maintaining around 4 nT (Fig. 2d). As illustrated in Fig. 3a, the NAM-SSB exhibits a significantly superior signal transmission range, reaching up to 20 meters, compared to the NAM-DSB, which is limited to 7 meters. Moreover, the NAM-SSB demonstrates the ability to carry a wide broadband baseband signal over distances exceeding 10 meters (Fig. 3b), further emphasizing its enhanced performance. These results demonstrate robust transmission and wide bandwidth capabilities for advanced miniaturized ME VLF antennas in underwater and underground communications. Additionally, the improvements in mobility reinforce the practical applicability of this antenna in various operational scenarios, offering a significant advancement in VLF antenna technology.

References

[1] B. Luo, AR Will-Cole, C. Dong, NX Sun, Magnetoelectric microelectromechanical and nanoelectromechanical systems for the IoT, Nature Reviews Electrical Engineering, 1, 317-334 (2024).

[2] C. Dong, Y. He, X. Liu, and N. X. Sun, "VLF Mechanical Antenna Arrays for Underwater Wireless Communications," New York, NY, USA, 2022: ACM, pp. 1-5.

[3] C. Dong et al., "A Portable Very Low Frequency (VLF) Communication System Based on Acoustically Actuated Magnetoelectric Antennas," IEEE Antennas and Wireless Propagation Letters, 19, 398-402 (2020).

[4] Y. He, "Magnetic and Magnetoelectric Devices for Communication and Energy Harvesting Applications," PhD Dissertations, 2023.

Low-noise, Self-biased Spin Wave-driven Thin-Film Integrated Giant Magnetoimpedance Sensors

Bin Luo[1*], Xianfeng Liang[1], Huaihao Chen[1], Cai Müller[2], Paul Raschdorf[2], Phillip Durdaut[3], Michael Höft[3],
Jeffrey McCord[2,4] and Nian-Xiang Sun[1]

[1]*Department of Electrical and Computer Engineering, Northeastern University, Boston, MA, 02115, USA*
[2]*Department of Materials Science, Kiel University, 24143 Kiel, Germany*
[3]*Department of Electrical Engineering and Information Technology, Kiel University, 24143 Kiel, Germany*
[4]*KiNSIS - Kiel Nano, Surface and Interface Science, Kiel University, 24118 Kiel, Germany*
**luo.bin1@northeastern.edu*

Magnetic sensors are vital in modern technology, with extensive applications across various engineering and industrial fields. The Giant Magnetoimpedance (GMI) effect offers advantages such as high magnetic field sensitivity and spatial resolution, making it a key focus for ultrasensitive magnetic sensors. However, conventional GMI sensors were fabricated based on either ribbon or microwire structures[1-4] requiring glass-coated melt-spinning and electrodeposition [5, 6], which makes conventional GMI sensors bulky, non-integrated, costly, and unsuitable for modern technology. Besides, a bias field is required for maximum sensitivity, which necessitates a fluxgate concentrator and pick coil, further limiting the miniaturization of GMI sensors[7].

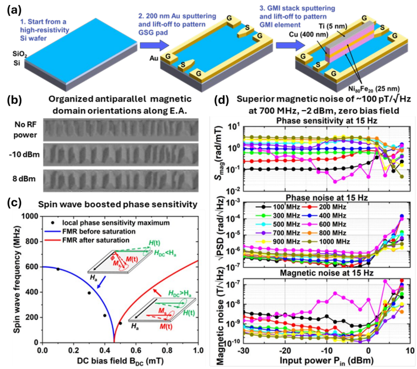

Fig. 1. Low-noise, self-biased spin wave-driven thin-film integrated giant magnetoimpedance sensors. (a) Fabrication flow. (b) magnetic domains at remanence. (c) RF frequency versus DC bias field at phase sensitivity maximum. (d) phase sensitivity, phase noise, and magnetic noise versus input power at different RF frequencies.

Here we present a self-biased, low-noise GMI sensor based on spin wave-driven S_{21} phase change in a NiFe/Ti/Cu/NiFe/Ti multilayer microstrip. Fabricated using photolithography and sputtering on a silicon wafer (Figure 1 (a)), the sensor exhibits favorable magnetic properties, including low coercivity, narrow ferromagnetic resonance linewidth, and well-defined magnetic domain walls along the microstrip width direction (easy axis), as shown in Figure 1 (b). The phase sensitivity maximum versus bias magnetic field accords well with the ferromagnetic resonance, as shown in Figure 1 (c), demonstrating uniform mode spin wave boosted phase sensitivity. Phase sensitivity, phase noise, and magnetic noise as functions of RF frequency, DC bias field, and input power were examined, achieving the best equivalent magnetic noise of ∼100 pT/√Hz at zero bias and 15 Hz, as shown in Figure 1 (d). The optimal RF frequency is 700 MHz with an input power of −2 dBm. The compact design, self-biased operation, low LoD, and MEMS-based fabrication make these integrated GMI sensors promising for fundamental research and industrial applications requiring precise magnetic field detection.

References

[1] S. Jiang *et al.*, "Surface microstructural design to improve mechanical and giant magneto-impedance properties of melt-extracted CoFe-based amorphous wires," *Materials & Design,* vol. 204, p. 109642, 2021.

[2] Y. Chen, J. Zou, X. Shu, Y. Song, and Z. Zhao, "Enhanced giant magneto-impedance effects in sandwich FINEMET/rGO/FeCo composite ribbons," *Appl Surf Sci,* vol. 545, p. 149021, 2021.

