

CHEMISTRY

Photochemistry and photographic processes

**ZnO: SiC NANOCOMPOSITES FOR OPTOELECTRONIC
DEVICES: EXPANDING OPPORTUNITIES BEYOND
PHOTOVOLTAICS**

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Received on January 31, 2026

Presented by V. Bankova, Member of BAS, on September 29, 2026

Abstract

Incorporating silicon carbide (SiC), known for its superior thermal conductivity and robustness against oxidation and chemical attack, into ZnO to create ZnO:SiC nanocomposites may offer a promising path forward. ZnO has been studied extensively in photovoltaics, but the potential applications of ZnO:SiC nanocomposites in wider optoelectronic platforms have been relatively little studied. This feature article reviews and describes the potential for ZnO:SiC nanocomposites in ultraviolet photodetectors, light-emitting diodes (LEDs), and transparent/high-power electronics. By relating inherent material properties to device requirements, we present how ZnO:SiC nanocomposites have considerable utility as a platform for next-generation optoelectronic technologies well beyond photovoltaics.

Key words: perovskite solar cells, optoelectronic devices, ultraviolet photodetectors, light-emitting diodes (LEDs), thermal management

Introduction. Zinc oxide (ZnO) is a wide-bandgap semiconductor ($E_g \approx 3.3$ eV) extensively studied for optoelectronic applications, including ultraviolet (UV) photodetectors, transparent thin-film transistors, and light-emitting diodes (LEDs), owing to its high optical transparency, electron mobility, and low-cost

The authors acknowledge the research support provided by the NEC-2025 grant (number J510051140) from Universiti Tenaga Nasional, Malaysia.

<https://doi.org/10.7546/CRABS.2026.10.03>

processing [1]. Despite these advantages, conventional ZnO films often suffer from intrinsic defect states, thermal instability, and chemical reactivity, which degrade their performance under high-intensity illumination or elevated operating temperatures. These shortcomings limit the long-term stability and scalability of ZnO-based optoelectronic devices.

Silicon carbide (SiC), by contrast, is a robust wide-bandgap semiconductor ($E_g = 2.3\text{--}3.2$ eV) with exceptional thermal conductivity ($> 490 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ in cubic 3C-SiC) and chemical inertness, making it highly attractive for high-power, high-temperature electronics. Its ability to withstand harsh environments and suppress thermally induced degradation has already made SiC a cornerstone material in power electronics and high-frequency devices.

Incorporating SiC into ZnO to form ZnO:SiC nanocomposites provides a pathway to combine the desirable optoelectronic properties of ZnO with the thermal and mechanical robustness of SiC [2]. Recent studies on ZnO/SiC hybrid structures have reported improved optical transparency, reduced defect densities, and enhanced thermal endurance compared to pristine ZnO. These synergistic effects suggest that ZnO:SiC nanocomposites could play a vital role in enabling next-generation optoelectronic devices, particularly where strong light–matter interaction is coupled with high thermal loads. Recent reviews on ZnO-based electron transport layers have highlighted significant challenges in maintaining long-term stability under moisture, UV, and thermal stress, despite advances in interface engineering and tandem device architectures [3].

This feature article explores the potential of ZnO:SiC nanocomposites as versatile candidates for optoelectronic applications beyond solar cells. By analyzing their intrinsic material properties and mapping them against the performance requirements of different device platforms, we provide new perspectives on their utility in high-performance, thermally stable, and multifunctional optoelectronic technologies. This research goes beyond traditional optimization methods, focusing solely on the properties of the materials themselves, to highlight ZnO:SiC nanocomposites as engineered and robust optoelectronic materials for enhanced performance through their interfaces.

Material properties and rationale. The functionality of optoelectronic devices strongly depends on the interplay between material properties and operational conditions [4, 5]. ZnO:SiC nanocomposites offer a promising balance by combining transparency and electronic performance. Recent studies report that incorporating SiC nanoparticles into ZnO matrices can improve optical transmittance and enhance device durability under thermal stress. ZnO:SiC characteristics are predominantly dictated by the choice of composition, SiC polytype, microstructure, and interface quality. ZnO provides wide band gap optoelectronic transparency and carrier conduction, while SiC supposedly affects the effective band gap value and optical response and improves thermal stability. Therefore, ZnO:SiC optoelectronic characteristics differ depending on the composition

and fabrication conditions [1, 6–8]. Table 1 summarizes representative literature-reported properties of ZnO, SiC, and ZnO composites for comparative discussion.

