Best of Intermag 2009

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Intermag 2009

- 86 Sessions/964 papers/8 invited symposia/will be in IEEE Trans. Mag
- Attendance: 840 from 37 countries-impacted by economy & H1N1 flu
- 15 Exhibitors
- Tutorial: Magnetism – CMOS Integration
- Plenary Speaker: Stan Trout, Spontaneous Materials
  “Rare Earth Permanent Magnets Raw Materials, Magnets, & Opportunities”
- Recognition: R. Wood, HGST Mag. Soc. Achievement Award
  S. Wang, Stanford IEEE Fellow
- 2008 Dist. Lecturers: P. Freitas, S. Parkin, R. Stamps, B. Terris

DISKCON USA 2009/Best of Intermag / R.F. Hoyt
Sessions Overview: Storage/HDD related

- 31/86 Sessions, (306/964 papers)
  - Heads (28) 3
  - MR (48) 5
  - Tunnelling (40) 3
  - Mag. Mem/Spintronics (45) 7
  - Disks/Media (63) 5
  - Mag. Recording/Integ. (64) 6
  - Head-Disk Interface (18) 2

- 3/8 Symposia
  - AA Current-Induced Domain Wall Motion
  - EA New Materials for CPP-GMR Devices
  - FA Shingled Writing & 2D Magnetic Recording
Sessions Details

• Heads & MR
  • Heads (28)
    DC(8)  Recording Head & Materials
    EQ(10) Exchange Bias (I)
    FG(10) Exchange Bias (II)

• MR (48)
  AQ(11) Spin Transport & Magnetoresistance (I)
  GF(11) Spin Transport & Magnetoresistance (II)
  DB(7)  MR-based Sensors
  ES(13) Magnetoresistive & Magneto Caloric Materials
  **EA(6) Symp. on New Materials for CPP-GMR Devices**
Enhancement of CPP-GMR by using spin-polarized ferromagnetic metals with high resistivity for future high-density magnetic read-heads.

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Advanced Magnetic Recording Lab., Fujitsu Laboratories Ltd., Atsugi, Japan

In recent magnetic recording read-heads, current perpendicular to plane - tunneling magnetoresistance (CPP-TMR) technology has been used to enhance the output signal. Development of a new tunneling barrier such as MgO makes the performance much better and leads to long-term utilization of CPP-TMR in a read-head sensor. However, its high specific resistance, RA (resistance area product) is a critical obstacle for downsizing the sensors for future fast data transfer. Moreover, it is difficult to keep high output and barrier reliability while reducing the RA.

On the other hand, CPP giant magnetoresistance (GMR) sensor can be applied for higher areal densities in terms of sensor resistance, because it uses metallic spin-valve (SV) films and therefore has quite a low RA of around or below 0.1 Ωμm². Accordingly, the CPP-GMR is expected to replace the current CPP-TMR. However, the small resistance-change area product (∆RA) is a major concern for realizing a CPP-GMR read-head. Several approaches to enhance the ∆RA have been proposed [1-6]. One of the recent hopeful suggestions is to use the half-metallic materials such as Heusler alloy [3-5]. It is expected to show large ∆RA due to high efficiency of spin filtering. However, the way to order its crystalline-structure for half metallicity during the fabrication process of magnetic recording-head products must be solved.

In this paper, we show a method that utilizes magnetic materials with high resistivity (ρ) and a certain spin asymmetry in spin-dependent bulk scattering (β) for free and reference magnetic layers in a CPP-SV system. According to the Valet and Fert model [7], when high ρ magnetic material has moderate β, even much larger ∆RA can be obtained compared to the material which has typical ρ and high β. However, it is usually difficult to satisfy both high ρ and moderate β. When an additional element is added much to a standard CoFe material to increase the ρ, spin-dependent bulk scattering is usually lost. However, when Al or Ge is added to the CoFe, not only increase in the ρ but also upkeep of β is observed, leading to large ∆RA from 7 to 9 mΩμm² in a 40-nm thick dual SV system, which is about four times larger ∆RA than that of the CoFe [2, 6]. In this case, the β is estimated to be from 0.5 to 0.6 by the Valet and Fert model despite their ρ of more than 100 μΩcm. These large ∆RAs are observed in relatively wide composition ranges. Therefore composition margins are not so severe unlike Heusler material which needs a chemically stoichiometric composition. Additionally, the increment of RA is less than 30% even with such high ρ materials, because parasitic resistance of such as an antiferromagnet is dominant in the SV system. Low coercivity in the free layer and high pinning field in the reference layers have also been confirmed.

Another important factor for the sensor is to obtain a high critical current density, Jc, which is mainly limited by spin transfer torque effect. It is because read-head output is basically proportional to a product of the ∆RA and Jc. We investigated Jc of the CPP-SV systems with the high ρ magnetic materials by measuring ∆RA dependence on applied current density. When the CoFeGe high ρ material is used, the Jc in a single SV system is about 35 MA/cm², which is almost the same as that of the CoFe standard material. Moreover, it increases up to about 110 MA/cm² in a dual SV system by spin torque canceling effect [8].

We have confirmed that both large ∆RA and Jc are achievable by using a high resistivity magnetic material and that implies the possibility of high performance CPP-GMR heads.


Table: Properties of films and CPP-SV elements

<table>
<thead>
<tr>
<th>Material</th>
<th>ρ (μΩcm)</th>
<th>β</th>
<th>∆RA (mΩμm²)</th>
<th>Jc (MA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoFe</td>
<td>12</td>
<td>062</td>
<td>1.0</td>
<td>7</td>
</tr>
<tr>
<td>CoFeGe</td>
<td>150</td>
<td>0.5</td>
<td>0.6</td>
<td>28</td>
</tr>
<tr>
<td>CoFeGe</td>
<td>114</td>
<td>0.6</td>
<td>0.7</td>
<td>38</td>
</tr>
</tbody>
</table>

Total thicknesses of single and dual SV are 30 and 40 nm, respectively.
All-metal current-perpendicular-to-the-plane (CPP) giant magneto-resistive (GMR) sensors are an attractive follow-on reader technology to tunnel-magneto-resistance (TMR) sensors as magnetic recording densities approach 1 TBit/in².1,2 With typical resistance-area products in the range 0.03-0.10 Ω-μm², CPP-GMR sensors can exhibit low resistance < 500 Ω and therefore low noise even at sensor dimensions below 30 nm. Compared to TMR sensors, the magneto-resistance (ΔR/R) of CPP-GMR sensors increases with thicker magnetic layers due to spin-diffusion length effects, but the thickness is limited by the desired shield-to-shield spacing (which determines the maximum linear density). Among the challenges that CPP-GMR sensors face are low signal levels due to their low resistance, low ΔR/R for thin magnetic layers, as well as current-induced noise and magnetic instability from spin-torque effects. We will discuss progress achieved in developing advanced materials and multilayer structures for CPP-GMR sensors for ultra-narrow magnetic recording head sensors.

