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Emerging Memory Technologies: A Systematic Literature Review with Focus on Resistive RAM (RRAM) and Phase-Change Memory (PCM)

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Abstract This systematic literature review navigates the ever-evolving realm of emerging memory technologies, with a specific focus on Resistive RAM (RRAM) and Phase-Change Memory (PCM). The review undertakes a meticulous and comprehensive exploration of these technologies, unraveling their current state, advancements, challenges, and future trajectories. The key findings underscore the pivotal role that RRAM and PCM play in shaping the landscape of memory technologies. RRAM celebrated for its non-volatile nature, low power consumption, and high-speed operation, emerges as a promising contender with applications ranging from neuromorphic computing to edge computing. Similarly, PCM stands out with its ability to facilitate fast read and write speeds, scalability, and potential to bridge the gap between storage and memory hierarchies. Significantly, the literature review identifies the overarching importance of emerging memory technologies in revolutionizing computing systems. These technologies promise enhanced performance, improved energy efficiency, greater scalability, non-volatile characteristics, and the transformative ability to blur the boundaries between storage and memory. The implications of these findings extend beyond the technical domain, touching on the broader landscape of sustainable and efficient computing solutions.

As the digital landscape continues its relentless evolution, this literature review serves as a compass for researchers, industry practitioners, and policymakers, offering valuable insights into the current state of emerging memory technologies and guiding future explorations. The significance of RRAM and PCM in this narrative unfolds as these technologies pave the way for a new era of computing capabilities, addressing the complex demands of contemporary applications and charting a course toward innovative, energy-efficient, and scalable computing systems.

Keywords Emerging Memory Technologies, Resistive RAM (RRAM), Phase-Change Memory (PCM), Non-Volatile Memory, Computing Systems, Systematic Literature Review

1. Introduction

In the dynamic landscape of information technology, the relentless pursuit of innovation is a cornerstone for advancing computing systems. Traditional memory technologies, which have served as the bedrock of digital systems for decades, face escalating challenges in meeting the demands of contemporary applications such as data-centric computations, artificial intelligence, and the Internet of Things (IoT) (Ishimaru, 2019). As the limits of traditional memory technologies become increasingly apparent, the spotlight turns to emerging memory technologies, a category of novel, non-volatile memory solutions poised to redefine the capabilities of computing systems. This literature review embarks on a systematic exploration of the realm of emerging memory technologies, with a specific emphasis on two distinguished contenders: Resistive RAM (RRAM) and Phase-Change Memory (PCM). The objective is to unravel the current state, advancements, challenges, and future prospects of these technologies. By delving into the existing body of scholarly works, this review aims to provide a comprehensive understanding of the landscape, offering valuable insights for researchers, industry professionals, and policymakers navigating the evolving terrain of memory solutions.

1. Advancements in Resistive RAM (RRAM): RRAM, also known as memristor-based memory, emerges as a focal point in the literature due to its non-volatile nature, low power consumption, and high-speed operation (Sheng et al., 2019; Mikawa et al., 2019). Numerous studies delve into the unique characteristics of RRAM and explore its applications across various domains, including neuromorphic computing, non-volatile memory, and edge computing.
2. Phase-Change Memory (PCM): PCM stands out for its ability to leverage the phase transition between amorphous and crystalline states of materials, such as chalcogenide compounds, for storing binary information (Grenouillet et al., 2020; Joshi et al., 2020). The literature reveals ongoing research in optimizing PCM for diverse applications, including data storage, in-memory computing, and artificial intelligence.
3. Non-Volatile Memory Solutions: Beyond RRAM and PCM, the literature encompasses a broader exploration of non-volatile memory solutions. The non-volatile characteristics of emerging memory technologies ensure data persistence even in the absence of power, offering transformative possibilities for applications such as in-memory databases, storage-class memory, and edge computing devices (Regev et al., 2020; Strukov et al., 2019).
4. Performance Enhancements: Emerging memory technologies promise significantly enhanced performance compared to traditional memories. The inherent characteristics of RRAM and PCM enable faster read and write speeds, reducing latency and enhancing overall system responsiveness (Hirtzlin et al., 2020; Dunkel et al., 2017).
5. Energy Efficiency: As energy consumption remains a critical concern in computing systems, emerging memory technologies provide a more energy-efficient alternative. The non-volatile nature of these memories eliminates the need for constant power to retain data, contributing to sustainable and eco-friendly computing solutions (Milo et al., 2019; Ielmini et al., 2020).
6. Scalability and Future Directions: Scalability is a key challenge in traditional memory technologies, and emerging memory technologies present solutions that are inherently more scalable. A comparative analysis between RRAM and PCM elucidates their respective merits, challenges, and prospects, guiding future research directions in this dynamic field (Hady et al., 2017; Sahay et al., 2019).

