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CMRR Report

Center for Magnetic Recording Research

Number 29 Winter 2008

Research Highlight

Spin Transfer Torques in High Anisotropy Magnetic Nanostructures
by Eric Fullerton
Jordan Katine
Stephane Mangin
Yves Henry
Dafine Ravelosona

Contents:

Paul H. Siegel Elected to NAE

Professor **Paul H. Siegel** – a leading authority on coding for hard disk magnetic recording systems – has been elected to the National Academy of Engineering "for the invention and development of advanced coding techniques for digital recording systems."

Prof. Siegel is an electrical engineering professor and the director of UCSD's Center for Magnetic Recording Research (CMRR) – a collaboration between UCSD, companies in the magnetic recording industry and government agencies. The CMRR mission is to advance the state-of-the-art in magnetic storage, and to produce highly trained graduate students and postdoctoral professionals.

In the 1980s and early 1990s, Siegel was part of an IBM team that helped to revolutionize the hard disk industry through advances in signal processing. Siegel's work on signal processing systems has increased the reliability of information retrieval from hard disk drives. His patents and publications provided part of the framework for the introduction of a signal processing approach called "coded

(Continued on page 11)

Four NAE members (left to right): Prof. Jack K. Wolf, Prof. Paul H. Siegel, Dr. Andrew J. Viterbi, and Dean Frieder Seible.

On February 13, 2008, a reception was held at CMRR to honor Professor Paul Siegel's election to the NAE. It was attended by Chancellor Marye Anne Fox, Professor Emeritus Andrew J. Viterbi, Jacobs School Dean Frieder Seible, and many of Paul's campus colleagues, former students, friends, and family members. Dean Seible presented Paul with an official NAE tie (still being worn by the Dean when the photo above was taken!) and Paul's wife Darcy with a bouquet of flowers. Paul expressed his sincere thanks to his colleagues and family for their enduring support.

MRS Fellow Awarded

Professor **Sungho Jin** has been selected as a Fellow of the MRS (Materials Research Society) for pioneering research on magnetic, superconducting, environmental, nano and bio materials, and for significant publications, patents and industrial applications. The title of MRS Fellow honors scientists who are notable for their distinguished research accomplishments and their outstanding contributions to the advancement of materials research world-wide. The recognition of the newly selected MRS fellows took place at the 2008 MRS Spring Meeting, March 24-28, in San Francisco, CA. Congratulations Sungho.

2008 Sheldon Schultz Prize for Excellence

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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
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Marcus Marrow – June 2004
Joseph B. Soriaga – May 2005
Sharon Aviran – May 2006
Ismail Demirken – May 2006
Maik Duwensee—May 2007
Bart Raeymaekers— May 2007

If you are interested in making a donation of any amount to the **Schultz Prize**, you 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." You can also submit an online donation at http://www.jacobsschool.ucsd.edu/external/external_giving/ Click on "Give Now" and under "fund" select "Schultz Prize."

Your donation is 100% tax-deductible, and an official acknowledgement of your contribution will be provided to you. All correspondence pertaining to the Schultz Prize can be directed to:

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

From the Director

The Center will soon reach a remarkable milestone - the 25th anniversary of its founding. A major reason for this longevity is our strong and vital relationship with our storage industry sponsors.

At CMRR, we are constantly working to add value to that relationship. We are very selective in our choice of students, post-doctoral researchers, and faculty. Internal awards such as the Schultz Prize for Excellence in Graduate Student Research (see p. 2) and the newly created Shannon Memorial Fellowship (see p. 3) encourage the brightest students to direct their energies to advancing the frontiers of knowledge in information storage technology. Our faculty members pursue carefully defined forward-looking programs of fundamental, technologically relevant research, as illustrated in this issue's Research Highlight contributed by our newest chaired faculty member Eric Fullerton. The many external awards received by CMRR faculty and students provide validation of the course that we steer in partnership with CMRR sponsors, as well as with other storage industry colleagues through, for example, active participation in INSIC programs.

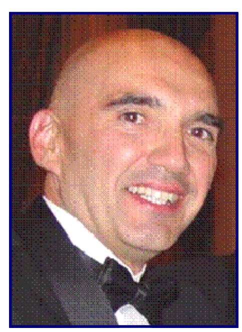
We are always seeking ways to enhance the return on the investment made by our sponsors. With this objective in mind, we will now begin offering through our Information Center a web-accessible recording of all technical presentations, including slides and the accompanying audio track, from our semi-annual Research Reviews (see p. 12 for details.) And let me remind you that DVD recordings of lectures given at our regular CMRR Seminar Series are also available. Please take advantage of these opportunities to "connect" with CMRR!