The conceptual description of the band structure and its interrelation to ZnO/SiC interfaces is shown in Fig. 1. The band structure is presented schematically, using previously known material properties, and is not calculated by new first-principles electronic structure calculations presented in this study. The same procedure is applied for the comparison of the crystal lattice parameters to demonstrate potential mismatch in structure and possible interface strain. Different synthesis methods, such as sol-gel processing, RF magnetron co-sputtering, and other techniques, may give rise to variations in the crystal structure, imperfections, and interface structure impacting optoelectronic properties [1, 6–8].

Potential applications in optoelectronics. The multifunctional properties of ZnO:SiC nanocomposites, combining optical transparency, defect tolerance, and thermal robustness, make them highly promising for a broad spectrum of optoelectronic applications beyond solar photovoltaics.

Simulation insights for ZnO:SiC-based solar cells. To provide a device-level perspective on the possible functionality of ZnO, this section considers a representative multilayer perovskite solar-cell architecture that incorporates ZnO:C as the electron transport layer (ETL) in a standard ITO/ETL/MAPbI₃/HTL (Fig. 2a). The numerical analysis was previously presented by the authors at IC-NST 2026 [9] and is incorporated here to connect the reported material properties of ZnO with its potential role as an electron transport layer. The present article does not claim these simulated results as newly generated experimental measurements; instead, they are used as a supporting device-level perspective within this feature article. The MAPbI₃ device exhibits the highest short-circuit current density (J_{sc}), underscoring its superior absorption and carrier transport properties (Fig. 2b). This establishes MAPbI₃ as the optimal reference absorber for evaluating the role of ZnO:SiC at the ETL interface. Additionally, the influence of various buffer/ETL layers, ZnO:SiC, CdS, GZO, PCBM, and TiO₂, when paired with MAPbI₃. ZnO:SiC exhibits a competitive photocurrent profile comparable to GZO and CdS, and clearly superior to TiO₂ and PCBM (Fig. 2c). This smooth turn-on behaviour and higher J_{sc} indicate efficient electron extraction and minimal interfacial recombination, consistent with the expected benefits of SiC-induced defect suppression. Furthermore, the thermal performance (Fig. 2d) shows that ZnO:SiC maintains higher efficiency as temperature increases from 300 to 500 K, outperforming TiO₂ and closely matching CdS and GZO. The lower degradation rate indicates the inherent thermal toughness of the composite, due to SiC's high thermal conductivity and chemical stability, properties which are vital for high-temperature optoelectronics and space applications. This composite also offers a strong spectral response across the visible region, nearly identical to CdS and GZO (Fig. 2e). Minor enhancements in the 450–650 nm region indicate improved carrier extraction, which aligns with the composite's favourable band alignment

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Representative literature-reported properties of ZnO, SiC, and ZnO:SiC composites relevant to optoelectronic applications

Property	ZnO	SiC	ZnO:SiC*
Bandgap (E_g) [eV]	3.2–3.4	2.3–3.2 (polytype-dependent)	Tuneable 3.0–3.4
Thermal conductivity (κ) [$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$]	~ 50	> 490 (3C-SiC)	Intermediate (~ 100 –250)
Exciton binding energy [meV]	~ 60	~ 40 –60	Comparable to ZnO
Optical transparency [%]	> 80 in the visible	~ 70 –80	> 85 (reported for optimized films)
Defect tolerance	Moderate (oxygen vacancies common)	High	Enhanced over ZnO
Mechanical robustness	Moderate	Very high	Improved over ZnO

*ZnO values represent reported/representative ranges and depend strongly on composition, SiC polytype, microstructure, interface quality, and preparation conditions; they are not measurements from the present study.

