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# Next-Generation Ultraviolet Sensors Enabled by Metal Oxide Nanostructures and Interfaces

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## ABSTRACT

**Ultraviolet (UV) photo detectors have become essential for applications ranging from military and space exploration to environmental monitoring and secure communications. Traditional semiconductors such as silicon and GaN face limitations in achieving solar blindness, environmental stability, and cost-effective scalability. In contrast, metal oxide semiconductors—with their wide band gaps, chemical robustness, and highly tunable nanostructures—have emerged as promising candidates for next-generation UV sensing. This review highlights the role of nanostructure design and interface engineering in advancing metal oxide–based UV photo detectors. We examine how morphology, dimensionality, and defect states influence optical detection mechanisms, and how engineered interfaces—including Schottky contacts, heterojunctions, and hybrid architectures—enable improved responsivity, selectivity, and response speed. After presenting comparative performance benchmarks, we discuss emerging strategies such as alloying, hybrid integration, and flexible device architectures. Finally, we identify key challenges related to device stability, scalability, and reproducibility, and offer perspectives on the future of metal oxide nanotechnology for UV sensing.**

**Keywords— Photo detectors, Metal oxides Responsivity, Detectivity**

## 1. INTRODUCTION

Ultraviolet (UV) radiation detection has garnered significant attention due to its wide range of applications across environmental, industrial, biological, and defense sectors. Reliable UV sensors play a critical role in secure optical communication systems, early flame detection, sterilization control, and the monitoring of solar radiation and atmospheric chemistry. They also enable solar-blind plume and imaging functions in aerospace and military operations, as well as wearable dosimetry for consumer health applications. Recent studies indicate a growing shift in performance and application requirements toward low-power operation, fast response dynamics, and solar-blind functionality [1-4]. Although conventional semiconductors such as silicon (Si), gallium nitride (GaN), and silicon carbide (SiC) have been used for UV detection, they still face significant limitations that restrict their effectiveness in meeting the demands of next-generation UV sensing technologies.

Conventional semiconductors such as silicon (Si), gallium nitride (GaN), and silicon carbide (SiC) have been used for UV detection, despite their considerable drawbacks. In addition to inherent qualities, interface engineering and nanostructuring are important performance enablers. In contrast to designed interfaces such as Schottky contacts and oxide–oxide or oxide–2D heterojunctions, which reduce dark current, improve carrier separation, and allow self-powered operation, oxide nanostructures (such as ZnO nanowires and β-$Ga_2O_3$ nanobelts) promote light–matter interaction and can provide high gain. Recent studies have demonstrated high-quality Schottky diodes, fast, solar-blind β-$Ga_2O_3$ heterojunctions, and hybrid oxide/graphene systems that combine high mobility and great UV selectivity. [3, 5–6, 8–11] At the device-physics level, surface and interface states significantly mediate response. This mechanism is supported by contemporary research and experiments, which also outline mitigation strategies (passivation, catalytic metals, interfaces design). Under UV irradiation, oxygen adsorption/desorption and associated surface-trap dynamics in ZnO produce significant photoconductive gain but can hinder recovery. [4–5, 12–13] There are still issues despite the quick advancements: (i) the trade-off between sensitivity and speed that is inherent in high-gain photoconductors; (ii) reproducible, scalable growth of nanostructures/thin films appropriate for wafer-level integration; and (iii) long-term stability for flexible platforms under mechanical stress and ambient/outdoor conditions.Recent benchmarking and solution-processing evaluations demand standardized illumination conditions, consistent reporting, and manufacturable techniques. [7, 14–15] In this review we concentrate on how next-generation UV light detectors are made possible by metal oxide nanostructures and interfaces. Our (i) mapping of material properties and morphologies (ZnO, $GaO_3$, and allied oxides), (ii) analysis of interface strategies (Schottky, p–n/p–i–n, and hybrid heterojunctions), (iii) linking mechanisms to figures-of-merit, and (iv) synthesis of recent developments in alloying, hybridization, and flexible/transparent devices result in a forward-looking perspective on practical, scalable UV sensors. The direction of travel is indicated by sample examples of flexible solar-blind β-$GaO_3$ and oxide hybrids [3, 10–11, 16].

## 2. Metal Oxide Nanostructures for UV Detection

Because of their broad band gaps, chemical stability, affordability, and compatibility with various nanostructuring techniques such nanowires, nanorods, thin films, and quantum dots, metal-oxide semiconductors are used as the building blocks for ultraviolet (UV) light detectors [17,18]. These customized morphologies enable manipulation of optical and electrical characteristics, while the high surface-to-volume ratio of nanostructures promotes carrier dynamics and light–matter interactions, hence enhancing sensitivity and responsivity [18]. Zinc oxide (ZnO), which offers a variety of morphologies and high photo gain; gallium oxide ($Ga_2O_3$), which has an ultra-wide band gap that allows solar-blind operation; tin oxide ($SnO_2$) and titanium dioxide ($TiO_2$), which are valued for low dark current and chemical robustness; and emerging ZnMgO alloys, which allow band gap tunability for wavelength-selective detection, are some of the most thoroughly studied systems [17–19].Metal-oxide nanostructures are great options for next-generation UV sensing platforms because each material has unique benefits, from thermal endurance and solar-blind capacity to low-cost production and spectral tunability.

### *2.1. Zinc Oxide (ZnO)*

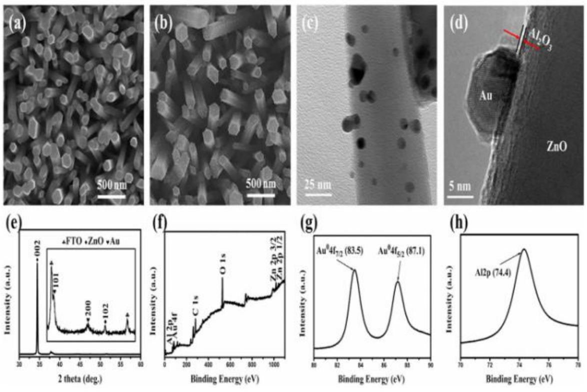
Because of its relatively broad band gap (~3.3 eV), natural abundance, chemical stability, and simplicity of synthesis into a variety of nanostructures, zinc oxide (ZnO) has been the material most fully researched for UV light detection [20–22]. Scalable methods like hydrothermal growth, sol–gel processing, sputtering, and chemical vapor deposition (CVD) have created a range of morphologies, including nanowires, nanorods, nanosheets, thin films, and quantum dots [21,23]. These geometries have a considerable impact on the density of surface states and the transport pathways for light produced carriers in addition to modifying optical absorbance. Because of their high surface-to-volume ratio, which optimizes photon absorption and facilitates effective carrier separation, ZnO photo detectors operate especially well in one-dimensional (1D) nanostructures [24]. For example, lateral ZnO nanowires made hydrothermally on quartz showed a photocurrent 103 times higher than ZnO films in UV photo detectors. Peak performance with 14.9 A/W responsivity, $2.3 \times 10^{12}$ jones detectivity, and $5.0 \times 10^{3}$ % EQE was reached with tailored nanowire length, proving controlled nanowire formation as a viable technique for high-efficiency optoelectronics [25]. However, because the prevailing oxygen adsorption–desorption dynamics at the surface limit device speed, such mechanisms also result in delayed reaction and recovery times, usually on the range of hundreds of milliseconds to seconds [26]. Recovery times in ZnO nanorods surpassing 1 s were observed by Zhang et al. (2022), showing that oxygen-mediated conduction is still a bottleneck for real-world applications [23].

Several engineering ideas have been put out to address these limits. It has been established that surface passivation with high-κ dielectrics, like $Al_2O_3$, reduces surface trap states and dramatically speeds up reaction times. By increasing light harvesting and reducing carrier recombination through enhanced interfacial charge separation, the synergistic combination of Au nanoparticles for plasmon-enhanced visible absorption with Al2O3 surface passivation on ZnO nanorod arrays greatly increases solar-to-hydrogen efficiency—up to 6.7 times higher than pristine ZnO [27].

A typical SEM image of the ZnO NRs array with smooth surfaces, high density, and well-aligned orientation was displayed in Fig.1(a). Fig.1(b) demonstrated that each ZnO nanorod's surface had a consistent distribution of Au nanoparticles while the nanorods continued to exhibit their vertical orientation. Fig.1(c) displayed a HRTEM image taken close to the edge of the ZnO nanorods, while the overlayer (shown by a red arrow in Fig.1(d)) revealed the amorphous properties of the $Al_2O_3$ shell with an average thickness of roughly 0.56 nm. According to X-ray diffraction, every diffraction peak of the ZnO nanorod array matches the typical diffraction of an impurity-free wurtzite structure (JCPDS file No. 36-1451).

The characteristic peaks of (111) and (200) of Au nanocrystal can be distinguished by their centers at 2θ of 38.1° and 44.4° (JCPDS file No. 04-784) Fig. 1(e). The presence of Zn, O, Al, and Au components in the ZnO/Au/$Al_2O_3$ sample was demonstrated by the XPS spectrum in Fig. 1(f). Parts (g) and (h) of Fig.1 displayed the high-resolution spectra of the Au and Al species, respectively. Au 4f7/2 and Au 4f5/2 are responsible for the two peaks in Fig. 1(g) that have centers at 83.5 eV and 87.2 eV, respectively. was given a peak at 74.4 eV in Fig. 1(h), which is the usual location of pure $Al_2O_3$.

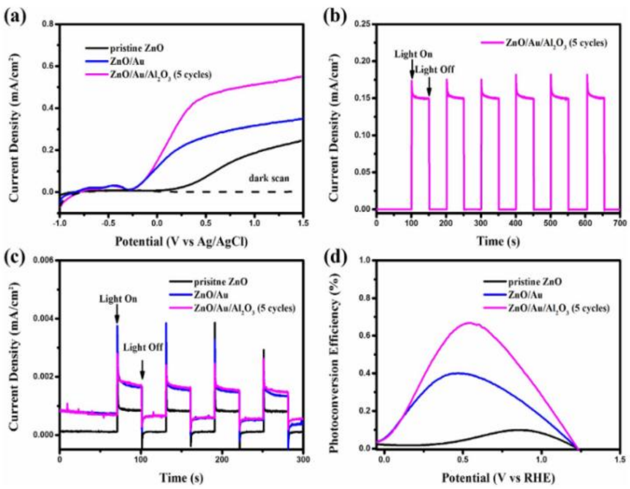
In Fig.2(a) LSV curves demonstrated that ZnO/Au/$Al_2O_3$ (5 cycles) photo anodes display considerably improved



Ref-27.Fig.1(a) Top view SEM image of pristine ZnO. (b) Top view SEM image of ZnO/Au.(c) A low-magnification TEM image and (d) a HRTEM image of ZnO/Au/Al2O3 (5cycles).

photocurrent under simulated sunlight compared to pristine ZnO and ZnO/Au. Transient photocurrent measurements at 0 V vs Ag/AgCl demonstrated a quick and steady charge response for ZnO/Au/Al2O3 (Fig. 2(b)).

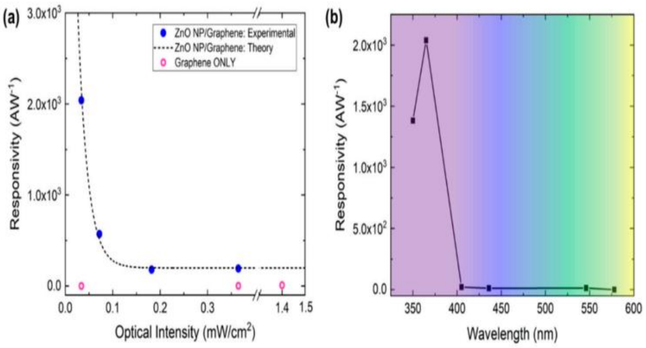
In Fig.2(c) Chronoamperometric measurements under visible light show $ZnO/Au/Al_2O_3$ consistently outperforms the others, while Fig.2(d) demonstrate photo conversion efficiency is highest across applied potentials for this optimized composite, demonstrating its superiority for PEC water splitting applications. Another effective technique is hetero junction formation. By creating intrinsic electric fields at the interface, ZnO can be used with graphene or $TiO_2$ to enhance charge separation and reduce



Ref-27 Fig. 2(a) LSV curves recorded for pristine ZnO, ZnO/Au and ZnO/Au/Al2O3 (b) Transient photocurrent density for ZnO/Au/Al2O3 (5 cycles) (c) Chronoaperoetric I-t curves collected at 0.5 V vs Ag/AgCl for the three different photo anodes under visible light (>420 nm). (d) Photo conversion efficiency of the PEC cell with three different photo anodes as a function of the applied potential (vs RHE).

