SP 4 Magnetic memories and magnetic recording, sensors

SP4 - Parallel session 1

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SP4.1.02

Magneto-resistive sensors for detection of magnetic resonance at micron scale

A. Doll, A. Solignac, E. Paul, M. Pannetier-Lecoeur, C. Fermon

Text Magneto-resistive sensors feature an outstanding sensitivity to radio-frequency magnetic fields down to the picotesla range combined with a micrometric sensor footprint. Thanks to these characteristics, magneto-resistive sensors are promising candidates for the detection of magnetic resonance at micron scale [1]. In particular, magnetic resonance gives rise to coherent spin precession within the investigated sample. For small samples with precession frequencies of few MHz, a magneto-resistive sensor in proximity to the sample can detect the dipole fields emerging from the precessing sample magnetization.

Our research is primarily dedicated to nuclear magnetic resonance of ^{1}H proton spins in water that precess at 30 MHz in an external field of 0.7 T. Our reference sensor is a rectangular 12x100 μm^{2} spin valve exhibiting giant magneto-resistance. By immersing this sensor into the sample, ^{1}H precession can be detected with a spectral linewidth of 1.1 ppm at an amplitude on the order of 100 pT.

A critical aspect of this approach is the external field required for polarization of the sample spins. With respect to the sensor, this strong out-ot-plane field alters its magneto-transport and magneto-static properties. The consequences of these effects for the proposed application in magnetic resonance are discussed and corrective actions taken. Moreover, magnetic tunnel junctions are being developed for improved detection sensitivity.

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SP4 - Parallel session 1

SP4.1.03

Domain wall as a tunable spin wave phase shifter

R. Yanes, L. Torres, L. Lopez-Diaz

Text Magnonics intends to use spin waves (SWs) for carrying and processing information [1], for which it is crucial to be able to manipulate SW properties, such as amplitude and phase. Controlling SW phase is, however, still a challenge. Hertel et al. [2] showed theoretically that SWs acquire a phase when they pass through a magnetic domain wall (DW), opening the door to using DWs as phase-shifting elements. Besides, this phase shift is intimately related to the magnetic structure of the DW.
In this work, we propose a method to control the DW induced phase shift (PS) in perpendicularly magnetized nanowires by tuning the internal profile of the DW with a small in-plane field. Using micromagnetic simulations we show that there is a linear dependence of the PS with the internal DW in-plane angle which, itself, can be tuned with the in-plane field if appropriate dimensions are chosen.
A systematic analysis is carried out in order to optimize the geometry, spin waves frequency and the required amplitude of the DC-field. It shows that it is possible to tune the DW profile with applied field smaller than 10 mT, with the optimal frequency range close to FMR frequency. Additionally, we also find that the linear dependence of the spin wave PS is kept even in a more complex scenario where the DW is pinned.

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SP4 - Parallel session 1

SP4.1.04

Comprehensive model of the ΔE effect for cantilever magnetic field sensors

B. Spetzler, P. Durdaut, C. Kirchhof, R. Knöchel, M. Höft, E. Quandt, F. Faupel

Text Investigations into the ΔE effect of magnetoelastic materials have revealed the exciting promise of detecting low frequency and small amplitude magnetic fields [1]. Typical approaches are based on electrically exciting a resonator via application of a voltage to a magnetoelectric composite structure with soft magnetic properties [2]. In these structures, the sensor properties and performance result from a complex interplay of magnetic, mechanical and electrical properties. In this work, we close the gap between application and theory currently found in the literature. A comprehensive magneto-electromechanical model is to be presented that considers the interaction of magnetic, mechanical and electrical properties. With the model, we discuss the ΔE effect in general and its application in diverse types of electrically excited sensors, focused on the most common types such as cantilevers or bulk resonators. Realistic detection limits are predicted in combination with a noise model. The simulations are validated with experimental data using different sensor designs and magnetic layers. All in all, new insights are gained on the ΔE effect and its use in magnetic field sensing.

