**Heusler Alloys for Spintronic Devices**

Thank you for attending the “Heusler Alloys for Spintronic Devices” workshop at the University of Minnesota in Minneapolis, Minnesota, July 30 – 31, 2015. The workshop has been organized by The Center for Spintronic Materials, Interfaces, and Novel Architectures (C-SPIN), one of six centers of STARnet, a Semiconductor Research Corporation program, sponsored by MARCO and DARPA.

Materials with 100% spin polarization and high perpendicular magnetocrystalline anisotropy have been the ideal for next generation spintronic memory and logic devices. Heusler alloys are a candidate for such materials and have been extensively studied over the past decade. There have been some promising results, but many roadblocks remain. This workshop candidly discusses these promises and challenges by bringing together leading experts working in this field.

**Workshop Organizers**

William H. Butler, University of Alabama  
Paul Crowell, University of Minnesota and C-SPIN Co-director  
Jian-Ping Wang, University of Minnesota and C-SPIN Director
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<td><strong>William H. Butler</strong>, University of Alabama</td>
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<td>10:45 AM</td>
<td><strong>Claudia Felser</strong>, Max Planck Institute for Chemical Physics of Solids</td>
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<td><strong>Kanta Ono</strong>, High Energy Accelerator Research Organization (KEK)</td>
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<td><strong>Günter Reiss</strong>, Center for Spinelectronic Materials and Devices, Department of Physics, Bielefeld University</td>
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<td><strong>Gautam Shine</strong>, Stanford University</td>
<td><strong>Modeling Transport in Heusler-Based Spin Devices</strong></td>
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<td><strong>CPP-GMR and Related Phenomena in Half-Metallic Heusler Alloy Systems</strong></td>
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<td>Matthew Carey, Spin Transfer Technologies</td>
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<td>Kazuhiro Hono, National Institute for Materials Science and University of Tsukuba</td>
<td>Heusler-Alloy-Based Magnetoresistive Devices with High MR Outputs</td>
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<td>Martin Jourdan, Johannes Gutenberg University, Mainz, Germany</td>
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<td>11:55 PM</td>
<td>Chris Leighton, University of Minnesota</td>
<td>Magnetic Phase Competition in Off-Stoichiometric Heusler Alloys: ( Ni_{50-x}Co_xMn_{25+y}Sn_{25-y} )</td>
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<td>Paul Crowell, University of Minnesota and C-SPIN Codirector</td>
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<td>End of Workshop. Thank you for your participation!</td>
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**Ian Young**, Intel

*Spintronic Logic and Memory Devices: Prospects and Challenges*

**Abstract:** Continued scaling of computational efficiency may be achieved via gradual introduction of new materials and computational state variables. In particular, for spin based computing and memory, novel materials and devices are essential to meet the demands of non-volatile embedded memory as well as logic. However, such devices also need to be scalable and have low error rates. We will look at the material requirements for anisotropy and saturated magnetization. We will also place this in the context of RA product scaling for memory. We will give an example of a spin logic device which benefits from improvements in magnetic material properties. We will also comment on non-volatility and retention errors.

**Speaker Bio:** Ian Young is a Senior Fellow and director of Exploratory Integrated Circuits with the Technology and Manufacturing Group of Intel Corporation, Hillsboro, Oregon. He leads a research group exploring the future options for the integrated circuit in the beyond CMOS era.

He received the B.E.E and the M. Eng. Science, from the University of Melbourne, Australia. He received the PhD in Electrical Engineering from the University of California, Berkeley.

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**William H. Butler**, University of Alabama

*Heusler Alloys*

**Abstract:** In collaboration with colleagues at the University of Virginia, our team at the University of Alabama is completing a survey of approximately 1,000 Heusler alloys using density functional theory (DFT). These materials are intriguing, for many reasons, but from the point of view of spintronics they are of interest because of their tendency to form Slater-Pauling phases. These are solutions to the DFT equations with a gap in the center of the s-d band, i.e. a region of zero density of states that occurs with three electron states per atom below the gap. These Slater-Pauling phases can be found for most of the Heusler alloys in our survey, although they are often not the lowest energy solution. The origin of these gaps can be discussed qualitatively in several ways. One view starts from an observation of Slater and Koster in 1954 that A-B transition metal alloys on a B2 lattice considering d-states and nearest neighbor interactions only will have a gap extending from the d-onsite energy of the A atom to the d-onsite energy of the B atom. A quantitative theory of the occurrence and stability of these phases should also include the magnetic polarizability of the transition metal atoms involved and its dependence on volume. The basic picture that emerges is that nature has an “additional” strategy that it can use to reduce the energy of a system of atoms. This strategy consists of shuffling electrons between majority and minority create and maximize a gap in one of the spin channels and then place the Fermi energy into this gap.

Our survey, which will soon be available at http://heusleralloys.mint.ua.edu, should make it easier to test, extend or modify these or other models for the formation and stability of Slater-Pauling
phases. Experimentalists may be more interested in phases that can be easily fabricated than in phases that can be easily calculated. We have made a start in this direction by calculating formation energies of all of the considered Heusler phases and by testing them for stability against tetragonal distortions. We have also chosen the parameters for our calculations so that they are consistent with the oqmd database of calculated alloy phases, oqmd.org, which currently contains DFT calculations of 285,780 compounds. We include a link that allows one to easily determine whether the Heusler phase is predicted to be stable relative to other binaries and ternaries in the oqmd database. We hope that the database will be useful to the scientific community and solicit its help in finding errors, adding references and making extensions.

