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Exchange anisotropy, engineered coercivity and spintronics in atomically engineered $L1_0$ heterostructures.

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- Mr. Wei Zhang, Ph. D. Student from Beijing Univ. working on this project since June 23, 2008, passed qualifying exam (expected graduation, June 2012)
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Collaborators:

- Dr. Hendrik Ohldag, Stanford Synchrotron Radiation Laboratory (PEEM measurements at the ALS)
- Mr. K. J. Kennewell and Prof. R. L. Stamps, Department of Physics, University of Western Australia (Ferromagnetic resonance)
- Dr. W. Xia , Dr. Z. Akase and Prof. D. Shindo, IMRAM, Tohoku University (Electron Holography of cross-section TEM samples)
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- Dr. A. Schmidt, National Center for Electron Microscopy, Berkeley (Spin polarized low-energy electron microscopy)
- Dr. M. E. Bowden, EMSL/PNNL (X-ray structural analysis)

I. Research Summary:

We identified and investigated some of the scientific and technically most challenging issues in thin film magnetism focusing on epitaxially grown layers of specific $L1_0$ ordered, intermetallic, heterostructures with well-controlled crystallography and interface structures [1-4]. Specifically, we addressed antiferromagnetic/ferromagnetic heterostructures, exhibiting exchange bias (EB) in both in-plane (MnPd/Fe) and perpendicular (IrMn/$(Co/Pt)_n$) geometries [5-7], and ferromagnetic/ferrimagnetic ($Co/Y_3Fe_5O_{12}$) bilayers [8] with strong interlayer exchange coupling and exhibiting spin reorientation transitions [9]. In the former case, the work included experimental and theoretical studies to gain more fundamental insight into the origin and magnitude of EB, as well as to address important aspects of EB such as the asymmetry in the magnetic reversal mechanism [10-12], the role of interfacial structure [13], including compensated or uncompensated spins [14] , AF domains, competing anisotropies [15] and the angular dependence [16-18] of the magnetization reversal process.

Exchange bias is central to many magnetic technologies and driven by the fast development of nanotechnology, there is much interest in understanding the phenomenon of exchange bias on the nanoscale. By patterning, as the FM domain size reaches a lateral scale comparable to the AF domain size (~100nm), each nano-element can be treated as a separate and isolated exchange bias system that behaves independently. Therefore, the non-averaged, intrinsic, exchange bias, in all its complexity, can be studied. Such size and dimensionality effects, particularly in structures with lateral dimension of the order of their domain sizes, were studied by developing and implementing a novel Nano-imprint [19-21] as well as convention optical [22-24] lithography/patterning. However, one limitation of the NIL method is that after imprinting the material-deposition or -evaporation has to be done at around room temperature in order to keep the resists structure undisturbed. As a result, the method is unsuitable for epitaxial growth, since the latter often involves growth at elevated temperatures higher than the glass transition temperature of the resist. Therefore, a mask transfer NIL process was developed to grow *epitaxial* nanostructure arrays at elevated temperatures where organic resists are rendered unstable. In the case of the metal/oxide heterostructures, the domain structure of the metal is carefully modulated by that of the underlying oxide, opening the possibility of carrying out novel experiments to study spin-dependent domain-wall scattering and quantify domain wall resistance in mesoscopic geometries. Utilizing state-of-the-art characterization methods, using synchrotron radiation [25] and electron holography [26, 27], we addressed the critical role of all aspects of the microstructure, at relevant length scales, in determining these specific magnetic properties. Two significant highlights of this project were the use of photoemission electron microscopy (PEEM) work to elucidate their asymmetric magnetization reversal mechanism [10] and the use of element-specific X-ray magnetic reflectivity and x-ray resonant scattering to probe buried interfaces [13], both of importance in understanding the fundamental physics of exchange bias. In the latter case, a complex magnetic interfacial configuration in Fe/MnPd, consisting of a 2-monolayer-thick induced ferromagnetic region, and pinned uncompensated Mn moments that reach far deeper (~13 Å), both in the antiferromagnet, were found. Such epitaxial EB samples also show in-plane reorientation transitions, determined by the competition between the interface exchange coupling and the intrinsic uniaxial energies, and is driven by the temperature, as well as the thickness of MnPd and Fe layers. Complementing these results, work on multilayers show that perpendicular EB arise from a complex interplay between unidirectional anisotropy at the terminating FM/AFM interface, the perpendicular anisotropy of the FM/nonmagnet(NM) multilayer stack and the overall magnetostatic energy of the structure. Collaborative work with Prof. R. Stamps (UWA) in modeling and analysis of slow-dynamics, using an inductive ferromagnetic resonance technique, were also carried out [28]. Further details of our research is presented below broadly in five thematic areas. Overall, this research allowed us to obtain a deeper understanding of the range of related magnetic phenomena and establish pathways for potential technological applications of these thin film and patterned heterostructures.

