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Research on the Application of Novel Perovskite Materials in Wide-Bandgap Power Electronic Devices

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Abstract: Perovskite materials exhibit tremendous potential in the field of power electronic devices due to their wide bandgap characteristics, high carrier mobility, tunable bandgap, and low-temperature solution processability. This paper reviews the structural classifications of perovskite materials (such as ABX_3-type metal halides and lead-free perovskites) and their electronic and optical properties (including high breakdown field strength and low defect density). It further discusses recent advances in their applications in power devices, including MOSFETs, HEMTs, Schottky diodes, and PN junction rectifiers. Studies indicate that device performance can be significantly enhanced through compositional optimization, interface engineering, and defect passivation; however, challenges related to stability and toxicity remain. Looking ahead, the development of lead-free perovskites and heterojunction design will be key research focuses to advance the practical application of perovskites in efficient and low-cost power electronic devices.

Keywords: Perovskite, Tunable Bandgap, Low-Temperature Solution Processability, Power Devices

1. Introduction

With the rapid development of modern electronic technology, power electronic devices, as the core components for power conversion and control, require significant performance improvements. Wide-bandgap semiconductor materials possess excellent characteristics such as high breakdown field strength, high ion mobility, and high thermal conductivity. These features make them a key foundation for manufacturing high-performance power electronic devices, with enormous application potential in power systems, electric vehicles, and renewable energy generation.

Silicon carbide (SiC) and gallium nitride (GaN) are representatives among wide-bandgap semiconductors. The strong affinity between SiC and silicon allows SiC-based devices to adopt silicon device structures and processes. SiC devices demonstrate high operational stability, exhibit much lower threshold voltage shifts, and avoid issues related to dynamic on-resistance effects [1]. They are suitable for harsh environments, with lifespan and short-circuit robustness comparable to those of insulated-gate bipolar transistors (IGBTs). In contrast, the technological advantages of GaN mainly manifest in high-electron-mobility transistors (HEMTs). The presence of a natural two-dimensional electron gas (2DEG) enables lower on-resistance and higher switching frequencies [2].

Novel perovskite materials have developed rapidly in recent years. Their wide bandgap characteristics provide a high breakdown field and low conduction loss. High carrier mobility supports high-frequency switching and reduces switching losses. The tunable electronic properties

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allow flexible adjustment of the perovskite bandgap width, and their low-temperature solution-processable film formation reduces manufacturing costs [3], giving them unique advantages in the field of power devices. Therefore, novel perovskite materials hold great potential in the wide-bandgap power electronics domain. This paper will elaborate on the classification and electronic and optical properties of perovskite materials, review the latest research progress in power electronic devices, and introduce development trends and future prospects.

2. Basic properties and classification of perovskites

The crystal structure of perovskite originates from the cubic prototype of the natural mineral $CaTiO_3$, with an ideal molecular formula of ABX_3. It can be viewed as a framework formed by corner-sharing BX_6 octahedra, as shown in Figure 1. The A-site is typically occupied by larger cations located at the eight corners of the cube. Common A-site cations include organic cations (such as methylammonium ion $CH_3NH_3^+$) or inorganic cations (such as cesium ion Cs^+). This structure exhibits adaptability to bond length mismatches in the A–X and B–X bonds by means of BX_6 octahedral rotation distortions or ionic displacement, transforming into lower-symmetry structural forms. The B-site is usually occupied by smaller metal cations located at the center of the cube, with common ions including tin (Sn^{2+}), lead (Pb^{2+}), and germanium (Ge^{2+}). The X-site is generally occupied by halide anions (such as I^-, Br^-, Cl^-), situated at the face centers of the cube.

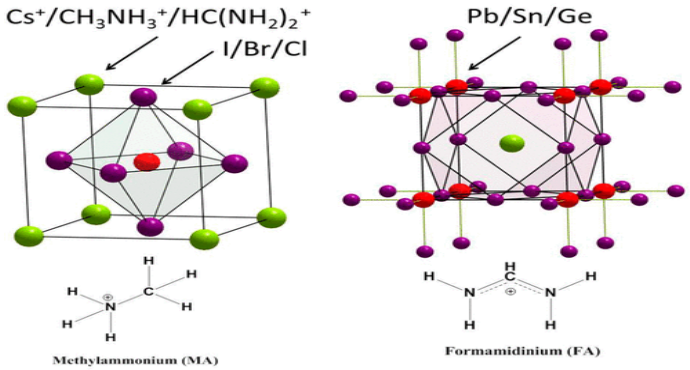

Figure 1: Schematic diagram of typical perovskite structure [4]

