Book of Abstracts

International Symposium on Integrated Magnetics 2024
iSIM 2024

May 4–5, 2024

Rio de Janeiro, Brazil

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May 4–5, 2024, Rio de Janeiro, Brazil
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1. Sensing
   magnetoresistive sensors, magnetoimpedance sensors,
   flexible magnetic field sensors, printed magnetoelectroelectronics

2. Integrated circuits
   power supply on chip (PwrSoP), power supply in package (PwrSiP),
   materials for integrated magnetics, communication circuits

3. Disruptive technologies
   quantum sensing, e.g., magnetometry and scanning microscopy,
   neuromorphic computing, reservoir computing

4. Flexible & eco-sustainable magnetoelectronics
   biocompatible, biodegradable, self-healable

Venue

The conference will be held at the Brazilian Center for Physics Research (CBPF)

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Schedule

Saturday, May, 4		
8:00	Bus transfer from hotels	
8:30	**Registration starts** (until 17:00)	
9:00	Opening address *Denys Makarov*	
Session: Sensing Session chair: To be announced		
9:15	Tailored magnetostrictive multilayers for magnetoelectric sensors (Invited) *Dirk Meyners*	P. 14
9:50	Design and optimization of ultra-low damping magnetostrictive thin films for sensing applications (Invited) *Kumar Srinivasan*	P. 15
10:25	Perspective and applicability of planar-Hall magnetoresistive sensors *Proloy Taran Das*	P. 16
10:45	**Coffee break**	
Session: Sensing & Disruptive technologies Session chair: To be announced		
11:15	Magnetic noise in magnetoelastic resonators *Elizaveta Spetzler*	P. 17
11:35	Machine learning-guided magnetic tracking and diagnosis of COVID-19: A new perspective (Invited) *Manh-Huong Phan*	P. 18
12:10	Sensors based on magnetic nanowires (Invited) *Thomas Mühl*	P. 19
12:45	**Lunch**	

Session: Disruptive technologies		
Session chair: To be announced		
14:15	Nanoscale diamond magnetometry (Invited) *Jan Rhensius*	P. 20
14:50	Highly sensitive magnetic nanoparticles characterization at radio-frequency (Invited) *Jose L Marqués*	P. 21
15:25	An MTJ-network system for spintronic accelerometers *Giovanni Finocchio*	P. 22
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16:50	Imaging spin textures in functional multiferroic materials with a quantum sensor (Invited) *Paul Stevenson*	P. 24
17:25	**Banquet + Networking**	
Sunday, May, 5		
8:00	Bus transfer from hotels	
8:30	**Registration starts** (until 15:00)	
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Session chair: To be announced		
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9:50	Sputtering growth of nanometer-thick $Y_3Fe_5O_{12}$ films (Invited) *Mingzhong Wu*	P. 26

10:25	Optimization of high-frequency permeability of thick magnetic material *Shin Yabukami*	P. 28
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Session: Integrated circuits

Session chair: To be announced

11:15	Measurement of noise suppression performance in 22–30 GHz band of magnetic noise suppressor embedded into digital integrated circuits *Masahiro Yamaguchi*	P. 29
11:35	Soft magnetic thin films for high-frequency integrated inductors (Invited) *Claudiu Falub*	P. 30
12:10	Magnetics on silicon for future power inductor technology (Invited) *Ranajit Sai*	P. 31
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Session: Flexible magnetoelectronics

Session chair: To be announced

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14:50	Multifunctional smart skins for human machine interfaces and robotics (Invited) *Yevhen Zabila*	P. 33
15:25	Magnetic composites for eco-sustainable magnetoelectronics *Denys Makarov*	P. 34
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Session: Flexible magnetoelectronics

Session chair: To be announced

16:15	Magnetoresistive sensors for surface exploration with 1D and 2D magnetic elastomers (Invited) *Susana Cardoso de Freitas*	P. 35
16:50	Interfacial spin configuration controllable strain-driven training effect in flexible IrMn/[Co/Pt]$_n$ multilayers *Xilai Bao*	P. 36
17:10	How curvature-induced effects emerging in corrugated strips can shape magnetic domain walls for advanced applications *Jose A. Fernandez-Roldan*	P. 38
17:30	**Awards Ceremony & Closing remarks**	
18:15	**End + bus transfer**	

Talks

Tailored Magnetostrictive Multilayers for Magnetoelectric Sensors

D. Meyners[1*], L. Thormählen[1], E. Spetzler[1], E. Elzenheimer[2], N. Wolff[1], P. Hayes[1], V. Schell[1], L. Kienle[1], M. Höft[2], G. Schmidt[2], J. McCord[1], E. Quandt[1]

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The focus of the talk is on sputter-deposited magnetostrictive multilayers whose properties are tailored for their use in magnetic field sensors based on magnetoelectric (ME) composites. The overarching goal is to measure smallest magnetic fields with a high signal-to-noise ratio and a low detection limit in the low-frequency signal range. In addition, the magnetic field sensors should have a directional response and their optimum operating point in the zero field. Using surface acoustic wave (SAW) [1] and electrically modulated ME sensors [2] as examples, we discuss how the design freedom of the multilayer approach and magnetic couplings can be leveraged to meet the partly conflicting sensor requirements.

Both sensor concepts involve a strong piezoelectrically driven excitation acting on the magnetostrictive sensor phase via a time-varying stress field. Since magnetic domain structures can respond in a non-deterministic manner, the multilayer approach should establish a magnetic phase with single-domain states on a layer-by-layer basis to mitigate magnetic noise contributions. With this aim in mind, the paper discusses the application of exchange-biased stack units as building blocks for the magnetostrictive multilayers. It is highlighted how sensor-specific requirements lead to customized solutions. In the case of SAW sensor fabrication, e.g., it is necessary to take into account that thermal annealing can lead to undesired stress-induced magnetic anisotropies caused by anisotropic expansion of the quartz substrate. It is therefore advantageous to adjust the exchange bias coupling by the deposition process. A single domain state can then be achieved by antiparallel alignment of magnetizations in two sequences of layers consisting of $2x[Ta/(Fe_{90}Co_{10})_{78}Si_{12}B_{10}/Ni_{81}Fe_{19}/Mn_{80}Ir_{20}/Ta]$ (nominal composition in at-%). Following this approach and using a total FeCoSiB thickness of 200 nm, the limit of detection reached is 28 $pT/Hz^{1/2}$ at 10 Hz and 10 $pT/Hz^{1/2}$ at 100 Hz.

Due to the sensor design and inductive readout, the presented electrically modulated ME sensors require large magnetic layer thicknesses for high sensitivity. The magnetostrictive multilayer is built up by an 8-fold repetition of Ta (10 nm)/Cu (3 nm)/MnIr (8 nm)/FeCoSiB (500 nm). The silicon substrate allows for post-deposition field annealing, which is applied to influence the magnetic properties. In the example discussed, a single-domain state has not been achieved. However, the study demonstrates that magnetic multilayers with flux closure properties lead to a significant improvement in sensor performance and a detection limit less than 10 $pT/Hz^{1/2}$ at 10 Hz.

