



# CMRR REPORT

Center for Magnetic Recording Research

## RESEARCH HIGHLIGHT

# FastMag Micromagnetic Framework: Current State and Roadmap

*By: Vitaliy Lomakin*

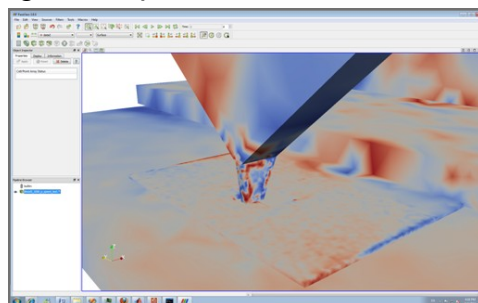
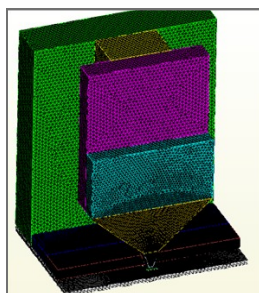
## 1 Introduction

Micromagnetic solvers have a significant predictive power and are important for our ability to analyze and design magnetic devices and systems. However, micromagnetic analysis of complex and large-scale devices may be very time consuming or impossible. The computational complexity is due to the geometrical and material complexity of many structures, a large number of required discretization elements, and the numerical difficulties associated with time integration. One example of a highly complex structure for simulations is a magnetic write head, which may have size of several tens of microns and require a mesh resolution of 5-10 nm to fully resolve all dynamic processes. More examples include a large array of Magnetic Random Access Memory elements, granular media, bit patterned media, magnonic crystals, etc. Such systems may have a large size, fine features, and highly non-uniform domains required to be discretized on a fine scale. Realistic modeling of such structures can be very complex.

Here, we describe a highly flexible and efficient micromagnetic framework, FastMag. FastMag includes a set of modules that makes it well suited for the micromagnetic analysis and design of many magnetic structures. It has a convenient interface and general meshing capabilities, can address various physics types, and runs on massively parallel Graphics Processing Unit (GPU) computer systems. The rest of the presentation summarizes our recent progress on the development of FastMag and outlines a roadmap for the FastMag development.

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*Figure 1:  
Cubit/Trelis model of a write  
head (left) and magnetization  
snapshot in Paraview.*

## FROM THE DIRECTOR

This newsletter comes at a time with many new and returning faces to CMRR. We welcome 3 new visiting researchers; Dr Hemant Thapar formerly from Link a Media, Professor Amir Shlivinski from Ben-Gurion University of the Negev Israel and Wenwei Zhang from Advanced Throughput Shanghai Biotech. We also welcome 3 new visiting graduate students: Jin-Kyu Byun from Soongsil University, Weilong Cui from Peking University and Li Chen from Hunan University. Welcome to all of you.



Over the summer, we had 13 graduate students participating in summer internships with a range of companies including Western Digital, IBM, HGST, Maxim, Samsung, Microsoft Research and General Atomics. Their summer research covered much of the current research at CMRR. This strong interaction of our students with our industrial partners is a clear part of the CMRR mission to train students for the information technologies industries. I hope we continue to keep this strong participation of our students with our corporate sponsors in the coming years. We plan on expanding these efforts to undergraduates researchers. We are encouraging undergraduates to join CMRR research projects and working with Sandra Ponting who oversees Undergraduate Industry Research Opportunities at Research Affairs on establishing an undergraduate internship program.

We continue to expand our educational and outreach efforts by organizing various conferences and workshops. On July 8 -12 , 2013, CMRR organized and hosted the International French-US Workshop: Toward low power spintronic devices. This workshop gathered the scientific and engineering communities in the fast growing field of spintronics and its applications. The workshop covered the innovation process from scientific discovery to creating new products, including STT-MRAM, oscillators, and novel magnetic memory and logic structures. It also provided attendees opportunities to discuss new developments and to initiate collaborations and research projects. The workshop included well-known contributors from academy (including Nobel Prize winner Albert Fert), industry, startups, and representatives from funding agencies and venture capital firms.