We show that several pathways are available to increase signal and reduce spin-torque effects in CPP-GMR sensors. For example, highly spin-polarized chemically ordered Heusler alloys can be implemented in the reference and free magnetic layers to increase ΔR/R. However, these ordered alloys are challenging to synthesize in a thin film form within the low growth and post-annealing temperature limitations. Among the Co$_2$Mn(Si, Ge, Al) full-Heusler alloys, Co$_2$MnGe crystallizes at the lowest temperature. Accordingly, Co$_2$MnGe spin-valves exhibit higher magnetic moment and resulting ΔR/R for given magnetic layer thickness (Fig. 1a and 1b). Still, further deposition and processing optimization is required to improve the applicability of these alloys to realistic sensor structures. Another class of magnetic materials that can be used to enhance ΔR/R are high resistivity magnetic alloys like CoFeAl or CoFeGe with a short spin-diffusion length of about the same order as the typical magnetic layer thickness, so that spin-scattering is maximized within the magnetic layer thickness and high ΔR is achieved.3-5

Several strategies can be employed to reduce or eliminate spin-torque induced instabilities. For example, these instabilities are reduced (while ΔR/R is increased) in a dual-spin-valve sensor due to the symmetric arrangement of the two reference layer structures.6,7 However, the ultimate performance of a dual spin-valve is limited by its relatively large shield-to-shield spacing and a complex stack structure. More recently, it was shown that spin-torque instabilities can also be suppressed (while ΔR/R is also increased) by using a synthetic free layer design in which the antiparallel coupling allows for extra free layer thickness,8,9 provided the electron current is flowing from the free to the pinned layer. Yet another successful path to suppress spin-torque instabilities is the addition of rare-earth cap layers that enhance the damping of the free layer. These layers are applied extrinsically to the stack and therefore do not decrease ΔR/R significantly.10

High film-level ΔR/R of ~ 8% has been obtained with a suitable choice of materials even for relatively thin sensors stacks < 45nm. However, even the most advanced structures with antiparallel coupled free layers or damping layers still suffer from significant signal roll-off under realistic voltage bias conditions. Thus a further reduction of spin-torque excitations along with a further increase in ΔR/R are key to the successful implementation of CPP-GMR sensors in future high-density recording heads.

Figure 1 (a) ΔR/R of simple spin-valves having 50 Å of Co$_2$MnGe, Co$_2$MnSi, and Co$_2$MnAl in the free layer, (b) free layer magnetic moment for 50 Å Co$_2$MnGe and Co$_2$MnSi.
Sessions Details (cont’d)

• Tunnelling & Magnetic Memory/Spintronics
  - Tunnelling (40)
    **AE(11) MgO Magnetic Tunnel Junctions**
    BQ(17) Magnetic Tunnel Junctions
    FF (12) Magnetic Tunnel Junctions & Spin Injection

• Magnetic Memory/Spintronics (45)
  AA(6) Symposium on Current-Induced Domain Wall Motion
  **CF(9) Spin Electronics & Applications MRAM**
  ET(13) Magnetic Memory & Logic
  **ED(10) Spin Transfer Torque (I)**
  FD(10) Spin Transfer Torque (II)
  **CT(10) Spin Transfer Torque (III)**
  XA(3) Tutorial on Magnetics – CMOS Integration
High magnetoresistance tunnel junctions with Mg(B)O barriers and NiFeB free electrodes.

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High tunneling magnetoresistance (TMR) in MgO magnetic tunnel junctions (MTJs)[1-3] is key to the realization of next generation magnetic random access memory (MRAM) and high-performance sensors for high-density data storage, biomedical, and security applications. The best results in the thin barrier, <1.5 nm, low resistance-area (RA) regime required for many applications are generally obtained with sputter deposition of MgO between amorphous CoFeB electrodes that crystallize during annealing[4]. This deposition process partially oxidizes the base electrode, resulting in a Mg(B)O barrier with ~5% B trigonally coordinated with O (BO3)[5-7]. To optimize the utility of high TMR MgO MTJs for both MRAM and sensor applications, an ideal free layer material is required. Permalloy (Py), Ni81Fe19, which has essentially no magnetostriction, low microcrystalline anisotropy, saturation magnetization (Ms), coercivity, and damping, is such a material[8]. We demonstrate that annealed CoFeB/Mg(B)O/NiFeB MTJs have textured Py free electrodes. These MTJs achieve high TMR values (~150%) in the low RA regime (<20 Ω(μm)2), provided the NiFeB alloy is sufﬁciently B rich.

Current-in-plane tunneling (CIPT) data shown in Fig. 1 conﬁrm that Mg(B)O barriers yield high values of TMR that do not strongly depend on barrier thickness. The TMR of junctions with symmetric Co60Fe20B20 (CFB) (Fig. 1a) and Fe60Co20B20 (FCB) (Fig. 1b) electrodes increases with annealing, reaching 160-190% after a 350 C anneal. Fig. 1c shows the use of a Ni77Fe18B5 (Py95B5) free electrode results in TMR of ~40% upon moderate annealing, but higher temperatures deteriorate TMR. The Ni65Fe15B20 (Py80B20) material (Fig. 1d) works better, showing an increasing TMR with annealing temperature. Annealed CFB/1.1nm Mg(B)O/Py80B20 MTJs achieve 155% TMR and low RA (15 Ω(μm)2).

Transmission electron microscopy (TEM) images of the two types of PyB junctions are shown in Fig. 2. The ~1.1 nm Mg(B)O barriers are polycrystalline, and the as-grown Py95B5 electrode is polycrystalline (Fig. 2a) and becomes less textured after annealing to 350 C, as shown by the nanometer spot size convergent beam electron diﬀraction (CBED) image (Fig. 2c inset). In contrast, the as-deposited Py80B20 electrode is amorphous (Fig. 2b), as expected for such a high concentration of glass-forming B, but after annealing to 350 C, TEM and CBED measurements (Fig. 2d and inset) reveal that it has highly textured (001) bcc crystal structure. Electron energy-loss spectroscopy (EELS) data shows that this crystallization is accomplished by diﬀusion of any B that is not incorporated into the oxide barrier out of the Py80B20 into the capping layer[7]. We also examined the electronic structure of the Mg(B)O material using scanning tunneling spectroscopy which shows that Mg(B)O has a smaller, better deﬁned bandgap with fewer low energy defect states than MgO[9].

Magnetization measurements indicate that the Ms of CFB and FCB increases during annealing as B diﬀuses out of the electrodes. However, the Ms of Py80B20 is roughly the same as Py. We ﬁnd that the magnetic coupling between electrodes (Hcl) in as-deposited MTJs with FCB base electrodes is nearly twice that found in MTJs with CFB base electrodes. This is consistent with the former being magnetically rougher, due to greater oxidation of the Fe rich electrode. Upon 350 C annealing, Hcl decreases in all samples, with the most pronounced decrease apparent in MTJs with Py80B20 free electrodes. After annealing, these MTJs with barrier thicknesses >1.1 nm, exhibit Hcl ≤2.5 Oe, indicative of very magnetically smooth junctions. However, Hc is higher (~10 Oe) for the 1.1 nm barrier case, which we attribute to the onset of signiﬁcant ferromagnetic interlayer exchange coupling[10].

In summary, the combination of boron-alloyed ferromagnetic electrodes with sputtered MgO yields MTJs with thin Mg(B)O tunnel barriers that exhibit high TMR. Mg(B)O barriers have better electronic properties than MgO and can be used in conjunction with PyB free electrodes to form very structurally and magnetically smooth junctions. Further development of these growth techniques could be advantageous for magnetic sensing and spin-torque MRAM applications.

