Testing experimental samples of solid state drives

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Abstract. The paper presents the results of electrical and functional testing of 160 experimental samples of solid-state drives with capacities ranging from 256 to 1024 GB, assembled using 4 types of NAND-memory chips. As a result of testing, read and write speeds of SSD were measured in sequential and random modes. The maximum read and write speeds in the sequential mode were 540 and 410 MB/s, and in the random mode, 72000 and 68000 IOPS. When measuring disks of the same type, a relative speed variation was observed, which was significantly greater with write operations (3.7\%) than with read operations (0.45\%). It was also found that the write and read speeds were limited by the performance of the disk controller.

1. Introduction

The development of high-speed Internet access infrastructure [1], an increase in the number of transactions in e-commerce [2], and an increase in user requirements for the speed of personal computers [3] push to use high-speed storage devices [4]. The most common alternative to traditional hard drives (HDD) are solid state drives (SSD), which, at a relatively low cost of storing information (for 1 TB), have an order of magnitude greater speed of information exchange in real-world application scenarios [5]. The speed characteristics of the disks are one of the most important criteria in determining the choice of a particular model by end users of products. Despite the abundance of data on the comparative testing of various models of SSD, obtained by manufacturers [6,7] and consumers of disks [8], at present little attention is paid to measuring the spread of characteristics of individual batches of SSD specific models. This scattering makes it possible to obtain a more accurate estimate of disk performance by means of which one can select SSDs for use in personal computers, data storages, and data centres [9]. In the latter case, it is especially relevant, since the variation in the characteristics of even one batch can be quite significant (as we show in our work), which can lead to a significant difference in data centre throughput. Also, this variation in characteristics can explain the differences in the speed values obtained for the same models by different testers [6,8].

Read and write speeds should be measured by disk manufacturers at the final testing, and their values are recorded into the product passport. Testing of produced disks is a routine operation and, in the case of even small batches of products, should be automated. In this work, a multichannel functional testing system was used to determine the speed characteristics of disk operation. In addition, the produced disks underwent the automated electrical testing by means of the stand that implementing in-circuit testing using bed-of-nail technology. Using the above stands, 160 SSDs were tested, divided into 4 groups, each
of which differed in the number and capacity of NAND-memory chips. NAND-memory chips and SSD were manufactured at the enterprises of GS Technopolis.

2. Production of experimental samples
BGA NAND flash memory chips for SSD disks had single-die or two-die package organization. For manufacturing memory modules, MLC-type dies with a capacity of 128 Gbit (2D) and 256 Gbit (3D) using the Open Nand Flash Interface (ONFI) interface were used. Die packaging in BGA modules included the following operations: grinding and cutting the NAND memory wafer, mounting the dies on a substrate using a DAF adhesive film layer, wire bonding, molding, ball placing and singulation. The assembled BGA memory modules underwent electrical and functional testing on the system described in [10]. Functional testing allowed to reveal problems in NAND-memory. To do this, errors were detected during the write and read operation of the specified patterns and the command execution time was monitored. In the event of functional errors or exceeding the command execution time, NAND memory testing stopped and the chip was marked as failed. To produce SSDs, 4 types of 512-ball packaged (BGA) memory chips with a volume of 128–512 Gbit and 14 × 18 mm in size (figure 1) were manufactured and tested.

![Manufactured NAND-memory chips: from the front (a) and back side (b).](image)

**Figure 1.** Manufactured NAND-memory chips: from the front (a) and back side (b).

Table 1 shows the variants of the NAND-memory chips, and the numbers of the chips indicated in the table will be further used to designate them in the text. The chips were packaged using 2 types of dies: 128 Gbit (No. 1 and 2) and 256 Gbit (No. 3 and 4). Both single-die (No. 1 and 3) and two-die (No. 2 and 4) memory chips were manufactured.

| No | Memory size (Gbit) | Memory size and quantity of NAND memory dies | Memory type |
|----|-------------------|---------------------------------------------|-------------|
| 1  | 128               | 128 Gbit x 1                               | 2D MLC      |
| 2  | 256               | 128 Gbit x 2                               | 2D MLC      |
| 3  | 256               | 256 Gbit x 1                               | 3D MLC      |
| 4  | 512               | 256 Gbit x 2                               | 3D MLC      |