The 2014 Non-Volatile Memories Workshop (NVMW) will be held on March 9-11, 2014. This workshop provides a unique showcase for outstanding research on solid state, non-volatile memories. It features a "vertically integrated" program that includes presentations on devices, data encoding, systems architecture, and applications related to these exciting new data storage technologies. For more information visit <http://nvmw.ucsd.edu/2014/>.

We plan on having more of these workshops in future years and as part of future research reviews and would like input on potential topics.

*Eric E. Fullerton*

## 2 FastMag Structure and Capabilities

### 2.1 Structure Definition and Discretization

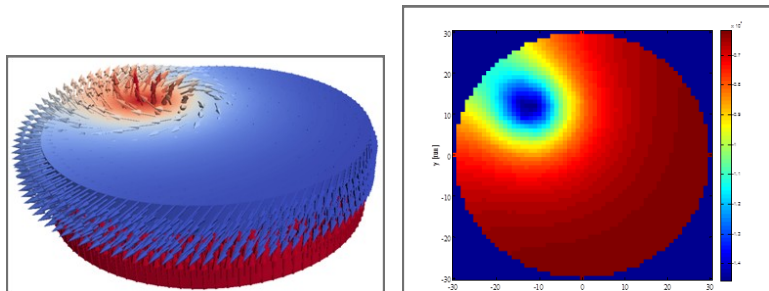
FastMag is based on Finite Element Method (FEM) discretization of the computational domain. It uses Cubit (currently Trelis) to create a computer model of the structure of interest. The model can be created via a Graphics User Interface (GUI) or via a Python script. A large set of geometry operations are allowed for the model creation, including Boolean operations. The structure creation is followed by the discretization into a mesh of tetrahedral elements. The tetrahedral discretization permits the analysis of highly non-uniform structures. Trelis provides several methods for the creation of meshes. It also provides tools for mesh quality assessments and improvements in terms of the element shape uniformity and size. Creating high-quality meshes is critical for the ability to simulate complex magnetic structures. As an example, creating a mesh with  $\sim 10$  million elements typically takes a few minutes. Using Python allows a great flexibility in analyzing and designing structures. Python scripts can be created, which construct a structure with a set of parameters, run a micromagnetic simulation, assess the obtained results, and use this assessment to modify the structure to “close the loop” for the structure design and optimization. The simulations can be run via a GUI interface, via command line, or via a script.

Figure 1 shows snapshots of the Cubit CAD/mesher interface and Paraview postprocessor. Figures 2-4 demonstrate some of the simulation capabilities of FastMag.

### 2.2 Available Modules and Capabilities

The current version of FastMag includes the following capabilities and modules:

- Solver for the Landau-Lifshitz-Gilbert equation for the study of the magnetization dynamics in general magnetic structures.
- Solver for computing energy barriers using the Nudged Elastic Band (NEB) method.
- Explicit and implicit time integration methods.
- Stochastic thermal fields in the LLG solver.
- Discretization of the structures over uniform and non-uniform tetrahedral meshes.
- Any ferromagnetic and anti-ferromagnetic surface coupling between different volumes through common structure interfaces.
- Spin transfer torque (STT) effects in spin valves, including accounting for magnetoresistance.
- No need to discretize non-magnetic domains.
- The ability to define pinned volumes and surfaces.
- Magnetostatic fields can be computed in magnetic and non-magnetic domains.



*Figure 2: Vertex dynamics (left) and corresponding current distribution due to magnetoresistance.*

- The speed of the solver scales linearly with the number of elements.
- The simulator runs on massively parallel GPU-based computer systems.
- The execution efficiency, fast algorithms, and GPU acceleration makes FastMag able to handle complex problems on a desktop computer.

