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Smart Materials for Next-Generation Electronics and Energy Storage

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ABSTRACT

Smart materials have emerged as a transformative class of materials that respond dynamically to external stimuli such as temperature, light, pressure, and electrical or magnetic fields. These materials are driving innovations in next-generation electronics and energy storage, enabling the development of flexible electronics, self-healing devices, and high-performance energy storage systems. This review explores recent advancements in smart materials, including shape-memory alloys, piezoelectric materials, conductive polymers, phase-change materials, and nanomaterials. We also discuss their applications in wearable electronics, self-powered sensors, advanced batteries, and supercapacitors. Finally, we address the challenges and future research directions to harness the full potential of smart materials in modern technology.

Keywords: Smart Material, Nano Electronics, Energy Storage, Wearable and Flexible Electronics.

I. INTRODUCTION

The rapid advancement of modern technology has significantly increased the demand for high-performance, sustainable, and energy-efficient electronic and energy storage devices. The widespread adoption of portable consumer electronics, electric vehicles (EVs), renewable energy systems, and Internet of Things (IoT) devices has highlighted the limitations of conventional materials, which often lack the necessary flexibility, adaptability, and long-term durability required for next-generation applications [1], [2]. Traditional materials used in electronic and energy storage devices struggle to meet the growing needs for miniaturization, high energy density, and prolonged operational lifespans. These challenges have led researchers to explore the development and integration of smart materials, which possess the ability to actively respond to external stimuli such as temperature, pressure, light, magnetic fields, and electrical signals. Smart materials, including shape-memory alloys, piezoelectric materials, conductive polymers, and nanomaterials, offer enhanced performance characteristics, such as self-healing capabilities, real-time adaptability, and improved energy efficiency [3]. Their incorporation into modern electronic and energy storage technologies not only enhances device functionality but also promotes sustainability by reducing material wastage and extending the lifespan of components. Consequently, the exploration and advancement of smart materials have become crucial for the development of future electronic and energy storage devices, ensuring they meet the growing demands of efficiency, reliability, and environmental sustainability [4].

These materials possess unique properties, such as:

- Self-healing abilities to repair microcracks and enhance device longevity
- Shape-memory effects to return to pre-defined forms, enabling reconfigurable and flexible electronics
- Energy-harvesting capabilities to generate power from mechanical, thermal, or electromagnetic energy
- Such features make smart materials highly versatile for applications in flexible electronics, biomedical devices, and high-capacity energy storage systems.

The Role of Smart Materials in Next-Generation Electronics:

Smart materials have emerged as key enablers of advanced electronics, allowing devices to be flexible, transparent, self-powered, and adaptive to environmental changes. Unlike conventional materials, which are static and non-responsive, smart materials dynamically interact with their surroundings, improving the efficiency, functionality, and durability of electronic systems.

Some of the most prominent applications of smart materials in electronics include:

Flexible and stretchable circuits that can bend and conform to different shapes without breaking.

Transparent conductive materials used in OLED (organic light-emitting diode) displays and touchscreens

Self-powered sensors and wearables that generate energy from motion, heat, or light.

For example, piezoelectric materials generate an electrical charge when subjected to mechanical stress, enabling self-powered wearable devices such as health-monitoring smartwatches. Similarly, conductive polymers like PEDOT:PSS (Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate) provide flexibility and electrical conductivity for bendable displays and electronic skins.

The integration of nanotechnology into smart materials has further improved their electrical, mechanical, and thermal properties, allowing for the development of ultra-thin, highly efficient electronic components. Moreover, artificial intelligence (AI) and machine learning algorithms are being employed to optimize smart material properties, enhancing their adaptability and efficiency in real-time applications.

The Role of Smart Materials in Energy Storage:

The growing reliance on renewable energy sources, portable electronics, and electric transportation has created an urgent need for high-performance, long-lasting, and sustainable energy storage systems. Conventional lithium-ion batteries and supercapacitors, while widely used, suffer from limitations such as limited charge capacity, slow charging speeds, and environmental concerns related to toxic materials [5].