References

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Design and Optimization of Ultra-low Damping Magnetostrictive Thin Films for Sensing Applications

K. Srinivasan[1*], V. Brajuskovic[1], S. Karki[1], J. Laprade[1], G. Jaramillo[1], I. Volvach[1], A. Kotila[1], D. Labanowski[1]

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Biomagnetic sensing of human physiological processes has seen renewed interest in recent times due to the potential for enhanced signal fidelity compared to bioelectrical sensing. Given the need for extremely high sensitivity (detectability of pTesla and lower magnetic field strengths) and miniaturization (ease-of-use under room temperature operations), the development of sensors based on synthetic multiferroic heterostructures is seen as a promising route to achieve these objectives. In these heterostructures, a travelling surface acoustic wave (SAW) in a piezoelectric substrate elastically interacts with a magnetostrictive thin film and drives it into resonance, in a phenomenon described as acoustically-driven ferromagnetic resonance (ADFMR) [1-2].

In this work, we describe the growth, optimization and design considerations of FeGaB based thin films on *yz*-cut $LiNbO_3$ piezoelectric substrates for ADFMR based biomagnetic sensing applications. Two types of thin film stacks were prepared via sputter deposition: (i) single-layered, homogenous FeGaB thin films, and (ii) multilayer or superlattice thin films consisting of alternating FeGa and B layers. For both types of film stacks, ADFMR characteristics such as rf power absorption and gradient / sensitivity parameters were investigated on lithographically patterned delay-line devices, where the SAW propagates across the magnetic film stack deposited between two interdigital transducers [3].

Figure 1 shows the ADFMR angular absorption scan together with selected line-cut scans for a 20nm-thick $\{FeGa(1nm)/B(1nm)\}_{10}$ superlattice thin film stack at 2.2 GHz SAW frequency. The angular absorption scan shows four lobes with a symmetry that reflects that of the magnetoelastic internal tickle field, and the line scans illustrate that sharp absorption peaks including at near zero applied fields can be achieved with this stack design. We will discuss various aspects of multilayer film stacks of this type including broadband FMR characteristics, thermal response, field-anneal and cap layer effects, and compare & contrast them with single-layered films.

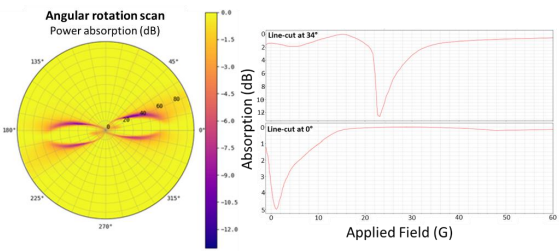

Fig. 1. Angular ADFMR power absorption scan (left) and selected line-cut scans (right) from 20 nm thick FeGaB multilayer film stack consisting of 10 alternating repeats of {FeGa(1nm)/B(1nm)}.

References

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Perspective and applicability of planar-Hall magnetoresistive sensors

Proloy T. Das[1,*], J. Schmidtpeter[1,2], Y. Zabila[1], L. Guo[1], O. Bezsmertna[1], R. Xu[1], E. S. O. Mata[1], T. Wondrak[2], and D. Makarov[1,*]

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Advancements in micro-, and nanotechnology lead to rapid employment of thin film based magnetic field sensors in both recording (MRAM) and non-recording applications [1,2]. The contemporary demands of smart magneto resistive (MR) sensors are to improve the overall design to make them smaller and cheaper while maintaining the required resolution values in detection to address many applications such as space, aerospace, magnetic flux leakage detection, domoticz, environmental, IoT, mobile, logic devices and healthcare [3]. This work deals with promising magnetic field sensors based on the planar Hall effect. It provides an overview of current studies that summarise the imperative requirements for material properties and processing, sensor architectures, noise suppression, measurement capability comprises with its high repeatability, high temperature stability and high flexibility [4]. All these high performances together based on detailed theoretical approaches and careful experimental analysis, allow a cost-effective, robust micro-sensor for versatile novel applications. Especially, a recent noteworthy study combining integrated magnetic sensors with microfluidic channels enhance their potential for highly localized magnetic fields sensing suitable for Lab-on-Chip technologies with a few pT resolutions [5].

The present work demonstrates a critical evaluation planar Hall effect sensors based on previously published studies, as well as unpublished datasets of multiple studies[3,4]. Additionally a theoretical perspective on the off-diagonal Magneto Resistance is discussed. The recent experimental datasets on sensor noise and sensitivity depicts the potential improvement of sensing resolution in MR sensors category. In particular, we would like to reckon a substantive domain of planar Hall-effect sensors in the MR sensors category, which has not been somehow addressed so far. This detailed work on the development of sensor materials, including sensor noise and sensitivity provides an informative roadmap for future industrial applications.

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[5] J. Schutt et al. "Modular Droplet-Based Fluidics for Large Volume Libraries of Individual Multiparametric C odes in Lab-On-Chip Systems," Advanced Sensor Research, vol. 2, no. 11, pp. 2300101, Nov.2023.

Magnetic Noise in Magnetoelastic Resonators

E. Spetzler[1*], B. Spetzler[2], J. McCord[1,3]

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Intrinsic magnetic noise is one of the main limiting factors in the performance of magnetic field sensors employing ferromagnetic films as their sensitive elements. In this work [1], we provide evidence for the existence of a previously unrecognized magnetic noise mechanism related to the inherent magnetostriction of ferromagnetic materials. To demonstrate that, we apply magnetic noise theory to composite magnetoelectric magnetic field sensors and perform experiments on a cantilever-based ΔE-effect sensor as an example system (Fig. 1a).

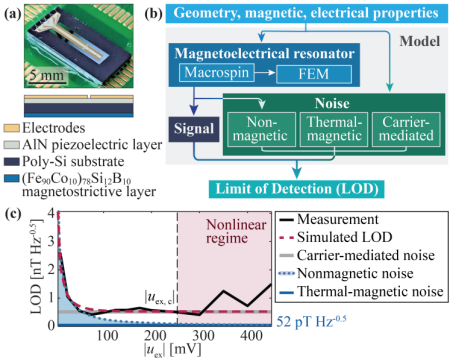

Fig. 1. (a) Photograph and structure of the ΔE-effect sensor. (b) Flowchart of the sensor system model. (c) Comparison of the model with the measurements for a dependency of LOD at 5 Hz on the excitation voltage amplitude $|u_{ex}|$. Adapted from [1] under Creative Commons CC-BY license.

The flowchart of the sensor system model is shown in Fig. 1b. The model is separated into three main blocks: the magnetoelectrical resonator model, the signal model, and the noise model, with sub-models corresponding to different noise sources. The main output of the model is the equivalent magnetic noise density of the sensor system, also referred to as the limit of detection (LOD). Intermediate results of the simulations include the sensitivity S_V and output voltage noise density N_V.

Fig. 1c shows a comparison of simulations with experimental data. The model accurately reproduces the dependency of the LOD on the excitation voltage amplitude $|u_{ex}|$. Only at high values of $|u_{ex}|$ (marked red) the measurement data deviates from the model. Above a threshold, the noise floor increases, leading to a degradation and scatter of the LOD. Using magneto-optical microscopy, we confirmed that the surge of LOD cannot be explained by carrier-mediated magnetic noise connected to magnetic domain wall motion. However, it correlates well with the increased nonlinearity of the magneto-mechanical resonator, which indicates that this additional noise source is tied to the inherent nonlinearity of the magnetostrictive properties of the ferromagnetic layer. This effect imposes significant limitations on functional devices that rely on ferromagnetic thin films as their sensitive components.

