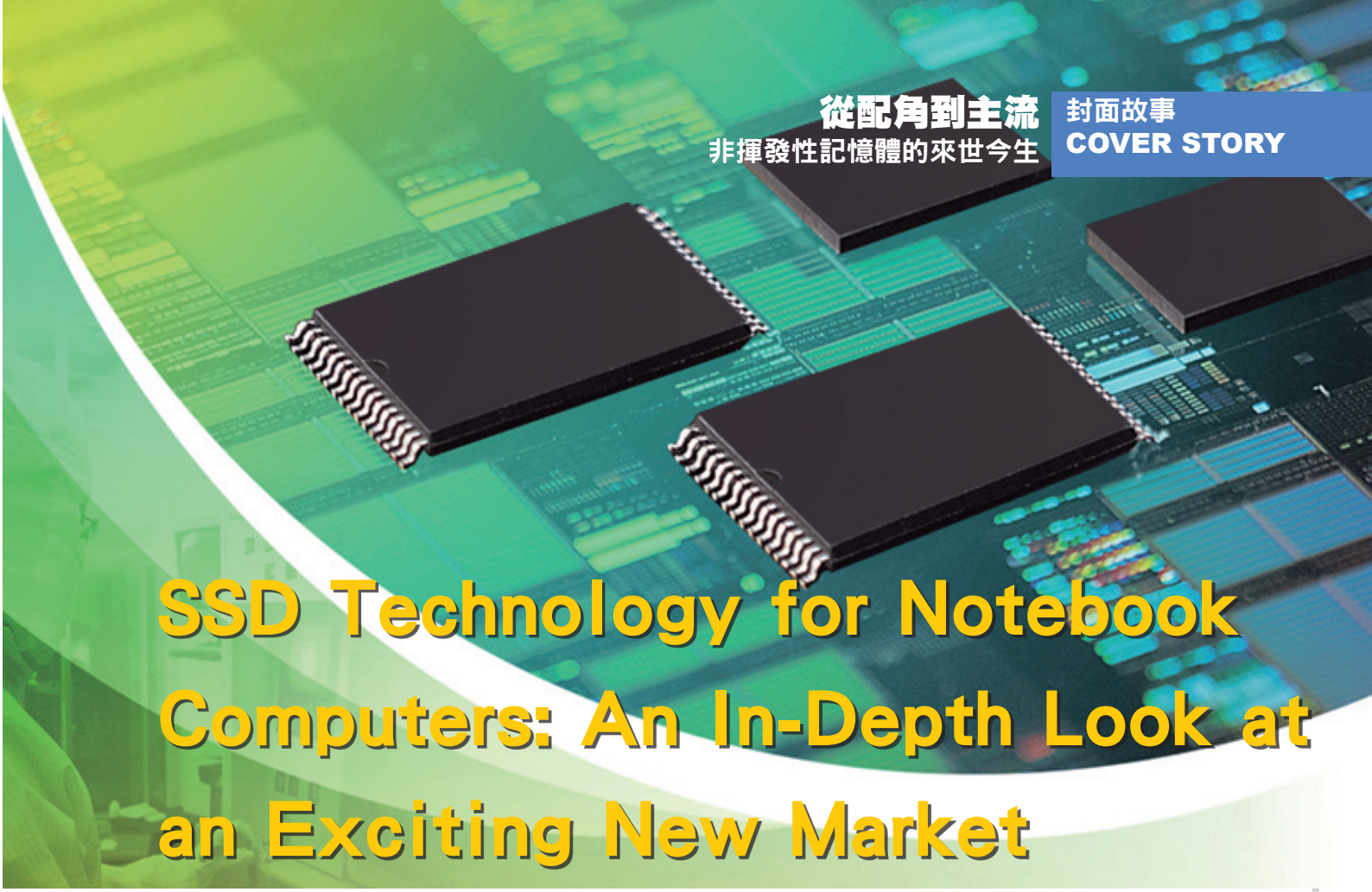


SSD Technology for Notebook Computers: An In-Depth Look at an Exciting New Market

The benefits of flash-based solid state drive (SSD) technology are now becoming available to yet another market, notebook computer users, as a drop-in replacement for the traditional mechanical hard disk drive (HDD). This article describes the benefits of SSD versus HDD technology, why just recently SSD technology has become a viable storage solution for the computer notebook market, the major hurdles that SSD manufacturers have had to surmount along the way, SSD success in penetrating the enterprise notebook niche, and its exciting growth potential as predicted by key industry analysts.