4. Yuasa et al., APL 87, 242503(2005)
5. Read et al., APL 90, 132503(2007)
6. Cha et al., APL 91, 062516(2007)
7. Cha et al., unpublished
9. Read et al., unpublished
Sessions Details (cont’d)

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  CT(10) Spin Transfer Torque (III)
  XA(3) Tutorial on Magnetics – CMOS Integration
CF-01

After hard drives – what comes next?

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Introduction

With areal densities of today’s hard disk drives (HDDs) around 500 Gb/in2, they are far from fundamental limits and a demonstration of an areal density of 10 Tb/in2 is targeted in 2015 by the Information Storage Industry Consortium. Such a technology would enable over 7 TBytes (TB) to be stored on a single 2.5” disk, enabling a cost of the order of $3/TB for a two disk 2.5” drive. Given the current 40% compound annual growth rate in areal density, this technology should be in volume production by 2020. On the other hand, NAND flash memories have developed a significant presence in the non-volatile memory (NVM) market and are now attempting to move into the computer storage market in the form of Solid State Drives (SSDs). Although NAND flash based SSDs offer lower power, faster speed, and better mechanical reliability, they face a challenge in overcoming the price advantage of HDDs due to their dependence upon lithographic resolution as well as fundamental physical limitations beyond the 22nm process node. Thus, to replace HDDs, alternative non-volatile memory technologies that can overcome shortcomings of NAND flash and compete on a cost per TB basis with HDDs must be found. In this paper a dozen different alternative NVM technologies are studied with regard to cost, scalability, performance and likelihood of success in 2020.

Analysis and Results

A dozen alternative NVMs are summarized with regard to important performance parameters in Table 1, which are mostly projected assuming the technologies are successful and follow the ITRS lithography roadmap between now and 2020. In evaluating those technologies, the cost/GB was viewed as the most important and was projected by assuming that, to first order, cost/GB would scale with cell size. This should be a relatively good assumption given that the manufacturing cost and yield of a wafer do not vary by a large amount. The second most important performance parameter is believed to be power efficiency since power is today a significant part of the expense of operation in mobile devices or large data centers. Read and write access times, endurance, and retention are generally less important, so long as they meet minimum criteria. Endurance and retention are only important, when they fall below the levels required for system applications. Systems require endurance of the order of 1015 for the file allocation table, but by dynamically moving data around an endurance of 105 has been shown adequate in NAND flash devices. This requires some added complexity in the controller and a sacrifice in performance, but these are not major issues.

With a minimum feature size, F, given by a read head width which is half the track width, and a 6:1 bit aspect ratio, the effective cell size of HDDs is roughly 2/3 F2. To compete with the cost of HDDs, SSDs based upon alternative technologies must achieve a similar cell size. Probe storage and holographic storage offer two approaches to doing this. Probe storage, in principle, can use a featureless medium and only the heads require microfabrication. On the other hand, MEMS-based probe devices demonstrated thus far require relatively high power, high manufacturing cost and relatively slow access time. Holographic storage uses optics to store information in a transparent 3D medium, but requires a relatively complex and expensive opto-electronic system for recording and readback and so far has only been demonstrated with write-once media.

With a 2D planar technology, the simplest structure is generally the simple crossbar structure with a cell size of 4F2. To achieve smaller cell sizes, it is necessary to somehow store multiple bits per cell as is done in the NAND Flash Multi-Level-Cell (MLC) technology. Table 1 indicates that FRAMs, MRAMs, RRAMs, CBRAMs and SEMs all have cell sizes larger than 4F2 and therefore are not expected to be cost competitive with HDDs. Polymer and Molecular Memories could potentially be promising candidates to meet all NVM requirements, except perhaps for retention time, but their switching mechanism and temperature stability with CMOS processing are still issues. NRAMs with potential high density and speed have several major obstacles, which have prevented CNTs from being used in CMOS fabs. Racetrack Memories using magnetic domain walls to store information offer the possibility for making 3D memory. However, this technology remains to be demonstrated, and is not clear whether high density devices can be made with high yield and low cost. PCRAMs are relatively mature technology and may be a replacement for high density NOR flash memories. Recently MLC PCRAM technology has been demonstrated and hence might ultimately become cost competitive with HDDs; however, a high programming current density is still a bottleneck. Finally, STT-RAMs have been proposed to be capable of also storing multiple bits per cell. If this can be achieved in practical devices, then STT-RAM could also become a viable candidate to replace NAND flash memories and perhaps even HDDs in the 2020 timeframe when the ITRS lithography roadmap projects a minimum feature size of the order of 10nm.
Recent results on spin-torque MRAM arrays and technology outlook.

Everspin Technologies, Inc., Chandler, AZ

MRAM using spin-torque switching (ST-MRAM) has the potential to be a high-performance non-volatile memory like the toggle MRAM currently in production, but with higher density and lower power. Here we present the results from functional ST-MRAM bit arrays integrated with CMOS, demonstrating key characteristics necessary for a successful memory technology. We discuss the optimization of MgO-based magnetic tunnel junction (MTJ) material to meet requirements for ST-MRAM, as well as the effects of damping, bit shape, and pulse width. Programming an ST-MRAM bit is accomplished by passing a current, greater than the critical current for switching (Ic), through the magnetic tunnel junction. The current polarity determines the magnetization direction. For a viable memory array, the switching voltage (Vsw) distribution must be well separated from the breakdown voltage (Vbd) distribution, so that a voltage high enough to switch any bit in the array will not damage the weakest bits in the array. Practically, this means that the six-sigma tails of those distributions must be separated. If we define the separation between the means as, separation = Vbd – Vsw, then the requirement for feasibility is separation > 12σ, where σ is the average standard deviation of the two distributions. Figure 1 shows measured switching and breakdown distributions for an integrated ST-MRAM array with separation > 12σ.

For a given switching current density Jc, as determined from the materials and device design, the separation is strongly dependent on the tunnel barrier thickness. For an ideal barrier, Vbd is linear in thickness (constant breakdown field) and RA increases exponentially with thickness, making Vbd increase as log(RA) while Vsw is linear in RA. The measured dependence of Vbd on RA is nearly logarithmic. Figure 2 shows how the ratio Vsw/Vbd improves with decreasing RA for MgO-based devices with CoFeB and NiFe free layers made with an optimized natural oxidation process. As shown, lower RA improves separation as long as the barrier is well behaved. The lowest useable RA is determined by the onset of non-ideal behavior like shorting and early breakdown in thin junctions, and by the practical requirement for a bit resistance that is high enough to be compatible with the CMOS circuitry used for the read operation. For our bits, with dimensions of approximately 100 nm x 200 nm, we chose RA=5–8 Ω-μm².

Reducing Jc improves separation because it lowers Vsw. Reducing Jc is also critical to making the write current compatible with small transistor sizes since typical transistors source only about 0.6 mA per micron of width. Jc is proportional to the Gilbert damping constant α and inversely proportional to the spin-torque-transfer efficiency η. We measured the damping constant of the NiFe and CoFeB films using an inductive permeameter. Although NiFe has a lower damping constant α≈0.007, compared to α≈0.013 for CoFeB, we found that the write performance of ST-MRAM bits with NiFe and CoFeB free layers are quite similar, apparently because the ST efficiency is reduced in devices with the lower polarization NiFe free layer. Both types of devices had average Jc0=4.5 MA/cm² for free layers with the same energy barrier to thermal reversal, Eb~50 kT, corresponding to >10 year data retention. High-speed switching measurements made on integrated arrays of bits with different bit aspect ratio (AR) showed that the narrow high-speed switching distribution is nearly independent of AR with σsw=6% indicating less sensitivity to shape than for field switching, for which the switching distribution width increases significantly at low AR.