Smart materials are revolutionizing energy storage technologies by introducing:

- High-efficiency batteries with improved charge-discharge cycles and energy density.
- Self-charging supercapacitors that harvest energy from vibrations or sunlight.
- Solid-state energy storage systems with enhanced safety and performance For instance, graphene-based supercapacitors exhibit ultrafast charging speeds and high energy storage capacity, making them ideal for next-generation electric vehicles and smart grids. Similarly, phase-change materials (PCMs) are being utilized to manage heat dissipation in batteries, improving thermal stability and preventing overheating.

Federated with AI-driven energy management systems, these smart storage solutions contribute to greater efficiency in power distribution and consumption, reducing energy waste and promoting sustainable energy usage.

II. TYPES OF SMART MATERIALS FOR ELECTRONICS AND ENERGY STORAGE

The rapid evolution of smart materials has enabled the development of high-performance, adaptive, and energy-efficient electronic devices and storage systems. These materials possess unique physical, chemical, and electrical properties that allow them to respond dynamically to external stimuli such as heat, pressure, electricity, and mechanical stress. This section explores different categories of smart materials and their applications in electronics and energy storage [6], [7], [8], [9].

Shape-Memory Materials for Adaptive Electronics:

Overview

Shape-memory materials, including shape-memory alloys (SMAs) and shape-memory polymers (SMPs), can return to a pre-defined shape when exposed to external stimuli such as heat, light, an electric field, or mechanical stress. These materials exhibit a reversible phase transition, allowing them to be programmed and reconfigured multiple times without degradation.

Key Applications

Flexible Circuits and Reconfigurable Electronics:

- Shape-memory materials enable the development of flexible, stretchable circuits that can be bent, twisted, or stretched while maintaining their electrical conductivity.
- These materials help in self-repairing electronic components, ensuring longer lifespans for wearable devices and soft robotics.

Self-Healing Electronic Components:

- Smart polymers with shape-memory properties can autonomously repair minor cracks and damages, enhancing the durability of printed circuit boards (PCBs), sensors, and flexible displays.
- This technology reduces electronic waste and improves the sustainability of electronic devices.

Biomedical Devices and Artificial Muscles:

- SMAs are used in medical implants, such as self-expanding stents, which adapt to changes in blood vessel conditions.
- Shape-memory polymers are being explored for soft robotic actuators that mimic biological muscle movements.

Recent Advancements

- Nanostructured SMAs with improved response time and energy efficiency have enhanced their adaptability for next-generation wearable electronics and implantable medical devices.
- The combination of shape-memory materials with conductive nanomaterials has led to the development of smart textiles capable of changing shape while remaining electronically active.

Piezoelectric and Triboelectric Materials for Energy Harvesting:

Piezoelectric materials generate electricity when subjected to mechanical stress, while triboelectric materials generate charge through friction. These materials are crucial for self-powered sensors, IoT devices, and energy-harvesting systems, reducing dependence on conventional batteries.

Key Applications

Self-Powered Sensors in Wearable Electronics and IoT Devices:

- Piezoelectric materials convert body movements into electrical energy, enabling self-powered health monitoring devices such as heart rate sensors and glucose monitors.
- Triboelectric generators (TENGs) can be integrated into smart textiles and flexible electronics to power small electronic circuits.

Energy-Harvesting Systems:

- Piezoelectric nanogenerators (PENGs) capture ambient vibrations from wind, water, or human movement to produce renewable energy.
- Triboelectric materials are used in footstep-powered charging mats and motion-powered smartwatches.

Flexible and Stretchable Nanogenerators:

- These materials are used in bendy electronic skins (e-skins) and implantable medical devices, allowing continuous energy generation from slight movements [10].
- Piezoelectric MEMS (Microelectromechanical Systems) are being explored for wireless charging of low-power electronic devices.

Recent Advancements

- 2D piezoelectric materials, such as molybdenum disulfide (MoS_2) and graphene-based composites, have

demonstrated higher energy conversion efficiencies, improving their integration into compact, low-power electronic devices.
- Hybrid piezoelectric-triboelectric systems are being developed to maximize energy harvesting from multiple mechanical inputs, enhancing self-sustaining electronic ecosystems.

Conductive Polymers and Transparent Electronics:

Conductive polymers such as polyaniline (PANI), polypyrrole (PPy), and PEDOT:PSS offer a combination of electrical conductivity, flexibility, and transparency, making them ideal for next-generation electronic applications.