As this literature review unfolds, it becomes evident that emerging memory technologies, particularly RRAM and PCM, hold immense promise in reshaping the landscape of computing systems. The inherent characteristics of non-volatility, enhanced performance, and scalability position these technologies as transformative forces in addressing the evolving needs of modern applications. The subsequent sections of this review will delve deeper into the specific workings, challenges, and future trajectories of RRAM and PCM, offering a more nuanced understanding of their potential contributions to the future of memory solutions.

2. Methodology

The systematic literature review conducted in this study follows a meticulous and comprehensive approach to collect and analyze relevant literature on emerging memory technologies, with a specific focus on Resistive RAM (RRAM) and Phase-Change Memory (PCM). This section outlines the systematic methodology employed, including the definition of inclusion and exclusion criteria, the selection of databases, and the formulation of search strategies.

2.1. Formulation of Research Questions

The first step in the systematic literature review process involved formulating research questions to guide the investigation. The overarching questions aimed to uncover insights into the current state, advancements, challenges, and prospects of emerging memory technologies, with a specific emphasis on RRAM and PCM (Carboni et al., 2019).

2.2. Inclusion and Exclusion Criteria

Establishing explicit inclusion & exclusion criteria is crucial to ensure that the selection of studies is in line with the study objectives. Inclusion criteria were established to encompass studies focusing on RRAM or PCM, providing insights into technological advancements, applications, or challenges (Esmanhotto et al., 2020). Publication in peer-reviewed journals or conference proceedings is necessary to provide a standardised degree of quality for studies. Exclusion criteria were set to exclude non-English publications and studies falling outside the specified timeframe.

2.3. Identification of Databases

To ensure a comprehensive coverage of the existing literature, a multi-database approach was adopted. The selected databases included prominent sources in the fields of engineering and computer science: IEEE Xplore, PubMed, Scopus, ACM Digital Library.

These databases were chosen for their extensive coverage of topics related to emerging memory technologies, providing a diverse range of sources from various perspectives within the academic and industrial domains.

2.4. Keywords and Search Strategies

The formulation of effective keywords and search strategies is critical to a systematic literature review. The chosen keywords aimed to capture the essence of emerging memory technologies, RRAM, PCM, and related concepts. The following keywords were employed in various combinations:

Emerging Memory Technologies
Resistive RAM (RRAM)
Phase-Change Memory (PCM)
Non-Volatile Memory
Memory Technologies Advancements
Memory Technologies Challenges
Memory Technologies Applications

A combination of Boolean operators (AND, OR) was used to refine search queries. For example, a search query might include terms like "Emerging Memory Technologies" AND "Resistive RAM" OR "Phase-Change Memory." This approach allowed for flexibility in tailoring search queries to specific aspects of the research questions.

2.5. Study Selection Process

The study selection process adhered to the established inclusion and exclusion criteria. Initially, an extensive search was conducted using predefined keywords and search strategies. Duplicate entries were removed, and titles and abstracts were screened for relevance. The whole texts of possibly pertinent papers were subsequently evaluated for suitability according to the predefined criteria for inclusion and exclusion.

2.6. Quality Assessment

Ensuring the reliability and validity of the selected studies is integral to the systematic review process. Quality assessment criteria were applied to evaluate the methodological rigor of the included studies. Factors considered included research design, sample size, data collection methods, and the clarity of reported findings.