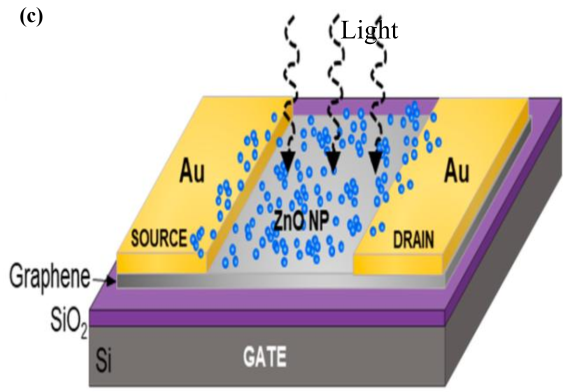
recombination. $TiO_2$/ZnO/Ag mixed-dimensional core-shell nanowires were produced. Combining 1D $TiO_2$, 2D ZnO nanosheets, and 0D Ag quantum dots improved light absorption, carrier separation, and response speed, resulting in high responsivity (730/490 mA•$W^{-1}$) over 380–420 nm. This method stresses mixed-dimensional heterostructures as a road toward optoelectronic devices with outstanding performance [28]. Similarly, ZnO/graphene hybrids have achieved broadband light detection with high responsivity and quick recovery thanks to graphene's enhanced carrier mobility [29]. Fig.3(a) ZnO nanoparticle/graphene photo transistors exhibit excellent UV responsivity, reaching up to $\sim 4 \times 10^4$ A/W as incident power approaches zero, and delivering $2 \times 10^3$ A/W at 34 µW/cm².

Their high gain and sharp spectrum selectivity result from ZnO's ~3.32 eV band gap, producing maximal photo sensitivity near 365 nm while effectively blocking visible light Fig.3(b). This makes these hybrids exceedingly sensitive and solar-blind, perfect for next-generation UV photo detectors. Fig.3(c) represent the schematic of the architecture of the ZnO nanoparticle/graphene photo transistor. Alloying techniques, particularly with magnesium, offer an additional means of modifying the band gap of ZnO.By extending the cutoff edge farther into the UV spectrum and keeping good transparency in the visible range, ZnMgO alloys allow for



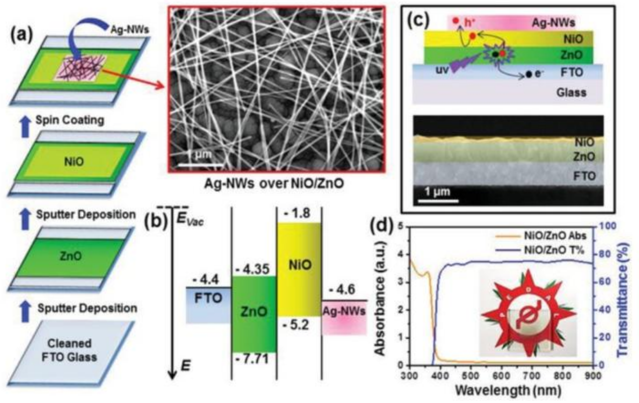
Ref-29 Fig. 3(a) shows the responsiveness as a function of optical intensity for ZnO nanoparticle/graphene devices (solid blue circles) and graphene-only devices (open pink circles). A simulated fit is depicted by a dashed black line. (b) ZnO nanoparticle/graphene device responsiveness vs incident wavelength.

p-NiO/n-ZnO [Fig.4] heterojunction UV photo det wavelength-selective UV detection [30]. In another advancement, a transparent ector—enhanced through thermal treatment—showed remarkable performance gains

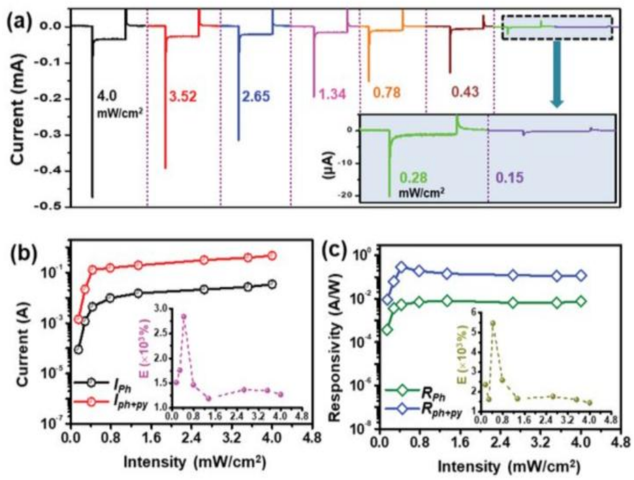



Ref.29 Fig.3(c) schematic of the device architecture of the ZnO nanoparticle/graphene photo transistor (not to scale)

due to the pyro-phototronic effect. The device exhibited a 1264% increase in pyrocurrent, more than a 5000% boost in responsivity and detectivity under weak UV illumination, an ultrafast response time (~3.9/8.9 µs), and over 70% transparency in the visible range [31].This simple fabrication approach supports the development of high-performance, self-powered, and transparent optoelectronic devices. Additionally, these junction architectures reduce the limitations associated with oxygen-trap effects by shifting carrier transport from surface-controlled pathways to internally driven field-assisted separation. Fig.4 gives an overview of how the NiO/ZnO heterojunction device is built, how it works, and how it interacts with light. The fabrication schematic [Fig. 4(a)] shows a straightforward construction process, while the energy band diagram [Fig. 4(b)] clarifies how the p-NiO/n-ZnO junction promotes effective charge separation. The working mechanism in [Fig. 4(c)] illustrates the self-powered photo detection, driven by the built-in electric field without the need for an external bias. Finally, the absorbance and transmittance spectra in [Fig. 4(d)],




REF-31 FIG.4A) SCHEMATIC ILLUSTRATION OF THE DEVICE CONSTRUCTION TECHNIQUE B) ENERGY BAND DIAGRAM OF THE P-NIO/N-ZNO HETEROJUNCTION. B) SCHEMATIC DEPICTION OF THE WORKING MECHANISM OF THE SELF-POWERED PHOTO DETECTION. D) ABSORBANCE AND TRANSMITTANCE SPECTRA OF NIO/ZNO FILMS. THE INSET SHOWS THE INITIAL IMAGE OF THE TRANSPARENT GADGET.

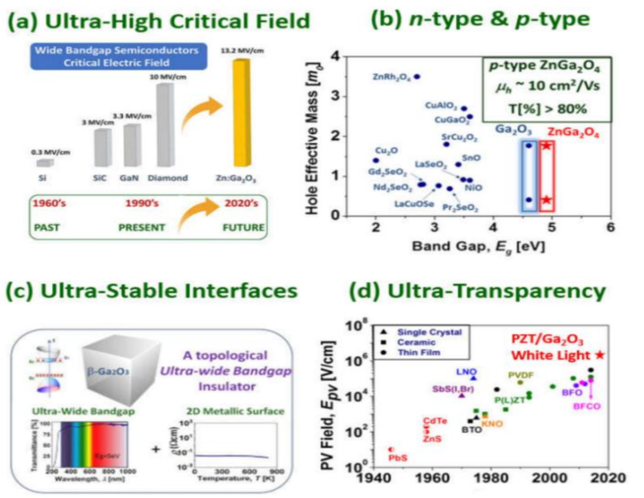



REF-31 FIG.5 A) I-T CHARACTERISTICS OF THE ZNO 300 °C SELF-POWERED PHOTODETECTOR UNDER UV 365 NM ILLUMINATION WITH VARYING INCIDENT POWER DENSITIES RANGING FROM 0.15 TO 4 MW CM⁻². THE INSET DISPLAYS AN EXPANDED VIEW OF THE I–T CURVES UNDER MATCHING ILLUMINATIONS. B) THE SHORT-CIRCUIT CURRENT RESPONSE AND C) THE RESPONSIVITY (R) RESPONSE DEMONSTRATING THE PHOTOVOLTAIC CONTRIBUTION MIXED WITH THE PYROELECTRIC CURRENT AT VARIED UV INTENSITY. THE INSETS OF (B) AND (C) DEMONSTRATE THE ENHANCEMENT OF I (E = (IPH+PY − IPH) /IPH) AND R (E = (RPH+PY − RPH) / RPH).

together with the inset image, highlight the high transparency of the device, supporting its potential for transparent optoelectronic applications. Fig.5 shows how the ZnO photo detector responds to 365 nm UV light without any external power. As seen in the I–t curves [Fig. 5(a)], the photocurrent is stable and increases steadily with higher light intensity. The short-circuit current and responsivity results [Fig. 5(b),(c)] suggest that the device performance is governed by both photovoltaic and pyroelectric effects, with the insets clearly illustrating the enhanced current and responsivity at stronger UV illumination. In a summary, ZnO continues to be a crucial material in the field of UV photo detectors due to its superior UV sensitivity, structural plasticity, and affordable cost of manufacture. Although surface-trap-induced slow dynamics continue to be a substantial impediment, ZnO's competitiveness is being strengthened by developments in passivation, heterostructure engineering, and alloying. ZnO is projected to continue to play a vital role in the development of flexible, affordable UV sensing devices, especially in applications that call for high responsivity and compatibility with flexible or transparent substrates.

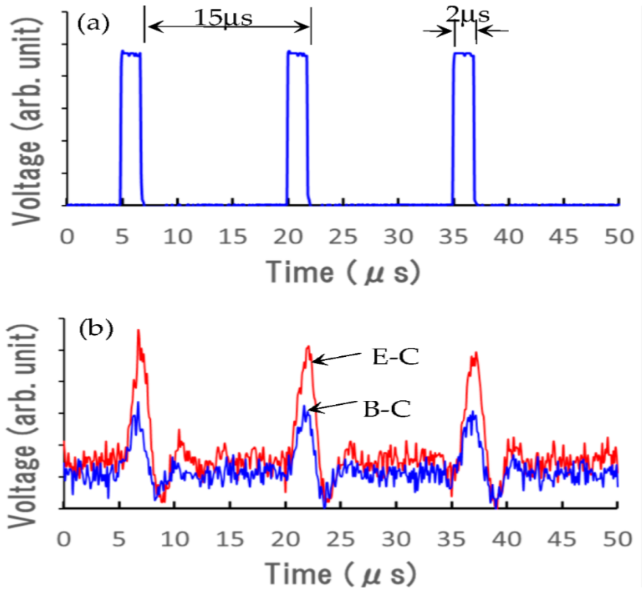
### 2.2 Gallium Oxide ($Ga_2O_3$)

Since gallium oxide ($Ga_2O_3$) contains an ultra-wide band gap (4.9–5.3 eV) [see in Fig.6] that naturally shuts out visible light without the use of external filters, it has swiftly established a benchmark material for solar-blind deep-ultraviolet (DUV) sensing [32]. Fig.6 highlights the key advantages of the material for advanced optoelectronic applications. Its ultra-high critical electric field [Fig. 6(a)] supports high-power operation, while the demonstrated n- and p-type conductivity [Fig. 6(b)] enables potential bipolar devices. The presence of ultra-stable interfaces [Fig. 6(c)] suggests the possibility of hosting a two-dimensional electron gas, and the extended UV-A transparency [Fig. 6(d)] further confirms its suitability for next-generation transparent conducting oxide applications. Unlike ZnO, which requires band gap engineering or optical filtering to limit visible response, $Ga_2O_3$ inherently offers strong spectrum selectivity. Because of this ability, it is extremely desirable for applications where suppression of background