This work is funded by the German Research Foundation (DFG) through the Collaborative Research Centre CRC 1261 and the Carl-Zeiss Foundation via the Project MemWerk.

References

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Machine Learning-Guided Magnetic Tracking and Diagnosis of COVID-19: A New Perspective

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Breathing is fundamental to human quality of life, making respiratory patterns vital health indicators. Abnormalities in these patterns often hint at respiratory diseases such as chronic obstructive pulmonary disease (COPD), obstructive sleep apnea (OSA), pneumonia, cystic fibrosis, asthma, and COVID-19. Timely diagnosis of COVID-19 has become especially critical for enhancing individual well-being and bolstering public health. Symptoms of COVID-19 may encompass an elevated respiratory rate, diminished tidal volume, and irregular breathing rhythms. Hence, precise and prompt evaluation of respiratory patterns is essential for the diagnosis and management of COVID-19 and its variants. In this talk, after assessing recent technologies developed for the diagnosis of COVID-19, I will show how to fuse our magnetic respiratory sensing technology (MRST) with machine learning (ML) to create a diagnostic platform for real-time tracking and diagnosis of COVID-19 and other respiratory diseases. The MRST precisely captures breathing patterns through three specific breath testing protocols: normal breath, holding breath, and deep breath. We collected breath data from both COVID-19 patients and healthy subjects in Vietnam using this platform, which then served to train and validate ML models. Our evaluation encompassed multiple ML algorithms, including support vector machines and deep learning models, assessing their ability to diagnose COVID-19. Our multi-model validation methodology ensures a thorough comparison and grants the adaptability to select the most optimal model, striking a balance between diagnostic precision with model interpretability. The findings highlight the exceptional potential of our diagnostic tool in pinpointing respiratory anomalies, achieving over 90% accuracy. This innovative sensor technology can be seamlessly integrated into healthcare settings for patient monitoring, marking a significant enhancement for the healthcare infrastructure.

Sensors based on Magnetic Nanowires

T. Mühl[1*], N. H. Freitag[1], M. Sharma[1], A. S. Prasad[1], C. F. Reiche[2], V. Neu[1], P. Devi[3], U. Burkhardt[3], C. Felser[3], D. Wolf[1], A. Lubk[1], B. Büchner[1]

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A quantitative, single-pass magnetic force microscopy (MFM) technique is presented that maps one magnetic stray-field component and its spatial derivative at the same time [1]. Our technique uses a special cantilever design and a high-aspect-ratio magnetic nanowire tip that approximates a monopole-like moment. The potential and limits of the monopole description are thoroughly discussed. We use single crystalline single domain iron nanowires embedded in multi-walled carbon nanotubes [2], [3]. To demonstrate the merit of our simultaneous magnetic field and field gradient microscopy it is applied to the examination of bubble-like magnetization patterns in polycrystalline MnNiGa bulk samples. The results indicate that the magnetic bubbles have a significant spatial extent in depth and a buried bubble top base.

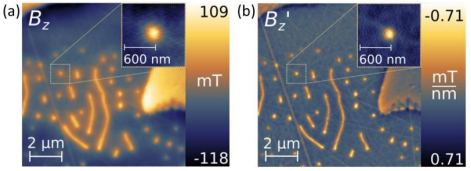

Fig. 1. Simultaneous magnetic field and field gradient microscopy of [001] MnNiGa. (a) Perpendicular magnetic field map. (b) Perpendicular magnetic field gradient map.

Furthermore, we will briefly discuss our recent work on the detection of nanowire flexural vibrations by coupling the nanowire oscillator to a conventional cantilever and by the exploitation of hybrid vibration modes which show clear signatures of avoided crossing [4]. Nanowires can be considered as miniaturized cantilever force transducers for magnetic microscopy and nano-magnetometry.

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Nanoscale Diamond Magnetometry

J. Rhensius[1*], S. Josephy[1], B. Josteinsson[1], A. Morales[1], G. Hellmann[1], C. Degen[2]

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With the advent of commercialized Nitrogen-vacancy (NV) diamond technology, the accessibility to this cutting-edge technology has markedly diminished entry barriers. Our turnkey solution for scanning NV magnetometer (QSM) also features Magnetic Optical Kerr Effect (MOKE), Piezo Force Microscopy (PFM), and Magnetic Force Microscopy (MFM) capabilities. This integrated system empowers users to effortlessly undertake intricate measurement tasks, eliminating the need to independently develop an entire microscope system.

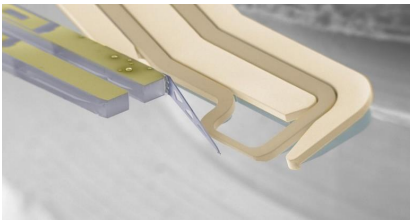

Fig. 1. Integrated scanning probe.

The QSM allows for high-resolution (~20nm) quantitative mapping of magnetic fields with uT sensitivity, all achieved at an unprecedented speed. Demonstrating versatility, the QSM has proven applications in imaging intricate magnetic textures like spin cycloids, skyrmions, domain walls in ferro- and antiferromagnets, and its capabilities extend to investigating memory devices and mapping electron currents [1].

Additionally, NV sensing tips featuring integrated microwave lines (Fig. 1) have been made available, simplifying installation and ensuring swift probe exchange. This design ensures reliable positioning of microwave wires without the need for intricate alignment procedures.

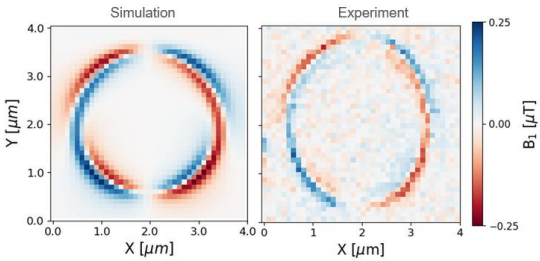

Fig. 2. Gradiometry measurement on Pd disc

This talk will focus on newly implemented sensing techniques e.g. fast-scan [3], allowing for scan speeds surpassing 100 pixels/s and magnetic gradiometry [2], specifically designed for sub-uT fields (Fig. 2). These sophisticated techniques enhance the instrument's versatility, providing users with the means to explore a wide spectrum of magnetic phenomena with precision and efficiency.

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Highly Sensitive Magnetic Nanoparticles Characterization at Radio-Frequency.

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Magnetic nanoparticles (MNPs) have numerous uses in health, environmental, and food safety applications [1]. Most of these use the magnetic nanoparticle's magnetic and electric susceptibilities, but the difficulty in characterizing and detecting these properties limits practical deployment. The measurement of the susceptibilities is challenging, given the necessity of measuring the nanoparticles in solutions or depositions with low concentrations. This type of measurement is needed to remove close interaction effects and simulate actual working conditions as closely as possible.

