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CMRR Report

Center for Magnetic Recording Research

Number 27 Winter 2007

Research Highlight

Micromagnetics of Composite Patterned Media .

by Boris Livshitz, Vitaliy Lomakin, Akihiro Inomata, and H. Neal Bertram

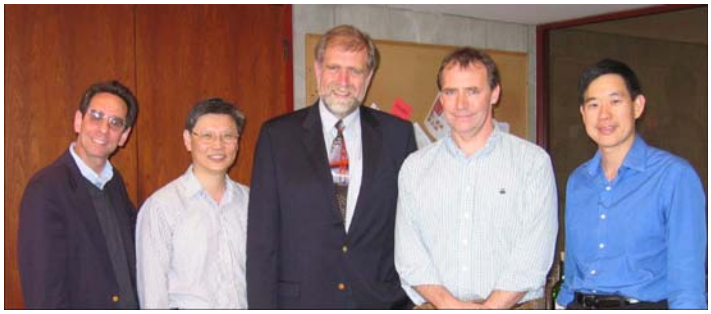
Contents:

Professors Jin and Talke Receive Awards

Sungho Jin, the Iwama Professor of Materials Science at UCSD, and a CMRR faculty member, has received The Minerals, Metals & Materials Society's (TMS) **2007 John Bardeen Award**. This award recognizes an individual who has made outstanding contributions and is a leader in the field of electronic materials. The award was presented at the TMS Awards Dinner on February 27, 2007 during the 136th TMS Annual Meeting in Orlando Florida.

Frank E. Talke, an Endowed Chaired Professor at CMRR has been awarded the **Humboldt Research Award** from the Alexander von Humboldt Foundation. This award is one of the most prestigious awards in German academia and based primarily on the scientist's/scholar's entire academic record. In addition, awardees are invited to conduct an original research project of their own design in close collaboration with colleagues in Germany over a period of six to twelve months.

Fullerton Reception



Left to right, Professors Paul H. Siegel and Paul Yu, Jacob School Dean Frieder Seible, Professors Eric Fullerton and Edward T. Yu

On February 6th, over 100 faculty, students and staff gathered in the CMRR lobby to welcome CMRR's newest Professor and Endowed Chair, **Eric Fullerton**. In the early 1990's Eric was a graduate student at UCSD. After graduation, he held positions at Argonne National Laboratory, the IBM Almaden Research Center, and most recently at Hitachi Global Storage Technologies. We are grateful that his career path has circled back to CMRR!

New Postdoctoral Scholars

Boris Livshitz joined the ECE Department at UCSD in March 2006 as a Post-Doctoral Scholar under the supervision of Professor Vitaliy Lomakin. He received his M.Sc. degree in physics and electrical engineering from St. Petersburg State Polytechnic University, Russia, in 1995, and his Ph.D. degree in electrical engineering from Tel Aviv University, Israel, in 2006. His research interests include fast numerical methods in computational electromagnetics and micromagnetics, algorithms for analysis, simulation, and modeling of electromagnetic fields in complex configurations. Outside of work, Boris enjoys reading, music, and swimming.

Zsigmond Nagy is a Post-Doctoral Scholar in Professor Paul Siegel's group working on constrained coding and interactive communication. He received his M.Sc. degree in electrical engineering in Budapest, Hungary. He came to UCSD and worked on his doctorate degree under the supervision of Professor Ken Zeger. After graduation in 2002, he moved back to Hungary, and worked at the R&D office of Ericsson, Hungary. Last year he returned to UCSD, and worked with Professor Alon Orlitsky for a year. In his free time, Zsigmond enjoys sports, outdoors activities, and traveling.

Ori Shental is a Post-Doctoral Scholar at CMRR under the supervision of Professors Paul Siegel and Jack Wolf. He received his B.Sc. and Ph.D. degrees in electrical engineering from Tel-Aviv University, Israel, in 1996 and 2006, respectively. During the years 1996-2002, he worked as a R&D engineer. His research interests are in the application of computational tools from statistical physics and probabilistic graphical models to information-theoretic problems in communications and data storage. Outside of work, Ori is a proud father to his two year old daughter Libi.