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SP4 - Parallel session 1

SP4.1.05

Single Domain Stabilization with Antiparallel Exchange Bias – A Novel Concept for Low Noise Composite Magnetoelectric Sensors

M. Klug, V. Röbisch, S. Salzer, L. Thormählen, M. Höft, E. Quandt, D. Meyners, J. McCord

Text We present a magnetic sensor scheme based on in layers antiparallel exchange bias (AEB) that drastically decreases magnetically induced noise in magnetoelectric (ME) sensors. AEB is achieved by controlling the magnetization states during the setting of exchange bias (EB) with in-situ large view Kerr effect imaging [1]. With AEB we introduce a stable antiparallel alignment of magnetization in subsequent magnetic layers. By minimizing the demagnetization effects, a pinned flux closed system is created by which single magnetic domain arrangement in individual layers is obtained. This leads to complete coherent magnetization rotation in the ferromagnetic layers during sensor operation.
Composite ME cantilever sensors with AEB multilayers were compared with sensors utilizing a multilayer parallel aligned EB system [2]. The AEB sensors yield an order of magnitude lower noise level compared to sensors with parallel aligned EB. Using frequency conversion [3], this leads to a significant improvement of the sensor's limit of detection of low frequency signals, reaching values as low as 60 $pT/Hz^{0.5}$ at 10 Hz. The demonstrated coupling scheme shows high potential also for other magnetic sensor concepts in which magnetically induced noise is a contributing factor. The authors thank the DFG for funding within the CRC 1261.

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SP 4 Magnetic memories and magnetic recording, sensors

SP4 - Parallel session 1

SP4.1.06

Nanometer-scale magnetic field imaging with a scanning SQUID-on-tip

G. Romagnoli, L. Ceccarelli, M. Wyss, D. Vasyukov, M. Poggio

Text We employ state-of-art nanometer-scale superconducting quantum interference devices (SQUID) as scanning probes in two separate nanometer-scale magnetic imaging experiments. These devices consist of a nanometer-scale Pb SQUID fabricated at the apex of a quartz tip [1]. This so-called SQUID-on-tip (SOT) device operates at temperatures up to 7 K and external fields up to 1 T (at 4.2 K) with spatial resolutions and sensitivities reaching better than 50 nm and 10 nT/√Hz, respectively. This combination of sensitivity and resolution can be used to reveal previously inaccessible information in both magnetic and superconducting systems. In a first experiment, we use a SOT sensor to make images at a series of applied magnetic fields as the ferromagnetic nanotubes (FNTs) are led through magnetic reversal. Near zero field, sufficiently short FNTs show the signatures of equilibrium vortex states [2].
In a second experiment, we study both the static and dynamic properties of vortices in a MoSi thin film. We image the dynamics and pinning of single vortices under the influence of a driving current.

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SP 4 Magnetic memories and magnetic recording, sensors

SP4 - Parallel session 1

SP4.1.07

Magnetic position sensor system with submicron accuracy

J. Paul, H. Knoll, F.-J. Braun, P. Frank, A. Lenkl, F. Klose, M. Theis, M. Saumer, K. Zoschke, H. Oppermann

Text Magnetic position measurement systems are regarded to be very robust and cost effective compared to optical systems but do not achieve the same accuracy. A new system concept including tunnelmagnetoresistive (TMR) sensors to close this accuracy gap will be presented. The new approach consists of a miniaturized system with extremely small magnetic length scales fabricated from different magnetic materials with highest precision. The position of a sensor head with regards to the scale is read out by means of highly sensitive TMR elements arranged in wheatstone bridges. A small air gap between sensor and scale is possible by means of through silicon vias (TSV) which allow to route the signals from the sensing elements through the chip directly to its back side superseding interconnecting structures like wire bonds. High precision position measurements with better than 700 nm accuracy and better than 110 nm bidirectional repeatability have been demonstrated on a scale with 25 mm travel length. The system supports true power on functionality, meaning that the absolute position on the full scale is given immediately after power on without any reference check. The measurement system can be used in various applications like microscope stages or drilling tools.

SP4 - Parallel session 2

SP4 - Parallel session 2

SP4.2.02

Interconnected MTJs as spintronic synapse

E. Raymenants, A. Vaysset, D. Wan, S. Couet, J. Swerts, M. Manfrini, O. Zografos, D. Mocuta, I. Radu, M. Heyns, T. Devolder

Text Non-volatile memories are explored for their use as synaptic devices in brain-inspired computing networks. In this respect, we devised and tested chains of interconnected MTJs, targeting spintronic synapses. A single MTJ can reside in the parallel or anti-parallel state, leading to two possible conductance states. However, connecting N MTJs in series, could ideally provide up to 2^N conductance levels [1]. Here, we demonstrate experimentally more than 14 distinct conductance levels in a chain of 10 MTJs. Additionally, in a chain of 100 MTJs, we obtain the analog-like behavior desired for synapses. Two different methods were compared to reliably reach a targeted resistance within a preset tolerance. The first method consists of sweeping an external magnetic field until the targeted resistance of the chain is reached. The second method adds a voltage pulse of fixed amplitude at every field step. 91 out of 93 targeted resistance levels could be reached by the latter method, while only 58 could be reached varying the magnetic field only. Additionally, the field-only method needs many more iteration steps before reaching the target. This demonstrates the impact of voltage pulses which agitate the MTJ chain and allow it to reach more conductance states. This device shows promise for its application as a scalable spintronic synapse in next-generation neuromorphic computing.