### 2.3 Underlying Computational Methods

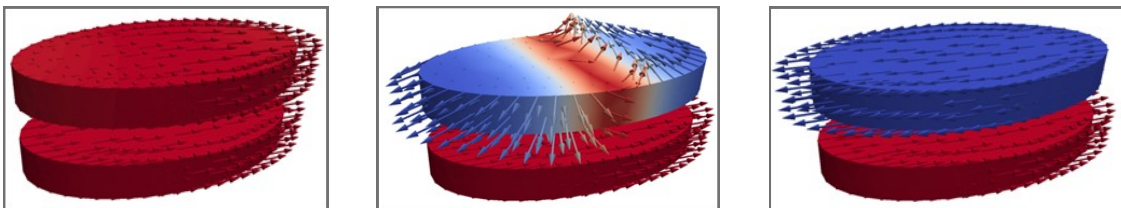
In the FEM approach used in FastMag the structure under study is discretized into a mesh of tetrahedral elements, which can accurately represent generally shaped geometries. The magnetization vector is expanded over a set of interpolatory basis functions. The unknowns are the magnetization states at the nodes of the tetrahedral elements and the magnetization in the elements can be found as a summation over the basis functions. This magnetization numerical expansion is substituted into the LLG equation or equations of NEB, which leads to a system of ordinary differential equation, solved by time marching. To overcome the modeling challenges, the following points are addressed.

#### 2.3.1 Fast Computation of the Effective Fields

One of the main costs of solving the equations of micromagnetics is the evaluation of the magnetostatic fields. In FastMag, the magnetostatic fields are computed via superposition integrals defined directly on the unstructured tetrahedral meshes. In this approach, equivalent magnetic charge densities are computed at the tetrahedron nodes, similar to the mixed-potential approach in electromagnetic integral equation solvers. The scalar potential is evaluated via superposition integrals. The magnetostatic field is, then, found by numerically evaluating the gradient of the potential.

The practical implementation of this approach involves several sparse matrix-vector products and a dense matrix-vector superposition product. The sparse matrices are introduced to define the differential operators, and a singularity extraction process for analytically computing the scalar potential/field for small charge-observer separations. The dense product effectively represents a superposition summation from a number  $N$  of charges to a number  $N$  of co-located scalar observers. The evaluation of the sparse matrix-vector products requires  $O(N)$  operations. The evaluation of the dense superposition products would require an  $O(N^2)$  operations if evaluated directly. FastMag implements a non-uniform Fast Fourier Transform (NUFFT) (also called adaptive integral method) approach, which has a computational cost of  $O(N \log N)$ . Both sparse and dense products are designed to be well suited to be implemented on massively parallel GPU and CPU computer systems.

The used approach for the magnetostatic field evaluation is highly efficient and flexible in that it does not require any iterative solvers and works for non-uniform meshes. In this respect this



*Figure 3: Switching in-plane STT MRAM cell.*



approach provides the flexibility of conventional Finite Element/Boundary Element solvers but also has a high speed as Finite Difference solvers. The high-speed is obtained for structures of different types, including mostly volumetric structures (in which most of the mesh nodes are in volumes) and mostly surface structures (in which most of the mesh nodes are on surfaces).

Other effective fields are evaluated by defining corresponding sparse matrices and using the same sparse matrix-vector product approaches, as in the magnetostatic field evaluation case.

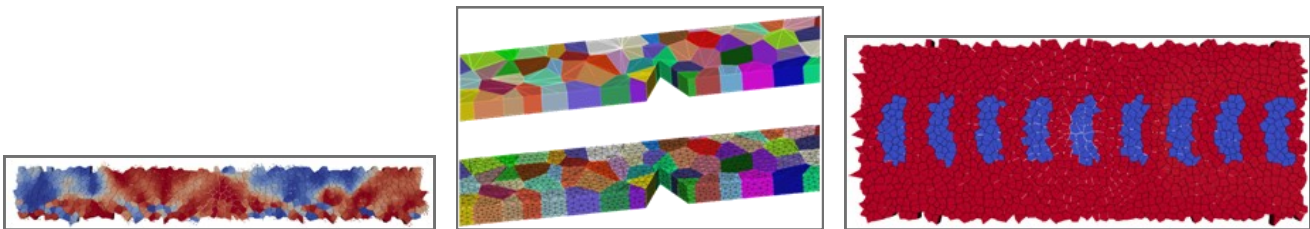
### 2.3.2 Time Integration

Many magnetic structures have strong exchange, which leads to numerical problem stiffness. The stiffness manifests itself in that the time step becomes very small and the linear solver part of implicit time integration methods becomes slowly convergent. Therefore, efficient time stepping schemes have been implemented in FastMag. In particular, the implicit schemes include the backward differentiation formula (BDF). The BDF method requires the evaluation of the numerical system Jacobian to enhance the time integration. FastMag implements a technique that allows evaluating the product of the numerical system Jacobian with the magnetization vector exactly without a need to create any matrices and it does it at the speed of the conventional effective field evaluation. The ability to execute this task allows using the BDF without a need for a linear solver preconditioner, which is important for allowing using GPUs with low memory.