II. Major results:

II.1 Phenomenon of exchange Bias

(a) **Direct imaging of asymmetric magnetization reversal in exchange-biased Fe/MnPd bilayers by x-ray photoemission electron microscopy [10]:** X-ray photoemission electron microscopy was used to probe the remnant magnetic domain structure in high quality, single-crystalline, exchange-biased Fe/MnPd bilayers. The induced unidirectional anisotropy was found to strongly affect the overall magnetic domain structure. Element specific, real space images of the ferromagnetic domains , using XMCD for magnetic contrast, provided direct evidence for an asymmetric magnetization reversal process after saturation along the ferromagnetic hard direction. The magnetization reversal occurs by moment rotation for decreasing fields while it proceeds by domain nucleation and growth for increasing fields. The observed domains are consistent with the crystallography of the bilayers and favor a configuration that minimizes the overall magnetostatic energy of the ferromagnetic layer.

(b) Magnetization reversal of epitaxial Fe/IrMn exchange biased bilayers under a domain-wall nucleation model [30]: We fabricated and characterized epitaxial Fe/IrMn exchange biased bilayers on MgO(001) substrates [15]. The magnetic switching showed a multi-step behavior indicating that the magnetization reversals are achieved via domain wall (DW) nucleation and propagation along the different Fe easy axes. Temperature effect of the exchange bias as well as the angular dependence was studied by anisotropic magnetoresistance, which showed the competing effect of anisotropies on the magnetization reversal. A DW nucleation model correctly predicts the occurrence of different magnetic switching processes over a broad temperature range. These results highlight the importance of the competing anisotropies in epitaxial exchange bias systems with incoherent rotation reversal mechanism, opening a new pathway for tailoring the magnetic properties of such systems

(c) Angular dependence of magnetization reversal process in exchange biased epitaxial MnPd/Fe bilayers [16]: The angular dependence of magnetization reversal in epitaxial MnPd/Fe bilayers grown on MgO(001) was studied using combined longitudinal and transverse magneto-optical Kerr effect. Square loops, asymmetrically shaped loops, and double-shifted loops were observed as the field orientation was varied from parallel to perpendicular to the bias direction. Additionally, including the effect of an induced uniaxial anisotropy in the ferromagnetic layers, an improved effective field model was used to interpret the complex angular dependence of the magnetic switching fields. The fitting shows good agreement with the experimental results for the samples with different thicknesses.

(d) Competing effects of magnetocrystalline anisotropy and exchange bias in epitaxial Fe/IrMn bilayers [15]: We systematically investigated the possible magnetization reversal behavior in well-characterized, epitaxial, Fe/IrMn exchange-biased bilayers as a function of the antiferromagnetic (AF) layer thickness. Several kinds of multistep loops were observed for the samples measured at various field orientations. The angular dependence of the switching fields, observed using longitudinal and **t**ransverse magneto-optic Kerr effect, were shown to depend on the competition between the magnetocrystalline anisotropy and the exchange bias (EB). A modified “effective field” model was applied to quantitatively describe the evolution of the magnetic behavior and correctly predict the occurrence of different magnetic switching processes. The dependence of the effective anisotropy fields on the AF layer thickness directly reflects the competing effects of the pinned and rotatable AF spins at the EB interface. See [13,14].

(e) **Antiferromagnetic layer thickness dependence of the magnetization reversal in the epitaxial MnPd/Fe exchange bias system** [18]**:** We investigated the antiferromagnetic layer thickness dependence of magnetization reversal in *c*-axis oriented MnPd/Fe epitaxial exchange biased bilayers. Several kinds of multistep loops were observed for different samples measured at various field orientations. The evolution of the angular dependent magnetic behavior evolving from a representative Fe film to the exchange biased bilayers was revealed. With increase of the thickness of the antiferromagnetic layers, asymmetrically shaped loops and biased two-step loops are induced by exchange bias. Including the unidirectional anisotropy, a model based on the domain nucleation and propagation was developed, which can nicely describe the evolution of the magnetic behaviors for MnPd/Fe bilayers and correctly predicts the critical angles separating the occurrence of different magnetic switching processes. For fields applied along the bias direction, the 180° magnetic reversal changes from two successive 90° domain wall nucleations to a single 180° domain wall nucleation at the critical thickness of the MnPd layer.