On January 22, 2007, the Advanced Communication Center (ACC) Prize for Outstanding Graduate Student Research was awarded to **Ori Shental** for his Ph.D. dissertation entitled "Probabilistic Inference in Graphical Models and Statistical Mechanics for Multiple-Access Communications." The Prize competition, sponsored by Intel Corporation, is organized by the ACC at Tel Aviv University and is open to all students of higher-education institutions in Israel.

From the Director

In January, we welcomed our new CMRR Professor and Endowed Chair, Eric Fullerton, who has already plunged into his research and teaching. His vast and deep knowledge of nanoscale magnetic materials and structures is already having a valuable impact on Center efforts in perpendicular and bit patterned media recording. We eagerly look forward to his future contributions to CMRR's technical programs.

The Patterned Media project continues to make important strides in many areas. As an example, the Research Highlight in this issue describes fundamental progress in a key part of CMRR's technical agenda - accurate nanomagnetic modeling to elucidate the write process in composite and patterned media recording. The results are the product of a successful joint effort involving CMRR Research Professor Neal Bertram, Professor Vitaliy Lomakin (ECE), Post-doctoral researcher Boris Livshitz, and CMRR Visiting Scholar Dr. Akihiro Inomata (Fujitsu).

As the remainder of the newsletter shows, all of the technical groups at CMRR, under the direction of our internationally recognized faculty and researchers, are pushing the frontiers of scientific and engineering knowledge in order to advance the state-of-the-art in storage technology. I encourage all of our members to stay in touch with the Center and to take advantage of the many benefits that sponsorship provides. There is a lot that goes on between Research Reviews and issues of CMRR Report. We are always eager to share it with you.

Shannon Symposium

The 5th Annual **Shannon Memorial Lecture** was held at the Center for Magnetic Recording Research on April 30, 2007, the anniversary of Claude Shannon's birth. This year, four speakers who represent the bright future of information theory were invited for a half-day mini-symposium. Each speaker has recently received a major paper award from the IEEE Information Theory Society. The speakers were:

Dr. Giuseppe Caire — a Professor at the University of Southern California. His research interests are in the field of communication theory, information theory and coding theory with particular focus on wireless applications.

Dr. Erik Ordentlich — a Senior Research Scientist at Hewlett-Packard Laboratories, Palo Alto, CA. His latest interests are in universal algorithms for various settings, coding for 2D constraints, image compression, the entropy rate of hidden Markov processes, and multi-user information theory.

Dr. Alon Orlitsky — a Professor at the University of California, San Diego. As a theorist, his research deals with concrete communication scenarios. He is actively studying interactive communication: if sender and receiver interact, they can reduce the number of bits that must be transmitted.

Dr. Alexander Vardy — a Professor at the University of California, San Diego. His research is leading to a better understanding of the uses and limitations of error-correcting codes in encoding data for transmission and storage.

Left to right: Alon Orlitsky, Erik Ordentlich, Giuseppe Caire, Alexander Vardy

The archival webcast of the event can be found at: http://www.calit2.net/newsroom/article.php?id=1094

Research Highlight

Micromagnetics of Composite Patterned Media.

Boris Livshitz[†], VitaliyLomakin[†], Akihiro Inomata[†*], and H. Neal Bertram[†‡]

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Introduction

Magnetic recording currently is the major data storage technology. Conventional magnetic media implement continuous magnetic layers consisting of microscopic grains. Such media have constraints of thermal instability due to the superparamagnetic effect, which occurs when the magnetic grains become too small. The superparamagnetic effect may set the fundamental limit of about 0.5Tbit/in^{2}on achievable densities of storage. Overcoming this constraint is one of the key challenges in the modern hard drive industry.

One of the most promising solutions to overcome the superparamagetic effect is to use patterned magnetic media, which comprise arrays of physically separated magnetic elements with perpendicular anisotropy [1-4]. Patterned media allow eliminating any transition noise and are intended to support area densities of storage of more than 1Tbit/in^2. Further improvements can be achieved by using composite structures, where every medium element is composed of two or more layers with different anisotropy that are ferromagnetically coupled through their common interfaces [5-9]. Such media allow switching hard layers with very high anisotropy, thus enhancing the thermal stability.