### 2.3.3 Parallelization

Using parallel computing systems for large-scale simulations is vital for scaling computational tools. Recently, new massively parallel high-performance GPU systems have emerged for applications in scientific computing, offering massive parallelization. For example, NVIDIA GeForce GTX 780 GPU at a cost of ~\$500 has 2304 stream processors with the performance of 4 TFLOPs, which is much higher than any existing CPUs. Multi-GPU nodes and clusters are also available. However, not all methods or codes are easily portable to GPUs. Often directly translating a complex CPU code to GPU architectures results in a low efficiency. Features of the GPU architecture have to be carefully accounted for when developing computational methods. The complexity of the GPU architecture may make developing computational methods challenging but it opens new opportunities for creating highly efficient methods for large-scale modeling.

Most components of FastMag are developed keeping parallelization in mind, including the data structure and numerical approaches. In particular, the NUFFT method has CPU-GPU speed-ups of 100-200 (single GPU vs. single CPU core). The sparse products have speed-ups of 8-20 (single GPU vs. single CPU core). Multi-GPU implementations of these methods also are



*Figure 4: Modeling granular materials.*

available with 65-85% multi-GPU parallelization efficiency for up to 8 GPUs. Another important property of the GPU implementation of the FastMag components is low memory use, which is achieved by running many critical operations on-the-fly rather than by pre-computing and storing various coefficients, as often done in CPU codes. The low memory consumption allows running large computational problems (over 100 hundred million elements) on a single GPU.

### 3 Roadmap of the FastMag Development

FastMag already is a general framework that allows simulating a broad range of magnetic devices and phenomena. However, we have plans of extending and improving FastMag capabilities significantly. In the last several years a new release with significant improvements and extensions has been presented about twice a year. A similar rate of advancement is expected in the future. Specific plans are listed next.

- Additional stepping integrators.
- Streaming computing of random realizations. In this approach, multiple simulations (a stream of simulations) will be processed simultaneously on the same GPU.
- Methods to reduce stiffness in thin films and general over-discretized systems.
- Adding more physics. Among other capabilities, it includes implementing a static Maxwell solver, spin transport equations, magnetostriction and electric field effects, atomistic models, and coupling of the LLG equation with Maxwell's equations.
- Updating the GUI interface + more post-processing options + more scripts for design and optimization.
- Full coupling with Python and Matlab to make the memory space of FastMag available in Matlab and Python and to allow controlling the FastMag execution through Python and Matlab.
- Coupling with SPICE for circuit models of magnetic devices, e.g. MRAM, write heads, and STT oscillators.

### 4 Development Team and Users

The development of FastMag has involved a significant multi-year effort. The following people have been involved in the development of the core code: Ruinan Chang, Shaojing Li, Marco Escobar, Marco Lubarda, Sidi Fu. In addition, Majd Kuteifan, Marco Menarini, and Simon Couture have joined our team more recently and have already made very important contributions. Matthew Hu has made major contributions to the development of scripts for generating FastMag input files in Cubit. Boris Livshitz was the first person in the group working on micromagnetic codes and thus made important contributions to generating ideas leading to the FastMag creation.

Finally, the users of FastMag are a critical part of the development cycle. Our team appreciates and enjoys the interactions with the users. Their feedback has been, is, and will be a highly valued source of inspiration for further FastMag development.

## Lele Wang is the 2013 Shannon Fellowship Recipient

Lele Wang is a graduate student in the Electrical and Computer Engineering department. Her thesis research advisor is Prof. Young-Han Kim. She has worked on a variety of problems in information theory, coding, and communication; such as optimal relaying, optimal broadcasting, interference management, coding for nonvolatile memories, network coding, and polar coding. Lele and fellow graduate student Minghai Qin received a 2013 Qualcomm Innovation Fellowship to support their research project on “Practical Coding Techniques for Network Communication.” Their proposal was among the 8 selected to receive the \$100K fellowship out of 138 submitted from top universities worldwide.