[3] C. Yang *et al.*, "Enhanced giant magnetoimpedance effect in FINEMET/TiO 2 composite ribbons," *Journal of Materials Science: Materials in Electronics,* pp. 1-9, 2022.

[4] C. Jia *et al.*, "Magnetic properties and giant magneto-impedance effect of FINEMET/IGZO composite ribbons," *Journal of Magnetism and Magnetic Materials,* vol. 544, p. 168662, 2022.

[5] P. SQUIRE, D. ATKINSON, M. GIBBS, and S. ATALAY, "AMORPHOUS WIRES AND THEIR APPLICATIONS," (in English), *Journal of Magnetism and Magnetic Materials,* Review vol. 132, no. 1-3, pp. 10-21, APR 1994 1994, doi: 10.1016/0304-8853(94)90295-X.

[6] X. Wang, W. Yuan, Z. Zhao, X. Li, J. Ruan, and X. Yang, "Giant magnetoimpedance effect in CuBe/NiFeB and CuBe/insulator/NiFeB electroless-deposited composite wires," (in English), *Ieee T Magn,* Article|Proceedings Paper vol. 41, no. 1, pp. 113-115, JAN 2005 2005, doi: 10.1109/TMAG.2004.832479.

[7] P. S. Traore, A. Asfour, and J. P. Yonnet, "Design Approach for an Off-diagonal Giant Magneto Impedance Sensor Based on Field Programmable Gate Array," *Sensors & Transducers,* vol. 245, no. 6, pp. 20-26, 2020.

Micro-fluxgate: Rod Core vs. Racetrack Core

J. Maier[1*], P. Ripka[1], P. Chen[2]

[1]*Faculty of Electrical Engineering, Czech Technical University in Prague, 166 27 Prague, Czech Republic*
[2]*National Taiwan University of Science and Technology, Taipei City 106, Taiwan*
**maierjir@fel.cvut.cz*

The core of TI DRV425, the only integrated fluxgate sensor available on the market, is formed by double rod [1]. We believe that racetrack is a better core shape compared to double rod due to the fact that the racetrack core is magnetically closed, and thus the excitation field for the same excitation current is higher. Thus, the improvement of perming, noise and long-term offset stability is expected. As usual, the reality is more complicated: once locally saturated, the core is no longer "closed". Also, racetrack has a higher demagnetization factor than a rod, which results in lower sensitivity. In this paper we analyze the mentioned differences by 1) FEM simulation, respecting material nonlinearity and eddy current effects – details of our fluxgate model will be described in [2]. 2) macro demonstrator using 32 mm amorphous cores. 3) micro-fluxgate sensor demonstrator using an 8 mm long core.

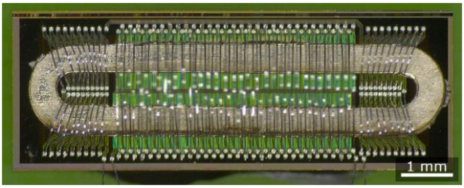

Fig. 1: Photo of the micro-fluxgate with racetrack core [3]

CMOS based micro fluxgate with racetrack core and wire-bonding solenoid coils (depicted in figure 1) was developed by our team, which is described in [3]. The material of the core is Vitrovac 6025F, an amorphous metal with excellent magnetic properties. The thickness of the core is 25 µm. That is the lowest commercially available thickness, but it is higher than desired due to low penetration depth of excitation fields above 1 MHz, which we examine in more detail in [2]. Sensitivity is in order of thousands V/T at excitation frequencies of hundreds kHz, reaching maximum of 5000 V/T at 1.55 MHz. This sensitivity is two orders of magnitude higher compared to similar sized micro-fluxgate with planar coils [4]. Noise as low as 2 nT/√Hz can be reached with sinewave excitation (minimum at 200 kHz, increasing above 1 MHz), which is significantly better than 12 nT/√Hz in [4] and 5 nT/√Hz in [1], Perming error after 10 mT field shock is 3.4 µT, slightly lower than 5 µT of the DRV425.

Pulse excitation was evaluated to reduce power consumption and improve perming and noise. In this way, it was possible to reduce power consumption 4 times while keeping perming and noise at the same level. The lack of improvement in noise and perming is attributed to higher harmonics of pulse signal not penetrating deeper inside the core due to skin effect. Operating the fluxgate at MHz frequencies would require using multilayer thin cores to reduce eddy currents.

The same micro-fluxgate structure will be tested with a double rod core instead of a racetrack core to compare their performance through measurements.

References

[1] M. F. Snoeij, V. Schaffer, S. Udayashankar et al., "Integrated Fluxgate Magnetometer for Use in Isolated Current Sensing," IEEE Journal of Solid-State Circuits, vol. 51, no. 7, pp. 1684-1694, Jul, 2016.

[2] J. Maier, P. Ripka, M. Mirzaei: Modeling Magnetic Field in Racetrack-Core Fluxgates at High Excitation Frequency, submitted for Intermag 2025

[3] J. Maier, P. Ripka, and P. Chen, "CMOS-based micro-fluxgate with racetrack core and solenoid coils," Sensors and Actuators A: Physical, vol. 379, 2024.

[4] C. C. Lu, Y. C. Lin, Y. Z. Tian et al., "Hybrid microfluxgate and current transformer sensor," IEEE Transactions on Magnetics, vol. 58, no. 8, Aug 2022.