Metal halide perovskites are typically based on the ABX_3 crystal structure (where B is a metal ion and X is a halide ion). $CsPbBr_3$, a common metal halide perovskite material, has a bandgap of approximately 2.3 eV (corresponding to the green light spectrum), which can be tuned to 1.7–2.9 eV through halide substitution (Cl^-, I^-), thereby achieving spectral coverage [5]. Films can be prepared via solution processing, with antisolvent vapor diffusion or Bridgman methods often employed to fabricate high-purity single crystals for radiation detection. Its excellent solution processability makes it suitable for low-cost, large-area fabrication methods such as spin coating and inkjet printing. $FAPbI_3$ is an organic–inorganic hybrid perovskite material. Due to its narrow bandgap (1.48 eV) [6], high efficiency, and low cost, it has become a core candidate for surpassing solar cell efficiency limits. Takeru Bessho, Hiroshi Segawa, and others used ligand-modified $FAPbI_3$ nanoparticles (NPs) as precursors for the light-absorbing layer, balancing crystallinity and defect passivation to effectively resolve phase instability and defect state issues [7].

$CH_3NH_3PbBr_3$ (abbreviated as $MAPbBr_3$) is also an organic–inorganic hybrid perovskite material. It has a bandgap of 2.3 eV, corresponding to green light absorption/emission, making it suitable for green light LEDs [8]. Additionally, it exhibits a high optical absorption coefficient suitable for ultra-thin optoelectronic devices. Its fast response time (nanosecond scale) and high sensitivity make it applicable for visible light detection. However, migration of Pb^{2+} ions leads to device hysteresis,

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phase segregation, and performance degradation. Ion migration is exacerbated under electric fields, illumination, or high temperatures, constituting a major bottleneck for long-term stability. A multi-alkali metal synergy strategy, employing a "lattice anchoring + interface passivation" dual-path approach to suppress ion migration, has effectively addressed this issue [9].

Most of the above metal halide perovskites are lead-based, containing soluble Pb^{2+} ions that are harmful to the environment and human health, thus limiting their large-scale application. In response to sustainable development demands, lead-free/environmentally friendly perovskites have been extensively studied. Lead-free perovskites mainly include tin (Sn^{2+})-based, bismuth (Bi^{3+})-based, germanium (Ge^{2+})-based perovskites, and double perovskites ($A_2B'B''X_6$), among others. Most effectively address toxicity and environmental issues but still face challenges such as low efficiency, poor stability, and difficult fabrication [10]. $CsSnI_3$ is a lead-free tin-based perovskite material. Its universal perovskite characteristics and low toxicity make it a promising candidate to replace lead-based perovskites. However, problems remain. Sn^{2+} is easily oxidized to Sn^{4+} in air, which adversely affects device performance, and the material is sensitive to phase changes, readily converting to an inactive yellow phase under high temperature or humidity [11]. I. Chabri, Y. Benhouria, and others used the degradation product γ-$CsSnI_3$'s Cs_2SnI_6 as a protective layer, providing both a physical barrier and band structure modulation, effectively suppressing Sn^{2+} oxidation [12]. $BaZrO_3$ (BZO) is an oxide perovskite material that offers high-temperature stability and wide-temperature-range dielectric properties. However, pure BZO has a relatively low dielectric constant; introducing $Bi(Zn_{1/2}Ti_{1/2})O_3$ via solid-state reaction can enhance its ferroelectric relaxation characteristics [13].

3. Electronic and optical properties of perovskite materials

Certain perovskite materials, such as the fully inorganic perovskite $CsPbBr_3$, have a relatively large bandgap (about 2.3 eV) and are classified as wide-bandgap materials. They are suitable for use as top cells in tandem solar cells and ultraviolet photonic devices. Wide-bandgap materials can surpass the Shockley–Queisser limit, thereby improving tandem cell efficiency (for example, perovskite/silicon tandem cells with efficiency greater than 33%). The highest power conversion efficiency (PCE) of tandem devices realized by six-junction configurations has exceeded 47% [14].

Perovskite materials feature tunable bandgaps, offering broad application prospects in optoelectronic devices. For instance, by adjusting the bandgap width, the spectral response range and magnitude of solar cells can be optimized [15] ; alternatively, light-emitting diode (LED) devices with specific emission wavelengths can be designed.