**Speaker Bio:** William H. Butler (as of August 1, 2015) is retired from the University of Alabama (UAT). He served as the Director of the Center for Materials for Information Technology at UAT from August 2001 - April 2010. During this period he also served as director of its NSF-sponsored Materials Research Science and Engineering Center. From August 2001 - July 31, 2015 he was Professor of Physics in the Department of Physics and Astronomy. He received a BS degree (with Highest Honor) in Physics from Auburn University in 1960 and a Ph.D. in physics in 1969 from the University of California San Diego where he studied under Nobelist Walter Kohn. From 1969-1972 he was Assistant Professor of Physics at Auburn University. He joined the Metals and Ceramics Division of Oak Ridge National Laboratory in 1972. He was leader of the Theory Group in the Metals and Ceramics Division of ORNL from 1984-2001. He has received DOE Awards for Outstanding Scientific Achievement and for Outstanding Sustained Research. He was the first recipient of the National Institute of Materials Science Award for Breakthroughs in Materials Science. He has authored more than 200 scholarly papers and is co-author of one book. He is member of the American Physical Society, the IEEE, the Materials Research Society, the American Association for the Advancement of Science. He is a fellow of the American Physical Society. He served as Meeting Chair for the Spring 1990 Meeting of the MRS and currently serves as Program Chair for the American Physical Society Topical Group on Magnetism and its Applications.

Dr. Butler’s recent research interests include: physics of magnetic materials, spin-dependent transport in magnetic multilayers and nanostructures, electronic structure of magnetic oxides and chalcogenides, domain wall switched graded media, electronic structure of half-metals, and precessional damping in magnetic materials.

**Claudia Felser,** Max Planck Institute for Chemical Physics of Solids

*Magnetism in Mn2-Heusler Compounds*

**Abstract:** Heusler compounds are a remarkable class of materials with more than 1,000 members and a wide range of extraordinary multifunctionalities including half-metallic high-temperature ferri- and ferromagnets, multiferroic shape memory alloys, and tunable topological insulators with a high potential for spintronics [1], energy technologies and magnetocaloric applications [2]. The tunabilty of this class of materials is exceptional and nearly every functionality can be designed [2]. Recently
a high spinpolarisation for spintronic applications was proven by angle resolved photoemission [3]. The development of efficient spintronic devices is based on the spin transfer torque (STT) phenomenon. In 2007 Mn3-xGa was identified as a potential electrode for STT applications [4,5].

In general Manganese-rich Heusler compounds are attracting much interest in the context of spin transfer torque, spin Hall effect, non collinear magnetism and rare-earth free hard magnets. Here we give a comprehensive overview of the magnetic properties of non centrosymmetric Mn2-based Heusler materials, which are characterized by n antiparallel coupling of magnetic moments on Mn atoms. Such a ferrimagnetic order leads to the emergence of new properties that are absent in ferromagnetic centrosymmetric Heusler structures. Tetragonal Heusler compounds with large magneto crystalline anisotropy can be easily designed by positioning the Fermi energy at the van Hove singularity in one of the spin channels. The Mn3+ ions in Mn2YZ cause a Jahn Teller distortion [6]. New properties can be observed such as, large exchange bias, non-collinear magnetism topological Hall effect, spin gapless semiconductivity and Skyrmions [7-10].


**Speaker Bio:** Claudia Felser studied chemistry and physics at the University of Cologne and completed her doctorate in physical chemistry there in 1994. After postdoctoral fellowships at the MPI in Stuttgart and the CNRS in Nantes (France), she joined the University of Mainz. She was a visiting scientist at Princeton University (USA) in 1999 and at Stanford University in 2009/2010 and a visiting professor at the University of Caen (France). She became a full professor at the University of Mainz in 2003.

In December, 2011 she became director of the Max Planck Institute for Chemical Physics of Solids. She is the chair of the DFG research group “New Materials with High Spin Polarization” and is the director of the Graduate School of Excellence “Materials Science in Mainz” of the German Science Foundation (DFG). She was honored with the order of merit “Landesverdienstorden” of the state Rhineland-Palatinate for the foundation of a lab for school students at the University of Mainz. The materials under investigation are Heusler compounds and compounds with related structure types. In 2010, she was the distinguished lecturer of the IEEE Magnetic Society, she received the Nakamura lecture award of the UC Santa Barbara and the SUR-grant award of IBM. In July 2014, Prof. Felser received the GRC-Alexander-M-Cruickshank-Lecturer Award at the “Gordon Research Conference” in New London, NH, USA. She has written more than 300 articles and been granted several patents. Her recent research focuses on the rational design of new materials.
for spintronics and energy technologies such as solar cells, thermoelectric materials, topological insulators and superconductors.

**Kanta Ono**, High Energy Accelerator Research Organization (KEK)

*X-Ray and Neutron Analysis of Heusler Alloys*

**Abstract:** Structure and magnetic structure analysis of Heusler alloys are very important to develop novel antiferromagnetic Heusler alloys that replace Iridium. We have performed structure and magnetic structure analysis of Heusler alloys using x-rays and neutrons, such as x-ray diffraction (XRD), neutron diffraction, x-ray magnetic circular dichroism (XMCD), and polarized neutron reflectometry (PNR).

At first, we performed a polarized neutron reflectometry (PNR) experiment at BL-17 of MLF, J-PARC, Japan. We have established an analysis method to estimate spin asymmetry and depth profiles from PNR for thin film samples. The structural and magnetic depth profile of the multilayer structure obtained by PNR is important for fabrication process optimization and magnetic structure analysis of Heusler alloys.