Flexible, Printable and Eco-sustainable Magnetoelectronics

R. Xu[1], L. Guo[1], X. Wang[1], P. Makushko[1], E. S. Oliveros-Mata[1], Y. Zabila[1], D. Makarov[1*]

[1] *Helmholtz-Zentrum Dresden-Rossendorf e.V., Institute of Ion Beam Physics and Materials Research, 01328 Dresden, Germany*
**d.makarov@hzdr.de*

Motion sensing is the primary task in numerous disciplines including industrial robotics, prosthetics, virtual and augmented reality appliances. In rigid electronics, rotations, displacements and vibrations are typically monitored using magnetic field sensors. Here, we will discuss on the fabrication of flexible, printable and eco-sustainable magnetoelectronic devices [1-3]. Their application potential is explored as mechanically reshapeable magnetic field sensors for automotive applications, spin-wave filters, high-speed racetrack memory devices, magnetic soft robots [4] as well as on-skin interactive electronics relying on thin films [4-6] as well as printed magnetic composites [7,8] with appealing self-healing performance [9]. This opens perspectives for magnetoelectronics in smart wearables, interactive printed electronics and motivates further explorations towards the realization of eco-sustainable magnetic field sensing relying on biocompatible and biodegradable materials [2,3,10].

References

1. G. S. Canon Bermudez et al., "Magnetosensitive e-skins for interactive devices," Advanced Functional Materials (Review) 31, 2007788 (2021).
2. E. S. Oliveros Mata et al., "Magnetically aware actuating composites: Sensing features as inspiration for the next step in advanced magnetic soft robotics," Phys. Rev. Appl. (Review) 20, 060501 (2023).
3. L. Guo et al., "Printable magnetoresistive sensors: A crucial step toward unconventional magnetoelectronics," Chinese Journal of Structural Chemistry (Review) 100428 (2024).
4. M. Ha et al., "Reconfigurable Magnetic Origami Actuators with On-Board Sensing for Guided Assembly," Advanced Materials 33, 2008751 (2021).
5. J. Ge et al., "A bimodal soft electronic skin for tactile and touchless interaction in real time," Nature Communications 10, 4405 (2019).
6. G. S. Canon Bermudez et al., "Electronic-skin compasses for geomagnetic field driven artificial magnetoception and interactive electronics," Nature Electronics 1, 589 (2018).
7. M. Ha et al., "Printable and Stretchable Giant Magnetoresistive Sensors for Highly Compliant and Skin-Conformal Electronics," Advanced Materials 33, 2005521 (2021).
8. E. S. Oliveros Mata et al., "Dispenser printed bismuth-based magnetic field sensors with non-saturating large magnetoresistance for touchless interactive surfaces," Advanced Materials Technologies 7, 2200227 (2022).
9. R. Xu et al., "Self-healable printed magnetic field sensors using alternating magnetic fields," Nature Communications 13, 6587 (2022).
10. X. Wang et al., "Printed magnetoresistive sensors for recyclable magnetoelectronics," J. Mater. Chem. A 12, 24906 (2024).

FeCo-based Isotropic Soft Magnetic Nanostructured Thin Films with Improved Electrical Resistivity

G. Wei[1*], A. Masood[1*], and R. Sai[1]

[1]*Tyndall National Institute, University College Cork, Cork, T12 R5CP, Ireland*
*[*guannan.wei@tyndall.ie](mailto:guannan.wei@tyndall.ie) & ansar.masood@tyndall.ie*

The rapid evolution of power semiconductor device technologies inspires a revolution in power electronics towards efficiency and miniaturization. Accordingly, the demand of low-lossy and miniaturized integrated magnetic components rises necessitating innovation in magnetic thin films capable of efficient performance at high frequencies around 100 MHz. Traditional uniaxially-anisotropic amorphous ferromagnetic thin films exhibit prohibitively lossy characteristics at such a high frequency due to substantial losses from eddy currents, magnetic damping, and poor magnetic alignment. Nanostructured and isotropic magnetic films have emerged as promising alternatives, offering enhanced magnetic and electrical properties tailored for high-frequency use.

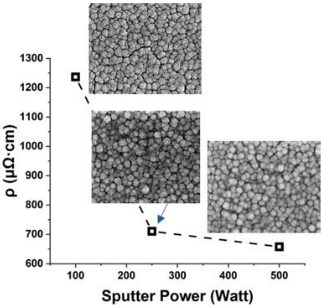

Fig. 1. Electrical resistivity of Fe-Co-B-N films as a function of sputter power. SEM images of the associated films are presented to illustrate how the granular structure looks like.

In this study, amorphous Fe-Co-B-N films were investigated for their unique combination of magnetic and electric properties and structural flexibility. XRD analysis confirmed their amorphous nature, while SEM and AFM affirms the formation of nanostructured grains of varied sizes, which in turn, contributes to isotropic magnetic behavior, making them well-suited for high-frequency applications. The sputtering recipe holds the key in controlling both magnetic anisotropy and permeability in these films. By increasing sputter power from 100 to 500 W, resistivity can be decreased from 1237 to 658 µΩ·cm, while permeability can be improved from 13 to 42 at 100 MHz.