(f) **In-plane reorientation of magnetization in epitaxial exchange biased Fe/MnPd bilayers [17] :** The in-plane reorientation of magnetization in epitaxial Fe/MnPd bilayers was studied as a function of the thicknesses of MnPd and Fe layers. Both conventional square and an unusual two-step exchange biased hysteresis loops were observed at different temperature. The shape of the loops is reproduced using the coherent rotation model and including the relative orientation of the uniaxial anisotropy with respect to the exchange bias. The parallel and perpendicular uniaxial anisotropies in the ferromagnetic layer are linked to the aligned and the reoriented states, respectively. The magnetic reorientation between the aligned and the reoriented states, which is determined by the competition between the interface exchange coupling and the intrinsic uniaxial energies, is shown to be driven by the temperature, as well as the thickness of MnPd and Fe layers..

(g) **Competing magnetic interactions in perpendicular exchange-biased $[Co/Pt]_y$ /FeMn multilayers** [6]: Perpendicular exchange bias in multilayers arise from a complex interplay between unidirectional anisotropy at the terminating ferromagnet(FM)/ antiferromagnet(AFM) interface, the perpendicular anisotropy of the FM/ nonmagnet(NM) multilayer stack and the overall magnetostatic energy of the structure. Exchange bias field (H_{eb}) and coercivity (H_c) of $[Co/Pt]_y$ /FeMn with perpendicular anisotropy have been investigated by varying the thickness of top Co layer in direct contact with the FeMn or number of Co/Pt bilayers. An unusual dependence of H_{eb} and H_c on these parameters has been observed. As the top Co layer thickness of $[Co/Pt]_y$ /FeMn multilayer varies, both H_{eb} and coercivity H_c show a peak in values and decrease when the top Co is too thin or too thick. H_{eb} of $[Co/Pt]_y$/FeMn is inversely proportional to the number of Co/Pt bilayer, y for $2 \leq y \leq 5$, while H_c increases. For $y > 5$, H_{eb} increases and H_c decreases with y until both of them reach constant values. These observations have been attributed to the role of the effective perpendicular anisotropy of the FM multilayer, especially the FM layer adjacent to AFM layer, in maintaining the perpendicular exchange bias.

(h) Asymmetric magnetic reversal of perpendicular exchange-biased $(Co/Pt)_5$/IrMn probed by magnetoresistance and magnetic force microscopy [12] : Magnetic reversal of $(Co/Pt)_5$/IrMn multilayers with perpendicular exchange bias (EB) has been studied by magnetoresistance (MR) and magnetic force microscopy (MFM). It has been found that as a function of perpendicular external field the resistance decreases with field above saturation and has sharp maxima at the reversal fields due to the domain wall resistance effect. The latter contribution has been found to be asymmetric, suggesting a corresponding asymmetry in the domain state in the two branches of the hysteresis loop. This asymmetry correlates with the fractal dimension of the domain wall projection deduced from MFM images, which is larger on the descending branch of the hysteresis loop than along the ascending branch. This in turn can be explained as due to the different intensity of domain wall nucleation in the two branches.

(i) Measuring exchange anisotropy in Fe/MnPd using inductive magnetometry [28]: Local effective fields created in Fe by MnPd through exchange anisotropy are studied using an inductive ferromagnetic resonance technique. The bilayers were prepared on single crystal MgO_001_ using ion beam sputtering in high vacuum and have a highly orientated crystalline structure with a _001_ orientation as determined by x-ray diffraction. Unidirectional and fourfold anisotropies are measured using a stripline resonance geometry. Experiments with the field applied along different crystalline directions indicate that the fourfold axes are well defined with magnitudes consistent with values expected for bulk Fe. Anomalies in the frequency studied as a function of applied field are interpreted as evidence for a distribution of unidirectional anisotropy field orientations and strengths.

