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Application-driven innovations in nanodevices for next-generation transistors, neuromorphic computing, neural interface and quantum computing

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The demand for aggressive scaling in integrated circuits technology has been a primary driving force behind the rapid advancement of nanotechnology, leading to groundbreaking innovations in nanoscience, engineering, and technology. Initially, the unique phenomena observed at nanoscale enable innovative applications in nanodevices. Now, as our understanding has greatly developed, nanodevices are increasingly being leveraged to provide solutions for a growing range of applications. In this perspective, several key areas are featured that are proposed to benefit significantly from advancements in nanodevices.

KEYWORDS

nanodevice, application, next-generation electronics, innovations, nanoelectronics

Introduction

Over the past few decades, continuous miniaturization has not only pushed the boundaries of traditional semiconductor devices but has also unlocked novel physical phenomena that emerge at the nanoscale (Veendrick, 2024). The unprecedented properties exhibited at nanoscale materials—such as ballistic transport and tailored optical behavior—fueled their integration into next-generation electronic and optoelectronic devices. And, as our understanding of nanomaterials and their interactions has deepened, their applications have expanded far beyond conventional electronic scaling. Today, nanodevices are playing an increasingly crucial role for transformative applications across multiple disciplines. As research continues to unlock new capabilities, many areas are expected to benefit significantly from the ongoing advancements in nanodevices. Here, we just mentioned few of them, as shown in Figure 1. From next-generation transistors and neuromorphic computing to neural interface and quantum computing, the potential for nanotechnology to drive innovation across multiple sectors remains vast and largely untapped.

Ultimate scaling in Moore's law

Aggressive device scaling of silicon technologies has dominantly driven the semiconductor industry for decades, which brings great benefits to digital circuits in

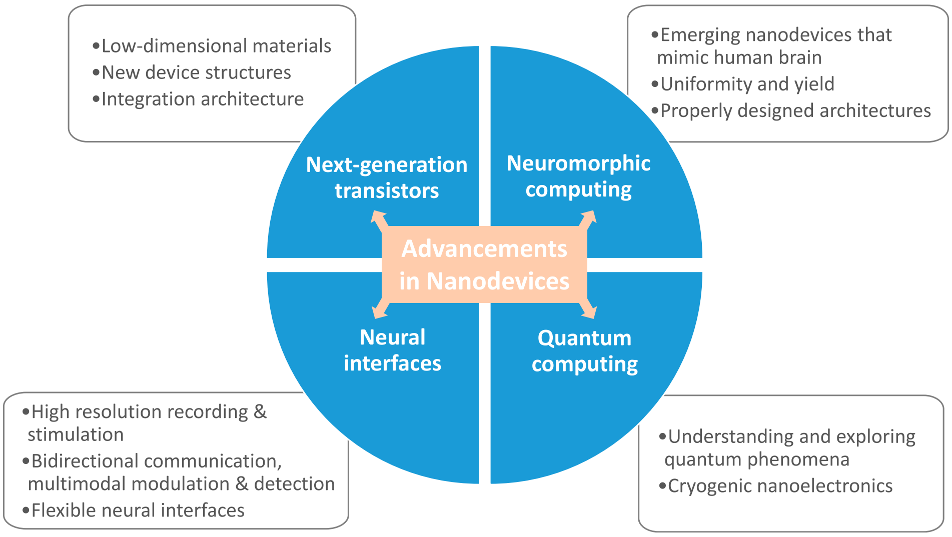

FIGURE 1
Featured key areas that may benefit significantly from advancements in nanodevices.

terms of speed, power consumption and density. As traditional silicon-based electronics approach their physical limits, nanodevices offer a pathway to continue Moore's Law through innovations in materials and device architectures. Low-dimensional materials (2D materials, carbon nanotube, etc.) with high mobility, ultrathin bodies and good immunity to short-channel effects are extensively studied to explore their potential to provide solutions toward the ultimate scaling (Das et al., 2021; Franklin et al., 2022). Among diverse transistor structures have been investigated, nanosheet field-effect transistors (NS-FETs) (Loubet et al., 2017; Hook, 2018), are expected to be alternative to FinFET technology, especially for advanced semiconductor technologies beyond the 3 nm node (Alabdullah et al., 2024), which can provide superior electrostatic control over the channel with higher current drivability compared to other structures, and are compatibility with the conventional FinFET fabrication processes. These advancements are pushing the boundaries of performance, enabling faster, smaller, and more energy-efficient devices. In addition, monolithic 3D integration technology provides another solution to extend conventional transistor scaling, by integrating multiple transistor layers via vertical interconnects above a single substrate to enables unprecedented integration density and high bandwidth communication (Dhananjay et al., 2021; Kim et al., 2024; Shulaker et al., 2015). Innovations provided by nanomaterials, new device structure and integration architecture are critical to support continuous advancements toward the ultimate scaling.

