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An Overview of the Future of Memory Cells: Advances in SSD Technology

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Abstract:

This paper explores the topic of Solid-State Drives (SSDs) and NAND flash memory. Information of this paper is mainly obtained from authoritative academic websites and papers related to SSDs and flash memory. Memory cells are fundamental components in various electronic devices. In the field of data storage, SSDs represent the latest generation of storage devices, offering significantly better performance and functionality than traditional hard disk drives (HDDs). NAND flash memory chips are crucial component of SSDs, particularly 3D NAND, which exhibits exceptional performance and holds significant potential for future advancements. This paper will commence by providing an overview of SSDs and HDDs, followed by a comparison between NAND flash and NOR flash, and ultimately analysing the future of NAND flash memory technology employed in SSDs, with a focus on elucidating the advantages of 2D NAND over 3D NAND. Additionally, this paper explains a few challenges that NAND technology faces currently, as well as some possible solutions.

Keywords: Solid-state drives, hard disk drives, NAND flash memory, NOR flash memory.

1. Introduction

Solid-State Drives (SSDs) have revolutionised the computing platform and memory industry by delivering significantly enhanced random and sequential read and write performance compared to traditional Hard Disk Drives (HDDs) [1]. Additionally, SSD capacities have increased significantly with competitive pricing, leading to its increasing popularity and demand. The semiconductor memory business has experienced significant growth over recent decades primarily driven by dynamic random-access memory (DRAM) and flash memory, especially, NAND flash memory technology which has developed rapidly for the past ten years [2]. Flash solid-state drives are semiconductor-based non-volatile storage that stores persistent data in flash memory. This means that data can be retained when power is turned off. The two predominant types of flash memory utilised in SSDs are NAND and NOR, with NAND being the most used type in SSDs. However, due to escalating demand for the SSDs, traditional 2D planar NAND flash memory technology fails to meet consumer requirements because of its limitations, for instance, restricted cell density per chip plane. This means less storage provided, leading to the reduction in size of cells, resulting potential reliability issues of 2D NAND associated with electron leakage from smaller cells. Consequently, an alternative approach addressing these challenges became imperative. This led to the development of resistive random-access (ReRAM) technology around ten years ago. It is a type of non-volatile random-access computer memory that works by changing the resistance across a dielectric solid-state material, often referred to as a memristor. With the increasing need for compact digital data storage, there has been a significant rise in memory density due to advancing technology over the past few years. There is a demand for a technology that can enable electronic functionality to be easily integrated on substrates such as plastic and paper at a low cost and in large quantities. Polymer memory and organic memory devices have garnered attention due to their straightforward processes, rapid operating speed, and impressive switching capabilities. One notable advantage of polymer memory over traditional designs is its ability to be stacked vertically, allowing for three-dimensional (3D) use of space. This means that solid-state devices with minimal transistor counts could potentially be as small as matchbooks while retaining data even after power is disconnected [3]. Over the past a few years, a new 3D NAND technology has been developed to replace 2D NAND, allowing for more flash memory cells to be fit on a single chip for greater capacity. It will be preferred in the future. In this paper, the basic concept and principles of SSDs will be introduced, NAND flash and NOR flash will be compared, and the advantages of 3D NAND and the reasons why it is preferred over 2D NAND will be discussed. This paper will include several figures and tables to illustrate and support these points.

2. Current SSD Technology

2.1 Comparison between SSD and HDD

2.1.1 Overview

SSD, also known as solid state drive, is a kind of nonvolatile memory for the purpose of storing permanent data on solid state flash memory. SSDs are a substitute for conventional HDDs in computing, providing the same essential functionality as a hard-drive, but also much more quickly compared to other devices. Using SSD enables your device to start up faster, to load more quickly, and to store files more quickly [4]. They are, however, more costly than conventional HDDs. An SSD can be priced at $0.08 to 0.10 a GB, whereas a HDD is priced at just $0.03 - 0.06 a GB [5]. SSDs are available in any location where it is possible to deploy a hard disk. For instance, in consumer goods, it is used in PC, notebook computers, PC games and smart phones. They are also incorporated with graphics cards.