■ **Doreet Oren**

Grasping the SSD Concept

Adoption of SSD technology for use inside notebook computers is now gaining tremendous momentum. From virtually zero in 2005, Gartner predicts that by 2010 some 29 million units, representing both consumer and professional notebooks, will contain SSDs.

Exactly what is this storage device that is making such strong inroads into traditional HDD territory?

A SSD is a data storage device that uses NAND flash media to store data instead of the spinning platter found in the mechanical HDD, as shown in Figure 1. A SSD is identical in size to the HDD, whether an 1.8" or 2.5" form factor, and is composed of flash media and a controller that optimizes SSD

functionality to meet notebook computer requirements. The flash media and controller are mounted on a printed circuit board that is equipped with a standard parallel ATA (PATA) or serial ATA (SATA) interface so that the SSD constitutes a drop-in replacement for the HDD.

The SSD offers major benefits as a storage solution for notebook computers over the HDD:

- With no moving parts, the SSD is much less likely to fail in conditions of vibration and shock when, for instance, the notebook is severely jolted during travel.
- The HDD requires seek time to locate files stored on its platter and latency time until it begins to spin into action. The SSD requires neither, resulting in faster access time and therefore better performance.
- The SSD enhances the overall user experience on notebook computers equipped with popular operating systems, such as Microsoft Windows Vista.

Figure 1: Solid State Components Inside a SSD

- With minimal power requirements, the SSD is more power efficient than the HDD. This is particularly important for road warriors, enabling them to remain productive on their notebook computers while in transit.
- Without the need of a motor, bearings or a moving head, the SSD generates less heat than the HDD and makes no noise.

Let's take a closer look at how these benefits affect day-to-day work with notebook computers.

Stacking up SSD Technology Benefits

Higher Reliability

SSDs are innately rugged due to the absence of moving parts. In conditions of extreme temperatures, humidity, shock, 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. Shock and temperature extremes are responsible for other HDD failures, such as off-track writes during write operations, particulates on the head and disk due to out-gassing at high temperatures, and micro-fretting on the hydrodynamic bearing during shipping.

According to Gartner, "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 ". This finding impacts on the total cost of ownership of a notebook computer

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 operating temperatures, ranging from 0°C to +70°C, whereas the operating range of the HDD is a much narrower +5°C to +55°C.

Sophisticated flash management software supports power management to provide data reliability even in the event of a power failure. Flash-based storage solutions can achieve actual/fielded mean time to failure (MTTF) rates significantly higher than those of the HDD. Compare, for example, a typical HDD MTTF rate of 300,000 operating hours with the MTTF rate of SanDisk SSD, 2 million operating hours, or more than six times better!

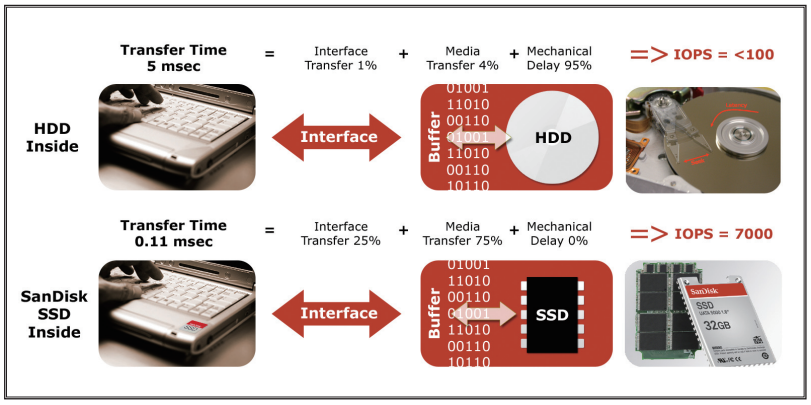
Recent independent studies on HDD failures indicate that the testing performed by HDD vendors is a poor predictor of actual failure rates.

Faster Performance

SSD native characteristics enhance notebook computer performance immediately, while maintaining the same high performance for the product's lifetime.