The goal of this work is to pursue a thorough study of reversal mechanisms in individual and arrayed elements of composite patterned media for a variety of reasonable magnetic and geometric parameters and to assess effects of these parameters on magnetic recording, including the investigation of the sensitivity of reversal field to timing errors and synchronization margins. The analysis is based on accurate micromagnetic simulations that make no assumptions on the medium parameters.

Structure configurations and method of analysis

The reversal mechanisms are modeled by the Landau-Lifshitz equation [10]:

$$\frac{d\mathbf{m}}{dt} = -\gamma H_K \mathbf{m} \times \mathbf{H}_{\text{eff}} - \alpha\gamma H_K \left(\mathbf{m} \times \left(\mathbf{m} \times \mathbf{H}_{\text{eff}}\right)\right) \tag{1}$$

where $\mathbf{m}=\mathbf{M}/M_s$ is the magnetization $\mathbf{M}$ normalized by the saturation magnetization M_s , t is time, γ is the gyromagnetic ratio, and α is the damping coefficient. The first and second terms in the right hand side of Eq. (1) represent gyromagnetic precession and torque components. The effective field $\mathbf{H}_{\text{eff}}$ is normalized by the element crystalline anisotropy H_k and is given by

$$\mathbf{H}_{\text{eff}} = (\mathbf{k}\cdot\mathbf{m})\mathbf{k} + \frac{\mathbf{H}_{\text{ext}}}{H_k} + 2\frac{M_s}{H_k} l_{ex}^2 \nabla^2 \mathbf{m} + \frac{M_s}{H_k} \nabla \int \frac{\nabla\cdot\mathbf{m}}{|\mathbf{r}-\mathbf{r}'|} d\mathbf{r}' \tag{2}$$

where the first, second, third, and fourth terms represent the normalized perpendicular uniaxial anisotropy field, external (reversal) field, exchange field, and magnetostatic field, respectively. In addition, $l_{\text{ex}} = A^{1/2}/M_s$ is the exchange length with A the exchange constant.

For numerical implementation, the patterned medium elements are discretized into small cells. The magnetostatic field $\mathbf{H}_{stat}$ is determined by allowing for non-uniform magnetization in each cell. All differential operators are evaluated using the second order finite difference scheme. The computation of the magnetostatic field can be accelerated by non-uniform grid algorithms [11, 12]. The techniques developed were used to study basic reversal mechanisms occurring in composite patterned media with perpendicular anisotropy under uniform and non-uniform reversal fields.

Simulation results

To demonstrate properties of composite patterned media, consider a configuration comprising an array of dual layer magnetic dots, recording head, and soft underlayer (SUL) (Fig. 1(a)). In the horizontal cross-section, the dots are square and have size w. In the vertical dimension, every dot is composed of two layers of identical thickness $t_h = t_s = w/2$. The bottom and top layers are magnetically hard (high K_h) and soft ($K_s = 0$), respectively (Fig. 1(b)). The two layers are coupled through their common interface with an exchange energy per surface area J_s.

