Thin Film
Room 104E - Session TF+MI-WeA
Thin Films for Magnetic and Optical Applications

Moderator: Subhadra Gupta, University of Alabama

2:20pm **TF+MI-WeA1 Tuning Static and Dynamic Magnetic Properties of FeGa/NiFe Multilayer Heterostructures via Magnetic anisotropy Dispersion***, **Colin Rementer**, Q. Xu, P. Nordeen, G.P. Carman, Y. Wang, J.P. Chang,* University of California Los Angeles

Iron-gallium (FeGa) is one of the most promising magnetic materials for use in composite multiferroics due to its high piezomagnetic coefficient (3 ppm/Oe) and high stiffness (70 GPa). It has been integrated into several multiferroic systems, but generally in MHz range or below.[1] In order to make it suitable for high frequency (GHz) applications, metalloid dopants have been used to soften magnetic materials and enhance their frequency dependent properties, but at the cost of the saturation magnetization as well as magnetoelastic properties.[2] A viable approach to circumvent this trade-off problem is to integrate a magnetic material with complementary properties into magnetic heterostructures. In this work, multilayer laminates were fabricated with FeGa and NiFe, a material with excellent properties in high frequency regimes.

FeGa (hard) and NiFe (soft) were sputtered via alloy targets with compositions $Fe_{85}Ga_{15}$ and $Ni_{81}Fe_{19}$ (at%) into multilayers with layer thicknesses ranging from 3-50 nm, with FeGa being used as the first and last layer in the stack. XPS confirmed the composition and showed there was no intermixing of the layers. Static magnetic properties were evaluated via SQUID magnetometry, and it was found that the incorporation of NiFe layers reduced the coercivity by up to 85%, from 30 Oe to 4 Oe. FMR studies showed a reduction of the linewidth of up to 50%, from 70 Oe to 38 Oe. It is believed that this effect is largely due to the decrease of magnetic anisotropy dispersion in the multilayers.[3] The multilayer films maintained a high magnetostriction of up to 190 ppm, on the same order of magnitude as giant magnetostrictive materials such as thin film Terfenol-D.[4] FeGa/NiFe heterostructures have been shown to be an excellent candidate for strain-coupled microwave multiferroics.

References:

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2.J Lou, RE Insignares, Z Cai, KS Ziemer, M Liu and NX Sun, APL (18) (2007).

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4. KP Mohanchandra, SV Prikhodko, KP Wetzlar, WY Sun, P Nordeen and G. P. Carman. AIP Advances **5** 097119 (2015).

2:40pm **TF+MI-WeA2 Magnetic Anisotropy of $CoFe_2O_4$ Nanotubes Synthesized by Radical-Enhanced ALD***, **Puilam(Cyrus) Cheung**, J. Chang,* University of California Los Angeles

Multiferroic materials, exhibiting ferroelectricity and ferromagnetism simultaneously, have attracted interests for energy efficient multifunctional applications at nanoscale such as memories, antennas and actuators. While room temperature single-phase multiferroic materials such as bismuth ferrite provide insufficient magnetoelectric effect, composite systems have enhanced magnetoelectric properties by combining piezoelectric materials and magnetostrictive materials through strain. However, such strain-mediated approach in thin film composites is limited by interfacial area and substrate clamping. Ferromagnetic nanowires, on the other hand, provides a new degree of freedom in manipulating magnetic properties through shape anisotropy.

In this work, cobalt ferrite ($CoFe\text{-}_2O_4$) nanotubes were grown on anodic aluminum oxide membranes using radical enhanced atomic layer deposition (RE-ALD) to study magnetic shape anisotropy. The deposition was achieved using metal tmhd precursors (tmhd = 2,2,6,6,tetramethyl-3,5-heptanedionato) and oxygen radicals at 200˚C. The ALD growth rate of cobalt ferrite was 0.18nm/cycle. Nanotubes array were formed inside the cylindrical pores of the membrane with diameter of 18nm, 35nm and 80nm. The morphology and magnetic properties of the nanotubes were studied using scanning electron microscopy, SQUID and energy dispersive X-ray spectroscopy. It was observed that as the wall thickness of the nanotube increases from 16nm to 32nm, the magnetic easy axis was switched from perpendicular to parallel to the nanowires axis, with a doubled saturation magnetization of $5.12x10^5$ emu. The out-of-plane anisotropy field was observed to be 18.7% higher than that from in-plane axis, indicating the out-of-plane axis was magnetically more favorable. As cobalt ferrite nanowires were formed, the preferential easy axis was reversed, which could potentially be implemented in manipulating of magnetization orientation if coupled to a piezoelectric material for device applications.