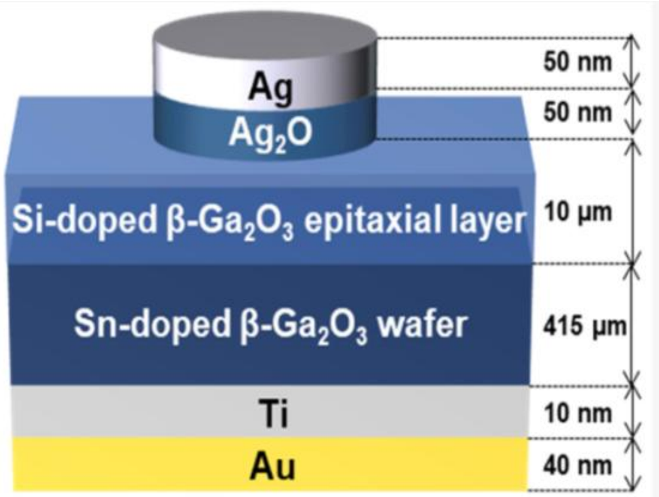

REF-32 FIG.6 (A) ULTRA-HIGH CRITICAL ELECTRIC FIELD, (B) POTENTIAL BIPOLAR OPERATION DUE TO ITS DEMONSTRATED N-TYPE AND P-TYPE CONDUCTIVITY, (C) ULTRA-STABLE INTERFACES THAT MAY HOST A 2D ELECTRON GAS, (D) EXTENDED TRANSPARENCY INTO THE UV-A REGION FOR TRANSPARENT CONDUCTING OXIDE (TCO) APPLICATIONS (TAIL STATE DENSITY IS LOCATED DEEPER IN THE ULTRAVIOLET THAN CONVENTIONAL TCOS).

sun radiation is critical, such as environmental monitoring, UV astronomy, missile plume monitoring, and flame detection. Additionally, $GaO_3$ photo detectors can be used. UV photo detectors are widely employed in both military and civilian applications, such as explosion and flame detection, heavy weapon and missile early warning, ozone hole monitoring, and ultraviolet early warning detection [33]. $Ga_2O_3$ thin films and nanostructures have improved greatly in recent years, enabling for a diversity of device designs. While epitaxial thin films created by MOCVD or pulsed laser deposition offer excellent crystallinity for reproducible device fabrication, nanobelts and nanowires offer high surface sensitivity. For example, Y. He et al., "A Review of β-$Ga_2O_3$ Power Diodes," PMC, 2024, reviews β-$Ga_2O_3$ Schottky diodes with low turn-on voltages, quick switching, and performances exceeding millisecond response times and very high detectivities (beyond $10^{14}$ Jones in some diode configurations)[34]. Similarly, a n–p–n UV light detector system based on β-$Ga_2O_3$/NiO/β-$Ga_2O_3$, displaying photocurrent amplification and response times smaller than a few microseconds. According to the study, the $Ga_2O_3$ photo diode is one of the quickest oxide-based UV photo detectors to date because of its fast response (~µs scale) and improved responsivity due to heterojunction design (Fig. 7(a) and (b)) [35].



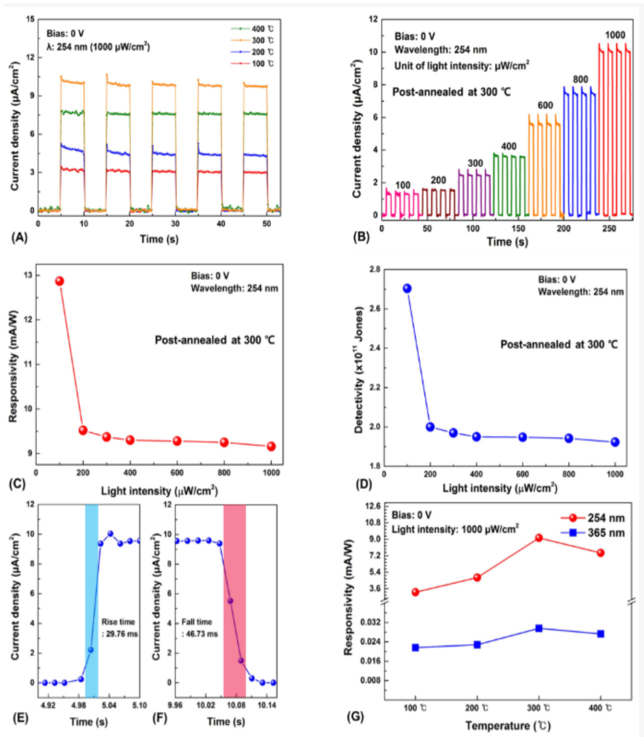

REF-35 FIG.7(A) WAVEFORM REPRESENTING THE PHOTOEMISSION GENERATED UNDER UV ILLUMINATION. (B) PHOTO RESPONSE CHARACTERISTICS OF DEVICES CONSTRUCTED WITH THE B-$GA_2O_3$/NIO/B-$GA_2O_3$ (E–C) STRUCTURE COMPARED TO THOSE WITH THE NIO/B-$GA_2O_3$ (B–C) CONFIGURATION.

Heterojunction devices have proven potential in overcoming the inherent restrictions of $Ga_2O_3$, in addition to Schottky diodes. Its weak electron mobility (typically less than 200 $cm^2 V^{-1} s^{-1}$) and lack of trustworthy p-type doping make freestanding $Ga_2O_3$ devices prone to performance restrictions. Heterostructures such $Ga_2O_3$/$Ag_2O$, $Ga_2O_3$/ZnO, and $Ga_2O_3$/2D materials have been designed to increase carrier transport and enable for self-powered operation in order to get around this. The schematic of the device architecture and performance matrices are depicted in Fig.8 and Fig.9.



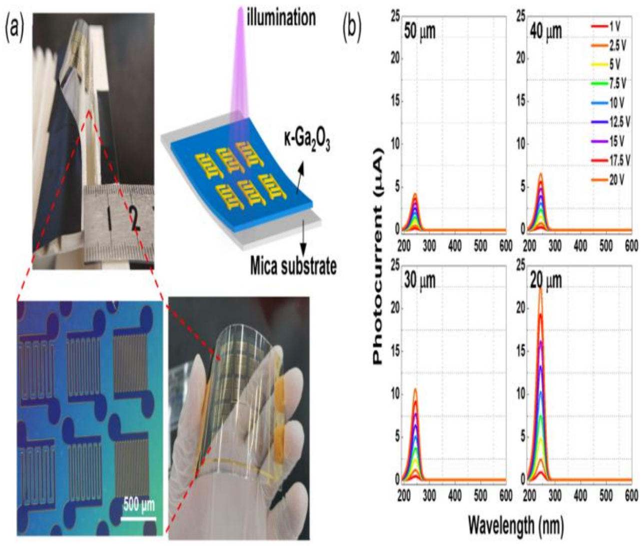

REF-36 FIG.8 SCHEMATIC ILLUSTRATION OF THE FABRICATED AG2O/B-GA2O3 HETEROJUNCTION PHOTO DETECTOR.

After 300 °C annealing, a self-powered $Ag_2O$/β-$Ga_2O_3$ heterojunction DUV photo detector showed outstanding performance with low leakage (4.24 × $10^{-11}$ A), high responsivity (12.87 mA/W at 254 nm) [Fig.9(C)], and detectivity of 2.70 × $10^{11}$ Jones [Fig.9(D)]. The device also showed quick response times (~30–47 ms), indicating its potential for high-performance ultraviolet sensing without external bias [36].



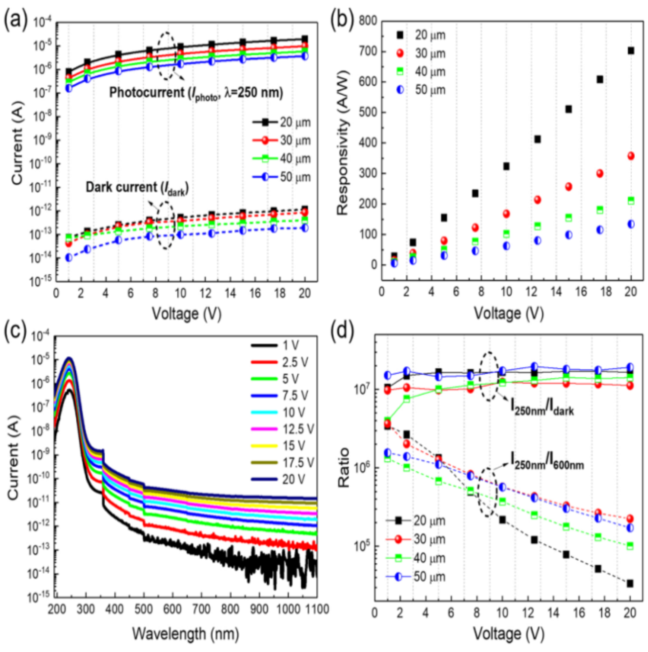

REF-36 FIG.9 THE OPTICAL RESPONSE AND CHARACTERISTICS OF THE AG2O/B-GA2O3 HETEROJUNCTION PHOTO DETECTOR UNDER ZERO-BIAS AT 254 NM IRRADIATION. (A) AG2O THIN-FILM DEVICES DEVELOPED AT VARIOUS POST-ANNEALING TEMPERATURES AND THEIR PHOTORESPONSE. (B) PHOTORESPONSE OF THE DEVICE POST-ANNEALED AT 300 °C WITH VARYING LIGHT INTENSITIES. (C) THE RELATIONSHIP BETWEEN RESPONSIVENESS AND LIGHT INTENSITY. (D) DETECTIVITY AS A FUNCTION OF THE LIGHT INTENSITY. (E) RISE TIME AND (F) FALL TIME. (G) RESPONSIVITY AT 254 AND 365 NM IRRADIATION AT ZERO BIAS.

Creating flexible $Ga_2O_3$ photo detectors is a highly exciting




Ref-37 Fig. 10 (a) Flexible κ-$Ga_2O_3$ photo detectors (1 cm × 1 cm and 5 cm × 5 cm) with interdigital electrode patterns shown in a bent condition, and (b) photocurrent spectra of the κ-$Ga_2O_3$ devices measured for various interdigital spacing distances and applied bias voltages.

avenue. At 680 °C, flexible κ-$Ga_2O_3$ thin films were produced epitaxially on mica. Fig.10 highlights both the mechanical flexibility and the photo response of the κ-$Ga_2O_3$ photo detectors. The images of bent devices in different sizes [Fig.10(a)] show that the detectors remain functional under mechanical deformation. Meanwhile, the photocurrent spectra [Fig.10(b)] indicate that the device response can be conveniently controlled by changing the interdigitated electrode spacing and the applied bias voltage.

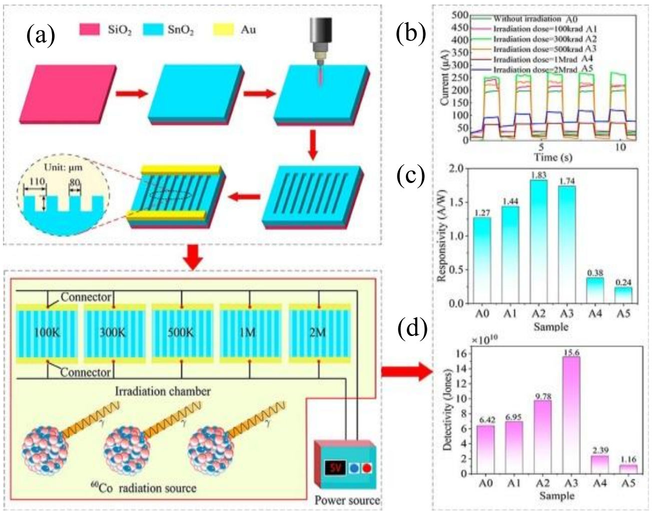



Ref-37 Fig. 11 shows the following: (a) photocurrent (λ = 250 nm) and dark current (shutter close) values; (b) responsivity (λ = 250 nm) of the PD for spacing distances of 20, 30, 40, and 50 mm under a bias; (c) log-scale photocurrent spectrum of the PD for a 30 mm spacing for wavelengths from 190 nm and I250 nm/I600 nm under various biases and spacing distances.

allowing high-performance solar-blind photo detectors with record responsivity (703 A/W), detectivity (4.08 × $10^{14}$ Jones), and robust adaptability. The devices remained stable despite high temperature (≤750 °C), repetitive bending (10,000 cycles), and small radii, showing their promise for future wearable and harsh-environment UV sensing [37]. Fig.11 gives a clear picture of how the photo detector performs under deep-UV light. The strong difference between the photocurrent and dark current at 250 nm [Fig. 11(a)] highlights its high UV sensitivity. Changes in responsivity with electrode spacing [Fig.11(b)] show how the device geometry influences performance, while the log-scale spectra [Fig.11(c)] confirm excellent solar-blind behavior with high $I_{250}/I_{600}$ ratios that depend on the applied bias and spacing.These tests broaden the applicability of $Ga_2O_3$ into aerospace applications that need lightweight, conformable sensors as well as wearable UV monitoring. Simultaneously, hydrothermally produced nano sheets were used to create a 3D/2D $Ga_2O_3$@$(Co,Ni)S_2$ heterojunction light detector that achieved a self-powered responsivity of 36.56 mA/W under 254 nm illumination. Compared to pure $Ga_2O_3$, the device displayed considerably greater responsivity (1.51 A/W), detectivity (7.68 × $10^{12}$ Jones), EQE (738%), and faster response due to advantageous band alignment, efficient charge transfer, and increased light absorption. These results indicate the promise of 2D bimetallic sulfides for high-performance, self-driven $Ga_2O_3$ UV photo detectors [38]. There are still obstacles in spite of these developments. Low carrier mobility limits responsiveness in high-speed devices, whereas inconsistent p-type doping makes it difficult to create complex designs like p–n junctions or complementary circuits. Heterostructure integration, nano membrane engineering, and surface/interface optimization are significant components of current solutions. The combination of $Ga_2O_3$'s solar blindness, heat tolerance, and rapid responsiveness, however, validates its place as a next-generation deep-UV sensing platform with potential applications that extend beyond those of ZnO or $TiO_2$.