Through the delicate manipulation of deposition parameters, including sputter power and pressure, significant control over the film's morphology, resulting in variations in grain size and accordingly unique combination of enhanced magnetic and electric performances. The high-resistive isotropic Fe-Co-B-N films, with a high permeability of 42 at 100 MHz and ferromagnetic resonance (FMR) frequency of ~1 GHz are particularly suitable for toroidal inductors, minimizing easy-axis excitation at joint parts of the magnetic loop. This reduces magnetic reluctance and boosts inductance while also minimizing flux leakage. Furthermore, the high resistivity of 658 µΩ·cm, nearly six times higher than that of commercial Co-Zr-Ta-B magnetic core material, significantly reduces eddy current losses, making these films highly efficient for high-frequency applications.

References

[1] H. Kijima, et. al., “High noise suppression using magnetically isotropic (CoFe-AlN)/(AlN) multilayer films,” (in German), J. App. Phys., vol. 117, p. 17E514, 2015.
[2] S. Wang, et. al., “Enhanced magnetic softness and high-frequency characteristics Fe51.1Co48.9B–Al2O3 nanogranular films,” Scr. Mat., vol. 65, pp. 45–48, 2011. doi:10.1016/j.scriptamat.2011.03.010.
[3] W. Wang, et. al., “Magnetic softness and high-frequency characteristics of Fe65Co35–O alloy films,” J. App. Phys., vol. 106, p. 013912, 2009.

Extending the Range of Flexible Planar Hall Effect Sensors by Use of an Exchange Bias

J. Schmidtpeter[1,2*], P. T. Das[1], P. Makushko[1], Y. Zabila[1,] T. Wondrak[2] and D. Makarov[1]

[1]*Helmholtz-Zentrum Dresden-Rossendorf e.V., Institute of Ion Beam Physics and Materials Research, 01328 Dresden, Germany*
[2]*Helmholtz-Zentrum Dresden-Rossendorf e.V., Institute of Fluid dynamics, 01328 Dresden, Germany*

**J.Schmidtpeter@hzdr.de*

Low resolution magnetometers have been explored for many years now, stretching from applications in fundamental research for materials science to industry applications in the automotive industry. New opportunities are emerging with the increasing development of small and flexible magnetic field sensors. Flexible magnetroesistive sensors generally provide benefits in application of beeing ultra-thin, light and mass-producable. These advantages in combination with a low resolution can provide new opportunities in bio-medical applications, technology and process monitoring [1,2]. Here flexible planar Hall effect sensors can provide a unique opportunity with field resolutions in the sub-nT region [3,4]. However due to their sub-mT measurement range they are not suitable for many applications at this moment, which is why recently an increase in measurement range was devised by increasing the uniaxial shape-induced anisotropy in elliptical planar Hall effect sensors [5].

In this study we explore the effect of an exchange bias to increase the measurement range of flexible elliptical planar Hall effect sensors. Sensors are prepared on polymer based substrates with varying thicknesses of the ferromagnetic and antiferromagnetic layers, varying the strength of the exchange bias. To obtain highly flexible and yet reliable sensors, rigorous bending tests are performed to investigate the effect of bending on sensor performance based on substrates and layer stacks. Additionally an outlook on sensitivity and noise performance is given to classify the sensors overall performance compared to state-of-the-art planar Hall effect sensors. This research aims to advance flexible sensor technology by providing insight into the material and sensor performance under mechanical stress, paving the way for reliable and high-performance flexible sensor systems.

References

[1] Cao, Bo, et al. "Development of magnetic sensor technologies for point-of-care testing: Fundamentals, methodologies and applications." *Sensors and Actuators A: Physical* 312 (2020): 112130.

[2] Lee, Sungho, et al. "High accuracy open-type current sensor with a differential planar Hall resistive sensor." *Sensors* 18.7 (2018): 2231.

[3] Granell, Pablo Nicolás, et al. "Highly compliant planar Hall effect sensor with sub 200 nT sensitivity." *npj Flexible Electronics* 3.1 (2019): 3.

[4] Nhalil, Hariharan, et al. "Flexible planar Hall effect sensor with sub-200 pT resolution." *Applied Physics Letters* 123.2 (2023).

[5] Lahav, Daniel, et al. "Planar Hall Effect Magnetic Sensors with Extended Field Range." *Sensors* 24.13 (2024): 4384.

Magnetoelectric Devices Towards Implantable Electronics

Prasanth Velvaluri[1*], Eckhard Quandt[2], Nian X. Sun[1]

[1]*Department of Electrical and Computer Engineering, Northeastern University, Boston, MA, 02115, USA*
[2]*Material Science and Engineering, Kiel University, Kiel, 24143 Germany*

**Email: p.velvaluri@northeastern.edu*

Brain-Computer Interfaces (BCIs) are advanced implantable devices that enable patients with severe disabilities to regain movement, such as controlling an exoskeleton [1], or communication, such as controlling a computer [2]. Recently, minimally invasive BCIs, such as the Stentrode (a stent with electrodes), have demonstrated the ability to restore communication in patients with paralysis [3]. This approach provides a less invasive alternative to traditional BCIs, which require open craniotomy for implantation. Minimally invasive BCIs offer significant benefits to both patients, through simplified surgical procedures, and physicians, by leveraging techniques that have been used for decades in treating vascular conditions like aneurysms and strokes.

However, the current Stentrode technology requires complex electronics to amplify and transmit data. To facilitate this, an additional control unit must be implanted and connected to the Stentrode via a wire [3]. These secondary wired connections are bulky, may lead to complications, and have the potential to malfunction. In such cases, novel implantable devices with integrated electronics could be advantageous. The major challenges in integrating electronics with implants are maintaining small size and ensuring functionality.