Our measuring method uses the self-resonant frequencies (SRFs) of multiple coils, influenced by both the magnetic permeability and the electric permittivity of the MNPs, resulting in an improved sensitivity. At the same time, this implementation considers the sensors' self-inductance and self-capacitance, allowing for high-frequency measurements and improving precision and speed [2]. We have developed a new astable oscillator configuration and a digital measurement architecture that offers low cost while maintaining high precision for managing many sensing elements. To assess our findings, we used full three-dimensional electromagnetic and SPICE simulations to ensure electromagnetic field uniformity across the sensing surface at the SRF and to have controlled sensitivity to the magnetic permeability and the electric permittivity [2]. This methodology is compatible and better suited for MNP characterization in solution and actual concentration conditions than previous techniques.

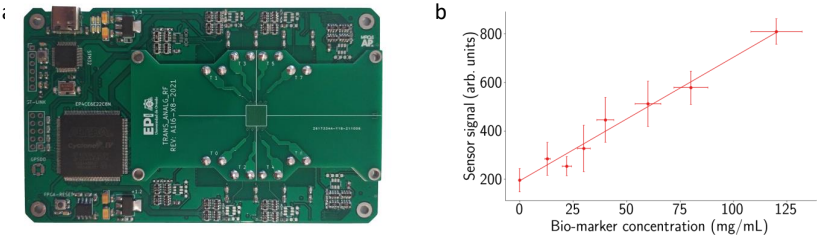

Fig. 1 a) Prototype used for MNPs characterization. Fig. 1 b) Signal of the device as function of concentration of pneumonia on a rapid magnetic test.

The current prototypes have sensitivity to the presence of 10 ng of Fe_3O_4,12 nm nanoparticles and 1 um spatial localization ability. We have used this device to characterize the refraction index of nanoparticles successfully and to measure magnetic lateral flow immunoassays of pneumonia.

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An MTJ-network system for spintronic accelerometers

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In this work we propose a spintronic-system based on a network of magneto-mechanically coupled of MTJs that relies on the spintronic accelerometer idea [1,2], shown in Fig. 1. The MTJs, working as spin-toque oscillators (STOs) and spin-torque diodes (STDs) are integrated on movable or excitable substrates such as microelectromechanical systems (MEMS) that can respond elastically to external excitations such as an external acceleration or temperature and are coupled via the dipolar coupling between the MTJ. The stray field varies when the relative displacement between the MTJs changes due to the elastic coupling transduction of the external excitation (a_{ext}), affecting the synchronization of the MTJs, which is reflected in the output signal as a change in the rectification voltage generated via spin diode effect [3].

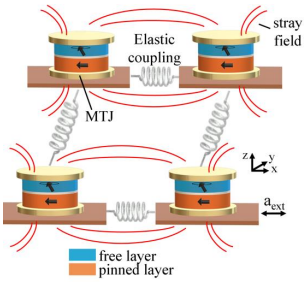

Fig. 1. Sketch of the MTJs' network studied in this work.

Building a network based on such a system allows to improve energy efficiency and sensitivity of the spintronic accelerometer, which are critical parameters for commercial applications. On the other hand, the system is suitable also to design spintronic microwave amplifiers and broadband receivers of coupled and synchronized oscillators without external magnetic field bias. Moreover, the large number of connections between the MTJs and the stimuli that are available via integration with substrates such as MEMS, e.g. non-linear excitations, can be exploited to build reservoir computing systems and spiking neural networks [3].

Here we study and investigate by means of micromagnetic simulations different network designs to find the optimal working conditions to improve the accelerometer performance, in particular to enhance the sensitivity of the device on the order of mV/*g*, where g is the acceleration of gravity, to compete with commercially available MEMS based systems. We explore also designs of MTJ's networks to achieve a low input power amplification system working without external magnetic field bias.

Acknowledgments

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Nanoscale magnetic sensing of antiferromagnets using nitrogen-vacancy centers in diamond

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Thin films with perpendicular magnetic anisotropy (PMA) are gaining attention as promising magnetic materials for information storage. They can reverse their magnetization at moderate external magnetic fields easily when compared to materials with in-plane magnetization. Therefore, understanding the properties of these materials is crucial for their implementation in information storage devices and spintronics. Here, we characterize thin films of antiferromagnets Thulium Iron Garnet / Gadolinium Gallium Garnets (TIG/GGG) using nanocrystal diamonds containing nitrogen-vacancy (NV) centers. NV centers can sense magnetic fields with unprecedented combination of sensitivity and spatial resolution [1] as they allow access to a single electronic spin that can be controlled by optical means. Room-temperature spin pumping or initialization is achieved by green laser excitation and a spin-dependence fluorescence enables to perform optically detected magnetic resonance (ODMR) to measure static magnetic fields. We monitor the magnetic field sensed by NV centers inside nanocrystal diamonds over TIG to sense its stray field as a function of the external magnetic field. The NV center present an anisotropic response to the applied magnetic field relative to its symmetry axis. This orientation can be determined by studying the NV center emission as a function of the polarization excitation [2]. By considering the response of differently oriented NV centers we can assess the anisotropic response of the sample. We observe jumps in the local magnetization of the sample at very well defined external magnetic fields. Using nanocrystal diamonds constitutes an accessible tool for characterizing thin films at low magnetic fields.

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Imaging spin textures in functional multiferroic materials with a quantum sensor

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The development of materials which enable new information and computing architectures is a long-held goal in material science. Specifically, coupling between electric and magnetic degrees of freedom offers a route to low-power, high-speed electronics. However, accessing the complex spin textures in candidate multiferroic materials has proven a significant obstacle to realizing the potential of these systems. In $BiFeO_3$, one of the most promising multiferroic systems, long-range cycloidal ordering of the magnetic moments is known to depend not only on the local electric field, but also on a slew of material parameters (*e.g.*, epitaxial strain) which must be optimized[1]. Directly imaging these cycloids, however, requires a technique with high spatial resolution (cycloid period is ~60nm) and high sensitivity.

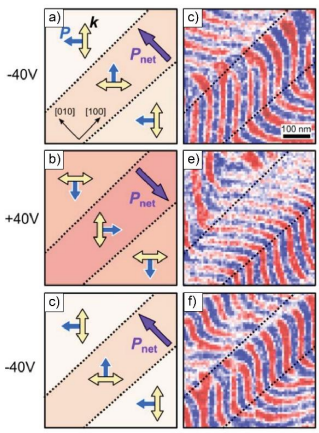

Fig. 1. Scanning-tip imaging using NV centers sensors enables nanoscale resolution of small magnetic fields from $BiFeO_3$. (a)-(c) Bias fields can be used to control the ferroelectric polarization, which switches the behavior of the cycloid ordering (c)-(f)

To address this challenge, we use the unique capabilities of the nitrogen-vacancy (NV) center defect in diamond to directly image the spin textures in a range of $BiFeO_3$ systems. Incorporating this sensor into a scanning-tip platform enables us to image nanoscale features with a sensitivity of $\mu T/\sqrt{Hz}$. We use these capabilities to unambiguously demonstrate deterministic switching of the cycloid with electric field and elucidate switching pathways[2]. Moreover, we are able to observe significant diversity in the type of cycloid observed and demonstrate that this plays a central role in governing spin transport in these systems. These new insights lay the foundation for new $BiFeO_3$-based devices based on deterministic control of the spin cycloid.

