The Role of Universities in the Development of Hard Disk Drives
ハードディスクドライブ開発における大学の役割り

Dr. James W. Harrell

Professor of Physics, Department of Physics & Astronomy and the Center for Materials for Information Technology, University of Alabama

Hard disk drives (HDDs) represent a remarkable technology. The storage capacity, performance, size and affordability of HDDs have improved dramatically since the first commercial drive, the RAMAC, was introduced by IBM in 1956. The RAMAC had a storage capacity of 5 M Bytes (MB) and consisted of fifty 24 inch disks. The rental price for 1 MB of storage was $130/month[(1)]. Today one can purchase a 3.5 inch drive for a desktop PC with a capacity of 2 TB for well under $200. An often used measure of this improvement is the increase in areal density over time. The RAMAC had a storage density of 2 kbits/in^2; whereas the storage density of high-end drives now exceeds 500 Gbits/in^2. HDD storage densities have increased nearly exponentially in time. Much of this increase has been a result of engineering developments that have allowed a scaling down of all relevant dimensions. However, this growth would not have been sustained without new technologies that were based on discoveries resulting from basic research, much of which has been done at universities throughout the world.

One of the main reasons for the continued increase in storage densities has been the development of read heads with increasing sensitivity, allowing the detection of ever smaller bits. One of the most notable contributions to this development was the discovery of Giant Magnetoresistance (GMR) in 1988 by Abert Fert at the University of Paris-Sud[(2)] and Peter Grünberg at Julich Research Center[(3)], for which they received the Nobel Prize in 2007. GMR read heads were first introduced in hard drives in 1997 as a replacement for MR heads and allowed the detection of ever smaller bits. Heads based on Tunneling Magnetoresistance (TMR) began to replace GMR heads in 2005. TMR was discovered by Jullière at the University of Rennes in France[(4)]. The original effect was observed in Fe/Ge-O/Co at 4.2 K but was very small at room temperature. Research done by Miyazaki at the University of Tohoku[(5)], Moodera at MIT[(6)], and others led to the development of TMR stacks with amorphous Al_2O_3 tunnel barriers with high room temperature sensitivity which was used in the first TMR heads. Current TMR read heads now make use of crystalline MgO as the tunnel barrier, which greatly enhances the magnetoresistance. Enhanced TMR using MgO was predicted theoretically by Butler at Oak Ridge National Laboratory (now at the University of Alabama[(7)]) and Mathon at City University in London[(8)].

University researchers have also played an important role in the development of new magnetic media. Conventional media have a granular structure with ten's of grains making up a single bit. Decreasing bit sizes have required media with deceasing grain sizes. Grain sizes in current media consisting of CoPt-based alloys are smaller than 10 nm and are rapidly approaching the superparamagnetic (SP) limit. In order to delay the SP limit, materials with higher magnetocrystalline anisotropy energy (MAE) must be employed. For grains with uniform anisotropy which reverse coherently, higher MAE means that higher write fields are required, but this is limited by the saturation magnetization of the head. Beginning in 2005, the HDD industry made a rapid transition from longitudinal to perpendicular recording (PMR). One of the main advantages of PMR was that it allowed a head configuration giving a larger write field. PMR is attributed to work originally done in 1976 by Iwasaki at Tohoku University[(9)]. Recent work done by Victora at the University of Minnesota[(10)] and Suess at Vienna University of Technology[(11)] has shown that magnetic media with appropriately designed MAE gradients can have a reduced switching field to thermal stability ratio. Appropriately graded media can further extend the SP limit. Other technologies that are under consideration for extending the SP limit include bit patterned media (for increasing the 'grain' size) and heat assisted magnetic recording (for reducing the required write field).