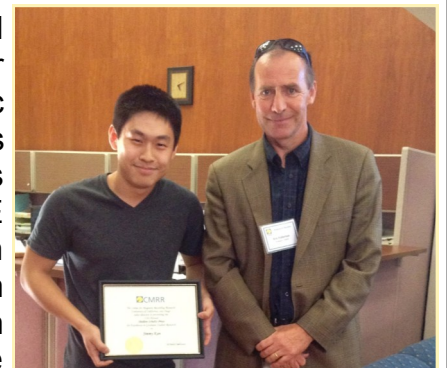
*[Photo credit: Alex Matthews]  
Lele Wang was presented with the award in a ceremony on May 1, 2013, following the Shannon Memorial Lecture.*

When asked about the Shannon Fellowship, Lele gratefully responded, “it is a great honor to receive this fellowship. Thanks a lot for Paul [Siegel], Young-Han [Kim], and the selection committee who kept the secret until the last minute and prepared such a big surprise too. That was definitely the most memorable moment for me at San Diego. I would like to give my deepest gratitude to my advisor, Young-Han Kim, who opened the door for me and guided me through every step in my research. Over the years, I hope I could pick up some of Young-Han's optimism, pursuit of excellence, and attention to details so that one day I become someone like him.”

Congratulations, Lele Wang!

## Jimmy Kan Awarded the 2013 Sheldon Schultz Prize for Excellence in Graduate Student Research

Jimmy is a doctoral student in the Materials Science and Engineering Program. His thesis research is advised by Professor Eric E. Fullerton. The title of his thesis is “Engineering of Metallic Multilayers and Spin Transfer Torque Devices.” Jimmy was recognized for the impact of his publications appearing in journals such as Nature Nanotechnology, Nanotechnology Letters, IEEE Magnetics Letters, and Physical Review Letters. Jimmy held an internship at Qualcomm, Incorporated where he worked on non-volatile memory technology. After graduation, Jimmy will join Qualcomm as a Senior Engineer with the Advanced Nonvolatile Memory group in the Qualcomm Technologies (QTI) division. His focus will be on development and characterization of chip-level STT-MRAM technologies.



*Jimmy Kan and his advisor, Eric Fullerton. Jimmy received a framed certificate and a cash award of \$1000.*

Jimmy humbly describes his experience, “to be honored and recognized for my accomplishments with the Shultz Prize is an overwhelming experience. However, I can’t help but immediately think on the never-ceasing support and encouragement that has kept me going strong and sane in my research and day-to-day life from my group members, and especially Eric Fullerton. I am a firm believer in the value of brotherhood and teamwork at every turn, and I can confidently say that without the sage-like advice afforded to me by my advisor and the tireless effort from the rest of the team, I could have accomplished only very little on my own. I am supremely humbled and motivated by their confidence.”

Congratulations, Jimmy Kan!

## CMRR FACULTY / RESEARCHER / AFFILIATES



**AMI E. BERKOWITZ** *Research Professor* <http://cmrr.ucsd.edu/people/berkowitz>

Dr. Berkowitz's research is based on thin film and fine particle phenomena related to magnetic recording. It involves production of these materials and characterization of their microstructural, magnetic, and transport properties. Some current research activities include giant magnetoresistance and magneto-impedance, antiferromagnetic oxides for MR head biasing, magnetic viscosity phenomena, new particulate and film media, finite size effects, and magnetic surface behavior.



**ERIC E. FULLERTON** *CMRR Chair, Endowed Chair Professor* <http://cmrr.ucsd.edu/people/fullerton/>

Prof. Fullerton's research areas include magnetic recording and nano-technologies, thin film and superlattice growth, interfacial and thin-film magnetism, and x-ray and neutron scattering.



**SUNGHO JIN** *Professor, MAE & Nanoengineering* <http://cmrr.ucsd.edu/people/jin/>

Prof. Jin's research interest include cutting-edge materials science, including nano-materials, magnetic alloys and thin films, and MEMS materials and devices.



**PAUL H. SIEGEL** *CMRR Endowed Chair Professor* <http://cmrr.ucsd.edu/people/siegel/>

Prof. Siegel's research interests include mathematical foundations of signal processing and coding, analysis and design of codes for constrained channels, trellis-coded modulation techniques, algebraic error-correction coding, algorithms and architectures for signal processing, and applications to digital data storage and wireless communications.