II.2 Competing anisotropies and magnetic reversal in confined geometries

(a) Competing anisotropies and temperature dependence of exchange bias in Co|IrMn metallic wire arrays fabricated by nanoimprint lithography [20]: The magnetic behavior of exchange biased Co|IrMn bilayer metallic wire arrays, fabricated by nanoimprint lithography, was studied and compared with identical thin film heterostructures. A significant uniaxial shape anisotropy, *KU*-shape, in addition to the unidirectional exchange anisotropy, *KE*, and the intrinsic uniaxial anisotropy, *KU*-intrinsic observed in the unpatterned film, was introduced in the wire arrays through wire patterning. The competing anisotropies were shown to modify the angular dependence of exchange bias, H_{EB}, and coercivity, *HC*, for wire arrays. In addition, an asymmetric behavior is observed for both wire arrays and unpatterned film and is attributed to the noncollinear alignment of uniaxial and unidirectional anisotropies. Temperature dependence of H_{EB} is different for the wire arrays from the unpatterned thin film. This and the large deviation from ideal cubic anisotropy in the antiferromagnet for the wire arrays are both in agreement with Malozemoff's model of exchange bias.

(b) **Thickness-dependent evolution of magnetization reversal in micron-scale polycrystalline Fe rings [24]:** The evolution of magnetic switching mechanism is investigated for micron-scale polycrystalline Fe ring arrays, fabricated by photolithography, with Fe layer thickness, t_{Fe}, varying between 10 nm and 50 nm. Single-step and double-step switching are observed for the 10 nm and 50 nm rings, with 30 nm sample showing a transient behavior. As thickness increases, the first-step switching field, H_{c1}, increases, while the second-step switching field, H_{c2} and remanence magnetization, M_r decreases. Magnetic force microscopy imaging and micromagnetic simulations reveal that in the reversal process, H_{c1} and H_{c2} respectively corresponds to the switching fields of two distinct halves of the ring. The relative separation between these two fields decides the switching behavior of the ring.

(c) **Magnetization reversal in exchange biased IrMn/Fe ring arrays [22]:** We investigated the effect of exchange bias on the magnetization reversal behavior in ring-shaped IrMn/Fe lithographic structures. The magnetic anisotropy geometry of the exchange biased ring is revealed by fitting for the angular dependence of the exchange bias, H_{EB}, and coercivity, H_c. Magnetic force microscopy images obtained at different field values along the hysteresis loop show that along the bias direction, the ring exhibits a magnetic reversal via nonuniform domain nucleation while perpendicular to the bias direction, the magnetic reversal occurs via coherent rotation. The difference in magnetic switching modes for these two field orientations is confirmed by micromagnetic simulations and interpreted by the effective field model.

II.3 Interface Effects

(a) **Coupling of Fe and uncompensated Mn moments in exchange-biased Fe/MnPd [14]** : A bilayer exchange-bias system composed of Fe/MnPd is investigated using x-ray magnetic circular dichroism (XMCD) and soft x-ray resonant magnetic reflectometry (XRMR). The absorption and XMCD data at the Fe *L* and Mn *L* edges are used to derive the optical and magneto-optical properties of the individual layers. Then the structural and magnetic depth profiles of the sample are obtained from XRMR. From reflectivity measurements at the Fe *L* and Mn *L* edges, a precise magnetic depth profiling of the interface region between the ferromagnet (F) and antiferromagnet (AF) was carried out. It reveals rotatable and pinned uncompensated Mn moments in the AF. By comparing the signs and magnitudes of the absorption, the relative coupling directions in the system are determined. It is found that rotatable Mn and the ferromagnetic Fe couple antiparallel. The pinned

Mn moments are oriented antiferromagnetic to the neighboring rotatable Mn and ferromagnetic with respect to the Fe during the field cooling process.

(b) Uncompensated Moments in the MnPd/Fe Exchange Bias System [13] : The element-specific magnetic structure of an epitaxially grown $Mn_{52}Pd_{48}$/Fe bilayer showing exchange bias was investigated with atomic-layer depth sensitivity at the antiferromagnet/ferromagnet interface by soft-x-ray magnetic circular dichroism and magnetic reflectivity. A complex magnetic interfacial configuration, consisting of a 2-monolayer-thick induced ferromagnetic region, and pinned uncompensated Mn moments that reach far deeper (13 Å), both in the antiferromagnet, were found. For the latter, a direct relationship with the magnitude of the exchange bias is verified by similar measurements perpendicular to the field cooling direction.