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SP 4 Magnetic memories and magnetic recording, sensors

SP4 - Parallel session 2

SP4.2.03

Reducing transition curvature in heat-assisted magnetic recording with state-of-the-art write heads

C. Vogler, C. Abert, F. Bruckner, D. Suess

Text A pronounced transition curvature of written bits significantly deteriorates the signal-to-noise ratio during the read-back process. For conventional perpendicular magnetic recording there exists no possibility to straighten such transition curvatures.

The situation is different with heat-assisted magnetic recording (HAMR). We present how to reduce the transition curvature with state-of-the-art write heads, by flipping the inductive write element by 180°[1]. To confirm the reduction we compare footprints of a conventional HAMR head and a head with the proposed design. The footprints are simulated with a coarse grained model based on the Landau-Lifshitz-Bloch equation, which allows to efficiently compute the magnetization dynamics of recording grains at fast varying temperatures with high accuracy[2].

Additionally, we investigate the footprints with an analytical model based on the effective recording time window[3]. These examinations shed light on the basic mechanisms that lead to the transition curvature reduction.

Finally it should be noted that, depending on the recording medium and the size of the heat spot, a curvature reduction of up to 60 % is feasible.

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SP 4 Magnetic memories and magnetic recording, sensors

SP4 - Parallel session 2

SP4.2.04

Magnetic memristor driven by spin-orbit torque

E. Jo, H.-G. Park, B.-C. Min

Text We demonstrate a memristive device with multi-level resistance tunable by a current. The device consists of multiple nano-dots with perpendicular magnetization on a heavy-metal Hall-bar geometry. The spin-orbit torque arising from in-plane current flowing the Hall bar leads to magnetization switching of nano-dots. The switching from high to low resistance or vice versa is controlled by direction of in-plane DC current and magnetic field. The magnitude of in-plane DC current determines the number of switched dots and consequent Hall resistance of the device. The memresistive response from multiple nano-magnetic dots could serve as artificial nano-synapses.

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SP4 - Parallel session 2

SP4.2.05

Highly thermally stable sub-20nm magnetic random-access memory based on perpendicular shape anisotropy

S. Lequeux, N. Perrssin, N. Strelkov, L. Vila, L. Buda-Prejbeanu, S. Auffret, R. Sousa, I.-L. Prejbeanu, B. Dieny

Text In order to go toward high density Spin transfer torque magnetic random access memory(STT-MRAM) at sub-20 nm nodes, one issue that still have to be solved is to increase the thermal stability of the storage magnetization for such small devices. Here, we present a novel approach to increase the downsize scalability of perpendicular STT-MRAM. It consists in significantly increasing the thickness of the storage layer in out-of-plane magnetized tunnel junctions (pMTJ), as compared to conventional pMTJ, in order to induce a perpendicular shape anisotropy (PSA). This PSA is obtained by depositing a thick ferromagnetic (FM) layer on top of an MgO/FeCoB based magnetic tunnel junction so that the thickness of the storage layer becomes of the order or larger than the diameter of the MTJ pillar. Therefore, the perpendicular anisotropy mainly arises from the shape of the storage layer and no longer from an interfacial anisotropy with the MgO. Using thicker storage layers in these PSA-STT-MRAM has several advantages. Thanks to the PSA, very high and easily tunable thermal stability factors can be achieved, even down to sub-10 nm diameters. Moreover, low damping material can be used for the thick FM material thus leading to a reduction of the write current. Finally, magnetic characterization of this new PSA-STT-MRAM concept demonstrates thermal stability factor above 200 for MTJs as small as 8nm in diameter and possibility to maintain thermal stability factor above 60 down to 4nm diameter.