We have demonstrated the feasibility of ST switching for MTJ bit arrays integrated with CMOS. The small shape dependence and narrow switching distributions of ST switching in these 65 nm-node bit sizes are good indicators for scalability and manufacturability beyond 65 nm. Additional improvements in reducing Jc and increasing MR are desirable for compatibility with minimum-size CMOS transistors.
A three-terminal spin torque driven MRAM cell.

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Spin torque driven MRAM (ST-MRAM) is an exciting option for a future high speed, low power, non-volatile memory that scales well to smaller bit dimensions. In any two-terminal ST-MRAM design, the write voltage pulse is applied across the tunnel barrier, which makes endurance of this tunnel junction a potential issue for memory lifetime and reliability. We have developed a nanopillar structure where a third contact can be made to any point within a thin-film multilayer stack. This substantially enhances the versatility of the device by providing a means of applying independent electrical biases to two separate parts of the structure. In this work, we demonstrate a joint magnetic spin valve/tunnel junction structure sharing a common free layer nanomagnet contacted by this third electrode. Due to the spin torque effect, a spatially nonuniform spin-polarized current flowing into the free layer via the low-resistance spin valve path can nucleate a reversal domain at the spin injection site. This domain then propagates across the free layer, completing the switching process. The magnetic state of the free layer can be read out separately via the higher-resistance magnetic tunnel junction. This three-terminal structure provides a route for developing high performance spin-torque magnetic random access memory (ST-MRAM) cells which maintains the benefits magnetic tunnel junctions for read-out (e.g. high signal, CMOS-compatible impedance), while avoiding the need to apply a large voltage across a magnetic tunnel junction during the writing step.

Device fabrication begins with sputter deposition of bottom lead/AP-pinned layer/MgO/free layer (5 CoFe/60 NiFe/10 CoFe)/spacer (32 Cu)/top pinned layer (25 CoFe/60 IrMn) /cap, where all thickness are in Angstroms. With all of the critical interfaces deposited in this initial process, multiple critically aligned lithography steps are used to etch material and define contacts, creating the device in Fig. 1.

Fig. 2 shows experimental results for a complete SV/MTJ structure patterned into a 70x200 nm elliptical shape, where we inject current through the spin valve while reading the resistance of the MTJ. Spin torque reversal occurs from the high to low resistance state with respect to the SV, and is simultaneously detected by the MTJ. This resistance change is equal to the change observed by sweeping an external magnetic field, which confirms that the current reverses the entire free layer, rather than forming a stable domain wall, which would result in an intermediate resistance level in the MTJ. In this first device generation, we were not able to reverse the spin valve device configuration from the P-to-AP state by flowing current in the positive direction (electrons from FL to RL2) due to the fact that before the critical current was reached, the circumferential Oersted field acting on RL2 became strong enough to overcome the exchange pinning field from the top IrMn layer and drive the magnetization of the approximately square RL2 into a vortex state. We have observed bipolar spin torque induced reversal in fully metallic companion devices, and believe bipolar switching is easily achievable with minor modifications to our SV/MTJ devices.
Sessions Details (cont’d)

- Tunnelling & Magnetic Memory/Spintronics
  - Tunnelling (40)
    - AE(11)  MgO Magnetic Tunnel Junctions
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    - CT(10)  Spin Transfer Torque (III)
    - XA(3)  Tutorial on Magnetics – CMOS Integration
Ultrafast time-domain switching studies of spin-torque nanopillars.

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Time domain measurements of spin torque-driven dynamics in nanopillar devices at low temperatures have demonstrated precessional coherence in the free layer switching process [1-2]. By using pairs of current pulses as narrow as 25 ps, much shorter than the free precession period ~ 300 ps, with adjustable amplitudes and relative delay, we apply spin torque at precise moments along the otherwise free-precession orbit. This novel time-domain approach allows a direct mapping of the regions where spin torque has the maximum effect on free layer switching, as well as coherent control over the magnetization dynamics [3]. This approach utilizes the signal-to-noise advantages of switching experiments while providing information on precession and damping phenomena.

Figure 1 shows such control at room temperature. Two 25 ps pulses with the same amplitude are used to switch a ~ 150 x 75 nm² Co₉₀Fe₁₀ (8.7 nm)/Cu(3 nm)/Co₉₀Fe₁₀(2 nm) nanopillar between the low resistance parallel (P) state and the high resistance antiparallel (AP) state. By only adjusting the relative pulse delay we can tune the nanomagnet switching probability $P_s$ from 4% to 93%, and we observe that two pulses with proper delay can switch a nanomagnet with larger $P_s$ than a single pulse with the same total energy. Finally, we are able to explain the key features of our data with a macrospin model [4].

Since the spin torque vector is largely collinear with the Landau-Lifshitz-Gilbert damping vector, a DC current can be used to cancel the damping, increasing the lifetime of precessional oscillations [1]. We have extended our measurements to include a precisely-timed pulse with duration > 10x the free precession period and a 25 ps risetime matching our ultrafast pulses (Figure 2).

Figures 3 and 4 compare $P_s$ vs. pulse-pulse delay for DC and 5 ns pulses respectively, for different amplitudes of DC and 5 ns pulse current. While DC currents approaching the critical current of 1.8 mA show only weak increases in oscillation amplitude for delays > 1 ns, in Figure 4 $P_s$ oscillates beyond 2 ns for currents greater than the DC critical current, suggesting that a larger spin torque is required to reduce damping. Macrospin simulations of the free layer dynamics [4] for this set of pulses, which includes a random thermal field, produce similar behavior.

Current-driven magnetization dynamics of vortex and onion states in a nanomagnet.

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We study spin-transfer torque induced magnetization dynamics in nanopillars comprising an extended magnetic reference layer and a nanomagnet of 20 nm thickness and 230 nm diameter with a circular cross section. The nanomagnet has strongly inhomogeneous, field dependent static magnetic configurations, namely a vortex and a canted state. The canted state has onion or s configuration with a non-collinear mean orientation relative to the reference layer. We measure reversible switching between these states by spin-transfer torque and show that in both cases steady state oscillations with different properties can be excited. We measure these properties from the current dependence of the generated microwave signals. In particular, we find that the emitted microwave power is maximized for the vortex state.

Current-induced switching between the low-resistive vortex and high-resistive canted state. Arrows on the curves indicate the current sweep direction. The black and purple curves start in the canted state, all others in the vortex state. For clarity the graphs measured at 40 and 30 mT are offset by +20 and +40 mΩ respectively, relative to the green curve.
Sessions Details (cont’d)

• Disks/Media (63)
  AC(12) Patterned Films & Elements (I)
  DQ(13) Patterned Films & Elements (II)
  AD(12) Advanced Recording Media, Perpendicular & Beyond
  BC(11) Patterned Media (I)
  CP(15) Patterned Media (II)
Tuning the magnetic properties of bit patterned media fabricated by blanket deposition of perpendicular anisotropy multilayers onto pre-patterned substrates.