II.4 Advances in nanoscale fabrication

(a) Thermal nanoimprint process for high-temperature fabrication of mesoscale epitaxial exchange-biased metallic wire arrays [19]: A thermal nanoimprint process for the high-temperature (400 °C) fabrication of submicron, epitaxial, metallic wire arrays over areas > 1x1 cm^2 was developed. Based on a method using antimprinted polymeric bilayer resist template that is transferred to a metallic (molybdenum)mask, this process is enabled by an appropriate undercut profile of the Mo mask. The undercut profile is obtained from a distinctive wedge-shaped profile of the polymeric resist layers by carefully controlling the etch parameters. Using flexible ethylene tetrafluoroethylene imprint molds, we demonstrated defect-free imprinting on MgO substrates. Epitaxial patterning is demonstrated with Fe/MnPd bilayer wire arrays subsequently grown along well-defined crystallographic orientations. X-ray diffraction of the patterned arrays reveals that the MnPd can be grown in two different crystallographic orientations (*c*-axis and *a*-axis normals). The epitaxial nature of the patterned arrays is further confirmed by magnetic measurements that demonstrate the competing effects of intrinsic (magnetocrystalline and exchange) and lithography-induced shape anisotropies on the magnetization reversal characteristics along different directions with respect to the axis of the wire arrays.

II.5 Advanced Characterization & Structure-Property Correlations

(a) Investigation of magnetic structure and magnetization process of yttrium iron garnet film by Lorentz microscopy and electron holography [26]: The micromagnetic structure and magnetization process of perpendicular $Y_3Fe_5O_{12}$ (YIG) films were studied by Lorentz microscopy and electron holography. The closure domain structure inside the thin transmission electron microscopy specimen exhibits the same period as the magnetization pattern observed by magnetic force microscopy indicating the perpendicular anisotropy of the YIG film. Through observation of stray fields, it is concluded that the shapes of domain and domain walls are sensitive to the specimen thickness; moreover, a closure domain configuration observed in thin specimen is the stable energy state as determined by the balance between the crystalline anisotropy and shape anisotropy. Domain wall movement is observed by applying a magnetic field, *in situ*, inside the microscope in both horizontal and perpendicular directions; the saturation fields observed are qualitatively in agreement with the results of the hysteresis loop.

(b) **Electron holography study of remanence states in exchange-biased MnPd/Fe bilayers grown epitaxially on MgO(001) [27]:** We investigated magnetic remanence states of epitaxially grown, exchange-biased MnPd/Fe bilayers by electron holography emphasizing the crystallographic orientations of the layers. Thin-foil transmission electron microscopy (TEM) specimens were carefully prepared along both hard and easy axes of the Fe layer. The *ex situ* magnetization-reversal process was carried out using the TEM specimens, and magnetic flux densities of the ultra-thin Fe layers were evaluated at different remanence states. The spin configuration in the TEM specimens is determined by the competition between an exchange coupling at the MnPd/Fe bilayer interface, shape anisotropy of TEM specimens and intrinsic magnetocrystalline anisotropy of Fe.

(c) **Spin Reorientation Transitions in Perpendicularly Exchange-Coupled Thin Films Studied Using Element Specific Imaging** [9]**:** Spatial variations in the spin-reorientation transition of an exchange-coupled Co-wedge/YIG ($Y_3Fe_5O_{12}$) bilayer, from perpendicular to in-plane domain structure, was studied using magnetic force microscopy (MFM) and photo-emission electron microscopy (PEEM). Even though MFM measurements of the YIG film showed perpendicular stripe domains, it was not possible to unambiguously resolve the domain structure of only the top ferromagnetic metal layer because of complications arising from the stray fields of the much thicker YIG underlayer. Hence, using element-specific, X-ray magnetic circular dichroism (XMCD) of the transition metal $L_{3\,2}$ edges (Co and Fe, respectively) for magnetic contrast, PEEM measurements were carried out to resolve the domain structure of the individual Co and YIG layers. The two were identical up to a Co thickness of 4.5 nm, confirming that the Co layer was exchange coupled with the YIG underlayer; however, a transition of the Co domains, from perpendicular to in-plane, was observed at thickness of 4.5–6 nm. For thicker regions of the Co film (~6 nm), a sizeable portion of the Co layer showed in-plane domains; their spins were perpendicular to the domain walls of the stripe domains with Co XMCD values in the range of 5% to +5%—a value much smaller than that of the perpendicular domains.