## *2.3 Tin Oxide ($SnO_2$)*

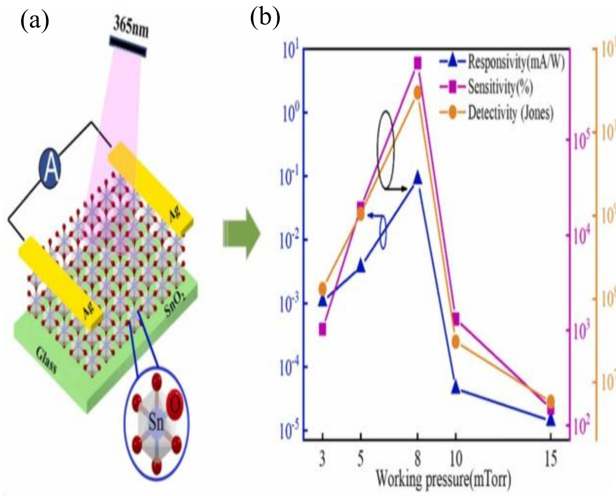
Tin oxide ($SnO_2$), because of its inherent low dark current, chemical stability, and excellent transparency, with a direct band gap of roughly 3.5–3.7 eV, has received great interest for UV photo detection [39]. Effective electron transport in heterojunction setups is further assisted by its excellent conduction band alignment, which is widely used in hybrid device designs. Thin films, nanoparticles, nanowires, and microwires have been produced using varied synthetic processes including sol–gel deposition, sputtering, hydrothermal growth, and chemical vapor deposition. The field of performance optimization has made great strides between 2020 and 2025.For example, under gamma-ray irradiation, $SnO_2$ microwire array UV photo detectors [Fig. 12(a)] demonstrated improved photo current and responsivity at low doses (≤500 krad) but deterioration at higher doses. At 300 krad, the device achieved 264 μA photo current and 1.83 A/W[Fig.12(c)] responsivity, representing ~35–44% improvement over the unirradiated condition.




REF-40 FIG.12 (A)SCHEMATIC DEPICTION OF THE MANUFACTURED DETECTOR.(B) TEMPORAL RESPONSE OF CURRENT WITH VARIOUS CONSTANT IRRADIATION (B) VARIATION OF RESPONSIVITY,ACROSS THE SAMPLES (D) VARIATION OF DETECTIVITY ACROSS THE SAMPLES

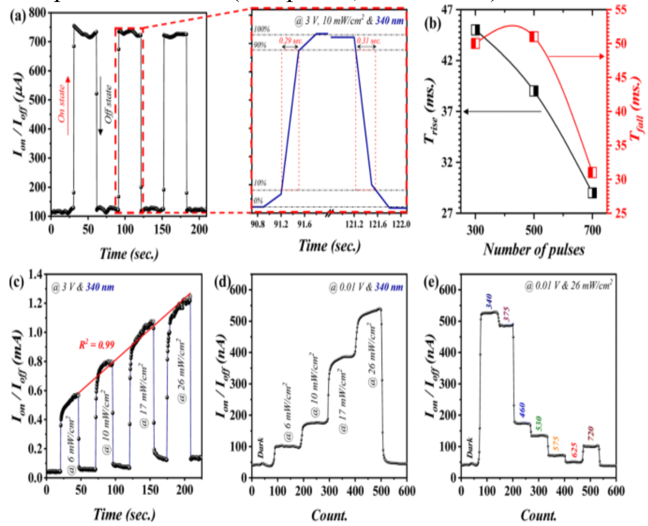
Fig.12(d) shows how the detectivity varies across different samples, highlighting differences in device sensitivity that arise from variations in material quality and device configuration. The detectors' excellent potential for long-term space applications was demonstrated by their resilience up to 500 krad, or around 20 years in low-Earth orbit [40].

A self-powered $SnO_2$ UV light detector was constructed

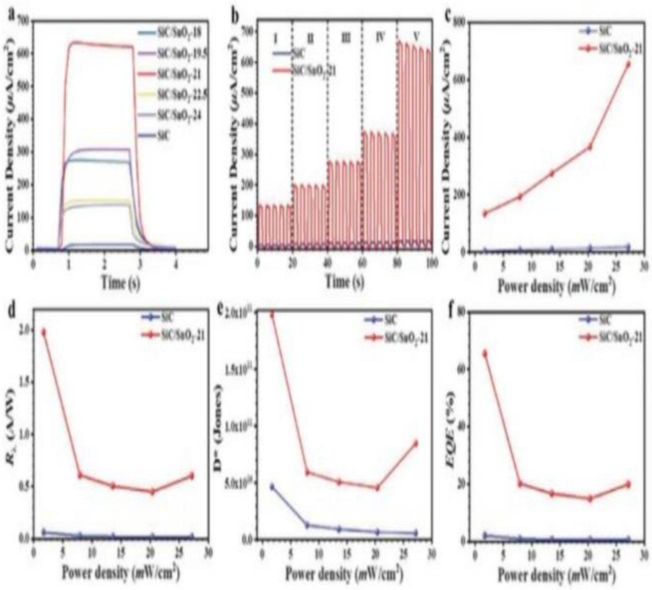



REF-41 FIG.13 (A)SCHEMATIC ILLUSTRATION OF THE FABRICATED PHOTO DETECTOR.(B) VARIATION OF RESPONSIVITY,SENSITIVITY AND DETECTIVITY OF THE DETECTOR WITH VARIATION OF WORKING PRESSURE

[Fig.13(a)] using reactive magnetron sputtering, with working pressure greatly influencing structure and performance. The optimized 8 mTorr film demonstrated high sensitivity ($6.41\times10^5$ %), responsivity (0.09 mA/W), detectivity ($2.99\times10^{10}$ Jones) [Fig.13(b)], and quick response/recovery (0.75/0.99 s), sustaining consistent performance for ~100 days without encapsulation. These findings demonstrate the potential of $SnO_2$ thin films as next-generation self-powered optoelectronic devices [41]. A nanostructured $SnO_2$/Si heterojunction UV light detector was produced using pulsed laser deposition, with device performance highly controlled by laser pulse number and incident power.A viable option for low-bias UV detection, the optimized device (700 pulses, λ = 340 nm) demonstrated



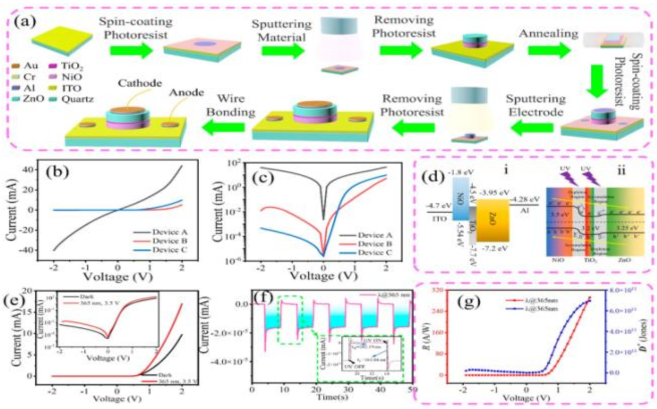

REF-42 FIG.14 TIME-RESOLVED MEASUREMENTS OF THE OPTIMIZED DEVICE (AT 700) INCLUDE: (A) ITS SWITCHING CHARACTERISTICS, (B) RISE AND FALL TIMES RELATIVE TO THE APPLIED LASER PULSES, AND (C) SWITCHING BEHAVIOR UNDER A 3 V BIAS. THE PERFORMANCE OF THE SAME OPTIMIZED DEVICE AT AN ULTRA-LOW OPERATING VOLTAGE (0.01 V) IS FURTHER EVALUATED AS A FUNCTION OF (D) INCIDENT POWER AND (E) WAVELENGTH RESPONSE.




REF-43 FIG.15 (A) TRANSIENT PHOTOCURRENT DENSITY CURVES RECORDED AT VARIOUS REACTION TIMES. (B) TRANSIENT PHOTOCURRENT RESPONSES AND (C) THE CORRESPONDING PHOTOCURRENT DENSITY VALUES MEASURED UNDER DIFFERENT ILLUMINATION POWER LEVELS. CALCULATED PARAMETERS INCLUDE (D) RESPONSIVITY ($R_\lambda$), (E) DETECTIVITY (D*), AND (F) EXTERNAL QUANTUM EFFICIENCY (EQE).

strong responsivity (32.9 mA/W), EQE (120.2), outstanding visible-blindness (rejection ratio 516%), and quick response times (0.29/0.31 s). The performance matrices are shown in Fig.14 [42] Fig.14 presents the time-resolved performance of the optimized device. The switching behavior and fast rise/fall times at 700 [Fig. 14(a)–(c)] indicate stable and efficient photo response under bias, while measurements at an ultra-low voltage of 0.01 V.[Fig. 14(d),(e)] demonstrate reliable operation with clear power-dependent and wavelength-selective responses. In $SnO_2/SiC$ ; Zou et al. described a self-powered PEC UV photo detector based on $SiC/SnO_2$ heterojunction nanoarrays was demonstrated for robust underwater operation across variable pH, salinity, and temperature. The performance matrices of the detector are displayed in Fig.15. It illustrates the photo response evolution and performance metrics of the device. The transient photocurrent density increases with reaction time and illumination power [Fig.15(a–c)], indicating improved charge generation and transport. The calculated responsivity, detectivity, and external quantum efficiency [Fig.15(d–f)] further confirm the enhanced photo detection performance under optimized conditions. The device demonstrated its potential for all-scenario underwater optical communication by achieving fast response (30/120 ms), high responsivity (1.97 A/W), and good detectivity ($1.98 \times 10^{11}$ Jones) [43]. Hybrid structures can further improve functionality. For instance, $SnO_2/SiO_2$ thin films with around 80% visible transmittance were used to create hybrid high-performance visible-blind transparent UV photo detectors. The hybrid device attained a responsivity of 769 mA/W, detectivity of $1.24 \times 10^{14}$ Jones, and above $10^6$ UV-C/UV-A rejection ratio, while $SiO_2$ passivation doubled the response speed by eliminating surface imperfections. [44]. .