I hope you enjoy this issue of CMRR Report, and all of us at CMRR thank you for your continued support.

Shannon Graduate Fellowship

Professor **Jack Keil Wolf**, holder of the Stephen 0. Rice Chair in the Center for Magnetic Recording Research at UCSD has established a new endowment fund called the **Shannon Graduate Fellowship Fund**. The purpose of this endowed fellowship is to honor an outstanding graduate student at UCSD whose research is in the field of information theory. The naming of the fund is to commemorate the achievements of the late Claude E. Shannon, a Bell Labs mathematician who in 1948 originated the "information theory" on which the fundamental principles of digital telecommunications and information storage are based. The income from the endowment will be used to fund a graduate fellowship that well be awarded annually. The selection of the Shannon Fellow will be announced at the CMRR Shannon Memorial Lecture which is held annually on Claude Shannon's birthday, April 30th.

Shannon Memorial Lecture



The 6th **Annual Shannon Memorial Lecture** will be held on April 30, 2008, the anniversary of Claude Shannon's birthday. Each year an outstanding information theorist is selected to present the lecture. Professor Sergio Verdú from Princeton University will deliver this year's lecture. The title of his talk is "Information Theory and Minimum Mean-Square Estimation."

Research Highlight SPIN TRANSFER TORQUES IN HIGH ANISOTROPY MAGNETIC NANOSTRUCTURES

Eric Fullerton[1], Jordan Katine[2], Stephane Mangin[3], Yves Henry[4], Dafine Ravelosona[5], *1) University of California, San Diego, 2) Hitachi GST San Jose Research Center - San Jose, 3) Laboratoire de Physique des Matériaux –Vandoeuvre-les-Nancy,4) Institut de Physique et Chimie des Matériaux de Strasbourg, 5) Institut d'Electronique Fondamentale - Orsay*

Introduction

Spin-based electronic devices emerged in the hard disk market a little over a decade ago with the introduction of the giant magneotoresistance (GMR) read head. The basic functionality results from spin dependent scattering of polarized currents by magnetic layers separated by a non-magnetic spacer layer known as GMR for metal interlayers or tunneling magneto-resistance (TMR) for insulating spacer layers. The application of GMR in devices has sparked research in the broader field of spintronics, which relies on manipulating the spin rather than the charge of the electron via spin injection, manipulation and detection and was awarded the Nobel Prize in physics in 2007 to P. Grunberg and A. Fert [1].

While in most magnetic applications the orientations of the magnetic elements within devices are controlled by external magnetic fields, it has recently been appreciated that the relative orientations of nano-magnets can be controlled directly by the injection of spin polarized currents known as spin transfer effects. The basic phenomena of spin transfer occur for current flowing through two magnetic elements separated by a thin nonmagnetic spacer layer. The current becomes spin polarized by transmission through or upon reflection from the first magnetic layer (the reference layer) and mostly maintains this polarization as it passes through the non-magnetic spacer and interacts with the second ferromagnetic layer (the free layer). This interaction leads to a change of resistance depending on the relative orientation of the magnetic layers giving rise to GMR. Commensurate with the GMR, there is a transfer of angular momentum from the polarized current to the free layer magnetization that can be described as an effective torque. This spin transfer torque can exciting spin waves and reverse the direction of the free layer magnetization.

As a result of theoretical predictions by Slonczewski [2] and Berger [3] in 1996 and early experimental verification [4-6] of spin transfer torques, there has been tremendous excitement driven by a number of factors. First, spin transfer effects provide a probe of interactions between spins and magnetism and strengthen our fundamental understanding of magnetic materials [7]. These effects are described by additional terms to the traditional Landau-Lifshitz-Gilbert (LLG) equations. Thus, spin transfer links phenomena of magnetic excitations, damping, reversal, micro-magnetic configurations with spin transport [8].