III. Publications funded by this grant

[1] P. Blomqvist Kannan M. Krishnan and D.E. McCready, "Growth of exchange-biased MnPd/Fe bilayers", *Jour. Appl. Phys* **95** (12): 8019-8022 (2004).

[2] P. Blomqvist and Kannan M. Krishnan, "Magnetization process in exchange-biased MnPd/Fe bilayers", *Jour. Appl. Phys* **95** (12): 8487-8489 (2004)

[3] P. Blomqvist and Kannan M. Krishnan, "Exchange coupling in nanoscale MnPd/Fe heterostructures", *Journal of Magnetism and Magnetic Materials* **272-76**: 1237-1239 (2004)

[4] P. Blomqvist, Kannan. M. Krishnan, S. Srinath and S.G.E. te Velthuis, "Magnetization processes in exchange-biased MnPd/Fe bilayers studied by polarized neutron reflectivity", *Jour. Appl. Phys*. **96**, 6523-6526 (2004)

[5] Xiaosong Ji, Honglyoul Ju, David E. McCready and Kannan M. Krishnan, "Perpendicular exchange bias in ion-beam sputtered $(Co/Pt)_n$/FeMn multilayers" , *Jour. Appl. Phys.* **98**, 116101 (2005)

[6] Xiaosong Ji and Kannan M. Krishnan "Competing magnetic interactions in perpendicular exchange-biased $(Co/Pt)_x$/FeMn multilayers", *Jour. Appl. Phys.* **99,** 08C105 (2006)

[7] Xiaosong Ji (Dual Ph.D. in Materials Science and Engineering and Nanotechnology, UW) "Perpendicular anisotropy and exchange bias in magnetic thin film heterostructures", 2007.

[8] Y.S. Chun (Ph.D. in Materials Science and Engineering, UW) "Domain wall stability and resistance in perpendicularly-coupled metal/oxide bilayers", 2007

[9] Y.S. Chun, H. Ohldag and Kannan M. Krishnan "Spin reorientation transitions in perpendicularly exchange-coupled, ferromagnetic, ultra-thin films studied using element specific imaging", *IEEE Trans. Mag*., **43,** 3004 (2007).

[10] P. Blomqvist, Kannan. M. Krishnan and H. Ohldag, "Direct imaging of asymmetric magnetization reversal in exchange-biased Fe/MnPd bilayers by x-ray photoemission electron microscopy", *Phys. Rev. Lett*., **94**, 107203 (2005)

[11] http://www.als.lbl.gov/als/science/sci_archive/107exchange_bias.html

[12] X. Ji, A. B. Pakhomov and Kannan M. Krishnan, "Asymmetry magnetic reversal of perpendicular exchange-biased $(Co/Pt)_5$/IrMn probed by magnetoresistance and magnetic force microscopy", *Jour. Appl. Phys*., **101**, 09E507 (2007)

[13] S. Bruck, G. Schutz, E. Goering, X. Ji, and Kannan M. Krishnan, Uncompensated magnetic moments in the MnPd/Fe exchange bias system, Phys. *Rev. Lett.* **101**, 126402 (2008)

[14] Sebastian Brück, Xiaosong Ji, Sebastian Macke, Q. Zhan, Kannan M. Krishnan, and Eberhard Goering,"Coupling of Fe and uncompensated Mn moments in exchange biased Fe/MnPd", *Phys. Rev. B* **81** 134414 (2010)

[15] W. Zhang, Mark E. Bowden and Kannan M. Krishnan, "Competing effects of magnetocrystalline anisotropy and exchange bias in epitaxial Fe/IrMn bilayer, *Appl. Phys. Lett.* **98**, 092503 (2011)

[16] Q. Zhan and Kannan M. Krishnan, "Angular dependence of magnetization reversal process in exchange biased epitaxial MnPd/Fe bilayers", *Jour Appl. Phys.* **107,** 09D703 (2010)

[17] Q. Zhan and Kannan M. Krishnan, In-plane reorientation of magnetization in epitaxial exchange biased Fe/MnPd bilayers, *Appl. Phys. Lett.* **96,** 112506 (2010)

[18] Qing-feng Zhan, Wei Zhang, and Kannan M. Krishnan, "Antiferromagnetic layer thickness dependence of magnetization reversal in epitaxial MnPd/Fe exchange bias system", Phys. Rev. B **83**, 094404 (2011)