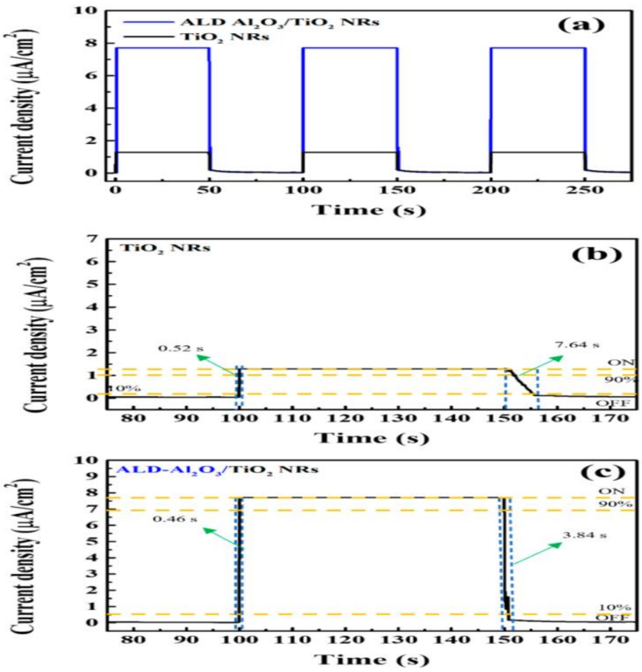
Although excessive surface states typically constrain recovery speeds, $SnO_2$ photo detectors primarily work through Photo conductivity and interface-controlled transport, where oxygen vacancies play a significant role in carrier dynamics. While the addition of high-κ dielectrics (e.g., $SiO_2$, $Al_2O_3$) or heterojunction partners successfully suppresses dark current and increases response speed, doping techniques like Bi incorporation have been demonstrated to modulate carrier density and improve responsivity, making $SnO_2$ appealing for imaging and optical communication [45,46].



REF-50 FIG.16 (A) SCHEMATIC ILLUSTRATION OF THE FABRICATION STEPS FOR THE UV PHOTODETECTOR. (B, C) I–V CHARACTERISTICS AND CORRESPONDING LOGARITHMIC PLOTS FOR DEVICES "A," "B," AND "C." (D) ENERGY BAND DIAGRAM OF THE METAL OXIDE–BASED HETEROJUNCTION UV PHOTODETECTOR. (E) I–V CURVES OF DEVICE "C" MEASURED IN THE DARK AND UNDER 365 NM ILLUMINATION, SHOWN IN BLACK AND RED, RESPECTIVELY (WITH THE INSET PRESENTING THE LOGARITHMIC PLOT). (F) SWITCHING RESPONSE OF DEVICE "C" UNDER 365 NM LIGHT (INSET: ENLARGED VIEW OF A SINGLE CYCLE). (G) RESPONSIVITY (RED) AND DETECTIVITY (BLUE) CHARACTERISTICS OF DEVICE "C".

Although hurdles remain in defect control and attaining uniform large-area deposition, $SnO_2$ offers a promising mix of transparency, low noise, and structural adaptability, placing it as a good contender for next-generation self-powered and fast-response UV sensors.

Scalable, high-performance $SnO_2$-based UV photo detectors




REF-51 FIG.17(A) SWITCHING BEHAVIOR OF SLHJ UV PHOTODETECTORS FEATURING $TiO_2$ NANOROD (NR) STRUCTURES AND $Al_2O_3/TiO_2$ NR STRUCTURES. (B) ENLARGED VIEW OF THE TURN-ON AND TURN-OFF TIMES FOR THE PHOTODETECTOR WITH THE $TiO_2$ NR CONFIGURATION, AND (C) ENLARGED VIEW OF THE CORRESPONDING SWITCHING TIMES FOR THE DEVICE INCORPORATING THE $Al_2O_3/TiO_2$ NR STRUCTURE.

are being made possible by ongoing advancements in thin-film growth and micro/nano structuring.

### *2.4 Titanium Dioxide ($TiO_2$)*

Among the most common and affordable metal oxides, titanium dioxide ($TiO_2$) has a band gap of roughly 3.0–3.2 eV in its anatase and rutile phases. Its chemical inertness, thermal stability, and compatibility with low-cost solution processing make it an interesting material for stable and scalable UV photo detectors [47,48]. Despite these advantages, $TiO_2$'s relatively low carrier mobility often necessitates integration with partners with higher mobilities to improve response time and responsiveness. $TiO_2$ excels in heterojunctions, interlayers, and passivation techniques, as recent discoveries have shown. For example, Zhang et al. created $TiO_2$ nanorod/polyterthiophene ($TiO_2$ NRs/PTTh) and $TiO_2$NRs/Au/PTTh heterojunction UV photo detectors. It demonstrated stability, quick reaction, and great sensitivity Incorporation of Au nanoparticles considerably boosted performance via the pyro-phototronic effect, obtaining responsivity of 1.894 mA/W and detectivity of $1.67 \times 10^{10}$ Jones. $TiO_2$ NRs/Au/PTTh is a promising design for effective self-powered UV photo detectors, according to these results [49].

The $TiO_2$ interlayer functioned as an electron-blocking medium in the $NiO/TiO_2/ZnO$ layered photovoltaic device disclosed by Shang et al. (2023), enabling responsivity in the hundreds of A•W$^{-1}$ under bias while keeping low noise.

After annealing, the device attained a rectification ratio of $10^4$, responsivity of 291 A/W, and detectivity of $6.9 \times 10^{11}$ Jones. Future metal oxide-based UV photo detectors have a lot of potential thanks to this architecture. [50]. Fig.16 outlines the fabrication [Fig.16(a)], electrical behavior, and performance of the UV photo detector. The I–V characteristics of Devices [Fig.16(b,c)] and the energy band diagram [Fig.16(d)] reveal effective heterojunction formation, while Device C shows clear photo response, stable switching, and enhanced responsivity and detectivity under 365 nm illumination [Fig.16(e–g)].The vital significance of surface/interface engineering was further underscored by Yang et al., who showed that atomic-layer-deposited $Al_2O_3$ passivation on $TiO_2$-based detectors considerably increased responsivity, decreased dark current, and expedited reaction times. The improved device displayed a four-order photocurrent-to-dark current ratio and quick response times (0.46/3.84 s). The performance charactristis are illustrated in Fig.17.These results demonstrate that ALD-deposited $Al_2O_3$ effectively boosts $TiO_2$-based UV photo detector performance. [51].

Fig.17(a) compares the switching performance of SLHJ UV photo detectors with $TiO_2$ nanorods and $Al_2O_3/TiO_2$ nanorod structures. The devices exhibit fast and stable turn-on and turn-off behavior, with the enlarged views [Fig. 17(b,c)] highlighting improved switching speeds for the $Al_2O_3/TiO_2$ NR configuration.

Furthermore, PMMA-based thin film coatings containing $TiO_2$, ZnO, and $TiO_2$/ZnO nanohybrids were created and extensively studied for UV-shielding. According to UV-Vis data, UVA absorption increased as nanoparticle content increased, with 0.1 weight percent $TiO_2$, 0.1 weight percent ZnO, and 0.025:0.025 weight percent $TiO_2$:ZnO providing the best protection. FTIR demonstrated partial polymer degradation after continuous UV exposure, while XRD suggested the amorphous character of the films [52]. When applied in heterostructures, $TiO_2$ usually works as a passivation layer, carrier-selective interlayer, or stability enhancer, enhancing detectivity and temporal response in multilayer topologies. Mechanistically, isolated $TiO_2$ devices usually display modest responsivity and longer recovery due of limited mobility and trap-mediated transport. Overall, $TiO_2$ may not be as responsive as ZnO or $GaO_3$, but it is crucial for the development of flexible, self-powered, and stable UV detectors due to its durability, affordability, and synergistic activity in heterostructured systems. In order to concurrently attain high responsivity, stability, and speed, future improvements are expected through integration with 2D materials and organic semiconductors.

### *2.5 Other Oxides (NiO, $In_2O_3$, ZnMgO Alloys)*

The ability of nickel oxide (NiO), a rare p-type wide-band gap oxide (~3.7–4.0 eV), to form strong p–n heterojunctions with ZnO, $GaO_3$, and Si—typically achieved via scalable solution-processed or spin-coated nanocrystal thin films—has made it a promising candidate for solar-blind and self-powered UV photo detectors [53,54]. At heterointerfaces, Ni vacancies function as intrinsic acceptors that improve p-type conductivity and facilitate effective carrier separation. Recent examples are Cu-doped NiO detectors with improved responsivity (0.281 A•W$^{-1}$) and detectivity ($1.3 \times 10^{13}$ Jones) in comparison to undoped devices [55], NiO/Si heterojunction devices with high responsivity (2.0 A•W$^{-1}$) and detectivity ($8.5 \times 10^{13}$ Jones) at zero bias [54], and a low-cost NiO/NB-rGO nanomaterial was produced via co-precipitation and annealing for UV photo detection, displaying high responsivity (800 A/W), detectivity ($9.4\times10^{11}$ Jones), and quick rise/fall durations (1.38/2.17 s).The Schottky contact enabled tunable positive and negative photo conductance under reverse and forward bias, underlining its potential for high-performance UV photo detectors [56]. Additionally, photovoltaic responsivity of ~0.15 A•W$^{-1}$ has been demonstrated using p-NiO/Si detectors with $Al_2O_3$ interlayers [57]. Indium oxide ($In_2O_3$), which has a bandgap near 3.6 eV, is increasingly being used for UV detection in thin-film and transparent electronics platforms, particularly in hybrid or solution-processed designs [58]. While NiO–$In_2O_3$ heterojunction nano spheres have exhibited better sensitivity and quick switching performance in multifunctional device topologies, their films offer high optical transparency, stability, and compatibility with flexible substrates [59].

In contrast, alloys of zinc magnesium oxide (ZnMgO) exploit the incorporation of magnesium into ZnO to adjust the bandgap from 3.3 eV to above 4.0 eV, enabling for wavelength-selective detection in the UVA, UVB, and UVC regimes [60,61]. With examples such as PbS quantum-dot solar cells that integrate Mg-doped ZnO window layers that exhibit reduced recombination, tenfold lower leakage current, and less than 3% efficiency loss after 30 days [62] and alloyed ZnMgO films that enable narrowband, wavelength-selective UV detectors with improved responsivity through precise compositional control [63], ZnMgO-based devices demonstrate strong potential, despite the fact that uniform alloy composition and crystallinity remain major obstacles. When coupled, these new oxide systems offer distinctive properties in heterostructures, hybrid devices, and selective detection architectures, widening the design space of UV light detectors beyond traditional ZnO and $Ga_2O_3$.

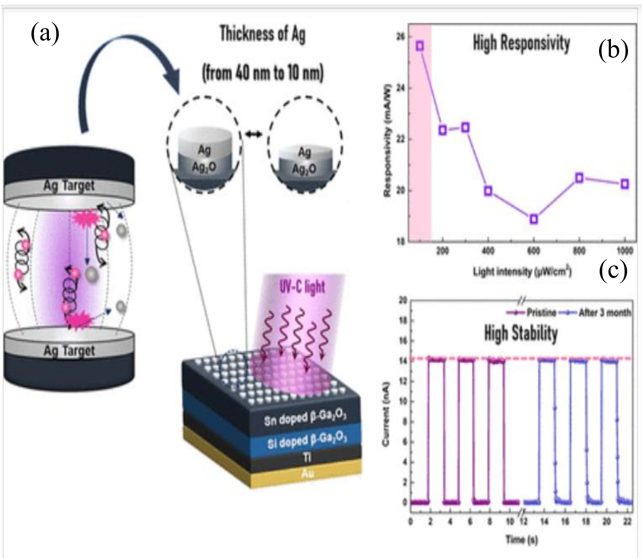
## 3. INTERFACE ENGINEERING IN UV PHOTO DETECTORS

Interface engineering plays a crucial role in maximizing the performance of metal oxide–based ultraviolet (UV) photodetectors. Although the intrinsic optoelectronic properties of oxides such as ZnO, $Ga_2O_3$, $SnO_2$, and $TiO_2$ determine light absorption and carrier generation, the separation and transport of carriers, recombination behavior, and noise levels are strongly influenced by interface characteristics including metal–semiconductor contacts, heterojunctions, and surface states. Well-designed interfaces enable simultaneous enhancement of responsivity, detectivity, and response speed, making them essential for high-performance UV sensing.