Key Applications

Flexible Touchscreens and Stretchable Displays:

- Conductive polymers are used in bendable OLED displays and foldable smartphones, providing flexibility without compromising electrical properties.
- Transparent conductive coatings enable high-resolution, flexible touchscreens in consumer electronics.

Bioelectronics and Implantable Medical Devices

- Conductive polymers facilitate bio-signal sensing and neural interfaces, enhancing wearable health devices.
- These materials are used in implantable pacemakers, brain-machine interfaces, and biosensors for continuous health monitoring.

Printed Electronic Circuits for Smart Textiles

- Conductive polymers allow for low-cost, flexible printed circuit boards (PCBs), making them ideal for wearable electronics, smart textiles, and interactive clothing.
- Their lightweight nature enhances energy efficiency in IoT applications.

Recent Advancements

- Improved doping techniques have enhanced the electrical conductivity of PEDOT:PSS, making it a viable alternative to indium tin oxide (ITO) for flexible electronics.
- Hybrid polymer-nanoparticle composites are being developed for improved durability and charge transport efficiency in wearable and implantable electronics.

Phase-Change Materials (PCMs) for Data Storage and Cooling:

PCMs exhibit reversible phase transitions between amorphous and crystalline states, making them useful for non-volatile memory devices, thermal management, and adaptive optics.

Key Applications

- Next-Generation Non-Volatile Memory (PCM-RAM)

Phase-change memory (PCM) offers faster switching speeds and higher endurance than traditional flash memory, making it ideal for AI and big data applications.

Thermal Management in Electronic Devices

- PCMs regulate heat dissipation in batteries, smartphones, and processors, improving device efficiency and lifespan.
- Graphene-enhanced PCMs are being explored for cooling high-performance computing systems.

Adaptive Optical and Photonic Applications

Chalcogenide-based PCMs enable tunable photonic circuits and reconfigurable optical components, improving the performance of optical communication networks.

Recent Advancements

- $Ge_2Sb_2Te_5$ (GST)-based PCMs are being integrated into high-density neuromorphic computing architectures, enhancing AI-driven processing efficiency.
- Hybrid PCM-nanocomposite materials are improving the thermal stability and data retention capabilities of next-gen storage devices.

Nanomaterials for High-Performance Energy Storage

Nanomaterials such as graphene, MXenes, and carbon nanotubes (CNTs) are revolutionizing energy storage technologies, enabling higher charge storage capacity, faster charge transfer, and enhanced mechanical stability.

Key Applications

High-Capacity Lithium-Ion Batteries (Li-ion)

- Graphene-based electrodes enhance battery performance by reducing charging time and increasing energy density.
- Supercapacitors with Ultrafast Charging Capabilities
- MXene-based supercapacitors exhibit high power density and long cycle life, making them ideal for electric vehicles and smart grids.

Next-Gen Solid-State Batteries

- Nanostructured solid-state electrolytes improve safety, longevity, and performance in energy storage systems.

Recent Advancements

Graphene-silicon anodes are being explored for 10x higher energy densities in lithium-ion batteries.

Flexible supercapacitors with CNT-enhanced electrodes are enabling wearable energy storage solutions.

These advancements in smart materials are driving breakthroughs in electronics and energy storage, paving the way for more efficient, adaptive, and sustainable technologies.

III. EMERGING APPLICATIONS OF SMART MATERIALS

To Smart materials are revolutionizing modern technology by enabling self-adaptive, energy-efficient, and high-performance electronic and energy storage systems. These materials have found significant applications in wearable technology, self-healing electronics, high-efficiency energy storage, and the Internet of Things (IoT). This section explores the cutting-edge applications of smart materials and their impact on next-generation technologies [11], [12].

Wearable and Flexible Electronics:

The integration of smart materials into wearable and flexible electronics has enabled the development of lightweight, stretchable, and energy-efficient devices. These materials provide mechanical flexibility while maintaining excellent electrical and thermal conductivity, allowing for innovations in bendable displays, smart textiles, and flexible energy storage.

Key Applications

Stretchable and Foldable Displays

- Transparent conductive materials such as silver nanowires, graphene, and conductive polymers have enabled the creation of foldable OLED displays in smartphones and tablets.
- Electrochromic materials allow displays to change color in response to voltage, enhancing low-power screen technologies.
- Next-gen e-paper displays use flexible substrates to enable rollable screens with minimal energy consumption.