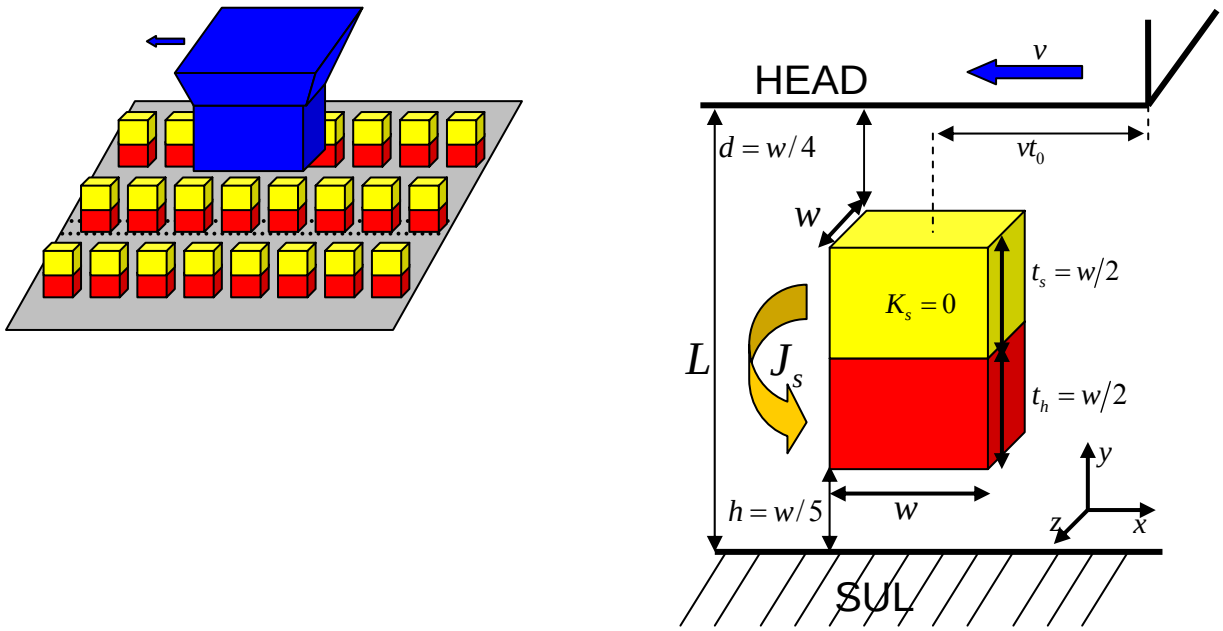

Fig. 1: (a) Dual layer patterned medium. (b) Dual layer dot near an SUL under a moving recording head

First, consider a model where $\mathbf{H}_{ext} = H_{ext}(x)\,\hat{\mathbf{y}}$ is applied to a single dot. The field is applied uniformly across the width (z dimension in Fig. 1(b)) and through the height (y dimension) of the dot, but only over varying percentages of the length (x) direction. Figure 2(a) plots the normalized reversal field H_r / H_k versus normalized exchange coupling per area $J_s/(2K_h t_h)$. Two phenomena are observed. First, for all curves, there exists an optimal value of $J_s / (K_h t_h) \approx 0.32$ leading to the minimal reversal field, which agrees qualitatively with approximate results of recent analytical works [8, 9]. Second, the reversal fields for smaller percentages of the dot coverage increased only by a relatively small amount. The weak increase is associated with highly non-uniform reversal mechanism [4]. It is worthwhile mentioning that all (scaled) results in Fig. 2 (a) remain valid for *any* value of the damping constant α ranging from very small (e.g. $a = 0.01$) to very large (e.g. $a = 1$).

Next, consider a structure that, in addition to the dual layer magnetic dots, incorporates a semi-infinite head moving leftward with a velocity v (Fig. 1(b)). The head field is given by $\mathbf{H}_r = H_{r0}\psi(x - vt, y)\, f(t)$, where H_{r0} is the head (reversal) field

magnitude, $\psi(x,y)$ represents the spatial distribution of the head field [13], $f(t) = (1\text{-}erfc[(t - t_0)/\tau])$ is the function describing the head time dependence with rise time τ and switching time t_0 (i.e. the instant of time when the head switches its field to become positive; $t_0 = 0$ corresponds to the head corner located at the dot center). Figure 2(b) depicts the reversal field vs. normalized time $\Delta_{t0} = vt_0/w$ for different normalized rise times $\Delta_r = vt_0/w$ and different damping constants α. Large positive Δ_{t0} correspond to the dot being in the uniform vertical head field so that the reversal is achieved for low H_{r0}. Negative values of Δ_{t0} correspond to the head's corner being shifted left to the dot so that the reversal can be achieved only for high values of H_{r0}. It is further evident that larger values of τ lead to higher H_{r0} as the dot is exposed to a larger field for a shorter time. It is worthwhile mentioning that for small τ, there is a significant difference in the reversal field in the high damping ($\alpha = 1$) and low damping ($\alpha = 0.01$) regimes, whereas in the case of large τ the difference is minor. The reason for the difference is ultra-fast precessional switching occurring when applied fields have tilted components, the damping parameter is low, and the applied field rise time is short [14]. Note that every curve in Fig. 2(b) is a border between the values of H_{r0} and t_0 that allow reversal (the region to the right of the curve) and does not allow the reversal (the region to the left of the curve). These results are important for phase margin assessments for patterned media.