Magnetoelectric (ME) devices, which are based on the combination of magnetostrictive and piezoelectric materials, have recently gained popularity due to their compact size and enhanced functionality. In this poster presentation, we report advances in ME-based devices, including antennas, energy harvesters, and sensors, which have the potential to be integrated with implants for minimally invasive BCI applications.

Recently, miniature ME antennas have been developed, and their size reduction is attributed to their ability to operate at acoustic resonance rather than electromagnetic resonance. This allows for a reduction in size by over five orders of magnitude compared to traditional antennas. Moreover, ME antennas do not suffer from ground plane immunity issues, unlike conventional antennas that are mounted in-plane on conductive substrates. This makes them highly attractive for data transfer in implantable BCI applications. Two configurations of ME antennas are currently under investigation: one that is partially released from the substrate [4], and another that is mounted on the substrate [5].

A stand-alone implantable device requires a power source, but batteries are not ideal due to their limited lifespan, bulkiness, and inability to be delivered minimally invasively through a catheter. Wireless power transfer using energy harvesters offers a promising alternative. ME-based energy harvesters have demonstrated a figure of merit of 3721, which is an order of magnitude better than coil-based devices [6]. Additionally, similar ME cantilevers have been used for wireless nerve stimulation in animal models [7]. Other related electronics for implantable applications include electrodes, blood flow sensors, and pressure sensors.

ME-based devices for implantable electronics are a relatively new field. There are several ways in which these ME devices can be integrated into implants. In this poster, we summarize the most promising ME-based devices, their working principles, fabrication methods, and characterization towards minimally invasive BCIs.

References

[1] M. Vilela and L. R. Hochberg, “Applications of brain-computer interfaces to the control of robotic and prosthetic arms,” in *Brain-Computer Interfaces*, vol. 168, N. F. Ramsey and J. del R. B. T.-H. of C. N. Millán, Eds. Elsevier, 2020, pp. 87–99.

[2] M. J. Vansteensel *et al.*, “Fully Implanted Brain–Computer Interface in a Locked-In Patient with ALS,” *N. Engl. J. Med.*, vol. 375, no. 21, pp. 2060–2066, 2016.

[3] P. Mitchell *et al.*, “Assessment of Safety of a Fully Implanted Endovascular Brain-Computer Interface for Severe Paralysis in 4 Patients: The Stentrode With Thought-Controlled Digital Switch (SWITCH) Study,” *JAMA Neurol.*, vol. 80, no. 3, pp. 270–278, 2023.

[4] T. Nan *et al.*, “Acoustically actuated ultra-compact NEMS magnetoelectric antennas,” *Nat. Commun.*, vol. 8, no. 1, pp. 1–7, 2017.

[5] X. Liang *et al.*, “Mechanically Driven Solidly Mounted Resonator-Based Nanoelectromechanical Systems Magnetoelectric Antennas,” *Adv. Eng. Mater.*, vol. 25, no. 21, 2023.

[6] M. Zaeimbashi *et al.*, “Ultra-compact dual-band smart NEMS magnetoelectric antennas for simultaneous wireless energy harvesting and magnetic field sensing,” *Nat. Commun.*, vol. 12, no. 1, 2021.

[7] F. Alrashdan, K. Yang, and J. T. Robinson, “Magnetoelectrics for Implantable Bioelectronics: Progress to Date,” *Acc. Chem. Res.*, 2024.

Area-Efficient Integrated MRAM for High-Performing AI Acceleration

Cheng Wang[1*], Sohan Salahuddin Mugdho[1], and Kshemal K. Gupte[1]

[1]*Department of Electrical and Computer Engineering, Iowa State University, Ames, IA USA*
**chengw@iastate.edu*

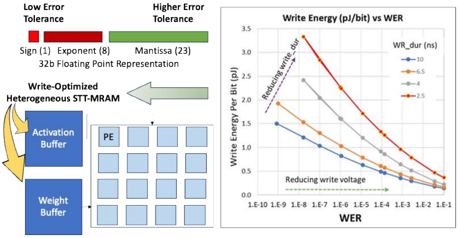

Fig. 1. MRAM as on-chip memory for AI acceleration.

Remarkable progress in artificial intelligence has been fueled by the ability to train large-scale deep neural networks (DNNs). Training DNNs is a memory-intensive process, requiring different data structures during different stages. Limited on-chip memory leads to many expensive DRAM operations, which dominate the system-level energy consumption and computational latency. Dense non-volatile memories are being explored to provide more on-chip memory capacity and mitigate the high leakage power of SRAM. Among the emerging non-volatile memories, Spin-Transfer-Torque MRAM (STT-MRAM) offers properties like high endurance and reasonable access time, making it suitable for training DNNs. Compared to SRAM, STT-MRAM provides 3-4 times higher density and significantly reduced leakage power. However, STT-MRAM requires high write energy and latency, limiting the memory performance when integrated as on-chip scratchpad memory near processing elements. To mitigate the large write overhead of MRAM, we perform a comprehensive device-to-system evaluation and co-optimization of STT-MRAM for energy and area-efficient ML training accelerator design. In designing MRAM for the scratchpad memory for a systolic-array-based DNN accelerator, our cross-layer simulation showed that the inefficiency of STT-MRAM writes can be mitigated by utilizing reduced write voltage and write pulse durations, at the cost of bit errors. To evaluate the accuracy-efficiency tradeoff, we studied the error tolerance of the different data structures. We develop a write-error-aware training methodology that exploits heterogeneous configurations of bit errors in the different portions of the numeric presentation. Importantly, our hardware-software co-design unveils that the improvement of write efficiency must be converted to area efficiency so that the memory bottleneck due to off-chip memory access can be addressed. We demonstrate that optimized MRAM memory cells with different sizing of access transistors can accommodate the various write current requirements. Our system-level results indicate that replacing SRAM with STT-MRAM with a mixture of cell sizes in a DNN training accelerator can provide up to 15x improvement in system-level energy for iso-area scenarios respectively, while maintaining the functional accuracy at benchmark image classification tasks. Our exploration suggests that integrated magnetic memory holds immense potential for providing the underlying hardware for machine learning and AI application at the edge with stringent resource constraints.