Smart Textiles with Embedded Sensors:

- Conductive fibers and e-textiles incorporate embedded sensors for real-time health monitoring, tracking parameters such as heart rate, body temperature, and hydration levels.
- Piezoelectric nanofibers integrated into clothing generate electricity from body movements, powering wearable IoT devices.
- Shape-memory textiles adjust their structure for adaptive clothing that regulates body temperature.

Flexible Batteries and Energy Storage for Wearables

- Solid-state lithium-ion batteries with stretchable electrodes provide safe and durable energy storage for smartwatches and fitness trackers.
- Flexible supercapacitors using graphene and MXenes enable fast-charging, lightweight power solutions.
- Bio-compatible batteries designed for implantable devices utilize self-healing electrolytes, enhancing battery longevity and safety.

Recent Advancements

Researchers have developed graphene-based conductive textiles that offer high flexibility and conductivity, making them ideal for wearable medical diagnostics.

Hybrid stretchable circuits using liquid metal and elastomers are being explored for next-gen on-skin electronic devices.

Self-Healing and Sustainable Electronics:

The introduction of self-healing materials in electronics has significantly enhanced device longevity, reliability, and sustainability. These materials autonomously repair microcracks and structural damage, reducing e-waste and improving device durability.

Key Applications

Long-Lasting Consumer Electronics:

- Self-healing coatings protect smartphone screens, tablets, and laptops from minor scratches, extending their usability.
- Conductive polymers with self-healing properties ensure flexible circuits recover from mechanical stress, preventing performance degradation in wearable electronics.

Military and Aerospace Applications

- Self-healing electronic coatings protect military-grade equipment from harsh environmental conditions.
- Polymers infused with microcapsules of conductive ink automatically restore electrical pathways in drones and satellites after damage.
- Self-healing batteries ensure reliability in extreme environments such as deep space missions and combat zones.

Sustainable Electronic Devices

- Smart materials reduce electronic waste by extending the lifespan of consumer electronics, thereby minimizing resource consumption.
- Biodegradable electronics use self-healing organic materials to create eco-friendly disposable sensors.
- Solar-powered self-healing circuits ensure uninterrupted function in remote IoT networks and smart cities.

Recent Advancements

Scientists have developed graphene-infused self-healing materials that restore conductivity within seconds, improving circuit longevity.

Bio-inspired self-healing polymers mimic the healing mechanisms of human skin, allowing printed electronics to repair themselves multiple times.

High-Efficiency Energy Storage Systems:

Smart materials are playing a crucial role in next-generation energy storage, enabling higher energy densities, faster charging, and improved safety. These advancements are reshaping battery technology and energy harvesting.

Key Applications

Smart Batteries with Adaptive Charge Cycles:

- AI-enhanced smart batteries analyze user behavior to optimize charging cycles, prolonging battery lifespan in smartphones, laptops, and electric vehicles.
- Shape-memory materials in batteries prevent structural degradation, improving long-term performance.
- Graphene-based battery electrodes enable high-capacity, ultra-fast charging solutions for portable electronics.

Self-Charging Energy Storage Systems:

- Piezoelectric and triboelectric nanogenerators (TENGs and PENGs) convert mechanical energy into electricity, enabling continuous self-charging in wearables and IoT devices.
- Hybrid energy storage systems integrate piezoelectric nanomaterials with solar and thermal energy harvesting, ensuring sustainable power generation.

Ultrafast Charging Supercapacitors for Electric Vehicles (EVs)

- Graphene-based supercapacitors enable rapid charging within seconds, significantly improving energy storage solutions for EVs.
- MXene-enhanced supercapacitors provide high power density while maintaining long cycle life and durability.
- Carbon nanotube (CNT) electrodes increase charge retention, making supercapacitors ideal for hybrid energy systems.

Recent Advancements

Researchers have developed solid-state lithium-metal batteries with self-healing electrolytes, improving safety and longevity.

Hybrid nanomaterial electrodes are enhancing supercapacitor performance, making them viable for next-gen power grids and smart cities.

Internet of Things (IoT) and Smart Sensors:

Smart materials are essential for IoT and Industry 4.0, enabling the development of autonomous, energy-efficient, and adaptive sensors that optimize industrial and environmental monitoring.