Thanks to their high electron mobility, high carrier concentration, and low defect density, perovskite materials demonstrate excellent performance in fields such as LEDs, solar cells, and field-effect transistors (FETs) [16]. Tin dioxide (SnO_2), due to its high transmittance, high electron mobility, good ultraviolet stability, and low-temperature processability, is widely used as an electron transport material in perovskite solar cells (PSCs) on a large scale [17]. Xi Jiahao et al. used SnO_2 as the electron transport layer (ETL) and employed a dual-functional modification strategy to simultaneously achieve defect passivation and energy level regulation. The comprehensive characterization of the morphology, electrical properties, and photoelectric conversion performance of the perovskite solar cells is shown in Figure 2. A high carrier concentration means more charge carriers are available for conduction within the material, directly enhancing the material's conductivity and improving direct current power generation performance [19]. In FETs, a high carrier concentration can increase the device's on/off ratio and transconductance. However, an excessively high carrier concentration may exacerbate Auger recombination. Nevertheless, the low defect density of perovskites effectively reduces such recombination [20]. Low defect density is a critical advantage of perovskite materials, as defects (such as grain boundaries, vacancies, and interstitial atoms) are the main centers for carrier recombination. Liu Ye et al. used 3-(decyl dimethyl ammonium)-propane

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sulfonate inner salt (DPSI) as an additive ligand in solution, growing high-quality single-crystal perovskites through this method. The trap density in these crystals is 23 times lower than that without DPSI [21]. A low defect density reduces ion migration and material degradation, slowing device aging; it also makes perovskite films more uniform, decreases leakage current, and improves device reliability and reproducibility [22].

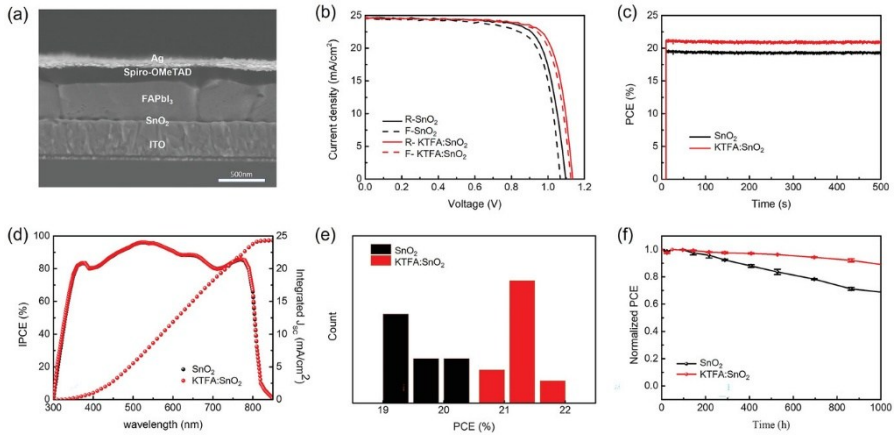

Figure 2: Comprehensive characterization of morphology, electrical properties, and photoelectric conversion performance of perovskite solar cells [18]

Although perovskite materials face challenges such as stability and interface defects in their application to wide bandgap power electronic devices, their advantages—such as tunable bandgaps, high carrier mobility [23], and solution processability [24] —make them promising candidates for next-generation power semiconductors. Professor Yang Yiming's research group precisely controlled the axial halide composition gradient in nanowires through a source-limited anion exchange method, thereby optimizing carrier transport and photophysical properties. The group successfully fabricated perovskite nanowires with ultralong compositional gradients [25].

The high ionic mobility of perovskite materials can reduce conduction loss, enhance voltage endurance and breakdown performance, and improve dynamic response speed. Bandara R. M. I. et al. developed a novel antisolvent formula (Sn^{2+} chelating agent + low polarity solvent), and through antisolvent engineering, increased the Hall mobility of films to 320 $cm^2/V{\cdot}s$ (originally 50 $cm^2/V{\cdot}s$) [26]. Rahman M. W. et al. introduced the ferroelectric material $BaTiO_3$ below the Schottky contact, which reduced SiN_x/AlGaN interface traps and increased the breakdown field strength from 2.5 MV/cm to 3.8 MV/cm [27]. Zhang Chi et al. constructed a $CsPbBr_3/MoS_2$ monolayer heterojunction, where electron transfer from the $CsPbBr_3$ conduction band to MoS_2 takes only 0.5 ps, and hole reverse transfer takes 2 ps. This photodetector achieves a conversion efficiency of 10^4 A/W (λ = 500 nm), which is 100 times higher than pure $CsPbBr_3$ devices. Relevant experimental images are shown in Figure 3.