A second driver for the growth of the study of spin-transfer effects is that experimental fabrication techniques have only recently been developed that allow devices to be readily made at the sub 100 nm dimensions. Such dimensions are needed for the devices to sustain high current densities. Finally, spin transfer has significant potential for novel applications for spin-based devices. Spin transfer effects provides a local means of manipulating magnetization rather than relying on the long-range effects mediated by a remote current via its Oersted field. Potential applications include spin-transfer written magnetic random access memory (MRAM) and high frequency non-linear oscillators [8] and may provide an approach for three dimensional solid state memories or magnetic logic operations.

In this report we highlight recent research on using spin-transfer torques to manipulate nano-elements having strong perpendicular magnetic anisotropy (as shown schematically in Fig. 1). In such structures the magnetic response is more strongly determined by the intrinsic properties of the materials rather than by the shape of the device. The performance of devices is less sensitive to lithography variations and is controllable by judicious engineering of materials properties. Other advantages of high anisotropy materials include: higher stability against thermal activation, more efficient coupling of the spin-current to magnetic excitations, and higher magnetic resonance frequencies. Finally, the study of spin-transfer reversal of perpendicular anisotropy elements provides insight into the magnetic reversal of patterned media elements

Theoretical background

The effects of spin-transfer on the local magnetization can be understood via the LLG equation modified to include spin-torque terms. For the case of the nanopillar where you have free and fixed magnetic layers, the dynamics of the free layer magnetization can be described by:

$$\dot{\mathbf{M}} = -\gamma \mathbf{M} \times \mathbf{H}_{\mathbf{eff}} + \frac{\alpha}{M_S} \mathbf{M} \times \dot{\mathbf{M}} + \eta(\theta) \frac{\mu_B I}{eV} \mathbf{M} \times \left(\mathbf{M} \times \mathbf{M}_{fixed} \right) \tag{1}$$

where M and M_{fixed} are the magnetization direction of the free and fixed layers, H_{eff} is the effective field which includes the dipolar, exchange and anisotropy fields, γ is the gyromagnetic ratio, α is the damping parameter, I is the current, and V is the volume of the free layer on which the spin torque acts. $\eta(\theta)$ is the angle-dependent term that depends on the spin polarization of the current (*p*) and describes the spin-torque efficiency where θ is the angle between the M and M_{fixed}. The first two terms are the standard LLG equations and the third term arises from the spin-transfer interaction between two nanomagnets.

In the simplest geometry shown in Fig. 1 the applied field, M_{fixed}, and the anisotropy are along the z-axis. For a tilting of the free layer away from the z-axis, the damping term will move the magnetization back to the z-axis. When a current is applied, the spin-torque term is either parallel or anti-parallel to the damping depending on the sign of the current. For one sign of the current, the spin-torque opposes the damping, either reduces the effective damping, or for sufficient current strength can destabilize the magnetization and amplify the deviation of the magnetization. This can lead to persistent spin-waves modes or reversal of the magnetization.

The current needed to induce spin transfer reversal assuming a collinear geometry can be estimated from a stability analysis of Eq. 1. The resulting critical current is given by:

$$I_c = \left(\frac{2e}{\hbar} \right) \left(\frac{\alpha}{\eta} \right) M_s V \left(H + H_k \right) \tag{2}$$

where H is the field applied along the easy axis (also the uniaxial anisotropy direction including the dipole field from the reference layer) and H_K is the anisotropy field. For in-plane devices the current must overcome the additional additive term $2\pi M_S$ resulting from the shape anisotropy added to H_K that does not contribute to the stability of the bit against thermal fluctuations but suppresses spin-torque induced switching. This is one of the key advantages of the perpendicular geometry [9].

Magnetic nanopillars

To take advantage of the perpendicular geometry one needs materials system with perpendicular anisotropy while maintaining the other parameters such as *p* and α. In particular the critical current depends linearly on the H_K and α and also on the spin polarization through η. For efficient current reversal, one wants low α and high *p*. In general, there is a close coupling of the magnetic anisotropy, magnetic dynamics and the spin currents in these systems.

While the study of perpendicular anisotropy films is a well established field with current applications as perpendicular recording media, these materials often don't fulfill the requirements for use in magneto-electronic devices. Perpendicular anisotropy materials such as Co/Pt multilayers tend to have high α [10]. In addition, it is thought that the presence of weakly or non-magnetic Pt layers within the magnetic layers leads to high spin-orbit scattering and reduced spin polarization. We found that Co/Ni multilayers are one example of perpendicular anisotropy materials that maintains low α and high *p* and are the basis for the magnetic structures discussed here.