Key Applications:

Energy-Autonomous IoT Devices:

- Self-powered IoT devices harvest energy from the environment using piezoelectric, solar, and thermoelectric nanogenerators.
- AI-driven adaptive materials regulate energy consumption in IoT networks, ensuring efficient data transmission in smart cities.

Smart Sensors for Industrial Automation

- Wearable chemical and gas sensors detect environmental pollutants in real time, improving air quality monitoring.
- Self-healing electronic skin (e-skin) enables robotic hands and prosthetic limbs to sense pressure, temperature, and damage autonomously.
- Nano-biosensors embedded in smart factories optimize predictive maintenance and reduce downtime.

AI-Driven Adaptive Materials for Real-Time Response

- Programmable smart surfaces adjust their properties in response to light, heat, and humidity, improving energy efficiency in IoT systems.
- AI-integrated shape-memory materials allow adaptive antennas for 5G and next-gen communication networks.
- Self-learning materials optimize structural health monitoring in infrastructure and industrial automation.

Recent Advancements

- Researchers have developed nanoengineered piezoelectric sensors capable of detecting low-frequency vibrations, enhancing seismic monitoring and industrial safety.
- Graphene-enhanced IoT devices are improving wireless communication efficiency while reducing power consumption.

IV. CHALLENGES AND FUTURE DIRECTIONS

The widespread adoption of smart materials in next-generation electronics and energy storage systems faces several challenges, including material stability, scalability, AI integration, and environmental sustainability. Addressing these issues requires interdisciplinary research and innovative solutions to ensure efficient, cost-effective, and eco-friendly applications of smart materials.

Material Stability and Longevity:

One of the critical challenges in deploying smart materials is their degradation over time, which directly affects their performance, efficiency, and durability. Factors such as mechanical stress, temperature fluctuations, exposure to moisture, and chemical instability can reduce the lifespan of these materials. Ensuring long-term stability is essential for applications in wearable electronics, energy storage devices, and autonomous sensors.

Key Challenges

Structural Degradation:

- Shape-memory alloys (SMAs) experience fatigue and phase instability, reducing their ability to return to their original form after repeated use.
- Conductive polymers, such as PEDOT:PSS, suffer from oxidation and reduced conductivity over time, affecting their efficiency in flexible electronics.
- Piezoelectric and triboelectric nanogenerators (TENGs and PENGs) degrade due to mechanical wear, limiting their long-term energy-harvesting capabilities.

Electrochemical Instability in Energy Storage:

- Lithium-ion batteries (Li-ion) experience electrode degradation and electrolyte breakdown, reducing energy density over multiple charge cycles.
- Supercapacitors using nanomaterials like graphene face issues with surface degradation and ion diffusion limitations, affecting charge retention.

Future Research Directions

Nanostructured Materials: Developing nanostructured composites and hybrid materials can enhance mechanical strength and chemical stability.

Self-Healing Materials: Incorporating self-repairing polymers and coatings into electronic circuits and battery electrodes can extend lifespan.

Sustainable Alternatives: Research into biodegradable conductive polymers and eco-friendly battery electrolytes will promote green electronics.

Scalability and Manufacturing Challenges:

Despite the promising potential of smart materials, large-scale commercial production remains a significant challenge due to high fabrication costs, complex synthesis processes, and limited availability of raw materials. Scalability issues hinder industrial adoption, especially in consumer electronics, healthcare, and energy storage sectors.

Key Challenges

High Production Costs

The synthesis of graphene, MXenes, and carbon nanotubes (CNTs) is expensive and energy-intensive, limiting widespread adoption in flexible batteries and sensors.

Shape-memory materials require precise alloy compositions and fabrication techniques, making mass production costly.

Complex Manufacturing Techniques

Piezoelectric nanogenerators rely on precise nanoscale engineering, requiring advanced fabrication techniques such as chemical vapor deposition (CVD) and atomic layer deposition (ALD).

Conductive polymers and organic semiconductors suffer from low uniformity and process instability, affecting device performance.

Material Availability and Supply Chain Issues

Rare earth elements (REEs) used in some smart materials have limited global supply, creating economic and geopolitical challenges.

Sustainable alternatives to indium tin oxide (ITO) for transparent electronics are still under development, limiting scalable solutions for flexible displays.