[19] W. Zhang, D. N Weiss and Kannan M Krishnan, " Thermal nanoimprint process for high-temperature fabrication of epitaxial exchange-biased metallic nanostructures", *Jour. Micrmech. Microeng.* **21**, 045204 (2011)

[20] Wei Zhang, D. N. Weiss and Kannan M. Krishnan. "Competing anisotropies and temperature dependence of exchange bias in Co/IrMn metallic wires fabricated by nanoimprint lithography, *Jour. Appl. Phys*. 107, 09D724 (2010)

[21] Wei Zhang and Kannan M. Krishnan, Direct release of synthetic antiferromagnetic nanoparticles fabricated by defect-free thermal imprinting", *Jour. Appl. Phys*., (in prep)

[22] Yu-feng Hou, Qing-feng Zhan, and Kannan M. Krishnan, "Magnetization reversal in exchange biased IrMn/Fe ring arrays", *Appl. Phys. Lett.* **98,** 042510 (2011)

[23] Yu-feng Hou and Kannan M. Krishnan, "Thickness-dependent evolution of magnetization reversal in micron-scale polychrystalline rings", *Appl. Phys. Lett. (submitted)*

[24] Yu-feng Hou and Kannan M. Krishnan, "Thickness-dependent magnetization reversal behavior of lithographic IrMn/Fe ring structures", *Jour. Appl. Phys*., (in prep)

[25] G. Srajer, L. H. Lewis, S.D. Bader, … Kannan M. Krishnan ….J.Z. Sun, "Advances in nanomagnetism via x-ray techniques", *Jour. Mag. Mag. Mat.*, **307**, 1-31 (2006)

[26] W.X. Xia , Y.S. Chun, S. Aizawa, K. Yanagisawa, Kannan M. Krishnan, D. Shindo and A. Tonomura , "Investigation of magnetic structure and magnetization process of yttrium iron garnet film by Lorentz microscopy and electron holography", *Jour. Appl. Phys.* **108,** 123919 (2010)

[27] J. S. Jeong, Zentaro Akase, Daisuke Shindo, Qing-feng Zhan and Kannan M. Krishnan, "Electron holography study of remanence states in exchange-biased MnPd/Fe bilayers grown epitaxially on MgO(001) " , *Jour. Elect. Mic.*, doi: 10.1093/jmicro/dfr015

[28] K. J. Kennewell, Xiaosong Ji, J-G Hu, R. C. Woodward, K. M. Krishnan, R. L. Stamps, "Measuring exchange anisotropy in Fe/MnPd using inductive magnetometry", *Jour. Appl. Phys*., **101,** 09E518 (2007)

[29] Kannan M. Krishnan, Alexandre B. Pakhomov, Yuping Bao, Peter Blomqvist, Yoonsoo Chun, Marcela Gonzales, Kelli Griffin, Xiaosong Ji and Bradley K. Roberts, "Nanomagnetism and spin electronics: materials, microstructure and novel properties", *Jour. Mat. Sci.* **41**, 793–815 (2006)

[30] Wei Zhang and Kannan M. Krishnan, "Magnetization reversal of epitaxial Fe/IrMn exchange biased bilayers under a domain-wall nucleation model", *Jour. Appl. Phys.*, (in prep)

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1. At professional societies

a. X. Ji and Kannan Krishnan, "Growth and structure-property correlations in perpendicular exchange biased magnetic multilayers", *2005 APS March Meeting,* March 21–25, 2005; Los Angeles, CA

b. X. Ji and Kannan Krishnan, "Competing magnetic interactions in perpendicular exchange-biased [Co/Pt]/FeMn multilayers*" 50th Conference on Magnetism and Magnetic Materials,* Oct. 30th to Nov 3rd, 2005 San Jose, CA

c. Kannan Krishnan, Invited Plenary Speaker, Tohoku University 21st Century COE program, "Spins, bytes and cures: science and technology of magnetic nanoparticles", Sendai, Japan , January 23-25, 2007.

d. K. J. Kennewell, Xiaosong Ji, J-G Hu, R. C. Woodward, Kannan M. Krishnan, R. L. Stamps, "Measuring exchange anisotropy in Fe/MnPd using inductive magnetometry", 10th Joint MMM/Intermag meeting, January, 2007, Baltimore, Md.