2.1.2 Principles

SSDs utilize printed circuit board (PCB) technology to mount flash memory chips along with controller and interface components in a ruggedised enclosure. NAND flash storage chips and the flash controller is critical parts of a SSD. This configuration is optimized to provide a good read/write capability for both sequential and random data requests. In HDDs, data is stored in magnetic material on disks using patterns of ‘0’ and ‘1’, resulting in the inability to consistently write data in the same location. As a result, when data is deleted, it is merely marked as erased and can still be recovered from unused sectors. However, with technological advancements, modern SDDs have the capability to constantly clear all sectors within the drive and create new ones, making it extremely difficult to recover deleted files [6]. As a key component of SSDs, flash memory chips play a significant role in retaining data. The data on the flash drive has to be deleted before it can be re-written back to the ones that are normally found on the SSD. Research has shown that devices utilizing flash memory delete data at the block-level and overwrite it at either the byte or multi-byte page level [6].

2.2 Comparison between NAND Flash and NOR Flash

There are two main types of flash memory, NAND flash and NOR flash. Both flash memory technology are types of non-volatile storage technology that does not require power to retain data. In NAND Flash, memory units are stacked next to each other on the transistor die while in NOR flash, memory cells are aligned horizontally, making NOR flash faster than NAND flash at reading data, with a structure that allows for faster data locating [7]. Fig. 1 demonstrates the structure of NAND flash and NOR flash.

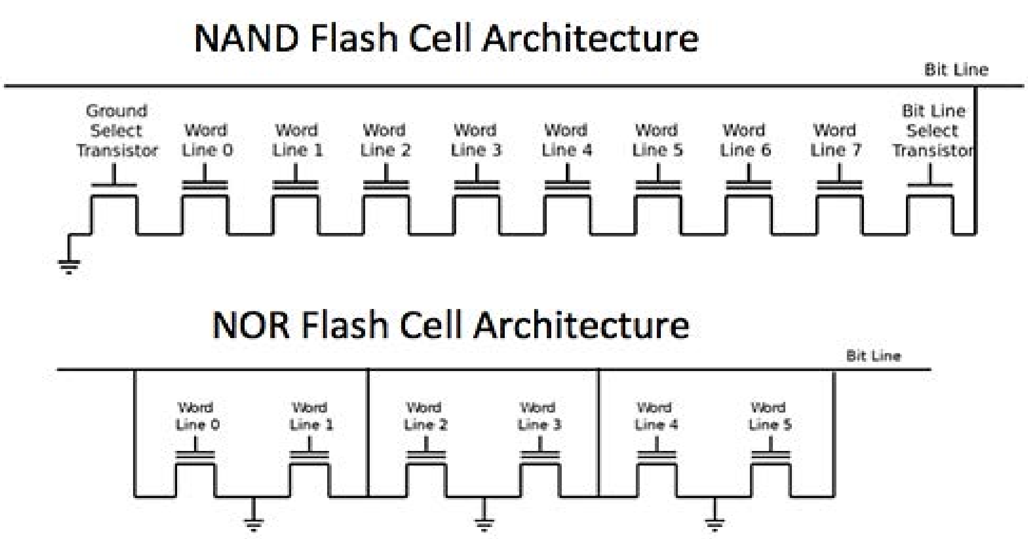

Fig. 1 NAND flash and NOR flash structure [6].

A NAND gate’s output is 1 only if none of the inputs is 1. In comparison, a NOR gate gives an output of 1 if both inputs are 0. NAND performs a sequential access on code areas and has a higher storage capacity. NOR performs a random a random access on code areas and has a lower storage capacity. NAND also performs faster erase than

NOR. Overall, NAND flash is more complicated to use but is cheaper than NOR.