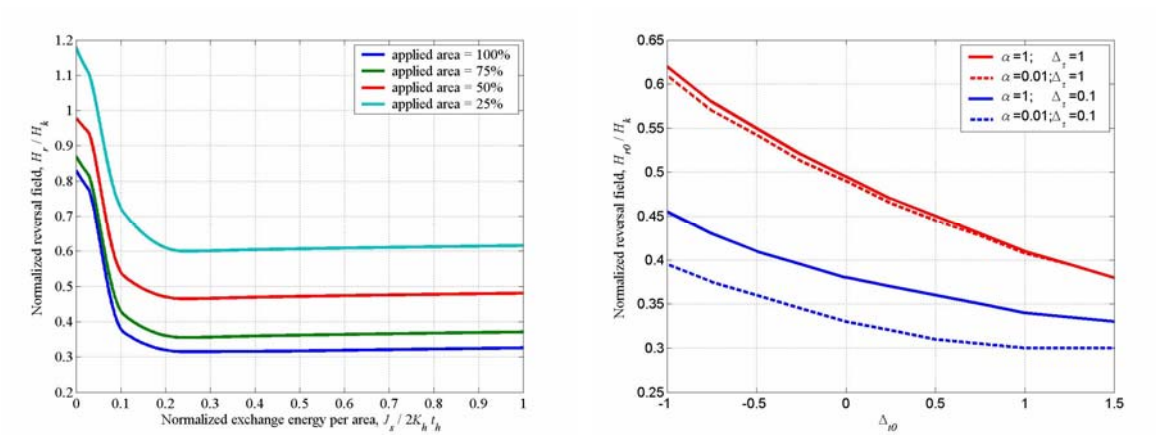

Fig. 2: (a) Normalized reversal field vs. normalized exchange surface coupling for non-uniform reversal fields applied for different area percentages of the composite dot. (b) Normalized reversal field vs. normalized starting time for different switching rise times. In all simulations, the structure parameters were M_s = 500 emu/cc, H_k = 15kOe, $l_{ex} = w$, and $v/w = 10^9$ s^{-1}.

Summary

Magnetization reversal mechanisms in dual (soft and hard) layer elements with parameters suitable for patterned media recording at more than 1Tbit/in^2 have been studied under uniform and non-uniform fields by means of accurate micromagnetic simulations based on the Landau-Lifshitz equation. Optimal ferromagnetic coupling between the soft and hard layers was found that lead to small reversal fields even for very large anisotropy in the hard layer. Under non-uniform fields, only a slight increase of the applied field was required for reversal. In addition, results for timing margins and head fields allowing reversal of the dual layer elements were obtained for a moving semi-infinite head for reasonable medium and head parameters. The effects identified have important consequences in magnetic recording for both down track and cross track phenomena.

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Recent Papers and Invited Talks

Professor Emeritus Ami E. Berkowitz

Hong JI, Solomon VC, Smith DJ, Parker FT, Summers EM, Berkowitz AE. **One-Step Production of Optimized Fe-Ga Particles by Spark Erosion.** *Applied Physics Letters,* vol. 89, no.14, pp. 142506-1-3, October 2006.

Lee DW, Wang SX, Tang Y-J, Hong J-I, Berkowitz AE. **Permeability of Fine Magnetic Particles: Measurements, Calibration, and Pitfalls.** *IEEE Transactions on Magnetics,* vol. 42, no. 10, pp. 3335-3337, October 2006.

Solomon VC, Hong J-I, Tang Y-J, Berkowitz AE, Smith DJ. **Electron Microscopy Investigation of Spark-Eroded Ni-Mn-Ga Ferromagnetic Shape-Memory Alloy Particles.** *Scripta Materialia,* vol. 56, no.7, pp. 593-596, April 2007.

Professor Emeritus H. Neal Bertram

Chaichanavong P, Bertram HN, Siegel PH**. Design Parameter Optimization for Perpendicular Magnetic Recording Systems.** *IEEE Transactions on Magnetics*, vol. 42, no. 10, pp. 2549-2554, October 2006.

Goll D, Macke S, Bertram HN. **Thermal Reversal of Exchange Spring Composite Media in Magnetic Fields.** *Applied Physics Letters,* vol. 90, no. 17, pp. 172506/1-3, April 2007.