FePt is a prime candidate high anisotropy material for new media. In the ordered $L1_0$ phase, its anisotropy is approximately 10 times that of the CoPt-based alloys. Shouheng Sun (then at IBM and now at Brown University) demonstrated that FePt nanoparticles with narrow size distribution could be chemically synthesized and could self-assemble into highly ordered arrays[(12)]. This led to great interest in

chemically synthesized nanoparticles as potential new media. Subsequent research, much of which was done at universities, has shown that fabricating media using chemical synthesis is extremely challenging, and more attention is now directed at fabricating FePt media using sputter deposition. As an example, I note some of the work done on FePt at the University of Alabama. Butler and Chepulski showed theoretically that FePt nanoparticles cannot be fully ordered and the maximum order parameter decreases with decreasing particle size.[13] Thompson, Nikles, and I demonstrated that certain metal additives can significantly reduce the ordering temperature, but enhance sintered grain growth. We also showed that nanoparticles, although uniform in size, can have a considerable compositional and anisotropy distribution[14]. These findings are also relevant to sputtered granular FePt films. One of the challenges with sputtered FePt films is limiting grain growth while thermally annealing the films to obtain the ordered phase. Yuki Inaba, working with Thompson and myself, recently studied the effect of pulse laser processing on chemical ordering and grain growth of FePt films.[15] The study demonstrated that chemical ordering can be obtained in the millisecond regime and that, compared with conventional annealing, grain growth during ordering is reduced. (Inaba is currently working at Fuji Electric on HDDs.)

Clearly, universities have played a significant role in HDD development and will continue to do so in the future. University-industry interactions are critical in this effort and their research can be complimentary. Universities are not structured for short-term research. Much of the university research is done with and by graduate students whose dissertation projects typically takes several years. Industry, on the other hand, is motivated by market concerns and has the resources for rapid product development. In order to promote university-industry interactions, several university research centers related to magnetic recording have been established in the US during the past few decades. These include the Data Storage Systems Center (DSSC) at Carnegie Mellon University, the Center for Magnetic Recording Research (CMRR) at UC San Diego, the Center for Micromagnetics and Information Technologies (MINT) at the University of Minnesota, and the Center for Materials for Information Technology (MINT) at the University of Alabama, as well as several other centers. The larger centers typically have industrial sponsors which provide financial support for research and provide guidance on technologically relevant problems. In return, the centers hold annual and bi-annual reviews during which the research results are presented. Some centers also host industry scientists and engineers for extended periods of time and sponsor topical workshops for industry. One of the important roles played by universities is training of graduate students and postdoctoral fellows for employment by industry. At the MINT Center at the University of Alabama, the majority of graduate students and postdocs go into the information storage industry. Some of these students hold internships in industry during part of their graduate study.

The great New York Yankees baseball catcher Yogi Berra is famously quoted as saying "It's tough to make predictions, especially about the future." Likewise, no one really knows the future of magnetic recording. What we do know, however, is that it will be unlike the past since exponential growth cannot be indefinitely sustained. It should be a challenging and exciting adventure in which universities are expected to play a critical role.

References

(1) http://www.magneticdiskheritagecenter.org/MDHC/RAMACBrochure.pdf

(2) M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas (1988). "Giant Magnetoresistance of (001) Fe/(001) Cr Magnetic Superlattices". *Physical Review Letters* **61** (21): 2472-2475.

(3) P. Grünberg, R. Schreiber, Y. Pang, M. B. Brodsky, and H. Sowers (1986). "Layered Magnetic Structures: Evidence for Antiferromagnetic Coupling of Fe Layers across Cr Interlayers". *Physical Review Letters* **57** (19): 2442-

