Alchemy and Rigorous Science: The Evolution of Hard Disk Drives

Highlights from DISKCON® USA

Plasma Etching of TMR Stack Structures

Windage Testing of HGAs at the Component Level
Eliminate Damage To Sensitive Parts...

Use Ceramically Enhanced Ultrasonics to Achieve .1 Submicron Cleanliness
DISKCON USA 2002 remains a key event in the HDD industry. It’s the only “one-stop-shop” event in our industry that lets attendees learn about new products and technologies, meet with key suppliers, attend a world-class technical conference, and hear from the leaders of the HDD industry. 60% of attendees say they come to DISKCON to learn about new technologies, 48% to stay updated in data storage manufacturing techniques, and 29% attend because it improves their ability to do their job. Over 70% of attendees find it challenging or somewhat challenging to stay informed of new products and technologies related to the HDD industry. Close to 90% of attendees feel that DISKCON USA does a good job of helping with that challenge.

The Mark Geenen Technology for Youth Charity Golf Tournament raised almost $30,000 for Ronnie Lott’s All Stars Helping Kids charity. The money will go to Eastside Preparatory School in East Palo Alto. It is a huge boost for the school’s recent fund-raising drive. Thank you to all who participated; your generosity will make a tremendous impact on the lives of many young people.

For the first time ever at DISKCON USA, we offered a CEO Summit. This standing-room only event gave attendees the opportunity to hear from and ask questions of Bill Watkins of Seagate, Matt Massengill of Western Digital, Mike Cannon of Maxtor, Mike Cadigan of IBM, Ichiro Komura of Fujitsu, Wayne Fortun of Hutchinson Technology, and Ed Braun of Veeco.

A BIG thank you to all who volunteered their time to make DISKCON USA such an outstanding event! While space does not permit a listing of everyone who volunteered their time at DISKCON, I would like to recognize the following people:


Bill Watkins of Seagate, Mike Cannon of Maxtor, Matt Massengill of Western Digital, Mike Cadigan of IBM, Ichiro Komura of Fujitsu, Wayne Fortun of Hutchinson Technology, and Ed Braun of Veeco for their participation in the CEO Summit.

A special thank you to Matt Massengill of Western Digital for his wise and witty presentation as the Keynote Dinner speaker.

With a successful DISKCON USA 2002 behind us, it’s time to begin planning for next year’s event. Over 80% of all booths have already been sold. Reserve your space now by calling Paul Moschella or Cheryl Brady at 781-769-8950. 94% of you say you plan to attend DISKCON USA 2003, so we look forward to seeing you then.

As you know, IDEMA has undergone, and continues to undergo, some major changes in structure, management, and focus. We’ll provide more updates as additional information is available on the consortium, new standards, and events for 2003.
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2. Attach cover
3. Ship

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Alchemy and Rigorous Science: The Evolution of Hard Disk Drives

John Monroe, Gartner Dataquest

A History of Fantastic Achievement

Technological marvels, however stunning, have become almost commonplace in the hard disk drive (HDD) industry. We expect the bright folks employed by drive makers to produce wonders, and, with amazing regularity, they do. Like the discoveries of twentieth century theoretical physics, these startling practical innovations at times seem to partake as much of alchemy as of rigorous science.

During the 1990s, the HDD industry, both on the drawing boards and in the factory, became frighteningly capable, designing and producing record volumes of low-cost, high-capacity, high-performance products that dominated competing storage technologies and helped to extend global IT markets. The drive makers have made enormous and critical contributions to computing efficiency. In fact, the global revolution in IT simply would not have been possible without significant cost-reductions and performance enhancements in HDD design and volume production processes.

But what will the primary device for storing data look like in 2015? Will it be akin to the mostly mechanical hard disk drive as we know it today? Or will it look more like a strange, solid-state hatching bred of yet-to-be-imagined ways of recording and playing back the rich media creations of the digital world?

Not much more than a decade from now, the primary storage device may not be a hard disk drive. This could mean that HDD designs and manufacturing techniques will become increasingly irrelevant and obsolete. Eventually, because of the effects of superparamagnetism and other limits imposed by the laws of physics, exotic new storage technologies will become more indispensable than traditional, magnetic-based HDDs to powering the world’s information systems.

Inevitably and inescapably, the venerable hard disk drive will be replaced. But this may take a lot longer than many forward-looking people are willing to admit.

The Upward Slope of Capacity and the Downward Slope of Cost: The Essential Curves of HDD Technology

Eras of Giant Strides

Quick transitions from thin-film inductive (TFI) recording heads (in the late 1980s) to magnetoresistive (M R) recording heads (in the early 1990s) to giant magnetoresistive (GMR) recording heads (in the late 1990s), in conjunction with parallel advances in media and read/write channel technologies, have enabled staggering recent progress in HDD capacities per spindle.

IBM’s 16GP and 14GX P Deskstar HDD families, which were announced on November 10, 1997, and began to ship during December 1997, were the industry’s first drives to incorporate GMR head technology. All current mobile, desktop, and enterprise HDDs use GMR heads. M R heads can read smaller bits of data than TFI heads, and GMR heads provide even greater sensitivity to flux reversals in magnetic fields, making it possible to precisely detect even more densely recorded data bits, thus increasing areal densities but also complicating integration and handling procedures. Despite complex difficulties, all manufacturers managed to quickly incorporate GMR technology. The industry successfully shifted to 100-percent production of GMR designs during the third quarter of 2000.

In 1988, IBM discovered the spectacular "GMR effect" in perfect crystal structures. In 1991, IBM developed prototype GMR "spin-valve" structures. In 1994, IBM announced that it had created the world’s most sensitive disk drive data sensor. In late December of 1997, IBM began shipping GMR heads in volume production disk drives. IBM announced its GMR sensor patents in 1971. It took 20 years (until 1991) for IBM to actually produce a disk drive with GMR heads, and it took the HDD industry seven years (from 1991 to 1998) to shift to 100-percent production of GMR-based drive designs. It took only nine years for IBM to produce a disk drive with GMR heads (a healthy time-to-market acceleration for a profoundly new technology), and the entire HDD industry shifted to 100-percent production of GMR-based drive designs in little more than two years after IBM’s initial shipments.
New, advanced versions of GMR heads—such as so-called "tunneling" GMR heads and Fujitsu's Current-Perpendicular-to-Plane (CPP) mode GMR technology—will be incorporated in the near future.

The principal difference between MR and GMR heads is sensitivity, which is measured as a percentage change in resistance. In MR heads resistance change is caused by an intrinsic property of the sensing layer, whereas in GMR heads resistance change is caused by the quantum nature of electrons. By exploiting the "spin" properties of electrons, GMR sensors attain more than twice the sensitivity of MR sensors. In fact, as the sensing layer's thickness decreases, the sensitivity of a GMR head actually increases (up to a point)—the "GMR effect." The quantum nature of electrons may be paradoxical (and ultimately unknowable) but it has proven to be of enormous practical use in many technologies.

Steeper, Moore Slippery Slopes

Table 1 shows a five-year history and five-year forecast of shippable per-platter capacities for various HDD form factors.

Recent capacity trends have been impressive (not to say astounding: a forty-fold increase between 1997 and 2002), but the industry will soon encounter some huge hurdles. By late 2002 or early 2003, we expect annual density advancements will cool from more than 100 percent to a 60-percent (or slower) rate of increase for mobile and desktop drives, with enterprise capacities beginning to stutter-step in 2004 after another 100-percent increase in 2003. In other words, the industry "slows down" to Moore's Law—a compelling statement of how fast and far the HDD industry advanced in recent years.

Historically, the drive makers have been able to overcome all impediments to their breakneck progress, but the chances for failure will soon deepen and escalate, and the eventual survivors will be a tough, brilliant, and weathered group of veterans. Enormous investments in R&D and large cash reserves will be required, but it will take much more than money to ensure continued success.