**FRANK E. TALKE** *CMRR Endowed Chair Professor, MAE* <http://cmrr.ucsd.edu/people/talke/>

The focus of Professor Talke's work is in the areas of tribology, precision engineering, instrumentation development as well as modeling and mechanical design optimization. Projects currently under way include a) simulation of thermal asperities; slider dynamics and contact force analysis; investigation of proximity and thermal flying height control (TFC) sliders; improvements in the pre- and post- processing software of finite element based air bearing simulation; lubrication and thermal studies of HAMR (heat assisted magnetic recording) recording sliders; analysis and experimental study of touchdown sensors and thermal flying height control sliders; and b) design and optimization of biomedical devices such as precision instruments for measurement of middle ear dimensions for stapedectomy and development of a MEMS-type optical pressure transducer for intra-ocular pressure measurements.



**FREDERICK E. SPADA** *Associated Research Scientist* <http://cmrr.ucsd.edu/people/spada/>

Dr. Spada's research interests include evaluation of bulk degaussing methods for securely erasing magnetic media, structure-property relationships in both thin film and particulate magnetic materials, and chemical aspects of wear.



**DIMITRI B. BASOV** *Professor/Chair, Physics* <http://infrared.ucsd.edu/pi.html>

Prof. Basov's research interests are electronic and magnetic properties of novel materials. Current research directions include physics of strongly correlated electron systems, magnetic semiconductors, molecular and organic nano-electronics, electromagnetic metamaterials, and charge dynamics in grapheme.



**RAYMOND DE CALLAFON** *Professor, MAE* <http://maeresearch.ucsd.edu/callafon/>

Prof. de Callafon's research interests include topics in the field of experiment-based approximation modeling, control relevant system identification and recursive/adaptive control. In particular, he is interested in designing and analyzing experiment-based modeling techniques for control relevant identification of linear systems and extending these techniques to specific classes of (block) non-linear and linear parameter varying (LPV) systems.



**MASSIMILIANO DI VENTRA** *Professor, Physics* <http://physics.ucsd.edu/~diventra/>

Prof. Di Ventra's research interests are in the theory of electronic and transport properties of nanoscale systems, non-equilibrium statistical mechanics, DNA sequencing/polymer dynamics in nanopores, and memory effects in nanostructures for applications in unconventional computing and biophysics.



**Y. SHAYA FAINMAN** *Professor/Chair, ECE* [http://jacobsschool.ucsd.edu/faculty/faculty\\_bios/index.sfe?fmp\\_recid=32](http://jacobsschool.ucsd.edu/faculty/faculty_bios/index.sfe?fmp_recid=32)

Prof. Fainman is involved in design and realization of ultrafast and miniature optical systems. Current research interests in his group include photonic crystals (band gap); 3-D holographic optical storage for image processing; the investigation of artificial dielectric properties of nanostructures; transparent photonic switching fabric and networks; diffractive optics with multifunctionality; and quantum communications and cryptography for photonic network security and privacy.





**VITALIY LOMAKIN** *Associate Professor, ECE* <http://cmrr.ucsd.edu/people/lomakin/>

Prof. Lomakin's interests are in electromagnetic theory and applications. Lomakin's recent research has focused on wave phenomena associated with scattering of electromagnetic fields from metallic plates perforated by holes of subwavelength size.



**VLADO LUBARDA** *Adjunct Professor, MAE* <http://maeresearch.ucsd.edu/~vlubarda/research/>

Prof. Lubarda's research field is Mechanics of Solids and Materials. He did research and published papers in linear and nonlinear elasticity, finite strain plasticity, viscoelasticity and viscoplasticity, dislocation mechanics, damage and fracture mechanics, mechanics of thin films, mechanics of composites, micromechanics, nanomechanics, and biomechanics.



**SHIRLEY MENG** *Associate Professor, Nanoengineering* <http://ne.ucsd.edu/smeng>

Prof. Meng's research focuses on the field of energy storage and conversion materials: nano structured electrodes for advanced rechargeable batteries, dye-sensitized solar cells and thermoelectric conversion; charge ordering, structure stability, processing – structure – property - performance relation in functional ceramics and combining first principles computation with high-skilled experiments for rational materials design and optimization for energy applications.



