

Effective NiO channel engineering for performance enhancement of lateral perovskite-based UV photodetectors

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Abstract. Lateral perovskite-based ultraviolet photodetectors (UV PDs) are attractive for their simple fabrication and easy integration, but their performance is often limited owing to nonuniform film formation on patterned substrates and trap-assisted recombination during lateral charge transport. In this paper, a ~70 nm sputtered NiO thin film is introduced as an interfacial channel layer prior to solution processing of halide perovskite on patterned ITO/glass with a 1 mm electrode gap. The NiO underlayer provides a crystalline wide-bandgap platform that improves perovskite film uniformity and promotes larger grains with fewer grain boundaries. Photoluminescence quenching and electrochemical impedance spectroscopy techniques further indicate reduced recombination and lower charge-transfer resistance, which is consistent with enhanced hole transport in the NiO-assisted architecture. Consequently, the NiO-integrated device exhibits a markedly increased photocurrent (0.476 to 1.28 μA at 370.92 $\mu\text{W}/\text{cm}^2$ under 254 nm illumination), together with improved responsivity (17.4 to 33.04 mA/W) and EQE (8.5% to 16.2%). These results demonstrate that sputtered NiO serves as an effective interfacial channel to simultaneously improve film formation and charge extraction in lateral perovskite UV photodetectors.

Keywords: lateral ultraviolet photodetector, halide perovskite, NiO thin film, interfacial engineering

1 Introduction

Recently, metal-halide perovskites have garnered substantial attention as low-cost semiconductors for optoelectronic devices, including solar cells, light-emitting diodes, artificial synapses, semiconductor lasers, and ultraviolet photodetectors (UV PDs) [1–5]. These materials offer several key advantages, such as high crystallinity achievable at low processing temperatures, strong and broadband optical absorption, high charge-carrier mobility, and facile solution processability that enables cost-effective fabrication [6, 7]. Accordingly, employing halide perovskites as efficient photoabsorber layers represents a promising strategy for realising high-performance optoelectronic devices. In the context

of UV photodetection, halide-perovskite-based devices exhibit rapid photoresponse and can cover a wide spectral range extending from X-rays to the near-infrared region [8, 9]. This broad detectability supports diverse applications, including missile warning systems, secure optical communications, space exploration, partial-discharge monitoring, flame detection, and related sensing scenarios [10–13].

Regarding the development of UV photodetectors, perovskite photodiodes can be implemented in either vertical or lateral architectures, each offering distinct advantages [14, 15]. Vertical devices can enable self-powered operation, in which photogenerated charge carriers (electrons and holes) are separated and

transported to the electrodes by the built-in electric field arising from appropriately aligned energy bands at the semiconductor interfaces [16, 17]. In contrast, lateral UV PDs are attractive for their structural simplicity and ease of integration. In numerous cases, lateral photodetectors can be realised by using a metal-semiconductor-metal configuration, where the photoabsorber is positioned between two coplanar electrodes and the device performance is strongly governed by the electrode spacing [18, 19].

Despite these advantages, halide-perovskite metal-semiconductor-metal photodiodes face notable fabrication challenges. First, defining lateral top electrodes on perovskite films via photolithography is difficult because the perovskite layer is susceptible to dissolution in common solvents and processing chemicals. Second, when perovskite films are deposited by spin coating onto pre-patterned, electrode-bearing substrates, achieving a uniform and continuous layer remains challenging [20]. To partially address these issues, we propose inserting a thin nickel oxide (NiO) film on the patterned substrate prior to depositing the halide perovskite via a solution process. Although NiO has been widely employed in perovskite optoelectronic devices, most previous studies focused on its role as a hole-transport layer in vertical architectures, particularly in perovskite solar cells and conventional photodiodes. By contrast, the role of NiO in lateral perovskite UV photodetectors remains much less explored, especially for the devices fabricated on patterned substrates with relatively large electrode gaps, where nonuniform film formation and trap-assisted recombination become more critical. In this work, the novelty does not simply lie in introducing NiO into a perovskite system, but in using a sputtered NiO thin film as an interfacial channel layer in a lateral UV-photodetector architecture. This NiO underlayer simultaneously improves perovskite