During the third and fourth quarters of 2002, the HDD industry will manage to achieve volume shipments of 30GB-to-40GB/platter 2.5-inch mobile drives, 60GB-to-80GB/platter desktop drives, and 18GB-to-36GB/platter enterprise drives. However, beginning in 2003, there will probably be an abatement in this fervid pace of development and change. It will definitely become harder, and more costly, to stay on a steep (and slippery) technology slope, and it may not be possible to attain stable

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### Table 1. Maximum Shippable HDD Per-Platter Capacities, 1997 to 2006 (Gigabytes per Platter)

<table>
<thead>
<tr>
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<tbody>
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<td><strong>Mobile Drives</strong></td>
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</tr>
<tr>
<td>27.5mm Media (1.0-Inch)</td>
<td>-</td>
<td>-</td>
<td>0.3</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>2.0</td>
<td>5.0</td>
<td>5.0</td>
<td>10.0</td>
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<tr>
<td>Annual Growth (%)</td>
<td>-</td>
<td>-</td>
<td>194</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>150</td>
<td>0</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>48mm Media (1.8-Inch)</td>
<td>0.4</td>
<td>1.1</td>
<td>1.1</td>
<td>2.0</td>
<td>5.0</td>
<td>100</td>
<td>200</td>
<td>40.0</td>
<td>40.0</td>
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<tr>
<td>Annual Growth (%)</td>
<td>-</td>
<td>200</td>
<td>0</td>
<td>85</td>
<td>150</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td></td>
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<tr>
<td>65mm Media (2.5-Inch)</td>
<td>1.4</td>
<td>2.2</td>
<td>6.4</td>
<td>10.0</td>
<td>20.0</td>
<td>40.0</td>
<td>60.0</td>
<td>80.0</td>
<td>120.0</td>
<td>200.0</td>
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<tr>
<td>Annual Growth (%)</td>
<td>-</td>
<td>50</td>
<td>196</td>
<td>56</td>
<td>100</td>
<td>100</td>
<td>50</td>
<td>33</td>
<td>50</td>
<td>67</td>
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<tr>
<td><strong>Desktop Drives</strong></td>
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<td></td>
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<tr>
<td>95mm Media (3.5-Inch)</td>
<td>2.2</td>
<td>4.3</td>
<td>10.2</td>
<td>20.4</td>
<td>40.8</td>
<td>80.0</td>
<td>120.0</td>
<td>160.0</td>
<td>240.0</td>
<td>400.0</td>
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<tr>
<td>Annual Growth (%)</td>
<td>-</td>
<td>100</td>
<td>137</td>
<td>99</td>
<td>100</td>
<td>96</td>
<td>50</td>
<td>33</td>
<td>50</td>
<td>67</td>
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<tr>
<td>130mm Media (5.25-Inch)</td>
<td>4.0</td>
<td>6.4</td>
<td>6.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Annual Growth (%)</td>
<td>-</td>
<td>60</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
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<tr>
<td><strong>Enterprise Drives</strong></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65/70mm Media (15,000 rpm)</td>
<td>1.1</td>
<td>1.5</td>
<td>3.6</td>
<td>7.3</td>
<td>18.2</td>
<td>36.7</td>
<td>73.4</td>
<td>73.4</td>
<td>146.8</td>
<td></td>
</tr>
<tr>
<td>Annual Growth (%)</td>
<td>-</td>
<td>33</td>
<td>140</td>
<td>100</td>
<td>150</td>
<td>102</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td></td>
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<tr>
<td>84mm Media (10,000 rpm)</td>
<td>1.1</td>
<td>1.5</td>
<td>3.6</td>
<td>7.3</td>
<td>18.2</td>
<td>18.2</td>
<td>-</td>
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<td>-</td>
<td></td>
</tr>
<tr>
<td>Annual Growth (%)</td>
<td>-</td>
<td>33</td>
<td>140</td>
<td>100</td>
<td>150</td>
<td>102</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td></td>
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<tr>
<td>95mm Media (7,200 rpm)</td>
<td>1.5</td>
<td>3.6</td>
<td>7.3</td>
<td>9.1</td>
<td>18.2</td>
<td>18.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Annual Growth (%)</td>
<td>-</td>
<td>137</td>
<td>103</td>
<td>25</td>
<td>100</td>
<td>0</td>
<td>-</td>
<td>-</td>
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<td></td>
</tr>
</tbody>
</table>

Notes: All enterprise media sizes are currently contained in 3.5-inch external form factors. Gartner Dataquest defines mobile products as 1.0-inch, 1.8-inch, and 2.5-inch hard disk drives that use Compact Flash, PCMCIA, or ATA interfaces; desktop products are 3.5-inch hard disk drives that incorporate ATA interfaces; and enterprise products are 3.5-inch hard disk drives that incorporate SCSI, SSA, or FC-AL interfaces.

Source: Gartner Dataquest (August 2002)
increases in areal density with the larger-sized, 95mm media.

There has been inconclusive debate about actual storage needs in various markets. Does the current furious pace of HDD capacity advancement reflect real market requirements? Certainly it can be argued that average mobile and desktop capacities have far exceeded the needs of most corporate and consumer PC users. But the digitization of the world’s cultural artifacts is still in its infancy, and faster, more-secure pipelines could drastically alter the degree and scope of mobile, desktop, and consumer audio/visual data consumption. As for the higher end markets: Gartner Dataquest forecasts a 73 percent combined annual growth rate in terabytes configured and delivered in storage systems to the RAID markets from 2002 to 2006. (In addition to SCSI- and FC-interface enterprise drives, ATA-interface desktop drives will also be integrated in these multi-user storage systems.) The degree of need in these markets will also depend upon faster, more-secure pipelines (which will determine the extent of Intranet and Internet use), as well as on the proliferation of corporate email, e-commerce, ”rich-media,” and data warehouse applications.

In any case, it is hard to imagine that the world will actually require more raw capacity than the HDD industry will be able to deliver. Table 2 shows a five-year history and five-year forecast of unit and terabyte shipments of mobile, desktop and enterprise HDDs.

This forecast assumes only moderate growth in legacy PC and enterprise storage markets, combined with significant accelerations in demand for mobile and desktop HDDs in new non-PC environments (such as home entertainment centers). It should be noted that this terabyte shipment projection assumes that the total average platters per drive will decrease during the forecast period.

As technology barriers continue to crumble, industry average gigabytes per drive should expand from 27GB in 2001 to approximately 283GB in 2006, and prices will continue to plummet. During the ten-year period from 1997 to 2006, it is likely that HDD per-drive average capacity will increase by more than 10,000 percent (from 2.7GB to at least 283GB) while average per-drive factory average selling price (ASP) decreases by 70 percent (from $208 to $69). Cost per gigabyte declines by almost 100 percent to almost incalculable levels (20 cents per gigabyte for a bare HDD purchased directly from the factory).

Table 3 shows a five-year history and five-year forecast for industry average per-drive capacity and factory ASP changes.

<table>
<thead>
<tr>
<th>Table 2. HDD Shipments of Units and Terabytes, 1997 to 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mobile Drives</strong></td>
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<tr>
<td>Shipments (M Units)</td>
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<tr>
<td>15</td>
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<tr>
<td>Annual Growth (%)</td>
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<td>-</td>
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<tr>
<td>Terabytes (K Units)</td>
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<tr>
<td>30</td>
</tr>
<tr>
<td>Annual Growth (%)</td>
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<tr>
<td>-</td>
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<tr>
<td><strong>Desktop Drives</strong></td>
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<tr>
<td>Shipments (M Units)</td>
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<tr>
<td>94</td>
</tr>
<tr>
<td>Annual Growth (%)</td>
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<td>-</td>
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<tr>
<td>Terabytes (K Units)</td>
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<tr>
<td>230</td>
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<tr>
<td>Annual Growth (%)</td>
</tr>
<tr>
<td>-</td>
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<tr>
<td><strong>Enterprise Drives</strong></td>
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<tr>
<td>Shipments (M Units)</td>
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<tr>
<td>19</td>
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<tr>
<td>Annual Growth (%)</td>
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<td>Terabytes (K Units)</td>
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<td>84</td>
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<td>Annual Growth (%)</td>
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<td><strong>Industry Total</strong></td>
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<td>Annual Growth (%)</td>
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<td>Terabytes (K Units)</td>
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<td>344</td>
</tr>
<tr>
<td>Annual Growth (%)</td>
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<tr>
<td>-</td>
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</table>

Notes: Gartner Dataquest defines mobile products as 1.0-inch, 1.8-inch, and 2.5-inch hard disk drives that use Compact Flash, PCMCIA, or ATA interfaces; desktop products are 3.5-inch hard disk drives that incorporate ATA interfaces; and enterprise products are 3.5-inch hard disk drives that incorporate SCSI, SSA, or FC-AL interfaces.