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High Performance Metal Chip Power Inductor and Magnetics for IVR

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In this work, a metal-based multilayer chip power inductor (LSCN series) is introduced. This inductor has been adopted to mobile devices and other many applications about 10 years. Its advantages are (1) multilayer process and unique metallic magnetic materials, (2) small case size and low profile (for example 0.8×0.5×0.4 (mm) size), and (3) customizability (flexibility of size and design such as an array or 2-in-1). Therefore, high performance can be provided in a wide range (inductance × thickness). And it is estimated that the inductors packed with this technology are suitable for IVR/VR and are able to contribute to improving its value.

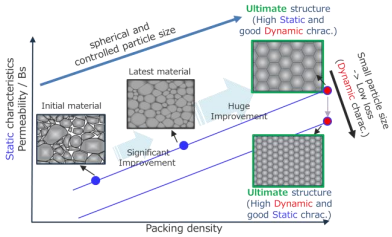

Fig. 1. Outline of Magnetic Material Improvement

Figure 1 shows the outline of the magnetic material improvement. In order to improve the performance of small size chip inductors, one of key technologies is to increase the packing density of magnetic materials. Since our unique magnetic materials contain no resin binder, high packing density can be obtained, high heat resistance and stability can be achieved by chemically bonding magnetic particles with oxide insulating layers formed by heat treatment [1]. In response of the demand for inductor performance, we are developing new technologies to realize the ultimate magnetic material structures as shown in Fig. 1.

		Conventional		LSCN series
Inductor Technology		ACI [2]	Composite core [2]	Coil
		 Source: Intel, ECTC 2020		
Magnetic Material	Packing Density	— (Non-Magnetic)	Low	High
Inductor specifications	Inductance	1.2nH [2]	2.5nH [2]	40nH
	DC Resistance	7mΩ [2]	12mΩ [2]	8mΩ
	Imax	8A [2]	8A [2]	4.4A
	L/Rdc	171nH/Ω [2]	208nH/Ω [2]	5000nH/Ω
	Area	2.0mm² [2]	0.4mm² [2]	0.5mm²
	Current Density	4A/mm²	20A/mm² [2]	8.8A/mm²
	Thickness	0.2mm	0.7mm	0.5mm

Fig. 2. Comparison of Inductor technologies for IVR

The other key technology is the flexibility of multilayer structure design. Structural customizability is a strong point of the LSCN series. Through hole and printing technology, complex structures can be created, enabling a variety of devices such as the array or 2-in-1. Figure 2 shows a comparison of inductor technologies for IVR [2]. The LSCN series has very high performance especially in inductance and L/Rdc due to high packing density material and design flexibility. Thus, LSCN series can provide high performance over a wide range (inductance × thickness) due to the variety of structures and materials.

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Sputtering Growth of Nanometer-Thick $Y_3Fe_5O_{12}$ Films

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Magnetic damping in yttrium iron garnet (YIG) $Y_3Fe_5O_{12}$ is lower than in any other magnetic materials. As such, YIG materials have been widely used in microwave devices that include oscillators, phase shifters, circulators, and isolators. Recent years witnessed a strong interest in the use of YIG materials for spintronic and magnonic devices, as well as quantum transduction and entanglement, but such applications often require YIG films with a thickness in the nanometer (nm) range. This presentation reports (i) the feasibility of using magnetron sputtering, a mainstream semiconductor technique, to grow nm-thick YIG films with very low damping [1], (ii) sputtering growth of YIG thin films with both low damping and perpendicular magnetic anisotropy [2], (iii) fabrication of YIG/topological insulator bi-layered structures [3], and (iv) patterning of YIG thin films with e-beam lithography and dry etching. Figure 1 gives representative results on a YIG/topological insulator heterostructure. The transmission electron microscope (TEM) images show the cross section of a YIG/Bi_2Te_3 bi-layered structure, in which both the layers were grown by radio-frequency sputtering. The bilayer was deposited on a single-crystal gadolinium gallium garnet (GGG) substrate and was capped by an aluminum layer. The bottom TEM image indicates the nearly epitaxial growth of the YIG film on the GGG substrate. The rightmost TEM image clearly shows the van der Waals layered structure of the Bi_2Te_3 film.

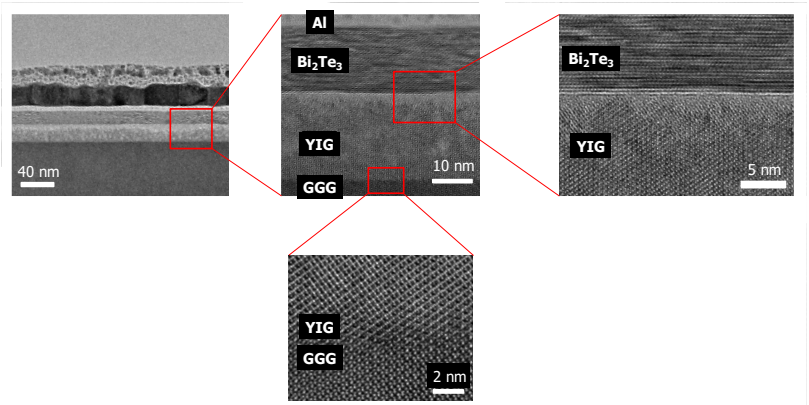

Fig. 1. Transmission electron microscope cross-section images of a YIG/Bi_2Te_3 bi-layered structure fabricated by sputtering. The bilayer was deposited on a single-crystal gadolinium gallium garnet (GGG) substrate and was capped by an aluminum layer.

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Optimization of High-Frequency Permeability of Thick Magnetic Material

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I. Introduction

The need to measure the high-frequency permeability of magnetic material has increased due to the 5th-generation mobile communication system. We developed a microstrip line-type probe and demonstrated comprehensive bandwidth permeability measurement up to 67 GHz [1, 2]. For the permeability measurement of the thick magnetic sample, the demagnetizing effect caused the measurement error and the shift of the ferromagnetic resonance (FMR) [3]. In this study, a microstrip conductor has been developed to reduce the demagnetizing effect in the thick magnetic material using FEM analysis.

II. Experimental Procedure

This study developed a microstrip line-type probe to enhance the impedance matching and reduce the demagnetizing effect in the thick magnetic material. 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 coaxial connectors. The microstrip conductor has a flexible substrate, a straight portion, and a tapered portion. The straight portion of the microstrip conductor is close to the sample. Since the microstrip line slopes, large samples can be placed close. Since the probe has a flexible substrate, it can be evaluated with a high SN ratio by directly attaching a low permeability or permittivity sample. The system setup resembled those used in earlier studies [1]. The electromagnetic sample was in contact with the microstrip conductor via a PET film (100 μm thick). Firstly, S_{21} is calibrated by applying a strong DC field (around 2 T) in the direction of the easy axis to saturate the magnetic film. Secondly, S_{21} is measured without a strong DC field. The complex permeability was optimized by the complex impedance and FEM analysis.