film continuity on the patterned substrate and promotes lateral hole transport, thereby addressing two key limitations of large-gap lateral perovskite photodetectors at the same time. As a proof-of-concept, the device incorporating the NiO thin film exhibits a markedly increased photocurrent, and its responsivity reaches 33.04 mA/W, compared with 17.39 mA/W for the control device without NiO.

2 Experimental

2.1 Materials

Nickel (II) oxide powder (NiO, >97%) was purchased from Duksan company (Gyeonggi, Korea). Lead (II) iodide (PbI₂, 99.99%), N,N-dimethylformamide (DMF, 99.8%), dimethyl sulfoxide (DMSO, 99.9%), and isopropyl alcohol (IPA, 99.5%) were purchased from Sigma-Aldrich. Formamidinium iodide (FAI), methylammonium bromide (MABr), and methylammonium chloride (MACl) were procured from GreatCell Solar.

2.2 Preparation of photodetector

First, indium tin oxide (ITO)-coated glass substrates (2 cm × 2 cm) were patterned by wet chemical etching with zinc powder and an HCl solution, yielding a 1 mm electrode gap. The patterned substrates were then sequentially cleaned in acetone, isopropanol, deionised water, and ethanol by using ultrasonication for 10 min in each solvent and dried prior to film deposition. Second, a thin NiO film was deposited onto the patterned substrates by magnetron sputtering with a laboratory-fabricated NiO target. The 1-inch-diameter NiO target was prepared by uniaxially pressing high-purity NiO powder, followed by sintering at 1,300 °C for 24 h. The sputtering conditions, including working pressure, gas flow rate, deposition time, and substrate temperature, are summarised in Table 1. Finally, a halide-perovskite UV-absorber layer was deposited on

the NiO film via a two-step spin-coating procedure, following our previous report [21]. Briefly, the substrates were treated with ozone for 15 min. A 1.3 M PbI₂ precursor solution in DMF/DMSO (0.95:0.5, v/v) was then spin-coated at 2000 rpm for 30 s and annealed at 70 °C on a hot plate. Subsequently, a mixed organic-halide solution containing FAI/MABr/MACl (60:6:6 mg) dissolved in 1 mL isopropanol was spin-coated onto the PbI₂ layer at 4000 rpm for 20 s (loading time: 20 s), followed by thermal annealing at 150 °C for 15 min to form the perovskite layer.

Table 1. Preparation parameters of NiO thin film with sputtering method

Parameters	Value
Target material	lab-made NiO target
Substrate	patterned ITO-coated glass
Working pressure (mTorr)	50
Sputtering power (W)	50
Gas flow rate (SCCM)	Ar/O ₂ = 0:40
Sputtering time (minutes)	45
Substrate temperature	ambient temperature
Post-annealed temperature/time	500 °C/1 hour

2.3 Characterisation and measurements

The crystallinity of the sputtered NiO thin films was examined by using X-ray diffraction (XRD; D8 Advance Eco, Bruker AXS, Germany) with Cu K α radiation ($\lambda = 1.506 \text{ \AA}$). The optical properties of the NiO films were characterised by using UV-vis absorption spectroscopy (V-770, Jasco, Japan) and steady-state photoluminescence (PL) spectroscopy (Horiba, Nanolog). The surface morphology and film thickness were analysed by using scanning electron microscopy (SEM; IT200, JEOL, Japan). The charge-transfer resistance of the perovskite photodetectors was assessed by using

electrochemical impedance spectroscopy (EIS; VSP, Bio-Logic Science Instruments, France). The photoresponse characteristics were recorded with a Keithley 2400 SourceMeter (USA) coupled to a 254 nm UV lamp (Analytik Jena, USA).