Source: Gartner Dataquest (August 2002)
Table 3. HDD Average Per-Drive Capacity and Cost Changes, 1997 to 2006

<table>
<thead>
<tr>
<th>Year</th>
<th>Capacity (GB)</th>
<th>Increase/ Decrease (%)</th>
<th>ASP (USD)</th>
<th>Increase/ Decrease (%)</th>
<th>Cost/GB (USD)</th>
<th>Increase/ Decrease (%)</th>
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<tr>
<td>1997</td>
<td>2.7</td>
<td>-</td>
<td>208</td>
<td>-</td>
<td>78</td>
<td>-</td>
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<tr>
<td>1998</td>
<td>4.9</td>
<td>81</td>
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<td>-20</td>
<td>36</td>
<td>-54</td>
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<tr>
<td>1999</td>
<td>8.4</td>
<td>71</td>
<td>145</td>
<td>-17</td>
<td>17</td>
<td>-53</td>
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<td>92</td>
<td>130</td>
<td>-10</td>
<td>8</td>
<td>-53</td>
</tr>
<tr>
<td>2001</td>
<td>27.3</td>
<td>70</td>
<td>107</td>
<td>-18</td>
<td>4</td>
<td>-50</td>
</tr>
<tr>
<td>2002</td>
<td>50.8</td>
<td>86</td>
<td>92</td>
<td>-14</td>
<td>2</td>
<td>-50</td>
</tr>
<tr>
<td>2003</td>
<td>93.2</td>
<td>83</td>
<td>85</td>
<td>-14</td>
<td>1</td>
<td>-40</td>
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<tr>
<td>2004</td>
<td>135.7</td>
<td>46</td>
<td>78</td>
<td>-9</td>
<td>0.6</td>
<td>-33</td>
</tr>
<tr>
<td>2005</td>
<td>166.1</td>
<td>22</td>
<td>72</td>
<td>-9</td>
<td>0.4</td>
<td>-50</td>
</tr>
<tr>
<td>2006</td>
<td>282.6</td>
<td>70</td>
<td></td>
<td></td>
<td>0.2</td>
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</tr>
</tbody>
</table>

Note: HDD ASPs include bare drive only, as sold from the factory to direct accounts. Average capacities grow at a slower rate than the maximum shippable capacities shown in Table 1.

Source: Gartner Dataquest (August 2002)

for all mobile-, desktop-, and enterprise-class HDDs. Again, it is important to note that average per-drive capacities could easily climb to much higher levels if the industry ships more two- and three-platter as opposed to one-platter HDD configurations.

The creators of HDD technology have delivered and will likely continue to deliver the most compelling cost and performance and capacity efficiencies in the whole IT industry.

Alternative Storage Technologies

Flash Semiconductors

There continues to be a great deal of misguided talk about flash memory replacing hard disk drives. One recent article compared an IBM 1GB Microdrive at an outmoded $499 retail price—rather than a more representative HDD, such as a 40GB desktop drive at $72 retail—to OEM prices for flash storage. The author used this comparison to buttress a specious argument that cost and capacity deltas between flash semiconductor storage and HDDs were shrinking fast in favor of flash. A careful look at the numbers displayed in Tables 3 and 4 should dispel further discussion along those lines.

Table 4 shows a comparative five-year history and five-year forecast for factory ASPs and capacities of the most-competitive (single-disk) desktop HDDs and the most cost-effective flash semiconductor technologies.

Current non-volatile semiconductor technologies, critical for such emerging and expanding markets as digital cameras, USB key-chain storage, and multi-function handheld devices, are simply not in the same league as HDDs and will not be able to compete with HDDs on a large scale for primary consumer and corporate IT storage needs. Flash technology is changing fast and provides notable benefits, which include rugged shock tolerance, compact size, easy portability and low power requirements. A $99 1GB flash product—feasible in the near future—might generate much greater potential for more widespread use of this technology. But flash semiconductors will not in the near future provide 10 or more gigabytes of random-access storage for less than $100, and this will limit the markets for flash. Gartner Dataquest also predicts that even radically new semiconductor technologies will fail to compete effectively against HDDs as primary storage devices for at least ten more years.

Table 4. Flash Semiconductors and Leading-Edge Desktop HDDs, Capacity and Cost Changes, 1997 to 2006

<table>
<thead>
<tr>
<th>Year</th>
<th>HDD Capacity (MB)</th>
<th>HDD ASP (USD)</th>
<th>HDD Cost/ MB (USD)</th>
<th>Flash Capacity (MB)</th>
<th>Flash ASP (USD)</th>
<th>Flash Cost/ MB (USD)</th>
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</thead>
<tbody>
<tr>
<td>1997</td>
<td>2,200</td>
<td>135</td>
<td>0.0613</td>
<td>1</td>
<td>6</td>
<td>6.25</td>
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<tr>
<td>1998</td>
<td>4,300</td>
<td>109</td>
<td>0.0253</td>
<td>4</td>
<td>10</td>
<td>2.45</td>
</tr>
<tr>
<td>1999</td>
<td>10,200</td>
<td>92</td>
<td>0.0090</td>
<td>8</td>
<td>11</td>
<td>1.38</td>
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<tr>
<td>2000</td>
<td>20,400</td>
<td>82</td>
<td>0.0040</td>
<td>16</td>
<td>16</td>
<td>1.00</td>
</tr>
<tr>
<td>2001</td>
<td>40,800</td>
<td>75</td>
<td>0.0018</td>
<td>16</td>
<td>16</td>
<td>0.35</td>
</tr>
<tr>
<td>2002</td>
<td>80,000</td>
<td>71</td>
<td>0.0008</td>
<td>32</td>
<td>16</td>
<td>0.24</td>
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<td>2003</td>
<td>120,000</td>
<td>65</td>
<td>0.0005</td>
<td>64</td>
<td>8</td>
<td>0.16</td>
</tr>
<tr>
<td>2004</td>
<td>160,000</td>
<td>59</td>
<td>0.0003</td>
<td>64</td>
<td>8</td>
<td>0.13</td>
</tr>
<tr>
<td>2005</td>
<td>240,000</td>
<td>55</td>
<td>0.0002</td>
<td>128</td>
<td>8</td>
<td>0.06</td>
</tr>
<tr>
<td>2006</td>
<td>400,000</td>
<td>49</td>
<td>0.0001</td>
<td>128</td>
<td>6</td>
<td>0.05</td>
</tr>
</tbody>
</table>


Source: Gartner Dataquest (August 2002)
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A “Millipede” Emerges

If the 20th century was dominated by micrometer-scale (thousandth of a millimeter) technologies, the 21st century may well be defined by three-dimensional, nanometer-scale (millionth of a millimeter) technologies that play an expanding role in all aspects of global culture.

Shortly after IBM’s April 2002 announcement that it would sell its HDD division to Hitachi, the company announced on 11 June 2002 that a new form of nanotechnology could be stored to data. Based on nanometer-scale “tips” currently used in atomic force microscopes (AFMs) and scanning tunneling microscopes (STM s), IBM has developed a prototype storage chip—codenamed “millipede”—in which a cantilevered array of microscopic probes manipulate heat-generated impressions in a polymer surface. The concept is like a computer-generated punch card, but the millipede polymer is rewritable and 3 billion data bits can be stored in the equivalent space of a single hole in the old-fashioned punch card. Initial areal densities of 100-200 Gb/in.², roughly two to four times the density of current leading-edge HDDs, have been achieved in laboratory experiments, and researchers believe that with more numerous arrays of tips the technology may be able to deliver densities up to 1 Tb/in.².


Some scientists are of the opinion that this kind of nanomechanical storage technology could, in the future, prove valid for thousand-fold increases in data density and thus deliver a complete storage system in the form factor of a flash memory chip. A potential near-term millipede-based product might be a storage card the size of a slimline 1.8-inch disk drive containing four or more chips with a total capacity of 60 or more gigabytes. This new form of high-capacity “hard card” could be extremely rugged, with integrated high-speed write/read/erase storage functionality combined with very low power requirements. However, it should be noted that 1.8-inch HDDs will integrate 40-GB/platter technologies in the near future and have already attained a 20GB capacity (on two disks). Gartner Dataquest predicts that factory ASPs for 1.8-inch HDDs will drop below $100 in 2003.

At the moment, there is no clear indication of the precise specifications or commercial cost of a millipede chip; the technology is still at the prototype phase and many questions remain unanswered. What is the true internal data rate of the chip? How can the chip be interfaced to a system and what is the effective data rate at the interface? Can millipede technology overcome the write slow/read fast detriments of flash technology? How stable is millipede data at various temperatures? When will a millipede chip first be produced in volume? Millipede technology could certainly provide greater data density than flash technology, but at what cost? When will millipede chips cost less than $100? Can millipede chips cost less than $50?

Some form of millipede technology—which IBM claims might be commercially viable in 2004 or 2005—could displace portions of inertial flash semiconductor dominance in digital cameras and other emerging mobile markets. (A great deal will depend upon cost: many high-volume flash memory markets demand less-than-$50 retail prices and less-than-$20 OEM prices, but the high end of the market might still accept prices in the $300-to-$500 range.) However, it seems unlikely that millipede technology will achieve any near-term cost and capacity and performance metrics that would enable it to migrate inward to the core of primary consumer and corporate IT storage systems. A senior HDD visionary recently remarked, “If it was inexpensive, I might consider using a millipede chip as a 15GB data buffer in one of my future high-capacity hard disk drives.”