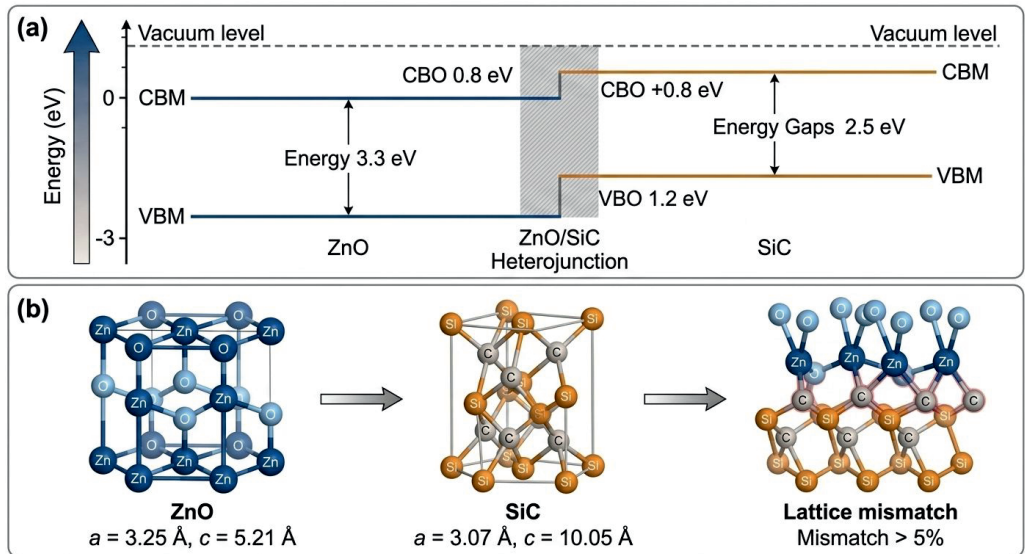


Fig. 1. Conceptual schematic of the reported band alignment and lattice-parameter relationship of ZnO and SiC relevant to ZnO interfaces. The illustration is based on reported material characteristics and is not a new theoretical band-structure calculation performed in this work

and reduced trap density. This composite provides balanced performance confirmed by software-driven simulation performance, positioning it as a promising alternative to traditional ETLs for thin-film-based solar photovoltaics and other optoelectronic platforms [9,11].

Ultraviolet photodetectors. The primary function and value of ZnO:SiC nanocomposites lie in their functionality at the interface level and their ability to regulate defect formation under high-performance conditions. The addition of SiC to the ZnO nanocomposite alters the pathways by which charge carriers can reach the edge of the ZnO material, and the charge distribution between the two materials changes, which significantly alters the behaviour of the photocarrier under ultraviolet light in optoelectronics [1]. This means that the main benefit of ZnO structures lies in their effective distribution of optical properties, carrier transport, and thermal management. ZnO is the main UV-absorbing semiconductor matrix and photocarrier, while the SiC component impacts the transport of charge carriers, interfacial charge distribution, defect states, and heat management. The functionality of the proposed architecture is governed by the amount of SiC and the characteristics of the SiC phase, quality of the interface, position alignment, and the defect density. Therefore, the application of interface engineering will make it possible to minimize thermally activated traps and improve the stability of the created structure [12,13].

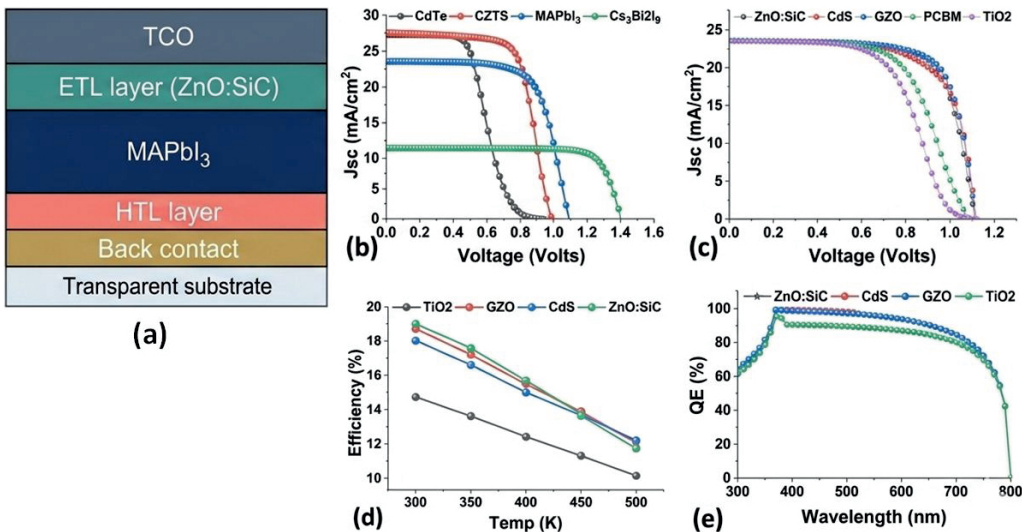


Fig. 2. Simulation-guided analysis of ZnO as an electron transport layer in a perovskite solar-cell architecture: (a) device structure, (b) J–V characteristics, (c) comparison of transport-layer configurations, (d) temperature-dependent efficiency, (e) spectral/EQE response. The detailed analysis was previously presented by the authors at ICNST 2026 [9] and is incorporated here as device-level supporting evidence within the present feature article