Professor Eric Fullerton

Ravelosona D, Mangin S, Katine JA, Fullerton EE, Terris BD. **Threshold Currents to Move Domain Walls in Films with Perpendicular Anisotropy.** *Applied Physics Letters,* vol. 90, no. 7, pp. 72508-1-3, February 2007.

Ravelosona D, Mangin S, Henry Y, Lemaho Y, Katine JA, Terris BD, Fullerton EE. **Current Induced Domain Wall States in CPP Nanopillars with Perpendicular Anisotropy.** J*ournal of Physics D (Applied Physics),* vol. 40, no. 5, pp. 1253-6, March 2007.

Spin-Torque-Induced Reversal in Nanopillars Containing Perpendicularly Magnetized Layers. Presented at the American Physical Society (APS) Meeting, Denver CO, March 2007, (Invited speaker).

Soft X-ray Techniques for Characterizing Magnetic Nanostructure. Presented at Harvey Mudd College, Claremont, CA, April 2007, (Invited talk).

Dr. Gordon Hughes

Security for Disk Drive Data at Rest — New Disk Drive Opportunities. Presented at MEDIA-Tech Conference, October 2006, (Invited paper).

Professor Sungho Jin

Bandaru PR, Park J, Lee JS, Tang YJ, Chen L-H, Jin S, Song SA, O'Brien JR. **Enhanced Room Temperature Ferromagnetism in Co- and Mn-Ion-Implanted Silicon.** *Applied Physics Letters,* vol. 89, no. 11, pp. 112502-1-3, September 2006.

Professor Paul H. Siegel

Taghavi MH, Papen GC, Siegel PH. **On the Multiuser Capacity of WDM in a Nonlinear Optical Fiber: Coherent Communication.** *IEEE Transactions on Information Theory,* vol. 52, no. 11, pp. 5008-5022, November 2006.

Immink KS, Siegel PH (Book Reviewer)**. Codes for Mass Data Storage Systems (Second Edition)** *IEEE Transactions on Information Theory,* vol. 52, no. 12, pp. 5614-5616, December 2006.

Han J, Siegel PH. **Improved Upper Bounds on Stopping Redundancy.** *IEEE Transactions on Information Theory,* vol. 53, no. 1, pp. 90-104, January 2007.

(Continued from page 8)

Soriaga JB, Pfister HD, Siegel PH. **Determining and Approaching Achievable Rates of Binary Intersymbol Interference Channels Using Multi-stage Decoding.** *IEEE Transactions on Information Theory,* vol. 53, no. 4, pp. 1416-1429, April 2007.

Professor Frank E. Talke

Taylor, RJ, Chung M, Talke FE. **Dynamic Simulation of in-plane Transverse Displacement of Tape.** *Microsystem Technologies,* vol. 12, no. 12, pp. 1117-1124, August 2006.

Murthy AN, Feliss B, Gillis D, Talke FE. **Experimental and Numerical Investigation of Shock Response in 3.5 and 2.5 in. Form Factor Hard Disk Drives.** *Microsystem Technologies,* vol. 12, no. 12, pp. 1109-16, August 2006.

Duwensee M, Suzuki S, Lin J, Wachenschwanz D, Talke FE. **Air Bearing Simulation of Discrete Track Recording Media.** *IEEE Transactions on Magnetics,* vol. 42, no. 10, pp. 2489-2491, October 2006.

Xu JF, Kiely JD, Hsia YT, Talke FE. **Head-Medium Spacing Measurement Using the Read-Back Signal.** *IEEE Transactions on Magnetics,* vol. 42, no. 10, pp. 2486-2488, October 2006.

Deoras SK, Talke FE. **Effect of Intermolecular Forces on the Dynamic Response of a Slider**. *Journal of Tribology,* vol. 129, no. 1, pp. 177-180, January 2007.

Raeymaekers B, Etsion I, Talke FE. **The Influence of Operating and Design Parameters on the Magnetic Tape/Guide Friction Coefficient**. *Tribology Letters,* vol. 25, no. 2, pp. 161-171, February 2007.

