EMERGING APPLICATIONS OF SPIN TRANSFER TORQUE (EASTT)

ABSTRACTS

Theoretical limits of Microwave Assisted Magnetic Recording (MAMR) effective field gradient (invited)

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The subject of maximum areal density capability (ADC) attainable in magnetic recording comprises the basis of understanding the viability of said technology. In Microwave Assisted Magnetic Recording (MAMR) the emphasis is on two characteristics of spin torque oscillator (STO) based RF field generation: confined footprint of the RF field, allowing for narrow written tracks, and rapid reduction of MAMR effect close to the STO center, caused by the rapid change of the RF field angle. The latter can theoretically lead to effective field gradients exceeding 1000 Oe/nm. However, almost every single model or experiment conducted this far demonstrated some unexpected difficulties with attaining high linear density. We show that this can be explained in the model as degradation of writing probability. It is an effect which s present in all energy-assist systems, and can be shown to be equivalent to increasing the jitter parameter in accordance to the formula, where is noise to signal ratio. We also demonstrate that taking this phenomenon into considerations has obvious impact on design rules applicable to MAMR system

Modelling of spin torque oscillators for microwave assisted recording

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Microwave Assisted Magnetic Recording (MAMR) is a breakthrough technology able to provide continuous growth in recording areal density [1]. By using resonance, recording medium can be written by writer magnetic field, which is significantly lower than the medium coercive field. Therefore, magnetic grains with higher magnetocrystalline anisotropy can be used, which in turn will provide thermal stability for the written bits. The current state of the art microwave field generator is Spin Torque Oscillator (STO) which is positioned in the gap between the main pole and trailing shield [1]. In order for MAMR technology to push areal densities beyond 2 Tb/in2, a reliable STO capable of providing microwave magnetic field with the amplitude in excess of 1 kOe has to be engineered. Stability of STO oscillator as well as effect of the interaction with the magnetic writer are crucial in development of MAMR. By stability we mean precession of two magnetic layers with constant frequencies and polar angles. Fig. 1 demonstrates examples of unstable and stable STO designs. There has been a substantial amount of analytical and numerical work done in the recent years for the case of STO with a fixed spin polarization layer [2, 3]. Analytical solutions were thought for a free layer under assumption that the reference layer does not move. When two layers are free to rotate in space, the problem is reduced to the dynamics of coupled oscillating magnetic layers. The coupling originates from the spin transfer torque and it depends on polar angles of both layers as well as on the difference between their azimuthal angles. By using the model of STO it is possible to derive analytical formulae for the angular dependence of the spin torque direction in for each layer. Stability analysis is done by obtaining fixed point solutions for the nonlinear system of equations describing time evolution of two polar angles and of the difference between azimuthal angles. The system is derived from LLG equations for two macro-spins in spherical coordinate system. Fixed point solutions are obtained using Newton iterations. A linear stability analysis about fixed points was used to select only stable solutions.

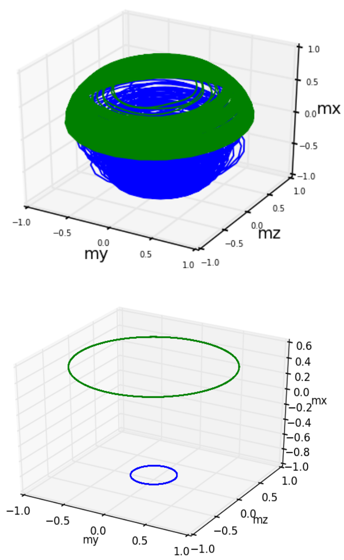

Figure 1. Example of unstable (top) and asymptotically stable (bottom) oscillators with two freely rotating magnetic layers

Magnetostatic coupling between trailing shield and STO does affect stability of the precession angle and the frequency of STO. We demonstrate the interaction of the STO with the trailing shield of the writer, in a micromagnetic model of the recording head with the STO in the gap. For such simulations we use an in-house micromagnetic software TGMag. TGMag solver is based on FEM micromagnetic formulation [4]. The feature of TGMag is its fast solver for the magneto-static field with $O(N)$ complexity both in memory usage and computation time. Acceleration of simulations is achieved by using NVIDIA GPUs for all linear algebra operations.

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Non-uniform spin transfer torque switching dynamics in CoFeB/MgO magnetic tunnel junctions

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This Spin transfer torque magnetic random access memory (STT-MRAM) is a high-density non-volatile data storage device based on magnetic tunnel junctions (MTJs), trilayer stacks composed of two magnetic layers separated by a thin insulating layer. CoFeB/MgO-based MTJs represent a suitable candidate for STT-MRAM due to the high perpendicular magnetic anisotropy, low Gilbert damping and high TMR, required to obtain a high efficiency STT-MRAM device. The nature of the magnetisation reversal determines the switching properties of such devices and therefore, a deep understanding of the mechanism of the magnetisation reversal under the application of a spin-polarised current is of fundamental interest. Nonetheless, a model able to provide a complete description of this phenomenon has not emerged yet. Here we use an atomistic spin model to investigate the nature of the magnetisation reversal in STT-induced switching and its time-scale. The STT field is modelled based on Slonczewski's approach [1] as parametrised by Zhang et al [2] and adapted to an atomistic level. Our results show a non-uniform switching of the magnetisation for diameters larger than 20nm, with a reversed region forming near the edge and enlarging. This non-uniform magnetic structure rotates rapidly, on a precessional time scale, and can be seen of as an interference pattern between normal modes [3], whose orientation depends on the instantaneous relative phase of the modes. The rotation persists even after the mean magnetization reverses and the system switches, and occurs both at 0K and at finite temperature. Interestingly, we observe a transition from coherent reversal mechanism to non-collinear for MTJ diameters close to the single domain limit depending on the injected current and the temperature. Our results suggest a more complex switching dynamics than often assumed for STT devices and should lead to better understanding of the phenomenon.