Then we characterize Heusler alloy samples using XRD at BL-8 of Photon Factory, KEK for structure analysis and XMCD at BL-16 for magnetic analysis. As we use two-dimensional x-ray detector (imaging plate IP) in our XRD system, we can obtain both in plane and out of plane diffraction patterns in a short time (~5min.). XMCD measurements were also performed for samples.

For the analysis of antiferromagnetic Heusler alloys, we have performed neutron diffraction experiments for Ni$_2$MnAl and Mn2(Co,V)Ga bulk samples.

**Speaker Bio:**

1991 BA University of Tokyo
1993 MS University of Tokyo
1996 Dr.Sc University of Tokyo
1996 ~ 2003 Research Associate, School of Engineering, University of Tokyo
2003 ~ Associate Professor, Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK)
Heusler Compounds in Magnetic Tunnel Junctions

Abstract: Heusler compounds already demonstrated their potential in Magnetic Tunnel Junctions (MTJs). Record values are currently a TMR slightly below 2000% at low temperature (around 350% at room temperature) for $\text{Co}_2\text{Mn}_\alpha\text{Si}/\text{MgO}/\text{Co}_2\text{Mn}_\alpha\text{Si}$ ($\alpha \approx 1.3$) and a GMR larger than 74% for $\text{Co}_2\text{Fe}_{0.4}\text{Mn}_{0.6}\text{Si}$ films sandwiched with Ag. In addition, also inverse Heusler compounds (which lack crystal inversion symmetry) show high TMR ratio. In this contribution, we will address standard CoFeB/MgO tunnel junctions and discuss two aspects of recent developments with Heusler compounds:

i) Systems such as $\text{Mn}_{3-x}\text{Ga}$, $\text{Mn}_x\text{X}_y\text{Ga}$ ($X=\text{Co, Fe}$) or $\text{Mn}_x\text{Ge}$ have a low $M_S$ combined with perpendicular magnetization with a high $K_U\perp$. Thus they can rival the established CoFeB/MgO-system. We discuss tetragonally distorted, highly $L1_0$ textured $\text{Mn}_{3-x}\text{Ga}$ thin films with $0.1 < x < 2$ with a large $K_U\perp$ and low $M_S$. However, a direct capping of these films with MgO is problematic due to oxide formation.

Two alternatives to the MnGa-system are $\text{Mn}_x\text{Ge}$ and Heusler compounds that have a perpendicular anisotropy due to their interface with MgO. We show, that the $\text{Mn}_x\text{Ge}$ system does have very large $K_U\perp$. In addition, $\text{Co}_2\text{FeAl}$ on TiN capped with MgO also shows perpendicular magnetization.

ii) In addition to their TMR, magnetic tunnel junctions also show a spin-dependent Seebeck voltage when the temperatures of the two magnetic electrodes are different. We have shown, that the readout contrast of this spin dependent Seebeck voltage can be drastically increased by adjusting the electronic states on either side of the barrier to obtain a larger DOS-asymmetry at the Fermi level.

Here, we demonstrate that in particular Heusler compounds with half-metallicity could be of strong interest for the Spin-Seebeck-Effect, because their band structure promises both a large Seebeck voltage as well as a strong change of the voltage when the magnetizations change from parallel to antiparallel alignment.

Speaker Bio:

Education

02/1989 PhD in Physics, Regensburg University (with Prof. Horst Hoffmann)
08/1994 Habilitation, Regensburg University

Professional Development

Since 10/1997 Full Professor (C4) of Experimental Physics, Bielefeld University
02/1992 - 10/1992 Post Doc at IBM (T.J. Watson Research Center, Yorktown Heights)
03/1989 – 01/1992 Post Doc (Regensburg University)
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July 30-31, 2015
University of Minnesota, Minneapolis, MN

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**Miscellaneous**

Coordinator of the M-Era.net Project HeuSpin (since 2014)
Senator at Bielefeld University (since 2011)
Dean of the Faculty of Physics (2004-2006)
Coordinator of the EU STREPs Project MagLog
Gaede Award of the German Vacuum Society (1994)

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**Gautam Shine**, Stanford University

*Modeling Transport in Heusler-Based Spin Devices*

**Abstract:** Assessing the technological potential of Heusler alloys requires modeling them under realistic conditions. Here we present a methodology that uses extended Huckel theory to model the electronic structure coupled with non-equilibrium Green’s functions to rigorously calculate transport properties. The combination allows us to study the impact of variation and defects as well as determine how Heusler-based devices perform when subjected to high bias.

**Speaker Bio:** Gautam Shine is a Ph.D. student in electrical engineering at Stanford University. He is advised by Prof. Krishna Saraswat and studies electron and spin transport, with a focus on interfaces and tunneling structures.

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**Koki Takanashi**, Tohoku University

*CPP-GMR and Related Phenomena in Half-Metallic Heusler Alloy Systems*

**Abstract:** We have been working on CPP-GMR (current-perpendicular-to-plane giant magnetoresistance) in pillar-type junctions with half-metallic Heusler-alloy electrodes. They attract much interest as not only GMR devices [1-3] promising for read-head application in hard disc drives, but also nano-scale microwave oscillators [4,5], Peltier cooling devices [6], and so on. In my talk, I will make an overview on our recent work on CPP-GMR and related phenomena in pillar-type junctions with half-metallic Heusler-alloy electrodes.