Manufactured memory chips were used to assemble SSDs with a physical memory of 256, 512 and 1024 GB. Assembled SSD had a 2.5-inch form factor, SATA 3.1 interface, the SM2246 microcontroller and were produced by surface mounting technology (SMT). When assembling a SSD 256 GB, 16 memory chips with a capacity of 128 Gbit (No. 1, table 1) or 8 memory modules with a capacity of 256 Gbit (No. 2 and 3, table 1) were used. To produce SSDs with physical volumes of 512 and 1024 GB, 8
and 16 modules with a capacity of 512 Gbit were used (No. 4, table 1). Figure 2a shows an image of a SSD printed circuit board PCB with passive (resistors, capacitances, inductors) and active (SM2246 disk controller, NAND memory chips, MT41K256M DRAM buffer, linear voltage regulators, etc.) components. A part of the chips is mounted on the back side of the PCB. Figure 2b shows a functional diagram of an 8-chip (2 dies in each chip) SSD of 512 GB. In this version, the controller is connected to the memory chips using 4 data buses: two data buses for every 4 chips. Two data buses are used to connect each memory chip: 1 channel per each die (Logical Unit Number, LUN). The interaction between the controller and NAND-memory chips is carried out using the ONFI 3.2 protocol. Two DRAM buffer chips are connected in parallel and interact with the controller using the DDR 3 protocol. The presence of a buffer is necessary to speed up I/O operations. Data transfer between SSD and personal computer is performed through SATA 3.1 interface.

![SSD printed circuit board PCB](image)

**Figure 2.** 512 GB SSD image with mounted microelectronic components (a) and its functional diagram (b).

### 3. Testing methods
Testing of SSDs was carried out in two stages. At the first stage electrical testing was performed. SSDs that passed the testing at the first stage underwent functional testing at the second stage. The objectives of electrical testing were to determine whether the voltage values at the test points (figure 3) of the SSD PCBs as required. Additionally, the current consumed by the SSD was measured in the absence of disk operations.
Electrical testing was performed on a specially designed stand (figure 4) using bed-of-nails technology. The PCB under test was rigidly fixed in the boarding socket of the electrical testing stand, after which the needle system was positioned at the control points of the PCB. The PCB was supplied with a 5V DC from the Hantek PPS2116A power supply and the voltage measurement procedure was started at the indicated control points. To measure the voltage NI-6009 multifunctional input/output controller was used.

The controller was operated from the workstation using the NI Test Stand software. The software made it possible to automatically read the voltage values at the control points. The voltage values at control points TP_1 - TP_5 was calculated relative to the earth reference potential (TP_0). Also during testing, the current consumption was recorded, which averaged 70 mA. For each SSD, all measurements were repeated three times, after which they were saved in a file. If the measured results did not fall within the interval of the required values, then the disks were considered not to pass the tests, they were rejected and did not participate in further functional testing. Table 2 presents the results of electrical testing of one of the disks.

### Table 2. SSD electrical test results.

| Circuit name                        | Measurement point | Required value (V) | Measured value (V) |
|-------------------------------------|-------------------|--------------------|--------------------|
| MCU core supply voltage             | TP_1              | 1.2 ± 0.045        | 1.202              |
| NAND FLASH core supply voltage      | TP_2              | 3.3 ± 0.042        | 3.302              |
| Supply voltage of MCU and NAND FLASH interfaces | TP_3              | 1.8 ± 0.09         | 1.804              |
| DRAM supply voltage                 | TP_4              | 1.503 ± 0.045      | 1.503              |
| DRAM reference voltage              | TP_5              | 0.75 ± 0.0375      | 0.753              |
The SSDs that passed the electrical testing got to the next technological stage, where the SSD controller firmware was installed. The SSD PCBs were installed in a specialized Silicon Motion Chorus stand, and the firmware was loaded into the disk controller (figure 5). After the controller firmware was loaded, each SSD was tested for correct functioning. The electrically tested SDDs passed to the next stage - functional testing.

![Figure 5. Stand for downloading firmware to the SSD controller.](image)

The purpose of functional testing was to determine the basic characteristics - read and write speeds in sequential and random modes. The read and write speeds in sequential mode were measured in MB/s, and in random mode, in the number of I/O operations per second (IOPS). To connect a large number of SSDs, a SATA interface extender board connected to the computer via the SAS interface was used. Measurements were made using the vdbench software and a test script, with all speeds being measured 6 times to improve measurement accuracy. The results of the functional testing of each disk were saved in a separate file.