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Utilization of phase information in spin torque oscillator

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Spin torque oscillator (STO)[1] is an auto-oscillator fabricated by patterning a magnetic tunnel junction (MTJ). It generates a high-frequency signal by first exciting magnetization precession through spin transfer torque, then converting it into an electrical signal through magnetoresistance effect. STOs are very small devices, whose typical sizes can be down to sub-100 nm. Moreover, the frequency tuning range of the STO is larger than that of general oscillators because of the strong nonlinear magnetization dynamics. These characteristics are very attractive features for mobile communication application. Therefore, STO has been intensely studied during the past decade.

Researches on the phase control and utilization of it for practical applications have also been conducted for these years. Rippard[2] and Zhou[3] showed that the phase difference between the STO and external high frequency signal injected into the STO can be controlled by the synchronization phenomenon. This can be applied for a phased array[4] microwave generator which electrically scans a microwave beam.

Another example that exploits the phase of the STO is a read sensor of a HDD head. The application of a STO for sensing high-speed magnetic fields was initially proposed by HGST[5]. And a demonstration of reading a very high speed magnetic field pulse (1 ns) by a phase change of the STO was later performed by Toshiba corp.[6,7]

For developing high performance STOs, we have also realized high power output of the STO[8-10] and phase locked loop (PLL) circuit[11] etc. In the presentation, I will show the detailed introduction of the above researches and the results of our experiments related to them.

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Phase locked loop operation of spin torque oscillators

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Through spin polarized transport properties spintronic devices provide microwave functions that are of interest for wireless communication schemes. These functions include microwave signal generation (DC-to-RF converter), modulation and frequency selective microwave signal detection (RF-to-DC converter). In this presentation we discuss the signal generation using spin torque oscillators (STO) within a phase locked loop (PLL) [1, 2]. A phase locked loop is used (i) to provide a variable output frequency from a stable fixed frequency oscillator and (ii) to improve the phase noise of a frequency tuneable oscillator of lower performance. In order to provide a flexible design of the constituting rf components, to decrease losses and reduce noise, and to realize a first step towards compact system design, we have fabricated hybrid phase locked loops on 0.18µm BiCMOS. The PLL's frequency divider, loop filter and voltage-current converter were designed for two types of STOs: vortex devices emitting in a frequency range of 0.1-1GHz and uniform magnetized devices emitting in the 1-10 GHz range. PLLs were assembled on two different PCBs with appropriate signal amplification and DC current source to adapt to different power levels and operation condition. Results will be presented for magnetic tunnel junction devices with RA≈2Ωµm² and TMR of 50-100%. The Polarizer Pol is an in-plane magnetized synthetic antiferromagnet and the free layer is made of CoFeB2/Ta0.2/FeNi(t) with thickness t=7nm for vortex devices and t=2nm for uniform devices. The PLL of vortex devices shows a reduction of phase noise of -50dBc at 100kHz offset frequency in a bandwidth of 2MHz. The corresponding free running parameters are f=337MHz, Δf=100kHz and P=1µW. For uniform devices (f=4.2GHz, Δf=15MHz and P=100nW) temporarily locking is also demonstrated within a bandwidth of 1MHz. The frequency of the oscillator clearly follows the PLL target frequency, while the phase noise reduction is not yet complete due to instabilities of the free running signal. Besides phase noise reduction we also demonstrate the possibility to shift the PLL output frequency through variation of frequency division which gives prospect to use the PLL for frequency shift keying. Further improvements of PLL operation such as locking via a field line will be discussed. The achieved results are a first step towards integration of spin torque oscillators for microwave applications.

Acknowledgements

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Phase shift keying in spin torque oscillators

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Spin torque oscillators (STO) are promising for wireless communication schemes due to their nano-scale size and their frequency tunability over a decade frequency range via either a dc current or an applied field. However, one of the main issues is their relatively large linewidth and high phase noise figure which can limit for STOs the data transmission rate in frequency and amplitude shift keying schemes [1,2]. One possibility to reduce the STO phase noise and hence the linewidth is to couple several oscillators or to injection lock the STO to an external rf current or field source [3, 4]. Such synchronization opens the possibility of implementing the third concept of data transmission which is phase shift keying (PSK) as will be demonstrated here. A specific feature of the synchronization phenomenon is that the phase of the locked oscillator is shifted with respect to the source [5]. This phase shift $\Delta\psi$ is determined by the detuning which is the frequency difference of the free running oscillator and the rf source. For STOs, due to their non-isochronous properties the frequency of the free running state and thus the detuning can be easily changed through the DC current or DC field. In this presentation we validate this concept of PSK for magnetic tunnel junction based vortex STOs whose free running parameters are f=300MHz, Δf=100kHz and P=1µW. They are characterized by perfect locking to external sources at 2f and f/2 for which the phase noise is strongly reduced [4]. The vortex devices studied here show a phase noise reduction of -50dBc/Hz at 10kHz offset frequency in the synchronized state. The frequency detuning of the STO that leads to a phase shift $\Delta\psi$ of the locked signal, is induced by connecting an additional low frequency modulation current source. Maximum phase difference between $\Delta\psi$ shifts close to $\Delta\varphi = \pi/2$ and π were achieved for the synchronization at 2f and f/2 respectively. We obtained 4Mb/s PSK data transmission rate for the synchronization at 2f which is of the order of the amplitude relaxation frequency. We also demonstrate advanced PSK techniques such as quadrature phase shift keying QPSK and discuss the use of a field line for synchronization and modulation. This concept can be applied also for uniform devices oscillating at higher frequencies and consequently at higher data rates [2]. This gives prospect for novel, robust wireless communication schemes based on STOs, at high signal to noise ratio.