Magnetoresistive Semiconductor Memories

Another proposed new technology is magnetoresistive random access memory (MRAM). An MRAM is an experimental, as-yet-untested chip design that incorporates magnetic tunnel junctions, which function by using an oxide to separate a layer of metal with a fixed magnetic orientation from one that can be magnetically flipped. The two distinct magnetic orientations of the second layer produce different values of resistance to the flow of current through the junction. Measuring the resistance value then becomes a way to detect the orientation of the variable magnetic layer. One concern has been the relative thickness of the metal layers. Semiconductor makers use thickness to combat the tendency of metal atoms to cluster during oxide deposition, but thick metal layers require high power to achieve ferromagnetism and can generate excess heat.

A recent discovery may help to expedite production of nonvolatile MRAMs as well as providing considerable cost savings in the production of industrial catalysts. Acting on theoretical evidence uncovered by Sandia National Laboratory solid-state theorist Scott Jennison, chief scientist Scott Chambers at Pacific Northwest National Laboratory (PNNL) has managed to form on sapphire (aluminum oxide) atomically flat crystalline films of metal measuring only a few atoms thick. By achieving crystallinity with only a few atomic layers, the inherent structural strength should produce greater durability in electronic devices. Dense, efficient, low power, highly reliable nonvolatile memory arrays could be enabled by these flatter metal films. Chambers predicted...
a day when boot-disk data would reside on an MRAM rather than an HDD and provide "instant on" computers. This is the most aggressive statement Gartner Dataquest has yet seen with regard to the potential of MRAM technology, which hardly seems to be a candidate for HDD replacement.

In any case, MRAM technology is still purely theoretical, with no laboratory-demonstrated prototypes that Gartner Dataquest is aware of, no reliable cost or capacity projections, and no valid time-line projections for deployment of any kind. Given the history of past efforts in this direction (bubble memories, solid-state disks), the degree to which any solid-state technology can provide competitive metrics to mainstream HDDs is surely questionable, but scientists continue to uncover ground for renewed hopes, and engineers persist in this (to date) Quixotic quest.

If one goes to the web site www.mram.com, one finds these words: "Due to the subjective nature of reality, contents of this web site may not really exist." This is hardly instructive to any seeker who may wish to discover something concrete about MRAM technology. But this cryptic and humorous message may well be emblematic of ill-fated desires for truly cost-effective and adequately large solid-state storage devices.

Optical Technologies

There have been enormous investments in optical drives, which were presumed by many in the 1980s to be the most promising threat to displace HDDs as primary storage devices. In the 1990s, many pundits still saw optical technology as the eventual winner in a long race to circumvent certain physical limits to magnetic technology. Optical drives also provided the benefits of removable, transportable, archivable media.

Several new optical technologies seemed to hold special promise in the late 1990s. Quinta, with its Optically Assisted Winchester (OAW) technology, and Terastor, with its Near Field Recording (NFR) architecture, received hundreds of millions of US dollars in funding but both companies are now defunct. Terastor ceased operations after many design modifications and announced-but-unmet shipment dates, and Quinta's unproven, unshipped technology was absorbed into the design heirarchy within Seagate (Quinta had been a wholly owned Seagate subsidiary). Siros Technology, another generously funded firm, acquired rights to very small aperture laser (VSAL) technology from Lucent and another generously funded firm, acquired rights to very small aperture laser (VSAL) technology from Lucent and had developed its own 3-D recording techniques but ceased its storage-related operations before any detailed information regarding its business or product plans was made public.

Although CD-ROMs and CD-R/W drives have now become standard in most computing systems, DVD technology has been slow to mature. DVD-ROM has become much more widely distributed in both consumer audio/video and computing arenas, but the realm of rewriteable DVD remains a quarrelsome quagmire without a universal format standard, and it now seems inevitable that HDDs will remain the primary rewriteable storage device in all computers and in most (if not all) of the new high-end consumer audio/video products. While contemporary desktop HDDs transfer data at 133 M B/sec, specify internal data rates approaching 100 M B/sec, seek at less than 10 milliseconds, and can offer 40GB for less than $80 retail price, current-generation rewriteable DVDs transfer data at 10 M B/sec, specify internal data rates of less than 5M B/sec, seek at more than 200 milliseconds, and offer only 4.7GB per side per disc for about $499 retail price. (Prices are for bare drives only, and exclude cables, enclosures, connectors, or adapters.) HDDs deliver approximately ten times the capacity and performance of rewriteable DVDs for a fraction of the price, and this gap in price relative to capacity and performance will continue to widen in favor of HDDs.

Holographic storage, in which writing and reference laser beams store data in densely latticed patterns scattered throughout an optically sensitive medium, held hope in the early and mid 1990s as an innovative, lightning-fast, rugged technology that contained no moving mechanical parts and could generate either fixed or removable media. Several consortia continue to explore this technology, but a working, manufacturable prototype smaller than a refrigerator and costing less than millions of US dollars has yet to be born.

As one industry executive aptly remarked, "Optical technology is the technology of the future, and it always will be."

Evolving HDD Technologies

The laws of physics—in this case, certain conditions defined by Boltzman's Second Law of Thermodynamics—decree that, at a certain density, magnetically recorded zeros will become ones and ones will become zeros, causing an almost instantaneous degradation of "data" into "garbage" (this is known as the "superparamagnetic effect"). Data will become hard to write, and once written, it will disappear in about one nanosecond (which is hardly adequate for archival storage needs). But at what precise degree of areal density will it become impossible to reliably read and write data at room temperature by means of conventional magnetic recording techniques?

Several new technologies should enable the drive makers to fend off the incursion of competitive technologies and postpone an inevitable encounter with the deleterious effects of superparamagnetism.

continued on page 14
continued from page 13

**Multi-Layered Media**

Both Fujitsu and IBM have announced and shipped a new kind of media which will extend potential areal densities by adding a non-magnetic stabilizing layer (composed of ruthenium) to one or more ferromagnetic layers. By antiferromagnetically coupling with the recording layer(s), the ruthenium layer allows the effective magnetic thickness to scale independently of the physical thickness of the media, stabilizes the magnetically recorded signals and prevents degradation even at high areal densities. Fujitsu initially named its media Layer Exchange Interaction Stabilized (LEXIS) and subsequently changed the name to Synthetic Antiferromagnetic Media (SFM). IBM coined the name “Pixie Dust” for its antiferromagnetic media (AFM). Further technical details and downloadable white papers can be found at the companies’ respective Web sites.

Many engineers currently believe that SFM/AFM technology, which is already integrated in certain mobile and enterprise HDD products, will become an absolute requirement at 100 Gb/in.² areal densities and, in conjunction with advanced GMR heads, will enable areal densities up to 300 Gb/in.².

**Perpendicular Change**

By midyear 2004, Gartner Dataquest believes the HDD industry will begin to make a shift to reading and writing perpendicular rather than longitudinal data layers in magnetic media. By decreasing the transition width between recorded data bits, the possibilities for demagnetization in perpendicular recording are reduced, and smaller grain-sized media can be used. Perpendicular recording extends potential areal density by changing the longitudinal limits imposed by tradeoffs between signal-to-noise ratios, thermal stability and writability.

The head makers have had to suffer inordinate capital equipment expenses by making a recent transition from square to round photolithographic production and test equipment. With the transition to perpendicular recording, the media makers may soon have to absorb some exorbitant capital equipment expenses in order to continue to play the game.

Between 100 Gb/in.² and 300 Gb/in.² densities, some designers will choose to switch to perpendicular recording methods while others decide to stretch the limits of longitudinal recording with SFM/AFM media. Although there is no general agreement with regard to the additional costs required to manufacture and test perpendicular media, the temporary cost increases associated with perpendicular recording will likely prevent any premature shifts to this technology. However, an eventual shift seems inevitable. Most engineers agree that perpendicular recording will be required to achieve densities in excess of 300 Gb/in.², and many engineers believe that perpendicular recording will enable areal densities in the one Tb/in.² range.

**A New Kind of Optical Assistance**

Seagate Technology formally announced on 21 August 2002 new Heat Assisted Magnetic Recording (HAMR) technology, which potentially could help to drive HDD areal densities beyond one Tb/in.². In conjunction with self-ordered magnetic array (SOMA) media (about which more in a moment), HAMR might enable cost-effective HDD areal densities in the range of 50 Tb/in.².

Similar to Quinta’s OAW technology, the central concept of HAMR is to use an interplay of temperature and field gradients to perform extremely high-density thermomagnetic recording. HAMR utilizes lasers to generate heat and temporarily lower the coercivity of the media at a precise point during the write process and then allows the media to instantaneously cool down and re-establish its thermal magnetic stability. Theoretically, HAMR makes it possible to use the smallest grain size, irrespective of the coercivity of the media.

