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A review of emerging non-volatile memory (NVM) technologies and applications

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ABSTRACT

This paper will review emerging non-volatile memory (NVM) technologies, with the focus on phase change memory (PCM), spin-transfer-torque random-access-memory (STTRAM), resistive random-access-memory (RRAM), and ferroelectric field-effect-transistor (FeFET) memory. These promising NVM devices are evaluated in terms of their advantages, challenges, and applications. Their performance is compared based on reported parameters of major industrial test chips. Memory selector devices and cell structures are discussed. Changing market trends toward low power (*e.g.*, mobile, IoT) and data-centric applications create opportunities for emerging NVMs. High-performance and low-cost emerging NVMs may simplify memory hierarchy, introduce non-volatility in logic gates and circuits, reduce system power, and enable novel architectures. Storage-class memory (SCM) based on high-density NVMs could fill the performance and density gap between memory and storage. Some unique characteristics of emerging NVMs can be utilized for novel applications beyond the memory space, *e.g.*, neuromorphic computing, hardware security, *etc*. In the beyond-CMOS era, emerging NVMs have the potential to fulfill more important functions and enable more efficient, intelligent, and secure computing systems.

1. Introduction

Temporary and permanent data storage is required in any functional information processing systems, which has so far been fulfilled by CMOS-based memories, *i.e.*, SRAM, DRAM, and Flash memory. The speed gap between logic and memory has become a critical system performance bottleneck, *i.e.*, the "memory wall" [1]. Hierarchical memory systems made from devices with varying speed, density and cost have been adopted to optimize the performance-cost tradeoff. With CMOS scaling approaching fundamental limits, some novel non-volatile memory (NVM) concepts have been proposed and made significant progress in recent years [2]. Although high-performance computing is still an important driver for semiconductor technology innovation, consumer electronics is shifting toward mobile, pervasive connectivity, and data-centric applications. The changing market trend imposes different requirements on hardware, *e.g.*, ultra-low power computing, high-density and low-cost data storage, novel functions, *etc*. Emerging NVMs with high performance, good scalability, and new functionalities may become important technology enablers to fulfill these requirements.

2. Emerging NVM device options

2.1. Memory taxonomy and emerging NVM candidates

Fig. 1 shows the memory taxonomy from the 2013 International Technology Roadmap for Semiconductors (ITRS) Emerging Research Devices (ERD) chapter [2]. NVMs with prototype test chips or early production are included in the "prototypical" category, which covers ferroelectric random-access-memory (FeRAM), phase change memory (PCM), magnetic RAM (MRAM), and spin-transfer-torque RAM (STTRAM). However, some of these prototypical memories may still be considered "emerging" in the research community, with significant R&D activities. Therefore, this paper will start with a broad scope of emerging memories including devices in both "prototypical" and "emerging" categories in Fig. 1.

Emerging NVMs often involve novel mechanisms and materials different from those of mature memories based on Si CMOS. These materials include ferroelectric dielectrics, ferromagnetic metals, chalcogenides, transitional metal oxides, carbon materials, *etc*. Their switching mechanisms extend beyond classical electronic processes, to quantum mechanical phenomena, ionic reactions, phase transition, molecular reconfiguration, *etc*. Most of the emerging NVMs are based on two-terminal switching elements,

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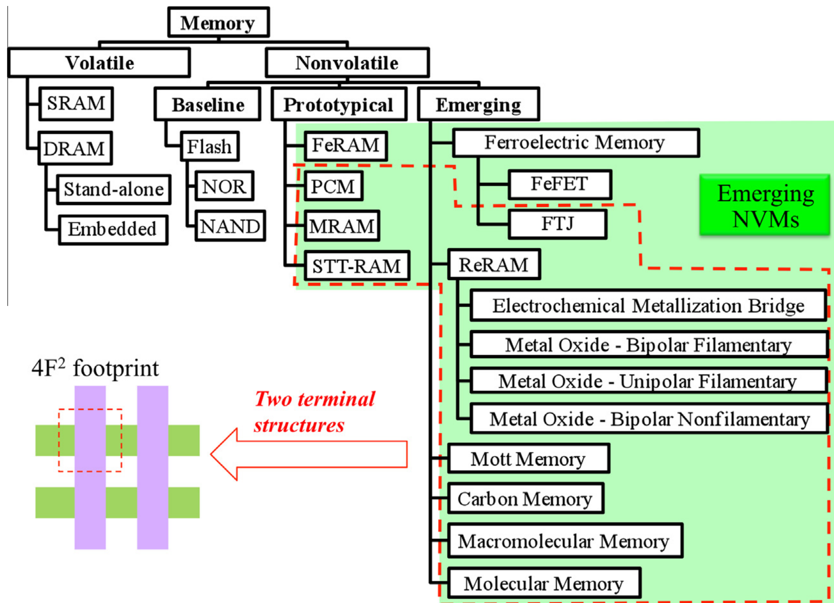