Shown in Fig. 1 is the type of structures used for spin-torque measurements [9, 11, 12]. The magnetic heterostructure is patterned into a nano-pillar sandwiched between a Cu lower lead and a Au upper lead to allow vertical spin transport through the structure. The nano-pillar device is made up of two perpendicular magnetic anisotropy layers separated by a thin Cu layer. One layer is a reference high-coercivity layer which is a $[Co/Pt]_4/[Co/Ni]_2$ multilayer. The second layer is the free layer that reverses under the action of either current or field is a [Co/Ni] multilayers. Shown in Fig. 2a is the resistance (*dV/dI*) versus field applied along the anisotropy axis. The layers switch in discrete jumps between the AP (high resistance) and P (low resistance) alignment with a GMR ratio of 1.0%. The coercive field of both layers has significantly increased over the continuous film values. The reference layer has a coercive field of 10 kOe and the free layer 2.65 kOe.

Shown in Fig. 2b is the resistance versus the dc current bias (I_B) in zero applied field. By cycling the current, there is hysteretic switching between the AP and P configurations. Starting from the P alignment, the free layer switches into the AP configuration for $I_C^{P\text{-}AP}$ = 2.7 mA (7.5x10^7 A/cm^2) and switches back for $I_C^{AP\text{-}P}$= -0.85 mA (-2.6x10^7 A/cm^2). This demonstrates the ability of current to reverse thermally stable, high anisotropy magnetic elements.

Summary

Experiments such as the one shown in Fig. 2 have been extended to include both field and current to map out an H-I_B phase diagram [9,11, 12] and the angular dependence of reversal. These results combined with micromagnetic modeling of the free layer show that, depending on the bias current and applied field, there are regions of irreversible magnetic switching, domain formation, coherent and incoherent spin waves, or static non-uniform magnetization states. Such complex behaviors are somewhat surprising but highlight the complexity of nano-magnetic systems. A complete understanding of these phenomena will provide a clearer picture of magnetization at the nano-scale and allow the potential applications of spin-torques effects to be judged. For applications such as MRAM, lower critical currents for reversal and incorporation with magnetic tunnel junctions are needed. This requires continued research on new and improved materials and exploration of novel device architectures. While challenging the progress in understanding spin torque effects over the last decade [13] suggests there will be new phenomena discovered that drive emerging technologies.

1. E. E. Fullerton and I. K. Schuller, *The 2007 Nobel Prize in Physics: Magnetism and Transport at the Nano-scale*, ACS Nano **1**, 384 (2007).

2. J.C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).

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4. M. Tsoi, A. G. M. Jansen, J. Bass, W. C. Chiang, M. Seck, V. Tsoi, P. Wyder Phys. Rev. Lett. **80**, 4281 (1998).

5. J. Z. Sun, J. Magn. Magn. Mater. **202**, 157 (1999).

6. J.A. Katine, F.J. Albert, R.A. Buhrman, E.B. Myers, D.C. Ralph, Phys. Rev. Lett. **84**, 3149 (2000).

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8. J.A. Katine and E. E. Fullerton, *Device implications of spin-transfer torques*, J. Magn. Magn. Mater. **320**, 1217 (2008).

9. S. Mangin, D. Ravelosona, J. A. Katine, M. J. Carey, B. D. Terris and E. E. Fullerton, *Current-induced magnetization reversal in nanopillars with perpendicular anisotropy*, Nature Materials **5**, 210 (2006).

10. A. Barman, S. Wang, O. Hellwig, A. Berger, E. E. Fullerton, and H. Schmidt, *Ultrafast magnetization dynamics in high perpendicular anisotropy [Co/Pt]n multilayers*, J. Appl. Phys. **101**, 09D102 (2007).

11. D. Ravelosona, S. Mangin, Y. Henry, Y. Lemaho, J. Katine, B. Terris and E. E. Fullerton, *Current induced domain wall states in CPP nanopillars with perpendicular anisotropy*, J. Phys. D: Appl. Phys. **40** 1253–1256 (2007).

12. D. Ravelosona, S. Mangin, Y. Lemaho, J. A. Katine, B. D. Terris and E. E. Fullerton, *Domain wall creation in nanostructures driven by a spin-polarized current*, Phys. Rev. Lett. **96**, 186604 (2006).