**IVAN SCHULLER** *Professor, Physics* <http://ischuller.ucsd.edu/>

Professor Schuller's researches includes superlattices, nanostructures, vortices, organic semiconductors, insulating thin films, proximity effects, and devices



**LU JIU SHAM** *Professor Emeritus, Physics and Adjunct Professor Emeritus, ECE*  
<http://physics.ucsd.edu/~ljsst/ljs.html>

Prof. Sham is a condensed matter theorist specialized in many-body physics in solids: electrons and phonons, density functional theory, quantum optics in semiconductors. Hi current interests are optical control of quantum information in semiconductors and spintronics.



**OLEG SHPYRKO** *Associate Professor, Physics* <http://oleg.ucsd.edu/>

Prof. Shpyrko's group studies nanoscale dynamics and structure of materials using novel x-ray, light and neutron scattering probes. They are particularly interested in developing novel coherent x-ray scattering techniques.



**SUNIL K. SINHA** *Professor, Physics* <http://sinhagroup.ucsd.edu/>

Prof. Sinha's group's research is concerned with studying the structure and dynamics of Condensed Matter using the techniques of X-Ray and Neutron Scattering. They have ongoing programs in both hard and soft Condensed Matter.



**STEVEN SWANSON** *Associate Professor, CSE* <http://cmrr.ucsd.edu/people/Swanson/>

Prof. Swanson's research focuses on understanding the implications of emerging technology trends on computing systems. He leads the Non-Volatile Systems Laboratory and co-leads the GreenDroid project team. The projects focus on building prototype systems that must deal with hardware, software, and the boundary between them.



**KENNETH S. VECCHIO** *Professor/Chair, Nanoengineering*  
[http://www.jacobsschool.ucsd.edu/faculty/faculty\\_bios/index.sfe?fmp\\_recid=156](http://www.jacobsschool.ucsd.edu/faculty/faculty_bios/index.sfe?fmp_recid=156)

Professor Vecchio is interested in the processing and performance of metallic-intermetallic laminate (MIL) composites for advanced structural applications, including: light-weight armor, aerospace applications and other high performance, weight-critical applications.



**ALEXANDER VARDY** *Professor, ECE* [http://www.jacobsschool.ucsd.edu/faculty/faculty\\_bios/index.sfe?fmp\\_recid=76](http://www.jacobsschool.ucsd.edu/faculty/faculty_bios/index.sfe?fmp_recid=76)

Professor Vardy is a leading expert in coding theory. His research is leading to a better understanding of the uses and limitations of error-correcting codes in encoding data for transmission and storage.

## NEW SCIENTISTS / STUDENTS

### Visiting Research Scientist



**Dr. Hemant Thapar** is a veteran of the storage industry, where he contributed to the first-time commercial deployment of modern signal processing and coding methods, including PRML, EPRML, MLSD, and LDPC, in magnetic disk drives. He worked at Bell Telephone Laboratories and IBM Corporation before founding two successful startups, DataPath Systems and Link-A-Media Devices, where he was also the CEO. His current technical interests are in tiered storage, both at the device and the system level. Dr. Thapar joins Prof. Siegel's research group.



**Dr. Amir Shlivinski** received his B.Sc., M.Sc., and Ph.D degrees all in electrical engineering from Tel-Aviv University, Israel, in 1991, 1997, and 2003 respectively. From 2003 to 2005 he was a Post Doctorate Fellow at the Department of Electrical Engineering, University of Kassel, Germany. Since 2005 he is a faculty member at the department of Electrical and Computer Engineering, Ben-Gurion university of the Negev, Beer-Sheva, Israel. His main fields of interest are analytical and numerical methods in wave theory, antenna theory, time-domain phenomena, imaging and inverse scattering.

### Graduate Students



**Serdar Yavuz** is a 1st year Ph.D. student in the department of Material Science and Engineering at UCSD. He obtained his MS in Atomic and Molecular Physics at Recep Tayyip Erdogan University, Rize, Turkey, 2011 after he graduated from Department of Physics, Ataturk University, Erzurum, Turkey, 2009.

Working under the supervision of Professor Sungho Jin, his research interests are solar cells, nano-devices, nano-structures and CNTs.