**Speaker Bio:** Koki Takanashi received his BS, MS, and Ph.D. degrees in Physics from the University of Tokyo. Then he joined the Institute for Materials Research at Tohoku University
Oleg Mryasov, Western Digital

*Electronic Structure, Spin Transport, and Magnetic Anisotropy in Selected Cubic Heusler, Tetragonal, and Hexagonal Heusler-like Alloys*

**Abstract:** In this presentation we focus on the following selected key properties of Heusler and Heusler like heterostructures: (1) spin dependence electronic structure (band gap, band matching); (2) dependence of electronic structure on alloying; (3) conductance spin polarization in bulk; (4) conductance spin polarization for CPP-GMR hetero-structures; (5) Curie temperature, magnetization and magnetic anisotropy. The set of high spin polarization materials selected for this presentation include: (i) Ternary and Quaternary cubic symmetry Heusler alloys; (ii) perpendicular anisotropy materials such as hexagonal Heusler like alloys. Spin polarized transport properties calculated Co$_2$MnGe (CMG)/Ag/Co$_2$MnGe (CMG) and CMG/Cu$_2$TiAl (CTA)/CMG. The case of (001) Ag “band folding” enables good band matching with the CMG majority spin, whereas for more practical (110) textured CMG/CTA/CMG combination higher performance can be achieved due to natural band matching effects. We calculate magnetic anisotropy and its temperature dependence cuss hexagonal alloys based combination of Fe, Co, Ge elements. To summarize to discuss mechanisms of high spin polarization and perpendicular anisotropy contrasting different solutions for different prospective devices utilizing spin degrees of freedom.

**Speaker Bio:** Dr. Mryasov recently has joined Advanced Technology Group at WD as Senior Technologist Systems Architecture. From 2009-2014 he was an Associate Professor of Physics and Graduate Advisor of Materials Science and Engineering Tri-Campus Program at the University of Alabama, Tuscaloosa (UAT). From 2001-2009, he was Principal Research Engineer at Seagate Technology Research Center. From 1999-2001 he held joint appointment of Research Engineer - III Technical Staff at UC Berkeley/Sandia National Laboratories (Livermore). He performed his post-doctoral research at Northwestern University in the group of Professor Arthur Freeman (1994-1999). He received the Ph.D. in Physics and Math from Russian Academy of Sciences in
Matthew Carey, Spin Transfer Technologies

Heusler Compounds for CPP-GMR Heads and MRAM

Abstract: 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-plane 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 (<3nm) polycrystalline 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 to detect Heusler order peaks. The thermal parameters involved with CPP-GMR and MRAM are quite distinct from each other. Back end of the line (BEOL) processing for MRAM can involve 400°C anneals while the magnetic shields for heads limit anneals to below 300°C. So while some high temperature stable compounds like Co$_2$MnSi or Co$_2$Fe(AlSi) may be promising in MRAM, a lower temperature material such as Co$_2$MnGe 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.

**Speaker Bio:** Matt Carey has been working in thin film magnetic materials for nearly 30 years. As a graduate student he studied exchange anisotropy and giant magnetoresistance. As part of that work he developed thin film NiO as an antiferromagnetic layer for exchange bias, and this was used in the first spin valve GMR read head. He worked at IBM Research, and Hitachi Global Storage Technologies Research focusing largely on read head magnetic materials. In that time he worked on the development of the GMR spin valve read head, the TMR read head and most recently on CPP-GMR as a potential follow on for TMR. He also contributed to media efforts, including as an inventor of AFC (anti-ferromagnetically coupled) media, which extended in-plane media until perpendicular recording was rolled out.

For the past few years he has worked on magnetic materials for MRAM and is currently with Spin Transfer Technologies.

**Kazuhiro Hono,** National Institute for Materials Science and University of Tsukuba

**Heusler-Alloy-Based Magnetoresistive Devices with High MR Outputs**

**Abstract:** A current-perpendicular-to-plane (CPP) giant magnetoresistance (GMR) device has been considered to be a potential alternative to the tunneling magnetoresistance (TMR) read sensor for future high density hard disk drives (HDD) beyond 2 Tbit/in$^2$ owing to its intrinsically low device resistance. However, the MR outputs of typical CPP-GMR devices have remained insufficient. An appropriate combination of ferromagnet Heusler alloys and a nonmagnetic spacer with a good band matching is expected to enhance MR substantially. We recently found the usage of CuZn and AgZn spacers in combination with Co$_2$Fe(Ga,Ge) Heusler alloy leads to very large MR outputs. $\Delta R_A$ exceeding 20 m$\Omega$µm$^2$ with MR ratio of 60% was...
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ABSTRACTS

obtained at room temperature. The MR ratio is enhanced to 200% at low temperature, suggesting the improvement of temperature degradation of MR will lead to very high-output MR devices. The underlying physics for the high MR outputs and their temperature degradation will be discussed based on our thorough STEM structural characterization results. We also investigated the effects of the crystal orientation and the development of (100) textured polycrystalline devices, which is of great importance for the development of practical polycrystalline devices.

Speaker Bio: Kazuhiro Hono received his BS (1982) and MS (1984) degrees in Materials Science at Tohoku University and a Ph.D. degree in Metals Science and Engineering at Penn State in 1988. After working as a post doc at Carnegie Mellon for a year, he became a research associate at the Institute for Materials Research, Tohoku University in 1990. He moved to the National Research Institute for Metals (currently National Institute for Materials Science, NIMS) as a senior researcher in 1995, and is now a NIMS Fellow and the Director of the Magnetic Materials Unit. He is also a professor in Materials Science and Engineering at the Graduate School of Pure and Applied Sciences, University of Tsukuba. His major research interest is microstructure-property relationships of metallic materials, in particular magnetic materials.