4. Analysis of the results
The test results are presented in the form of graphs, where the identification numbers of the disks start on the abscissa, beginning from 1 till 80 (for convenience of comparison). Each point on the graph (read or write speed) is averaged over 6 measurements. Figure 6 shows a graph of sequential read and write speeds (block size 1 MB) for 256 GB disks using different types of dies (No. 2 and 3, table 1).

![Figure 6. The speeds of sequential (block size 1 MB) read (a) and write (b) tested SSDs with a capacity of 256 GB, assembled using different chips (No. 2 and 3, table 1).](image)

It is worth noting that both the sequential read speed and the write speed have a significant variation in values, however, the differences in the write speed are more significant. For disks with 128 Gbit dies (No. 2, table 1), the standard deviation was ~ 2.4 MB/s for reading, and ~ 3.7 MB/s for writing. Moreover, for disks with 256 Gbit dies, the standard deviation was ~ 2 MB/s for reading, and ~ 9.8
MB/s for writing. Thus, the relative standard deviation reached 3.7% when writing, and no more than 0.45% when reading. In addition, analysing this graph, it can be noted that the reading speed of two types of disks is almost the same (average values for all disks differ ~ 2 MB/s), and writing speed differs much more (average values for all disks differ by ~ 40 MB/s). This is due to the implementation of the data exchange mode Interleaved die (MULTI-LUN) operation, which provides independent access to each LUN (die) within one chip. This mode allows us to transfer data for writing in LUN 2 when performing data writing in LUN 1, without waiting for the end of the writing in LUN 1. As shown by the test results, the Interleaved die mode significantly improves performance when performing relatively slow write operations. A significantly greater variation in writing values was observed when measuring the speeds of various SSD variants (due to different memory chips used, see table 1), and when using other modes, for example, in a random writing mode (figure 7). Apparently, this is due to a more complex (iterative) process of writing information into cell of NAND-memory.

![Figure 7](image1.png)

**Figure 7.** The speeds of a random (block size 4 KB) read (a) and write (b) SSDs with capacities of 256, 512 and 1024 GB, assembled using different chips (No. 3 and 4, table 1).

Figure 8 shows the reading speeds of disks with one type of dies, but with different types of assemblies and the number of chips installed on the SSD PCB. With increasing disk capacity, the sequential read speed of SSD based on two-die chips is slightly reduced (figure 8a) with respect to single-die ones, while all values are near the maximum throughput of the controller in sequential read mode (540 MB/s). It should be noted that the sequential write speed (figure 8b) sufficiently increases when disk capacity rises from 256 to 512 GB. This is also explained by the use of the Interleaved die data exchange mode, moreover, by reducing the writing time in 3D NAND dies (as compared to figure 6b), the performance increases significantly. A further increase in the number of dies (with an increase in capacity up to 1024 GB) does not lead to an increase in the writing speed, since in this case it is limited by the performance of the disk controller (410 MB/s).

![Figure 8](image2.png)

**Figure 8.** The speeds of sequential (block size 1 MB) read (a) and write (b) tested SSDs with capacities of 256, 512 and 1024 GB, assembled using different chips (No. 2 and 3, table 1).
5. Conclusion
As a result of this work, 4 types of a BGA packaged NAND-memory chips were manufactured with a memory capacity from 128 to 512 Gbit, with which 160 experimental SSD samples of 256 to 1024 GB were produced. The manufactured disks passed electrical testing, during which the voltage levels at test points and the current consumption were checked. Then, the firmware was loaded into the disk controller and functional testing was performed, as a result of which read and write speeds were measured in sequential and random modes. The maximum read and write speeds in sequential mode were 540 and 410 MB/s, and in random mode - 72000 and 68000 IOPS. It was shown that the read and write speeds depend on the total number of memory dies in SSD chips. In the case of using 3D NAND memory, the write speed is limited by the capabilities of the SM2246 controller when working with 16 dies, and in the case of read operations, it is limited to 8 dies. It was found that the speeds within a batch of identical SSDs may differ due to the variation of the characteristics of the assembled NAND memory chips, while the relative standard deviation of the write speed (3.7%) was almost an order of magnitude larger than reading (0.45%). The latter is likely due to the complex (iterative) process of writing information into NAND-memory cell. In the future, it is planned to continue testing batches of SSD samples using more efficient disk controllers and chips using other memory dies to obtain higher read and write speeds, as well as using other form factors that imply a faster PCI-e communication interface between the solid-state drive and computer.

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