2445.
(4) M. Jullière (1975). "Tunneling between ferromagnetic films". *Phys. Lett.* **54A**: 225–226.
(5) T. Miyazaki and N. Tezuka (1995). "Giant magnetic tunneling effect in Fe/Al_2O_3/Fe junction". *J. Magn. Magn. Mater.* **139**: L231–L234.
(6) J. S. Moodera *et al.* (1995). "Large Magnetoresistance at Room Temperature in Ferromagnetic Thin Film Tunnel Junctions". *Phys. Rev. Lett.* **74**: 3273–3276.
(7) W. H. Butler, X.-G. Zhang, T. C. Schulthess, and J. M. MacLaren (2001). "Spin-dependent tunneling conductance of Fe/MgO/Fe sandwiches". *Phys. Rev. B* **63**: 054416.
(8) J. Mathon and A. Umerski (2001). "Theory of tunneling magnetoresistance of an epitaxial Fe/MgO/Fe (001) junction". *Phys. Rev. B* **63**: 220403.
(9) S-I. Iwasaki (2004), "Development of perpendicular magnetic recording conference", *J. Magn. Magn. Mater.* 287: 1–8.
(10) R.H. Victora and X. Shen (2008), "Exchange Coupled Composite Media," *Proceedings of the IEEE* 96: 1799–1809.
(11) D. Suess (2006), "Multilayer exchange spring media for magnetic recording". *Appl. Phys. Lett.* **89**, 113105-1-3.
(12) S. Sun, C. B. Murray, D. Weller, L. Folks, and A. Moser (2000), "Monodisperse FePt Nanoparticles and Ferromagnetic FePt Nanocrystal Superlattices," *Science* **287**: 1989–1992.
(13) R.V. Chepulskii and W. Butler (2005), "Temperature and particle-size dependence of the equilibrium order parameter of FePt alloys", *Phys. Rev. B.* **72**: 134205-1-8.
(14) J. W. Harrell, S. Kang, D. Nikles, G. Thompson, S. Shi, C. Srivistava, "FePt and Related Nanoparticles," in *Nanoscale Magnetic Materials and Applications, editors* J. Ping Liu, Eric Fullerton, Oliver Gutfleisch, and David Sellmyer, Springer, 2009.
(15) Y. Inaba, S. Kang, G.B. Thompson, J.R. Izatt, I. Zana, J.W. Harrell, Y. Kubota, and T.J. Klemmer (2009), "L10 ordering of FePt thin films using sub-10 millisecond laser pulses," *J. Appl. Phys.* **105**, 07B715-1-3.

■和文抄録（社内にて作成）

1956年に業務用の最初のハードディスクドライブRAMACがIBMによって発表されて以来，HDDの記憶容量，性能，サイズおよび価格は，飛躍的に改善されてきた。この進化を支えているのは，指数関数的に続く面記録密度の伸長である。これには世界中の大学で実施された基礎研究とそこから生まれた発見が大きく貢献している。

第一は，微細なビットを検出する，高感度な再生ヘッドの開発である。巨大磁気抵抗効果（GMR）の発見，トンネル磁気抵抗効果（TMR）の発見，その効果を室温で達成したアモルファス酸化アルミニウムによるトンネル障壁の研究，磁気抵抗を大幅に高めることに成功した結晶性MgOによるトンネル障壁の研究などの成果が，再生ヘッドへ次々と導入されている。

第二は，磁気記録媒体の開発である。垂直磁気記録の研究，結晶磁気異方性エネルギーの勾配を適切に制御することで熱安定性とスイッチング磁界の低減を両立した媒体の研究，ビットパターンドメディアの研究，熱アシスト磁気記録媒体の研究，結晶磁気異方性エネルギーそのものを高めるFePt規則合金の研究がある。著者が所属するアラバマ大学においては，FePtに関する研究成果を挙げている。HDD業界は2005年に，従来の長手磁気記録から垂直磁気記録への移行を急速に進めた。

大学が，今後ともHDD開発の一翼を担っていくためには，大学産業間の相互交流が重要である。米国では過去数十年の間に，磁気記録に関するいくつかの大学研究センターが設立された。センターには，研究に対して財政支援を行い，技術的な関連問題について助言を与える企業スポンサーがつき，センターは見返りとして，レビュー会議や話題性のある研究会を開催する。産業界から来た大学院生および博士研究員を教育することも大学の重要な役割の一つである。大学院在籍期間中に，インターンシップ制度を活用し，業界で就業経験を積む学生も多い。

磁気記録の将来について正確に予測することは難しいが，過去と違ったものになることは間違いない。それは，大学にとって挑戦しがいのある魅力的な冒険になるだろう。