Table 1. Comparison between NAND and NOR flash memories [8]

	NAND	NOR
Memory size	<= 512 Mbit	1-8 Gbit
Sector size	~ 1 Mbit	~ 1 Mbit
Output parallelism	Byte/Word/Dword	Byte/Word
Read parallelism	8-16 Word	2 Kbyte
Write parallelism	8-16 Word	2Kbyte
Read access time	< 80 ns	20 µs
Program time	9 µs/word	400 µs/page
Erase time	1s/sector	1 ms/sector

For Table 1 the following definitions hold:
Dword: 32 bits.
-Output parallelism: the number of bits that the memory is able to transfer to the output at the same time;
-Data read/programmed in parallel: the number of addressable bits at the same time during read/program operation;
-Read access time: time taken to perform a read action, excluding the time to transfer the read data to output [8].
Table 1 compares the electric characteristics of NAND flash with NOR flashes. Due to their advantages, NOR Flash is mostly used for cell telephones, science tools and medical equipment, while NAND has found a market for equipment that often stores and exchanges big files, e.g. MP3 players, Digital Cameras, and Universal Serial Bus (USB) flash drive . Sometimes NAND or NOR Flash is available in some equipment. Given its widespread use in SSDs, the following sections will focus primarily on NAND flash memory.

3. Future SSD technology (3D NAND)

3.1 Advantages of 3D NAND

One of the main objectives for developing NAND Flash is to lower per-bit cost and maximise the size of the chip. These improvements allow flash memory to better compete with magnetic storage devices, such as hard disks. 2D NAND, also called Plane NAND, is a kind of flash storage device that uses the flash storage unit to be positioned next to each other on the transistor die. It works by storing memory bits as voltage states within an electrical circuit. This type of flash memory technology is widely used worldwide. The main limitation of 2D NAND has been the amount of cells that can be accommodated in one surface on a chip. The smaller the cell, the more can be put on a single transistor plane. However, a smaller cell size decreases reliability by increasing the probability of electron leakage. Therefore, it is essential to develop a newer and more reliable flash memory technology. Around 2015, NAND flash technology underwent a paradigm shift, moving away from focusing solely on miniaturization. This new approach involved transitioning from 2-D to 3-D arrays, with the aim of achieving high gross bit storage density (GBSD), i.e., the ratio between the storage capacity and the total chip area, even with larger memory cells by stacking multiple cells vertically. The mainstream solution for implementing these 3D NAND Flash arrays quickly became the integration of vertical-channel NAND strings using a punch and plug process due to its cost-effectiveness and various advantages in terms of array performance and reliability [9]. Over the past a few years, 3D NAND flash memory technology has been developed. Being the newest NAND technique, it is usually preferred over 2D NAND. NAND flash memory is based on a single unit that is stacked on a tiny chassis, which allows the user to have a much more compact and more efficient memory unit.

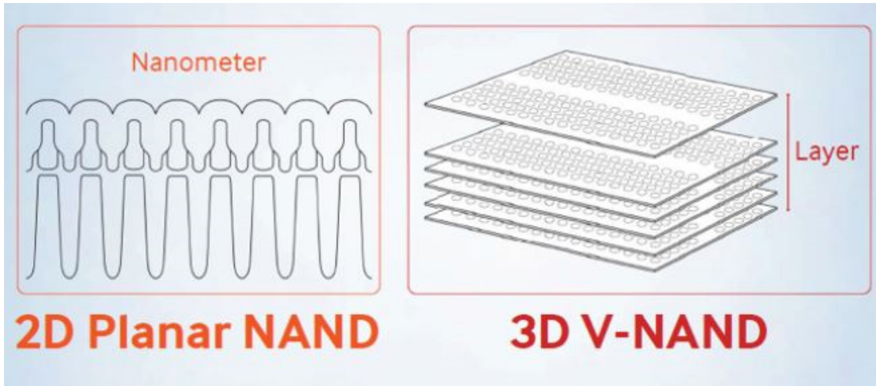

Fig. 2 2D NAND vs 3D NAND [9].