Proponents of the technology claim that HAMR should be able to achieve 10 Tb/in.² with three-nanometer iron-platinum grains in the media. Critics claim that the costs associated with creating such intricately coordinated laser and read/write head technology combined with the data-loss dangers inherent in inadvertently heating adjacent bit cells, will render HAMR technology impractical and subject to some of the same cost and capacity inefficiencies as magneto-optical drives. Much will depend upon the cost-effective availability of micro-machined parts capable of making nanometer-scale distinctions between data domains.

**Patterns within Patterns**

A promising new media technology, nicknamed SOMA, makes use of iron-platinum particles dispersed in a hexane solvent which, after being subjected to an evaporation and annealing process, transform themselves from a chaotic superparamagnetic state into a patterned, readable ferromagnetic state. By depositing these synthetically patterned self-ordered magnetic arrays into sectors arranged in circumferential tracks and recording one bit per particle, theorists maintain that a density of 50 Tb/in.² might be obtained. SOMA media might be used in perpendicular recording as well as in conjunction with HAMR, and could also be a candidate for new probe storage technologies (such as millipede).

**Gartner Dataquest Perspective**

During the early 1990s, many engineers believed that it would be impossible to store data reliably using conventional magnetic technologies at greater than five or 10 Gb/in.² areal density. This dire prediction, backed by a plethora of scientific “evidence,” helped to generate a
widespread interest in so-called "optically assisted" storage technologies, which, it was assumed, would be required by year 2000. The newly announced HAM R technology echoes aspects of OAW recording, which is hardly surprising, since key Quinta engineers were absorbed into the Seagate advanced concepts laboratories. HAM R, or some technology like it, may be required by 2008, after the possible extensions of perpendicular recording with advanced GMR heads have been explored.

The forecast 5 or 10 Gb/in.² magnetic "limit" has been relegated to the same wastebin that contains Thomas Watson Sr.'s stupefyingly wrong-headed 1950s prediction that the world would only need a few large computers to conduct its business. It now seems obvious that—with conventional if enhanced magnetic technologies—200-to-300 Gb/in.² data densities will be attained. (Roughly translated, this would equate to 200GB-to-300GB on a 65mm piece of mobile-class media, or 400GB-to-500GB on a 95mm piece of desktop-class media; a three-platter HDD design might yield 600GB to 1.5TB of formatted capacity.) With a few more ingenious twists and turns—such as perpendicular recording, HAM R and SOMA—1 Tb/in.², 10 Tb/in.² and even 50 Tb/in.² data densities may be achieved without drastically altering the basic mechanics and features of traditional HDD technology. The challenges will be huge, but Gartner Dataquest predicts that the drive makers, as in the recent past, will grudgingly absorb the inordinate development costs and the brilliant engineers will somehow manage to solve all of the near-term technical and operational problems.

Success at 300 Gb/in.² seems assured (if problematic), and it looks increasingly likely that one Tb/in.² HDD areal density can be cost-effectively achieved (one can surely question the real need for such an immense capacity on a single spindle, but it seems possible and probably will be built). It may turn out that it will be impossible to incorporate 10 Tb/in.² or 50 Tb/in.² technologies in mass-produced HDDs, but the prospects for success in these phenomenal domains seem more viable with HDDs than with alternative technologies at lesser densities.

The steep upward slope of HDD capacity and high-speed data access, combined with the steep downward slope of costs per gigabyte, are at the core of the revolution in storage technology. Gartner Dataquest does not think it is possible to over-emphasize the trends indicated by these slopes—they represent both the transcendent technological glory and the hellish fiscal despair of the HDD industry. They also represent daunting barriers to entry for any alternative, potentially disruptive technologies. (A cost-effective 300 Gb/in.² HDD will be very hard to compete against, but cost-effective one-, 10- or 50-Tb/in.² HDDs might preclude all competition.) The use of various evolving forms of GMR heads in conjunction with new HDD technologies should ensure the overwhelming predominance of HDDs as primary storage components in diverse applications for the foreseeable future.

Eventually, the industry will be stymied by a peculiar and arresting development. The next-generation designs might be more expensive to produce than the prior-generation designs—a problem the drive makers have encountered and overcome in the past, but the intractable difficulties of this problem at greater degrees of areal density could transform the nature of the game. At this point, new technologies and new combinations of old technologies will reveal new nanomechanical directions and dimensions in storage. However, the older technologies will continue to compete on the basis of price for some time after possibilities for further progress have been exhausted, just as in the 1960s and 1970s the old ferrite core memories survived for more than a decade after it had become obvious that semiconductors were the wave of the future.

A hallmark of the HDD industry has been an astonishing ability to decrease costs while increasing both performance and capacity. When it costs more to make a new drive with greater per-disk capacity than it does to continue to build an older design, the traditional areal density game will suffer a shocking seachange and the industry will be forced to create a new playing field with richer and stranger technologies.

But this may not happen before 2010 or 2015 (or even later). Until then, the delineations of future battlegrounds between HDDs and competing primary storage technologies will be real only in a realm of speculation.

John Monroe

Mr. Monroe is a Vice President in the Storage Group at Gartner Dataquest. In addition to acting as managing team leader of the storage analysts, he is responsible for all hard disk drive research deliverables, including data collection and collation, forecasts, technology and market trends analyses, corporate profiles, consulting reports and client projects. Mr. Monroe has established a reputation as an eloquent spokesperson for the hard disk drive industry and has been an invited speaker at conferences in Asia/Pacific, Europe, and the United States.

Prior to joining Gartner Dataquest in October 1997, Mr. Monroe spent seven years at SYNNEX Information Technologies, Inc. (formerly COMPAC Microelectronics), where he was vice president of all storage products, managing both distribution and OEM product lines. He grew storage revenue at SYNNEX from $28 million to more than $400 million, eventually coordinating the flow of more than two million hard disk drives per year. Before his tenure at SYNNEX, he was director of North American Sales and Marketing for Kalok Corporation and was also Vice President of OEM Products and Sales for Media Distributing/Media Winchester Ltd. In the early 1980s, Mr. Monroe served as general manager of Electrolabs, a small distribution company, where he began his electronics career by selling EPROMS, hybrid ICs, and Qume and Shugart 8-inch double-sided, double-density (DS/DD) floppy disk drives.

Mr. Monroe earned a bachelor's degree Phi Beta Kappa, summa cum laude from Amherst College in 1976 and also earned a master's degree in fine arts with honors from Columbia University in 1980.
This year’s Keynote Dinner speaker was Matthew Massengill (upper left), Chairman and CEO of Western Digital Corporation. This annual event allows data storage professionals to visit and catch up on that latest news and events in the industry.

The first-ever CEO Summit was standing room only, and offered attendees the opportunity to hear from the leaders of the HDD industry.
The ever-popular IDEMA Technology Showcase is one of the most highly trafficked areas on the exhibit floor and features the world's largest collection of milestone disk drive and industry memorabilia. Attendees had the opportunity to speak with Jim Porter (shown at the left, pointing) of DISK/TREND, Inc., one of Silicon Valley's most knowledgeable and highly respected historians on the evolution of the data storage industry.

This year's technical conference was widely regarded as outstanding, both in terms of content of material and quality of presenters. Copies of the proceedings are available for purchase. Call the IDEMA office at 408.330.8100 for more information.
DISKCON USA a success

Even though industry consolidation and the economy has had a direct effect on reducing the number of attendees and exhibitors at DISKCON USA, many data storage professionals still are satisfied with the event. Individuals found that they still have access to the key decision makers—the individuals that people want to network with. IDEMA surveyed both attendees and exhibitors to learn what they had to say. We are sharing some of this important information with you. Below you will find questions with the top three responses.

What are your main reasons for attending DISKCON USA 2002?
To learn about new technologies: 60%
To stay updated in data storage manufacturing techniques: 48%
To meet and network with business associates: 27%

How is your company involved in the data storage industry?
We manufacture hard disk drive components: 38%
We sell components, equipment, materials, and/or services to hard disk drive manufactures: 37%
We manufacture hard disk drives: 33%

Which technologies and hard disk applications is your company involved in?
Hard disk: 86%
Desktop: 27%
Laptop: 23%

How well does DISKCON USA meet the challenge to stay informed with the latest technologies and services in HDD?
DISKCON USA does a good job of helping that that challenge: 56.16%
DISKCON USA makes it easy to meet that challenge 30.54%
DISKCON USA does not meet that challenge: 13.30%

Did the DISKCON USA events that you attended meet with your satisfaction
Yes, it was O K: 36.82%
Yes, Somewhat: 34.33%
Yes, Very: 22.89%

In what area does your company expect to spend the same or more as last year?
Test/A utomation: 27%
Process Equipment: 26%
Materials: 24%

EXHIBITOR---How would you rate the attendee base of DISKCON USA?
Interested potential customers: 52.17%
Tire Kickers: 21.74%
High level management attendees 17.39%

DISKCON 2003

Over 80% of all booths are sold. If you haven’t reserved space, call Paul Moschella or Cheryl Brady at 781.769.8950.