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SP4 - Parallel session 2

SP4.2.06

BEOL compatible top-pinned magnetic tunnel junctions with a synthetic ferromagnetic pinning layer design

J. Swerts, E. Liu, S. Couet, S. Mertens, R. Carpenter, W. Kim, S. Rao, K. Garello, S. Van Elshocht, G. S. Kar

Text Integration of magnetic tunnel junctions (MTJ) as memory or logic element in CMOS technology has been demonstrated with bottom-pinned STT-MRAM MTJ stacks for embedded memory applications [1]. One of the key requirements for integration was the compatibility of the MTJ stack with the thermal budgets (400°C) used in back-end-of-line (BEOL) CMOS processes. Whereas bottom-pinned MTJ stacks with synthetic *antiferro*magnetic (SAF) pinning layers can meet these requirements, only recently top-pinned MTJ stacks have been reported to have high annealing tolerance [2,3]. Top-pinned MTJ's are envisaged to enable advanced applications such as spin-torque majority gates (STMG) and spin-orbit torque (SOT) MRAM. We compare the magnetic and electrical properties of blanket and patterned top-pinned STT-MRAM stacks with a conventional [Co/Pt]-based SAF pinning layer to stacks with a [Co/Pt]-based synthetic *ferro*magnetic (SFM) pinning layer. Micromagnetic simulations identify the impact of the pinning layer design on the current driven free layer reversal. Whereas simulations suggest the SAF design being slightly beneficial for switching speed, experiments show the SFM design to maintain higher perpendicular anisotropy, a higher TMR (180%) after 400°C annealing, and higher R-H loop squareness after patterning. Diffusion control during the anneal is key. References: [1] J.J. Kan, et al., IEDM, 27.4.1-4 (2016), [2] J. Swerts et al., IEDM, 38.6, 1-4 (2017), [3] G. Hu et al. IEDM, 38.3, 1-4 (2017).

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SP4 - Parallel session 2

SP4.2.07

Mechanical detection of nanomagnetic phenomena employing coupled nano- and micro-cantilever systems

T. Mühl, C. Reiche, J. Körner, B. Büchner

Text Magnetic force microscopy (MFM) and cantilever magnetometry are nanomagnetic measuring techniques that rely on cantilever-based force transducers. Their sensitivity can be improved by reducing the cantilever's dimensions which may lead to difficulties in their read-out by conventional means, e.g. by optical detection.

Our recently developed sensor concept [1,2] addresses this issue by a co-resonant coupling of a tiny nanocantilever to a rather conventional microcantilever. The co-resonance is achieved through matching of the eigenfrequencies of the two cantilevers which induces a strong interplay between them. Thus, if the highly sensitive nanocantilever is subject to an external interaction, the oscillatory state of the coupled system as a whole is changed. This change can be detected at the microcantilever with standard equipment. We present analytical approximations of the resonant behavior, amplitude relations, and effective quantities with respect to damping, mass, and spring constant of the co-resonantly coupled system. Furthermore, we show how the experimental implementation of the co-resonant approach in MFM enables a huge sensitivity enhancement in case of an in-plane sensitivity imaging mode with the nanocantilever arranged in a pendulum-type geometry.

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SP4 - Parallel session 3

SP4 - Parallel session 3

SP4.3.01

SOT-MRAM 300mm integration for low power and ultrafast embedded memories

K. Garello, F. Yasin, S. Couet, K. K. Vudya Sethu, L. Souriau, J. Swerts, S. Rao, S. Van Beek, W. Kim, E. Liu, S. Kundu, D. Tsvetanova, N. Jossart, K. Croes, E. Grimaldi, M. Baumgartner, D. Crotti, A. Furnémont, P. Gambardella, G. S. Kar

Text Among non volatile memory technologies, spin-transfer torque (STT)-MRAM has gained a lot of attention due to its scalability, low power and high speed, as well as compatibility with scaled CMOS processes and voltages. Despite all these advantages, STT-MRAM cannot operate reliably at sub-ns scales due to large incubation delays, making it an unsuitable solution to tackle L1/2 SRAM cache replacement. In addition, the shared read/write path can impair the read reliability, and imposes severe stress on the magnetic tunnel junction (MTJ) leading to time dependent degradation of the memory cell. To mitigate these issues, spin-orbit torque (SOT)-MRAM has been proposed. SOT induces switching of the free layer of MTJ by injecting an in-plane current in an adjacent SOT layer. This enables a three terminal MTJ-based concept that significantly improves the device endurance and read stability. Moreover, due to SOT spin transfert geometry, incubation time is negligible which allows for reliable switching operation at sub-ns timescales. Here, we report the first successful integration of top-pinned perpendicular MTJ on 300 mm wafer using CMOS-compatible processes for SOT-MRAM architectures. We show that 62 nm devices with a W-based SOT underlayer have very large endurance, sub-ns switching time of 210 ps, and operate with power as low as 300 pJ. Our work shows that SOT-MRAM has the capacity to tackle SRAM cache replacement.