An Ultra-Broadband Measurement of Magnetic Nanoparticle and Protein

S. Yabukami[1,2,3], R. Masui[1], T. Murayama[1], J. Honda[1], L. Tonthat[2], K. Okita[3], A. Kuwahata[1,2]

[1] *Graduate School of Biomedical Engineering, Tohoku University, 6-6-05 Aoba, Sendai 980-8579, Japan*
[2]*Graduate School of Engineering, Tohoku University, 6-6-05 Aoba, Sendai 980-8579, Japan*
[3] *Tohoku-TMIT Corporation, Sendai, 2-3-14 Odawara, Sendai 983-0803, Japan*
*shin.yabukami.e7@tohoku.ac.jp

I. Introduction

There is a need for simple and rapid detection in various protein detection, such as rapid diagnosis of metastatic cancer [1], mitochondrial disease [2], hypertension, and diabetes. However, these methods require lengthy evaluation in a laboratory by highly skilled technicians. Therefore, our goal is to develop a low-cost, accurate and easy-to-use protein sensor. Magnetic nanoparticles (MNPs) are functional in biomedical applications, as magnetic fields can easily be manipulated remotely. The GDF15 (Growth Differentiation Factor-15, a stress response cytokine) is a well-known biomarker for the early identification of mitochondrial diseases [2]. This report applies vast bandwidth and sensitive techniques to measure magnetic susceptibility and FMR for small amount of protein and MNPs.

II. Experimental Procedure

We applied the microstrip line-type probe[3] for the evaluation of protein in this work. The probe consists of a microstrip conductor (0.36 mm wide) on a flexible substrate (RT/duroid® 5870), a ground plane, lead lines, and two V-type (1.8 mm) coaxial connectors. The microstrip conductor has a flexible substrate and a straight portion. The straight portion of the microstrip conductor was positioned close to the sample. The main point of the approach is that high-density secondary MNPs reacted with antigen several times to enhance the magnetic signal of FMR by using a biotin-avidin reaction. Firstly, the primary MNPs reacted with the primary antibody (100 µl/sample) for 30 minutes; then the unreacted antibody was removed by washing. Secondly, antigen (GDF15) was reacted with the MNPs with antibodies for 30 minutes; then the unreacted antigen was removed by washing. Thirdly, the secondary antibody (100 µl/sample) was reacted with the antigen for 30 minutes, and then the unreacted secondary antibody was removed. Fourthly, the secondary MNPs and fluorescent microbeads reacted continuously to enhance the magnetic signal five times; then the unreacted secondary MNPs were removed by washing. Finally, the sample was dropped onto a cover glass (150 µm thick).

III Experimental Results

Fig. 1 shows the frequency dependence of the real part of the transmission coefficient (S_{21}) plotted against the DC magnetic field when the antigen (GDF15) of 0.1 µg/ml was reacted. The absorption of MNPs at FMR was observed around 10-40 GHz. The clear ferromagnetic resonances were not observed in a low DC field (0 T) because the MNPs were randomly oriented. However, increasing the DC magnetic field made the FMR sharp, and the FMR frequencies shifted to the higher frequency. The FMR peaked positively at 2 T because the S_{21} was calibrated at 2 T. The difference of FMR between 1.5 T and 2 T depends on the density of antigen (GDF15). Therefore, we can detect the antigen density using the ultra-broadband measurement technique.

References

[1] L. Wu, X. Qu, Chem Soc Rev. 21;44(10):2963-97(2015).

[2] K. Sawalha, N.B. Norgard, B.M. Drees, A. López-Candales, Current Heart Failure Reports, 20:287–299(2023).

[3] S. Yabukami, C. Iwasaki, K. Nozawa, S. Takahashi, K. Okita, K. Chatani, IEEE Transactions on Magnetics, Vol. 58, No. 2, p. 1-5 (2022).

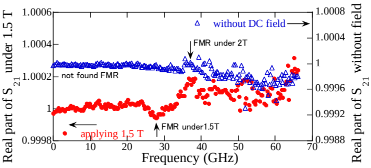

Fig. 1 Relative magnetic permeability of the noise suppression sheet.