Chris Palmstrøm, University of California, Santa Barbara

Heusler Compound/III-V Semiconductor Heterostructures

Abstract: Heusler alloys are analogous to the Perovskite complex oxides with over 1,000 possible combinations of elements. Their properties depend on the number of valence electrons per formula unit and have been predicted to be semiconductors, metals, ferromagnets, antiferromagnets, half metals, superconductors and topological insulators. Similar to compound semiconductors, the band structure and lattice parameters of Heusler alloys can also be tuned through alloying but over a much larger range of properties. The half-Heusler compounds can be thought of as a zincblende lattice with additional atoms in the octahedral sites. The lattice parameters and FCC crystal structure make them excellent candidates for integrating with conventional III-V semiconductors. Magnetic tunnel junctions using Heusler alloys that are predicted to be half metals have shown record tunneling magnetoresistance. We have demonstrated record high spin accumulation at Heusler/GaAs interfaces in lateral spin transport device structures and also the growth of semiconducting half-Heusler alloys on III-V semiconductors with comparable electron mobilities to Si. Using a combination of molecular beam epitaxy and in-situ scanning tunneling microscopy and x-ray photoelectron spectroscopy, we have investigated the interface formation and growth mechanisms. Ab-initio theory and ex-situ transmission electron microscopy studies have been used to corroborate the Heusler/semiconductor interfacial atomic structure. In-situ scanning tunneling microscopy and spectroscopy have been used to investigate the electronic structure and compared with angle resolved photoemission spectroscopy studies of the band structure.

Speaker Bio: Professor Chris Palmstrøm, one of the world’s leading researchers of electronic materials, joined the ECE faculty at the University of California, Santa Barbara in the fall of
ABSTRACTS

2007. Born in Norway, Palmstrøm received his Ph.D. in Electrical and Electronic Engineering from the University of Leeds (England) in 1979. After five years of research on semiconductor materials and contact technologies at Cornell, he joined Bellcore in 1985. There, he did groundbreaking research on semiconductor surfaces, semiconductor doping, polymer/polymer diffusion and the molecular beam epitaxial growth of metal/semiconductor heterostructures. In 1994, Dr. Palmstrom went to the University of Minnesota, where he soon became a leading researcher in several fields, including new spintronic materials that combine the functions of electronic and magnetic manipulation and storage on information.

Hiroaki Sukegawa, National Institute for Materials Science

*Interface-Induced Perpendicular Magnetic Anisotropy and Giant Tunnel Magnetoresistance in Co$_2$FeAl Heusler Alloy Based Heterostructures*

**Abstract:** Co-based Heusler alloys Co$_2$YZ with L$_2$$_1$ or B$_2$ structure have attracted great attention due to their excellent magnetic properties such as perfect spin polarization at the Fermi level, high Curie temperatures, and low Gilbert damping. Therefore, a magnetic tunnel junction (MTJ) with Co-based Heusler alloys could be a promising magnetoresistive element for the spin transfer switching - magnetoresistive random access memories (STT-MRAMs).

Among the Co-based Heusler alloys, Co$_2$FeAl (CFA) is known to have one of the smallest damping factors (around 0.001 [1]). In addition, we reported a large tunnel magnetoresistance (TMR) ratio over 300% at room temperature using a CFA/MgO/CoFe(001) epitaxial MTJ [2]. The large TMR ratio is mainly due to high spin polarization of the CFA layer and strong spin-dependent coherent tunneling effect. Their remarkable features of CFA will be favorable for ferromagnetic layers of MTJs.

In this talk, I will show recent works on CFA-based spintronic heterostructures. Firstly, I will introduce a perpendicularly magnetized ultrathin CFA film using an MgO interface [3-5]. We found that the strong perpendicular magnetic anisotropy (PMA) was induced at an ultrathin CFA (~ 1 nm)/MgO interface. Interestingly, large PMA energy is observed when a Ru buffer layer with a (02-23) high-index orientation is used [4]. Secondly, I will talk about CFA-based MTJs in combination with a newly-developed spinel MgAl$_2$O$_4$ epitaxial barrier [6]. MgAl$_2$O$_4$-based MTJs exhibit giant TMR effect due to the coherent tunneling like MgO-based MTJs. Importantly, the lattice spacing of the MgAl$_2$O$_4$ can be easily tuned by Mg-Al composition of the layer, which enables us to achieve a lattice-matched MgAl$_2$O$_4$/bcc-based ferromagnet (or Heusler alloy) interface. In fact, a misfit dislocation-free MTJ with a large TMR ratio over 280% at room temperature was achieved using CFA and MgAl$_2$O$_4$.

This work was partly funded by ImPACT Program of Council for Science, Technology and Innovation, Cabinet Office, Government of Japan.

Heusler Alloys for Spintronic Devices
July 30-31, 2015
University of Minnesota, Minneapolis, MN

ABSTRACTS


Speaker Bio: Hiroaki Sukegawa received his M.S. degree in materials science from Tohoku University, Sendai, Japan in 2004, and his Ph.D. degree in Materials Science from Tohoku University, in 2007. He became a researcher at National Institute for Materials Science in 2007. He is currently a senior researcher of Magnetic Materials Unit, National Institute for Materials Science. His research interests include magnetic thin films and spintronics devices.

Paul Crowell, University of Minnesota
Spin Transport in Epitaxial Heusler Alloy/III-V Semiconductor Heterostructures

Abstract: The prospects for half metallicity as well as favorable conditions for lattice matching to the InGaAs family of semiconductors make a variety of half and full Heusler alloys desirable candidates for spin injection. I will review recent results on spin injection into GaAs from Co2MnFe1-xSi. Non-local spin valves operating at room temperature have been demonstrated. A combination of magneto-transport, spin transport and ferromagnetic resonance data suggest that Co2MnSi is highly polarized, allowing for the highest spin accumulations that we have observed in transition metal ferromagnet/III-V heterostructures. Although Co2FeSi is apparently not half-metallic, the absence of Mn interdiffusion has made it a more reliable material for devices. In particular, the Co2FeSi-based heterostructures have allowed for a systematic study of the spin lifetime and diffusion length in GaAs at high temperatures.