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Picosecond reorientation of in-plane magnetisation within a nano-element by spin orbit torque

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In-plane magnetised devices activated by spin-orbit torque (SOT) combine simplicity of design with energy efficient switching for future magnetic memory elements. SOT switching of in-plane magnetised CoFeB(2 nm) nanoscale ellipses fabricated at the centre of Pt Hall crosses has previously been investigated using a differential planar Hall effect technique.[1] Their planar nature allows complimentary optical techniques to probe switching speed and uniformity. Here, time-resolved scanning Kerr microscopy was used to probe picosecond magnetisation dynamics of a 400 nm×1000 nm ellipse in response to a current pulse passed through a Pt(6 nm) Hall cross parallel to the ellipse minor (hard) axis. The associated Oersted magnetic field (Oe-field), and the polarisation of spins traversing the Pt/CoFeB interface due to the spin Hall effect, were then parallel to the ellipse major (easy) axis. When magnetised along the easy axis, between remanence and the reversal switching field, asymmetry in the amplitude and relaxation of the dynamics was observed for opposite field history, *i.e*. magnetisation parallel or anti-parallel to the spin polarisation, indicating active SOTs on picosecond timescales. When magnetised away from the easy axis, a transient offset and temporary suppression of the dynamics was observed at the centre of the ellipse, while its ends revealed remarkably different dynamics. Time-resolved images indicate a precessional reorientation of the magnetisation that nucleates at one end of the ellipse and rapidly propagates along its major axis (Figure 1), before returning to the equilibrium state. Further measurements and modelling are required to disentangle the Oe-field and SOT contributions to the reorientation.

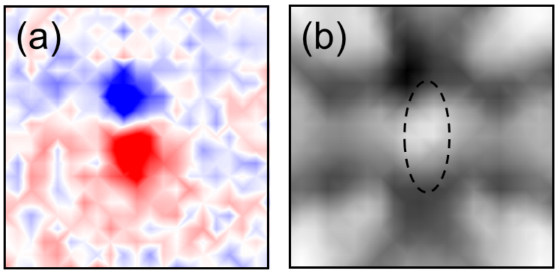

Figure 1. (a) Time-resolved polar Kerr image of the 400 nm×1000 nm ellipse. The location of the ellipse is indicated by the dashed line in the reflectivity image (b).

Acknowledgements

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Superposition of precessional modes within spin Hall nano-oscillators

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Spin Hall nano-oscillators (SHNOs) exhibit magnetization precession driven by pure spin currents generated by the spin Hall effect [1,2]. While focusing of current within the active area is key to the excitation of spin waves, significant Oersted field is generated in extended regions of the device. The combined action of the spin transfer torque (STT) and Oersted torque allows multiple precessional modes to be excited. Here a SHNO was formed by fabricating two Au(150nm) triangular nano-contacts on top of a 4 micron diameter bi-layer disk of Py(5nm)/Pt(6nm). Using electrical microwave measurements and time-resolved scanning Kerr microscopy (TRSKM) the dynamics excited by both RF and DC currents were explored. For the RF case, the STT and Oersted field induce ferromagnetic resonance (FMR). The optical data can be used to determine the relative strengths of the STT and Oersted torques in a similar manner to the STT-FMR teqhnique, but with the advantages that an optical probe confers. In contrast the DC case is expected to excite a localized spin wave bullet between the nano-contacts, which may be synchronised to the TRSKM by RF injection [3]. When observing the injection-locked mode a superposition of two modes can be seen (see Figure 1), the FMR excited by the RF current and the bullet mode. Separation of the two excitations yields spatially assymetric in-plane dynamics associated with the bullet mode. Furthermore, the dynamic structure extends over a greater distance than expected for the free-running bullet mode, suggesting an additional interaction between the bullet and FMR modes. Improved understanding of the character of the injection-locked bullet mode is essential for the mutual synchronisation of multiple SHNOs for increased output power..

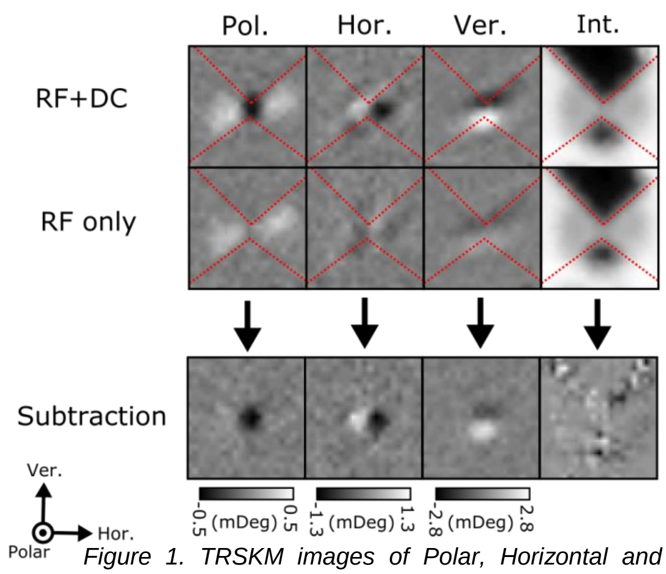

Figure 1. TRSKM images of Polar, Horizontal and Vertical dynamic magnetization, and Intensity for different injected currents. A DC current of 16 mA, and RF current of 1.4 mA at 6 GH,z were used, with a, field applied of 650 Oe applied at 120° to the vertical. Subtraction of the top two datasets yields the dynamics resulting from the DC current.

Acknowledgements

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Auto-generators of sinusoidal and pulsed THz-frequency signals based on antiferromagnetic dielectrics driven by spin current

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The antiferromagnets (AFM) are seen as materials for novel THz-frequency signal processing devices [1,2]. In contrast to the devices based on ferromagnets (FM), the AFM-based devices do not require any external bias magnetic field. Also, the ultrafast magnetization dynamics of the AFM devices is determined by the strong internal exchange field that exists in AFM materials, and keeps their magnetic sublattices anti-parallel to each other. This exchange field determines the high natural **frequenc**ies of the AFM resonance, lying in the sub-THz to THz frequency range. Thus, it is tempting to use AFM as active layers in THz-frequency spin-torque nano-oscillators, where the output electromagnetic signal is received using the inverse spin-Hall effect (ISHE) in the NiO/Pt layered structure [3]. Unfortunately, the amplitude of the generated THz-frequency signal is such an AFM oscillator decreases with the increase of frequency, making the generation process less efficient (see Fig.1).