Rapid Detection of Bacteria in Saliva using Magnetic Susceptibility

S. Yabukami[1,2,3,4], A. Ban[1], T. Murayama[1], K. Okita[2], S. Tohtake[3], L. Tonthat[4], Y. Ozawa[5], S. Asamitsu[5],
H. Okamoto[5], T. Kamei[5] and T. Abe[1, 5]

[1] *Graduate School of Biomedical Engineering, Tohoku University, 6-6-05 Aoba, Sendai 980-8579, Japan*
[2] *Tohoku-TMIT Corporation, 1-7-1-2205 Shintera, Wakabayashi, Sendai 984-0051, Japan*
[3]*School of Engineering, Tohoku University, 6-6-05 Aoba, Sendai 980-8579, Japan*
[4]*Graduate School of Engineering, Tohoku University, 6-6-05 Aoba, Sendai 980-8579, Japan*
[5] *Graduate School of Medicine, Tohoku University, 2-1 Seiryo, Sendai 980-8575, Japan*
*shin.yabukami.e7@tohoku.ac.jp

I. Introduction

There are many bacteria being beneficial or harmful to humans in the mouth or intestinal. Fusobacterium nucleatum is a type of anaerobic bacteria with a size of about 1 μm, and it is one of the species that inhabit the oral cavity and pharynx behind the mouth. It is regarded as a causative agent of gingivitis, periodontal disease and colorectal cancer [1]. There are many other detection methods for bacteria such as polymerase chain reaction (PCR) [2] and dielectrophoretic impedance measurement (DEPIM) [3]. We have developed a simple bacteria detector detected magnetic susceptibility of magnetic nanoparticles and bacteria aggregation. Obtained results are high correlation coefficient with the results of polymerase chain reaction (about 70 %, P value <0.0001).

II. Experimental Procedure

We constructed a system consisting of a drive coil, a pick-up coil, a signal generator, a preamplifier and a lock-in amplifier. The detection device is composed of a drive coil (400 turns, length of 100 mm, diameter of 90 mm), a differential pick-up coil (200 + 200 turns, length of 110 mm in total, diameter of 36 mm). The drive coil is connected to a signal generator to apply a uniformly changing magnetic field to the sample. After the sample is put into the detection device, the pick-up coil will convert the changing magnetic field that is affected by the sample into an electrical signal because of Faraday's law of induction. Since the signal of the sample is too small, the differential structure of pick-up coil consisting of two identical reverse-wounded coils connected in series is used. The magnet yoke is used to magnetize the MNPs and gather the MNPs to form aggregates to improve detection accuracy. The magnetic susceptibility of the aggregates was measured by with and without magnetic nanoparticles. We used a microtube with PBS as a reference sample. The concentration of the *Fusobacterium nucleatum* was calibrated by the already bacteria. The magnetic nanoparticle of 500 nmϕ, Rabbit Anti *Fusobacterium nucleatum* (polyclonal antibody, DIATHEVA ANT0084) was reacted with saliva of the subjects.

III Experimental Results

Fig. 1 shows the measured concentration of *Fusobacterium nucleatum* of 28 subjects (cancerous 7 patients and 21 healthy subjects). The horizontal axis indicates the results measured by PCR (relative values). The concentration of *Fusobacterium nucleatum* measured by magnetic measurement and the PCR evaluation results were highly correlated at approximately 70% (P value < 0.0001), demonstrating the effectiveness of this measurement method. Red circles represent esophageal cancer patients, and blue circles represent non-cancer patients. Cancer patients had higher concentrations of *Fusobacterium nucleatum*, however, the number of subjects needs to be increased.

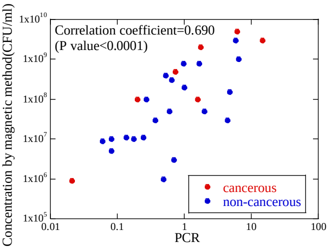

Fig. 1 Evaluation of *Fusobacterium nucleatum* by the magnetic method and PCR.

References

[1] T. Ohkusa: *Journal of Intestinal Microbiology*, **27**, 169–179 (2013). [2] R.K. Saiki, S. Scharf, F. Faloona, et al: *Science*, **230**, 1350–1354 (1985). [3] J Suehiro, R Hamada, D Noutomi, et al: *Journal of Electrostatics*, **57**, 157-168 (2003).

Effect of Mutual Interaction on Microwave Behavior of Integrated Nanopatterned Ferromagnetic Thin Film Array

Haosen Yin[1*], Amal El-Ghazaly[1]

[1]*Department of Electrical and Computer Engineering, Cornell University, Ithaca, NY, 14853, USA*
**hy584@cornell.edu*

Magnetic thin films have been integrated into MMIC devices including inductors, filters, antennas, and phase shifters to boost inductance, achieve more compact designs, and introduce magnetic tunability to the device [1]. To overcome the problem of low ferromagnetic resonance (FMR) frequency and large eddy current loss of large magnetic films, while retaining high permeability, nanopatterned ferromagnetic thin film arrays have been introduced and incorporated into various microwave components [2]. However, due to the complexity of mutual interaction between the magnet array elements, the design and optimization of such devices have rarely been discussed, limiting the potential of this strategy in improving device performance through this avenue.

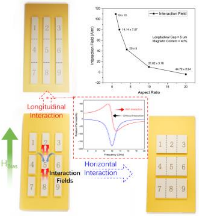

Fig. 1. Schematic of mutual interaction fields in patterned magnetic arrays

Here, we did a systematic study on the mutual interaction between the ferromagnetic elements in a nanopatterned array. We selected $Fe_{65}Co_{35}$ as the ferromagnetic material for its high saturation magnetization (> 200 emu/g), FMR, and permeability. We found that among the four adjacent elements, the longitudinal elements (along the remanent magnetization direction) increase the mutual interaction field by attracting the field lines, whereas lateral elements effectively reduce the interaction. Therefore, when patterns are closely placed in longitudinal direction, the effective FMR increases, whereas when they are closely placed in the lateral direction, the effective FMR decreases (Fig. 2). These mutual interactions contribute to the FMR increase/decrease estimated by Kittle's Equations due to the shape anisotropy. With the same gap in both directions, the longitudinal elements impose stronger mutual interaction fields than the lateral elements. We also found that for patterns covering the same percentage of total area, patterns that has higher aspect ratios have weaker longitudinal interaction fields. In conclusion, we systematically studied the influence of proximity, external bias and aspect ratio on the mutual interaction in a nanopatterned ferromagnetic array. These results would provide valuable guidance for designing ferromagnetic arrays integrated microwave devices with optimal performance.