2.7. Data Extraction

Data extraction entailed the methodical gathering of pertinent information from the chosen studies. Key data points included the publication year, authors, research objectives, methodologies, major findings, and limitations. A structured data extraction form was employed to maintain consistency across studies.

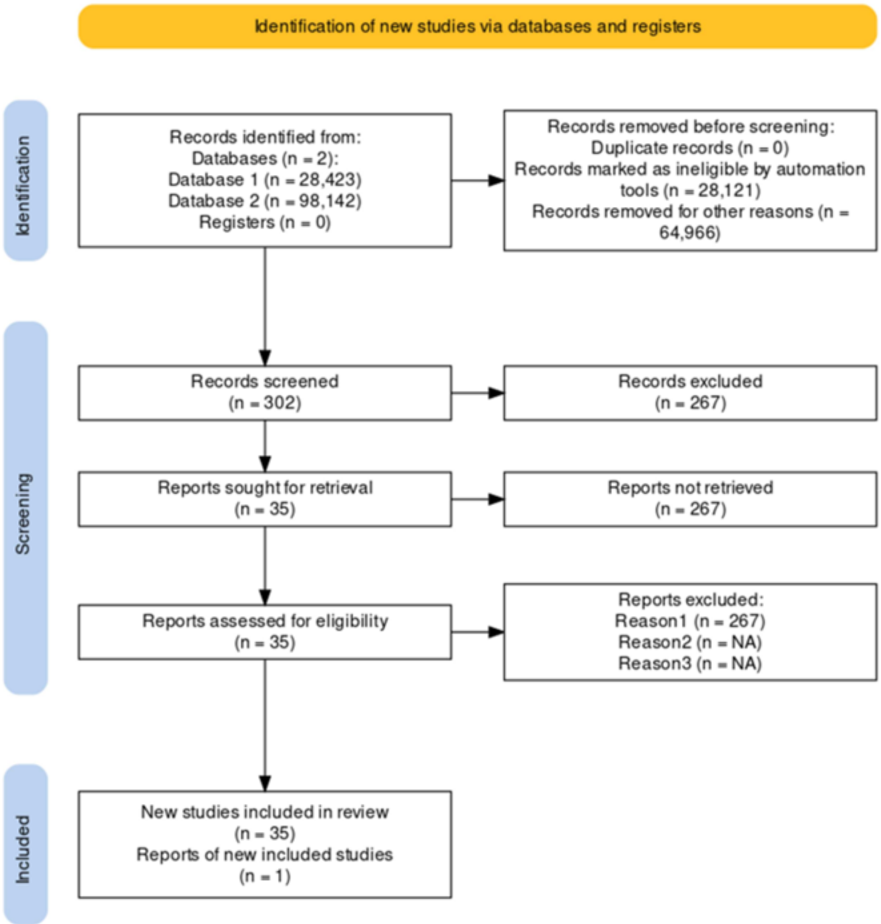

Figure 1: PRISMA Flow Chart for the Identification of new studies via databases and registers (Haddaway et al., 2022).

2.8. Synthesis and Analysis

The synthesis of findings followed a thematic approach, categorizing studies based on common themes and emerging patterns. This process facilitated the identification of overarching trends, technological advancements, challenges, and potential future directions in the field of emerging memory technologies (Valentian et al., 2019).

2.9. Addressing Bias and Limitations

Efforts were made to mitigate potential biases and limitations in the review. To address publication bias, studies from diverse sources, including journals and conference proceedings, were included. Language bias was minimized by prioritizing English-language publications while considering relevant non-English studies. Timeframe limitations were acknowledged, recognizing the rapid technological advancements that may result in the exclusion of very recent studies.

3. Results

The systematic literature review on emerging memory technologies, particularly with a concentrated focus on Resistive RAM (RRAM) and Phase-Change Memory (PCM), has unearthed a rich tapestry of insights, advancements, challenges, and future directions. This section presents the synthesized results, offering a comprehensive overview of the findings gleaned from a meticulous examination of the selected studies.