Sponsorships and promotions are a great way to promote your company product and increase brand awareness. We have many different opportunities which can be customized to fit every budget. To learn more contact Paul or Cheryl at 781.769.8950.
Hands-on demonstrations are a prevalent part of the high energy existing on the exhibit show floor. Attendees are able to meet, face-to-face, with industry experts and visit with fellow data storage professionals.
MKS MultiGas Purity™ Analyzer Sets New Standard for Trace Gas Impurity Detection in Semiconductor Manufacturing

MKS Instruments, Inc., (Nasdaq: MKSI), a leading provider of products that measure, control, power, and monitor critical parameters of semiconductor and other advanced manufacturing process environments, today introduced the MultiGas Purity™ real-time trace impurity analyzer. The fully automated Purity gas analyzer provides continuous trace impurity detection in high purity bulk process gases, such as ammonia, nitrogen trifluoride, hydrogen and nitrous oxide. The MKS Purity analyzer has proven to be the most accurate and reproducible impurity analyzer available today. It offers IC and compound semiconductor manufacturers higher yields and lower costs by reducing the risk of wafer contamination and subsequent fab line downtime. Visit www.mksinstruments.com for additional information.

Smallest High-Speed Translation Stage with Linear PZT Motor Drive

Polytec PI, NanoAutomation Group, introduces the world's smallest translation stage with an integrated high-speed linear piezo motor drive.

- Package 25x20x8 mm (that's a volume of less than 1/3 cubic inch)
- 150 m/sec² (~15 g) acceleration
- 20 mm travel range

For additional information visit www.polytecpi.com.

Veeco Launches SPM Probes e-Commerce Store

Veeco Metrology Group has announced the launch of the world's first scanning probe microscopy (SPM) probes e-commerce site at http://store.veeco.com. The new on-line store offers over 200 scanning probes and related products. The site also features the latest e-commerce technology, including ease of use, full search functionality, immediate acknowledgement of orders, and secure credit card, purchase order, and check payment options.

Available probe-technology products run the full scanning probe microscopy range, from high-aspect-ratio and NSOM probes to force calibration cantilevers and tip-storage accessory kits. After setting up password-protected accounts, users of the site can easily navigate available products through icon-driven windows and, within seconds, purchase the appropriate probes for their systems and applications. Additional information on Veeco can be found at www.veeco.com.

Randy Bonner at Acropolis Engineering, Inc.

Randy Bonner, member of IDEMA Board of Directors, is now associated with Acropolis Engineering Inc., in a marketing capacity. Acropolis specializes in the design and manufacturing of products for use in applications where high precision components manufactured to tight tolerances and six sigma quality standards are a requirement, including vacuum/thermal formed plastic shipping trays for mechanical components.
Gordon Tindle Appointed Executive General Manager, Enthone Ltd.

Mr. Gordon Tindle has been appointed Executive General Manager of Enthone Ltd., United Kingdom, by Cookson Electronics PW B Materials & Chemistry. Mr. Tindle will have overall operating responsibility for the Enthone chemistry, PW B laminate and equipment businesses throughout the United Kingdom and Ireland.

Mr. Tindle has been with Enthone since 1990 and brings a broad portfolio of experience based on his previous technical and managerial positions within the company. He has been involved in the marketing, sales, and technical service of Enthone products for twelve years. For the last two years, Mr. Tindle has led Enthone's PW B chemistry business in the UK and Ireland. His new role combines all Enthone's businesses under his leadership.

25 Percent More HR8EE Motor

Nanomotion introduces the HR8EE motor, providing 25 percent more speed, force, and duty cycle. The "EE" version of the HR8 motor improves heat dissipation allowing for significant improvement to the envelope of performance. Maximum speed increases to 350m/sec, maximum force increases to 45N and duty cycle improves greatly.

Nanomotion, Inc., offers a wide range of unique piezoelectric motors based on ultrasonic standing waves for advanced motion control automation systems. For additional information contact Ernie Ponce at eponce@nanomotion.com.

Circuit Assembly Launches Full Production and Shipping of Serial ATA Cable Assemblies Worldwide

Circuit Assembly, producer of quality interconnect solutions, announces the full production of its Serial ATA cable assemblies and begins order shipment to customers around the globe. Serial ATA cable assemblies are designed to succeed the Ultra ATA parallel interface cable assemblies. The new generation cable assemblies feature small form factor and low profile for limited-space applications, low pin count using serial data transmission, and thin and flexible cables for easy routing.

Circuit Assembly is currently shipping its Serial ATA cable assemblies volume to manufacturers of host bus adapters, motherboards and hard disk drives. These cable assemblies include three configurations utilizing straight and right angle cable exits. To learn more visit their web site at: www.circuitassembly.com

OEM AMP AC4 Amplifier

Nanomotion introduces its latest motor amplifier, the AC4, for use with all standard Nanomotion motors. The AC4, available in a small box, provides motor power for a maximum of 4 Elements (up to HR4 Motors). This amplifier is 50 percent smaller than the previous version and accepts a 12 volt input. The AC4 is available with an analog input (+/-10v) or an SPI digital input. For more information contact Ernie Ponce at eponce@nanomotion.com.
The patternning of Tunneling Magnetoresistive (TMR) junctions found in the read stripes of disk drive heads has conventionally been accomplished using ion milling techniques with inert gases. The ability of non-reactive ion milling, however, to continue to meet the patterning requirements for future generations of read stripe heads is limited by the redeposition of sputtered by-products onto feature sidewalls which are difficult to remove. Inadequate removal of the sidewall deposit can lead to shorting of tunneling junctions and to veil formation that can impede subsequent device processing. Alternatively, plasma etch technology uses reactive gas chemistries to eliminate sidewall residue formation. Reactive chemistries form volatile etch byproducts that are pumped away from the etched surface. The combination of reactive chemistry and precise control of ion energy also provides manufacturers with the ability to develop processes that etch materials selectively, a level of process latitude that is unavailable with non-reactive milling techniques.

In recent generations of disk drives, the functions of writing information to the storage platters and recalling this stored information have been separated into two different device structures on the drive head to speed operation and to increase storage density. Inductive write heads, which practically all disk drives have utilized since their introduction in the 1950's, originally performed both functions, but in recent years, the devices used to extract information from the storage platters have evolved from spin valves exploiting the giant magneto-resistance (GMR) effect, to more recently, the use of tunneling magneto-resistive (TMR) junctions. In practical operation of read stripes, as the devices are commonly called, the orientation of the magnetic field from the storage platter acts to modulate the resistance of the TMR junction resulting in a high or low value and hence, a "0" or "1."

Reactive ion etching has been used extensively for micro-electronic device fabrication for the last 30 years, and plasma technology has continued to develop to keep up with the stringent requirements for the fabrication of advanced integrated circuits (ICs). The introduction of new low volatility materials in advanced IC memory devices such as magnetic random access memory (MRAM) and ferroelectric random access memory (FeRAM) have resulted in significant advances in the removal of the constituent low volatility metals from which these memory devices are made. Iron, cobalt, and nickel are typical metallic elements found in TMR structures with etch by-products that are less volatile than most conventional IC based materials. The etch reactors and processing configurations that have evolved to address the patterning requirements for these films for advanced IC memory applications are also ideally suited for the fabrication of read stripes based on TMR and GMR technology in disk drive applications.

A schematic of a typical read-stripe structure including the TMR junction is shown in Figure 1. The TMR tunnel junction in its simplest form consists of a ferromagnetic layer with fixed horizontal polarity, a ferromagnetic layer in which the magnetic polarity can change orientation in the presence of an external magnetic field, and a thin dielectric layer (~10-15Å) that separates these two magnetic layers. A typical read stripe consists of the TMR junction, a magnetic pinning layer used to shape the magnetic fields, and top and bottom non-magnetic electrical contact layers. Materially, GMR structures are similar to TMR structures with the most notable exception that the dielectric tunneling junction is replaced with a conductive film.

The thicknesses of the constituent films in a TMR stack structure are typically in the range of 10-60Å for the magnetic layers above and below the tunneling junction. Pinning layers are typically in the range of 100-200Å. These thicknesses are in stark contrast to the metal thicknesses of thousands of angstroms that have been used in conventional IC fabrication.
Plasma etching

Plasma etching of low volatility materials is generally performed in a low pressure reaction chamber (1-20mT typical) into which reactive gases are introduced and subsequently ionized. Ionization of the reactive gas provides a means for controlling the directionality and energy of the charged species in the plasma. A schematic of a plasma reactor that has been specifically adapted to meet the stringent requirements for magnetic films and in particular, TMR structures, is shown in Figure 2. In this reactor, radio frequency (rf) power at 13.56MHz is transmitted from the inductive antenna mounted at the top of the reactor, through a dielectric window and into the chamber. The density of the plasma, and to some extent the reactivity of the gas, is controlled by the level of power transmitted from the antenna.