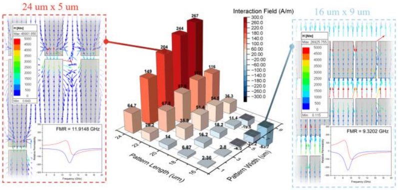

Fig. 2. Pattern dimensions vs interaction fields

References

[1] B. Kuanr, Z. Celinski, and R. E. Camley, "Tunable high-frequency band-stop magnetic filters," Appl Phys Lett, vol. 83, no. 19, pp. 3969–3971, Nov. 2003, doi: 10.1063/1.1625424.

[2] T. Wang et al., "Integrating Nanopatterned Ferromagnetic and Ferroelectric Thin Films for Electrically Tunable RF Applications," IEEE Trans Microw Theory Tech, vol. 65, no. 2, pp. 504–512, 2017, doi: 10.1109/TMTT.2016.2616869.

Flexible Mechanical/Magnetic Sensors Based on the Magnetic Amorphous Wire

Shengbin Li[1], Yiwei Liu[1]*, Run-Wei Li[1]*

[1]CAS Key Laboratory of Magnetic Materials and Devices, Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences, Ningbo 315201, People's Republic of China
*liuyw@nimte.ac.cn; *runweili@nimte.ac.cn*

The advent of smart wearable technology has spurred significant interest in flexible electronic devices, renowned for their adaptability to human form, and their light, thin, and comfortable properties, alongside the benefits of low energy consumption and superior biocompatibility. Serving as conduits for harvesting human health data, flexible sensors have emerged as a crucial component within these systems, capturing vital indicators of physical movement and body health. Additionally, the ability to detect magnetic fields introduces a potential "sixth sense," which plays an important role in the fields of magnetic field early warning and human-computer interaction. In this context, the development of multifunctional flexible sensors capable of measuring strain and magnetic fields represents a pivotal step towards digitizing health information. The use of Co-based magnetic amorphous wire, characterized by its excellent flexibility, high magnetic permeability, and remarkable giant magnetoimpedance effect, positions it as an optimal material for crafting these sensors. Addressing the challenge of merging low detection thresholds with broad detection ranges in a singular device, a novel cantilever beam structure utilizing this material was devised, culminating in the creation of a flexible magnetic sensor [1]. This sensor boasts an impressive detection scope ranging from 22nT to 0.4T. To tackle the complexities associated with integrating sensor batteries and ensuring consistent power supply, a pioneering approach was employed: a liquid metal-based inductor coil, centered around Co-based magnetic amorphous wire [2,3], was developed to fabricate an elastic, self-powered sensor capable of large deformation (up to 200%) and magnetic field detection (up to 200 mT). Leveraging the Faraday electromagnetic induction effect, the sensor autonomously generates voltage/current under strain, achieving a peak current output of 2 mA. Moreover, addressing the challenge of signal decoupling in multifunctional sensors, a novel self-decoupling mechanism was introduced for the DC (resistance) and AC (inductance) signals of the liquid metal inductor coil. This innovation led to the creation of a dual-mode sensor that employs DC resistance for strain detection and AC inductance for discerning environmental magnetic fields and strain. Through the establishment of mathematical models and equations, this design effectively decouples strain and magnetic field signals across a range of 0-10% strain and 0-10 Oe magnetic field, facilitating real-time monitoring of finger movements. These breakthroughs open new avenues for the application of flexible electronic devices in virtual reality and human-computer interaction domains.

References

[1] S. Li, Y. Wu*, W. Asghar, F. Li, Y. Zhang, Z. He, J. Liu, Y. Wang, M. Liao, J. Shang, L. Ren, Y. Du, D. Makarov*, Y. Liu* and R-W. Li*, "Wearable Magnetic Field Sensor with Low Detection Limit and Wide Operation Range for Electronic Skin Applications", Adv. Sci., vol. 11, no. 37, pp. 2304525, Nov. 2023.

[2] H. Xiao, S. Li, Z. He, Y. Wu, Zhiyi Gao, Chao Hu, Siqi Hu, S. Wang, C. Liu, J. Shang, M. Liao, D. Makarov*, Y. Liu* and R-W. Li*, "Dual Mode Strain–Temperature Sensor with High Stimuli Discriminability and Resolution for Smart Wearables", Adv. Funct. Mater., vol. 33, no. 16, pp. 2214907, Feb. 2023.

[3] S. Li, P. Cao, F. Li, W. Asghar, Y. Wu*, H. Xiao, Y. Liu*, Y. Zhou, H. Yang, Y. Zhang, J. Shang, D. Makarov* and R-W. Li*; "Self-powered stretchable strain sensors for motion monitoring and wireless control", Nano Energy, vol. 92, pp. 106754, Feb. 2022.