We are bringing to you a workshop on spintronics, magnetic sensing, and multiferroics. Gourmet lunch and tea/coffee breaks will be included to encourage active discussions and acquaintances. We will also feature special guests from the National Science Foundation (NSF), among other distinguished speakers from around the world (see the agenda and abstracts as follows).
# Frontier of Spintronics and Magnetic Sensing Workshop

## Agenda

<table>
<thead>
<tr>
<th>Start Time (5 min)</th>
<th>Invited Speaker</th>
<th>Institution</th>
<th>Title</th>
</tr>
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<tbody>
<tr>
<td>8:30am</td>
<td>Prof. Shan Wang</td>
<td>Stanford University USA</td>
<td>Welcome</td>
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### Session I: Spintronics and STT RAM – Chair: Prof. Nian Sun

(All talks will be 20 min + 5 min Q&A unless specially noted)

<table>
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<tr>
<th>Time</th>
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<tbody>
<tr>
<td>8:35am</td>
<td>Dr. Daniel Worledge</td>
<td>IBM Research Division USA</td>
<td>Low Current STT-RAM and Outlook</td>
</tr>
<tr>
<td>9:00am</td>
<td>Dr. Hendrik Ohldag</td>
<td>SLAC National Lab USA</td>
<td>Time resolved magnetic microscopy to study magnetization dynamics due to spin injection and spin torque transfer.</td>
</tr>
<tr>
<td>9:25am</td>
<td>Prof. Jianping Wang</td>
<td>University of Minnesota USA</td>
<td>Novel Spintronic Devices and C-SPIN</td>
</tr>
<tr>
<td>9:50am</td>
<td>Prof. Jongill Hong</td>
<td>Yonsei University Republic of Korea</td>
<td>Switching of Co/Pd superlattice only by spin-orbit torque (SOT)</td>
</tr>
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</table>

### Tea/Coffee Break (10:15-10:40 am)

### Session II: Magnetic Sensors – Chair: Prof. Shan Wang

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<th>Time</th>
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<tr>
<td>10:40am</td>
<td>Prof. Samir El-Ghazaly</td>
<td>National Science Foundation USA</td>
<td>NSF’s Interests in Magnetic Sensing and Imaging</td>
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<tr>
<td>10:55am</td>
<td>Prof. Paulo Freitas</td>
<td>International Iberian Nanotechnology Institute Portugal</td>
<td>Microfluidic Magnetoresistive Biosensors</td>
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<tr>
<td>11:20am</td>
<td>Prof. Jing Shi</td>
<td>UC Riverside USA</td>
<td>Magnetic Graphene and Sensing</td>
</tr>
<tr>
<td>11:45am</td>
<td>Qunwen Leng</td>
<td>Western Digital Corp. USA</td>
<td>Interlayer Magnetic Coupling in Low RA Magnetic Tunnel Junctions</td>
</tr>
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### Gourmet Lunch (12:10am - 1:10 pm)
## Frontier of Spintronics and Magnetic Sensing Workshop

### Agenda

<table>
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<th>Session III: Magnetics and Global Collaboration – Chair: Prof. Shan Wang</th>
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<tr>
<td><strong>Start Time</strong></td>
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<tr>
<td>1:10pm (15 min)</td>
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<td>1:25pm</td>
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<tr>
<td>1:50pm</td>
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<td>2:15am</td>
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**Tea/Coffee Break (2:40-3:05 pm)**

<table>
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<tr>
<th>Session IV: Multiferroics and Spintronics – Chair: Prof. Nian Sun</th>
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<tr>
<td><strong>Start Time</strong></td>
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<td>3:05pm</td>
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<td>3:30pm</td>
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<td>3:55pm</td>
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<tr>
<td>4:20pm</td>
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**Workshop Close and Social Time (5:10 – 5:35 pm)**

**Dinner and Entertainment for Invited Speakers and Workshop Organizers (6:15 – 8:15pm)**

**Venue: Courtyard mansion and theatre (正院大宅门 大戏院店)**
Spin Transfer Torque Magnetic Random Access Memory (MRAM) possesses a unique combination of high speed, high endurance, non-volatility, and small cell size. Among the emerging new memory technologies, including phase change memory, resistive random access memory, and conductive bridging random access memory, Spin Transfer Torque MRAM is the only candidate with the potential for unlimited endurance, since no atoms are moved during writing. This makes it the only potential candidate to replace dynamic random access memory (DRAM), when DRAM scaling comes to an end. Write current largely determines the cost of Spin Transfer Torque MRAM, since the transistor and hence cell area must be sized large enough to source the write current. This talk will give a brief overview of Spin Torque MRAM, including potential applications and materials challenges. I will then review the discovery of interface perpendicular anisotropy in the Ta|CoFeB|MgO system at IBM and the subsequent perpendicular magnetic tunnel junctions which were developed using it, including demonstration of reliable, high speed spin torque writing, and results on scaling down to 20 nm. Recent experimental results showing low Ic10ns and high efficiency, and theoretical predictions for lowering the switching current will also be shown.
Time resolved magnetic microscopy to study magnetization dynamics due to spin injection and spin torque transfer.