With no need to spin up into action and no mechanical arm that must move over a rotating platter to seek data – a time-consuming and cumbersome method subject to wear-and-tear of the parts – the SSD accesses files much faster than the HDD and achieves much better random read performance for small files. Users can feel the difference during boot and when they launch and run applications, for which many 4KB and smaller files are required. In fact, about 95% of the time required to transfer these small files is wasted in HDD mechanical delay. SanDisk SSD, for example, achieves an average access time of 0.11 ms as compared with a HDD access time of 14ms, as shown in Figure 2, or a difference of 127 times!

Figure 2: Mechanical Delay of HDD Drastically Reduces Access Time and IOPS



What's more, SSD sequential performance remains stable over time whereas HDD performance degrades, as Figure 3 shows. 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 the HDD. When data is first written to the HDD, it is stored in the sectors near the outer edge of the spinning platter, which moves 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 SSD.

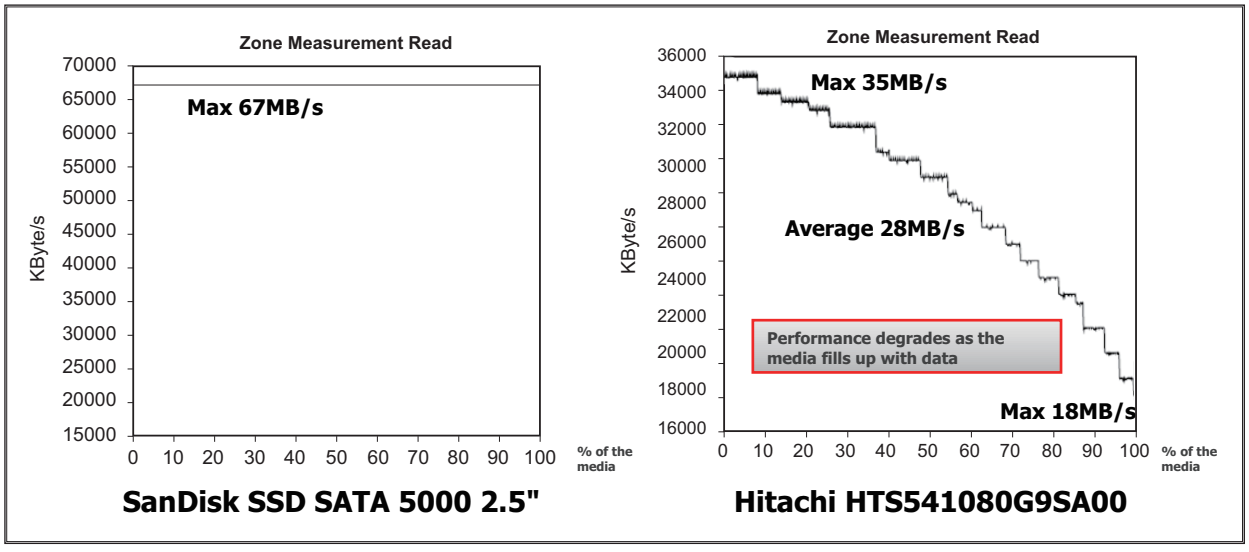
More Power Efficient

The HDD consumes significantly more power than the SSD. The faster the HDD is, measured in revolutions per minute (RPMs), the more power it consumes (see Figure 4). The SSD consumes about 50% less power than a HDD operating at 5400 RPMs and about 75% less than a 7200 RPM HDD. This is particularly important in extending the battery life for road warriors, enabling them to remain productive while in transit. The actual battery saving in the system is, of course, dependent on the system architecture. According to DRAMeXchange in an independent evaluation conducted of SanDisk SSD

More Environmentally Friendly

The SSD brings additional value over the

Figure 3: Sequential Read Comparison: SSD Performance Remains Stable Over Time While HDD Performance Degrades



HDD in three environmental areas:

- **Less heat production**: Since flash consumes less power in the absence of a motor, bearings and a moving arm, it generates up to 50% less heat than the HDD.
- **Quieter**: 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 1.8" and 2.5 " HDD, but its weight and size can be scaled down to meet the design specifications of increasingly compact laptops.

These benefits have made flash use increasingly prevalent in the consumer electronics space, incorporated into USB flash drives, MP3 players, cell phones, global 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.