Fig. 1. Memory taxonomy from the 2013 ITRS Emerging Research Devices (ERD) chapter [2]. Many emerging NVMs have a simple two-terminal structure, suitable for high-density crossbar memory arrays.

which are suitable for high-density memory architectures, *e.g.*, cross-bar arrays (CBAs).

With the large variety of emerging NVMs, it is necessary to compare their performance and evaluate their long-term potential. ERD conducts a regular survey-based critical review of devices in the "emerging" category, using eight criteria and a 1–3 score (with 3 representing the best and 1 the worst). The result of the 2013 ERD critical review is summarized in Fig. 2. Good scalability is considered one of the key advantages of emerging NVMs, while reliability is a common challenge. RRAM stands out as the most promising device among the six candidates in Fig. 2, followed by FeFET memory. "Carbon-based memory" involves mixed types of carbon materials (*e.g.*, carbon nanotube, graphene, amorphous carbon, *etc.*) and has attracted growing interest [3–5]. "Molecular memory" is pursued mostly for ultimate scalability, while its performance is relatively poor [6,7]. Progress has been made on "Mott memory" based on metal–insulator transition, but materials with high transition temperature are needed for practical applications [8–10]. "Macromolecular memory" may be useful in flexible electronics and low-cost applications, but has limitations in performance and reliability [11,12].

In a recent workshop organized by ERD in 2014, nine emerging NVM technologies were evaluated based on both demonstrated performance ("most promising") and foreseen potential ("most need of resources"), as shown in Fig. 3. PCM, STTRAM, and RRAM (including both oxide based RRAM and conductive-bridge RAM) are among the top candidates with the most promising performance. Emerging ferroelectric memory, especially FeFET with doped ferroelectric HfO_x, is considered the top choice that needs more resources to explore its long-term potential. The rest of the paper will focus on these four NVM devices: PCM, STTRAM, RRAM, and FeFET memory.

PCM, STTRAM, and RRAM are all back-end-of-line (BEOL) memories with two-terminal memory elements integrated between two metal layers. The structures of these memory elements are shown in Fig. 4. Behind the simplicity on the appearance, each memory involves complex issues in stack engineering, thin-film deposition, process optimization, and device designs, which will be explained in details in the following sections. PCM switching is based on Joule heating induced phase transition in chalcogenides, which is unipolar (*i.e.*, switching on and off in the same bias direction). STTRAM switching involves direction-dependent

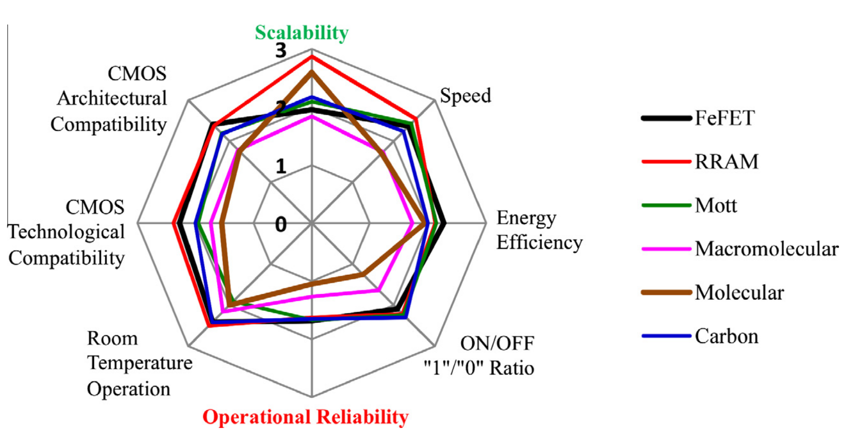

Fig. 2. 2013 ITRS ERD critical review of emerging memories based on eight criteria, where "3" and "1" represent the best and the worst assessment scores, respectively.

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