Hendrik Ohldag, Stefano Bonetti, Roopali Kukreja, Dirk Backes, Ferran Macia, Zhao Chen, Jordan Katine, Sergei Urazdhin, Joseph Frisch, Andrew D. Kent, Hermann Duerr and Joachim Stoehr

1) SLAC National Accelerator Laboratory
2) Stanford University
3) New York University
4) Hitachi Global Storage Technologies
5) Emory University

Understanding magnetic properties at ultrafast timescales is crucial for the development of new magnetic devices. Such devices will employ the spin torque or spin Hall effect, whose manifestation at the nanoscale is not yet sufficiently understood. The samples of interest are often thin film magnetic multilayers with thicknesses in the range of a atomic layers. This fact alone presents a sensitivity challenge in Scanning transmission x-ray microscopy, which is more suited toward studying thicker samples. In addition the relevant time scale is of the order of 10 ps, which is well below the typical x-ray pulse length of 50 – 100 ps. To obtain the necessary time resolution and sensitivity our x-ray microscope is equipped with a single photon counting electronics that effectively allows using a double lock-in detection at 476MHz (the x-ray pulse frequency) and 1.28MHz (the synchrotron revelation frequency). The pulsed or continuous sample excitation source is synchronized with the synchrotron source with a few picosecond drift over 24 hours.

In the first year of operation the setup has enabled us to image localized spin waves, excited via a 150nm spin torque nanoscillator in a perpendicular media and we were able to extract the lateral extent and magnitude of the excitation [1]. We were also able to image the higher order spin wave modes with non-cylindrical symmetry in such nano oscillators, by using samples with in plane anisotropy and taking into account the effects of dipolar fields and oersted field from the current and the nanocontact itself [2]. Finally we have successfully detected the change in magnetization in a non-magnet (Cu) by injection of a spin-polarized current from an adjacent ferromagnet (Co) [3]. The spectroscopic signature of the transient x-ray absorption provides direct insight into the different contribution of interface and the bulk to the spin diffusion length.

Novel Spintronic Devices for Memory, Logic and Sensing and

Overview of C-SPIN

Jian-Ping Wang

Electrical and Computer Engineering Department, University of Minnesota, 200 Union Street
SE, Minneapolis, MN 55455

An energy efficient memory and logic device for the post-CMOS era has been the goal of a variety of research fields. The limits of scaling, which we expect to reach by the year 2025, demand that future advances in computational power will not be realized from ever-shrinking device sizes, but rather by innovative designs and new materials and physics. Magnetoresistive based devices have been a promising candidate for future integrated magnetic computation because of its unique non-volatility and functionalities. The application of perpendicular magnetic anisotropy for potential STT-RAM application was demonstrated and later has been intensively investigated by both academia and industry groups, but there is no clear path way how scaling will work for both memory and logic applications. One of main reasons is that there is no demonstrated material stack candidate that could lead to a scaling scheme down to sub 10 nm. Another challenge for the usage of magnetoresistive based devices for logic application is its available switching speed and writing energy. Although a good progress has been made to demonstrate the fast switching of a thermally stable magnetic tunnel junction (MTJ) down to 165 ps, it is still 8-10 times slower than its CMOS counterpart. In this talk, I will review the challenges and discuss the opportunities and some potential path ways for magnetoresistive based devices for memory, logic and sensing applications and their integrations. By end of my talk, I will brief introduce C-SPIN center and its activities.
Giant Spin-Orbit Torque and its Switching of Reduced Co/Pd Superlattice

Sanghoon Kim¹, Jehyun Kim¹, Soogil Lee¹, Seong-Hun Park³, Hyun Hwi Lee², Jae-Hoon Park³, Han-Koo Lee² and Jongill Hong¹*

¹Department of Materials Science and Engineering, Yonsei University, Seoul 120-749, Korea
²Pohang Accelerator Laboratory, Pohang 790-784, Korea
³Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Korea