Speaker Bio: Paul Crowell has been on the faculty of the University of Minnesota since 1997 and is currently a Professor of Physics.


Service: General Chair, Joint MMM/Intermag Conference; Chair-Elect of the APS Topical Group on Magnetism and its Applications (2011-2012); Organizer, Focus Session on Spin-Dependent Phenomena in Semiconductors, APS March Meeting, 2010; Program Committee, Conference on Magnetism and Magnetic Materials, 2005-2008, 2010; Program Committee Seventh International School of Spintronics and Quantum Information Technology, Japan (2011); Program Co-Chair, Conference on Magnetism and Magnetic Materials, Austin (2008).

Paul Crowell received his PhD in low-temperature physics from Cornell University in 1994 and was a postdoctoral associate at the CNRS, Grenoble and the University of California at Santa Barbara before joining the faculty of the University of Minnesota in 1997. He is currently a Professor of Physics. Professor Crowell’s research focuses on spin dynamics in ferromagnets on sub-nanosecond
ABSTRACTS

time scales and spin transport in hybrid ferromagnet-semiconductor and ferromagnet/normal metal systems. He is a fellow of the American Physical Society.

**Martin Jourdan**, Johannes Gutenberg University, Mainz, Germany

*100% Spin Polarized Surface Resonance in the Half Metallic Heusler Compound Co₂MnSi*

**Abstract:** The magnitude of the room temperature spin polarization of ferromagnetic materials is a key property for their application in spin transport-based electronics. Thus Heusler compounds, due to their predicted bulk half-metallic properties, i.e. 100% spin polarization at the Fermi energy, are in the focus of interest. However, for most applications it is not the bulk but the surface or interface of the material, which is relevant. Investigating optimized thin films of the compound Co₂MnSi by in situ spin-resolved UPS, we were able to demonstrate for the first time half-metallicity in combination with directly measured (93±7-11) % spin polarization at room temperature in the surface region of a Heusler thin film [Jou14]. Our novel band structure and photoemission calculations including all surface-related effects [Bra14, Bra15] show that the observation of a high spin polarization in a wide energy range below the Fermi energy is related to a stable surface resonance in the majority band of Co₂MnSi extending deep into the bulk of the material. Spin-integrated ex situ HAXPES with a photon energy of 6 keV on Co₂MnSi thin films and spin-integrated in situ UPS was carried out. The UPS and the HAXPES results fundamentally agree although the information depth of both experiments varies from less than 1 nm to 20 nm. Nearly quantitative agreement of the calculations with the experiments for both, UV and hard X-ray photon energies, was obtained. As an outlook, results of HAXPES investigations of epitaxial Co₂MnSi/ (Cr, Ag) interfaces will be shown, which deliver a first insight into the development of the Co₂MnSi surface resonance into interface states.


**Speaker Bio:** Dr. Jourdan is a Senior Scientist at the Institute of Physics, Mainz University.

Studies: Physics, Technical University Darmstadt, Germany 1980 - 1985
Degree: Diploma (“Diplom-Physiker”)
Habilitation: Experimental Physics, Mainz University, Germany 2010 (lecturing qual.)
Ph.D. Thesis: Physik, Mainz University, Germany 1999
Research Associate, Mainz University 1995 - 1999
Senior Research Associate (C1), Mainz University 2001 - 2006
Senior Scientist/ Group Leader, Mainz University 2006 -
Heusler Alloys for Spintronic Devices  
July 30-31, 2015  
University of Minnesota, Minneapolis, MN

ABSTRACTS

Areas of Interest: Unconventional superconductivity, Heavy Fermion compounds, Iron Pnictides, novel materials for spintronics (Heusler compounds, Mn2Au, etc.), epitaxial thin films, photoemission spectroscopy, transport measurements

Richard James, University of Minnesota  
Transformational Multiferroic Heusler Alloys and Energy Conversion

Abstract: We discuss the development of Heusler alloys with strongly first order phase transformations, combined with multiferroism, for use in the direct conversion of heat to electricity or, conversely, the direct conversion of electricity to cold. Fundamentally, the discovery of suitable alloys for this purpose exploits the generic lattice parameter sensitivity of “ferroic” properties. Hence, at a phase transformation with a change of lattice parameters, there is the possibility of an abrupt change of ferroic properties. Heusler alloys readily combine these features. We focus in particular on 1) very recent results on spectacular reversibility achieved by tuning lattice parameters to achieve strong conditions of compatibility between phases, and 2) the thermodynamics of energy conversion in these kinds of materials.

Speaker Bio: Dr. Richard James is a Distinguished McKnight University Professor at the University of Minnesota in the Department of Aerospace Engineering and Mechanics. Professor James currently works in two areas. The first involves phase transformations in materials, especially shape-memory, magnetostrictive and multiferroic materials. A recent discovery is a new understanding of the origins of hysteresis and reversibility in phase transformations. Applications of this research range from the development of highly reversible shape memory alloys for use in medical devices to new multiferroic materials that directly convert heat to electricity. His second area of research revolves around the concept of “Objective Structures”, a way to look at the structure of matter that includes simple and complex crystals, but also non crystalline structures like viral capsids, buckyballs and carbon nanotubes. Members of his group working on objective structures are discovering quantum mechanical methods to analyze noncrystalline materials, new multiscale methods for molecular dynamics, new x-ray methods for the determination of atomic structure, and are designing molecules that spontaneously self-assemble into useful nanostructures.