**Uday Khandelwal** received his B.E in Electronics and Communication from Manipal Institute of Technology, India. He is currently a second year Masters student in the Electrical and Computer Engineering department working in Professor Siegel's STAR group. He is interested in signal processing and its applications in magnetic recording

systems. His current research is in data reconstruction from a Hard disk drive using Magnetic Force Microscopy.

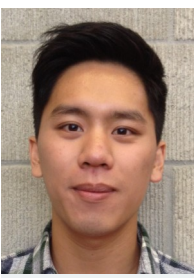


**Calvin Gardner** received his B.S. degree in Mechanical Engineering, Applied Physics, and Philosophy from Brigham Young University. He received his M.S. degree in Engineering Physics from UCSD and is currently pursuing his Ph.D. in the same area. His main research interests focus on the application of materials knowledge to fill specific engineering needs including nanotexturing metal surfaces for biomedical applications, mitigating electronics failure with nanoscale geometries, and controlling odor molecule delivery through reversible material properties.

### Undergraduate Students



**Peter Dvorak** is a fourth year undergraduate student. He is studying mechanical engineering. He has focused in on solid mechanics and controls. He will be studying the properties of 3D printed materials in Dr. Talke's lab, as well as assisting the current graduate students.



**Harry Siu** is currently a 4th year undergraduate studying mechanical engineering. He plans to graduate by the end of this academic year, and will be pursuing a Masters in mechanical engineering after a year break. He is currently part of the Talke group and in research on developing an intraocular pressure sensor to help detect glaucoma early, a condition which abnormal IOP damages optic nerves.

## SELECTED PAPERS AND TALKS

### Professor Eric E. Fullerton

M. S. Pierce, J. E. Davies, J. J. Turner, K. Chesnel, **E. E. Fullerton**, J. Nam, R. Hailstone, S. D. Kevan, J. B. Kortright, K. Liu, L. B. Sorensen, B. R. York, O. Hellwig, "The influence of structural disorder on magnetic domain formation in perpendicular anisotropy thin films", *Physical Review B*, 87, 184428, 17 pages, May 24, 2013.

E. Mancini, F. Pressacco, M. Hartiger, **E. E. Fullerton**, T. Suzuki, G. Woltersdorf, and C. H. Back, "Phase transition in iron-rhodium thin films probed by ferromagnetic resonance", *Journal of Physics-Condensed Matter*, Vol. 46, No. 24, 5302, June 3, 2013.

S-W. Chen, H. Guo, K. Dumesnil, V. Lauter, C. Sanchez-Hanke, E. Fohntung, M. Marsh, O. Shpyrko, **E. E. Fullerton**, and S. Sinha. "Interfacial Magnetic Response of  $\text{PbZr}_{0.2}\text{Ti}_{0.8}\text{O}_{0.3}\text{La}_{0.67}\text{Sr}_{0.33}\text{MnO}_3$  Heterostructures." *Bulletin of the American Physical Society, APS March Meeting*, Maryland, 58, March 2013.

D. B. Gopman, D. Bedau, S. Mangin, **E. E. Fullerton**, J. A. Katine, and A. D. Kent. "Bimodal switching field distributions in all-perpendicular spin-valve nanopillars." *arXiv preprint arXiv:1309.4312* Submitted September 2013.

J. J. Kan, K. Lee, M. Gottwald, S. H. Kang, and **E. E. Fullerton**. "Low-temperature magnetic characterization of optimum and etch-damaged in-plane magnetic tunnel junctions." *Journal of Applied Physics* 114, 114506, September 2013.

D. B. Gopman, D. Bedau, G. Wolf, S. Mangin, **E. E. Fullerton**, J. A. Katine, and A. D. Kent. "Temperature dependence of the switching field in all-perpendicular spin-valve nanopillars." *Physical Review B* Vol. 88, No. 10, 100401, September 2013.

E. Mancini, F. Pressacco, M. Haertinger, **E. E. Fullerton**, T. Suzuki, G. Woltersdorf, and C. H. Back. "Magnetic phase transition in iron-rhodium thin films probed by ferromagnetic resonance." *Journal of Physics D: Applied Physics* Vol. 46, No. 24, 245302, June 2013.

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### Professor Sungho Jin

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