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In general, there are two fabrication approaches for Bit-Patterned Media (BPM). In one approach, substrates are patterned prior to any magnetic media deposition, and then the magnetic thin film is blanket deposited on these pre-patterned substrates. The major advantage of this technique is that the pattern fabrication process and the magnetic recording media can be fabricated and optimized independently from each other, and etching of the magnetic material is avoided. One disadvantage is the formation of magnetic trench material that increases the readback noise level (see Fig. 1). In the other approach, the magnetic media is deposited as a continuous thin film and then patterned into discrete islands. The major advantage of this approach is that there is no magnetic material left between the islands or in the etched trenches. An additional advantage is that the magnetic film is grown on a flat substrate, so overgrowth and curvature effects that may disturb the magnetic thin film growth on pre-patterned substrates are avoided. However, at competitive densities of 500 Gbit/in² and beyond, impact on and damage of the magnetic properties during patterning with either ion beam milling or reactive ion etching are still existing issues [1-4].

After an introduction to the above described two alternative fabrication approaches for BPM I will focus in my talk on the blanket deposition onto pre-patterned substrates using perpendicular anisotropy magnetic Co/Pd multilayers. I will present a technique of how to avoid magnetic trench material [5] that is based on pre-patterned substrates consisting of two different materials, namely material 1 (here SiN) for the pre-patterned pillars and material 2 (here Si) for the flat substrate below the pillars (see Fig. 2a). Then an additional in vacuum post-annealing process after media deposition is used to trigger an inter-diffusion process between the trench substrate material and the magnetic material that suppresses the magnetic moment in the trenches and the corresponding noise in readback (Fig. 2b-e). Moreover we will highlight the importance of a Ta cap layer that seals the surface in order to prevent any diffusion of the trench substrate material (here Si) onto the islands [5]. We will demonstrate the success of “magnetic trench poisoning” down to 50 nm island size and discuss the challenges that have to be overcome at higher area densities.

Finally I will demonstrate the realization of tight magnetic Switching Field Distributions (SFD) on polymer rectified/interpolated pre-patterned substrates with long range order defined by e-beam lithography assistance and highlight the importance of controlling and minimizing dipolar interactions within the Bit Patterned Media concept [6].

Sessions Details (cont’d)

- Magnetic Recording Integration & Head-Disk Interface
  - Magnetic Recording Integration (64)
    BP(18) Magnetic Recording Physics & Channel
    CD(12) Magnetic recording Physics
    DP(17) Advanced Magnetic Recording
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    EF(11) Magnetic Recording: Systems, Coding & Channel

- Head-Disk Interface (18)
  CC(11) Head-Media Interface & Tribology
  EW(7) Head-Media Interface (II)
Effect of inter-track interference on the areal density of magnetic tape sputtered media.

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Recently, sputtered thin film media has gained a great deal of attention in the magnetic tape storage industry due to its potential for high areal data density1. We investigate the magnetic recording characteristics of a novel application of sputtered media on tape. Thin film magnetic media was deposited in a facing target sputtering system on a 4.5μm thick Aramid substrate. The structure of the media is: Ru(20nm)/CoPtCrSiO2(15nm)/C(5nm). The coercivity of the media is Hc=3.51kOe with a magnetic remanence of MrT=0.45 memu/cm² and a squareness of S=0.63. The grain structure of the thin film media has been analyzed with a TEM and we find the average grain size to be about 8nm in diameter.

The magnetic recording characteristics of the sputtered tape media is measured with an HDD recording head with a 0.1μm wide GMR sensor and a high resolution piezoelectric nanopositioning system. The tape speed in this system is approximately 100μm/s. Linear density for isolated tracks is determined by measuring the broadband SNR (BBSNR) at a range of spatial frequencies (SF) at optimum write current. We find that a BBSNR value of 10dB can be obtained at a spatial frequency of 2.5μm⁻¹, which corresponds to a linear bit density of 254kbpi. Read-back signal amplitude can be measured at linear densities as high as 500kbpi or spatial frequencies of 5μm⁻¹. Using signal amplitude rolloff characteristics in the frequency domain, we estimate the effective magnetic spacing (d+a) to be about 108nm. In this system, the head is applied to the tape with minimal normal force and we believe that the effective spacing is limited by asperities on the tape surface.

The track pitch is estimated by measuring inter-track interference with squeezed adjacent tracks. A center track is written with spatial frequency of 5μm⁻¹ (508kbpi) and adjacent tracks with a spatial frequency of 1μm⁻¹ are written with variable spacing on either side of the center track. The Fourier transform of the readback waveform of the center track is calculated and the side-track interference (STIR) is measured as the amplitude ratio of the center track written frequency (5μm⁻¹) and the side track frequency (1μm⁻¹). The STIR becomes significant at track spacings smaller than 0.45μm. This spacing corresponds to a track density of about 56ktpi. Combined with the linear density of 254kbpi, this amounts to a potential areal density of 14Gb/in².

Effect of tape longitudinal dynamics on timing recovery and channel performance.

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While using smoother media designed for reduced magnetic spacing, we find that increased head-tape friction fluctuations can excite a compressional tape sound wave resonance between rollers adjacent to the head. The phase of the recording waveforms is altered, deterring effective timing recovery. This problem is reduced by improving the tape formulation.

Introduction

Increasing recording areal density requires a reduction in head-tape spacing [1], since it is expected that linear density must also increase. In contrast to hard disk drives, where the head is separated from the disk by an air bearing, (at least for a majority of the time), in tape recording, the asperities of the tape and head define the head-tape spacing. The mechanical effects of sliding in a range of environmental conditions, coupled with the need for media interchange, present a significant challenge to the rate of tape recording areal density growth. Tape sliding dynamics affects the soft error rate as a function of the tape velocity as is evidenced in the waveform phase.

Recording results

Using a prototype tape drive with a GMR read sensor, the soft error rates were measured as a function of velocity for two barium ferrite tape samples, which we denote as sample A and sample B. The magnetic and physical properties are shown in Table 1, illustrating the similar magnetic properties of both samples and only a slight difference in the surface of the magnetic layer. However, this difference in surface roughness produces a very large difference in the friction coefficient and is also reflected in the measured soft error rates in Fig. 1. The soft error rate difference between the two samples is quite remarkable and is due to the more pronounced effect of friction variation at lower velocities. Measurements of velocity variations, as determined by single frequency writing experiments and writing and reading of random data corroborate friction measurements. The difference in the phase of the waveforms written and read from the two samples is apparent and is attributable to the soft error rates and the dependence on velocity.

Conclusion

The increase of the soft error rate at lower velocities, coupled with measurements of the head-tape friction and the waveform phase, show that reduced tape-head spacing results in greater head-tape friction variation. We find that a subtle modification of the tape formulation is quite effective in reducing this phenomena substantially, allowing effective timing recovery by the channel. The improved timing recovery permits the exploration of more complex channels.

Study of perpendicular AME media in a linear tape drive.

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The magnetic recording performance of perpendicularly oriented Advanced Metal Evaporated (AME) media in a linear tape drive is studied. Modifications to the evaporation conditions produce the perpendicular orientation, which eliminates the writing asymmetry of obliquely oriented AME media in a linear recording environment. While the readback signal exhibits characteristic aspects of perpendicular media, features of the timing based servo are retained to permit track-following performance that indicates a 1 sigma PES (position error signal) of .2 microns. Our data shows that equalization of this waveform is effective in allowing a soft error rate at the LTO Gen 4 operating point of 10^-6 and the durability of the tape exceeds 100,000 passes without signal degradation.