III Experimental Results

Fig. 1 shows the relative permeability of the noise suppression sheet (NiZn ferrite sheet, 3 mm x 3 mm, 0.1 mm thick [4]) when the DC magnetic field is 0. The symbols show the permeability optimized by the above method based on the finite element analysis, and the solid lines show the permeability evaluated by the Nicholson-Ross-Wier method [5]. The measured values and the results of the Nicholson-Ross-Weir method almost corresponded to each other. In particular, the imaginary part of the permeability peaked around 1 GHz, indicating that the proposed parallel wires suppressed errors by demagnetizing fields.

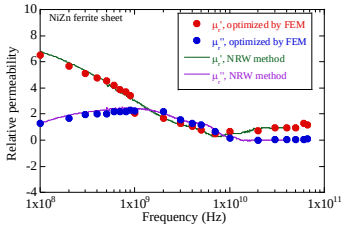

Fig. 1 Relative magnetic permeability of the noise suppression sheet.

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Measurement of Noise Suppression Performance in 22–30 GHz Band of Magnetic Noise Suppressor embedded into Digital Integrated Circuits

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Sub-mm-wave cellular networks are featured in the 5th generation (5G) communication system, where the power loss is higher than in sub-6 GHz bands. This makes electromagnetic interference (EMI) problems more serious [1]. This paper introduces the measurement methodology of this noise and demonstrates performance of magnetic noise suppressor embedded into the interposer of digital IC in 22 GHz to 30 GHz.

A test IC chip in this work is designed and fabricated in a 65 nm complementary metal oxide semiconductor (CMOS) technology. The noise generation circuits, called standard cell based noise source (SBNS) circuits, are embedded in the chip [1]. The sub-mm-wave noise is captured by an waveguide antenna because its insertion loss is lower than a conventional dipole antenna with coaxial cables in sub-mm-wave frequencies. The antenna is placed perpendicularly on the surface of the IC chip package without any gaps. The antenna signal is lead to low noise amplifier, band bass filter (BPF), external down converter, and spectrum analyzer in series as shown in Fig. 1. The frequency ranges of BPF and local oscillator (LO) are divided into 22-26 GHz and 26-30 GHz, respectively. The typical total conversion gain is 65 dB and the noise figure is about 3 dB.

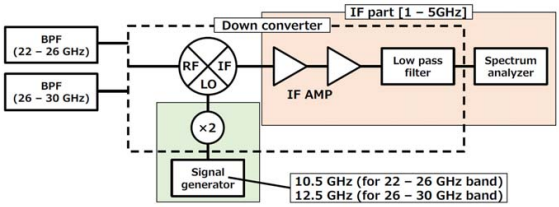

Fig. 1. Measurement system in the submillimeter wave band [1]

The new Fe-Cr-Co flakes[2] were mixed together with epoxy resin and pasted on the interposer to 30-60 μm thick. Sendust and carbonyl iron powders were similarly applied for the test. The IC chip was flip-chip mounted on it using a commercially available mounting process. Resulting magnetic composite thickness is 37-38 μm, with estimated magnetic volume ratio between 15-40 %. Number of test IC chip was3. Each chip was measured the noise twice and its average is shown in Fig. 2. The even harmonics of digital switching noise generated from IC chip operating at 500 MHz clock signal was successfully suppressed in 26-30 GHz range up to 8.5 dB by the Fe-Cr-Co flake composite.

This work was supported in part by Development of Technical Examination Services Concerning Frequency Crowding (JPJ000254), MIC, Japan.

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Soft Magnetic Thin Films for High-Frequency Integrated Inductors

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The relentless drive towards miniaturization in the semiconductor industry necessitates addressing the critical power density limit attributed to the nanometer-sized transistor gate length. Hence, there is a vital need to develop cost effective manufacturing techniques of high-frequency (10-100 MHz) fully integrated voltage regulators (FIVR), whether assembled directly on the microprocessor package or in the die itself.

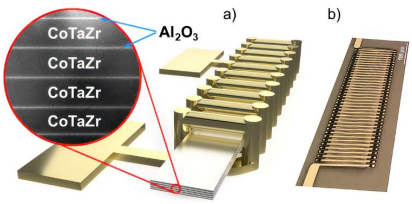

Fig. 1. a) Schematics of a 3D integrated magnetic solenoid inductor; the inset shows a cross-sectional TEM micrograph of the inductor core, consisting of a sputtered soft magnetic multilayer. b) Optical micrograph of a 190 nH ultra-low profile integrated magnetic inductor.

Previous FIVR applications have been hindered by the unavailability of appropriate power inductors, but recently solutions based on 3D inductors with integrated thin film soft magnetic cores have been proposed by device manufacturers [1]. While ferromagnetic cores allow for a much higher inductance density, the quality factor (ratio of the energy stored in the inductor and the power loss) will be reduced due to various losses associated with the magnetic material, which brings serious design challenges for inductor miniaturization. One solution is to increase the saturation magnetization ($4\pi M_s$) and the thickness of the magnetic core material, but the latter could lead to altered microstructure and internal stress, which raises the coercive field (H_c) and can spoil the high-frequency inductor performance. High-frequency inductor operation brings additional obstacles due to the increase of loss mechanisms in the magnetic core material (e.g., hysteresis, eddy currents, ferromagnetic resonance) that result in a significant increase of the inductor resistance at higher frequencies. This obstacle can be overcome by laminating the magnetic material with intermediate non-magnetic interlayers, which stop the crystallite growth, so that even films up to several micrometers thick can still exhibit low coercivity (see Fig. 1a). Lamination also helps reduce the eddy current loss and improve magneto-static coupling between adjacent magnetic layers, crucial for device performance at high frequencies [2].

Despite all these critical challenges, by carefully tuning the parameters during the multilayer thin-film deposition process (e.g., pressure, power, temperature, angular distribution), selecting the soft magnetic material (e.g., saturation magnetization, electrical resistivity) and choosing the dielectric interlayer (e.g., dielectric constant), while also carefully tuning the in-plane anisotropy field (H_k), we show that ultra-low-profile magnetic-core inductors with an inductance density of ~3500 nH/mm^2 and peak quality factor of 26 can be fabricated on 8-inch wafers with a back-end-of-line (BEOL) process, as shown in Fig. 1c [3]. The process uses thick copper metallization, polymer coating, and laminated amorphous Co–Zr–Ta magnetic material. The substrate was thinned to obtain an inductor thickness of 150 µm. By varying the core size and winding pitch, a broad set of inductance values was obtained, ranging from 20 to 500 nH in the 1 MHz to 3 GHz frequency range.

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Magnetics on silicon for future power inductor technology

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We are moving towards a society of zillions of IoT edge devices wherein efficiency and miniaturization are the 'mantra' while powering them. As a consequence, we are witnessing a (r)evolution in power electronics. Contemporary low-power applications such as integrated voltage regulators (IVRs) and system-on-chip (SoC) require ultra-high power density, and thus, continue to inspire technological innovations and trends in design, integration, and packaging of high-frequency magnetic components. Magnetic devices such as inductors and transformers are the most bulky and lossy components in the circuit and they demand a thorough understanding of power loss mechanism, especially in the magnetic core material. Different applications pose different challenges in magnetics design – be it in terms of power specification or physical sizes, be it in terms of choice of magnetic materials or their integration strategy.