Professor Jack K. Wolf

Wu Z, Siegel PH, Bertram HN, Wolf JK. **Design Curves and Information-Theoretic Limits for Perpendicular Recording Systems.** *IEEE Transactions on Magnetics,* vol. 43, no. 2, pp. 721-726, February 2007.

The Spring 2007 Research Review and Advisory Council Meeting will be held on May 9-10, 2007. For further information on the Spring Review, please contact Betty Manoulian at 858-534-6707 or bmanoulian@ucsd.edu .

CMRR Research Review Highlights

The Fall Research Review held in October 2006 was a well attended success. Over fifty people from CMRR Industrial Sponsor companies and other invited guests participated in the meeting, including several who participated via teleconference.

In addition to the sessions devoted to technical presentations of CMRR research results, the Review featured a special presentation by **Professor Eric Fullerton** entitled, "Current-Induced Reversal of Magnetic Islands with Perpendicular Anisotropy."

CMRR Sponsor company employees may access the abstracts and viewgraphs of all Research Review presentations on the CMRR website in the Sponsor Resources section at http://cmrr.ucsd.edu/sponsors/subpgset.htm Contact Jan Neumann with any questions regarding Sponsor Resources at jneumann@ucsd.edu .

Sheldon Schultz Prize for Excellence

The Schultz Prize is intended to recognize CMRR graduate students who have distinguished themselves through the creativity of their research and the impact of their publications

The Sheldon Schultz Prize for Excellence in Graduate Student Research was established in 2003 to recognize CMRR graduate students who have distinguished themselves through the creativity of their research and the impact of their publications.

The Prize is named in honor of former CMRR Director, Sheldon Schultz, who skillfully guided the Center from November 1990 through August 2000. The first Schultz Prizes were awarded at the 20th Anniversary Celebration dinner May 6, 2003.

The selection of the recipient is based upon the recommendation of a committee consisting of CMRR faculty members, with input from selected experts in information storage technology. CMRR's goal is to endow the Prize so it can be awarded annually and in perpetuity.

Previous Recipients:

Geoffrey Beach – May 2003
Kai-Zhong Gao – May 2003
Brian Kurkoski – June 2004
Marcus Marrow – June 2004
Joseph B. Soriaga – May 2005
Sharon Aviran – May 2006
Ismail Demirkan – May 2006

Those interested in making a donation of any amount to the Schultz Prize will help move us closer to the endowment target of $50,000. Checks should be made payable to "UC San Diego Foundation" with a notation on the check or a brief cover letter designating the contribution for the "Schultz Prize." Donations are100% tax-deductible, and an official acknowledgement of contributions will be provided.

All correspondence pertaining to the Prize can be directed to:

Professor Paul H. Siegel, Director
Center for Magnetic Recording Research
University of California, San Diego
9500 Gilman Drive, 0401
La Jolla, CA 92093-0401

INSIC Awards

The Information Storage Industry Consortium (INSIC) has awarded research support under the EHDR program to the following:

Professor Frank E. Talke for a project entitled, "Air numerical Simulation and Tribology of Discrete Track and Bit Patterned Media for 1 Tbit/inch Head/Disk Interfaces."

Professor Paul H. Siegel and **Dr. Neal Bertram** for joint research work on "Design Parameter Optimization:Enhanced Channel Modeling and Advanced Coding."

Also awarded under the Tape Program was a grant to **Associate Professor Ray de Callafon** for research on the "Integrated Modeling of Dynamics and Disturbances for Servo Performance Evaluation in a Linear Tape Drive."

Graduate Students & Researchers Near Completion

Student	Level	Advisor	Dept	Research	Completion
Maik Duwensee	Ph.D	Talke	MAE	Patterned media and discrete track recording	2007
Junsheng Han	Ph.D.	Siegel	ECE	Error-correcting codes, iterative decoding, network coding	2007
Aravind Murthy	Ph.D.	Talke	MAE	Head/disk interface simulation, shock modeling of operational and non-operational head disk interface, textured and patterned media	2007
Bart Raeymaekers	Ph.D.	Talke	MAE	Head tape mechanics studies (LTM, dual stage actuator, friction and tribology)	2007
Jianfeng (John) Xu	Ph.D.	Talke	MAE	Head/disk interface, near contact recording, simulation tribology	2007

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