3 Results and discussion

Fig. 1a presents the XRD pattern of the NiO thin film deposited by sputtering. All characteristic diffraction peaks confirm the formation of crystalline NiO and can be indexed to the (111), (200), (220), (311), and (222) planes, in good agreement with the standard NiO pattern (ICDD card No. 47-1049). The optical properties of the sputtered NiO film are shown in the UV-vis spectrum in Fig. 1b. The absorption edge is located at approximately 340 nm. The optical bandgap (E_g) of the as-prepared NiO film was estimated to be $\sim 3.69 \text{ eV}$ from the Tauc plot, consistent with previous reports on NiO thin films [22]. Fig. 1c and 1d show the top-view and cross-sectional SEM images, respectively, revealing the surface morphology and thickness of the sputtered NiO layer. The micrographs indicate a dense, compact microstructure, forming a continuous, uniform thin film. The thickness of the NiO film is approximately 70 nm.

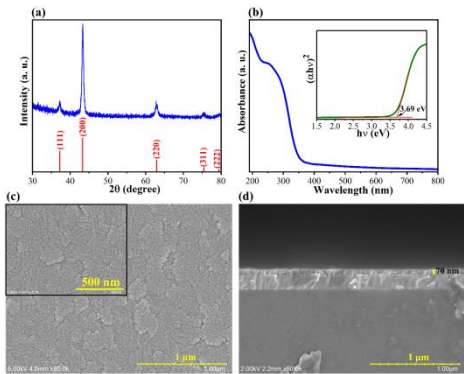


Fig. 1. (a) XRD pattern; (b) UV-vis absorption spectrum (inset: Tauc plot); (c) top-view SEM image (inset: higher-magnification view); (d) cross-sectional SEM image of sputtered NiO thin film

Fig. 2a and 2b compare the surface morphology of the perovskite films deposited directly on patterned ITO/glass and on the same substrate incorporating a 70 nm NiO underlayer, respectively. As shown in Fig. 2a, the perovskite film formed on the patterned ITO/glass exhibits relatively small grains and poor film continuity. This behaviour is likely associated with the step discontinuity at the etched gap between the ITO electrodes and the bare glass region in the lateral architecture, which can hinder uniform spreading and crystallisation during spin coating, thereby leading to film non-uniformity. Similar limitations have been reported for perovskite deposition on pre-patterned, electrode-coated substrates [20]. By contrast, introducing a NiO thin film beneath the perovskite layer improves the film formation (Fig. 2b). In addition to functioning as an effective hole-transport layer, the NiO layer bridges and passivates the electrode-gap region, providing a more homogeneous surface for solution coating. Consequently, the perovskite film deposited on NiO exhibits larger grains, a more compact morphology, and reduced grain-boundary density compared with the control film without NiO.

After surface defects in the perovskite film are mitigated, the NiO channel also suppresses charge recombination and promotes hole transport in the lateral halide-perovskite UV photodetector. Fig. 2c shows the steady-state PL spectra of the perovskite-only and NiO/perovskite films collected over 650–950 nm under 520 nm excitation. The pronounced quenching of the emission peak at ~775 nm for the NiO/perovskite sample indicates reduced radiative recombination, consistent with more efficient charge extraction at the NiO/perovskite interface [23, 24]. This interpretation is further supported by the EIS results in Fig. 2d. The UV PD incorporating the NiO thin film exhibits a smaller impedance (i.e., lower charge-transfer resistance) than the control device without NiO, indicating improved

interfacial charge transport. Collectively, these results confirm that the NiO interlayer facilitates hole transfer from the perovskite absorber to the external electrodes in the lateral device architecture.