Fig. 2 demonstrates the structure of 2D NAND compared to 3D NAND. 2D NAND devices place storage cells side by side while 3D NAND adds another layer and stacks cells vertically. By storing more cells within the drive's chassis, 3D NAND provides more storage at faster speeds and lower prices compared to 2D NAND device. In addition, the newer 3D NAND technology reduces power consumption and increases the speed at which the device can write data to cells. Since shrinking cells reduces the reliability, the vertical stacking also gives the room to use larger cells for improved reliability. The end result is a net increase in both capacity and reliability of a NAND chip.

Table 2. Comparison between 2D NAND and 3D NAND

	2D NAND	3D NAND
Capacity per die	Max. 128 GB	256 GB/512 GB
Design	Floating gate	Floating gate or charging gate
Endurance (P/E Cycles)	Lower	Higher
Performance	Slower	Faster
Power consumption	High	Low

Table 2 demonstrates the differences between 2D NAND flash and 3D NAND flash. 3D NAND has better performance in general, and most importantly to consumers, it is cheaper than 2D NAND. While the initial production cost of 3D NAND is higher than 2D NAND, it can accommodate significantly more memory cells, resulting in a lower cost per cell. Hence the price per cell of 3D NAND is lower. This cost-effectiveness is a key factor driving the anticipated obsolescence of 2D NAND and the preference for 3D NAND in the future. Additionally, 3D NAND has a potential to stack more layers, which provides even more storage.

3.2 Challenges of 3D NAND

While 3D NAND technology represents a significant advancement in flash memory, it is not without challenges. Despite the advantages it offers, 3D NAND technology encounters certain obstacles that hinder its full potential and scalability. One of the major challenges is the complexity and costly manufacturing process of 3D NAND. This entails employing more advanced and expensive equipment as well as implementing complex procedures like etching, deposition, and testing compared to traditional 2D NAND production methods. As additional layers are incorporated, managing heat dissipation becomes increasingly challenging. Additionally, maintaining structural stability is also a concern. Furthermore, ensuring compatibility and interoperability between 3D NAND and various controllers, interfaces, and protocols presents yet another obstacle. Addressing this issue may necessitate the establishment of new standards and specifications to guarantee optimal performance without compromising compatibility with existing memory systems. To address the challenges associated with 3D NAND, the industry and academia are actively developing and implementing various solutions and innovations. These include advancements in manufacturing techniques and materials, such as the utilization of self-aligned quadruple patterning (SAQP) and charge trap flash (CTF) technologies. Additionally, optimization of 3D NAND architecture and design is being pursued through approaches like string stacking and enhancements for 3D NAND, including the application of advanced algorithms and protocols for data management, error correction, and encryption [10]. Innovations such as multi-hole architectures, trap-cut techniques, 3D NAND based on novel materials, and the WF bonding schema are among the novel approaches that have been introduced. Moreover, an exploration of advanced process and cell design technologies, including whole pitch scaling in conjunction with the augmentation of HARC etch capabilities and the extension of multi-bit cell configurations, should be contemplated [11]. The future trends of 3D NAND indicate that it will continue to evolve and improve in terms of capacity, performance, reliability, and efficiency. Some of the trends include increasing the number of layers and bits per cell, such as 176-layer QLC or 512-layer PLC. Other trends involve developing new technologies and architectures, such as 3D XPoint, BiCS FLASH, or ReRAM. Another trend is integrating 3D NAND with other components and systems, such as CPU, GPU, or DRAM, to create hybrid or heterogeneous memory solutions.

4. Conclusion

To summarize the key points discussed in this paper, the performance of SSDs and traditional HDDs was compared, concluding that SSDs offer superior performance but at higher prices, with rapid development expected in the future. Two main types of flash memory used in SSDs, NAND flash and NOR flash, are also compared, with the conclusion that NAND flash is more complicated to use but is cheaper than NOR. Then the advantages of Then the limitations of 2D NAND is discussed and compared with 3D NAND, with the conclusion that 3D NAND has better performance, lower power consumption and larger capacity. Currently, up to 232 layers can be stacked on a NAND chip. This layering capability underscores the high potential of 3D NAND technology, as future advancements in stacking techniques could lead to even larger capacities and higher reliability.

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