Abstract. A technique of low-energy proton irradiation has succeeded in increasing perpendicular magnetic anisotropy (PMA) of phase-transformed Co/Pd superlattice and confirmed to provide a capability of achieving a magnetic recording density over 2.5 Tb/in² [1]. Our x-ray magnetic circular dichroism study confirmed that the strong PMA is originated from an increase in the out-of-plane component of spin-orbit coupling at the interface between the phase-transformed Co and the metallic Pd layers; the orbital to spin moment ratio was increased by ~30% after proton irradiation, meaning that the increase in spin-orbit coupling is responsible for the PMA. We also found by ac measurements that the Co/Pd superlattice phase-transformed by proton irradiation shows a damping-like and a field-like torque an order of magnitude larger than all the metallic superlattice. As a result, such a large spin-orbit torque was finally able to switch this Co/Pd superlattice having an $H_k$ of 3 T without an additional external magnetic field. In this presentation, we report and discuss this giant spin-orbit torque found in our phase-transformed superlattice.

TMR sensors: from industrial to biomedical applications

P.P.Freitas $^{1,2}$, S Cardoso $^{2}$, and R.Ferreira $^{1}$

INL and INESC MN, Portugal

TMR sensors are gradually becoming an alternative to more conventional technologies (Hall effect, AMR, and even GMR), for their higher sensitivity and correspondent larger output, large field span (from 10pT at few Hz to 50 mT), adaptable impedance, low power consumption, large bandwidth response, and offering also the possibility of monolithic integration with CMOS wafers, and with flexible polyimide substrates. GMR sensors can be an option for low frequency operation where TMR sensors show higher 1/f noise. For industrial sensing, application examples will be shown for scanning probes (current, magnetic nanoparticle, magnetic material imaging) and for non-destructive testing of conductive materials where S/N in critical but is often dominated by materials noise. In the biomedical application area, we will discuss new applications of multiplexed magnetoresistive biochip technology to biomarker detection (as a protein chip, biomarker detection for brain ischemia patients), as well as Circulating Tumour Cell detection in blood using our integrated spintronic cytometer. Finally, results will be shown for TMR/GMR sensors integrated in neural probes (SOI and thin Si wafers) and used to record magnetic fields generated in the visual cortex of a cat.
Interlayer Exchange Coupling in Low RA Magnetic Tunnel Junctions

Qunwen Leng

Director of Advanced Sensor R&D

Western Digital Corporation

Magnetic Head Operation, Fremont, CA

QunWen.Leng@WDC.com

Interlayer exchange coupling (IEC) effect is interaction between the two ferromagnetic layers across the nonmagnetic spacer layer. Why the study of IEC phenomenon is very important and interesting? Because the study of this mechanism leded to the first manmade antiferromagnetic interlayer exchange coupling in Fe/Cr/Fe layered structures in 1986, it therefore resulted in discovery of GMR effect in 1988. The GMR based sensor has been the core technology in the high density recording heads since 1995. Professor A. Fert and Professor P. Gruenberg were awarded the 2007 Nobel laureate for their discovery of the GMR effect.

This presentation studies the mechanism of the IEC at sputtered magnetic tunnel junction at RA as low as 0.3 Ωµm², i.e. coupling between two ferromagnetic layers across a MgO insulating spacer, including capping effects and impact on the junction between layers of low resistance of the tunnel, ferromagnetic and antiferromagnetic coupling phenomenon and so on. The IEC field is smaller with Ta capping than that with Ru one. It may be attributed to changes in the band structures and thus influence the IEC across the MgO tunnel barrier due to lattice constant changes in free layer. The layered structures could be engineered by sputtering process to show oscillation of IEC versus the tunneling barrier thickness or RA. Therefore, the IEC strength can be controlled at given RA. Magnetic tunnel junction is key techniques in high-density disk drives, random access memory and a STT-RAM and other spintronic applications. IEC mechanism in the MTJs and IEC in different scales of tunnel junction will also be discussed in this talk.
Transport in magnonic Bose-Einstein condensates
Burkard Hillebrands

Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universität
Kaiserslautern, Germany

The field of magnonics addresses the transfer and processing of information by spin waves and their quanta, magnons. Magnons are bosons and, thus, they can condense into a macroscopic quantum state. Condensates of magnons relate to Bose-Einstein condensates (BEC), and they spontaneously form a spatially extended, coherent ground state, which can be established independently of the magnon excitation mechanism even at room temperature. It is expected that magnon condensates can show transport in a form of a supercurrent, which represents a novel type of macroscopic quantum transport phenomenon analogous to the low-temperature effects of superconductivity and superfluidity.Magnon supercurrents constitute the transport of angular momentum, which is driven by a phase gradient in the magnon-condensate wave function. In this presentation, the concept and first experimental evidence of a magnonic supercurrent will be presented and its further implications will be discussed.
Analysis and Control of Intra Digital Noise Coupling on RF IC