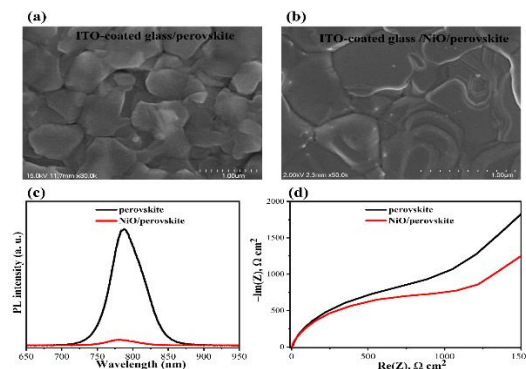


Fig. 2. (a, b) Top-view SEM images of perovskite films deposited on patterned ITO/glass without and with a NiO underlayer; (c) Steady-state PL spectra; (d) EIS Nyquist plots of perovskite and NiO/perovskite films

Fig. 3a and 3b schematically illustrate the lateral photodetector architectures fabricated without and with an inserted NiO thin film, respectively. In the control device (perovskite-only), the perovskite absorber is deposited directly on the patterned ITO/glass substrate, and the photocurrent is collected laterally between the two coplanar electrodes. Because the perovskite film formed on the patterned surface is relatively non-uniform and contains a higher density of grain boundaries and interfacial defects, photogenerated carriers are prone to trapping and recombination within the perovskite layer and at the perovskite/substrate interface. As a result, under UV illumination, a considerable fraction of electron-hole pairs recombines before being extracted, limiting the net photocurrent even under an applied bias. In the NiO/perovskite device (Fig. 3b), a thin NiO layer is introduced prior to perovskite deposition, forming a continuous lateral transport channel and a selective interfacial contact. Upon contact, the energy bands of NiO and the halide perovskite align, establishing a favourable junction for hole

extraction. Under UV irradiation, electron-hole pairs are generated in the perovskite absorber. When an external bias is applied across the lateral electrodes, the built-in band offsets at the NiO/perovskite interface promote charge separation and directional transport: holes are preferentially transferred from the perovskite into the NiO layer and then transported laterally to the collecting electrode, whereas electrons are impeded from entering NiO because of the conduction-band barrier. Simultaneously, the valence-band alignment facilitates hole-selective transport, thereby reducing carrier accumulation in the perovskite and suppressing interfacial and recombination (Fig. 3c). Therefore, incorporating the NiO thin film provides two synergistic benefits: (i) it creates a more homogeneous interfacial platform that improves perovskite film quality and reduces defect-assisted recombination pathways, and (ii) it functions as a hole-transporting/electron-blocking layer that enhances charge separation and extraction in the lateral configuration.

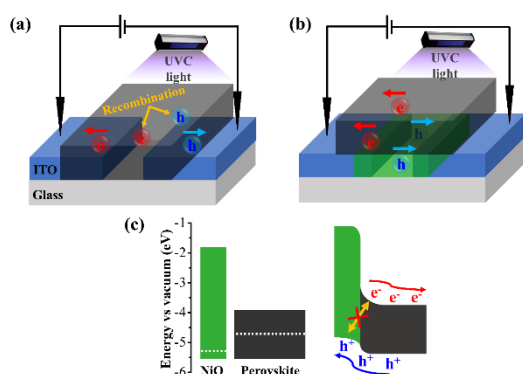


Fig. 3. (a, b) Schematic architectures of lateral photodetectors without and with a NiO thin film; (c) Proposed operating mechanism of the ITO/NiO/perovskite/ITO photodetector [25, 26]

Fig. S1 compares the current-voltage (I - V) characteristics of the devices fabricated without and with a NiO interlayer to assess the impact of the NiO channel on the performance of lateral perovskite-based UV PDs. The dark current (I_D) and current under illumination (I_L) were measured for devices with a 1 mm lateral electrode spacing

by sweeping the bias from -50 to $+50$ V under different UV illumination conditions. As shown in Fig. 4a and 4b, the I - V curves in the forward-bias region exhibit a clear separation between I_D and I_L , confirming the photoresponse of both devices. Notably, introducing the NiO thin film leads to (i) a pronounced increase in I_L , attributable to more efficient photocarrier separation and accelerated charge transport enabled by the NiO channel, and (ii) a slight increase in I_D , which is reasonably ascribed to the additional conductive pathway provided by the NiO layer.