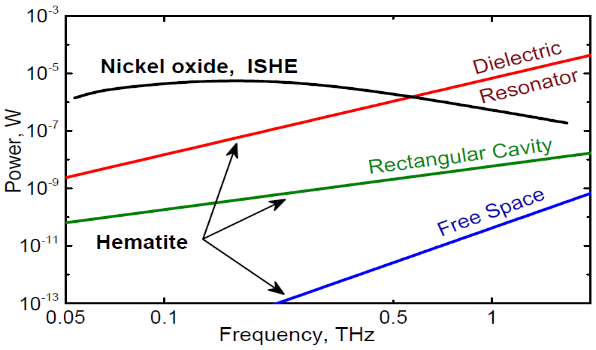

Figure 1. Generated power vs. frequency for an auto-oscillator based on a layer (thickness d_{AFM} = 5 nm) of a current-driven canted AFM (Hematite) creating dipolar radiation into different types of adjacent resonance systems. For comparison, a similar curve is presented for an oscillator based on a usual AFM (NiO), where the signal is extracted using ISHE in the adjacent Pt layer.

To meet this challenge, we propose a design of a THz-frequency signal generator based on a the AFM/Pt layered structure where the magnetization vectors of the AFM sublattices are *canted inside the easy plane* by the Dzyaloshinskii-Moriya interaction (DMI), resulting in the formation of a small net magnetization $\mathbf{m}_{DMI}$ (e.g. Hematite (Fe_2O_3)). The perpendicularly polarized spin current, created by a driving DC current in the Pt layer, tilts the DMI-canted AFM sublattices out of the easy plane, thus exposing them to strong internal exchange magnetic field of the AFM. The sublattice magnetizations, along with the small net magnetization vector $\mathbf{m}_{DMI}$ of the canted AFM, start to rotate about the hard anisotropy axis of the AFM with the THz frequency proportional to the injected spin current and the AFM exchange field. The rotation of the small net magnetization $\mathbf{m}_{DMI}$ results in the THz-frequency dipolar radiation that can be directly received by an adjacent (e.g. dielectric) resonator.

We demonstrate theoretically that the radiation frequencies in the range f = 0.05 - 2 THz are possible at the experimentally reachable magnitudes of the driving current density, and evaluate the power of the signal radiated into different types of resonators, showing that this power increases with the increase of frequency and could reach several μW when a dielectric resonator with a typical quality factor of Q= 750 is used.

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Interfacial spin phenomena and opportunities for spintronics in flexible electronics (invited)

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Flexible electronics is an exciting and rapidly growing field encompassing a wide range of technologies and applications that spans current consumer applications, such as flexible displays, through to demonstrators and concepts, including sensing textiles and 'electronic skin'. Flexible thin-film integrated circuits (ICs) hosted on polymeric substrates offer lightweight, rugged, conformable and potentially foldable electronic circuits for novel and seamless integration into a wide range of products, creating new uses, adding benefits from embedded electronic functionality and providing technology for the 'Internet of Things', which alone is estimated at 30 billion dollars by 2019. In comparison to conventional MOS (silicon) IC device fabrication, flexible IC production facilities can be much smaller, cost less to implement and have significantly lower overall production costs, along with short design cycles and other production benefits. Although high-end silicon technology will not be directly replaced by flexible integrated circuits, for many applications larger circuit component features and lower clock speed ICs can meet functional device needs, presenting a huge opportunity for applications of low cost flexible electronics. This broad applications landscape and relatively large feature sizes open opportunities and challenges for wide-ranging applications of spintronics in sensors, memory and logic for integration into flexible electronics technology.

In the decades since the discovery of GMR, a range of interfacial physics has emerged in ferromagnetic/non-magnetic (FM/NM) systems that opens up new avenues for physical understanding and offers potential for the creation of synthetic materials with designer properties for spintronic applications in current and future technology. There are many exciting areas of research linked to interfacial effects in ferromagnetic/non-magnetic (FM/NM) systems, such as interface spin-orbit interactions (SOI), spin-currents from the spin Hall effect (SHE), spin-orbit torques (SOT), interfacial Dzyaloshinskii-Moriya interaction (DMI), proximity-induced-magnetization (PIM) of non-magnetic metals and ferromagnetic damping that can yield new insights and applications. Examples of these including interfacial damping effects [1] are outlined and discussed in terms of non-magnetic layer thickness [2] and crystal structure [3]. Considerations of FM film growth and structure on spintronics [4] and interface effects associated with damping, interfacial DMI and PIM in NM transition metals in direct contact FM thin-films are also described [5]. The status of flexible spintronics concepts and applications, and issues of implementing such spintronic structures on flexible substrates will be discussed.

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Towards spin torque nano oscillators based on topological insulators

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Topological insulators are well known for their conducting surfaces, harbouring fully spin-polarised currents due to spin-momentum locking [1]. They are a consequence of spin-orbit coupling, very high in these materials. Consequently, large spin-orbit torques in an adjacent ferromagnet can be generated, even larger than in their heavy metal counterparts such as Pt and Ta [2].

This raises the question how topological insulators can improve spintronic devices. One example for a device which could benefit is the spin-torque nano oscillator (STNO), which transforms DC currents into Gigahertz radiation. Here, a nanocontact provides the current passing through a spin-valve and counteracts the damping of spin precession by means of the spin-transfer torque [3]. The main obstacle for practical applications is the large current density needed, leading to Ohmic heating and limiting the lifetime of the devices.

Topological insulators could potentially solve this problem by providing sufficiently high 'pure' spin currents, avoiding the heating problem altogether. The goal of this contribution is to present an overview of the challenges involved in integrating topological insulators with magnetic thin film layer stacks, and to suggest potential new device concepts. These deliberations will be informed by my recent research in both topological insulators [4] and spin-torque nano oscillators [3]. Importantly, I will focus on how industry partners could be involved in this research, aiding to both the research and commercial outcome.