Future Research Directions

Advanced Manufacturing Technologies:

3D printing and roll-to-roll fabrication can enable large-scale, low-cost production of flexible circuits, sensors, and wearable electronics.

Scalable electrochemical deposition techniques can improve the efficiency of self-healing conductive polymers and transparent conductors.

Alternative Materials for Mass Production:

Developing abundant and cost-effective materials (e.g., copper-based alternatives to silver nanowires) can reduce reliance on scarce resources.

Organic and biodegradable materials can replace traditional metal-based components, improving sustainability.

Automated and AI-Driven Manufacturing:

AI-enhanced material synthesis can optimize production processes, reducing waste and improving efficiency.

Robotic assembly techniques can streamline the fabrication of complex smart material-based devices.

Integration with AI and Advanced Computing:

The next generation of smart materials will require integration with Artificial Intelligence (AI), quantum computing, and neural interfaces to achieve adaptive, real-time performance. AI can significantly enhance material design, property prediction, and functional optimization, leading to breakthroughs in electronics, energy storage, and biomedical applications.

Key Challenges

AI-Driven Smart Material Design:

- Traditional material discovery methods are time-consuming and expensive.
- AI can predict material properties and optimize compositions, but integrating AI with material synthesis remains challenging.

Quantum Computing for Material Discovery:

- Quantum simulations can accelerate the discovery of new conductive polymers, nanomaterials, and piezoelectric compounds.
- The challenge lies in developing quantum algorithms that accurately model material behavior at atomic and molecular levels.

Neural Interfaces and Bioelectronics

Smart materials must be biocompatible, flexible, and responsive for integration into brain-machine interfaces (BMIs) and medical implants.

Current limitations include signal stability, energy efficiency, and long-term biocompatibility.

Future Research Directions

AI-Optimized Smart Materials:

Machine learning models can be trained to predict and enhance material properties, improving the efficiency of self-healing, shape-memory, and conductive materials.

AI-assisted material synthesis platforms will enable faster discovery and optimization of novel energy storage materials.

Quantum-Assisted Simulations:

Quantum computing can simulate material behavior at the nanoscale, leading to the discovery of superior battery electrodes, high-performance semiconductors, and ultra-thin transparent conductors.

Biocompatible Smart Materials for Neural Interfaces:

Developing graphene-based neural electrodes and bioelectronics can advance brain-machine communication and prosthetics.

Self-adaptive hydrogels can enable responsive drug delivery systems for medical applications.

Environmental and Ethical Considerations:

Overview

While smart materials improve technological efficiency, they also introduce environmental and ethical concerns related to e-waste, resource scarcity, and material toxicity. Ensuring the sustainability of smart materials requires a shift toward biodegradable alternatives, efficient recycling strategies, and green manufacturing.

Key Challenges

Electronic Waste (E-Waste) Accumulation

The short lifespan of smart electronics leads to excessive e-waste, contributing to global pollution.

Current recycling technologies struggle to recover nanomaterials and rare earth elements from discarded devices.

Resource Scarcity and Ethical Sourcing:

Many smart materials rely on rare metals (e.g., lithium, cobalt, indium) with limited global availability.

Mining these materials raises ethical concerns regarding labor exploitation and environmental damage.

Toxicity and Biodegradability

Some nanomaterials (e.g., MXenes, CNTs, quantum dots) pose potential toxicity risks to humans and the environment.

Developing biodegradable and non-toxic smart materials is essential for sustainable adoption.

Future Research Directions

Green and Biodegradable Smart Materials:

Research into bio-based conductive polymers and organic nanomaterials can reduce reliance on synthetic chemicals.

Compostable electronics using cellulose-based substrates can minimize e-waste accumulation.

Advanced Recycling Technologies:

AI-powered recycling systems can improve the extraction of precious metals and nanomaterials from discarded electronics.

Electrochemical recycling methods can enable sustainable recovery of battery and supercapacitor materials.

V. CONCLUSIONS

Smart materials are revolutionizing next-generation electronics and energy storage by enabling flexible, self-healing, and energy-efficient devices. From wearable electronics to high-performance batteries, their applications are vast and transformative. However, challenges related to material stability, scalability, and environmental impact must be addressed to unlock their full potential. Future research, particularly at the intersection of nanotechnology, AI, and sustainable materials, will play a crucial role in shaping the next era of smart material-based technologies.

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