Chris Leighton, University of Minnesota  
Magnetic Phase Competition in Off-Stoichiometric Heusler Alloys: Ni_{50-x}Co_xMn_{25+y}Sn_{25-y}

Abstract: Recently, motivated both by basic scientific interest and technological applications, and utilizing both experiment and theory, a number of research groups have identified a specific group of off-stoichiometric Heusler alloys as having unusually interesting magnetic properties. These alloys take the form Ni_{50-x}Co_xMn_{25+y}Z_{25-y} (Z = Sn, In, Ga, etc.), being Co-doped off-stoichiometric versions of the better-known
Ni₂MnZ full Heusler compounds. In certain critical composition ranges these alloys are found to display unusually reversible martensitic phase transformations, multiferroicity (coexisting ferroelasticity and magnetic order), heightened sensitivity to compositional changes, and acute magnetic phase competition, leading to phenomena such as spontaneous nanoscale magnetic inhomogeneity, superparamagnetism, and intrinsic exchange bias. In terms of applications they exhibit magnetic-field-induced phase transformations, magnetic shape memory behavior, magnetocaloric effects, and remarkably low thermal hysteresis, making them attractive for sensors and actuators, magnetic refrigeration, and energy conversion devices. In this talk we present our recent work on bulk polycrystalline samples around the critical composition Ni₅₀₋ₓCoₓMn₄₀Sn₁₀ (0 ≤ x ≤ 14), using magnetometry [1,2], exchange bias [1,2], neutron diffraction [2], small-angle neutron scattering [1], and Mn NMR [3]. In addition to providing detailed phase diagrams, application of these techniques has provided a number of new insights, including the first direct proof of the suspected nanoscale magnetic inhomogeneity, the first measurements of ferromagnetic cluster sizes and densities, and a detailed understanding of the antiferromagnetic interactions in the martensite matrix. The results are interpreted in terms of a chemical disorder picture.


Speaker Bio: Dr. Chris Leighton is a Distinguished McKnight University Professor in the Department of Chemical Engineering and Materials Science at the University of Minnesota. Electronic and magnetic materials are the central focus of our group's research. We study a wide variety of types of materials such as nanostructures, thin films, multilayered heterostructures, and bulk polycrystals and single crystals. We have interests in several areas including the interplay between electronic transport and magnetism in novel materials, and the study of interfaces between dissimilar materials, particularly metals, oxides, and sulfides. The intention is to focus on topics that are attractive from the viewpoint of fundamental science but lie in close proximity to important technological applications such as information storage and microelectronics. Each of the projects requires fabrication of magnetic/electronic materials and/or structures, detailed atomic level characterization, and in-depth measurement by numerous techniques, particularly electronic transport, magnetometry, and neutron scattering. The work often requires that collaborations be forged, both within the University of Minnesota and with external investigators.

The bulk of our current research can be divided into eight primary categories: magnetism in the perovskite cobalites, perovskite oxide heterostructures, spin transport in metals, highly spin polarized ferromagnets, sulfide-based heterostructures and photovoltaics, novel magnetic alloys, magnetic nanostructure arrays by block copolymer patterning, and transport in conductive polymers and small molecule systems.
Atsufumi Hirohata, University of York  
*Heusler Alloy Films for Spintronic Devices*

**Abstract:** As is commonly understood, epitaxial films have great advantages over polycrystalline films for achieving $L_2^1$ ordering with abrupt and smooth interfaces. However, due to the lattice mismatch, epitaxial films always suffer from small activation volumes induced by misfit dislocations at the Heusler-alloy/(buffer)/substrate interface. Polycrystalline films, on the other hand, reveal their activation diameter, which defines the average diameter of a cylindrical volume with domain-wall-free magnetisation switching, to be much larger, on the order of 40 nm. By controlling the sputtering conditions, the grain size of polycrystalline films can be tuned to be of the same size as the activation diameter, thus allowing for extremely fast switching. This is ideal if Heusler alloys are to be utilised in magnetoresistive nano-pillars in the next-generation read heads for hard disk drives and the cells for spin-transfer-torque magnetic random access memories.

**Speaker Bio:** Dr. Atsufumi Hirohata is a Professor at the Department of Electronics in the University of York. He has over 10 years of experience in spintronics, ranging from magnetic-domain imaging to spin-current interference. Before coming to York in 2007, he was a researcher at RIKEN, a Japanese governmental research institute, where he designed a spin-current interference device. He was before working at Tohoku University and Massachusetts Institute of Technology. He received his Ph.D. in Physics at the University of Cambridge in 2001. He was originally graduated from Keio University for his BSc and MSc studies in Physics.
Heusler Alloys for Spintronic Devices  
July 30-31, 2015  
University of Minnesota, Minneapolis, MN

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How to Connect to the UMN Wireless Network

When using your own computer for a UMN wireless connection, you will be required to use a UMN Internet ID and Password to connect to the wireless network. Your wireless username and password can be found on the back of your nametag. Connect to the network named UMN, not UMN Guest.

Follow these steps to configure your computer to use its wireless card.