### *3.1. Metal–Semiconductor Interfaces (Schottky Junctions)*

Schottky junctions—formed at the interface between a semiconductor and a metal with an appropriate work function—play a key role in tailoring the performance of UV photo detectors. By introducing a rectifying barrier, these junctions significantly reduce dark current and enhance carrier transport. Unlike conventional photoconductive devices, the Schottky barrier suppresses thermally generated carriers in the absence of light, resulting in a higher signal-to-noise ratio and improved detectivity. The built-in electric field at the interface also enables rapid collection of photogenerated carriers, giving the device much faster rise and decay times.Examples include Au/ZnO/p-Si Schottky photodetectors, which exhibit low dark current and high responsivity [64]. Another notable demonstration is a self-powered $Ag_2O/\beta\text{-}Ga_2O_3$ deep-UV photodetector that uses thin Ag films as top electrodes. When optimized to a 20 nm thickness, the device achieved a responsivity of 25.65 mA/W, a detectivity of $6.10 \times 10^{11}$ Jones, and an impressive on/off ratio of $3.43 \times 10^8$. It also delivered fast response times and excellent air stability, making it a strong candidate for reliable deep-UV detection [65]. The key performance metrics are shown in Fig. 18. Fig.18 presents the design and performance of the fabricated photo detector. The schematic [Fig.18(a)] shows the device structure, while the responsivity [Fig.18(b)] increases with light intensity, and the temporal current response [Fig.18(c)] demonstrates stable and reliable operation.

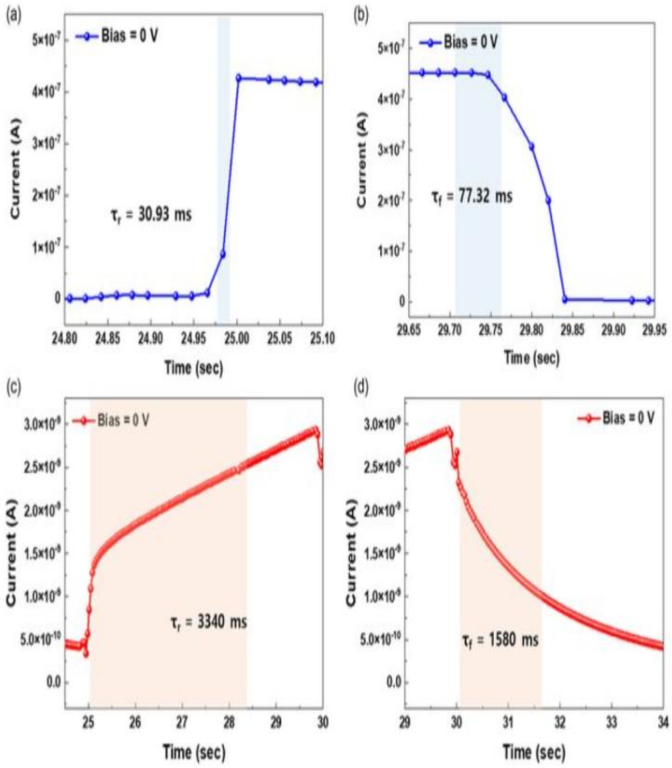
Despite their advantages, Schottky junctions also come with certain challenges. Their performance can be affected by fabrication-related defects and by the sensitivity of the barrier height to surface states, which may lead to trap-assisted leakage currents and reduced long-term stability. However, advances in fabrication methods—such as improved metal deposition processes and techniques to better control barrier formation—have helped address these issues. By minimizing interface traps and improving junction uniformity, these strategies have strengthened the reliability and consistency of Schottky-based devices, reinforcing their importance in the development of next-generation UV photodetectors [66, 67].




REF-65 FIG.18 (A)SCHEMATIC ILLUSTRATION OF THE FABRICATED PHOTO DETECTOR.(B) VARIATION OF RESPONSIVITY WITH THE INCIDENT LIGHT INTENSITY (C) TEMPORAL RESPONSE OF CURRENT

### 3.2. Heterojunction Interfaces

By allowing carrier separation, preventing recombination, and boosting photo responsiveness, heterojunctions formed between semiconductors with different band gaps or electron affinities introduce built-in electric fields that significantly improve UV photo detector performance. $ZnO/TiO_2$ n–n heterojunctions are among the most investigated systems; they use staggered band alignment to promote effective electron transport from ZnO to $TiO_2$, which boosts photocurrent collection and responsivity. However, due to large internal electric fields, $ZnO/\beta\text{-}Ga_2O_3$ wide-band gap n–n heterojunctions have demonstrated solar-blind UV detection with faster response times. Hybrid designs like as ZnO/organic polymer interfaces are attractive for flexible and wearable sensing systems because they offer mechanical flexibility, variable spectrum response, and enhanced interfacial charge separation. Crucially, self-powered functionality and wavelength selectivity—features crucial for energy-efficient and application-specific UV detection—are made achievable by heterojunction engineering, which provides operation at zero or low bias [68–70]. To fully utilize the potential of heterojunction architectures in next-generation UV photo detectors, however, problems like lattice mismatch, interfacial defects, and fabrication reproducibility must be resolved by means of sophisticated material design, surface engineering, and precise growth techniques.




REF-71 FIG.19 TIME-DEPENDENT PHOTOCURRENT OF THE POST-ANNEALED PHOTODETECTOR SHOWING (A) RISE TIME AND (B) FALL TIME UNDER ZERO BIAS WHEN EXPOSED TO 254 NM UVC LIGHT AT AN INTENSITY OF 1000 MW CM$^{-2}$. THE CORRESPONDING PHOTORESPONSE OF THE PRISTINE DEVICE IS SHOWN IN (C) RISE TIME AND (D) FALL TIME MEASUREMENTS UNDER ZERO BIAS WITH 365 NM ILLUMINATION AT THE SAME LIGHT INTENSITY.

***3.3. p–n and p–i–n Junctions:*** P–n and p–i–n junctions are basic device designs for photovoltaic-mode UV detection. The intrinsic electric field at the junction improves the effective separation of light produced electron–hole pairs, which minimizes recombination, speeds up temporal responsiveness, and allows for self-powered operation with low dark current and low power consumption. These junction-based designs are suitable for high-speed applications because they achieve significantly better rise and decay times than conventional photoconductive devices. The NiO (p-type)/β-$Ga_2O_3$ (n-type) heterojunctions, give high detectivity and rapid millisecond-scale response for solar-blind detection [71]. Fig.19 compares the time-dependent photocurrent of post-annealed and pristine photo detectors. Under zero bias, the post-annealed device shows faster rise and fall times with 254 nm UVC light [Fig.19(a,b)], while the pristine device exhibits slower response under 365 nm illumination [Fig.19(c,d)], highlighting the improved dynamics after annealing. The Ag/p-NiO/n-ZnO/Ag heterojunctions coated by spray pyrolysis and annealed to 500 °C demonstrate a low dark current (22 nA) and a selective, fast photo response (Tr = 4.6 ms, Td ≈ 20.3 ms) at 253 nm and 900 nm. Because of their powerful, visible-blind UV–IR detection, which arises from defect-mediated interfacial transport and efficient carrier separation by the built-in field, these scalable oxide p–n junctions are appealing for broadband, stable photo detector platforms [72]. Despite these developments, the majority of wide-band gap oxides, like $Ga_2O_3$ and ZnO, are naturally n-type, making it difficult to reliably fabricate high-quality p-type oxide layers and to mitigate interfacial imperfections that can trap carriers and reduce sensitivity and speed. Improving the performance and scalability of p–n and p–i–n junction-based UV light detectors requires addressing these constraints through creative doping, interface passivation, and heterostructure engineering.

### 3.4. **Role of Surface and Interface States**

The performance of UV photo detectors is greatly impacted by surface and interface states that result from structural flaws such oxygen vacancies and dangling bonds in two primary ways. On the one hand, they can be helpful by causing trap-assisted photoconductive gain, which boosts responsivity [73]. Conversely, high trap densities are harmful because they increase noise, lengthen decay durations, and compromise device repeatability [24]. Effective passivation techniques are crucial to reducing these negative impacts. Approaches include thermal annealing to reduce defect density at metal–semiconductor interfaces, surface chemical modifications with organic molecules to neutralize traps, and the deposition of $Al_2O_3$ capping layers by atomic layer deposition (ALD) to stabilize oxide surfaces and suppress defects [51,74].

## 4. DETECTION MECHANISMS

There is no universal approach to using metal oxides for ultraviolet (UV) detection. Instead, device performance is shaped by a combination of underlying mechanisms—from simple photoconductive switching to more advanced carrier processes controlled by interface properties [75]. Each detection pathway comes with its own strengths and limitations: some offer exceptional sensitivity but respond slowly, while others trade high responsivity for ultrafast operation or the convenience of self-powered functionality [75]. Understanding these mechanisms is not just academically valuable—it provides a practical framework for designing UV photo detectors tailored to specific applications, whether that means monitoring cosmic UV radiation in space, measuring solar exposure on Earth, or powering wearable biomedical sensors [50].

### 4.1. Photoconductivity: The Workhorse with Hidden Flaws

One of the most widely used mechanisms in UV photo detectors is photoconductivity, where absorbed UV photons produce electron–hole pairs that increase the material's conductivity. This mechanism is often seen as the "workhorse" in devices made from ZnO nanowires, $TiO_2$ nanotubes, and $SnO_2$ thin films because it can deliver high responsivity through strong photoconductive gain [24,76]. However, the very defect states that enable this gain also introduce a drawback: they tend to slow the device's response. A well-known example is persistent photoconductivity (PPC), in which the device stays conductive long after the UV light is turned off—mostly due to oxygen adsorption and desorption processes that are common in oxide nanostructures [77]. Encouragingly, recent research offers promising ways to manage these trap states. Techniques such as targeted doping, passivation via atomic layer deposition (ALD), and the formation of heterojunctions have all shown success in reducing surface defects and suppressing PPC while preserving high sensitivity. These advances are helping make oxide-based photoconductors more reliable and practical for real-world UV sensing applications [78].

### *4.2. Photovoltaic Effect: Power from Light Alone*

The photovoltaic effect is one of the most powerful mechanisms for UV detection, often compared to a "racehorse" because of its speed and ability to operate without external power. In this mode, p–n or p–i–n junction devices generate a current or voltage solely from the separation of electron–hole pairs produced by UV photons, driven by their built-in electric field [75]. This self-powered nature makes them especially appealing for portable, remote, and energy-constrained applications. A major advantage of photovoltaic detectors is their rapid response: by avoiding the slow, trap-related processes that limit photoconductive devices, they can achieve response times ranging from microseconds to milliseconds [79]. This category also includes vertical Schottky diodes and NiO/β-$Ga_2O_3$ heterojunctions, which manage to combine high detectivity with self-powered functionality [35]. However, widespread use of photovoltaic UV detectors is still hindered by the difficulty of producing stable, high-quality p-type metal oxides. Active research into doped ZnO, improved NiO, and organic–oxide hybrid systems is working to address this challenge. With these developments, photovoltaic UV detectors are becoming strong contenders for next-generation wearable devices and Internet of Things (IoT)–integrated technologies.

### *4.3. Photo gating and Surface-Trap Processes: Masters of Sensitivity, Slaves to the Environment*

Among UV detection mechanisms, few can rival the extraordinary sensitivity of photo gating. In this process, trapped charges—whether originating from intrinsic defects or from oxygen adsorbed on the surface—act like an invisible "gate electrode," modulating the conductivity of the channel [80]. This effect allows nanowire-based devices to achieve responsivities that can exceed those of bulk materials by several orders of magnitude. However, the strength of photo gating is also its biggest weakness. Because the mechanism relies heavily on surface interactions, device performance can vary dramatically with changes in the surrounding environment. Moreover, the response and recovery times are often limited by the slow adsorption and desorption of oxygen, taking seconds or even minutes to stabilize [80].Despite these challenges, photo gating remains a widely used approach, particularly in multifunctional sensors that combine UV and gas detection on the same platform—an attractive capability for environmental monitoring. Recent efforts to improve the reliability of photo gated devices have focused on techniques such as surface encapsulation, catalytic nanoparticle decoration, and defect passivation. These strategies help reduce environmental sensitivity and accelerate device response, making photo gating increasingly viable for next-generation, ultra-sensitive UV photo detectors [80].

### *4.4. Interface-Controlled Transport: Where Physics Meets Engineering*

Interface-controlled transport at the forefront of UV detection moves the emphasis from bulk material properties to the fine tuning of band alignment at semiconductor–semiconductor or metal–semiconductor junctions, where device performance and carrier flow are controlled by heterojunctions or Schottky barriers. This mechanism's strength is its controllability: researchers can systematically optimize responsivity, speed, and dark current by choosing suitable metals like Au, Pt, or Ag, or by engineering heterojunctions like $ZnO/TiO_2$ and $ZnO/Ga_2O_3$ [81,82]. This allows them to effectively tune device behavior as if they were turning knobs on an instrument. Such devices can achieve the highly desired balance of high temporal resolution, low noise, and operational stability with careful design. With heterostructures, oxide–organic hybrids, and 2D–oxide junctions providing previously unheard-of control over carrier dynamics, the interface appears to be the most promising engineering playground going forward. This opens the door for customized UV photo detectors with uses ranging from transparent, flexible, and wearable sensors to deep-UV solar-blind defense systems .