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Time-resolved X-ray detected ferromagnetic resonance measurements of a CoFe/NiO/Fe/NiFe multilayer structure

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Antiferromagnetic NiO films have been studied as media for the effective propagation of spin currents, mostly by means of the inverse spin Hall effect (ISHE) [1]. However their study is still incomplete because ISHE has only been used to probe the dc spin current, while the ac spin current has not been measured. X-ray detected ferromagnetic resonance (XFMR) allows an ac spin current to be detected via the spin transfer torque exerted upon a ferromagnet [2]. To this end, time-resolved element-specific XFMR measurements were performed upon a CoFe/NiO/Fe/NiFe multilayer. Microwaves of 4 GHz frequency were supplied through a coplanar waveguide (CPW) with a variable phase relative to the x-ray pulses, so as to generate an in-plane rf magnetic field orthogonal to the axis of the CPW, while a static magnetic field of magnitude H was applied parallel to the axis. Figure 1(a) shows XFMR delay scans acquired at the Co and Ni L_3 edges of the CoFe and NiFe layers respectively. The amplitudes and phases were extracted by fitting sine curves to the data acquired at different values of H, as shown in Figure 1(b) and (c). The FMR field was close to 60 Oe for both the CoFe and NiFe layers, and the precession was found to have very similar phase for both layers. These results indicate that the CoFe and NiFe layers are strongly coupled and exhibit an acoustic precessional mode. Since the intrinsic FMR frequency of the CoFe layer should be much higher than 4 GHz, the XFMR measurements may be interpreted as a signature of spin current propagation mediated by magnons within the NiO layer.

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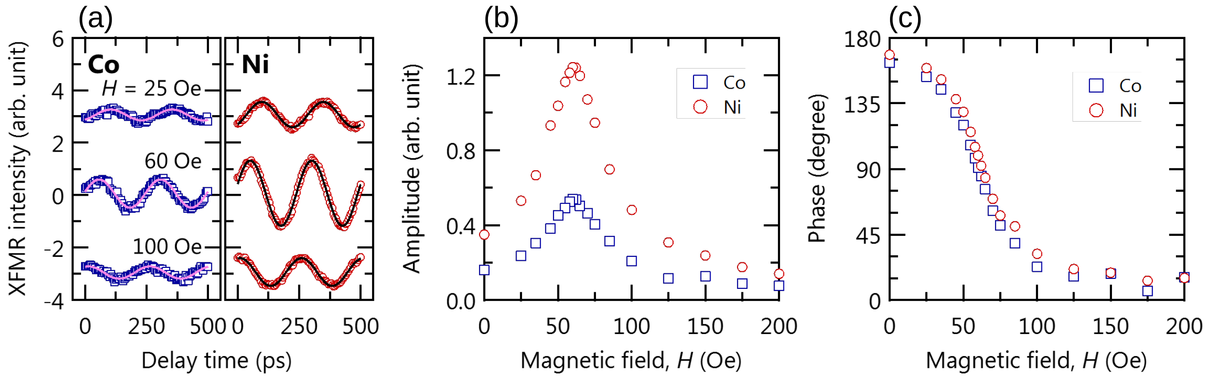

Figure 1. (a) XFMR delay scans measured at different H values, (b) fitted amplitudes, and (c) fitted phases for Co (blue squares) and Ni (red circles) L_3 edges. Sine curves in (a) are fits to the experimental data.

Spin-torque nano-oscillators for neuromorphic computing (invited)

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Spin-torque nano-oscillators are non-linear, nano-scale, low power consumption, tunable magnetic microwave oscillators which are promising candidates for building large networks of coupled oscillators. Those can be used as building blocks for neuromorphic hardware which requires high density networks of neurons-like complex processing units coupled by tunable connections. Recently a first demonstration of neuromorphic computing with a single spin-torque nano-oscillator was established allowing spoken digit recognition with state of the art performances [1]. However, to realize more complex cognitive tasks, it is still necessary to demonstrate a very important property of a neural network: learning - an iterative process through which a neural network can be trained using an initial fraction of the inputs and then adjusting internal parameters to improve its recognition or classification performance. Through the high frequency tunability of spin-torque nano-oscillators, we demonstrate experimentally the learning ability of coupled nano-oscillators to classify spoken vowels with a recognition rate of 88% [2]. To realize this classification task, we took inspiration from the synchronization of rhythmic activity of biological neurons and exploit the synchronization of spin-torque nano-oscillators to external microwave stimuli. These results open new paths towards highly energy efficient bio-inspired computing on-chip based on non-linear nano-devices that can adapt and learn.

Acknowledgements

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How synchronized spin Hall effect nano-oscillators will enable microwave and pattern matching applications (invited)

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Spin Hall nano-oscillators (SHNOs) [1] is an emerging class of nano-scopic microwave signal generators with potential for new disruptive applications ranging from microwave signal generation/detection to neuromorphic computing [2,3]. SHNOs are based on an intrinsic magnetodynamic resonance with frequencies in the GHz range, which depends on material parameters, device layout, and external parameters such as magnetic field and drive current. For sufficiently high current densities, the resonance can be driven into a state of coherent auto-oscillation, similar to that of optical lasers. Through the magnetoresistance of the device, the auto-oscillation can be used to generate a current- and field-tunable microwave voltage.

The auto-oscillation state is highly non-linear in nature, and neighbouring SHNOs can therefore interact with each other and even mutually synchronize, which further increases the power and coherence of the microwave signal [4]. This is important, as the nano-scale volume of the auto-oscillating spin wave mode is susceptible to thermal noise, leading to detrimental phase noise in the microwave signal. I will present resent results how the intrinsic linewidth of a single SHNO can be reduced by two orders of magnitude by synchronizing 64 SHNOs together [5]. Based on these results I will present a viable path towards commercial microwave signal generators based on mutually synchronized SHNO arrays.

The mutual synchronization phenomenon can also be used for ultra-fast pattern matching with potential for speeding up image recognition by orders of magnitude. With the recent rapidly increasing interest in artificial intelligence and neuromorphic computing, mutually synchronized SHNO chains and arrays hence represent a highly attractive emerging technology platform for low-power, and ultrafast non-conventional computing.

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Mutual Synchronization of Spin Torque Nano Oscillator with Magnetic Field Feedback

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We experimentally demonstrate the mutual synchronization [1] of two STNOs via magnetic field coupling. As shown in fig 1a, the rf output of the first (second) STNO is connected to a waveguide below the second (first) STNO, which results in a coupling via Oersted magnetic field. We applied a fixed magnetic field to the first STNO and varied the magnetic field applied to the second STNO. The power spectrum plotted in fig 1b, shows the mutual synchronization in a certain magnetic field range. We explored the synchronization as a function of the coupling strength and phase by using amplifiers and adjustable delays in the signal paths. We further found that at higher amplification, the power spectrum develops side bands separated by the inverse of the time delay in the signal path [2,3].