13. For general reviews see the *Current Perspectives* sections of J. Magn. Magn. Mater. **320**, 1189 – 1311 (2008).

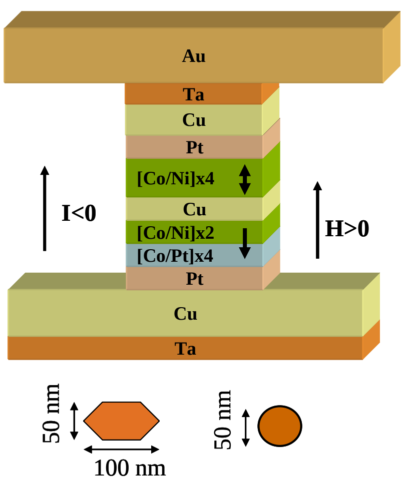


Figure 1: Schematic representation of patterned Co/Ni samples. The reference layer is a composite [Co/Pt]x4/[Co/Ni]x2 multilayer and the free layer is a [Co/Ni]x4 multilayer. The magnetization direction of the reference layer, positive field direction and the direction of electron flow for negative current are shown.

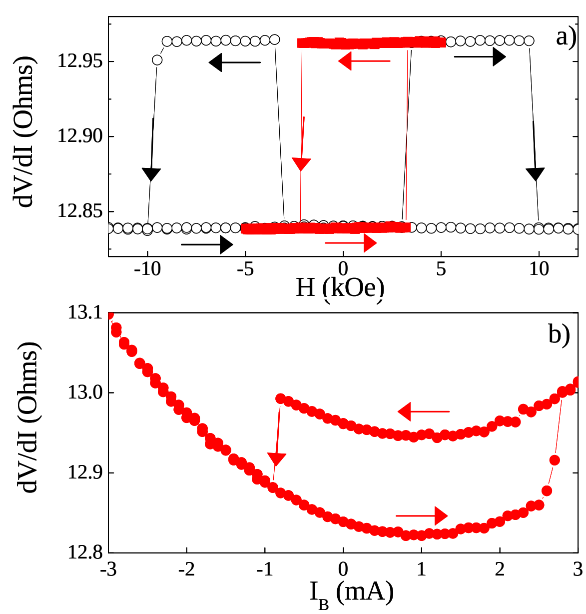


Figure 2: Transport measurements of the 50x100 nm^2 Co/Ni sample. (a) *dV/dI vs. H* for H perpendicular to the film plane. The open symbols correspond to the major loop showing discrete transitions between the P and AP states. The solid symbols are a minor loop where only the free layer reverses with the reference layer magnetization pointing down. (b) *dV/dI vs.* I_B for H=0 showing discrete transitions between the AP and P states.

Selected Papers and Talks

A complete listing of CMRR papers & talks can be found at: http://cmrr.ucsd.edu

Professor Emeritus Ami E. Berkowitz

Invited talk, "A doubly inverted core-shell system: antiferromagnetic MnO nanoparticles with ferrimagnetic Mn_3O_4 shells," 6th International Conference on Fine Particle Magnetism: New Trends in Nanoparticle Magnetism (ICFPM-07) - Rome, Italy, October 2007.

T. Leo, J.I. Hong. **A.E. Berkowitz**, and D.J. Smith, "Correlation of microstructure and magnetic properties for exchange-biased Co ferromagnets grown above and below the diluted antiferromagnet Co(Mg)O," *Journal of Applied Physics*, Vol. 102, No. 12, (Dec. 2007), pp. 123904-1-5.

A.E. Berkowitz, G.R. Rodriguez, J.I. Hong, K. An, T. Hyeon, N. Agarwal, D.J. Smith, and **E.E. Fullerton**, "Antiferromagnetic MnO nanoparticles with ferrimagnetic Mn_3O_4 shells: Doubly inverted core-shell system," *Physical Review B*, Vol. 77, No. 2, (January 2008), pp. 024403-1-6.

Professor Emeritus H. Neal Bertram

S. Karakulak, **P.H. Siegel**, **J.K. Wolf**, and **H.N. Bertram**, "A new read channel model for patterned media storage," *IEEE Transactions on Magnetics*., Vol. 44, No. 1, (January 2008), pp. 193-197.