Research-driven angle for transparent optoelectronics. In transparent optoelectronic devices, the primary challenge is no longer optical transparency but thermal and electrical compatibility across multilayer stacks. Heat accumulation in ZnO-based LEDs leads to “efficiency droop” and spectral shifts [14]. ZnO:SiC composites provide a tuneable interface that enables control of electron injection as well as localised heat build-up. The term “tunable interface” refers to the ability to modify the electronic and thermal behaviour of the ZnO-SiC interface through SiC content, phase distribution, layer thickness, crystallinity, defect concentration, and deposition conditions. These parameters can influence carrier injection or extraction, interfacial barriers, recombination, and local heat dissipation. Thus, the potential value of the composite lies in enabling simultaneous consideration of optical, electrical, and thermal requirements during the translation of thin-film materials toward functional device architectures [4]. Experimental and device-physics-driven analyses demonstrate that SiC-based UV photodetectors achieve exceptional responsivity, detectivity, and thermal robustness through heterojunction and interface engineering [15].

High-temperature and radiation-resilient optoelectronics: A systems perspective. Space-based optoelectronic systems require materials that can withstand extreme temperature fluctuations, ionizing radiation, and prolonged exposure to vacuum and UV radiation [16]. ZnO has shown moderate radiation tolerance, while SiC is widely recognized for its exceptional radiation hardness. ZnO has been widely investigated for transparent thin-film transistors (TFTs) and flexible electronics, but its mechanical and chemical weaknesses hinder integration into next-generation devices [14]. By embedding SiC, ZnO:SiC composites exhibit enhanced structural robustness and tolerance to mechanical stress, making them suitable for wearable and flexible optoelectronic systems. Multiphysics modelling and experimental analyses confirm that SiC-based systems retain functional integrity under extreme thermo-mechanical and electromagnetic conditions [17]. ZnO:SiC nanocomposites can thus be classified as ‘Invented Thermal-Electronic Co-Engineering Systems.’ These nanocomposites can effectively conduct heat throughout their structures while simultaneously allowing localized charge transport at defined locations along with the structure(s) of the nanocomposite materials. Figure 3 illustrates an overview of potential applications for ZnO:SiC nanocomposites beyond solar cells, including ultraviolet photodetectors, LEDs, TFTs, high-power electronics, and thermal management coatings for space applications.

Thermal conductivity versus recombination trade-off. Although enhanced thermal conductivities are commonly thought to be advantageous for increasing the rate at which carriers cool down via nonradiative recombination processes, this is mainly true for homogeneously constructed semiconductor materials that have been poorly engineered to minimize defects. High thermal conductivity is assumed to be only true for homogeneous, blind materials where the range of de-