The photoresponse was further evaluated by measuring current-time (I - t) plots at an applied bias of 50 V under 254 nm UV illumination with intensities ranging from 90 to 370.92 $\mu\text{W}/\text{cm}^2$ (Fig. 4c and 4d). In comparison with the control device, the NiO-integrated device exhibits a substantially higher steady-state photocurrent. Specifically, at 370.92 $\mu\text{W}/\text{cm}^2$, I_L increases from 0.476 μA for the device without NiO to approximately 1.28 μA for the device with NiO. This marked enhancement indicates that the NiO channel facilitates more efficient charge extraction from the perovskite absorber and improves lateral carrier transport toward the ITO electrodes, thereby strengthening the overall photodetection signal in the lateral architecture.

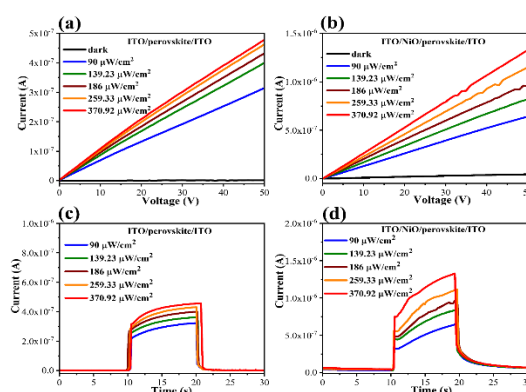


Fig. 4. (a, b) I - V curves in the dark and under 254 nm illumination at different power intensities; (c, d) Time-dependent photocurrent at 50 V under 254 nm illumination at different power intensities

To compare the charge-collection efficiency of the NiO-integrated device (ITO/NiO/perovskite/ITO) with that of the control device (ITO/perovskite/ITO), we defined the photocurrent as $I_{\text{photo}} = I_L - I_D$. As shown in Fig. 5a, I_{photo} increases monotonically with the incident intensity over the range of 90–370.92 $\mu\text{W}/\text{cm}^2$, and the NiO-coated device consistently exhibits a substantially higher photocurrent than the control. This observation confirms that the NiO channel enhances the effective extraction and lateral transport of photogenerated carriers from the perovskite absorber to the ITO electrodes.

The dependence of photocurrent on optical power was further analysed by using a power-law relationship, $I_{\text{photo}} \propto P^\theta$, as presented in Fig. 5b [27]. The fitted exponent θ increases from 0.29 (control) to 0.55 (NiO-integrated device). A larger θ indicates a reduced degree of sublinearity in the photoresponse, which is commonly associated with a lower density of trap states and suppressed trap-assisted recombination under illumination [28, 29]. Therefore, the increase in θ supports that incorporating NiO mitigates defect-mediated carrier loss and improves the photocarrier collection efficiency in the lateral configuration.

Key UV PD figures of merit, including responsivity (R) and external quantum efficiency (EQE), are summarised in Fig. 5c and Fig. 5d, respectively. For both devices, R and EQE decrease as the optical power density increases. This trend is consistent with a sublinear photoresponse ($\theta < 1$), where the photocurrent scales less than proportionally with incident power because of trap-state filling, enhanced recombination, and space-charge-limited transport at higher excitation levels [30]. Notably, the NiO-integrated device outperforms the control across the entire intensity range, exhibiting consistently higher R and EQE. Specifically, the maximum responsivity increases from 17.4 mA/W for the control device to 33.04 mA/W with NiO, while the maximum EQE

rises from 8.5 to 16.2% upon introducing the NiO thin film. Furthermore, the statistical results obtained from five devices fabricated with the same procedure (as shown in Fig. S2) indicate good reproducibility, supporting the reliability of the above conclusions.

