

## Magnetic Interfaces and Nanostructures Division Room 203A - Session MI+EM-FrM

### Magnetism and Spin-Orbit Coupling at Surfaces, Interfaces and Thin Films

**Moderator:** Valeria Lauter, Oak Ridge National Laboratory

8:20am **MI+EM-FrM1 Interfacial Spin-orbitronics: Spin-charge Current Conversion in Topological Insulators and Rashba Interfaces, Juan Carlos Rojas Sánchez**, Institut Jean Lamour, Université de Lorraine, France **INVITED**  
Materials with large efficiency of spin-charge current interconversion are highly desirable to study new physical phenomena as well as for spintronics applications. Heavy metals or alloys exhibiting large spin-orbit coupling scatter the electrons in opposite directions when they have opposite spin. Thus an injection of charge current yields a transversal spin current in such materials. The charge-spin current conversion phenomenon in those 3D materials is so-called Spin Hall Effect (SHE). We can exploit this effect to manipulate a magnetization in a heavy metal/ferromagnetic structure [1-3]. We have shown such a manipulation in Si-SiO<sub>2</sub>/W(3 nm)/Co<sub>x</sub>Tb<sub>1-x</sub>(3.5 nm)/Al(3 nm) structures. Interestingly, we have found out that the temperature of the devices reach a novel characteristic temperature just before the magnetization switching takes place [3].

On the other hand, new classes of materials such as 3D topological insulator which are trivial insulator in their bulk but hold metallic states in their surfaces are also highly interesting for spintronics. The spin-orbit coupling (SOC) in the 2DEG states at Topological Insulator (TI) or Rashba Interfaces is predicted to be more efficiency than their 3D counterparts for spin-charge current conversion. Indeed, we have found the highest efficiency at room temperature using the topological insulator  $\alpha$ -Sn [4]. The underlying physics of charge-spin current interconversion in such 2D systems is different of the SHE and is called Edelstein Effect (EE) [5-7], also known as inverse spin galvanic effect [8]. I will show results of spin-to-charge conversion by spin pumping experiments and their analysis in term of inverse Edelstein Length [4-7]. Experimental results based on ARPES and spin pumping indicate that direct contact of metallic ferromagnetic layer is detrimental for the surface states of topological insulators but we can keep the surface states of  $\alpha$ -Sn using Ag spacer. I will use the conversion parameters obtained at room temperature with  $\alpha$ -Sn to demonstrate the very large advantage of the SOC effects in 2D interface states with respect to the Spin Hall Effect (SHE) of 3D metals and the resulting perspective for low power spintronic devices.

[1] M. Miron, P. Gambardella et al. *Nat.* **476**, 189 (2011)

[2] J.-C. Rojas-Sánchez et al. *APL* **108**, 082406 (2016)

[3] T. H. Pham et al. *arXiv* 1711.10790

[4] J.-C. Rojas-Sánchez et al. *PRL* **116**, 096602 (2016). *ArXiv* 1509.02973 (2015)

[5] J.-C. Rojas-Sánchez et al. *Nat. Comm* **4**, 2943 (2013)

[6] E. Lesne, J.-C. Rojas-Sánchez et al. *Nat. Mat.* **15**, 1261 (2016)

[7] S. Oyarzun, J.-C. Rojas-Sánchez et al. *Nat. Comm.* **7**, 13857 (2016)

[8] S. D. Ganichev et al. *Nature* **417**, 153 (2002)

9:00am **MI+EM-FrM3 Spin-orbit Coupling in Ion-surface Collisions Observed by a Polarized <sup>4</sup>He<sup>+</sup> Ion Beam, Taku Suzuki, O. Sakai**, National Institute for Materials Science, Japan

Recently, we found spin-orbit coupling (SOC) act as a mechanism of spin dependent low-energy He<sup>+</sup> ion scattering on solid surfaces. It is intuitively interpreted as the effect on the projectile electron spin of the magnetic field induced by the projectile angular motion around the target nucleus during the projectile-target binary collision (Biot-Savart law). Because a polarized He<sup>+</sup> ion beam is useful for studying surface magnetism, it is important to understand the mechanism of the spin dependent He<sup>+</sup> ion scattering. In the present study, we further investigated SOC from both the experimental and theoretical approaches. In the experiment, electron-spin-polarized <sup>4</sup>He<sup>+</sup> ion beam was projected onto the target surface, and the intensity of scattered He<sup>+</sup> ions was measured as a function of their kinetic energy (spin-polarized ion scattering spectroscopy). We found that the scattering angle  $\theta$  dependence of the spin dependent scattering is remarkably different between the targets of the transition metal and the non-transition metal. This is explained from SOC in the collisional intermediate state, in which an electron of the target is virtually transferred to the He<sup>+</sup> ion.