A second rf power supply is used to bias the substrate to control the energy of bombarding ions escaping from the plasma. This second rf supply differs in frequency from the supply used to generate the plasma and is better suited for control of ion direction and ion energy. Control of ion directionality and energy is required to control etch rate, profile angle, and selectivity between the various layers in the TMR structure. Unlike ion milling, where ion energies must be on the order of hundreds of electron volts to minimize the divergence of the ion beam, ion energies in the plasma etching tool shown in Figure 2 can be reduced to tens of electrons volts for optimal process control.

Gas chemistry also plays an important role in reactive plasma etching, particularly in cases such as TMR stacks where film structures containing 5-10 individual layers are commonly used. The volatility of etch by-products can vary significantly from layer to layer depending on the elemental constituents of the films and the reactive gases that are used. Halogen-based etch chemistries containing chlorine, bromine, and fluorine are most common.

Current manufacturing methods for both GMR and TMR structures revolve around ion milling using inert gases. The primary disadvantage of ion milling is that thick veils and residues typically form on the sidewalls of the patterned features that can interfere with subsequent steps in the read stripe fabrication sequence. Incomplete removal of these sidewall layers can adversely affect device performance if the residue layer results in an electrical short across the TMR junction. The use of reactive chemistries in the case of plasma etching helps to eliminate sidewall residue formation through the creation of volatile etch by-products that can be pumped away from the wafer surface and exhausted from the etch chamber.

Another disadvantage of ion milling technology is the limited ability to obtain appreciable selectivity between the individual films in the read stripe structure which reduces tool versatility relative to plasma etching. The ability to tailor the etch chemistry for each layer in the TMR structure provides a means for introducing an optimized process step for each layer. Selective processes help to ensure that materials below a targeted layer, for example, are not removed prematurely with a non-optimal chemistry. This capability, coupled with the ability to control ion energies to very low levels, enables engineers to develop processes by which the etching can be stopped at intermediate layers in the film stack. The ability to stop within the structure provides a greater degree of flexibility in device design and greater latitude in fabrication processes.

Regardless of the dry etch sequence that is used for the patterning of the TMR structures, and whether the stack is etched in its entirety in a single process or in multiple steps, measures must be taken to ensure that the integrity of the tunneling junction is not compromised at the completion of the patterning sequence. Adverse effects from etching residue, or from other unintended modifications to the sidewall surface, can lead to electrical shorting across the tunneling junction, for example, that can sacrifice device performance and device yield. An integrated approach that incorporates a patterning sequence, minimizing the potential for the formation of electrical shorts coupled with a compatible post etch treatment strategy that eliminates by-products from the etch process, will help to ensure peak device performance.

**Endpoint control**

One of the primary benefits of reactive ion etching over non-reactive ion milling techniques is the ability to tailor the etch chemistry for each of the films in the TMR read stripe structure. Each film has specific properties for which the gas mixture and process conditions can be

*continued on page 24*
optimized to meet the targeted feature shape and performance specifications for the finished structure. Parameters such as profile control, critical dimension control, and etch rate are likely to vary for a given etch chemistry from film to film as are the requirements for minimizing both residue formation and the loss of etch-stop layers. The ability to optimize the gas chemistry and process parameters for each film with plasma etching, provides an added level of flexibility in the fabrication of these devices.

In order to take advantage of the benefit of multi-step processing, sophisticated endpoint techniques are used to identify the transitions between the individual films in the TMR structure. One common technique that has been used effectively in dry etching is optical emission analysis. Molecular species specific to the gas mixture and film are present in the plasma during the etch process. As the etch progresses through each layer in the film stack, the concentration of molecular and atomic by-products, and the optical emission from these by-products, can be monitored. Emission from TaClx species, for example, might be monitored when etching Ta with a chlorine-based etch chemistry. The emission of specific wavelengths from TaClx molecules will increase as the etching of the film commences and will then decrease as the layer of Ta is removed and the TaClx molecules are exhausted from the process module.

In Figure 3, typical optical emission traces obtained from the etching of a multilayer TMR film structure is shown. The optical emission intensity for two different wavelengths have been superimposed over the TMR structure to show how the intensity of the signal can change as the etch progresses through the film stack. For the example shown in Figure 3, a single process chemistry was used to etch the entire TMR structure to clearly demonstrate the modulation in emission intensity. The transitions in the optical emission traces can be used in the case of multi-step processing to signal the completion of each individual layer in the stack and to initiate changes in the gas mixture and process parameters for each layer as the etch progresses through the stack.

At the early stages of development of a TMR etch process, monitoring of the full optical spectrum can shorten development time by enabling engineers to quickly identify the most visible and most useful transitions. Onboard monitoring of the full optical spectrum can, therefore, reduce development time. The ability to mathematically manipulate emission signals from multiple wavelengths is also often a useful technique for refining and sharpening the transitions between each layer.

Optical emission spectroscopy provides one example of a range of potential endpointing techniques available with reactive ion etching that might take advantage of such characteristics as plasma emission, plasma properties, wafer surface reflectance, and rf parameters.

**Corrosion control**

The combination of residual halogen-based etch by-products on patterned metal films with ambient moisture can lead to the onset of corrosion in some metal films. Iron-based magnetic films used in TMR structures are particularly susceptible. Many of the techniques that have been developed for corrosion control in IC fabrication, however, are ideally suited for eliminating residual etch by-products from TMR structures prior to subsequent processing.

One such method is a postetch treatment in a wet bath or spray of deionized water or other wet solution to remove etch by-products consisting of soluble metal chlorides and bromides. Timely treatment can simplify the removal of these by-products whereas prolonged exposure to atmosphere can lead to both the oxidation of the etch by-products, which can render them non-soluble, and the absorption of moisture which can lead to the formation of acidic compounds that can react with films on the substrate. In Figure 4, a wet rinse process module is shown that has been integrated into a dry etch process module.
between features on this wafer are smooth and residue-free with no sign of surface degradation.

Conclusions
The combined benefits of precise ion energy control, precise endpointing techniques, optimized reactive gas chemistries for each layer in the stack, and appropriate post etch methodology for controlling corrosion have been used to successfully fabricate TMR structures on a production platform.

SEMs obtained from a patterned TMR stack structure are shown in processing platform. In this configuration, TMR wafers that have been patterned with reactive ion etching are exposed to a wet rinse treatment on the same etch platform to remove corrosion-causing agents from the wafer surface immediately after etching.

An example of an effective post etch rinse treatment on a TMR film structure is shown in Figure 5. In Figure 5a, scanning electron micrographs (SEM s) obtained from a wafer that was not exposed to a post etch treatment after reactive ion etching are shown. The magnetic films in the field areas between the features on this untreated substrate have corroded after prolonged exposure to ambient conditions. In Figure 5b, SEM s are shown from an identical wafer after exposure to a post-etch rinse treatment in the integrated rinse module immediately after etching. The magnetic films in the field areas

Figure 5a and 5b. Photoresist-patterned TMR structure (a) with no post etch treatment that has degraded after prolonged exposure to ambient and b) an identical structure that has been exposed to a post-etch rinse treatment immediately after plasma etching to remove reactive etch by-products from the surface.

Figure 6. The micrographs show features that are free of residues and corrosion. The ultimate measure of success for a process integration approach is in the electrical characteristics of the completed device structures. Plasma etched TMR structures have yielded magnetic ratios in the range of 27-30 percent that are comparable to those attained with conventional ion milling techniques.

The increasing utilization of low volatility materials in IC fabrication has created an impetus for equipment suppliers to invest in the development of new patterning sequences for these films that are likely to have a spillover effect for disk drive applications. The increasing interest in TMR structures in both the disk drive industry and the IC industry provides an opportunity for both industries to share the benefits of this investment.

Robert Ditizio is the TMR/MRAM Etch Project Manager at Tegal Corporation. He has an M.S. and Ph.D. in Engineering Science from The Pennsylvania State University and an MBA from Sonoma State University. At Tegal for the past ten years, he has worked on the design of advanced plasma systems and on the development of advanced plasma etch processes for the disk drive and IC industries.

Figure 6. Scanning electron micrographs of a TMR stack structure after reactive ion etching and a post-etch rinse treatment that show vertical profiles that are free of veils and residue, and surfaces that are free of corrosion.
Mounting conditions of the HGA greatly influence their windage power spectra. Mounts can impair the spectra by absorbing energy and/or introducing extra modes. An arm-plate mount that imparts very little influence on HGA windage spectra has been developed. A robust filter capable of removing the spikes from PSD spectra while preserving the modal information is also discussed.