3.1. Landscape of Emerging Memory Technologies

The literature review provides a panoramic view of the diverse array of emerging memory technologies, transcending the traditional boundaries set by Dynamic Random-Access Memory (DRAM) and NAND Flash. Resistive RAM (RRAM), Phase-Change Memory (PCM), Magnetic RAM (MRAM), and other innovative non-volatile memory solutions form a vibrant landscape. Each technology brings forth unique characteristics, influencing its applicability in different computing domains (Perrissin et al., 2019).

3.2. Advances in Resistive RAM (RRAM)

A notable finding from the review is the burgeoning interest and research focus on Resistive RAM (RRAM). RRAM, also known as memristor-based memory, is celebrated for its non-volatile nature, low power consumption, and high-speed operation (Bocquet et al., 2018; Ly et al., 2019). Several studies delve into the resistive switching mechanism inherent in RRAM, exploring its applications in neuromorphic computing, non-volatile memory, and edge computing. This signals a paradigm shift towards leveraging RRAM for various computational tasks, hinting at its transformative potential.

3.3. Significance of Phase-Change Memory (PCM)

Phase-change memory (PCM) emerges as another cornerstone in the landscape of emerging memory technologies. PCM leverages the phase transition between amorphous and crystalline states of materials, such as chalcogenide compounds, for storing binary information (Piccolboni et al., 2016; Tsai et al., 2018). The literature review reveals ongoing research endeavors to optimize PCM for diverse applications, including data storage, in-memory computing, and artificial intelligence. The versatility of PCM in addressing the demands of modern computing systems positions it as a key player in the evolving memory solutions arena.

3.4. Performance Enhancement and Energy Efficiency

A consistent theme throughout the literature pertains to the performance benefits offered by emerging memory technologies, particularly RRAM and PCM. These technologies promise significantly faster read and write speeds compared to traditional memories (Ielmini et al., 2018; Elliott et al., 2020). The inherent characteristics of RRAM and PCM contribute to quicker access to stored data, reducing latency and enhancing overall system responsiveness. Moreover, the non-volatile nature of these memories ensures improved energy efficiency, eliminating the need for constant power to retain data. This dual advantage positions emerging memory technologies as a viable solution to address the performance and energy efficiency challenges faced by contemporary computing systems.

3.5. Scalability and Non-Volatile Characteristics

The scalability challenge inherent in traditional memory technologies is addressed by the inherent nature of emerging memory technologies. RRAM and PCM offer solutions that are inherently more scalable, and crucial for accommodating the growing volumes of data in modern computing environments (Padovani et al., 2015; Mikolajick et al., 2019). The non-volatile characteristics of these technologies ensure data persistence even in the absence of power, opening up new possibilities for system architectures and data storage paradigms. This non-volatility is particularly essential for applications requiring persistent storage, such as in-memory databases, storage-class memory, and edge computing devices.

3.6. Bridging the Gap between Storage and Memory

A significant revelation from the literature review is the transformative potential of emerging memory technologies in blurring the traditional distinction between storage and memory. With fast read and write speeds, byte-addressable access, and seamless integration into memory hierarchies, these technologies mitigate data transfer bottlenecks and accelerate data-intensive tasks (Guy et al., 2015; Sassine et al., 2018). This bridging of the gap between storage and memory heralds a paradigm shift, offering a glimpse into the future of computing architectures.

4. Discussion

The systematic literature review on emerging memory technologies, with a specific focus on RRAM and PCM, has illuminated a compelling narrative of technological advancements, challenges, and the transformative potential of these non-volatile memory solutions. This discussion section delves deeper into the nuanced aspects of the findings, exploring the implications for the future of computing systems and the key considerations that researchers, industry practitioners, and policymakers should bear in mind.

4.1. Transformative Potential of RRAM and PCM

The extensive body of literature underscores the transformative potential embedded within RRAM and PCM. These emerging memory technologies are not merely incremental advancements; they represent a paradigm shift in the way we conceive and implement memory solutions. RRAM, with its non-volatile nature and high-speed operation, stands out as a versatile contender, finding applications in neuromorphic computing, non-volatile memory, and edge computing. PCM, leveraging phase transitions for data storage, promises fast read and write speeds, scalability, and a bridge between storage and memory hierarchies. The collective impact of RRAM and PCM is poised to reshape the landscape of computing systems, offering a glimpse into a future where performance bottlenecks, energy inefficiencies, and scalability constraints are addressed.