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9:20am **MI+EM-FrM4 Transport and Magnetic Properties of LaAlO<sub>3</sub>/SrTiO<sub>3</sub> Heterostructure during Cooling and Warming, Zengming Zhang, X.Q. Wang, M. Zhang, A. Rahman, R.C. Dai, Z.P. Wang, Z.J. Ding, L. Cheng**, University of Science and Technology of China

The LaAlO<sub>3</sub> thin films were grown on TiO<sub>2</sub> terminated (001) SrTiO<sub>3</sub> substrate using pulsed laser deposition technique. The transport and magnetic properties of LaAlO<sub>3</sub>/SrTiO<sub>3</sub> (LAO/STO) heterostructure were studied during cooling and warming. The conductivity accelerated recoveries are found at around 70K and 160K for larger electrode interval of several mm, and more obvious for thicker LAO films. This indicated that the domain wall scale increases with the interface variation from fully strain state to partial strain state as the layers of LAO increase. During thermal cycling, both magnetoresistance( $\rho_{xx}$ ) and magnetization separate around the conductivity accelerated recovery temperature as seen in Fig. (c). The phenomenon is attributed to the mobile and trapping of defects such as single vacancy and divacancy by polarized domain walls due to the measuring current at the critical temperature [1-2].

#### References:

1. S. Seri *et al*, Interplay between sheet resistance increase and magnetotransport properties in LaAlO<sub>3</sub>/SrTiO<sub>3</sub>, *Phys. Rev. B* **86**, 085118 (2012).

2. S. Seri *et al*, Thermally activated recovery of electrical conductivity in LaAlO<sub>3</sub>/SrTiO<sub>3</sub>, *Phys. Rev. B* **87**, 125110 (2013).

9:40am **MI+EM-FrM5 Engineering the Magnetic Properties of Complex Oxide Heterostructures, Yuyoi Takamura**, University of California at Davis **INVITED**

Complex oxides possess a wide range of intriguing and technologically relevant functional properties including ferromagnetism, ferroelectricity, and superconductivity. Furthermore, the interfaces of complex oxides have been shown to exhibit unexpected functional properties not found in the constituent materials. These functional properties arise due to various structural and chemical changes as well as electronic and/or magnetic interactions occurring over nanometer length scales at interfaces, and they have the potential to be harnessed to enable new, more versatile, and energy efficient devices. In this talk, I will present some of our recent work investigating the interfacial interactions which occur at ferromagnetic/antiferromagnetic (FM/AF) and FM/FM interfaces. While these interfacial interactions have been widely studied in metallic systems, fundamental differences are observed in complex oxides systems. Specifically, I will discuss FM/FM heterostructures consisting of the soft-FM La<sub>0.7</sub>Sr<sub>0.3</sub>MnO<sub>3</sub> (LSMO) and hard-FM La<sub>0.7</sub>Sr<sub>0.3</sub>CoO<sub>3</sub> (LSCO) layers which display a unique exchange spring behavior where the chemical and magnetic interfaces no longer coexist. This phenomena is explained due to the formation of an interfacial layer characterized by magnetically active Co<sup>2+</sup> ions which forms due to a robust charge transfer interaction at the LSCO/LSMO interface. In the second half of the talk, I will discuss the development of measurement protocols for angle-dependent soft x-ray absorption spectroscopy measurements which can be used to unambiguously determine the orientation of the AF spin axis in (111)-oriented heterostructures and to probe how it responds to an applied magnetic field due to exchange interactions with the adjacent FM layer. For the LSMO/La<sub>0.7</sub>Sr<sub>0.3</sub>FeO<sub>3</sub> (LSFO) system, the LSFO layers possess two populations of AF order: the majority of AF moments cant out-of-the-plane of the film along low-index crystallographic directions, while a minority of AF moments lie within the (111)-plane. The relative orientation of the AF and FM spins differs for each type of AF domain. These results demonstrate how the many competing interactions in complex oxide heterostructures open up new opportunities to tailor their functional properties for future spintronic devices.

10:20am **MI+EM-FrM7 Location of the Valence Band Maximum in the Band Structure of Anisotropic 1T'-ReSe<sub>2</sub>, Markus Donath, P. Eickholt, J. Noky, Westfälische Wilhelms-Universität Münster, Germany; E. Schwier, K. Shimada, K. Miyamoto, T. Okuda, Hiroshima University, Japan; C. Datzler, M. Drüppel, P. Krüger, M. Rohlfing, Westfälische Wilhelms-Universität Münster, Germany**

Transition-metal dichalcogenides (TMDCs) are a focus of current research due to their fascinating optical and electronic properties with possible technical applications. ReSe<sub>2</sub> is an interesting material of the TMDC family, with unique anisotropic properties originating from its distorted 1T' structure (1T'). To develop a fundamental understanding of the optical and electric properties, we studied the underlying electronic structure with angle-resolved photoemission (ARPES) as well as band-structure