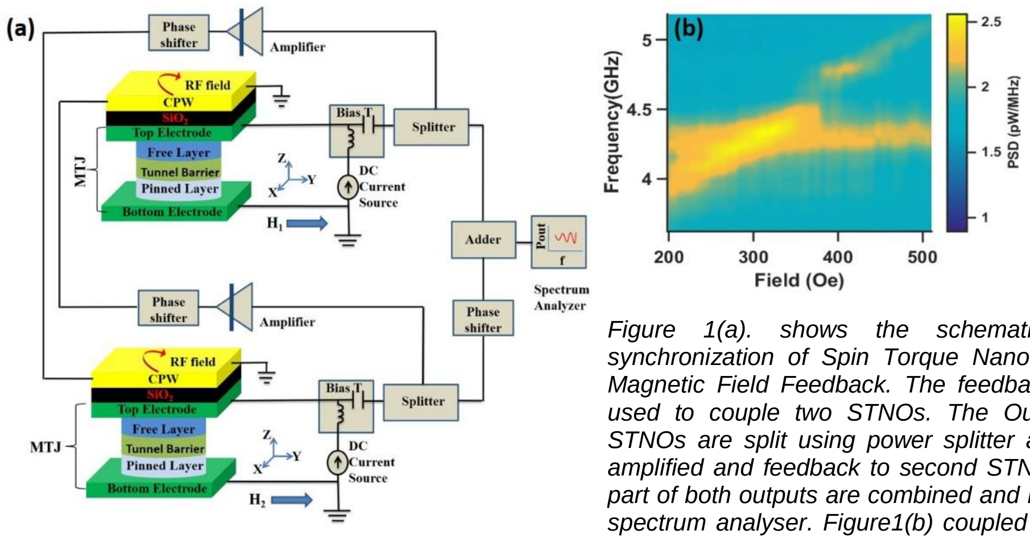

Figure 1(a). shows the schematic for mutual synchronization of Spin Torque Nano Oscillator with Magnetic Field Feedback. The feedback technique is used to couple two STNOs. The Output signals of STNOs are split using power splitter and one part is amplified and feedback to second STNO. And second part of both outputs are combined and measured using spectrum analyser. Figure1(b) coupled behaviour: The colour plot shows the mutual coupled power spectral density with variation of external applied field to one oscillator and other have fixed field.

Acknowledgements

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Time resolved imaging of coupled nano-contact spin transfer vortex oscillators

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In this work pairs of STVOs with NCs of 100 nm diameter and center-to-center separation ranging from 200 nm to 1100 nm have been studied, with a combination of electrical measurements and time-resolved scanning Kerr microscopy (TRSKM) being used to explore the microwave emission and associated magnetization dynamics as a function of NC separation. Electrical measurements were richly featured, often exhibiting multiple modes and their harmonics as in shown in Figure 1.a. The Kerr images acquired for the NC pair with 200 nm separation reveal significant differences in the spatial character of the magnetization dynamics when compared to those observed previously for a pair with 900 nm separation , for which the dynamic interaction is expected to be weaker. For a separation of 900 nm, localized regions of magnetization dynamics were observed close to each NC (Fig. 1.c and 1.e, yellow arrows), each region having similar spatial character to that found within single NC devices, suggesting that a separate vortex had formed at each NC.[3] However, for a pair of NCs with 200 nm separation (Fig. 1.b and 1.d, blue arrow), a single region of lower amplitude dynamics was observed to span the region occupied by the NCs. At the same time, large amplitude dynamics were also observed some microns from the NCs. We speculate that these dynamics are due to the oscillation of anti-vortices (AV) that were pushed away from the NCs, pinned by stray DC electromagnetic fields from the device contact pads, and then excited by the stray RF Oersted field. An improved understanding of the interaction of pairs of NC-STVOs obtained from time-resolved imaging of their magnetization dynamics is crucial for the realization of networks of phase-locked STVOs that share common magnetic layers.

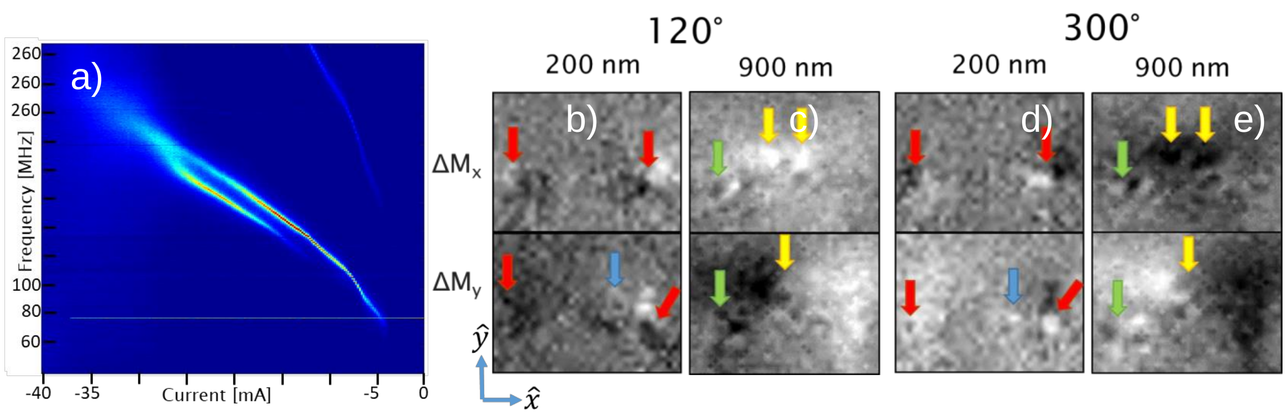

Figure 1: a) Transport measurements at zero external field for a STVO with a pair of NC of 100 nm diameter and separated by 200 nm where is possible to observe two gyration modes of magnetic vortices produce in the film. Time Resolved Scanning Kerr Microscopy (TRSKM) was used to image the dynamic magnetization within two devices with NC separation of 200 nm (b) and d) and 900 nm (c) and d). Blue and yellow are dynamics associated to vortex motion while red and green arrows are associated to antivortices motion.