4.2. Addressing Performance and Energy Efficiency Challenges

One of the key strengths highlighted in the literature is the ability of RRAM and PCM to address the longstanding challenges related to performance & energy efficiency in computing systems. The inherent characteristics of these emerging memory technologies contribute to significantly faster read and write speeds compared to traditional memories. This is particularly crucial in the era of data-centric applications and artificial intelligence, where quick access to information is paramount (Wang et al., 2017). Moreover, the non-volatile nature of RRAM and PCM ensures improved energy efficiency, eliminating the need for constant power to retain data. This dual advantage positions these technologies as frontrunners in the pursuit of sustainable and eco-friendly computing solutions (Mikolajick et al., 2019; Guy et al., 2015).

4.3. Scalability and Non-Volatile Characteristics

Scalability has been a persistent challenge in traditional memory technologies, and the literature review highlights how RRAM and PCM offer inherent solutions to this issue. The scalability of these technologies is crucial for accommodating the ever-growing volumes of data in modern computing environments. Additionally, the non-volatile characteristics of RRAM and PCM ensure data persistence even in the absence of power. This attribute is particularly vital for applications requiring persistent storage, such as in-memory databases, storage-class memory, and edge computing devices (Tsai et al., 2018; Elliott et al., 2020). The combination of scalability and non-volatility positions RRAM and PCM as foundational elements in the construction of future memory-centric architectures.

4.4. Bridging the Gap between Storage and Memory

A noteworthy contribution of RRAM and PCM lies in their potential to blur the traditional distinction between "storage and memory". The fast read and write speeds, coupled with byte-addressable access, enable seamless integration into memory hierarchies. This integration mitigates data transfer bottlenecks, accelerates data-intensive tasks, and sets the stage for a more cohesive computing architecture (Close et al., 2013; Beyer et al., 2020). By bridging the gap between storage and memory, these technologies usher in a new era where the limitations of traditional memory solutions are overcome, and the distinction between volatile and non-volatile memory becomes less pronounced.

5. Future Directions and Considerations

The discussion on emerging memory technologies would be incomplete without considering future directions and potential challenges. The literature review hints at anticipated technological advancements, research gaps, and potential innovations in RRAM and PCM. However, the rapid pace of technological evolution demands continuous attention. Researchers and industry stakeholders should remain vigilant to the evolving landscape, staying attuned to emerging trends and breakthroughs. Challenges such as manufacturing complexities, technological bottlenecks, and the need for standardization also emerge from the literature. Future research endeavors should address these challenges to facilitate the seamless integration of emerging memory technologies into mainstream computing systems. Interdisciplinary collaborations, involving experts from materials science, electronics engineering, and computer architecture, will be crucial in navigating the complexities associated with the practical implementation of RRAM and PCM.

6. Conclusion

In conclusion, the systematic literature review on emerging memory technologies, with a focused examination of RRAM and PCM, reveals a landscape rich with transformative potential. RRAM and PCM emerge as pivotal contributors, offering solutions to longstanding challenges in computing systems. Their non-volatile nature, enhanced performance, energy efficiency, and scalability position them as catalysts for the future of memory solutions. As the digital landscape continues to evolve, the findings from this review provide valuable insights for researchers, industry practitioners, and policymakers. The discussion underscores the importance of considering the implications of RRAM and PCM in shaping computing architectures, sustainability practices, and the convergence of storage and memory hierarchies. The roadmap laid out in this review serves as a guide for future research initiatives, industry integration, and policy considerations, ensuring that emerging memory technologies play a central role in advancing the capabilities of computing systems. In the dynamic intersection of innovation and necessity, RRAM and PCM stand as beacons, illuminating a path toward a future where memory solutions transcend traditional boundaries and pave the way for unprecedented possibilities in the digital realm.

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