e. X. Ji, A. B. Pakhomov and Kannan M. Krishnan, "Asymmetry magnetic reversal of perpendicular exchange-biased $(Co/Pt)_5$/IrMn probed by magnetoresistance and magnetic force microscopy", 10th Joint MMM/Intermag Conference, January, 7-11, 2007, Baltimore, Md.

f. Y.S. Chun, H. Ohldag and Kannan M. Krishnan "Spin reorientation transitions in perpendicularly exchange-coupled, ferromagnetic, ultra-thin films studied using element specific imaging", 10th Joint MMM/Intermag meeting, January, 2007, Baltimore, Md.

g. Y.S. Chun, Hendrik Ohldag, Kannan M. Krishnan, "Stabilization and confirmation of a perpendicular stripe domain structure in thin ferromagnetic metal films", 19th International Colloquium on Magnetic Films and Surfaces (ICMFS 2006), Sendai, Japan, August 14-18, 2006.

h. Kannan M. Krishnan, "Directions and opportunities in nanomagnetism", Keynote Talk, International Conference on Nanoscience and Nanotechnology, Mumbai, India, 2/19/10

i. Wei Zhang and Kannan Krishnan, "Competing anisotropies and temperature dependence of exchange bias in Co/IrMn metallic wires fabricated by NIL", Joint MMM and Intermag Meeting, Washington, DC, 2/19/10

j. Q. Zhan and Kannan Krishnan, "Angular dependence of magnetization reversal process in exchange biased epitaxial MnPd/Fe bilayers", Joint MMM and Intermag Meeting, Washington, DC, 2/19/10

k. Kannan M. Krishnan, "Nanostructured magnetic thin film heterostructures: Fabrication, exchange interactions and tailored anisotropies", invited Keynote Talk, American Vacuum Society Annual Meeting, Albuquerque, NM, 04/12/10

2. At other universities

a. Kannan Krishnan, Nanomagnetism and spin-electronics: the current status", Indian Institute of Science, Bangalore/India, September 8, 2005.

b. Kannan Krishnan, "Nanomagnetism and spin-electronics: physics, materials and applications", University of California, Davis, Physics Department Colloquium, November 7. 2005

c. Kannan Krishnan, " Spins, bytes and cures", Royal Technical University, Stockholm, Dept. of Materials Science, June 10, 2005

d. Kannan Krishnan, " Spins, bytes and cures", Danish Technical University, Copenhagen, Microelectronic Center, May 20, 2005

e. Kannan Krishnan, "Exchange, proximity and interface effects in magnetic thin film heterostructures", University of Copenhagen, Nanoscience Center, May 19, 2005

f. Kannan Krishnan, "Magnetic nanoparticles and thin film heterostructures", Korea Institute of Science and Technology ,August 10, 2006

g. Kannan Krishnan, "Nanoamgnetism and Spintronics: Physics, materials and novel applications" , University of Barcelona, Department of Physics, July, 2006

h. Kannan Krishnan, , "Spins, Bytes and Cures: The Magnetic Menagerie", University of Western Australia, Institute of Advanced Studies Public Lecture, March, 2006

i. Kannan Krishnan, "Nanomagnetism and Spin-electronics: Physics, Materials and Biomedical Applications", Curtin University, Interdepartmental Colloquium, March 2006

j. Kannan M. Krishnan, , "Spins, Bytes and Cures: Materials, Devices and Biomedical Nanomagnetics", University of California, San Diego. Center for Magnetic Recording Research and Department of Nanoengineering February 19,2008.

k. Kannan M. Krishnan, "Spins, Bytes and Cures: Materials, Devices and Biomedical Nanomagnetics", Nov 16, 2007. Arizona State University, School of Materials Colloquium .

l. Kannan M. Krishnan, "Spins, Bytes & Cures: Materials, Devices and Biomedical Nanomagnetics", September 17, 2007. Institute of Physics, Chinese Academy of Sciences, Beijing.

m. Kannan M. Krishnan, , "Spins, Bytes & Cures: Materials, Devices and Biomedical Nanomagnetics", August 27, 2007. Department of Materials Science, National University of Singapore .

n. Kannan M. Krishnan, "Nanomagnetic structures: fabrication, magnetic correlations and biomedical applications", Simon Fraser University, Canada, 4/16/10

3. At government labs, industry, etc

a. Kannan Krishnan, "Nanoamgnetism and Spintronics: Physics, materials and novel applications", Institute of Physical High Technology, Jena, Germany, June , 2006