### *4.5. Big Picture: Designing the Next Generation*

When combined, the four fundamental UV sensing techniques offer a variety of trade-offs: The photovoltaic effect allows for fast, self-powered operation, but is limited by the lack of high-quality p-type oxides [75]; photo gating provides extraordinary responsivity and even multifunctionality, coupling photon and gas detection, but its heavy dependence on ambient conditions undermines reliability [73]; interface-controlled transport offers the most balanced approach, offering tunability, stability, and fast response, but it requires meticulous precision in band alignment and fabrication [83]. Through carrier multiplication, photoconductivity provides unmatched sensitivity; nevertheless, persistent surface states sometimes result in slow recovery [75].

These limitations may be overcome in the future by hybridizing and co-engineering mechanisms, such as combining the high gain of photoconductivity with the speed of photovoltaic junctions or employing interface-controlled designs to stabilize photo gating processes. These strategies provide detectors that are not merely incremental improvements but revolutionary platforms that are faster, more sensitive, adaptable, and spectrally selective. By combining cutting-edge materials like organic layers, 2D semiconductors, or quantum dots with oxide nanostructures, researchers are paving the way for UV detectors made for specialized applications ranging from wearable medical monitors and environmental sensors to high-performance solar-blind systems for space exploration and defense [73,83,84].

## 5. PERFORMANCE BENCHMARKS & COMPARISON

Assessing the state of the art in metal oxide UV light detectors requires more than just listing device parameters; it also involves looking at how stability, responsivity, detectivity, and response time interact with different materials and topologies. The following benchmarks provide a framework for comparison in assessing progress and identifying opportunities for the future. They were extracted from representative works that were released between 2020 and 2025.

### *5.1 Responsivity: The Sensitivity Yardstick*

Responsivity (R), expressed in A/W or mA/W, is one of the key metrics used to evaluate a photo detector's performance. It is defined as $R = I_{ph} / P_{in}$, where $I_{ph}$ is the photocurrent generated and $P_{in}$ is the optical power incident on the active area. In simple terms, responsivity indicates how effectively a device converts incoming photons into electrical current, making it one of the most widely reported figures of merit. ZnO-based photo detectors often exhibit exceptionally high responsivity— sometimes reaching $10^2$ to $10^5$ A/W—especially in nanowire and nanorod structures. This impressive performance is largely due to strong photogating effects and trap-assisted gain [85,86]. The trade-off, however, is that these devices usually suffer from slower response times. $Ga_2O_3$ photo detectors, in contrast, typically show more moderate responsivity values in the range of $10^{-2}$ to $10^1$ A/W, but their inherent solar-blind nature gives them outstanding spectral selectivity [87,88]. ZnMgO alloys offer tunable responsivity thanks to their adjustable bandgap composition [89]. Meanwhile, $SnO_2$- and $TiO_2$-based devices generally fall within the 0.03–30 A/W range, depending on factors such as nano structuring, doping, heterojunction design, and applied bias [42,90]. Overall, $Ga_2O_3$ stands out when low noise and precise spectral filtering are essential, while ZnO remains the top performer when maximum sensitivity is the priority.

### *5.2 Detectivity: Seeing the Faintest Signal*

Detectivity (D*) is a more practical performance metric because it accounts for both the device's responsivity and its noise level, making it a strong indicator of how well a detector can sense very weak signals. It is defined as: $D^* = \sqrt{(A\Delta f)} \times (R / i_n)$, where $A$ is the active area of the detector ($cm^2$), $\Delta f$ is the electrical bandwidth (Hz), $R$ is the responsivity (A/W), and $i_n$ represents the noise current (A). $Ga_2O_3$-based devices typically achieve detectivities in the range of $10^{13}$–$10^{14}$ Jones because their Schottky or p–n junction structures naturally produce extremely low dark currents [37,91]. In contrast, ZnO photoconductors often show lower detectivity values ($10^{11}$–$10^{12}$ Jones); even though they can deliver high responsivity, surface trap states contribute significant noise [92,93]. Recent heterojunction designs—especially those incorporating NiO or organic layers—have begun to boost detectivity by improving charge separation and reducing leakage currents [54,94]. Overall, these findings highlight that ZnO excels in high-gain detection, while $Ga_2O_3$ remains the preferred material when low-noise, high-detectivity performance is required in real-world applications.

### *5.3 Response Time: The Speed Frontier*

Response time is a crucial criterion, particularly for applications that need to detect UV events quickly. It refers to how fast a photo detector can respond to changes in incident light intensity. It's typically measured as:

**Rise time ($\tau_r$):** time taken for the photocurrent to increase from 10% → 90% of its maximum value when light is turned on.

**Fall time ($\tau_f$):** time taken for the photocurrent to decrease from 90% → 10% of its maximum value when light is turned off.

Despite their remarkable responsiveness, ZnO photoconductive nanostructures often have recovery times ranging from hundreds of milliseconds to several seconds due to delayed oxygen re-adsorption processes [95]. However, because $Ga_2O_3$ Schottky diodes often generate responses at sub-millisecond or even microsecond scales, they are among the fastest oxide photo detectors to date [67]. Hybrid heterojunctions that offer intermediate performance include $ZnO/TiO_2$, $ZnO/Ga_2O_3$, and ZnO/organic devices. These devices typically balance moderate gain with reaction times in the 1–50 ms range [51, 96–97]. This illustrates a clear trade-off between speed and sensitivity: devices tuned for gain lose speed, while junction-based detectors emphasize quick response.

### *5.4 Stability and Environmental Robustness*

An equally crucial performance criterion is operational stability, which gauges a device's ability to function in real-world situations. $Ga_2O_3$ detectors are noteworthy for their remarkable chemical and thermal durability, which enables dependable operation even under extreme radiation or high temperatures [98]. Even though ZnO and $TiO_2$ devices have been studied extensively, their light response is quickly altered by moisture and adsorbed oxygen, making them sensitive to their environment. However, significant advancements have been demonstrated by encapsulation methods and dielectric passivation (such as $Al_2O_3$ capping layers) [99,51]. Meanwhile, by combining greater environmental tolerance with band gap tunability, ZnMgO alloys and NiO-based heterostructures offer increased robustness [100,101]. Stability benchmarking is becoming increasingly important as photo detectors move from lab demonstrations to deployable solutions.

### 5.5 *Comparative Landscape*

A similar environment emerges when all performance metrics are included. ZnO photo detectors have problems with noise and a delayed response, while being the most responsive [95]. $Ga_2O_3$ devices are the finest in terms of stability, ultrafast response, and solar-blind operation, but they compromise raw responsiveness [67]. $SnO_2$ and $TiO_2$ detectors offer a trade-off between performance and integration opportunities as versatile mid-range performers [102,103]. ZnMgO and NiO-based hybrids, which provide tunability and multifunctionality, expand the design area beyond traditional single-oxide techniques [104,100]. This panorama highlights the fact that each oxide material fits a distinct performance niche that is consistent with specific application areas rather than outperforming all others in every benchmark.

### 5.6 *Future Benchmarking Directions*

The discipline is moving toward more standardized benchmarking processes to enable insightful cross-comparisons. Future reports should prioritize normalized rise/fall time measurements for response speed, both responsivity and detectivity values, and consistent illumination conditions. Furthermore, a systematic evaluation of stability—including testing in different temperatures, humidity levels, and atmospheres—will be required to ensure reproducibility and application readiness. By creating consistent benchmarking standards, the community may uncover material–architecture combinations that combine sensitivity, speed, stability, and scalability more quickly. In the end, this will hasten the integration of metal oxide UV photo detectors into useful technologies.

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## 6. RECENT ADVANCES & STRATEGIES

Innovative approaches in device architecture, hybrid integration, surface engineering, and material design have greatly advanced the development of ultraviolet (UV) sensors based on metal oxide nanostructures and their produced interfaces.

### 6.1 *Doping and Alloying for Performance Enhancement*

A crucial strategy for improving UV sensor performance is doping and alloying metal oxides to alter their electrical structure. The band gap can be carefully adjusted by mixing ZnO and Mg to form ZnMgO, which extends the spectrum sensitivity into deeper UV regions [101]. Metal doping with elements such as Ag, Al, and Ga has been demonstrated to enhance responsivity and accelerate photoreaction by increasing carrier concentration and mobility and reducing trap states [105–107]. Because these dopants effectively passivate defect states and reduce recombination, for example, precise adjustment of electron depletion layers and Debye lengths in silver-doped ZnO nanostructures led to large gains in detectivity and signal-to-noise ratios [108].

### 6.2 *Surface Modification and Functionalization*

Recent studies show that UV detectors made from metal oxide nanostructures can achieve much better performance when their surfaces are engineered—for example, through surface modification or by adding plasmonic nanoparticles [109,110]. Techniques such as applying organic or inorganic coatings, chemical treatments, or decorating the surface with nanoparticles help control oxygen vacancies and passivate defect states. This leads to improved responsivity, faster response times, and reduced noise in the devices [109,110]. Plasmonic nanoparticles s Au, Ag, and Pt—can further enhance performance through localized surface plasmon resonance (LSPR), which boosts light absorption and promotes the efficient generation of charge carriers [111,112]. In many reports, UV detectors based on ZnO or GaN and decorated with Au nanoparticles have shown up to an order-of-magnitude improvement in both responsivity and detectivity. These nanoparticles help stabilize surface oxygen states, suppress electron–hole recombination, minimize persistent photoconductivity, and reduce dark current while increasing overall photon absorption [111,112]. In summary, combining surface modification with plasmonic engineering offers a powerful strategy for significantly enhancing the sensitivity, selectivity, and response speed of next-generation metal oxide UV photo detectors [112].

### 6.3 *Hybrid and Composite Architectures*

In the push toward high-performance UV photo detectors, hybrid and composite designs—where metal oxide nanostructures are paired with other functional materials—are becoming increasingly important. By integrating oxides such as ZnO, $SnO_2$, or $TiO_2$ with conducting polymers, quantum dots, or 2D materials, researchers can create systems that work together to enhance light absorption, charge separation, and carrier transport. Forming heterojunctions or closely bonded interfaces plays a key role: these structures promote efficient charge separation and suppress electron–hole recombination, which leads to faster response times, higher responsivity, and better detectivity. For instance, ZnO/$SnO_2$ and ZnO/polymer composites often produce stronger photocurrents and quicker photo responses than their pure metal-oxide counterparts, mainly due to improved interfacial charge transfer. Incorporating graphene-based materials or quantum dots can further boost surface area and enable flexible or even self-powered device configurations, making them ideal for wearable UV sensors. Overall, hybrid architectures enhance photon harvesting, stabilize surface states, and reduce noise—resulting in more sensitive, stable, and application-ready UV photo detectors [17,113–116].

### 6.4 *Flexible and Transparent Device Configuration*

The development of flexible and transparent ultraviolet (UV) light detectors based on metal oxide nanostructures is one of the key developments in next-generation optoelectronics. Metal oxides such as ZnO, $SnO_2$, and $TiO_2$ can be integrated onto flexible substrates like ultrathin glass and polymers because they can be manufactured at comparatively low temperatures. Because of their inherent high mechanical flexibility, large surface-to-volume ratio, and robust UV absorption, these nanostructures are suited for usage in transparent protective layers for smart windows or displays, wearable sensors, and foldable consumer electronics [113, 116,117]. Flexible UV sensors built with aligned ZnO nanorods, α-$MoO_3$ nanosheets, or other 1D/2D architectures continue to function steadily even after repeated bending or stretching due to strong crystal connections and the ability of nanostructure networks to endure strain. Strong UV sensitivity with minimal visible light interference is ensured by transparent arrangements using ultrathin nanofilms or nanowire arrays. Direct printing, hydrothermal growth, and solution-based methods enable the scalable and economical manufacturing of these state-of-the-art devices on large-area transparent and flexible substrates. [17, 116, 118].