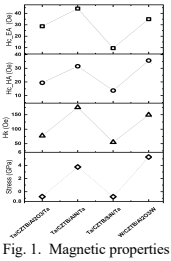

Fig. 1. Magnetic properties of CZTB with different dielectric and metallic buffer layers.

The focus of this work is on two major class of magnetic cores – (i) polymer composites for in-package inductors and (ii) thin amorphous films for on-chip inductors. This article will identify the key contributors towards core losses at frequencies from 1-100 MHz and provide a glimpse on the strategies to stem core losses in both composite and thin film materials. Furthermore, innovative solution for 3D packaging of large-footprint magnetic inductors will also be discussed.

Cobalt-based amorphous thin film laminates with ultra-thin dielectric layer have become industry standard for on-chip magnetics. Core losses in the laminates are being continuously lowered by varying magnetic and dielectric compositions, layer thicknesses, and even metallic buffer layers. For example, Co-Zr-Ta-B (CZTB) [1] with high resistivity (120 μΩ·cm) can result in lower eddy current loss at high frequency, thus frequently used in commercial application. By tuning the dielectric layer thickness, a suitable combination of permeability and loss can be attained. In addition, the effect of buffer layer is not limited only on stress-induced delamination of the laminates. Replacing Ta with W-based buffer layer enhances the anisotropy with minimal impact on easy axis coercivity as shown in Fig. 1. However, the hard axis coercivity of CZTB degrades notably. On the other hand, while AlN is industrially preferred as the dielectric material for the laminates, SiN-based laminates exhibit comparatively lower coercivity. Beside developing an efficient laminated core, we also demonstrate heterogeneous integration of on-chip thin film inductors by micro-transfer printing.

In contrast, the composition of magnetic composites for in-package inductor core are designed to maximize the effective permeability and material-Q (μ_r'/μ_r''). Accordingly, an insulating layer on the main magnetic filler particles/flakes is designed to stem the Eddy current losses. for, we have compared the effect of ultra-thin PDMS (~5 nm) and silica (~20 nm) coating on stemming the eddy current losses. Two toroidal magnetic cores comprised of aforesaid PDMS and SiO_2 layer coated FeSiAl flakes respectively are prepared by casting them on to a 3D-printed plastic mold in a way compatible with PCB manufacturing process. It is found that despite higher thickness SiO2-coated composite core is more lossy at 2-5 MHz. This result prompts usefulness of PDMS brush coating.

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Flexible magnetic thin films and sensors

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With the rise of the internet of things, humanoid robots, and mobile healthcare services, etc., flexible electronic materials and devices have received extensive attention. Sensors and memories based on magnetic materials are important components of electronic devices, the flexibility of which could facilitate the applications of wearable devices with low energy consumption and high sensitivity [1, 2]. However, some challenges need to be overcome so as to construct high-performance flexible magnetoelectronic devices. First, as a result of the inherent magnetoelastic coupling, the magnetic properties of many flexible magnetic films (such as Fe, Co, Ni) are sensitive to the external mechanical stress, which deteriorates the performance of flexible magnetoelectronic devices. Second, as many magnetic materials cannot withstand strain of more than 2%, cracks may form upon large deformation and hence induce device failure. This report mainly focuses on our research progress on overcoming these two challenges. We will first present our research progress on the quantitative regulation of magnetic anisotropy of flexible magnetic film under external stress [3, 4], followed with the proposed strategies of enhancing the magnetic anisotropy stability of flexible magnetic film under external stress [5, 6]. Then, strategies on improving the stretchability of flexible magnetic films and devices will be addressed [7, 8]. On these basis, super-elastic spin valve magnetic sensors, which can withstand strain up to 50% without noticeable loss of their physical properties (such as magnetoresistance value, magnetic sensitivity and resistance), are fabricated [9]. We have also developed spin-valve based flexible three-dimensional force sensors, which exhibit excellent stability (noise floor < 0.01%, repeat cycle > 6000) and fast response (~ 50 ms). These research results have laid a good foundation for the application of flexible magnetoelectric functional devices in human-computer interaction, health monitoring, and other fields.

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Multifunctional smart skins for human machine interfaces and robotics

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Mechanically soft electronics relies on functional elements, which are prepared on flexible and elastic membranes, allowing for bending, folding, or twisting. This technology enables applications in smart skins, smart textiles and soft robotics. Crucial to flexible interactive on-skin and wearable electronics are flexible magnetic field sensors [1], facilitating the monitoring of various types of motion. Typically, magnetic thin films are employed in flexible magnetoelectronics for detecting in-plane magnetic fields [2-4]. To enhance sensitivity to out-of-plane magnetic fields [5], Bi-based Hall effect sensors have demonstrated efficiency in smart wearables and electromobility applications [6].

Semi-metallic Bi thin films exhibit exceptionally high magnetoresistance (MR) and a robust Hall effect, even at room temperature, particularly when patterned to a small lateral size. Our research delves into the remarkable strain sensitivity of Bi thin films to create a multifunctional flexible device capable of simultaneously measuring strain and magnetic fields. We fabricate Bi thin films of different thickness on ultrathin polyimide foils. These sensors prove their mechanically stable, enduring severe mechanical bending with radii as small as 1 mm for 10,000 bending cycles. We introduce and validate a measurement sequence based on the spinning current approach, effectively decoupling signals measured by a single sensor element in transversal and longitudinal resistance channels. Furthermore, we have developed a method to analyze the measured transversal and longitudinal resistances, enabling the assessment of the out-of-plane component of the magnetic field (Hall effect) and vector components of in-plane strain (piezoresistive effect). These sensors find application as a component of smart skin for soft robotics and human-machine interfaces.

In this presentation, we will demonstrate the key aspects linking the fundamental properties of Bi thin films to their practical implementation in flexible sensor devices for simultaneous strain and magnetic field sensing.

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Magnetic composites for eco-sustainable magnetoelectronics

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Composites consisting of magnetic fillers in polymers and elastomers enable new application scenarios in soft robotics [1,2] and reconfigurable actuation [3]. Furthermore, they gave birth to the novel technology of solution processable magnetic field sensors, which can be seamlessly combined with magnetic soft actuators resulting in magnetically aware actuating composites [4]. We demonstrate that printed magnetoelectronics can be stretchable, skin-conformal, capable of detection of low magnetic fields and withstand extreme mechanical deformations [5,6]. We feature the potential of our skin-conformal sensors in augmented reality settings for remote and touchless control of virtual objects, scrolling electronic documents and zooming maps. We put forth technology to realise magnetic field sensors, which can be printed and self-heal upon mechanical damage [7]. This opens exciting perspectives for magnetoelectronics in smart wearables, interactive printed electronics. Moreover, this research motivates further explorations towards the realization of eco-sustainable magnetoelectronics. For the latter, we will discuss biocompatible and biodegradable magneto sensitive devices, which can help to minimise electronic waste and bring magnetoelectronics to new application fields in medical implants and health monitoring.