3:00pm **TF+MI-WeA3 Magnetic Anisotropy and Relaxation in Spintronic Materials***, **Claudia Mewes**, T. Mewes, J. Beik Mohammadi, A. Farrar, K. Cole,* The University of Alabama **INVITED**

Functional materials with optimized properties, such as the magnetic anisotropy and magnetic relaxation rate, are crucial for the next generation of spintronic devices. Therefore technological progress in this area depends heavily on the successful search for new materials as well as on a deeper understanding of the fundamental mechanisms of the magnetic relaxation and the magnetic anisotropy. This talk will focus on different aspects which can influence the magnetic relaxation as well as the magnetic anisotropy within a confined device setting.

For many spintronic applications the use of thin films with perpendicular anisotropy is often essential for the functionality of the device. For example the use of thin films with perpendicular anisotropy in spin transfer torque magnetic random access memories (STT MRAMs) leads to a reduction of the current density needed to switch the device state. In addition to the perpendicular anisotropy it is often crucial to have materials with a low magnetization relaxation rate. Therefore many spintronic applications rely on ultra-thin magnetic films with a low magnetization relaxation in which the perpendicular anisotropy is created through surface anisotropy. This approach is very sensitive to the interface morphology and chemical environment. In this talk I will discuss the effect of spatial fluctuations of the first order perpendicular anisotropy in thin films and its influence on the effective anisotropy for these materials.

Similar to the magnetic anisotropy the magnetic relaxation in thin ferromagnetic films can be affected by neighboring layers. Spin pumping is a well-known contribution that has to be taken into account for practical applications using multilayer structures. More recently a strong unidirectional contribution to the relaxation in exchange bias systems has been observed experimentally. To describe this phenomenon theoretically we use the formalism of an anisotropic Gilbert damping tensor that takes the place of the (scalar) Gilbert damping parameter in the Landau-Lifshitz-Gilbert equation of motion. In this talk I will discuss this approach to study the modified magnetization dynamics under the influence of unidirectional damping.

ACKNOWLEDGMENTS

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4:20pm **TF+MI-WeA7 Vacuum Furnace Annealing Block Copolymers for Bit Patterned Advanced Media***, **Allen Owen**, S. Gupta,* University of Alabama

Hard disk drive storage media is trending towards both smaller physical size and greater storage capacity, there by increasing the areal density of the magnetic storage media. Bit patterning shows potential as a method for increasing this areal density. A block copolymer template can be used to provide an etch mask for bit patterning a magnetic thin film. A statistical design of experiments was carried out to optimize the effect of nanopatterning via ion milling Co/Pd multilayers for PS-PFS block copolymers. The design of experiments varied the etch angle and etch time during ion milling. Samples that were sputter-deposited with Co/Pd multilayered thin films were spin-coated with PFS block copolymer and vacuum furnace annealed at 140 °C for 48 hours at a pressure of ~5 x 10^{-5} Torr. After vacuum furnace annealing, the films were ashed in oxygen plasma to remove the PS, leaving the PFS spheres as masks for the subsequent ion milling. The stack used was $Pd5/[Co0.3Pd1.0]_{14}$ /Pd 5 nm sputter deposited onto a Si substrate. The as deposited coercivity was ~1.3 kOe. After ion milling for 2 min at an angle of 45°, the coercivity was found to be ~0.6 kOe. Ion milling at 45° for 4 min resulted in a coercivity of ~0.07 kOe. This is in comparison with previous experiments using thermal annealing in atmosphere and solvothermal annealing with heptane, where the coercivity increased at ~4 min at the same 45° ion milling angle. The difference can be explained by the fact that for the previous experiments, the stack used was $Ta5/[Co0.3Pd1.0]_{14}/Ta5$ nm. The Ta capping layer must be more resistant to ion milling than Pd, which means the ion milling times must be adjusted to transfer the bit pattern to the media.

4:40pm **TF+MI-WeA8 Atomic Layer Deposition Enabled Synthesis of Multiferroic Composite Nanostructures**, ***Jeffrey Chang***, *A. Buditama,* University of California at Los Angeles*; A. Rosenberg,* Stanford University*; L. Kornblum,* Yale University*; S.H. Tolbert,* University of California at Los Angeles*; K.A. Moler,* Stanford University*; C.H. Ahn,* Yale University*; J.P. Chang,* University of California at Los Angeles

Multiferroic materials, which exhibit controllable ferromagnetic (ferroelectric) properties via electric (magnetic) field, are of great interest due to their potential in enabling new device applications. Due to the scarcity of single-phase multiferroics in nature and their weak responses at room temperature, composite multiferroics are proposed to realize robust multiferroic behaviors by coupling the functional properties from the constituent phases. A strain-mediated coupling strategy is achieved by interfacing magnetostrictive ferromagnets with piezoelectric materials, where the interfacial area per volume, as well as the material crystallinity, play important roles in the attainable functional properties. With the aim of enhancing the composite magnetoelectric behavior by nanostructuring, atomic layer deposition (ALD), with its high quality and conformal film growth, shows considerable potential in achieving high quality multiferroic composites with industrial scalability.

