A Smart Hybrid Solid-State-Drive Storage System based on Nonvolatile Storage-Class-Memories
- Device, Circuit Design and Architecture -

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***Abstract*—Recently, there are many kinds of non-volatile memories like NAND flash, MRAM, PCM and ReRAM. Since there is no perfect non-volatile memories, a co-design of device, circuits and systems is essential in order to achieve high performance and reliability with low cost and power consumption. To reach this goal, this paper proposes a hybrid solid-state drive based storage system with optimum circuits to manage each non-volatile memory characteristics.**

Keywords—Non-Volatile Memory, Emerging Memory, Solid-State Drive, SSD, Storage-Class-Memory, SCM, NAND flash memory, Magnetic RAM, MRAM, Phase-Change RAM, PCM, PRAM, Resistive RAM, ReRAM, RRAM, Hybrid SSD

I. INTRODUCTION

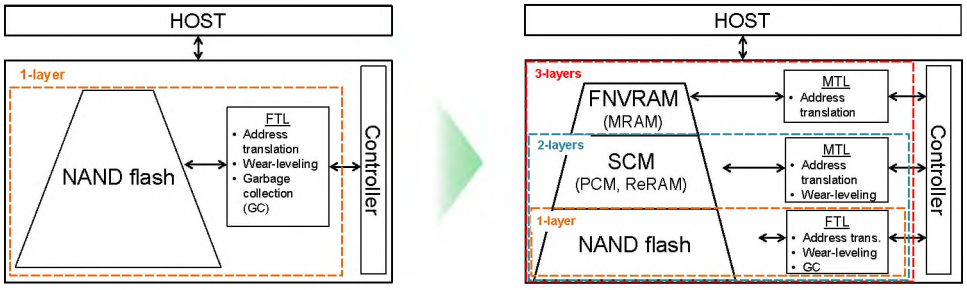
Computer logic has been improving at an exponential pace, as Moore's law. While a dynamic random access memory (DRAM) is a lot slower than logic, main memory has managed to keep up with the speed of logic by utilizing a hierarchical structure of caches, the upper layers of which use the more expensive and faster static random access memory (SRAM). On the other hand, while storage technology has indeed progressed, it has failed to keep up. There is a massive gap in response times between storage and memory. Thus recently, faster and more compact solid-state drive (SSD) based on NAND flash memories [1-3] has been replacing more traditional magnetic hard disks drives (HDDs) for many applications. SSDs provide better performance, consume less power and physical durability. However, since NAND flash memory is still much slower than main memory of DRAM. Especially when write operation, it suffers from write-induced wear and has an erase before write limitation.

Then, many alternative non-volatile memories (NVMs) technologies have emerged in recent years. Those technologies provide memory like performance while being persistent like storage and as such, came to be known as a storage class memory (SCM). Table I summarizes a current status of emerging non-volatile memories, for example magnetic RAM (MRAM) [4], phase change RAM (PRAM) [5], resistive RAM (ReRAM) [6]. As Table I shows, there is no perfect non-volatile memory which simultaneously realizes low-cost, high access speed, low energy dissipation and high reliability including infinite write limit. Hence, in order to handle these emerging memories, it is important to develop an optimum circuit design considering device physics and suitable architecture which includes advantages and disadvantages of each non-volatile memories in order to

Table I. SUMMARY OF EMERGING NON-VOLATILE MEMORIES.

	NAND Flash	**NOR Flash**	**MRAM**	**PRAM**	**ReRAM**
Method	Vth change w/ FN-tunneling	Vth change w/ HCI	Magnetic domain w/ ferro-electric materials	Phase change w/ chalcogenide	Soft-breakdown w/ metal oxide film
Cell size	$4F^2$	$\sim 10F^2$	$6 - 20F^2$	$4 - 6F^2$	$5 - 8F^2$
Capacity	Excellent	Fair	Poor	Good	Good
Write speed	$\sim \times 1$ ms	$\sim \times 10 - 100$ ns	$\times 1 - \times 10$ ns	$\times 10 - \times 100$ns	$\times 10 - \times 100$ns (w/o verify)
Operating voltage	> 15 V	~ 12 V	< 2V	< 3 V	~ 3 V
R_{on}/R_{off}	-	-	$< \times 2$	$\times 10 - \times 1000$	$\times 10 - \times 100$
Endurance limit	$< 10^7$ (SLC) $< 10^5$ (MLC) $< 10^4$ (TLC)	$\sim 10^5$	Infinite	$> 10^8$	$> 10^8$
Pros.	• High cell density	• High speed random access compared to NAND flash	• High speed • Unlimited write cycle • Stable retention	• Well-known materials • Stable write • Unipolar write	• Small write current • Fully compatible with Si-process • High-speed access
Cons.	• High-voltage required • Write cycle limitation • Difficult to scale down due to charge decrease	• Large cell area & cell current (compared to NAND flash)	• Low density (very large cell size) due to small R_{on}/R_{off}	• Large write current • Heat disturbance	• Bipolar write • Unstable read • Initial forming required

978-1-7281-6564-6/20/$31.00 ©2020 IEEE



(a) Conventional SSD (b) Hybrid SSD (3 layers)

Fig. 1. Proposed hybrid SSD architecture.

enhance access speed and reliability with low power consumption.

Therefore, this presentation will introduce and discuss device characteristic driven circuit design to overcome weak points of each non-volatile memories [7-13]. Also, it will propose a structure and control algorithms with a hierarchical hybrid solid-state drive as shown in Fig, 1 [14-17]. We will first tackle the architecture of hierarchical hybrid SSD: studying the difference between 1-layer, 2- layer and 3-layer designs and the impact of different interconnections on the performance of the system. After that, we will study various control algorithms of such a system and their impact on the performance of the system with a SSD simulator written in C++ language.

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