Overcoming Cost Limitations

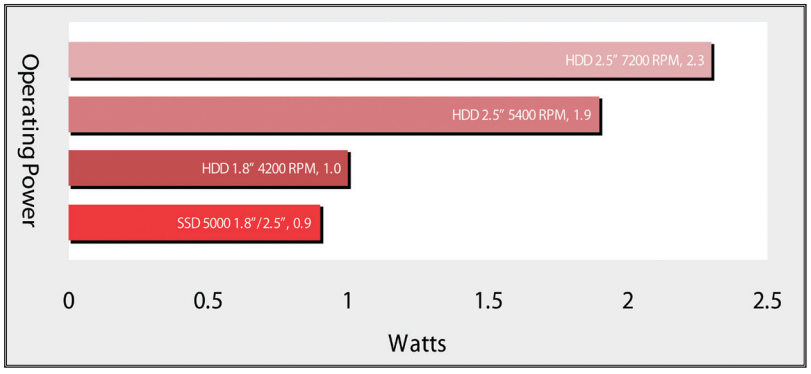
With this long and impressive list of benefits, why has flash still not fully penetrated the notebook computer market? After all, flash-based SSDs have proven their worth in the field for over a decade now, bringing reliable and rugged data storage solutions to the military and aerospace, for instance, which make demands on flash that surpass just about anyone else's.

Cost, for one, has kept flash on the sidelines for notebook computer use. The industry is just now beginning to transition to flash as its cost in higher capacities drops to meet the steady-state cost of equivalent HDD capacities. According to data from IDC, the price gaps at 60/64GB and at 120/128GB represent converging trends, as shown in Figure 5.

However, already today the SSD value proposition is attractive, since when calculating the cost of implementing flash in notebook computers, the total cost of ownership (TCO) should always be included as part of the equation. IDC emphasizes this point in a recent report.

Several factors must be taken into account when examining

Figure 4: Power Consumption of SDD vs. HDD, Which Increases As RPM Rate Increases

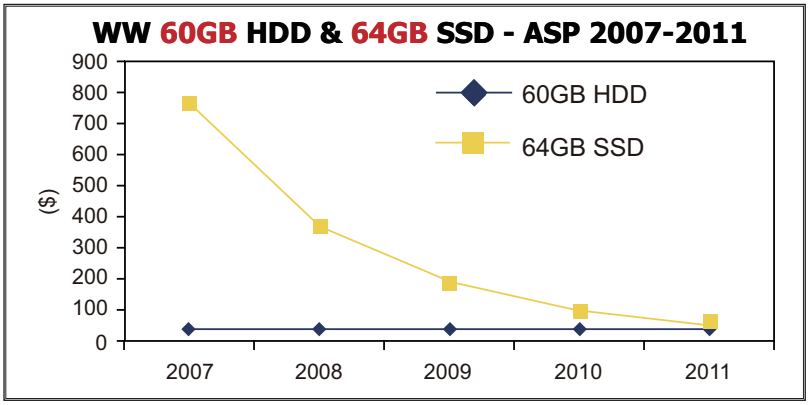


the TCO of a SSD versus a HDD:

- IT labor cost, including cost of HDD repairs as well as of IT people hours in configuring (and reconfiguring) the notebook
- Added productivity when using a SSD based on:
  - Less data loss as compared with the HDD, whose head crashes decrease productivity by forcing employees to redo their work
  - Less employee idle time due to the higher reliability of SSD-based laptops
  - Higher performance, benefiting SSD users from faster boot and application launch time, as well as from enhanced overall system performance
  - Longer working time when employees are in transit, due to better SSD power consumption rates which translate into longer battery life

The expectation is that over approximately a three-year period, return on investment in purchasing a SSD will be realized.

Figure 5: 60/64GB HDD vs SSD Cost, Converging Trends (US Dollars)



Applying Flash Management

To make the SSD affordable in capacities high enough to appeal to notebook computer users, it is being manufactured using NAND flash, which by its very nature is prone to read and write errors. Add to this the fact that finer production processes and much denser technologies are being applied to NAND flash to further reduce production costs. This saves on silicon, the most expensive component of flash, but makes the media even more vulnerable to errors, while also requiring more robust algorithms to overcome the limitations imposed by shifting to new processes. The challenge, then, that flash management experts face is to provide NAND flash memory that can deliver the data reliability, high performance and power efficiency that notebook computer users want. 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 (OS) 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 with a goal to overcome all of the limitations that are manufactured into NAND flash:

- **Virtual dynamic mapping:** The OS storage model is dynamically mapped to the flash physical model to enable consistently fast performance.
- **Dynamic bad block management:** SanDisk flash management dynamically maps out all NAND flash bad blocks inherent in the media to provide reliable data storage.
- **Dynamic and static wear-leveling:** Dynamic wear-leveling is performed on newly written data and static wear-leveling is applied on static data to enable high data retention levels.
- **Optimized erase algorithms:** SanDisk flash management includes algorithms for minimizing the number of erase operations to enhance overall performance.
- **Error detection/correction code:** Sophisticated mathematical algorithms, including error detection implemented in hardware, are designed for high data reliability without degrading performance.
- **Power failure immunity:** SanDisk flash management enables data integrity both during normal operation and in the event of a power failure.
- **Dynamic bad block detection and tracking:** Bad blocks are dynamically detected before data is written to them, and tracked to prevent their use in future operations. This allows for data reliability and enhances performance.

Catering to Notebook Computer Needs

In the enterprise computer notebook market, the needs of many users, such as road warriors, are satisfied by 32 or 64 gigabytes of storage, available in 1.8" and 2.5" form factors for use with a variety of laptops. They do not need to take all of their data with them on the road to perform their jobs 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, such as teenagers, for instance, who "must" download every hot multimedia clip. 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 can immediately respond to perspective customers, and they demand an extended battery life so that they can remain productive while in transit.

A capacity point of 32 gigabytes is the minimal capacity that lets enterprise users store their critical programs, files and even some personal data on their notebooks, as shown in Table 1. At the same time, 32 gigabytes is enough to enable management to curtail employees from spending their work hours on personal activities, and to meet IT department needs to secure the majority of information on corporate servers, thereby maintaining control both over confidential data and the level of security.

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

Program/File	Size (in GB)	Total GB
	Initial storage	9
Vista	7	
Office + programs file directory	1	
OEM Recovery partition	1	
	After one year	15
New Programs	1	
Saved email data file	1	
My Documents	2	
Multimedia	2	
	After three years	25
New Programs	2	
Saved email data file	5	
My Documents	5	
Multimedia	4	

Toward the Future

Data storage solutions are used in a wide variety of applications with an assortment of demands. There are already some segments, such as consumer electronics, where flash is replacing HDDs as a smaller, more rugged storage solution. The mobile PC market is now at the early stages of such a transition.

The factors contributing to the adoption of SSD technology are diverse, not solely dependent on manufacturing costs. Among the major additional factors are: required capacity, ruggedness, high performance and low power consumption. In addition, a shift in paradigm from the HDD to SSD technology requires market education, which can only happen over time. But just as 35mm film was replaced by flash cards and floppy disks were replaced by USB flash drives, the notebook computer industry is predicted to undergo a similar transition.

The cost of flash itself is a major factor in the adoption of SSD technology. The flash market is very dynamic, its cost fluctuating radically subject to supply and demand and in the wake of technology advances. The first mobile PC market to switch to SSD technology will be the enterprise segment, providing laptops for road warriors. The TCO of a SSD is significantly lower than the huge overhead required to maintain a HDD. In addition, this segment will most enjoy the high productivity, and better user experience provided by the SSD.

If, as predicted, the flash price decline trend

continues as it has over the past few years, we expect the SSD value proposition of ruggedness/reliability, high performance and power efficiency to become even more attractive, speeding up its adoption in particular in the enterprise market segment for notebook computers. Other segments are expected to follow suit, as:

- Consumers seek mobility of personal and business data
- There is a growing acceptance and expectation of connectivity
- Notebook computers are enhanced to deliver sufficient power and performance in smaller and more lightweight designs
- Notebook computers and SSD prices decline to meet middle-class buying power restrictions.

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 & light laptop, developed for information workers and consumers.

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.

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 MTTF rates that demanding enterprise and consumer environments require to bring notebook computer users a greatly improved experience and enhanced productivity.

The future, in fact, is already here. The excitement that SSDs have generated for use in notebook computers is spreading from flash vendors to PC OEMs, OS vendors, chipset vendors and most recently to some of the most successful HDD vendors, who have begun to share their plans to participate in this highly promising market. Based on field-proven SSDs that SanDisk has sold since 1995, SanDisk is currently supplying major OEMs with fifth generation SanDisk SSDs, and is well-positioned to meet future challenges.

This article contains certain forward-looking statements that are based on our current expectations and involve numerous risks and uncertainties that may cause these forward-looking statements to be inaccurate. We do not intend to update the information contained in this article.