In this work, lead-free ferroelectric/antiferromagnetic $BiFeO_3$ (BFO) and ferrimagnetic $CoFe_2O_4$ (CFO) thin films were grown on $SrTiO_3$ (001) substrates by ALD using tmhd-based metalorganic precursors(tmhd =2,2,6,6-tetramethylheptane-3,5 dione). The use of oxygen radicals as the oxidant provides a low temperature process capability at ~200°C. The growth rates for BFO and CFO are ~3.3Å/cycle and ~2.4Å/cycle, respectively. The BFO films showed epitaxial single crystalline growth in (001) pseudocubic orientation after being annealed under 650°C, while the CFO films are oriented polycrystalline due to the lattice mismatch between the film and substrate. The BFO piezoelectric properties were confirmed using piezo force microscopy, while tunable CFO magnetic properties were demonstrated by thickness-related strain relaxation measurements.

Multiferroic composite nanostructures were synthesized by implementing ALD processes with different substrates. Room-temperature magnetoelectric behaviors ($\alpha \approx 64\times10^{-3}$ Oe cm/V) and tunable magnetic anisotropies were observed in the BFO/CFO system with 2-2 and 1-3 orientations, respectively. The microscopic magnetic domain structures were characterized by the scanning SQUID systems. 0-3 CFO/PZT composites were enabled by using mesoporous PZT structures. The change in lattice parameters after poling was observed by high-resolution XRD measurements, showing that the strain interactions lead to the magnetoelectric behavior in the composite. Besides, the integration of the BFO/CFO system onto Si platforms demonstrated the versatility of the ALD processes, illustrating a path for integrating novel multiferroic materials into current industrial processes by ALD.

5:00pm **TF+MI-WeA9 Thin Film Challenges for High Performance Ir Plasmon Enhanced Photodiodes: from Simulation to Focal Plane Array Integration and Characterization**, ***François Boulard***, Univ. Grenoble Alpes, France*; O. Gravrand,* Univ. Grenoble Alpes,France*; D. Fowler,* Univ. Grenoble Alpes, France*; G. Badano,* Univ. Grenoble Alpes, France*; P. Ballet,* Univ. Grenoble Alpes, France*; M. Duperron,* Univ. Grenoble Alpes, France*; L. Adelmini, R. Espiau de Lamaestre,* Univ. Grenoble Alpes, France **INVITED**

For several decades now, Surface Plasmons (SP) have been increasingly studied for applications in many fields from chemistry, biology, to materials science. In the IR sensor community, the use of SPs to concentrate and channel light offers new possibilities to increase sensitivity or modify spectral response. However, the incorporation of metallic nanostructures in technologically mature components is challenging. This paper deals with the design and integration of a sub-wavelength photonic structure to add spectral functionalities to mid wave and longwave IR HgCdTe photodiodes. Based on simulation and experimental results, tradeoffs to reach the full potential of SP enhancement are discussed. The relationship between the metallic grating geometry and the excited optical mode is illustrated using numerical simulations. The agreement between the simulated and measured spectral response and dispersion relation on a test photodiode array is shown. The influence of the absorber, passivation, and adhesion layer properties and thicknesses on the resonance intensity and photodiode noise is experimentally illustrated. Finally, results of multicolor midwave IR focal plane arrays with shot noise limited operation and less than 0.3% defective pixels are presented.

6:00pm **TF+MI-WeA12 Watching Thin-film Aluminum Oxidize**, ***David Allred***, *M. Miles, S. Thomas, S. Willett, M.J. Greenburg, A. Vance, R.S. Turley,* Brigham Young University

In three years NASA will be in the midst of its decadal review, establishing priorities for the 2020s. Very likely one of the chief astrophysical missions will contain a LUVOIR (large, UV-optical-IR) telescope. This space-based observatory will likely contain the largest mirrors ever flown and will probe the cosmos seeking to address key questions of the origin, current status and evolution of our universe. These investigations will profit from a truly broad-band mirrors. Thus, the reflective coating will almost certainly be aluminum. To be viable, the top surface of such a space mirror needs to be bare without the tarnish layers that naturally form in air. This could open up the 11-15eV band for space-based astrophysics without sacrificing IR, visible and UV reflectance. We report on two techniques aimed at clarifying the oxidation mechanism for Al. First, we have used VUV (>10 eV) reflectometry of bare, freshly deposited aluminum mirrors as they age in controlled atmospheres, and second, variable-angle, spectroscopic ellipsometry is shown to be capable of measuring changes at the angstrom level in multilayers consisting of aluminum, protected by various vacuum-applied barrier layers. These ultrathin barrier layers included polymers such as parylene and inorganic films, such as MgF_2 and AlF_3. For example, we saw that the growth in oxidation thickness of aluminum protected by a 7nm MgF_2 film is logarithmic over a period of time of more than 1000 hrs.

Author Index

Bold page numbers indicate presenter