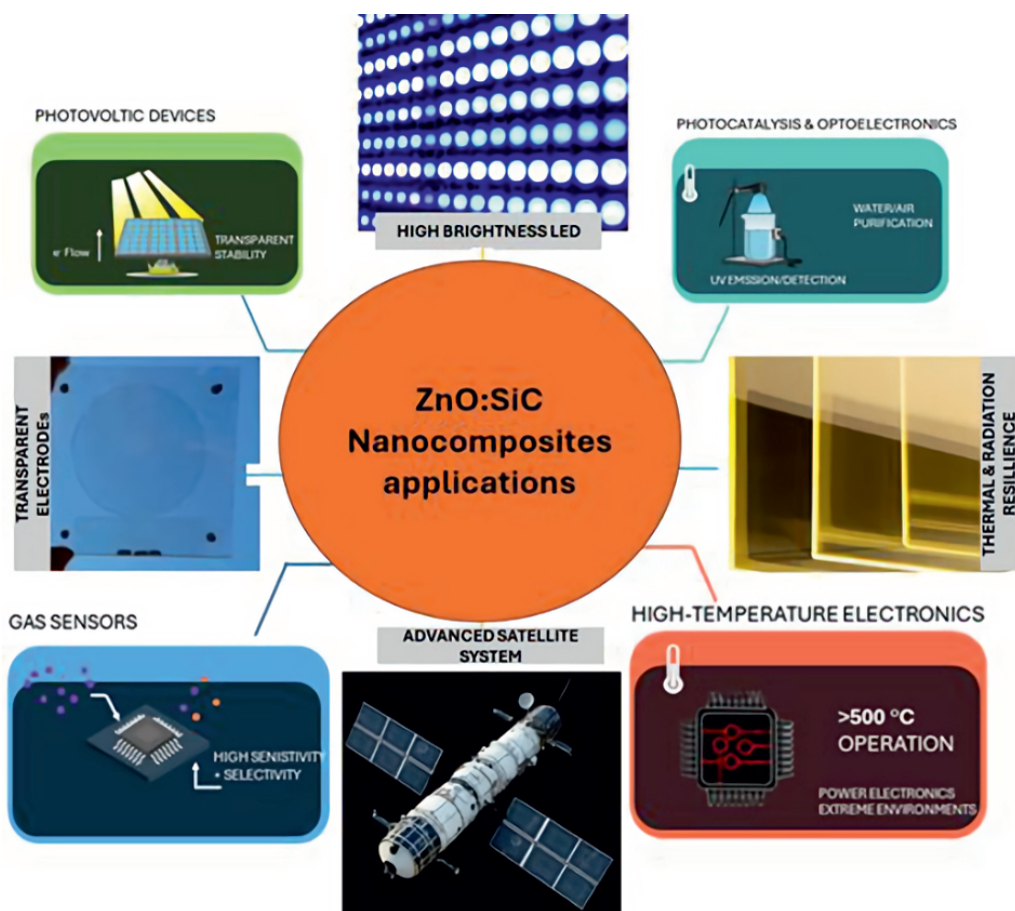


Fig. 3. A schematic diagram of other applications of this composite material

fect states has not been carefully controlled. In ZnO:SiC nanocomposites, the SiC phase enhances thermal conductivity because it acts more like a heat-spreading mechanism than a source of recombination. If proper engineering works to create a “heat sink”, this allows for high thermal conductivity to work to the benefit of the device by not allowing for thermally driven traps to form, and through the reduction of ‘hot spots’ caused by heating from adjacent electronic components, provides operational reliability without compromising charge selection.

Challenges and limitations. Despite their promising properties, ZnO:SiC nanocomposites face several challenges that must be addressed before they can be integrated on a large scale into optoelectronic devices. While SiC improves structural and thermal stability, its relatively wide bandgap and higher electron affinity can induce interfacial potential barriers or charge trapping at the ZnO/SiC or SiC/active-layer interfaces. Controlled processing and optimized SiC incorporation are necessary to minimize structural defects and secondary phase formation in

nanocomposites. Defect control, interface engineering, and reproducibility remain important challenges for translating ZnO:SiC nanocomposites toward reliable optoelectronic devices [1, 6–8]. From a device engineering perspective, the limited availability of systematic data linking SiC content to optoelectronic performance impedes predictive design.

Future prospects. The outlook for ZnO:SiC nanocomposites in optoelectronics is highly promising, provided that key scientific and engineering challenges are addressed. In the short term, simulation-guided optimization of SiC content within ZnO matrices can provide valuable insights into balancing conductivity, transparency, and thermal robustness. These predictive approaches can narrow down composition ranges (e.g., 5–20% SiC incorporation) before moving to fabrication trials, reducing development costs and time. Experimentally scalable deposition techniques such as RF magnetron sputtering and sol-gel processing should be adapted to achieve uniform ZnO:SiC thin films with controlled stoichiometry at low processing temperatures. Additionally, scalable deposition strategies compatible with transparent and flexible substrates warrant investigation to accelerate the translation of ZnO:SiC nanocomposites into next-generation optoelectronic systems. In the longer term, exploring ZnO:SiC composites in multifunctional devices, such as transparent displays, UV sensing arrays, and high-power optoelectronic switches, could significantly broaden their technological relevance.

Conclusion. ZnO:SiC nanocomposites present a promising material platform for advancing optoelectronic technologies beyond solar cells. This feature article has outlined their potential roles in ultraviolet photodetectors, light-emitting diodes, and transparent/high-power electronics, where efficient heat management and defect tolerance are essential. The discussion is supported by the simulation-guided ZnO electron-transport-layer study that demonstrated the value of linking materials properties with device-level requirements and is consistent with a broader translational perspective. However, future progress will depend on controlling the composition and fabrication process, which requires systematic experimental validation for reliable optoelectronic devices.

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