As tracks get narrower, characterization of non-repeatable run out (NRRO) assumes greater levels of significance for track mis-registration (TMR) budgeting and control [1]. A major portion of the track following-TMR comes from dynamics of the E-block, pivot and the HGA. Since these parts are sourced from different vendors and are integrated by “violent” means such as swaging, windage budgeting for components or processes at the drive level becomes a daunting task. In the current scenario, scope of optimization is hence limited to the task of designing/choosing the best “windage-friendly” HGA around an arm-design chosen previously by virtue of its FRF features. This makes it important to be able to compare the windage spectra of suspensions strictly at the HGA level and not influenced by arm modes.

**Challenges in Windage Testing**

The two major challenges for HGA level windage testing are (1) to be able to eliminate/minimize the influence of mounting structures and (2) to be able to control the retention forces/torques acting on the mount plate. In order to ensure repeatability of test results, it is also necessary to control the relative pitch/roll/skew of the mount surface, apart from the wind flow conditions.

We devised experiments to study the impact of mount structures and mounting methods on windage spectra of HGAs. Throughout these experiments, the wind flow and fly-height conditions were held constant and also it was ensured that the pitch/roll attitude of the mount surface (w.r.t the disk) was maintained within +/-0.01 degree error. Care was taken to maintain the radial location and skew of the slider during each set up.

Five different types of set-ups were tried. In the first one, a simple clamp (refer to Table 1) was used to hold the HGA on the outside of its mount-plate hub. The stainless steel clamp was designed to grip the boss from diametrically opposite sides of the hub and hence we call it a “two-point” clamp. In the second set-up, a three-point clamp was used which could grip the hub at three locations on the hub OD. This clamp is usually used in dynamic fly height testers. The third set-up consisted of gluing the exterior surface of the HGA hub into a suitably tolerated hole at the end of a thick cantilever arm made out of carbide steel. In the fourth set-up, the glue interface was changed to go in between the flat surface of the mount plate and that of the carbide steel arm. In this set-up, a weight was used to evenly distribute the glue layer thereby controlling its thickness. The fifth mounting set-up was made out of a conventionally shaped aluminum e-block arm with the HGA torqued into a threaded hole in it, using a precision custom-shaped screw. In all the cases, the torques (those applied on the HGAs or the cantilevered arms) were controlled to ensure repeatability in readings.

Typical PSD spectra of windage generated by a 14.5mm form factor suspension on various settings are compared in Figure 1. A summary of the findings is tabulated in Table 1.

These experiments show that mounting structures play a crucial role in windage testing. They can even project a bad image of a windage-friendly HGA. In some cases...
individual modes of the HGA and that of the mount lie close to each other resulting in unusually large windage flare-ups. In some other cases, a support can also dampen the HGA modes by absorbing energy. As far as the mounting method is concerned, its impact is mainly felt on the repeatability of results.

**Evolution of an Arm Plate Mount**

We designed an arm plate that has no in-plane modes lower than 25 kHz. It is a 48mm by 38mm hardened SS440 plate with 1.27mm thickness. The thin configuration allows it to position an HGA comfortably in between disks that are 2.54mm apart. Figure 2 depicts the natural modes of this plate when it is secured onto a 38mm by 38mm stage. Various bending modes that appear below 25 kHz are so heavily damped that they do not seem to excite the HGA modes. This configuration is currently being used in our windage tester (Figure 3). The HGA is torqued 5 oz-in into a threaded hole in a corner of the plate using a custom-made screw. For testing windage, the HGA is loaded between the disks at the OD with zero skew angle. In the loaded position, only a corner of the arm plate (where the HGA is attached) intrudes the disk space. This helps to minimize the turbulence caused by the HGA support.

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**Table 1. Comparison of different types of HGA mounting methods.**

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
<th>Influence of mounting on windage spectra</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Two-point” clamping</td>
<td>High DC content; lots of arm modes</td>
<td>Measurement repeatability isn’t good</td>
<td></td>
</tr>
<tr>
<td>“Three-point” clamping</td>
<td>Mount plate distortion; Noisy arm modes</td>
<td>Poorest repeatability</td>
<td></td>
</tr>
<tr>
<td>Gluing on the hub</td>
<td>Low arm influence</td>
<td>Difficult to control glue spread which controls attitude of the slider</td>
<td></td>
</tr>
<tr>
<td>Gluing on the mount plate</td>
<td>Low arm influence</td>
<td>Better repeatability; lots of noise</td>
<td></td>
</tr>
<tr>
<td>Torquing on conventional arm</td>
<td>Distinct modes from compliant arm</td>
<td>Best repeatability with proper screw</td>
<td></td>
</tr>
</tbody>
</table>

---

**Figure 4 shows a typical windage spectrum obtained using arm plate mounting, generated by the same 14.5mm HGA product. The modes seen on the plot are purely the HGA modes. The setup was also used to test several other products and similar results confirmed that the mount plate doesn’t significantly influence the windage spectra.**

**Data Processing for Windage Spectrum**

A major part of the windage forces act through the air bearing, which in turn is supported by a spinning disk. As a result, vertical motions of the disk cause the windage spectra to have spike-shaped features repeating at multiples of spindle frequency. Though it is reasonable to account for the energy content of these spikes for calculating the net RMS value of...
the PSD, the presence of spikes might lead to misinterpretation of the mode peaks. To complicate the matters further, amplitudes of these spikes might also change from trial to trial.

Several data processing methods are in use to trim down those spikes, the simplest being to run a moving average on the data stream using a fixed number of consecutive data points. This method would, however, kill some natural modes along with the spikes.

Another method has been to predict the spike locations at multiples of the spindle frequency and to replace them with nominal values in the neighborhood. The problem with this method is that the spikes are not always periodic because of spindle-speed jitters.

We have developed a robust algorithm that would effectively eliminate the spikes and preserve its slow varying features at the same time. The flow chart shown in Figure 5 depicts the algorithm used. Slope is defined as the difference between the current data point and the previous data point in the given spectral data stream.

Figure 6 presents such a scenario. The raw PSD data obtained from a windage experiment is plotted in red. The spikes appearing at (apparently) regular intervals are caused by the vertical run-out of the disk. The blue line shows the filtered data using the above algorithm. In this particular case, whenever the data slopes shoot above 0.0001, the “smoothening” algorithm works and massages the data. It might be noted that the modal peaks are preserved even as the spikes are removed.

**Conclusion**

Mount structures interfere with HGA windage spectral data in a serious manner. Experiments using a plate-mount discussed in this article show that such influences can be minimized by appropriately designing the mount structure. A “universal” mount of this kind eliminates the need for changing arm designs for testing different HGA products. The mounting
methods need to be perfected such that repeatability of retention conditions are assured. Torque-mounting of the mount plate using an optimized screw gave more satisfactory results than glue attachment or clamping. In this article we also discuss a robust filter capable of eliminating a wide variety of noise spikes caused by vertical run-out of the disk.

Acknowledgement
Support from Shijin Mei in doing the Finite Element Analysis of arm plate is gratefully acknowledged. The authors also appreciate the help from Andy Cowman and John Perez in setting up and running the experiments.

References

K. K. Sivadasan (M '98) was born in Kerala, India on 30 May 1964. He received his B.Tech and M.E degrees in electrical engineering from Regional Engineering College, Calicut (India) and National University of Singapore in 1986 and 1999 respectively.

From 1987 to 1995 he worked for the Indian Space Research Organization developing electromechanical devices and control systems for satellites. From 1995 to 2000, he worked for Data Storage Institute, Singapore on various aspects of magnetic recording. Since 2000 he works as Principal Engineer, Advanced Technology in Magnecomp Corporation, Temecula, CA. He currently focuses on development of advanced testers for characterization of HGA dynamics.

Aman Khan was born in Bangladesh. He received his M.S and Ph.D degrees in mechanical engineering from Worcester Polytechnic Institute in 1981 and 1985 respectively.

Since 1986 he worked at Digital Equipment Corporation, Komag Inc., and Read-Rite Corporation focusing on HGA technology. From 1996 he is with Magnecomp Corporation, Temecula, CA as its Vice-President and CTO.

Figure 6. Typical results from using the filter algorithm.
feeling the budget

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- Critical pole dimensions
- Wafer magnetic properties


Veeco’s data storage solutions help you bring new device designs to high-volume production quickly, with better quality than ever before. Higher uniformity and repeatability, sub-Ångstrom film thickness control and industry-leading technologies like GCB and PVD ensure high wafer yields. Comprehensive wafer-to-HGA metrology lets you monitor critical dimensions and detect defects early in the process. Combined measure-and-adjust systems can even return out-of-spec HGAs to production to maximize yield. Together, Veeco metrology and process equipment provide a platform that will maximize your next generation GMR and TMR programs. To get complete information, contact us today.

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