Neuromorphic computing and brain-inspired systems

Neuromorphic computing represents a paradigm shift in the way we design and implement computing systems. By mimicking the structure and function of the human brain, neuromorphic systems offer unparalleled efficiency and adaptability for tasks such as pattern recognition, real-time learning, and decision-making. New nanodevices that provide new physics to emulate synapse- and neuron-like functionalities, such as plasticity, spiking behavior and dispersion of conduction velocities (Kandel et al., 2020; Johansson and Flanagan, 2009), are the hardware foundations to realize useful features of the brain, like in-memory computing, spike-based information processing, signal processing resilient to noise, asynchronous communication, and analog computing (Upadhyay et al., 2019). Emerging nanodevices, memristor (Aguirre et al., 2024), phase change memory (Ambrogio et al., 2018), flash memory (Guo et al., 2017; Huang et al., 2023), ferroelectric transistors (Jerry et al., 2017; Kim et al., 2023), spintronics devices (Grollier et al., 2020), to name just a few, have demonstrated their tremendous role in this field. By further addressing device non-ideal challenges such as uniformity and yield, and adopting a properly designed architectures, the integrated systems can perform complex computations with minimal power consumption, which not only redefines artificial intelligence but also paves the way for applications in robotics, autonomous systems, and adaptive technologies (Zhang et al., 2020).

Neural interfaces and biomedical engineering

Neural interfaces are bridging the gap between biology and electronics, offering new possibilities for understanding and interacting with the human brain (Valeriani et al., 2022). Here, at the interface, both neural recording and brain stimulation play crucial roles in addressing a wide range of enhancement and therapeutic challenges (Shabani et al., 2023), including improving decision-making, improving learning efficiency, treating neurological disorders, intervening mental health, *etc.* For deep brain detection and regulation, integrating miniaturized nanodevices to create high-throughput implantable neural interfaces may enable high resolution neural recording and stimulation (Liu et al., 2020; Ranke et al., 2024). For example, by using a custom 130-nm CMOS fabrication processes, 960 recording sites were integrated on a single, 10-mm long, non-tapered shank with 70 × 20-μm cross-section (Jun et al., 2017). Also, higher integration density makes it possible to provide more functions in a limited space, like bidirectional communication and multimodal modulation and detection of neuronal activity, which are still very challenge but critical for understanding and interacting with the brain. Additionally, flexible neural interfaces are expected to overcome the limitations of traditional neurotechnology to minimizes damage to delicate brain tissue by conforming to the brain's natural movement and shape, allowing for more stable and long-term neural signal recording and stimulation compared to rigid implants (Zhu et al., 2024).

Quantum phenomena and nanoscale mechanisms

At the nanoscale, quantum phenomena dominate the behavior of materials and devices, providing new opportunities for innovation. Understanding and exploring quantum conductance, electrochemical dynamics, and ionic transport in nanoscale systems are critical for developing next-generation devices such as memristors (Kumar et al., 2022) and quantum computers (de Leon et al., 2021). These advancements not only expand our fundamental knowledge of quantum mechanics but also enable their practical applications in secure communication, high-performance computing, and energy-efficient electronics. In addition, cryogenic nanoelectronics are noteworthy for overcoming low-temperature circuit design challenges for quantum computing (Olšteins et al., 2023; Shiomi and Uchida, 2024).

Conclusion

Innovation enabled by nanodevices will play a major role in multiple fields, to name just a few, that are driving a technological revolution beyond traditional boundaries. From brain-inspired computing to quantum devices, nanotechnology is providing solutions to global challenges in healthcare, energy, and sustainability. By addressing critical challenges related to scalability, fabrication, and integration, their convergence will bring new possibilities for innovation, creating a future where smart, adaptive, and sustainable technologies are seamlessly integrated into our daily lives. By investing in these areas, we are not only advancing science and engineering, but also shaping a better, more connected world.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YH: Writing – original draft, Writing – review and editing.

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