V. Lomakin, R. Choi, **B. Livshitz**, S. Li, A. Inomata, and **H.N. Bertram**, "Dual-layer patterned media "ledge" design for ultrahigh density magnetic recording," *Applied Physics Letters*, Vol. 92, No. 2, (January 2008), pp. 022502-1-3.

H.N. Bertram, M.E. Schabes, **V. Lomakin**. and **B. Livshitz**, "Nucleation fields in composite medium grains," *Journal of Applied Physics*, Vol. 103, No. 7, (April 2008), pp. 07F508-1-3.

Professor Eric E. Fullerton

O. Hellwig, A. Berger and **E.E. Fullerton**, "Magnetic phase separation in artificial a-type antiferromagnetic films," *Physical Review B (Condensed Matter)*, Vol.75, No.13, (April 2007), pp. 134416-1-5.

M.S. Pierce, C.R. Buechler, L.B. Sorensen, S.D. Kevan, E.A. Jagla, J.M. Deutsch, T. Mai, O. Narayan, J.E. Davies, Liu Kai, G.T. Zimanyi, H.G. Katzgraber, O. Hellwig, **E.E. Fullerton**, P. Fischer, and J.B. Kortright, "Disorder-induced magnetic memory: experiments and theories," *Physical Review B (Condensed Matter)*, Vol.75, No.14, (April 2007), pp. 144406-1-23.

O. Hellwig, A. Berger, T. Thomson, E. Dobisz, Z.Z. Bandic, H. Yang, D.S. Kercher, and **E.E. Fullerton**, "Separating dipolar broadening from the intrinsic switching field distribution in perpendicular patterned media," *Applied Physics Letters*, Vol.90, No.16, (April 2007), pp. 162516-1-3.

O. Hellwig, A. Berger, J.B. Kortright, **E.E. Fullerton**, "Domain structure and magnetization reversal of antiferromagnetically coupled perpendicular anisotropy films," *Journal of Magnetism and Magnetic Materials*, Vol. 319, No. 1-2, (December 2007), pp. 13-55.

Dr. Gordon F. Hughes

G. F. Hughes, "Hard Drive! As the Disc Turns," available from Amazon: http://www.amazon.com/Hard-Drive-As-Disc-Turns/dp/1419634615.

Professor Sungho Jin

H. Hong, B. Wright, J. Wensel, **S. Jin**, X.R. Ye, and W. Roy, "Enhanced thermal conductivity by the magnetic field in heat transfer nanofluids containing carbon nanotubes," *Synthetic Metals*, Vol.157, (2007), pp. 437-440.

I-C. Chen, L.H. Chen, C.A. Orme, and **S. Jin**, "Control of curvature in highly compliant probe cantilevers during carbon nanotube growth," *Nano Letters*, Vol. 7, No. 10, (2007), pp. 3035-3040.

B. Wright, D. Thomas, H. Hong, L. Groven, J. Puszynski, E. Duke, X.R. Ye and **S. Jin**, "Magnetic field enhanced thermal conductivity in heat transfer nanofluids containing Ni coated single wall carbon nanotubes," *Applied Physics Letters*, Vol. 91, (2007), pp. 173116.

Professor Paul H. Siegel

H.D. Pfister and **P.H. Siegel**, "Joint iterative decoding of LDPC codes for channels with memory and erasure noise," *IEEE Journal Selec. Areas Commun., Special Issue on Equalization Techniques for Wireless Communications Theory & Applications*, Vol. 26, No. 2, (February 2008), pp. 320-337.

J. Chen, **P.H. Siegel**, "Markov processes asymptotically achieve the capacity of finite-state intersymbol interference channels," *IEEE Transactions on Information Theory*, Vol. 54, No. 3, (March 2008), pp. 1295-1303.

Professor Frank E. Talke

A.N. Murthy, M. Pfabe, J. Xu, and **F.E. Talke**, "Dynamic response of 1-in. form factor disk drives to external shock and vibration loads," *Microsystem Technologies*, Vol. 13, No. 8-10, (May 2007), pp. 1031-1038.

(Continued from page 8)

B. Raeymaekers and **F.E. Talke** "Lateral motion of an axially moving tape on a cylindrical guide surface," *Journal of Applied Mechanics*, Vol. 74, No. 5, (September 2007), pp. 1053-1056.