Masahiro Yamaguchi
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6-6-05 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan
yamaguti@ecei.tohoku.ac.jp

Throughput and error rate of a receiver circuit in a cell phone handset is deeply associated with electromagnetic noise, especially the digital noise. The digital noise addresses the harmonics of digital signal mixed into electrical and electronic devices, and cause malfunction of the devices. This paper discusses the on-chip digital noise detection by means of planar shielded-loop magnetic field sensor having RF high-spatial resolution, and its control/countermeasure by means of soft magnetic film. The technology has been applied to LTE-class RF front end receiver circuit chain for cell phone handset, and significantly improved the performance of telecommunication. A key research step was collaboratoin with different technology groups, including international collaborations.

Planar shielded-loop coils were developed for RF magnetic field detection\[1\], whose performance has been studied collaborating with EMC group, magnetic instrumentation group, and then applied for RF soft magnetic thin film evaluation by material scientists\[2\], and radiated emission measurement of ICs for EMC community as an international standard\(IEC 61967-6\).

A 60x60 \~180x180 μm² size miniature shielded-loop coils clarified the major intra-noise coupling path of an RF IC implemented with a fulle LTE compliant RF signal chain of a receiving path (Rx chain) hardware. The conductive noise coupling path was most responsible to the telecommunication performance through power/ground and control signal lines, rather than Si substrate or air coupling paths\[3\].

Crossed anisotropy\[4\] amorphous Co₈₅Zr₃Nb₁₂ thin film with total magnetic thickness of 2.0 μm well suppressed the conductive noise by more than 10 dB, in-band spurious tone by 10 dB, and minimum input power level to meet the 3GPP criteria by 8 dB\[5\] because of ferromagnetic resonance and eddy current losses of magnetic film.

The proposed technology is compatible to countermeasure any digital to analogue/digital noise. A future application target is to improve performance of 5th-generation cell phone system subjected to densely located „mobile“ power inverters (like EVs).

The author is grateful to Satoshi Tanaka, Yasushi Endo, Yutaka Shimada (Tohoku Univ.), Makoto Nagata(Kobe Univ.), Hiroaki Matsui(Renesas Electronics Co., Mizuki Iwanami and Kenta Tsukamoto(NEC Co.) for collaboration. This work was supported by Development of Technical Examination Services Concerning Frequency Crowding from the Ministry of Internal Affairs and Communications of Japan.

References
Semiconductor spintronics has for long concentrated on devices, such as the Datta-Das spin-FET, where the semiconductor plays a passive role. In the compelling quest for multifunctionality and non-volatility, however, a breakthrough would come from turning the semiconductor into an active element. We recently proposed to radically change the perspective of current semiconductor spintronics by bringing in a novel functionality, i.e. the coupling between ferroelectricity and Rashba effects in Ferroelectric Rashba SemiConductors (FERSC).

The test-case material is represented by GeTe, for which theory predicts a giant Rashba spin-splitting to be reversed upon switching ferroelectric polarization.[1] To exploit this peculiar property, different architectures of spin transistors can be proposed. For instance a spin-FET, whose impedance can be electrically controlled thanks to the interplay between Rashba effects, electronic spin precession and ferroelectricity. Noteworthy, non-volatility is ensured by the permanent polarization of the GeTe channel, so that a new generation of spintronics devices integrating memory and computing functions can be envisaged.

In this paper we provide evidence for the FERSC properties of GeTe via piezo force microscopy (PFM) and Angular Resolved PhotoEmission Spectroscopy (ARPES). In GeTe(111) thin films with outwards remanent ferroelectric polarization, a huge Rashba splitting of the valence band has been found. Noteworthy, the sense of circulation of spins is in agreement with DFT calculations for an outwards polarization. This demonstrates the intimate link between ferroelectricity and Rashba, which is the basis for the exploitation of FERSC. Preliminary experiments of spin pumping on Fe/GeTe heterostructures display the existence of an inverse Spin Hall effect, which is consistent with the Rashba bands detected by ARPES.

Heusler compounds for spintronic devices.

