Flash vs. hard drives:
The battle intensifies

EXECUTIVE OVERVIEW
Both flash memories and miniature disk drives have begun to replace each other in a variety of applications, mostly in portable but also in some fixed devices. In this article two seasoned analysts, one covering semiconductors and the other hard-disk drives (HDDs), probe the growing battleground between the two technologies, conclude that both have areas of strength and weakness, and forecast trends for their use in a wide variety of applications.

In May 2006, Samsung introduced ultra-notebook PCs with 32GB flash solid-state drives (SSDs) rather than standard 1.8-in. HDDs. While these are not the first notebook PCs to be introduced with a solid-state drive option, they are the first by a major manufacturer of notebook computers, which incidentally is the world’s leading manufacturer of NAND flash memory. Samsung spokespeople have claimed that this heralds the eventual end of HDDs. The introduction of SSDs for ultra-notebook PCs follows on the heels of Apple’s decision in mid-2005 to retire the Apple mini-iPod, which used 1-in. HDDs, and replace them with the flash-based iPod nano.

In server applications, SSDs are increasingly being used to speed up the performance of storage and server applications. They appear to offer server performance improvements at a lower cost than increasing processor speeds. In addition, these devices are finding homes on server blades and transaction processing front ends. SSDs are decreasing in price and increasing in capacity, helping them to become a serious member of the storage hierarchy.

Conversely, while SSDs and other flash memory devices have found their way into applications historically using HDDs, HDDs have begun to show up in markets such as cell phones, music and portable video players, and digital cameras that have typically used semiconductor (usually flash-based) digital storage.

Do these developments indeed suggest a major change in the digital storage landscape? Will HDDs become extinct? Will flash applications yield to HDDs? This article looks at the factors for and against flash or HDDs for various applications, and makes some predictions on what roles and applications these various digital storage devices will play. We will focus on notebook and mobile consumer electronic products since these are the products where there will be the biggest competition between the two storage types in the near future, although we will summarize the projected application roles of flash and HDDs.

Technology development lowers price
Both HDDs and flash memory show significant technical advances in storage capacity as well as performance and reliability with time. With magnetic recording, the amount of digital storage in gigabits (Gb) that can be stored in a square inch of disk surface is called the areal density (in Gbps). As the areal density increases, the digital storage capacity of a given form factor HDD increases. Figure 1 shows quarter-by-quarter disk drive public technology demonstration announcements on HDD areal density as well as quarter-by-quarter HDD product announcements areal densities since 1Q00. As can be seen, the increasing areal density of HDDs is not a continual process—it proceeds in fits and starts as new technologies are developed. Since the mid-1990s, the areal density of the average shipping product has increased by about 60% annually, although in the very late 1990s and early 2000s, annual areal density increases exceeded 100%. We believe that annual areal density increases of 40%–60% are sustainable by the HDD industry for some time to come. New technologies such as perpendicular recording, discrete track recording, patterned media, dual stage actuators, heat assisted magnetic recording, and continued development in drive electronics and error detection and correction will provide a means for growth in digital storage capacity for many years. By 2010, HDD areal densities should exceed 500Gbps while laboratory demonstration will exceed 1Tbps (Terabit per square inch). Note that the time from laboratory demonstration to announced products is generally a little less than two years.

Flash memory product development is also very aggressive, driven by both reduced line width as well as multilevel flash memory development. As a result, NAND prices can be expected to continue their historical price per gigabyte (GB) reduction of 40% per year.

Figure 2 gives some data [1] that illustrates the behavior of DRAM, NAND, and HDD price per megabyte from 1991 to the present.

Some in the NAND business believe that HDD capacities will reach a natural limit and that there will inevitably be an intersection...
of NAND and HDD price per megabyte. We have drawn curved arrows over the HDD lines to dramatize the apparent trends that have led to that conclusion.

In reality, NAND and HDD have stayed on nearly parallel paths of price per megabyte decreases over time. Furthermore, it appears that HDDs are poised to continue to follow a curve of price decreases roughly parallel to that of NAND for years to come. The outcome is that the relationship between the per-GB pricing of the technologies stays constant, with both curves decreasing at similar rates over time. HDD always gives a much less expensive price per GB than can be had with NAND, but the entry point for HDD is significantly higher than that of NAND due to higher fixed costs for the storage device. Figure 3 illustrates this point. Until the required storage capacity exceeds some level, the cost of flash memory will be less than that of HDDs. Note that the marks on the HDD curves represent actual HDDs available in 2006.

The crossover point for 1-in. disk drives and flash memory as well as the minimum 1-in. drive capacity trend is shown in Fig. 4. The ratio of 1-in. HDD to flash memory capacity for a given price remains at about 3x from 2006 through 2010.

**What storage is right?**

The choice of a digital storage device for various applications is the result of a trade-off of various cost, performance, and reliability parameters. Digital storage in portable devices, for example, must be appropriately priced, rugged, long lasting, and power miserly. These selection criteria result in a digital storage hierarchy, and the criteria differ depending upon the application. Some unique environments for storage in various devices are:

- Static or fixed consumer devices such as media servers, PVRs, and set top boxes
- Mobile consumer devices and computers such as MP3 players, cell phones, laptop computers, and automobiles

We will explore the storage hierarchy requirements for different applications and discuss why one type of storage would be more popular than another in several applications.

**Notebook computers.** There has been a lot of news lately about NAND-based replacements for HDDs. Such devices usually put NAND into the same form factor as the HDDs they are trying to replace, with a similar pin and software interface. NAND-based HDD-look-alikes are manufactured by a number of companies, and have been in production for 10 years. Why, then, are they not more popular?

To answer that question, consider what you get when you replace an HDD with NAND. Some of the advantages are clear, while others are less compelling. Key attributes touted by some manufacturers are impact tolerance, faster reads and writes, and reduced weight, noise, and power consumption.

Some of these attributes suggest military and industrial uses for this device, so it should come as no surprise that these have been the main markets for SSDs since their early introduction. The key reason why SSDs have not replaced HDDs in PCs over that time is cost. Let's have a look at that.

The typical 2.5-in. HDD sells to OEMs for ~$100, and stores (on average today) 80 GB. At today's prices, 80 GB of NAND should run ~$1600. We note that this is low owing to the price collapse earlier this year, and the price of sufficient NAND to match an HDD's capacity is likely to increase in the future. For the past three years, the cost of NAND-matching the capacity of the average PC's HDD would have been a relatively constant $4000. As the NAND's price came down, the competing HDD's capacity kept rising to make the $4000 number remain fixed.

The price of an SSD is not really approaching that of a HDD. The price per GB of HDDs is dropping at a rate similar to that of NAND (as illustrated in Fig. 2). Thus, only if the demand for storage capacity showed some upper limit would laptop computers move significantly to flash memory. This is not likely since software companies must increase the features and size of their software in order to stay in business. Add to this the fact that laptop computers with digital video recording (DVR) capability are becoming popular, demanding significantly greater storage capacity (particularly if HDTV takes off). This is a recipe for almost unlimited demand for storage capacity, which favors HDDs in at least the near future.

**Mobile consumer electronics.** Figure 5 shows a representation of the mobile consumer storage hierarchy showing several important characteristics such as cost/GB, environmental resistance, read speed, write speed, write life, and multitasking. Note that we include flash, HDDs, and optical disk in this hierarchy. Optical disk is included primarily as a low cost physical content distribution medium. In addition to these characteristics, there are some other useful characteristics such as physical size of the storage device and weight that should be taken into consideration.
Although weight, power consumption, and physical size are important considerations, economics tend to be the most important driver in the choice of the storage used in a consumer electronic device. As shown in Fig. 2, HDDs are more cost effective than flash memory for storage-intensive applications, but not in applications requiring lower storage capacity. Consequently, we expect that flash will become the dominant form of mass storage for consumer applications where the richness of the content is limited or the total storage required is otherwise constrained.

By contrast, some consumer storage applications will become richer and the expectations of the consumer will become greater over time. Furthermore, the growth of new ways to interact with consumer devices as well as technology improvements will increase resolution requirements to provide an enhanced experience of high-resolution content in mobile and fixed applications. This will drive demand for higher capacity storage from HDDs. The net result is various market levels for economy and premium consumer devices with various storage requirements in the years to come. We will analyze some storage devices in light of these requirements and expectations.

**MP3 players.** The MP3 music format is a lossy music compression format created to economize on scarce and relatively expensive digital storage. MP3 and similar technologies generally compress music files to about 10% of the capacity size of the original, removing most of the music "information" in the compressed file. Once this information is removed, it cannot be recovered, hence the term lossy. MP3 lossy compression takes advantage of the fact that the human auditory system doesn't notice certain types of signal degradation, but lossy compression can introduce artifacts that can be noticed by a keen ear, particularly in a quiet background.

This format has become very popular for use in relatively unsophisticated sound systems. A 10,000 song MP3 file takes less than 40GB of total storage capacity. By 2010, flash memory should provide relatively low cost storage in the 30GB capacity range. Thus we feel that the MP3 market will be more and more dominated by flash memory.

**Audiophile portable stereo.** With continuing decreases in storage prices, we anticipate the advent of a portable device that provides a loss-less compressed or uncompressed music experience. This compression reduces the size of the audio file without losing the original audio signal's integrity. Thus, an audio track compressed with loss-less compression can be decoded to its original uncompressed form without artifacts. A loss-less compressed music file is at most compressed down to 50% of the size of the original music file. A 10,000 song personal stereo player with 50% loss-less compression requires about 140GB of storage. Loss-less compressed music download services have recently become available and there are programs to support loss-less ripping of CDs.

A physical distribution media for mobile devices such as a small form factor optical disk or a flash memory device in a removable reader could be used for loading loss-less content. We expect that with higher capacity storage the need to economize storage space using MP3 files will be less compelling, driving the higher-end of the music player market to use higher-capacity HDDs.

**Personal media players.** The very large digital storage capacity that is available with small form factor HDDs will develop a new class of personal media player. This player will provide significantly higher-resolution audio and video content on an appropriately sized screen or some external viewing device. Just as greater memory on personal computers led to new features and higher performance, so too these new consumer electronic products will provide higher resolution and loss-less content storage, providing a more refined user experience. These sophisticated media player products will provide ready access to photographs and music, as well as video files.

In addition to playing pre-recorded content, these devices will support DVR (digital video recording) technology to record video and other content from cable, satellite, broadcast, or the Internet. They could also be portable repositories for our collection of family photographs and video, increasing the capacity requirements considerably. The only limit to the resolution requirements of these devices is the size of the display available. If these mobile devices are used to play on higher resolution displays, there is almost no limit to the storage requirements that such devices could have. A couple of examples show the sort of storage capacity required:

- A combination 20,000 4-megapixel photo, 10,000 MP3 song, 100 VGA movie player could need about 130GB.
- A combination 20,000 8-megapixel photo, 10,000 loss-less compressed song, 100 DVD (MPEG-2) movie player would need about 597GB.

**Figure 6** compares the hours of MPEG-2 video that can be stored on about $60 of 1.8-in., 1.0-in., and flash memory up to 2010. It is clear that such an application will stay with hard drives over the long term, as a reasonable amount of storage will not be available on NAND at an equivalent price point.

**Cell phones and convergence devices.** Semico expects the cell phone market to surpass one billion units soon. The majority of cell phones will continue to use flash memory to provide the basic...
functionality of contact storage, ring tones, etc., but other features are memory-intensive. Phones with video cameras could become a very portable content creation devices, potentially requiring significant amounts of storage for content capture which small form factor HDDs could provide. In addition, if some part of the cell phone market develops for true convergence devices with commercial and personal music, video, photographs, etc., then we could see some cell phones with demand for storage capacities exceeding 100GB by the end of the decade (similar to the projections for personal multimedia players).

Certain companies have experimented with adding a 1-in. HDD to a cell phone. Such a device is illustrated in Figure 7.

There has been limited acceptance of such models for a number of reasons. We will simply cite a few of them here. First, these phones are less rugged than their non-HDD counterparts, and phones frequently are subject to abuse. Second, the drive to minimize the size of a cell phone has been so relentless that it has driven new technologies—for example, the multichip package or MCP. The addition of an HDD goes against this trend.

Digital still cameras. Digital still cameras mostly use flash cards of various formats. Very high pixel count cameras used by professional photographers sometimes use removable 1-in. HDDs, especially if photos are being stored in an uncompressed format. It is likely that photograph resolution for professional use will continue to increase (it still doesn’t match the resolution available with traditional silver halide film) and thus we believe there will continue to be a niche market for removable HDDs for still cameras.

Camcorders. The camcorder market is relatively small today, averaging between 10-15 million units a year. This small market penetration is probably due to the $500–$2000 price tag that many of these units command, which is too high for a large number of users. High prices are driven in part by the recorder’s very intricate recording mechanism.

HDD-based camcorders are starting to make a dent in the market. One such unit, the $1300 JVC Everio, boasts a 30GB HDD capable of recording up to 7 hours of MPEG-2 DVD-quality video. The fact that the storage media is not removable may limit acceptance of this approach.

For lower-cost units, we expect card-based camcorders to take over this market as the price of NAND in the near future supports the storage of reasonable amounts of video on an affordable quantity of NAND. As the expensive tape transport or other mechanical media handlers are designed out of camcorders, the subsequent cost reductions are likely to reduce average camcorder prices below $100, opening up the market to many more users than can currently justify such a purchase. It is quite likely that the market for $100 camcorders is at least 10x the size of the market for $500–$2000 models.

The far future: Personal life recorders or Personal Memory Assistants (PMAs). Don Norman speculated about a “personal life recorder” (PLR) type of device in his 1992 book Turn Signals are the Facial Expression of Automobiles. He theorized that these PLRs would start out as a device given to young children called the “Teddy.” The Teddy would record all of your personal life moments, and as you mature, the data could be transferred to new devices that matched your maturity level. Projects such as “My Life Bits” from Microsoft are also exploring the requirements for such devices. Someday we may use such devices to share clips of our lives with our families or friends or to help recall past events and contacts. Combined with a capability of organizing and indexing the content, such devices could provide a very powerful personal database that could be accessed any time.

Such devices are laboratory concepts today, but in practice one could capture and sample one’s life including audio, video, and GPS information linked together. Depending upon the resolution, these devices would require huge amounts of information. The support system to store and organize the total aggregate content in the home could be even greater. A terabyte in the pocket, and a petabyte in the home would not be out of the question.

Conclusion

Figure 8 shows a conceptual drawing showing how market volumes vary as a function of price and features. Lower-cost products with lesser features tend to sell the most (assuming they are useful), although there can still be significant volumes of the highest profit margin products with greater prices and more features. Over time, the low-end/low-feature market for mobile consumer electronic products will be dominated by flash memory, while the high-end/high-feature set products will be dominated by HDDs. There is
<table>
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<tr>
<th>Application</th>
<th>2006 storage capacity</th>
<th>2010 storage capacity</th>
<th>Long-term capacity potential</th>
<th>Flash application</th>
<th>HDD application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enterprise storage</td>
<td>HDD: up to 300GB (SCSI/FC); SSD: up to 10s of GB</td>
<td>HDD: up to 1TB (SCSI/FC); SSD: up to 100s of GB</td>
<td>Unlimited (rapid growth for compliance and content)</td>
<td>Yes, for very high-performance applications</td>
<td>Yes, for performance or capacity applications</td>
</tr>
<tr>
<td>Desktop computer</td>
<td>HDD: up to 750GB</td>
<td>HDD: up to several TB</td>
<td>Unlimited (rapid growth due to rich applications and SW growth)</td>
<td>Yes, USB drives, other removable, hybrid HDDs</td>
<td>Yes, for internal mass storage</td>
</tr>
<tr>
<td>Notebook computer</td>
<td>HDD: up to 200GB; SSD: up to 32GB</td>
<td>HDD: up to 1TB; SSD: up to 200GB</td>
<td>Unlimited (rapid growth due to rich applications and SW growth)</td>
<td>Yes, USB drives, hybrid HDDs, some high-performance low-capacity ultralight notebooks</td>
<td>Yes, for internal mass storage for most notebooks</td>
</tr>
<tr>
<td>DVR/PVR</td>
<td>HDD: up to 750GB</td>
<td>HDD: up to several TB</td>
<td>Unlimited (HDTV and future high-definition formats, no limit to hours desired)</td>
<td>Maybe for camcorder input, removable device</td>
<td>Yes, for internal mass storage (could be 3.5 in. or even 2.5 in.)</td>
</tr>
<tr>
<td>MP3 player</td>
<td>HDD: up to 12GB; Flash: up to 8GB</td>
<td>HDD: up to 60+GB; Flash: up to 32GB</td>
<td>40GB is probably enough for the maximum capacity of a pure MP3 player</td>
<td>Yes, dominate internal mass storage</td>
<td>HDDs will eventually be displaced in pure MP3 players</td>
</tr>
<tr>
<td>Advanced AV player (PMP)</td>
<td>HDD: up to 80GB; Flash: up to 8GB</td>
<td>HDD: up to several hundred GB; Flash: up to 32GB</td>
<td>Unlimited if resolution limits expand and DVR/PVR included</td>
<td>Limited use of flash for this market by 2010</td>
<td>HDDs could help define and create this market since they have the required capacity at the right price</td>
</tr>
<tr>
<td>Digital camcorder</td>
<td>HDD: up to 80GB; Flash: up to 8GB</td>
<td>HDD: up to several hundred GB; Flash: up to 32GB</td>
<td>Depending upon desired resolution, flash could open up low end of market for &lt;$200</td>
<td>For low end products selling eventually for &lt;$200</td>
<td>Yes for high-end, high-resolution products</td>
</tr>
<tr>
<td>Digital still camera</td>
<td>HDD: up to 12GB; Flash: up to 8GB</td>
<td>HDD: up to 60+GB; Flash: up to 32GB</td>
<td>Bulk of market will work with flash memory</td>
<td>Yes, bulk of market (match for lower cost for flash)</td>
<td>Maybe for very high-resolution requirements</td>
</tr>
<tr>
<td>Cell phone</td>
<td>HDD: up to 12GB; Flash: up to 8GB</td>
<td>HDD: up to 60+GB; Flash: up to 32GB</td>
<td>Capacity depends upon application</td>
<td>Yes for bulk of market</td>
<td>Yes for high-end, rich feature set products</td>
</tr>
<tr>
<td>Personal life recorder</td>
<td>HDD: up to 1TB; Flash: up to 32GB</td>
<td>HDD: up to several TB</td>
<td>Storage capacities of 1TB possible</td>
<td></td>
<td>Best bet is a HDD</td>
</tr>
</tbody>
</table>

*Content for this article was extracted from two in-depth reports from Coughlin Associates and Semico Research.*

a region between these extremes that will be the battleground for flash vs. HDD as the mass storage device. In the table, we compile the arguments for applications where contention between HDDs and NAND can be anticipated.

References
1. HDD data collected by Ed Grochowski, currently Director of IDEMA USA, and Coughlin Associates.
2. HDD Data from Coughlin Associates and flash memory data from Semico, June 2006.

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for high-volume fabrication of PM disks, and electron beam lithography as the method required to produce nanoimprinting master stampers. However, many challenges in implementation of nanoimprinting technology into PM disk fabrication process still abound, such as choice of nanoimprinting resist, pattern transfer fidelity and uniformity, and lifetime of master stampers. System-level integration issues also create additional challenges in track-follwoing, head-disk interface, and signal processing.

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References

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