Introduction

Metal evaporated tape has been a commercially viable recording medium for video and helical scan data products for many years, but recent efforts to produce perpendicularly-oriented media permits the readback waveform to be identical in the forward and backward directions, as is required to reach the desired recording capacity in a linear tape drive [1]. While signal processing for perpendicular media is well known and would clearly optimize recording capacity, the effectiveness of signal processing methods designed for longitudinal tape recording for the detection of the position error signal (PES) and data on this media is investigated. Signal degradation with sliding distance, a critical aspect of linear tape recording, of a distinctly different head-tape interface is also measured.

Experimental results

High resolution drag tester studies, using advanced GMR sensors (.15 micron trackwidth) clearly exhibit the distinctive perpendicular nature of this media and provide a direct measure of media noise. The spatial resolution (~10 nm) as well as a synchronous detection method allow measurement of the response of the media to dc frequency with little or no electronic noise. The high dc content, as is measured in this apparatus, is modified somewhat in the drive electronics, where the high pass filter attenuates this signal and produces a pulse response similar to longitudinal media. This effect, coupled with a judicious choice of reader width, allows an accurate reproduction of the timing based servo pattern and PES. This permits this media, formatted with the timing based servo pattern, as adopted by the LTO (Linear Tape Open) Consortium to function fully in an LTO drive, decoding linear velocity, linear position, and lateral motion, controlling linear velocity and allowing quite acceptable track-following error. Our measurements of PES show that over a full wrap, the standard deviation is nominally .2 microns, which is what is required for LTO Gen 4. In addition, the readback signal can be equalized to allow recording at LTO Gen 4 densities with a soft error rate of 10^-6. With reduced width heads, the media is capable of supporting areal densities as high as 23 Gbits/in^2 [2]. Even more importantly, since in tape recording, the head-tape spacing is determined by asperities in the media and head, the sliding distance or total number of passes the head can make over the tape is a critical aspect. Fig. 1 shows the error rate, expressed as mean bits to failure (MBTF), as a function of the number of passes, showing that this media is capable of enduring greater than 100,000 passes before showing signs of signal degradation.

Summary

The fully functional operation of perpendicularly oriented Advanced Metal Evaporated media in a linear tape drive is verified. While the readback signals exhibits characteristic aspects of perpendicularly oriented media, features of the timing based servo are well detected, allowing appropriate closed loop operation of the transport and track-following systems. A soft error rate of 10^-6 at the LTO Gen 4 operating point is demonstrated and the tape-head interface withstands 100,000 passes without significant signal degradation.

Sessions Details (cont’d)

• Magnetic Recording Integration & Head-Disk Interface
  • Magnetic Recording Integration (64)
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• Head-Disk Interface (18)
  CC(11) Head-Media Interface & Tribology
  EW(7) Head-Media Interface (11)
Thermally-assisted magnetic recording experiments using a plasmonic near-field transducer with integrated waveguide.

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For Thermally-Assisted Magnetic Recording (TAR, TAMR, HAMR) to be realized, it will be necessary to confine heating to a single data track approximately 40 nm wide or smaller with high efficiency. In a typical TAMR head design, a waveguide delivers light to a plasmonic near-field transducer located at the air-bearing surface. The near-field transducer uses a low-loss metal (Au, Ag, Cu, etc.) with a size and shape necessary for the creation of resonant charge motion at the metal surface (surface plasmons) and includes a sharp tip to further enhance the charge motion in a localized region. Oscillating tip charge creates an intense near-field pattern, heating the disk. For example, when polarized light is aligned with the ridge of a ridge slot waveguide (also known as the “c-aperture”) an intense near field pattern is created at the end of the ridge [1].

Previously, optimized ridge waveguides for use at 780nm wavelength [2] were fabricated using e-beam lithography and a planar process on single-crystal quartz substrates to form a quartz aperture in a gold film. An example of this structure is shown in Figure 1. The resulting quartz sliders were mounted above CoPd super-lattice media and the disk was scanned using a static tester in recording experiments [3].

In a true TAMR head, a thin-film waveguide can be used to deliver light to the transducer. When designing an integrated TAMR head, the exact means of light delivery, the type of near-field transducer, and the magnetic head design must all be jointly optimized. We will discuss integrated TAMR head design, fabrication, and recording experiments using near-field transducers with integrated waveguides. Figure 2 shows a schematic of the basic head structure utilizing a Ta₂O₅ waveguide core with uniform cross section along its length. Both Al₂O₃ and SiO₂ cladding material was used. Ridge waveguides or similar plasmonic transducers were fabricated at the end of the waveguide. As shown in Figure 3, the overall optical performance of the integrated head was modeled. Light from an external 780nm wavelength diode laser was focused and end-fired into the top of the waveguide. Integrated heads were mounted on HGAs and recording was carried out in the static tester. Nanosecond laser pulses and external DC and AC magnetic fields were applied for recording experiments at sub-100nm track width. An example of a recorded track on a Co/Pd disk using the ridge waveguide is shown in Figure 4.

Optimal coupling of near-field light into magnetic recording media for HAMR.

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Today, conventional magnetic recording schemes are coming to an end because of the superparamagnetic limit. Heat-assisted magnetic recording (HAMR) may have potential to extend data densities beyond 1 Tbits/in² by utilizing thermal energy provided by a near-field light source co-aligned with the magnetic recording field. The key challenge in this implementation is the development of a near-field transducer capable of delivering a few microwatts of power into a spot with a diameter of less than 30 nm. Another challenge is the design of a recording system that would be capable of adequate management of the heat generated by the transducer. Although extensive research has been conducted on the design of near-field transducers in free space [1], little consideration has been given to the effects of media materials and structures on the recording performance. For example, such important properties as the media relaxation time and heat dissipation are extremely sensitive to the media composition and must be addressed in the integration of practical HAMR schemes. In this presentation, basic guidelines to design a complete HAMR system suitable for areal densities beyond 1 Tbits/in² are presented.

Using finite element method to solve both Maxwell’s and heat transfer equations, this work suggests that a special designed patterned recording medium with an optimized heat sink provides significant enhancements in terms of optical absorption and localized heating. Figure 1a illustrates the spatial distribution of average power output of a single ridge waveguide in free space. This waveguide can focus tens of microwatts into a 60-nm diameter spot when illuminated with only a few milliwatts of power. Figure 1b shows the effect of the recording medium on the near-field light distribution for which a sub-30-nm spot is observed with an order of magnitude loss in intensity compared to that in free space. To verify the simulation results, ridge waveguides were fabricated using focused ion beam milling of gold thin films (figure 2a) while near-field scanning optical microscopy (NSOM) was utilized to measure the near-field intensity distribution of these transducers (figure 2b).


Figure 1: (a) Spatial distribution of power output from a near-field transducer in free space, and corresponding (b) thermal profile on the surface of a magnetic disk.

Figure 2: (a) Electron image of single ridge waveguide (b) corresponding focusing capabilities measured using NSOM.
Micromagnetic modeling study of thermal gradient effect in heat assisted magnetic recording (HAMR).