Acknowledgements

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Complex spin configurations in hybrid magnetic multilayer structures due to mutual spin imprinting

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Hybrid Co/Pd-Permalloy multilayer structures exhibit multiple domain phases resulting from mutual spin imprinting, dependent on the precise layer composition and thickness. While such hybrid structures can support either a pure Landau closure-domain pattern or a perpendicular exchange-spring magnetization structure, numerical analysis also revealed an anomalous mixed Landau-maze domain state. Mutual imprinting of the spin configuration between the layers was strongest for the latter multi-domain state, which we propose is a consequence of exchange energy dissipation over the two lateral dimensions. An analytical derivation of domain phase boundaries was consistent with the micromagnetic simulations and gave important insight into their origin.

This model was used to predict an imprinted domain structure, which allows a controlled vortex core excitation in a sub GHz regime. This current driven vortex excitation can, due to a mutual interaction of the two magnetic layers lead to a periodic vortex core switching switching at the three-dimensional imprinted domain structure. Due presenting a controlled current driven vortex oscillator combined with a polarity change [1], therefor making it a multi-functional magnetic hybrid device [2], applicable to magneto-logic and magneto-processing devices.

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Femtosecond optical torques and electric currents at interfaces of magnetic metallic heterostructures

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The torques produced by circularly polarized femtosecond laser pulses are the fastest available stimuli acting on the magnetization. While the laser-driven torques in magnetic dielectrics have been commonly observed, their presence in magnetic metals has remained under question. Recently we demonstrated femtosecond optical tilting of the magnetization via the inverse Faraday effect or the optical spin transfer torque in the magnetic heterostructures at the interface between a ferromagnetic metal (e.g. Co) and a non-magnetic metal with a strong spin orbit interaction (e.g. Pt) [1]. Broken inversion symmetry in combination with the spin-orbit interaction at the interface enabled conversion of the magnetization tilting to the electric current and consequently THz electric field detected in our experiment.

Interfaces responsible for the inversion symmetry breaking must play an important role for femtosecond opto-magnetic torques in Co/Pt bilayers. In particular, these torques must depend on the nature and thickness of the interlayer between Co and Pt. The goal of this work is to elucidate how metallic Cu and semiconducting ZnO interlayers affect the generation of THz photocurrents in Co/Pt heterostructures. With the help of THz emission spectroscopy we find that the helicity dependent laser induced THz emission is more sensitive to the interface than the helicity independent one [2]. This helicity dependent emission can be explained in terms of spin-galvanic effects, for which the intermixing of spin-polarized electrons of Co and Pt is crucial.

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The Exeter Time-Resolved Magnetism facility (EXTREMAG)

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A dedicated facility for the time-resolved measurement of magnetic and spintronic materials and devices is currently being established in refurbished laboratories in the Department of Physics and Astronomy at the University of Exeter. The UK has a community of some 200 permanent academic researchers in universities and national laboratories working in magnetism, a field that continues to be an important arena for the discovery of new physical phenomena. Recent highlights include stabilization of novel magnetic textures such as droplets and skyrmions, manipulation of spin currents in antiferromagnets, and integration of magnetic materials with superconductors for exploitation of spin within quantum technologies. Improved understanding of magnetism at the nanoscale may be exploited immediately within information technology for non-volatile data storage and low-power computation, while improved permanent magnet materials will underpin development of green energy technology. The use of high frequency measurement techniques in magnetism research has increased enormously because the fundamental timescales for resonance and relaxation lie in the sub-nanosecond regime. Time-resolved magneto-optical measurement techniques offer a unique blend of temporal and spatial resolution within table-top experiments. The proposed facility will make expertise developed at Exeter available to the UK and international community via a short form proposal mechanism. A new ultrafast laser system with high repetition rate and large pulse energy will serve multiple user end stations providing magneto-optical pump-probe measurements, THz spectroscopy and microscopy, and time-resolved Kerr microscopy. The facility will be maintained by a scientific officer, who will support and train users who have limited previous experience of ultrafast optics. The specific objectives of the project are:

1. To procure a femtosecond laser system and measurement apparatus optimized for the study of magnetic and spintronic systems.
2. To appoint an experienced scientific officer to maintain the facility, configure the apparatus for different types of measurement, and support external users.
3. To install the equipment and demonstrate capability for magneto-optical pump-probe measurements, THz spectroscopy and microscopy, and time resolved Kerr microscopy, in a range of sample environments identified through consultation with external users.
4. To request and evaluate proposals for experiments from users from the UK and beyond, allocate time at the facility according to scientific merit, and monitor their success.
5. To promote the facility within the magnetism and spintronics community, publicise its achievements, and host a facility users meeting at the end of an initial 2 year period.

Figure 1. The EXTREMAG microscopy lab with dedicated laser enclosure at the far end. This lab space is one of two newly-refurbished, contiguous labs that will be served by the same ultrafast laser systems.

Acknowledgements

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Spin wave damping nonreciprocity in long-period magnetic structures: a phenomenological approach

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Spin waves propagating in long-period structures demonstrate the so-called nonreciprocity properties, i.e. the non-invariance of dynamical characteristics at a change of wave vector sign. Motivated by recent experiments, we studied spin waves relaxation peculiarities in inhomogeneous long-period magnetic structures. Spiral magnetic structures with a large helical period forming due to the exchange interactions competition or due to the exchange-relativistic (Dzyaloshinskii-Moriya, DM) interaction competition were considered. Corresponding dissipative functions have been constructed and have been analysed for crystals of different symmetry. In the frame of a general phenomenological approach it has been demonstrated that the nonreciprocity leads not only to a difference in the amplitude, phase and group velocities of spin waves of given energy with the opposite wave vector *k* sign, but results in their different damping. As an example, the results of numerical simulations of the spin-wave damping for relativistic spirals with different DM interaction value are shown in Fig. 1 for the case of small-*k* limit.