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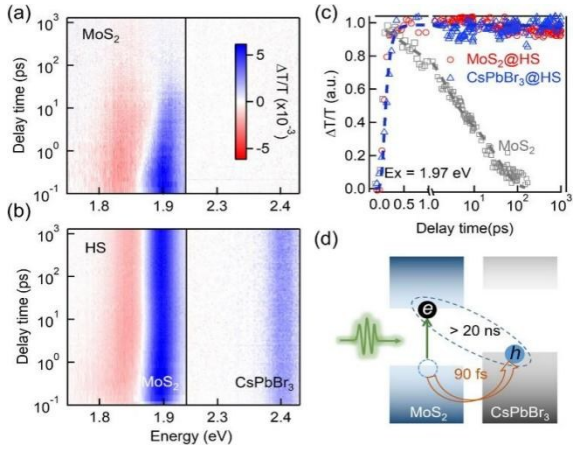

Figure 3: (a) Transient absorption (TA) 2D color map of monolayer MoS_2, (b) TA 2D color map of $CsPbBr_3/MoS_2$ heterojunction, (c) TA kinetic curves of MoS_2 (red circles) and $CsPbBr_3$ (blue triangles) in the heterojunction, (d) ultrafast interfacial hole transfer and interlayer electron-hole recombination processes [28]

The solution processing method of perovskites is compatible with lower temperatures and allows tunable bandgaps. Chen Bingbing et al. optimized the solution composition and precisely controlled the second-step spin-coating speed, achieving uniform composition and low-defect-density wide-bandgap perovskite films via a two-step sequential deposition method [29]. Peng Wei et al. proposed an innovative strategy using porous insulator contact (PIC) to suppress non-radiative recombination in perovskite solar cells (PSCs). Drift-diffusion simulations of cells with PIC showed about a 25% reduction in contact area, achieving a highest efficiency of 25.5% (certified stabilized efficiency of 24.7%) in p-i-n devices. In addition, this approach achieved low recombination, efficient charge extraction, and high stability [30].

4. Recent research progress of perovskite power devices

Perovskite power devices have made significant breakthroughs in recent years in terms of material design, device architecture, stability, and application scenarios, especially demonstrating great potential in high-voltage, high-frequency, and flexible domains. Perovskite-based MOSFETs (cross-sectional schematic, device structure, and working regions are shown in Figure 4) incorporate perovskite materials into the channel layer or gate dielectric layer of MOSFETs. The hybrid perovskite material $MAPbI_3$ ($CH_3NH_3PbI_3$) is the most extensively studied perovskite in perovskite field-effect transistors (Perovskite Field-Effect Transistor, PeFET) [31]. Mei et al. achieved dynamic balance of electron and hole mobilities at room temperature for the first time through electrostatic gate engineering, opening new pathways for the functional application of PeFETs [32]. Due to ion migration and interface defects, perovskite transistors generally suffer from current-voltage hysteresis and poor stability. Kim, Hyeong Pil et al. effectively resolved these issues by combining bulk molecular cross-linking with amine passivation at the interface as a synergistic passivation strategy [33]. Murali Gedda et al. proposed a novel memory transistor based on a Ruddlesden-Popper (RP) phase perovskite/organic small molecule blend system, cleverly combining the structural stability of RP phase and the charge regulation ability of organic molecules, which exhibits non-volatile memory and synaptic plasticity functions [34]. In recent years, most experiments on perovskite-based MOSFETs have focused on composition optimization, interface modification, defect passivation, and research on low-dimensional perovskites.

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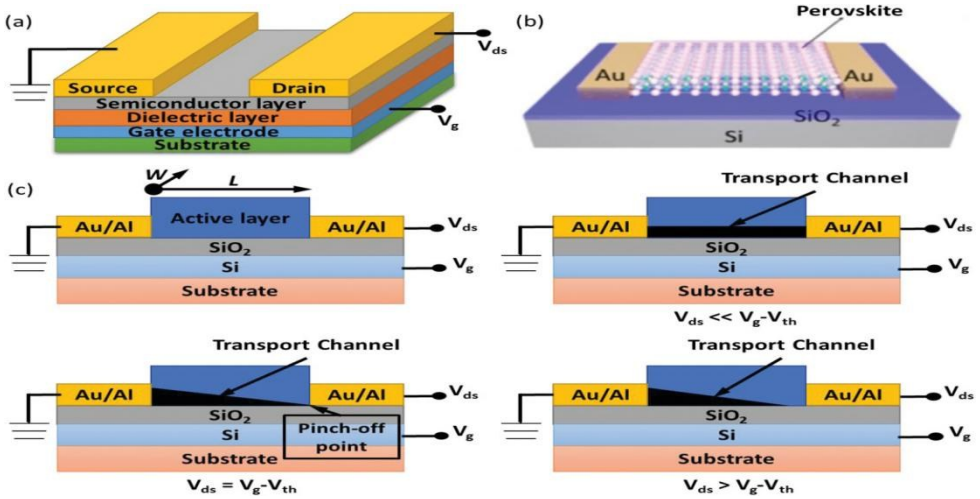