B. Raeymaekers, I. Etsion, and **F.E. Talke**, "A model for magnetic tape/guide friction reduction by laser surface texturing," *Tribology Letters*, Vol. 28, No. 1, (October 2007) pp. 9-17.

J. Lee, S-W. Chun, H-J. Kang, and **F.E. Talke**, "The effect of UV stabilizer on the photo degradation of perfluoropolyether lubricants used in hard disk," *Tribology Letters*, Vol. 28, No. 2, (November 2007), pp. 117-121.

A.N. Murthy, I. Etsion, and **F.E. Talke**, "Analysis of surface textured air bearing sliders with rarefaction effects," *Tribology Letters*, Vol. 28, No. 3, (December 2007), pp. 251-261.

Professor Jack K. Wolf

S. Aviran, **P.H. Siegel**, and **J.K. Wolf**, "Optimal parsing trees for run-length coding of biased data," *IEEE Transactions on Information Theory*, Vol. 54, No. 2, (Feb. 2008), pp. 841-849.

Graduate Students & Researchers Near Completion

Student	Level	Advisor	Dept	Research	Completion
Ralf Brunner	Ph.D.	Talke	MAE	Carbon coating and lubrication studies for wear protection of the head/disk interface	Summer 2008
Mohammad Hossein Taghavi	Ph.D.	Siegel	ECE	Information theory; algebraic and graph-based decoding algorithms for error-correcting codes; detection techniques; optimization methods	Summer 2008
Zheng Wu	Ph.D.	Siegel/ Wolf	ECE	Recording channel modeling; equalization and detection techniques; error-control coding algorithms and architectures	Fall 2008

The Spring 2008 Research Review and Advisory Council Meeting will be held on April 23-24, 2008. 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 2007 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 **Dr. Stuart S.P. Parkin,** from IBM Almaden Research Center entitled, "The Magnetic Racetrack Memory: A Novel Spintronic Device Based on Current-Induced Precessional Motion of Domain Walls."

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 .

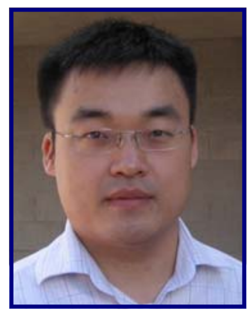
Graduate Degrees Awarded

Andrew Gapin, a member of Professor Sungho Jin's group received his Ph.D. in October 2007. His dissertation was entitled "Fabrication and Applications of Nanocomposite Structures Using Anodized Aluminum Oxide Membranes." His main research focus was on magnetic recording media fabrication. After graduation, Andrew plans to travel in South America and return to seek employment in the science and technology industries.

Junsheng Han, a member of Professor Paul H. Siegel's group received his Ph.D. in April 2008. His dissertation was entitled "Code Representation and Performance of Graph-Based Decoding." Junsheng has accepted a position at Qualcomm Corporation in San Diego.

Jianfeng (John) Xu, a member of Professor Frank Talke's lab received his Ph.D. in January 2008. His dissertation was entitled "Head/disk Interface Tribology in the Nanometer Regime." John has accepted a position at Western Digital, a CMRR sponsor.

New Postdoctoral Scholar



Hui Li is a new postdoctoral scholar in Professor Frank Talke's group. He received his double bachelor degrees in mechanical science & engineering and economics from Huazhong University of Science and Technology. He received his Ph.D. in electrical and computer engineering from National University of Singapore in 2005. His research areas include design and modeling of advanced head-disk interfaces for magnetic recording and tribology and head-disk interface technology for magnetic recording. Welcome Hui.

New Graduate Student and New Visitor

Tasha Vanesian, an ECE graduate student of Professor Ken Kreutz-Delgado is working with CMRR Project Scientist Gordon Hughes on drive systems. In 2003, Tasha received her B.S. in electrical and computer engineering from the California Institute of Technology. In 2006, she was awarded her M.S. degree from UCSD. In 2007, Tasha received the best student paper award from the IEEE Symposium on Computational Intelligence in Security & Defense Applications.

Andrea Tullj is a new visiting student in Professor Frank Talke's lab. He received his B.S. and M.S. degrees in aerospace engineering from the University of Bologna. He is currently a Ph.D. candidate at the University of Bologna. At CMRR , Andrea will participate in the academic research training program in composite materials.

(Continued from page 1)

partial response, maximum likelihood" (PRML) which is used in every disk drive today.