The specific detectivity (D^*) also shows a decreasing tendency with increasing light intensity for both devices (Fig. S3). However, the NiO-based device yields a lower D^* (1.23×10^{11} Jones) than the control (3.64×10^{11} Jones). This reduction is attributed to the increased dark current associated with the more conductive charge-transport pathway introduced by the NiO interlayer. Although the NiO layer markedly enhances the photocurrent by improving perovskite film uniformity, facilitating hole extraction, and suppressing recombination, the resulting increase in dark current partially offsets the benefit of the enhanced photoresponse in terms of detectivity. Therefore, the present result indicates a trade-off between improved photocarrier collection under illumination and increased background current in the dark. In addition, the device currently operates at a relatively high bias (50 V), which is mainly associated with the large lateral electrode spacing (1 mm) and the consequently weak lateral electric field at low voltage. Such a high operating voltage may limit practical applications because of increased power consumption and reduced compatibility with low-voltage integrated systems. Future work will therefore focus on reducing the electrode gap, optimising the thickness and conductivity of the NiO layer, and improving interfacial selectivity to achieve high photoresponse at lower operating voltage while maintaining low dark current. To further assess the dynamic response of the device, we provided a single-pulse photoresponse curve in Fig. S4. From the transient profile, the rise time (t_{rise} , 10–90% of the peak photocurrent) and fall time (t_{fall} , 90–10% of the peak photocurrent) were estimated to be

approximately 0.112 s and 5.6 s, respectively. The short rise time reflects efficient photocarrier generation and extraction upon UV illumination, while the comparatively longer fall time can be attributed to trap-mediated carrier release and recombination processes. The device stability was further examined under 254 nm UV illumination (Fig. S5). The NiO-integrated photodetector exhibits reproducible current switching over multiple light on/off cycles, indicating stable and repeatable operation under continuous UV modulation.

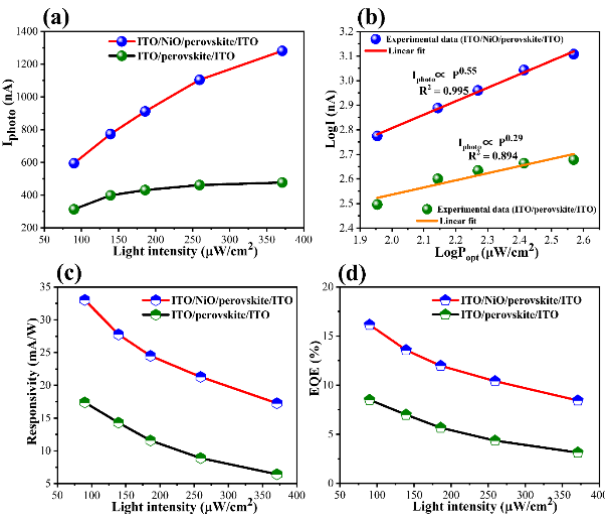


Fig. 5. (a) Generated photocurrent plots; (b) Relations of photocurrent and light intensity; (c) Responsivity; (d)

EQE of lateral devices without and with a NiO thin film under 254 nm illumination (90–370.92 $\mu\text{W}/\text{cm}^2$)

4 Conclusion

In conclusion, the performance of 1 mm-gap lateral perovskite UV photodetectors was enhanced by inserting a ~ 70 nm sputtered NiO interlayer on patterned ITO electrodes. The NiO film provides a more favourable coating platform for perovskite deposition, leading to improved film formation and grain growth, while simultaneously acting as a hole-selective transport channel that facilitates carrier extraction and suppresses recombination. As a result, the NiO-integrated device exhibits a stronger UV photoresponse at 254 nm, with the responsivity increasing from 17.4 to 33.04 mA/W and the EQE from 8.5 to 16.2%. Unlike the commonly reported role of NiO as a hole-transport layer in vertical perovskite devices, this study demonstrates that sputtered NiO can function effectively as an interfacial channel layer in a large-gap lateral architecture. These findings highlight a practical interfacial-engineering approach for addressing morphology- and recombination-related limitations in lateral perovskite UV photodetectors.