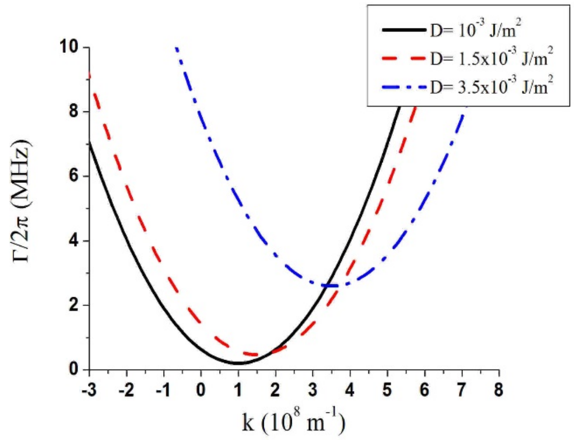

Figure 1 The spin-wave damping in the relativistic spiral for the case of small-k limit.

The simulations have shown that spin fluctuations of the dynamic state can not arise in inhomogeneous long-period magnetic structures in the vicinity of static spin structure due to the competitive interactions. This phenomenon results in a non-zero spin waves damping of the nonreciprocal magnons even for the Goldstone mode. This feature is sufficiently general and robust against the detailed magnon scattering mechanisms because it is mainly determined by the magneto-chiral nonreciprocity of the spin waves dispersion. Thus, the non-invariance of dynamic characteristics of long-period magnetic structures should be taken into account constructing the dissipation function for such systems. Our results also demonstrate the possibility to design an efficient diode for spin waves which is based on magneto-chiral nonreciprocity of spin waves in magnetic material with a chiral magnetic structure.

Acknowledgements

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Excitation and confinement of spin wave modes in arrays of cobalt microstripes formed on a permalloy underlayer

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We present ferromagnetic resonance measurements and theoretical description of standing spin-wave modes in arrays of long thin film cobalt microstripes formed on thin permalloy films. The measurements were performed at microwave frequency of 9.92 GHz while the swept bias magnetic field H was applied in the plane of the sample at various orientations relative to the symmetry axes of the stripes. The value of H was large enough to saturate both cobalt and permalloy magnetic subsystems at sufficiently large distances from the stripe edges. Up to four different spin wave modes were identified from the experiments and classified as belonging to two series, using their resonance field values and their dependence on the bias field orientation. The first of the two series ("cobalt modes") included modes with resonance fields that had an angular dependence typical for the easy-axis shape anisotropy of magneto-dipole origin expected for long stripes. Their resonance fields increased as the bias field orientation varied from that along the stripe length to that parallel to the stripe width. The second series included "permalloy modes", which had generally higher resonance fields. The angular dependence of the resonance field of the strongest permalloy mode was the same as that of the cobalt modes. However, its lower field satellite had an opposite angular dependence, i.e. its resonance field decreased as the bias field orientation varied from that along the stripe length to that parallel to the stripe width. The angular dependence of the permalloy modes is explained in terms of that of the stray magnetic field created by the magnetic charges formed at the edges of the cobalt stripes. The stray field increases / decreases the internal field in the permalloy film between / under the cobalt stripes. This interpretation is corroborated by the results of micromagnetic simulations and analytical theory. The discovered modulation of the internal magnetic field induced by the stripe array in the permalloy film is also periodic, which can be exploited to create magnonic crystals without physical patterning of the magnetic film used as a medium for spin wave propagation.

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Impact of Nb layer on the FMR properties of nanoscale magnetic films

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In this paper, we investigated experimentally the impact of a Nb superconductor film on the FMR properties of thin magnetic films at temperature 4.2 K and 300 K. The thin superconductor film (100 nm Nb) has been deposited on the Py film thickness 20 nm and FeCoB film thickness 20 nm.

It is revealed that at the liquid helium temperature (T=4.2 K) and at temperature 300 K the presence of superconducting film leads to the shift of FMR-peak (namely – the shift of magnitude of resonance magnetic field - H_{res}), Fig. 1. The magnitude of this shift depends both on the magnetic film material and on the temperature. Analysis shows that the origin of the phenomena is caused by the temperature dependence of saturation magnetization of magnetic films as well as by the influence of the superconductor film. Most likely that such influence of Nb film reduced to arising: either - the surface anisotropy field lied in the specimen plane, or – the anisotropy field, which has the diamagnetic origin and directed antiparallel to the external field.

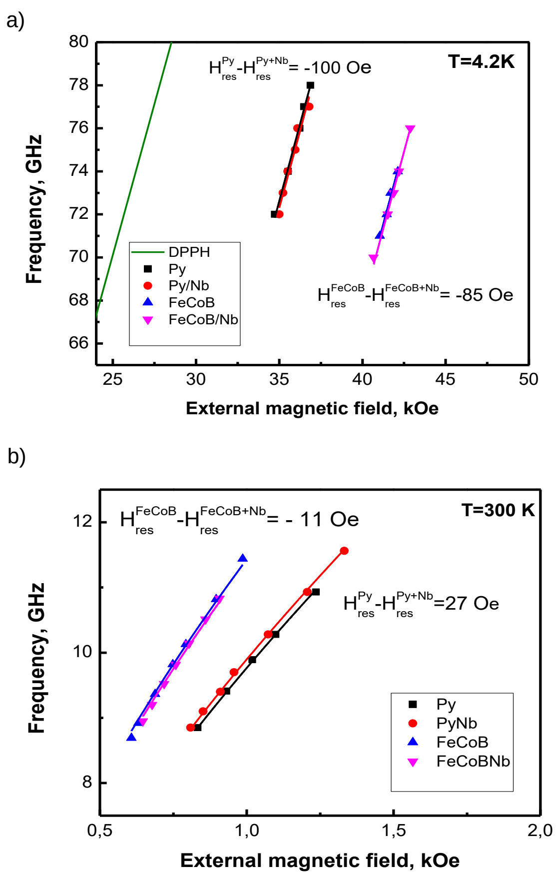

Figure 1. Experimentally obtained resonance *frequency-field dependences for FMR peaks in the structures under study: (a) T=4.2K (b)T= 300K.*

Acknowledgements

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