<table>
<thead>
<tr>
<th>Windows Vista</th>
<th>Windows XP**</th>
<th>Macintosh OS 10.5</th>
<th>Macintosh OS 10.4 and older</th>
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<tbody>
<tr>
<td>1. From the Start menu, click on the Connect To option</td>
<td>1. From the Start menu, select System Preferences.</td>
<td>1. From the Apple menu, select System Preferences.</td>
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<td>2. Select UofM Wireless from the list of connections.</td>
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<td>3. Click Connect</td>
<td>3. Select AirPort on the left.</td>
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<td>3. Select AirPort from Show dropdown.</td>
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<td>4. If prompted about connecting to an insecure network, click Connect Anyway</td>
<td>4. If “Status: Off” then click Turn AirPort On</td>
<td>4. Click Advanced. . .</td>
<td>4. Click TCP/IP</td>
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<td>5. You will be asked if you want to Save this network. You can avoid this steps in the future if you choose this option.</td>
<td>5. Click Connect</td>
<td>5. Click Advanced. . .</td>
<td>5. Click TCP/IP</td>
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<td>6. If asked to set the network location, choose Public Location.</td>
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<td>7. Choose the option to Close.</td>
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<td>8. Open a Web browser (Firefox, I.E.)</td>
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<td>9. The Wireless Network Login page appears. Login with the above Internet ID and password.</td>
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<td>10. The Wireless Network Login page appears. Login with the above Internet ID and password.</td>
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<td>10. The Wireless Network Login page appears. Login with the above Internet ID and password.</td>
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For more detailed instructions and other operating systems see: www.umn.edu/adcs/network

Don’t lose your wireless connection. Practice safe computing. If your computer is determined by Network Security to have an infection or to not be following the UM Acceptable Use Policies, your computer may be prevented from connecting to the UMN Network.

At http://safecomputing.umn.edu learn how to keep your computer, Internet account, and Wireless connection secure. Where to go for help: (612)301-4357 or http://1help.umn.edu
WORKSHOP LOCATIONS

A. Commons Hotel: Lodging.

B. Kenneth Keller Hall: All talks and coffee breaks. Rooms 3-176 and 3-180.

 skyrocket McNamara Alumni Center: Heritage Gallery Room. Social hour and dinner on Thursday, July 30th at 6:30 PM.
DINING OPTIONS

1. **Surdyk's Northrop Cafe**: Speciality deli sandwiches and salads. Outdoor seating on Northrup Mall.
2. **D'Amico & Sons Cafe in McNamara**: Salads, sandwiches, and hot options.
3. **The Beacon Public House at The Commons Hotel**: Dine-in, upscale option.
4. **Espresso Expose**: Across from the Commons Hotel. Worth crossing the street.
5. **My Burger**: Minneapolis-based. Burgers and fries. To-go or dine-in.
6. **Bona Vietnamese Restaurant**: UMN staple. Dine-in, but very quick.
7. **Punch Pizza**: Wood-fired pizzas or salads.
We would like to thank our sponsors for their generous support.

Seagate is the global leader in data storage solutions, developing amazing products that enable people and businesses around the world to create, share and preserve their most critical memories and business data.

Over the years the amount of information stored has grown from megabytes all the way to geopbytes, confirming the need to successfully store and access huge amounts of data. As demand for storage technology grows the need for greater efficiency and more advanced capabilities continues to evolve.

Today data storage is more than just archiving; it’s about providing ways to analyze information, understand patterns and behavior, to re-live experiences and memories. It’s about harnessing stored information for growth and innovation. Seagate is building on its heritage of storage leadership to solve the challenge of getting more out of the living information that’s produced everyday. What began with one storage innovation has morphed into many systems and solutions becoming faster, more reliable and expansive. No longer is it just about storing information; it is about accessing and interpreting information quickly, accurately and securely. To learn more about Seagate, please visit: http://www.seagate.com.

Semiconductor Research Corporation (SRC) is the world’s leading technology research consortium. With member companies and university research programs spanning the globe, SRC plays an indispensable part in the R&D strategies of the industry’s most influential entities. SRC-sponsored university research is of the highest caliber and creates knowledge breakthroughs that will invent the industries of tomorrow.

For more than thirty years, members of SRC research programs have invested millions in cutting-edge semiconductor research while supporting thousands of elite students and hundreds of faculty members at scores of universities worldwide. The diverse programs engage and challenge the most talented students in science, engineering and technology. While SRC graduates accrue a definitive advantage over their peers, SRC member companies and funding organizations secure access to the industry’s next big thing - and to big and small innovations still waiting to be discovered.

STARnet is a U.S. based university research program that is guided strategically by industry and the U.S. government, but managed by the U.S. university community. It provides a multi-university, multi-disciplinary, collaborative research environment that is highly leveraged by both industry and U.S. Department of Defense funding. STARnet focuses on beyond CMOS technology options and systems integration and discovery to enable both CMOS and beyond CMOS components. The program also provides access to highly trained university graduate students.

We would also like to thank the UMN's School of Physics and Astronomy (www.physics.umn.edu) and Center for Micromagnetics and Information Technologies (MINT) (www.ee.umn.edu/groups/mint/) for their additional support of the workshop.
NOTES
C-SPIN is a world-leading center that brings together top researchers from across the nation to develop technologies for spin-based computing and memory systems.

The center goal is to investigate ground-breaking technologies that will enable computer systems that operate using the spin of an electron, as opposed to its charge, the basis of today’s computers.

Spin-based logic and memory systems have the potential to overcome many of the limitations of conventional charge-based computer systems, which are reaching their fundamental limits. Therefore, spin-based computers have the potential to be faster, smaller and more energy-efficient.

The center is divided into 5 themes that address the numerous technological challenges involved in realizing such a revolutionary technology, and which range from basic materials, devices to systems and architectures.

C-SPIN is led by Prof. Jian-Ping Wang and is headquartered in the Electrical and Computer Engineering Department at the University of Minnesota, Twin Cities. The center brings together 32 leading experts from 18 different universities working in a wide range of scientific disciplines. Further information about C-SPIN sponsors can be found at www.cspin.umn.edu.