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Heat Assisted Magnetic Recording (HAMR) provides writeability on high anisotropy media and stabilizes bits against media thermal stability [1]. Both the field and field gradient limitations of conventional recording are overcome by engineering the thermal profile (gradient). The recording is done at write temperature near Curie Tc, where smaller head field is required. Thermal profiles of media are very important to maintain adequate writing and reasonable SNR through thermal gradient both in down track, cross track, and in perpendicular direction along the media.

This paper simulates the effect of thermal profile gradient in perpendicular media direction where optical spot is much smaller than magnetic write width of head. Micromagnetic modeling of recording media using LLG equation and finite element model of head field and thermal profile is used in the analysis of recording performance such as SNR as a function of thermal profile temperature gradient in media perpendicular direction.

Results & Discussions

High frequency data at 1150 kfci was written on perpendicular HAMR media with high anisotropy (Hk= 50KOe), saturation magnetization of 650 emu/cm3, thickness of 10nm, and head media spacing of 5nm. The write temperature was assumed to be close to Curie point of 700K with thermal spot close to 50nm in FWHM. The Callen Callen [2] theory was used for temperature dependent anisotropy and saturation magnetization. Media had a soft underlayer of 40nm in thickness and center to centre grain size of 5nm including 1nm grain boundary. The write head was a conventional monopole head with large physical width ~ 100 nm in width, and pole thickness of 200nm.

Thermal profiles of media were varied to create various temperature gradients along the thickness of media. This was done by using multi-layer micromagnetic code where each layer of recording layer has different peak temperature to simulate the thermal gradient in perpendicular media direction. Total of three micromagnetic layers were used in the write simulations.

Figure 1 shows simulated SNR vs. thermal gradient in perpendicular media direction. Thermal gradient has to be higher than -26 deg/nm in order to have no loss in media SNR. Thermal modeling of media was done using commercial software (COMSOL) in order to simulate the thermal gradient in media perpendicular direction. Based on thermal modeling, the temperature gradient in media is close to -18 deg/nm. It was assumed that media has thermal conductivity of close to 10 W/mK and heat sink layer with conductivity of 100 W/mK.

Sessions Details (cont’d)

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• Head-Disk Interface (18)
  CC(11) Head-Media Interface & Tribology
  EW(7) Head-Media Interface (II)
**FA-01**

**Future options for HDD storage**

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A recent study forecasts explosive growth of the digital universe from $281 \times 10^{18}$ (281 Exa) Bytes in 2007 (about 45GB per person) to $1.8 \times 10^{21}$ (1.8 Zetta) Bytes in 2011 [1]. It is thus vitally important to ensure the continued rapid increases in capacity of the ubiquitous hard disk drive (HDD) that provides the foundation for this digital universe. The biggest lever for higher HDD capacities is areal density. However areal density for conventional perpendicular recording seems to be quite strictly limited by the onset of superparamagnetic effects as researchers strive towards more finely grained recording media [2]. The highest areal density with a continuous perpendicular medium is 612Gb/in² reported at TMRC 2008 [2]. Fortunately, several new technology options are now being explored that promise to increase the areal density beyond these limits. These new options include bit patterned magnetic recording (BPMR) [3], heat assisted magnetic recording (HAMR) [4], and microwave assisted magnetic recording (MAMR) [5]. These options all involve considerable risk and significant engineering challenges, much greater, for example, than the recent transition to perpendicular recording.

The HDD industry is at a critical technology crossroads and it is paramount that we quickly establish comprehensive paths to push beyond the superparamagnetic limit while mitigating the R&D and tooling investment risks. Considering this situation, several precompetitive research projects and programs supported by the HDD industry and/or Government have recently started. These variously have targets of 2TB/in² by 2010 for the Storage Research Consortium (SRC)* [7], 5TB/in² by 2013 for the New Energy and Industrial Technology Development Organization (NEDO)** [8], and 10TB/in² by 2015 for the Information Storage Industry Consortium (INSIC) [9]. Figure 1 summarizes the areal density trends of these research targets as well as recent feasibility/demonstration studies and HDD products.

In addition to the three technology options of BPMR, HAMR, and MAMR, there is recent interest in a fourth approach that has the advantage of staying with a relatively conventional granular perpendicular medium and read/write head. This fourth approach combines shingled write recording (SWR) with two dimensional readback and signal processing. Either technique can be used separately to give large gains and the combination of the two, which we refer to as Two Dimensional Magnetic Recording (TDMR), promises particularly large gains [6]. One concern to be addressed, however, is that the use of these techniques may seriously complicate the interactions of the HDD with the host system. Figure 2 now illustrates these four technology options that the HDD industry must consider: BPMR, HAMR, MAMR, and SWR/TDMR.

As the introductory talk in this Symposium, this presentation will review the current industry status, the technology options ahead, and the pro & cons for each option. We include a brief introduction to SWR and TDMR which are the topics for the remaining papers in this session.

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* SRC is a non-profit mutual benefit corporation, dedicated to serving as an integrating force, bringing together the capabilities of industry, academia and government research organizations in developing of advanced, pre-competitive information storage technologies.

** NEDO is the Japan’s largest public R&D management organization for promoting the development of advanced industrial, environmental, new energy and energy conservation technologies.

High density data-storage using shingle-write.

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1. Introduction
Several technology options have been proposed and are being developed to increase areal density: bit-patterned media (BPM) [1], heat assist magnetic recording (HAMR) [2] and microwave assist magnetic recording (MAMR) [3], etc. However, none of them have shown a clear problem-free solution.

The difficulty of increasing areal density as grains approach the superparamagnetic limit is well-known, but what is the basic problem? That is degradation of the write field due to downsizing of the write head. The purpose in HAMR and MAMR is clearly write assist. The concept of BPM is that of ultimate easy-to-write media. But, if we can keep the write head size, there is no need for the write field to fall with track width. This is the fundamental idea of shingle-write.

R&D efforts for shingle-write have started with the target of 2Tb/in² in 2010 by Storage Research Consortium (SRC) [4] and some promising results were reported. In this paper, I would like to discuss advantages and challenges in shingle-write and the predicted gain in areal density.

2. Shingle-write concept

The concept of shingle-write is heavily overlapped writing at the corner edge of a wider head and resulting narrow track reading is shown in Fig.1. This system requires sequential write and random read.

Then, principle advantages are:
- Much stronger write field due to larger pole. Reduced adjacent track erasure (ATE) allows further stronger field. Stronger field brings improvement of linear density.
- Sharp corner-edge field brings a narrower erase band, which enables increase of track density. But there is a challenge:
- New format architecture for random access emulation.

3. Gain estimation

One of the key points in the shingle-write is how large and sharp write field is achievable by optimizing the head. Prof. Kanai successfully demonstrated [5], as shown in Table 1, by his head field simulation, relaxing ATE field criteria allows 1.3 times larger on-track field. Wider & longer pole brings further 1.2 (total 1.6) times larger field. Moreover, 1.5 times sharper gradient obtains in cross-track, as large as in down-track.

Based on this result, it is possible to predict a potential gain. Because of 1.6 times larger write field, 1.6 times larger Ku can be used without losing write-ability. Then, 1/1.6 times volume reduction will be achievable while keeping the same Ku/VkT. Grain diameter is then reduced by sqrt(1/1.6)=0.79, that is 20% reduction as shown in Fig.2. Assuming the same number of grains in a bit, the occupied area will be reduced by 0.64. Then, the areal density gain potential can be calculated as 1/0.64=1.56; that is more than a 55% gain expected.