Recent studies have demonstrated the remarkable device performance of flexible ZnO nanorod-based detectors, which provide high on/off ratios, quick response times, and responsivity values above 18 mA/W even after several bending cycles. Because of their mechanical durability, optical transparency, and high UV sensing efficiency, flexible and transparent metal oxide nanostructure photo detectors are positioned as a crucial part of future wearable and transparent electronics [113,118].

### 6.5 *Advanced Integration and Application Scenarios*

The ongoing development of ultraviolet (UV) sensors based on metal oxide nanostructures is being defined by an increasing variety of application scenarios and advanced integration approaches. Examples of advanced integration include monolithic sensor array assembly, hybrid SOCs, and seamless integration with new flexible, transparent, and wireless technologies. These developments enable the creation of multipurpose devices and high-density UV sensing arrays that offer spatially resolved UV imaging, real-time environmental monitoring, and on-body health diagnostics [17,119].These days, a wide range of application scenarios are realized by utilizing the inherent properties of metal oxide nanostructures, such as their high UV sensitivity, mechanical flexibility, chemical robustness, and low processing temperatures. These characteristics make them desirable for use in wearables, disposable smart patches, transparent electronics, and industrial safety systems. For example, flexible UV imaging with consistent responses to mechanical deformation has been demonstrated using ZnO and $SnO_2$-based multi-pixel UV imaging arrays. Scalable production methods such as low-temperature deposition, laser patterning, and direct printing further extend integration possibilities with soft substrates, fabrics, and even curved or uneven surfaces [17,116]. Additionally, the integration of UV detectors with wireless modules, energy harvesters, and signal processing circuits has enabled autonomous and remote sensor networks for agricultural monitoring, air pollution tracking, and environmental UV mapping. The reliability and high sensitivity of metal oxide nanostructures make them suitable for application in phototherapy equipment, clinical diagnostics, flame detection, and secure communication systems, highlighting the increasing significance of UV sensors in both cutting-edge industrial and everyday contexts [17,120,121].

## 7. CHALLENGES AND OPPORTUNITIES

Even while metal oxide-based ultraviolet (UV) sensors have advanced significantly, there are still several major barriers to their broader technological acceptance and improved performance.

### 7.1 *Sensitivity versus Speed Trade-off*

A significant problem with next-generation ultraviolet (UV) sensors based on metal oxide nanostructures is the trade-off between sensitivity and reaction speed. High sensitivity in these devices is typically achieved through enhanced surface adsorption of oxygen species, which results in a deep surface depletion layer and a substantial resistance difference during UV irradiation. An intrinsic characteristic of this surface-driven photoconductivity mechanism is the delayed desorption and re-adsorption of oxygen during the switching cycle, which leads to longer reaction and recovery times [122,123].

ZnO nanostructure devices such as tetrapods, nanorods, and nanoparticle films can demonstrate remarkable sensitivity with on/off ratios greater than 105. However, they often have response or recovery durations in the range of seconds or even minutes, especially at room temperature or in low light. This limits its application in situations where prompt, real-time detection is necessary. Attempts to increase device speed, such as by increasing carrier mobility or lowering the density of surface traps, sometimes result in decreased sensitivity because the surface interaction with oxygen (or other adsorbates) is diminished [122–124].

Several approaches have been proposed to solve this issue, including surface functionalization, doping, heterojunction engineering, and the introduction of light-sensitive interfaces that improve the adsorption/desorption dynamics or replace slow oxygen exchange with faster charge transfer processes. However, maintaining both high sensitivity and fast responsiveness is still a key research goal for wearable, imaging, and high-speed UV sensing applications [123].

### 7.2 *Reproducibility and Scalability of Nanostructure Synthesis*

The large-scale implementation of next-generation ultraviolet (UV) sensors is significantly hampered by the need to achieve both repeatability and scalability in the manufacturing of metal oxide nanostructures. Tight control over nanostructure morphology, crystallinity, and electronic properties is required for consistent device performance; however, small variations in growth conditions, such as temperature, substrate type, and precursor concentration, can cause significant variations in sensor response between batches [125,126]. Numerous high-sensitivity methods, such as hydrothermal growth, co-precipitation, and vapor-phase deposition, have been demonstrated to produce nanowires, nanosheets, or hierarchical assemblies with remarkable UV responsiveness. However, it is challenging to apply these methods to wafer-scale fabrication while preserving batch-to-batch consistency because to issues such non-uniform nucleation, aggregation, and sensitivity to environmental changes during synthesis. Even methods that show consistency in the lab may not be able to produce consistent particle size, doping levels, or crystalline phase when used on larger or roll-to-roll compatible substrates [17,125–127].

In order to enable the scalable and economical integration of nanostructures on transparent and flexible substrates, low-temperature or environmentally friendly techniques, such as green synthesis and printing, are also being researched. However, ensuring that these scalable processes produce nanostructures with the homogeneity and defect control required for commercial UV sensor arrays is an important subject for further research [116,128]. Innovations in automated synthesis, advanced process monitoring, and post-synthetic treatments (such annealing and surface modification) will enable the broader application of high-performance metal oxide nanostructure-enabled UV sensors.

### 7.3 *Interface Control and Defect Minimization*

Reducing defects in metal oxide nanostructures and managing interfaces effectively are necessary to improve ultraviolet (UV) sensor performance. Defects that can operate as both beneficial adsorption active sites and detrimental non-radiative recombination centers that reduce carrier lifetimes and increase noise include grain boundaries, interstitials, and oxygen vacancies. The interfaces that occur between different metal oxides or between metal oxides and other materials (such polymers or 2D nanomaterials) directly affect responsiveness, response speed, and stability. These interfaces have an impact on charge separation, transport, and trapping[17,128].

Recent advances focus on engineered heterojunctions, where carefully controlled surfaces enable efficient separation of photo generated electron-hole pairs, lowering recombination and raising photocurrent. ZnO nanostructures covered with DNA/RNA nucleo bases, for instance, have shown defect passivation and quicker charge transfer, which improve UV light detector sensitivity and reduce dark current. Layer-by-layer assembly, doping, or surface functionalization can also be used to enhance the absorption-desorption kinetics of oxygen ions, which are crucial for UV sensing. These methods have demonstrated success in regulating surface defect states and oxygen vacancy concentrations [116,129,130].

However, improperly maintained interfaces or an excessive defect density may introduce trap states that cause delayed persistent photoconductivity and lower device repeatability. Therefore, improved materials engineering is needed to obtain the necessary defect states and reduce damaging recombination pathways in a careful balance. This comprises meticulous synthesis, atomic-level passivation methods, and post-synthetic processes like annealing. Addressing interface and defect issues remains a crucial area for both fundamental research and practical device development in order to improve the sensitivity, speed, and long-term stability of metal oxide nanostructure-based UV sensors.

### 7.4 *Device Stability in Harsh Environments*

Maintaining device stability under difficult circumstances is one of the primary issues facing ultraviolet (UV) sensors based on metal oxide nanostructures. These sensors are frequently exposed to mechanical loads, temperature swings, humidity, and chemical contaminants, all of which may eventually cause them to malfunction. Metal oxide materials such as ZnO, $SnO_2$, and $TiO_2$ are naturally robust and chemically durable under UV irradiation; however, prolonged exposure to the environment can cause surface deterioration, defect formation, and interface instability in nanoscale structures [17,122].

The stability of UV sensors is largely dependent on the preservation of surface chemistry and defect states that are crucial to the photo response mechanism. For example, degradation caused by moisture or reactive gases may alter the amounts of oxygen vacancies, resulting in baseline current drift, reduced responsiveness, and prolonged response/recovery times. Additional challenges with mechanical fatigue, delamination, and cracks resulting from mechanical flexibility and the use of transparent substrates affect long-term operability [17,116,122].

Recent strategies to improve environmental durability include doping to lock in favorable defect states, surface passivation with protective coatings, and the creation of robust heterointerfaces that block degradation pathways while preserving charge transfer dynamics. Furthermore, packaging methods and encapsulating technologies are crucial for shielding sensitive components from environmental influences [116,131].

Improving device stability under harsh, real-world circumstances is necessary to move metal oxide nanostructure UV sensors from lab prototypes to commercial, wearable, and field-deployable smart sensing systems.

### 7.5 *Future Prospects*

Metal oxide nanostructure-enabled UV sensors are poised for substantial growth and development across numerous domains of research and application. The continued development of synthesis methods such as atomic layer deposition, direct printing, and scalable low-temperature processing will enable customized nanostructures with remarkable sensitivity, selectivity, and mechanical versatility for next-generation flexible and wearable electronics. Future advancements in heterostructure design and interface engineering will further improve charge separation efficiency, operational stability, and defect reduction, creating new opportunities for self-powered, multi-modal UV sensing systems [17].

Emerging developments include UV sensor integration with wireless modules and data analytics, secure communication systems, and on-body health diagnostics. Additionally, synergistic pairings with 2D materials, organic polymers, and quantum dots open up new possibilities for enhancing spectrum selectivity, device transparency, and ruggedness in harsh settings. Although there are still issues with reproducible wafer-scale production, long-term stability, and multi-function integration, rapid developments in materials engineering and device architectures point to broader commercialization and new applications in industrial safety, agriculture, healthcare, and environmental protection [11,17,116].

All things considered, interdisciplinary innovation at the nexus of materials science, electronics, and application engineering is propelling the development of UV sensors based on metal oxide nanostructures, setting the stage for high-performance, pervasive UV sensing technologies.

## 8. CONCLUSION & OUTLOOK

Because of their wide band gaps, excellent chemical and thermal stability, and tunable optoelectronic properties, metal oxides provide a versatile and promising material platform for ultraviolet (UV) photo detectors. Over the past ten years, significant advancements in interface design and nanostructure engineering—including the development of different morphologies like nanorods, nanosheets, and quantum dots—have enhanced sensor performance metrics including sensitivity, selectivity, and reaction time. The prospective applications of metal oxide UV sensors in wearable electronics, healthcare, environmental monitoring, and aerospace technology have been greatly enhanced by these developments.

The convergence of synergistic approaches, such as compositional alloying (e.g., ZnMgO), hybrid material integration with graphene and organic semiconductors, and novel flexible device topologies, supports the development of next-generation UV sensors. These devices stand out for their lightweight design, mechanical robustness, and compatibility with low-cost, scalable production methods including printing and solution-processing. The development of flexible and transparent sensors on unconventional substrates opens up new opportunities for continuous on-body UV exposure monitoring and real-time health diagnostics.

Many opportunities and avenues are apparent while looking ahead. The integration of metal oxide UV sensors into the expanding Internet of Things (IoT) ecosystem promises distributed, autonomous sensing networks capable of managing intelligent infrastructure and detecting environmental threats. The combination of edge computing and artificial intelligence may provide real-time, predictive analytics and personalized exposure risk assessments. Wearable and implantable UV sensor devices enable advanced skin cancer prevention and phototherapy monitoring. The intrinsic high radiation hardness of metal oxides makes these sensors appropriate for dependable deployment in space missions and military systems under challenging operating conditions, in addition to terrestrial applications. Check it out. To realize their greatest potential, they must overcome enduring challenges. These include increased device stability in the face of severe environmental conditions and prolonged UV exposure, scalable and reproducible fabrication techniques for nanostructures with controlled morphology and defect profiles, and precise interface management to lower recombination and noise. Innovations in surface passivation, encapsulation techniques, and heterostructure designs will be crucial to achieving long-term dependability. In conclusion, current multidisciplinary developments in device engineering, materials science, and nanotechnology could transform a number of fields with metal oxide-based UV light detectors. As research closes the existing gaps in performance, manufacturability, and integration, these sensors will be crucial to the creation of safer, smarter, and healthier technologies during the next 10 years. To realize their greatest potential, they must overcome enduring challenges. These include increased device stability in the face of severe environmental conditions and prolonged UV exposure, scalable and reproducible fabrication techniques for nanostructures with controlled morphology and defect profiles, and precise interface management to lower recombination and noise. Innovations in surface passivation, encapsulation techniques, and heterostructure designs will be crucial to achieving long-term dependability. In conclusion, ongoing interdisciplinary developments in device engineering, materials science, and nanotechnology have the potential to transform a number of fields through metal oxide-based UV light detectors. As research closes the existing gaps in performance, manufacturability, and integration, these sensors will be crucial to the creation of safer, smarter, and healthier technologies during the next 10 years.

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