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Magnetoresistive sensors for surface exploration with 1D and 2D magnetic elastomers

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The use of flexible magnetic materials in electronics has been extensively demonstrated for exciting applications ranging from biomedical to robotics [1]. The ability to incorporate homogeneous and dense nanoparticles in elastomer matrix opens a realm of opportunities for integrated, flexible electronics. These magnetic composites can be then read using flexible thin film magnetic sensors [2], providing a high degree of downsizing towards a nanoscale. Moreover, the excellent biocompatibility between the elastomers and liquid interfaces have been explored in magnetic cytometry [3] and tactile sensors for harsh environment applications [4].

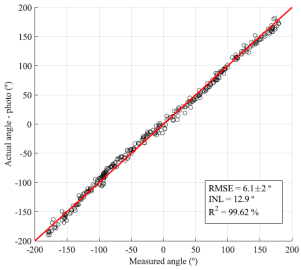

Fig. 1. Cilia deformation angle extracted from optical and magnetic detection.

Here we will discuss the integration of magnetoresistive sensors in tactile sensors, using 1D and 2D magnetic elements for the environment exploration. The 1D is accomplished with magnetic elastomer cilia, able to recognize bending upon touch, in x and y directions, using two pairs of magnetic sensors, sensitive in both directions. As a result, two full Wheatstone bridges created to detect Hx and Hy [5], enable the entire comprehension of the actions over the sensor surface. Figure 1 shows the fitting for the deflection angle, θ, when comparing the angle obtained from an optical analysis of the bent cilia, with the angle extracted analytically from the magnetoresistive. sensor Vx and Vy responses. The fitting adjust level of $R^2 >$ 99% demonstrates the viability of this architecture for ciliary tactile sensor applications. The sensor has been used in integrated probes for surface texture evaluation, in particular, fruit maturity classification and quality control in agro-robotics. This is now under development with a fine texture mapping, using fingerprints for the same purpose, with a minor texture than the ~200 µm long cilia. These configurations require an array of magnetic sensors distributed below the 2D flexible surface, able to recover the locations and orientation of the applied forces upon touch, from the changes in the fields. The number of sensors, and how these are to be distributed along the fingertip area are relevant to optimize, so to minimize the overall cost and electronic requirements in the reading matrix, for such an instantaneous sensor.

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Interfacial Spin Configuration Controllable Strain-Driven Training Effect in Flexible IrMn/[Co/Pt]$_n$ Multilayers

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Flexible spintronic applications such as smart textiles, soft robots, electronic skins, have been developed to be the primary link bridging the living and digital worlds[1,2]. Furthermore, spintronic devices including magnetic field sensors, MRAM, and logic devices rely on the phenomenon of the unidirectional anisotropy or the so-called exchange bias effect[3,4]. However, the application potential of prospective flexible magnetoelectronics based on perpendicular magnetic anisotropy (PMA) is not known as the stability of the perpendicular exchange bias (PEB) under mechanical strain is not studied[5].

In this work, we describe a flexible IrMn/[Co/Pt]$_3$ stacks with strong PMA and large PEB prepared on 50-µm-thick PI foils (Fig. 1a). The tensile strain is applied through a designed tensile holder. Relying on the advanced structural characterization employing SAXS combined with SEM, we confirm that metal layer stacks are elastically deformable when stretching the samples to 3% tensile strain (Fig. 1b). By applying tensile strain on samples, we observe decreasing PEB attendant with a new training effect, which is driven by the applied mechanical strain (Fig. 1c). Furthermore, the influence of magnetic configuration at the interface between IrMn and [Co/Pt]$_3$ multilayers are demonstrated in this work. By aligning moment of [Co/Pt]$_3$ multilayers parallel to the IrMn moment at the interface, the exceptional stability of the PEB effect without any training effect under tensile strain is observed in flexible IrMn/[Co/Pt]$_3$ stacks (Fig. 1d).

Our results indicate the important role of interface in strain-modulated PEB, providing an effective method to prepare flexible spintronic devices with stable performance under strain, rendering them strong contenders in the realms of sensors and storage applications.

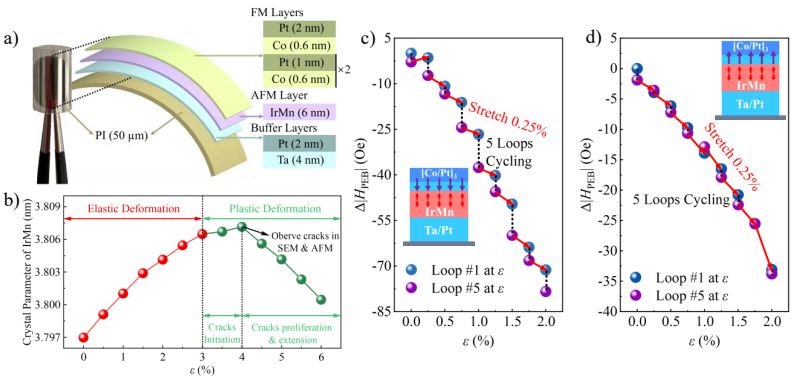

Fig. 1. Structural characterization and magnetic characterization of Ta(2)/Pt(2)/IrMn(6)/[Co(0.6)/Pt(1)]$_3$Pt(1) exchange biased samples on PI foil upon tensile strain. (a) A photo and schematic illustration of the sample. (b) Crystal parameters of IrMn under different tensile strain. (c-d) $\Delta|H_{PEB}|$ between the first and fifth loop following each stretching for one strain step of 0.25% with the PEB set in the (c) anti-parallel mode and (d) parallel mode.

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How Curvature-Induced Effects Emerging in Corrugated Strips can shape Magnetic Domain Walls for advanced applications.

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In recent years, curvilinear nanomagnetism is attracting notable attention for the broad range of effects emerging in curved geometries that are appealing for the innovative developments in stretchable and magnetoelectric devices, microrobots, sensors, flexible magnetic memories and nanoelectronics [1-5].

These phenomena encompass a vast range of exchange- and Dzyaloshinskii-Moriya (DMI)- induced interactions that typically result in topological magnetization patterning in shells, chiral symmetry breaking, and pinning of domain walls [1-5]. Less attention has been paid, though, to the role of the curvilinear effects in the magnetization dynamics of domain walls in curved geometries [4]. From application perspectives, spin-orbit torques are appealing as an alternative to achieve the manipulation of magnetic domain walls and magnetization [8] with the breakthrough of lower power consumption. Recent developments in ultra-thin planar asymmetric multilayered strips describe a method to extract DMI and damping estimations from the dynamical tilt of domain walls from static measurements [9]. Following a similar approach, here we provide first results in single 100 nm-wide periodically corrugated strips of CrO_x/Co/Pt with a thickness of 2 nm and average curvature of 0.06 nm^{-1}, tailored for an enhanced exchange-induced DMI. The orientation of the corrugation is tuned from the parallel to the perpendicular direction of the strip axis in different strips.

Our results indicate that curvature plays a crucial role in the pinning and tilting of domain walls through DMI-induced and exchange-induced effects. In particular, DMI-induced anisotropy leads a pinning mechanism, while it enhances the domain wall tilt in combination with exchange-induced effects. Our results here open an unforeseen perspective for shaping future spin-based nanoelectronics via curvature-induced effects [10].

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