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calculations within the density functional theory (DFT)–local density approximation (LDA) and *GdW* approximations [1]. We observe anisotropic valence-band dispersions parallel to the surface. We find that along  $\Gamma M_1$ , which is the direction perpendicular to the "diamond" chains, the bandwidth of the highest valence band is significantly smaller than in any other direction. Photon-energy-dependent measurements reveal a  $k_z$ -dependent band dispersion, reflecting the interlayer coupling. Two valence band maxima are identified within experimental limits of about 50 meV: one at the high-symmetry point Z, and a second one at a non-high-symmetry point in the Brillouin zone. Thus, the position in  $k$  space of the global valence band maximum is undecided experimentally. Theoretically, an indirect band gap is predicted on a DFT-LDA level, while quasiparticle corrections lead to a direct band gap at the Z point.

[1] P. Eickholt *et al.*, Phys. Rev. B **97**, 165130 (2018).

10:40am **MI+EM-FrM8 Controlling Antiferromagnetic Order at the Surface of La doped BiFeO<sub>3</sub>**, **Hendrik Ohldag**, SLAC National Accelerator Laboratory; *B.-K. Jang*, Korea Advanced Institute of Science and Technology; *J.H. Lee*, *K-E. Kim*, Korea Advanced Institute of Science and Technology, Republic of Korea; *H. Jang*, SLAC National Accelerator Laboratory; *K.-T. Ko*, Max Planck Institute for Chemical Physics of Solids; *M.H. Jung*, Pohang University of Science and Technology, Republic of Korea; *T.Y. Koo*, Pohang Light Source; *Y.H. Jeong*, Pohang University of Science and Technology, Republic of Korea; *J.-S. Lee*, SLAC National Accelerator Laboratory; *C-H. Yang*, Korea Advanced Institute of Science and Technology, Republic of Korea

Emergence of a triple phase point in two dimensional (*e.g.* pressure and temperature) space can offer useful opportunities for the inter-coupling of two seemingly independent order parameters because of phase proximity. To illustrate the significance of this potential capability we employ a generic concept regarding electric control of magnetic order by manipulating chemical pressure: *i.e.* lanthanum substitution into the model antiferromagnetic ferroelectric BiFeO<sub>3</sub>. Our results are made possible by the remarkable finding that a multiferroic triple phase point of a single spin disordered phase and two spin ordered phases emerges near room temperature in Bi<sub>0.9</sub>La<sub>0.1</sub>FeO<sub>3</sub> ferroelectric thin films. By using spatially resolved x-ray absorption spectroscopy, we provide direct evidence that electric poling of a particular region of the compound near the triple phase point results in an antiferromagnetic phase while adjacent un-poled regions remain magnetically disordered, opening a promising avenue for magnetoelectric applications at room temperature.

11:00am **MI+EM-FrM9 Control of Magnetism at the Antiperovskite/Perovskite Interface**, *D.-F. Shao*, *T.R. Paudel*, **Evgeny Tsymbal**, University of Nebraska-Lincoln **INVITED**

Complex oxide materials with the perovskite crystal structure (ABO<sub>3</sub>) are known for their interesting macroscopic physical properties involving the interplay between magnetism, ferroelectricity, and conductivity. Much less explored are the *antiperovskite* compounds (AXM<sub>3</sub>) where the atomic positions of cations and anions are inverted creating unique, wide-ranging properties different from perovskites. Due to the structural similarity, interfaces combining perovskite and antiperovskite compounds can be fabricated, forming a new playground for materials design, where the coupling across the interface may lead to new fundamental properties and functional behavior. Here, based on density-functional calculations, we explore the magnetoelectric effect at the (001) interface between antiperovskite GaNMn<sub>3</sub> and perovskite ATiO<sub>3</sub> (A = Sr and Ba). Bulk GaNMn<sub>3</sub> is an antiferromagnet with the magnetic moments of the Mn ions lying in the (111) planes, forming non-collinear  $\Gamma^{5g}$  spin configurations with a zero net magnetization ground state. We predict that different from the  $\Gamma^{5g}$  non-collinear magnetism of the bulk GaNMn<sub>3</sub>, strong magnetic moment enhancement and reorientation emerge at the GaNMn<sub>3</sub>/ATiO<sub>3</sub> (001) interface, resulting in a sizable net magnetization pointing along the [110] direction. Moreover, switching the ferroelectric polarization of BaTiO<sub>3</sub> leads to reversal of the net magnetization of GaNMn<sub>3</sub>. This phenomenon occurs due to the effect of ferroelectric polarization on the magnitude of the antiferromagnetic exchange coupling between the nearest Mn atoms at the interface. Reversal of magnetization by electric means is the holy grail of voltage-controlled spintronics, and thus our results pave a new route to achieve this functionality by exploiting antiperovskite/perovskite interfaces.

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