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SP4 - Parallel session 3

SP4.3.02

Spin-orbit torque induced domain switching in antiferromagnet/ferromagnet heterostructures

G. K. Krishnaswamy, M. Baumgartner, G. Sala, A. Kurenkov, F. Maccherozzi, S. Fukami, H. Ohno, P. Gambardella

Text Recent measurements have shown that ferromagnet (FM)/antiferromagnet(AFM) multilayer structures with perpendicular anisotropy can be efficiently switched by current-induced spin-orbit torques [1]. In such structures, the use of AFM results in analogue-like (memristive) switching with multiple nonvolatile states, similar to artificial neural networks. Here we use x-ray photoemission electron microscopy to image the ferromagnetic domains of $[Co/Ni]_2/Co/PtMn$ multilayers at intermediate switching states as a function of injected current. We find that trains of current pulses induce gradual switching of the Co/Ni multilayer by the expansion and nucleation of irregularly shaped domains with spatial features of the order of 100 nm. The domains reproduce themselves in repetitive switching sequences, commensurate with electrical measurements. The analysis of the size distribution and domain expansion pattern reveals a magnetization reversal mechanism that is different from the spin-orbit torque switching of FM/nonmagnet heterostructures [2]. Achieving a deeper understanding of the switching mechanism in FM/AFM structures is thus relevant for fundamental research as well as applications of AFM in spintronic devices. This work is supported by the ImPACT Program of CSTI and JST-OPERA, and the Swiss National Science Foundation.

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SP4 - Parallel session 3

Effect of N, C and B interstitials on the structural and magnetic properties of alloys with Cu_3Au-structure

I. Opahle, H. K. Singh, H. Zhang

Text High-throughput density functional calculations are used to investigate the effect of interstial B, C and N atoms on the stability, structural and magnetic properties of 21 reported alloys crystallizing in the cubic Cu_3Au structure. For 29 alloy/interstitial combinations the formation of stable interstitial alloys with interstitial concentrations above 5% is expected. The majority of stable interstitials prefers the anti-perovskite structure. It is shown that interstitials can have a huge impact on the magneto-crystalline anisotropy energy (MAE) when the cubic symmetry is broken. For $MnNi_3$ and $FeNi_3$ interstitial N leads to a tetragonal distortion with a moderate uniaxial MAE. Mn_3XN_x (X=Rh, Ir, Pt and Sb) are identified as alloys with strong magneto-crystalline anisotropy. For Mn*X*Ir interstitial N leads to a huge enhancement of the MAE. It is expected that N has also a strong influence on the MAE of amorphous Mn*X*Ir, which is one of the state-of-the-art materials for exchange bias in hard magnetic films. The impact of the N interstitials on the MAE is discussed at hand of the electronic structure.

SP 4 Magnetic memories and magnetic recording, sensors

SP4 - Parallel session 3

SP4.3.04

Time-resolved measurements of the switching of Spin Transfer Torque Random Access Memory down to the nanosecond scale

P. Bouquin, S. Rao, S. Couet, W. Kim, S. Kundu, D. Crotti, D. Tsvetanova, J. Swerts, G. S. Kar, T. Devolder

Text We use time-resolved measurements to study the switching mechanism in STTMRAM. Our samples are disk shaped pillars of diameter down to 40 nm [1]. We study the device time-resolved conductance response to fast rising voltage steps. Following [2] we describe the switching in two steps: an incubation delay during which the conductance is quiet followed by a fast change of the conductance.

The statistics of the incubation delay span from the µs to the ns range when increasing the applied voltage. We discuss our findings using material parameters deduced from spin wave spectroscopy at device level [3]. While a macrospin model based on these parameters fails to describe the experimental trends, a description of the µs to 25 ns regime based on effective energy barriers and attempt frequencies can still be applied. This can't be done below 25 ns because the incubation delay doesn't depend exponentially on voltage anymore.

In addition to the stochasticity of the incubation delay, the switching path also exhibits event-to-event variability. The slew rate of the conductance can vary by up to a factor of two. This comes in addition to the expected size and voltage dependence. Moreover, in the conductance traces, transient plateaus are sometimes observed, and more rarely back hopping can happen. We will discuss possible origins of those effects.

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