If one assumes that erase-band width (EBW) is to be estimated by the same theory as transition width, 1.5 times larger gradient and 20% smaller grain size makes 50% reduction of EBW possible.

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Sessions Details (cont’d)

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• Head-Disk Interface (18)
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  EW(7) Head-Media Interface (11)
Magnetic spacing trends: from LMR to PMR and beyond.

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This paper examines trends in magnetic spacing in the HDD industry for the last 20 years or so, as we transitioned from inductive to MR, GMR and TMR heads, and from longitudinal to perpendicular recording. Magnetic spacing, also known as head-media separation or HMS, is defined here as the mechanical separation between the bottom of the read-write head elements and the top of the magnetic media alloy.

Figure 1 shows HMS vs. product areal density (AD) for commercial disk drives, spanning over three orders of magnitude in areal density from ~300 Mb/in² in the early 1990’s to ~400 Gb/in² today. On the chart, historical projections for HMS at the 10 Gb/in² [1], 100 Gb/in² [2], and 1 Tb/in² [3] are also added. Interestingly, HMS trend over this AD range is very well behaved, crossing major technology shifts (inductive→MR, LMR→PMR) without discontinuities, and following a power law with an exponent of ~ -0.32. Also noteworthy is the fact that the theoretical projections typically deviate from the trend line, suggesting that simple scaling has historically been a better predictor of magnetic spacing than extensive model calculations.

A first order prediction for the power fit exponent would have been -1/2, as one would expect HMS to vary as the inverse square root of AD. The reason behind this discrepancy is twofold. First, the bit aspect ratio has continuously decreased from ca. 30 twenty years ago, to about 5 today (Figure 2). Accordingly, the bit length has decreased more slowly than 1/sqrt(AD) (Figure 3). But perhaps the most striking and useful result is that HMS has always been within 10-20% of half of the bit length (Figure 4).

Assuming that these scaling trends hold to the terabit-per-square inch point, allows us to speculate that this density point, in product, will have an HMS of ~8 nm and at a bit aspect ratio of ~4, compared to theoretical predictions of 6.5 nm and 3.5 respectively [3]. Finally, these results are useful in guiding the annual reduction in magnetic spacing HMS% as a function of the annual AD growth rate AD%, as follows:

\[ \text{HMS\%} = 1 - (1 - \text{AD\%})^{-0.32} \]

For AD growth rate of 20, 40, and 60%, this results in HMS% annual decrease of ca. 6, 10, and 14% respectively.


Experimental study of head-disk interface stability and durability at sub-1-nm clearance.

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Introduction

To achieve a higher storage density in hard disk drives, the physical spacing between the read/write element and the disk surface has to be made smaller. For the next generation hard disk drives with a density of 1 Tbit/in², a spacing of 3.5 nm is estimated to be required and the thickness of slider overcoat and disk overcoat will be reduced to 1 nm for each [1]. At such an ultra-small clearance, the intermittent/continuous contact at the head-disk interface (HDI) may occur, which will cause wear of the slider and/or disk and may affect the HDI reliability. Thus, how low a slider can fly stably and reliably is a major concern for the hard drives industry. Thermal protrusion of the heating element built in the dynamic fly-height (DFH) slider can be used to control the head-to-media spacing (HMS) by applying controllable electrical power. In this study, we achieved 1 nm or less head-disk clearance using the DFH slider and investigated experimentally the stability and durability of the DFH slider flying at such small clearance.

Experiments

The tests were performed on a VENA CSS & Load/Unload Tester equipped with acoustic emission (AE) sensor and friction gauge. Western Digital femto DFH sliders and Z-Tetraol lubed 2.5” disks were used in the experiment.

The relationship between the HMS change and heating power was calibrated by measuring the HMS magnetically using a Guzik system while applying a series of incremental powers to the heater. This HMS measurement technique is based on the Wallace Spacing Loss equation. A 2nd order polynomial was used to fit the measured data.

We made all of the sliders fly on the same outer diameter of the disks with a linear speed of about 16 m/s. To obtain the 1 nm clearance between slider and disk, we initiated touchdown (TD) firstly by gradually increasing the heater voltage. Simultaneously, AE, friction and laser Doppler vibrometer (LDV) signals were used to monitor the contact. When contact occurred, we reduced the voltage rapidly and recorded the TD voltage. Then, the power needed for 1 nm back-off was calculated by the calibrated equation and applied to the heater.

To understand the durability of the HDI at ultra-small spacing, virgin sliders with the same design were flown over the virgin disks at the 1 nm or less clearance condition described above for given test durations: 0 h (TD only), 0.5 h, 2 h and 15 h. During these tests, the AE sensor, friction gauge and LDV monitored the contact and slider bouncing. After that, we measured carbon wear on the slider ABS and disk using SEM and OSA respectively.

Results

Very little contact or bouncing was seen during all of the tests, according to the AE signal and LDV frequency spectrums before and after applying power as well as at the beginning and the end of 1 nm clearance flying. That is, this slider can fly stably over the disk with 1 nm clearance.

The wear results of the sliders flying for 0 h, 0.5 h, 2 h and 15 h respectively at 1 nm clearance are shown in Fig.1. The lower portion of the image is the slider body, while the upper portion is the alumina basecoat, read/write devices, and encapsulation layer. The bright region in the upper portion is the location of the read/write transducers as well as the peak of thermal protrusion, and therefore it is the most likely place to be worn. Fig.1(a) shows very light wear and a very few of scratches appeared after transitory and slight TD, while Fig.1(a)-(b) indicate that there was no obvious additional wear after a period (up to 15 h) of 1 nm flying. So the wear on the slider surface was mainly caused by the initial TD and was independent of the flying duration.

Fig.2 shows 1nm wide sections of two disks in S and P polarized light. As shown in the figure, a very light carbon wear track was observed both on the disk after only transitory TD and the one after TD and 15 h of 1 nm flying, but no significant additional wear was seen in Fig.2(b) compared with Fig.2(a), which indicates that the disk wear is also mainly related to the initial TD.

Conclusions

We investigated experimentally the stability and durability of the HDI at 1 nm DFH clearance and demonstrated the possibility of stable flying at such a small spacing. The test for smaller clearance is on-going.

Observations

- No Areal Density Demo papers
- Healthy Spectrum of Storage-related Topics
  - 2D/Shingled Magnetic Recording
  - Thermal Assisted Magnetic Recording
  - MRAM
  - Spin Torque
  - CPP GMR Heads
  - Patterned Media
  - Signal Processing
- Lots of non-HDD/Storage papers
- Good attendance considering challenging circumstances
- Great Facility
- Number of Exhibitors somewhat low
Upcoming Conferences

• 20th TMRC - Heads & Channels - Oct. 5-7, 2009  Tuscaloosa, AL
• Magnetics Conference 2010 – Jan. 28-29, 2010  Orlando, FL
• 55th Magnetism & Magnetic Mat’ls, Nov. 14-18, 2010, Atlanta, GA
• Intermag 2011 – April 26-29, 2011  Taipei, Taiwan
• 56th Magnetism & Magnetic Mat’ls, Oct. 30-Nov. 3, 2011 Scottsdale, AZ
• 12th Joint MMM/Intermag – Jan. 14-18, 2013, Chicago, IL