Matthew J. Carey
Spin Transfer Technologies

Many Heusler compounds are predicted to be half-metallic. While in practice 100% spin polarization is at best difficult to achieve, these compounds show much higher spin polarization than standard metallic magnetic alloys. This high spin polarization makes Heusler compounds attractive for applications, most notably in current-perpendicular-to-the-plan giant magnetoresistance (CPP-GMR) read heads for magnetic recording and for magnetic tunnel junctions (MTJ’s) for magnetic random access memory (MRAM). A primary reason is that the high spin polarization promises high magnetoresistance (MR). Beyond the high MR, the needs of CPP-GMR and MRAM are very different. For example, the low damping and high susceptibility to spin torque which makes Heuslers attractive for MRAM is a large source or noise in CPP-GMR and limits the sense current that can be used.

Heusler discovered the compounds that share his name in 1903 but it wasn’t until 1983 that band structure calculations predicted that a subset might be half metallic. The two decades that followed showed little progress in producing materials and devices that demonstrated the benefits predicted. Together with the rise of spintronics we have seen a rise in interest and success with Heusler compounds. CPP-GMR devices with Heusler compounds can achieve 10x the MR of their standard metal counterparts. MTJs with Heuslers are comparable in MR to standard metal devices, but with lower magnetic damping. Much of this advance has been made possible by overcoming the practical materials challenges presented in making the various Heusler compounds and the devices that contain them. In this talk I will discuss the challenges of producing thin film Heusler compounds by sputtering. Since these are chemically ordered compounds, thermal treatment and structural characterization are of key importance.

The gains demonstrated by academic groups have been truly impressive. However, more hurdles present themselves in applying Heusler compounds in applications. Much of the academic work has involved epitaxial thin films with thick Heusler and seed layers. Both MRAM and CPP-GMR require very thin films (<3nm) and polycrystalline thin films. Both these factors present challenges in processing and in characterization. For example, even with high intensity X-ray diffraction, 24 hour scans are not uncommon. The thermal parameters involved with CPP-GMR and MRAM are quite distinct from eachother. Back end of the line (BEOL) processing for MRAM can involve 400C anneals while the magnetic shields for heads limit anneals to below 300C. So while some high temperature stable compounds like Co2MnSi or Co2Fe(AlSi) may be promising in MRAM, a lower temperature material such as Co2MnGe may be more optimal in CPP-GMR. The most studied Heusler compounds are cubic and, thus, have in-plane magnetization. While this is beneficial for CPP-GMR, this is a limitation for MRAM. Some techniques have been attempted to increase perpendicular magnetic anisotropy in these cubic Heusler compounds, but it’s unclear that the films are still actual Heusler compounds or retain the low damping that makes them attractive for MRAM.

The past decade has seen an explosion in advances in Heusler compounds. In this talk we will discuss the advantages promised, the advances made and the challenges that remain.
Measuring Spin-Polarized Seebeck Coefficient in Ferromagnetic Conductors

C. H. Wan and X. F. Han*

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Corresponding author: xfhan@iphy.ac.cn

Abstract

Since birth of spintronics, pure spin current has long been aspired for its high efficiency, low energy consumption and versatile functionality to realize magnetization rotation, reversal or domain wall motion of magnetic nanostructures. Hitherto several electrical and optical methods of generating pure spin current such as nonlocal spin injection, spin Hall Effect, spin pumping and circular polarized optical excitation have been well developed and sophisticatedly established. Recently another novel method named as Spin Seebeck Effect (SSE) [1, 2, 3], utilizing waste heat which is produced abundantly in current nanoelectronics to produce spin accumulation and/or spin current, has been proposed and hotly debated. Unambiguous establishment of SSE is mainly hampered by difficulty in accurate controlling of temperature distribution and, more importantly, its entanglement with another mystery phenomenon Anomalous Nernst Effect (ANE) [1] whose physical scenario is still to be clarified though it was discovered very early. Here we found a linear dependence of ANE coefficient on anomalous Hall angle and spin-resolved Seebeck coefficient after taking spin polarization of normal Seebeck coefficient $p_s$, into account. According to the relation, $p_s$ and spin polarization of thermoelectric conductivity $p_T$ could be estimated as -(0.30±0.20) and -(0.62±0.14), respectively, for cobalt from experiments. And NiFe had larger $p_s$ than Fe, Co and CoFeB [4], similar with Ref. 5. Besides, another spin current fountain due to difference in normal Seebeck coefficient in multilayer system has been discovered, according to which, the higher conversion efficiency from thermal gradient to pure spin current could be expected in ferromagnetic/nonmagnetic system with larger variation of Seebeck coefficient.

References: