Bringing Solid State Drive Benefits to Computer Notebook Users

Yaron Weiler, Director, SSD Product Management

April 2007

01-WP-0107-00, Rev. 1.0

SanDisk®

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Scope

The benefits of flash are now becoming available to a new group of consumer electronics customers, computer notebook users. As a drop-in replacement for the traditional mechanical hard disk drive (HDD), the flash-based solid state drive (SSD) can be used inside thin and light laptops, ultra-portable, ultra-mobile PCs (UMPCs) and other portable computers. Research by Gartner predicts that by 2010 some 32 million units, representing both consumer and professional notebooks, will contain SSDs.[1]

The SSD offers major benefits over the HDD:

- With no moving parts, the SSD is much less likely to fail in extreme outdoor temperatures and conditions of vibration and shock when, for instance, it accidentally falls.
- Unlike the HDD, which has high read access time, the SSD has practically no access time since it requires neither seek nor latency time. This significantly improves system boot and file access speed as compared with the HDD.
- With minimal power requirements, the SSD is more power efficient. This is particularly important for road warriors, enabling them to remain productive while in transit.
- Without need for a motor, bearings or a moving head, the SSD generates less heat than the HDD and makes no noise.
- Because of its faster boot-up and read/write speeds, the SSD enhances the overall user experience[2] on computer notebooks equipped with new operating systems, such as Microsoft® Windows Vista™.

But there is a catch: To make the SSD affordable in capacities high enough to appeal to computer notebook users, it is being manufactured using finer production processes and much denser technologies. This saves on silicon, the most expensive component of flash, but makes the media more vulnerable to read and write errors, while also requiring more robust algorithms to overcome the limitations imposed by shifting to new processes. Now more than ever, flash management is required to maintain data reliability without adversely affecting the performance of the SSD for use in computer notebooks.

This paper reviews the benefits of flash over the HDD, presents the challenges that flash manufacturers are facing today to make it affordable in high capacities without jeopardizing its major benefits, describes various methods used by flash management to make the SSD right for computer notebooks, focuses on the SanDisk family of SSDs for computer notebooks, and then takes a look at the growth potential for SSDs inside computer notebooks.

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[1] Gartner, Inc. "Dataquest Insight: Expect PCs to Impact the NAND Flash Market After 2008," Joseph Unsworth, 15 December 2006

[2] Based on testing performed in SanDisk labs on SanDisk SSD SATA 5000 2.5" 32GB and 2.5" HDD MHV2080BH, 5400RPM, 80GB, SATA. Measurements for Vista were made using these components inside a Dell Latitude D620 notebook.

Stacking up the Benefits

The flash-based SSD has a number of distinct advantages over existing HDD technology for computer notebooks, including:

- **Reliability in conditions of extreme temperatures, humidity, vibration and altitude** – Flash is immune from the most common HDD failure, a head crash, which can lead to partial and sometimes total loss of data. "According to Gartner Dataquest's research, the motherboards and hard drives in notebooks account for the largest number of hardware failures (tying for first place, with each ranging between 25% and 45% of total failures) and are the two largest sources of failure in desktop PCs…. The better reliability of NAND flash could be a strong driver for its adoption in PCs as the resulting lower total cost of ownership (TCO) is likely to appeal to IT managers and consumers. (However, not all types of NAND flash are reliable.)"[3] Varying in severity, a head crash occurs when the read/write head of the hard disk drive comes into contact, momentarily or continuously, with the platter of the hard disk drive. Head crashes can be caused by a number of reasons, including physical shock, movement of the system, static electricity and power surges. Flash-based data storage can operate in extreme operating temperatures, ranging from 0°C to +70°C, whereas the operating range of mobile HDDs is a much narrower +5°C to +55°C.
- **Higher mean time between failure (MTBF) rates** – Because of its innate ruggedness due to the absence of moving parts and its sophisticated flash management software that supports power management to provide data reliability even in the event of a power failure, flash-based storage solutions can achieve actual/fielded MTBF rates of more than two million operating hours. This compares with 300,000 for mobile HDDs.
- **Faster system boot and access time** – Flash does not need to spin up into action but starts working almost immediately, making it able to boot popular operating systems up to twice as fast as the HDD. Because flash does not have any moving mechanism such as the spinning platter, it does not need to seek randomized sectors in the time-consuming and cumbersome way that the HDD does, by moving the head over a rotating platter. Flash achieves much better random read performance for small files.
- **Faster application launch/runtimes** – The lack of a mechanical seek process and spin-up, as described above, gives flash an advantage in launching and running applications, since flash does not need to access various files at different locations.
- **Fixed performance** – SSD performance remains stable over time. There are two major reasons for this. The first is file fragmentation. Files become more fragmented over time, requiring the HDD to perform additional seeks to retrieve a complete file. This reduces the effective performance of the HDD as compared to the SSD, which has minimal seek time penalty. The second reason is the manner in which data is stored on an HDD. When data is first written to HDDs, it

[3] Gartner, Inc., ibid.

is stored in the sectors near the outer edge of the spinning platters, which move faster than the sectors closer to the center of the platter. As the HDD fills up, data is written to the slower-moving inner sectors, reducing write and read speeds up to 50%. The SSD, in contrast, has no moving parts. So no matter how much data is written to it, performance is as fast as it was on day one for the lifetime of the drive.

- **Power efficiency** – Flash consumes up to 50% less power than the HDD (exact numbers are dependent on the system architecture). This is particularly important in extending the battery life for road warriors, enabling them to remain productive while in transit.
- **Less heat production** – Since flash consumes less power in the absence of a motor, bearings and a moving head, it generates up to 50% less heat than the HDD.
- **Quiet** – Flash operates without any noise, while the HDD, by virtue of its moving parts, produces some noise during read and write operations.
- **Potentially lighter and smaller** –Today, the SSD is a drop-in replacement for the HDD, but it can be supplied case-less to be made much smaller and lighter.

These benefits have made flash increasingly prevalent in the consumer electronics space in the last five years or so, incorporated into USB flash drives, MP3 players, cell phones, geographic positioning systems (GPS) and memory cards for digital cameras. Its widespread usage, along with other factors, enables it to be produced at a price point and capacity that is attractive to consumers.

Then why, you might wonder, has flash still not penetrated markets more effectively where you would expect it to be a winner, such as notebook computing for the enterprise and consumer markets? After all, flash-based SSDs have proven their worth in the field for over a decade now, bringing reliable and rugged data storage solutions to the military and aerospace, for instance, which make demands on flash that surpass just about anyone else's.

Overcoming Cost Limitations

Cost, for one, has kept flash on the sidelines for notebook computer use. But today, advances in flash semiconductor technologies and lithography (also known as production process, or geometry) are maximizing silicon usage. Whereas the cost of a 32 gigabyte SSD just two years ago was well over $1,000, today in the first half of 2007 it is available to original equipment manufacturers (OEMs) at $350. This price is expected to continue to decline rapidly over the next few years.

When calculating the cost of implementing flash in notebook computers, total cost of ownership (TCO) should always be included as part of the equation. TCO can be divided into tangible and intangible costs. Tangible costs include, for instance, the expense of IT services associated with recovering lost data, and the loss of productivity due to downtime. In both of these situations, the flash-based SSD reduces TCO as compared with the HDD for a 3-year timeframe. Among intangible costs for businesses associated with downtime are loss of opportunities and reputation, and poor user experience.

Overcoming Chip Package Density Limitations

Limited chip density in the semiconductor industry has until now been another key factor inhibiting the replacement of the HDD with flash-based SSD inside notebook computers. The density in a single TSOP chip package has recently grown from 2 gigabytes to 8 gigabytes[4]. This means that multi-chip packages can be used today to cost-effectively provide notebook computers with enough data storage in a case that is a drop-in replacement for the standard HDD.

Catering to Notebook Computing Needs

In the enterprise notebook computer market, many users such as road warriors do not require high capacities. They do not need to take all of their data with them on the road in order to do their job effectively. As long as they have enough memory to conduct their business, their major concerns differ from those of typical owners of consumer electronics devices. Enterprise users want their notebook computers to be durable so that their data remains intact and accessible in conditions outside an office environment. They want fast access to their data so that they don't have to keep perspective customers waiting, and they demand an extended battery life so that they can remain productive while in transit.

A capacity point of 32 gigabytes lets users such as these store their critical programs, files and even personal data on their notebooks, as shown in Table 1, while enabling IT departments to secure the majority of information on corporate servers to maintain control both over confidential data and the level of security that they deem appropriate.

Table 1: Storage Requirements in Notebook Computers Based on Typical Usage (numbers are estimated)

Program / File	Size (in gigabytes)
New Notebook Computer	
Vista	7
Office + programs file directory	1
OEM Recovery partition	1
Total:	9
One-Year Personal Data Accumulation	
Programs	1
Saved email data file	1
My Documents	2
250 new songs	1
500 new photos (5 megapixel)	1
Total:	6
3 Years on the Road	
Vista	7

[4] 1 gigabyte (GB) = 1 billion bytes

Program / File	Size (in gigabytes)
Office + programs file directory	2
Saved Email data file	5
My Documents	5
My songs	2
My photos	2
Total:	23

SanDisk SSD Flash Management

The challenge, then, is to achieve a "just right" combination of NAND flash memory that can deliver the data reliability, high performance and power efficiency that notebook computer users want. This requires flash management.

SanDisk uses flash management technology that consists of a software driver and controller combination that resides between the operating system and the flash media. This provides the operating system with full block-device functionality so that the flash device appears to the operating system as a standard HDD.

At the same time, SanDisk flash management transparently manages the flash media, masking all of the intrinsic problems that plague raw NAND flash. This technology is a critical element in overcoming OEM challenges to deliver high-performance applications that demand high-capacity data storage and bootable OS and application code.

SanDisk flash management employs these mechanisms to overcome all of the limitations that are, in essence, manufactured into NAND flash:

- **Virtual dynamic mapping** – The operating system (OS) storage model is mapped to the flash physical model to ensure consistently fast performance when accessing data. The Flash Translation Layer (FTL) enables flash to emulate the behavior of a standard HDD so that it can plug into almost any type of file system, without learning the internal structure of the flash media and its unique command interface.
- **Dynamic bad block management** – SanDisk flash management dynamically maps out all NAND flash bad blocks inherent in the flash media, making sure that they are not accessed for reliable data storage. It also remembers the bad block locations so that they are not accessed in subsequent operations. This not only ensures data integrity, but also enhances performance by eliminating the need for repeated write operations as a result of data being repeatedly mapped to the same bad block.
- **Dynamic and static wear-leveling** – SanDisk flash management uses two types of wear-leveling, dynamic and static. Dynamic wear-leveling is performed on newly written data based on statistical allocation, so that blocks are used evenly while not affecting high performance levels. Static wear-leveling is applied on static data, forcing data transfer over the entire media to ensure high data retention levels in cases where flash memory contains large static areas.

- **Optimized erase algorithms** – SanDisk flash management includes algorithms for minimizing the number of erase operations and optimizing folding operations, which enable "garbage collection" for future usage of blocks that no longer contain valid data. During garbage collection operations, space reclamation is performed.
- **Error detection/correction code** – SanDisk flash management implements sophisticated mathematical algorithms to ensure high data reliability and solve bit-flipping issues without degrading performance. Error detection is implemented in hardware by the controller to achieve faster results.
- **Power failure immunity** – SanDisk flash management uses algorithms including “erase after write” instead of “erase before write” to ensure data integrity during normal operation and in the event of a power failure. Used areas are reclaimed only after an operation is complete by erasing and updating the virtual maps. The “erase after write” algorithm is also used to update and store mapping information on the flash memory. This keeps the mapping information coherent, even during power failures. The only mapping information held in RAM is a table pointing to the location of the actual mapping information. This table is reconstructed from the information stored in the flash memory during power-up or after reset.

  Additionally, if a write operation is interrupted by a power failure that causes a sector to be corrupted, the sector is checked and marked as though it were never written to. This enables the sector to be overwritten without adding programming time for the next write.
- **Dynamic bad block detection and tracking** – The first time that a write operation is performed to a block, SanDisk flash management reads the data and verifies that the block is operative. On subsequent write operations to the same block, self-adapting algorithms “learn” the block status from the previous operation, enabling the verify operation to be omitted and thereby enhancing performance.

The Right SSD

The SanDisk family of SSDs for notebook computers, as shown in Figure 1, is based on field-proven solid state drives that have been used since 1995 in applications for the military and aerospace. SanDisk SSDs use cost-effective NAND flash managed by our flash management technology. This combination provides users with proven reliability, very high MTBF rates, and much faster performance than the HDD.

Figure 1: SanDisk SSD UATA 5000 1.8" and SATA 5000 2.5", drop-in replacements for the HDD

The major benefits of SanDisk SSDs are:

- **Field-tested durability** - Our 5th generation SSD, SanDisk SSD is based on field-proven SSDs that have been used for over a decade in the harshest of environments. It uses NAND flash enhanced by our patented TrueFFS® flash management technology. SanDisk SSD delivers an outstanding two million hour MTBF. This superior level results in reduced tangible costs, such as IT labor costs, while also decreasing intangible costs associated with inaccessible data.
- **Enhanced performance** – With no moving parts, SanDisk SSD works much faster that the HDD to boot the operating system and access files. Depending on the form factor and interface, UATA or SATA, SanDisk achieves a random read rate of 7000 inputs/output per second (IOPS) for a 512-byte transfer – more than 100 times faster than typical HDD. These performance figures boost system performance. For instance, SanDisk SSD SATA 5000 can boot Microsoft Windows® Vista™ Enterprise on a laptop in as little as 30 seconds. SanDisk SSD achieves an average file access rate of 0.11 milliseconds. On Windows Experience Index for Microsoft Vista, SanDisk SSD scores 5.6 out of a total 5.9.[5]
- **Power efficient** – Another advantage of SanDisk SSD is its low power consumption rate compared to the hard disk drive, approximately 50% less. This is particularly important to extend the battery life for the benefit of road warriors.

5 1 megabyte (MB) = 1 million bytes; 1 gigabyte (GB) = 1 billion bytes.

H2BENCH 3.6; average access time = average seek time + average latency time

Measurements were made on SanDisk SSD SATA 5000 2.5" 32GB and 2.5" HDD MHV2080BH, 5400RPM, 80GB, SATA. Measurements for Vista were made using these components inside a Dell Latitude D620 notebook.

Toward the Future

A whole new generation of notebook computers is now being brought to market, opening up new possibilities for the SSD. For example:

- Ultra-Mobile PC (UMPC) – regarded as the high end of the category, targeted at high-level professionals.
- Ultra portable notebook – designed for road warriors and information workers.
- Thin and light laptop – developed for information workers and consumers

Figure 2 shows that the total notebook computer market is predicted by Gartner to grow at a much faster rate than the desktop market, reaching 153 million units by 2010.

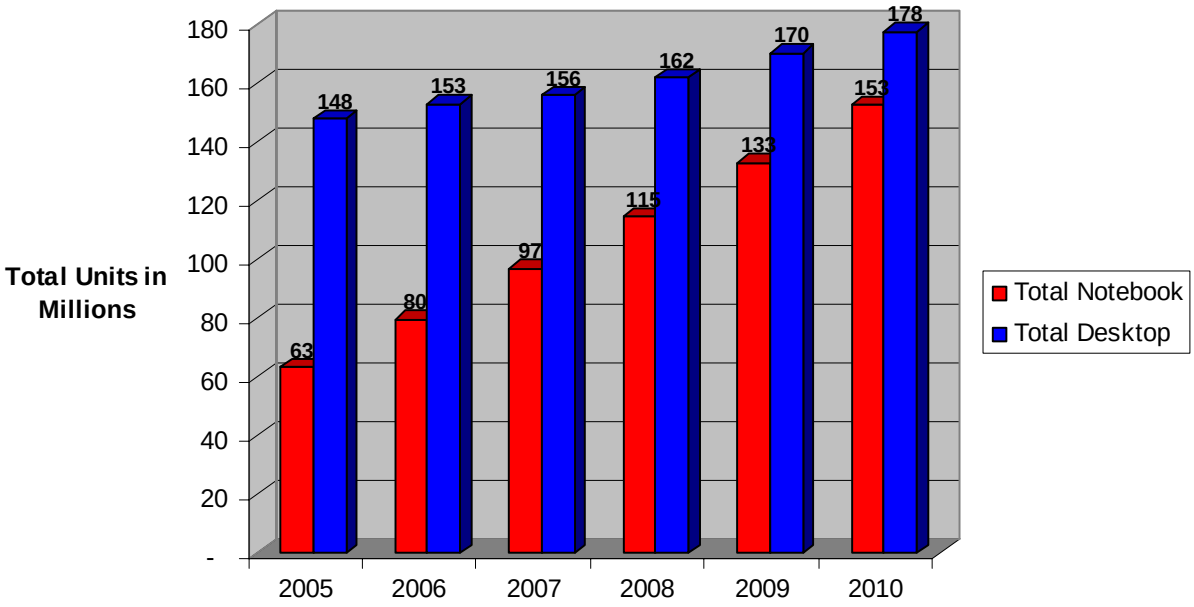

Figure 2: Notebook Computer Growth (Source: Gartner Inc., "Dataquest Insight: Expect PCs to Impact the NAND Flash Market after 2008," by Joseph Unsworth, 15 December 2006. Table was created by SanDisk from Gartner data, combining rows 114-117 of the Applications tab in this report)

The steep incline in Figure 3 indicates the penetration that Gartner predicts for SSDs inside consumer and professional notebooks, both in terms of units and megabytes.

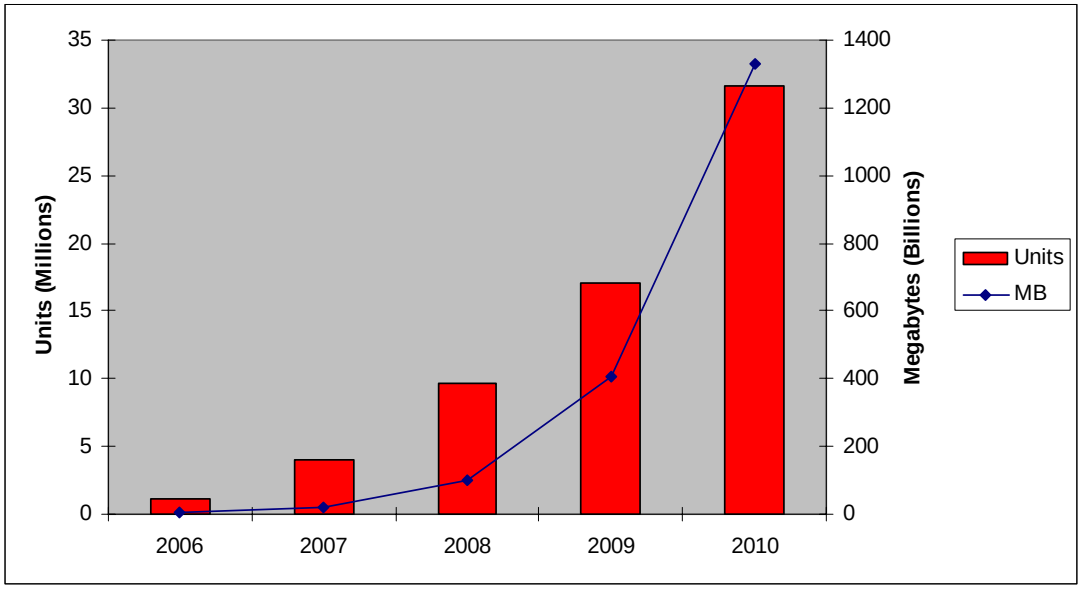

Figure 3: Penetration of SSDs into the Combined Consumer and Professional Notebook Computers
(Source: Gartner Inc., "Dataquest Insight: Expect PCs to Impact the NAND Flash Market after 2008," by Joseph Unsworth, 15 December 2006. Table was created by SanDisk from Gartner data, combining figures 7 and 8 in this report)

As high-density flash technologies such as multi-level cell (MLC) NAND, which stores twice the number of bits per cell than binary (also known as single-level cell) NAND, and finer processes combine to make flash increasingly cost-effective in higher capacities, smaller flash-based devices are set to revolutionize data storage in notebook computers. They will require sophisticated flash management to achieve the performance, durability, power efficiency and MTBF rates that demanding enterprise and consumer environments require to bring notebook computer users a greatly improved experience and enhanced productivity.

How to Contact Us

SanDisk Corporation
Corporate Headquarters • 601 McCarthy Blvd. • Milpitas, CA 95035
Phone (408) 801-1000 • Fax (408) 801-8657

www.sandisk.com