PRML, along with the introduction of advanced heads and disks, enabled the extremely rapid growth in capacity of magnetic hard disk drives. A one gigabyte hard disk drive in 1984 cost approximately $50,000 and was the size of a small washing machine. Today, mp3 players like iPods contain drives with 30 times this capacity and these are small drives by today's standards.

For information to be stored on a hard disk, electronic signals carrying the data first travel down a wire to one of the disk's writing heads. To record this information, the write heads leak flux which results in information stored on the disk.

Retrieval of this stored information requires a read head flying very close to the disk to read the information as pulses. These pulses must be converted back to electronic signals in an ultra reliable way – and this is where Siegel's work enters the picture.

Hard disk storage capacity is increased by packing more bits per unit of surface area. This increased density causes interference among read pulses – a phenomenon known as intersymbol interference or ISI – and makes reliable retrieval of data from hard disks more challenging.

One way to deal with ISI would be to narrow the pulses to reduce interference among pulses, but this increases the noise. Another approach could be to increase the space between bits on the hard disk thus increasing the inter-pulse distance – but that is counterproductive to the goal of increasing a disk's storage capacity.

Siegel was part of the IBM team that came up with a powerful solution to the ISI problem using signal processing called "modulation coding." In particular, he was the co-inventor of a kind of modulation code called "spectral null codes." This was the first comprehensive class of codes that allowed PRML systems to operate at a lower signal-to-noise ratio than uncoded PRML systems. He also invented a decoder for these codes that was much simpler than the optimal decoder but gave essentially the same performance.

With this work, Siegel demonstrated that ISI complications to the read process can be mitigated with signal processing. He and his collaborators showed that you can control this interference and then use the Viterbi algorithm to unscramble the PRML.

"Paul worked on finding codes that give better performance when the PRML is unscrambled by the Viterbi detector," said Jack Keil Wolf, the Stephen O. Rice Professor of Magnetics at the Department of Electrical and Computer Engineering at the Jacobs School.

The Viterbi algorithm and detector are named after their inventor, Andrew Viterbi, a co-founder of both Linkabit Corporation and Qualcomm Inc. In the 1970s and 1980s, Viterbi spent time as a UCSD professor while working at Linkabit and later at Qualcomm. He is now an Emeritus Professor at UCSD.

"Paul's early work at IBM was on both modulation codes and error correction codes. He showed that you want to prevent certain sequences from being written on the disk, even if those sequences correspond to the data. For example, if you write all zeros, nothing will come off the drive when you read it and this means you lose the timing, and you want to avoid that," said Wolf who is also a member of the National Academy of Engineering and leader of the Signal Processing Group within UCSD's CMRR.

More recently, Dr. Siegel introduced iterative techniques for applications in storage. Several manufacturers are now developing read-write chips which utilize this principle. At CMRR, Siegel oversees research activities on a wide range of issues related to digital data storage and communications. He leads the Signal Transmission and Recording Group (STAR) at UCSD and participates in UCSD's Center for Wireless Communications (CWC). Siegel is also an academic participant in the UCSD division of Calit2, and led the networked infrastructure "layer" during the institute's formative years. As an information theorist, Siegel is also a faculty member of Calit2's Information Theory and Applications Center (ITA). - *Daniel Kane*

Gifts, Grants and Awards

The Information Storage Industry Consortium (INSIC) has extended the research support provided by the EHDR program to **Professor Frank Talke** for his research in "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. H. Neal Bertram's** joint research on "Design Parameter Optimization: Enhanced Channel Modeling and Advanced Coding" has also been extended.

Hard Drive! As the Disc Turns

Gordon Hughes, a CMRR Project Scientist, and former Associate Director has written a new book entitled, "Hard Drive! As the Disc Turns." This book tells the remarkable story of Seagate Technology, as told through the eyes of one of Seagate's early engineering executives.

This book is available from Amazon (http://www.amazon.com/Hard-Drive-As-Disc-Turns/dp/1419634615/ref=si3_rdr_bb_product).

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New Calendar

CMRR has compiled an extensive calendar of forthcoming workshops, courses, meetings, symposia, and conferences related to the recording industry. Our calendar is located under the "Education" or "News" sections of the CMRR home page. The URL is: http://cmrr.ucsd.edu/education/calendar.shtml .

If you would like to post your workshops, meetings etc., please send information to jneumann@ucsd.edu .

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