5 Supplementary Materials

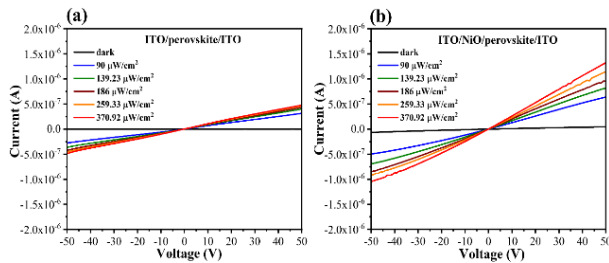


Fig. S1. Bias-dependent I-V curves (–50 to +50 V) for (a) ITO/perovskite/ITO and (b) ITO/NiO/perovskite/ITO measured in darkness and under 254 nm UV exposure at different intensities

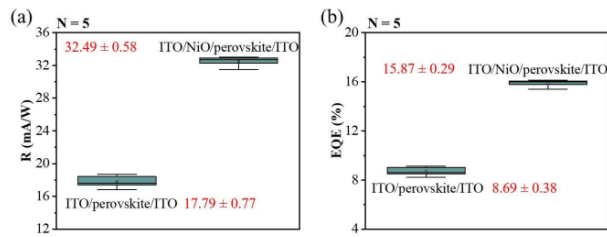


Fig. S2. Statistical distribution of (a) R and (b) EQE at 50 V under 90 $\mu\text{W}/\text{cm}^2$ for ITO/perovskite/ITO and ITO/NiO/perovskite/ITO devices based on five independently fabricated samples

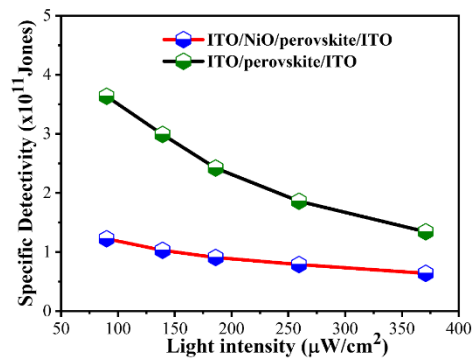


Fig. S3. Specific detectivity as a function of incident power density for the control and NiO-based lateral UV photodetectors

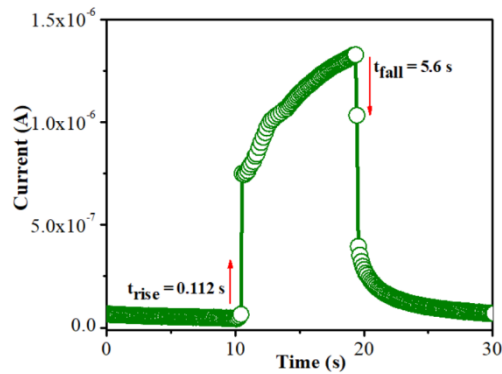


Fig. S4. Response time of the NiO-based UV photodetector

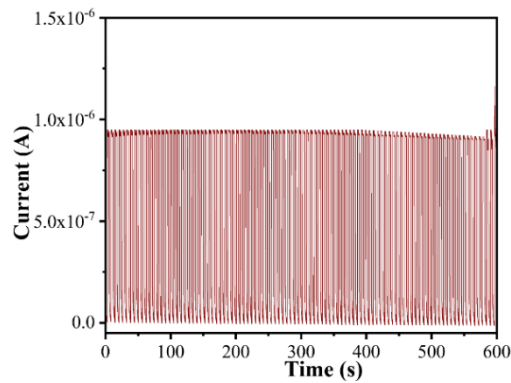


Fig. S5. Photocurrent stability of the NiO-based device under continuous 254 nm UV light on/off switching

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