Figure 4: (a) Typical cross-sectional schematic of a FET; (b) perovskite FET device structure; (c) illustration of FET working regions: linear region, pinch-off onset region, saturation region [35]

High Electron Mobility Transistors (HEMTs) are field-effect transistors based on two-dimensional electron gas (2DEG) formed at heterojunctions, featuring high frequency, high power, and low noise characteristics [36]. Hong Xitong et al. replaced traditional gate dielectrics with 2D perovskites and utilized the AlGaN/GaN heterojunction to form 2DEG, achieving high mobility (>1000 $cm^2/(V \cdot s)$) [37]. $BaTiO_3$ is a perovskite-type ferroelectric material. Li Guanjie et al. successfully constructed a $BaTiO_3$/MgO/AlGaN/GaN/Si ferroelectric-semiconductor heterostructure using the pulsed laser deposition (PLD) method. Experiments showed that the space charge region at the BTO/GaN interface induces upward spontaneous ferroelectric polarization in the BTO film, verifying the feasibility of ferroelectric gate-enhanced HEMT devices [38]. Current research on perovskite-based HEMTs mainly focuses on developing new lead-free perovskite materials, 2DEG modulation, and device power characteristics.

Perovskite-based Schottky diodes are rectifying devices formed by metal-perovskite semiconductor contacts, operating based on the Schottky barrier between the metal and perovskite material [39]. Traditional formamidinium lead halide perovskite ($FAPbX_3$) thin-film devices suffer from poor environmental stability and many interface defects. Monisha Nayak et al. improved Schottky diode performance by using $FAPbX_3$ in the form of nanocrystals (NCs), employing surface ligand engineering and interface optimization [40]. O. Akinbami et al. systematically studied the effects of synthesis temperature and reaction time on the morphology, optical properties, and defect states of Cs_2ZnBr_4 NCs, applying optimized NCs to Schottky barrier devices. Compared to traditional 3D perovskites, 2D Cs_2ZnBr_4 NCs exhibit stronger environmental stability (RH 40%) for over 100 hours [41]. Compared with conventional Schottky diodes, perovskite-based devices feature low cost, solution processability, and excellent optoelectronic performance; however, their long-term stability and interface control still require breakthroughs.

PN junction rectifiers utilize the unidirectional conductivity of PN junctions to convert alternating current (AC) to direct current (DC), and can be divided into half-wave and full-wave rectifiers. Half-wave rectifiers typically use a single PN junction, allowing only half of the AC cycle to pass through; full-wave rectifiers consist of two or four diodes that convert both positive and negative half cycles of AC into DC current. Perovskite PN junction rectifiers achieve rectification through interface charge separation in perovskites. Li Yujiao et al. used p-type $MAPbI_3$ films for both light absorption and hole transport and formed a PN heterojunction with n-type titanium dioxide (TiO_2) as the electron transport layer. The constructed heterojunction perovskite cell reached a power conversion efficiency (PCE) of 10.43% [42]. Tim Schramm et al. developed a vacuum co-evaporation process enabling in-

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situ doping of perovskites and for the first time applied co-evaporation-doped perovskites in PN junction rectifiers, verifying interface quality and performance advantages [43]. Recent advances in perovskite PN junction rectifiers mainly focus on process development, performance improvement, and long-term stability enhancement.

5. Conclusion

This paper briefly summarizes the crystal structure and chemical composition of perovskite materials, analyzes their electronic and optical properties and their effects, and reviews recent research progress on perovskite-based MOSFETs, HEMTs, Schottky diodes, and PN junction rectifiers in new material development, process innovation, and performance optimization. In the future, perovskite materials will continue to advance, with expected significant breakthroughs in novel lead-free perovskite materials and perovskite-traditional semiconductor hybrid heterojunction power devices. Future development of perovskite power devices will delve deeper into intrinsic material properties, effectively suppressing ion migration, phase separation, and decomposition under multi-field coupling through composition control and interface optimization. Additionally, more efficient surface passivation techniques will continue to be developed, achieving minimal surface state control by precisely designing the orientation and coverage density of passivation molecules, thereby significantly reducing interfacial recombination losses and enhancing carrier transport efficiency.

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