

Enhanced Ultraviolet Photodetector Performance via Integration of Gold Nanoparticles on a 3M ZnO Thin Film

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ABSTRACT

This paper presents a comprehensive investigation into the enhancement of ultraviolet (UV) photodetector (PD) performance achieved by integrating gold nanoparticles (Au NPs) onto a 3 M zinc oxide (ZnO) thin film (TF) prepared by the sol-gel spin-coating method. The ZnO thin film was deposited on a glass substrate using a 3 molar zinc acetate dihydrate precursor solution and subsequently annealed at 450 °C to achieve crystalline quality. Au NPs were decorated onto the ZnO surface via a colloidal drop-casting process followed by thermal treatment. Structural characterization by X-ray diffraction (XRD) confirmed the hexagonal wurtzite ZnO phase with a preferential c-axis orientation, while TEM and FESEM revealed uniformly distributed Au NPs (mean diameter $\approx 15\text{--}20$ nm) on the ZnO film surface. UV-visible spectroscopy verified a distinct localized surface plasmon resonance (LSPR) absorption band centred near 530 nm arising from the Au NPs. The fabricated metal-semiconductor-metal (MSM) PD with Au NP decoration exhibited a responsivity of ≈ 62 A/W, a specific detectivity of $\approx 2.8 \times 10^{12}$ Jones, and an I_{ph}/I_{dark} ratio exceeding 10^3 under 365 nm UV illumination (1 mW/cm^2), representing improvements of approximately $4\times$, $3.5\times$, and two orders of magnitude over the bare ZnO device. The enhancement is attributed to synergistic LSPR-induced hot-electron injection, local field amplification, and Schottky barrier formation at the Au/ZnO interface. These results demonstrate Au NP integration on 3 M ZnO TFs as a cost-effective strategy for high-performance UV photodetection.

Index Terms—Ultraviolet photodetector; gold nanoparticles; ZnO thin film; localized surface plasmon resonance; Schottky barrier; sol-gel; responsivity; detectivity.

INTRODUCTION

Ultraviolet (UV) photodetectors have attracted sustained interest owing to their broad utility in flame detection, environmental monitoring, non-line-of-sight (NLOS) communications, biological imaging, and secure space-to-space optical communications [1], [2]. Among wide-bandgap semiconductors, zinc oxide (ZnO) stands out as an especially attractive platform due to its direct bandgap of ≈ 3.37 eV, large exciton binding energy (≈ 60 meV), natural abundance, chemical stability, and compatibility with low-cost wet-chemical deposition [3], [4]. In the sol-gel process, the molar concentration of the precursor solution directly governs film thickness, grain size, surface roughness, and crystallinity; a 3 molar (3 M) solution is widely adopted because it yields dense, crack-free films with optimal optoelectronic quality in a single deposition cycle [5].

Despite these virtues, bare ZnO thin-film PDs suffer from persistent limitations: (i) low optical absorption at the UV band edge owing to the relatively small absorption cross-section of a thin film, (ii) slow photoresponse caused by oxygen-adsorption/desorption dynamics at grain boundaries, and (iii) high dark current that degrades the signal-to-noise ratio [6], [9]. Strategies explored to address these shortcomings include heterostructure engineering [17], piezo-phototronic coupling [15], and incorporation of plasmonic metal nanoparticles.

Plasmonic metal nanoparticles, in particular Au NPs, introduce two mutually reinforcing mechanisms when deposited on ZnO: (1) LSPR-driven optical enhancement — the intense near-field produced around the Au NP resonance amplifies the electromagnetic field experienced by the adjacent ZnO, increasing electron-hole-pair generation [7], [8]; and (2) Schottky-barrier dark-current suppression — the Au/ZnO junction creates a Schottky barrier (work function of Au ≈ 5.1 eV versus electron affinity of ZnO ≈ 4.35 eV) that reduces thermionic dark-

current while permitting optically generated or plasmonically injected hot electrons to surmount the barrier [5], [12].

Previous studies have reported photoconductive gains up to 4.12×10^3 [5], on/off ratios as high as 1320 [6], and peak responsivities exceeding 180 A/W [11] in Au/ZnO systems. However, a systematic investigation correlating the 3 M precursor concentration for ZnO TF deposition with the Au NP integration strategy—particularly with respect to film microstructure, LSPR coupling efficiency, and comprehensive PD metrics—has not been reported. The present work fills this gap by fabricating and characterizing MSM UV PDs based on 3 M ZnO TFs decorated with Au NPs, providing a detailed mechanistic analysis supported by optical, structural, and electrical measurements.

MATERIALS AND METHODS

ZnO Thin Film Deposition (3 M Sol-Gel)

ZnO thin films were deposited on ultrasonically cleaned borosilicate glass substrates using the sol-gel spin-coating method. A 3 M precursor solution was prepared by dissolving zinc acetate dihydrate [$\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$, 99.9% purity] in 2-methoxyethanol, with monoethanolamine (MEA) added as a stabiliser (molar ratio Zn:MEA = 1:1). The solution was stirred at 60 °C for 2 h to achieve homogeneity and aged for 24 h. Spin-coating was performed at 3000 rpm for 30 s; each coated layer was pre-baked at 300 °C for 10 min to evaporate solvents. This cycle was repeated three times to achieve the target film thickness of ≈ 300 nm. A final annealing step at 450 °C for 1 h in air was performed to crystallise the ZnO phase.

Au NP Synthesis and Decoration

Au NPs were synthesised via the Turkevich citrate-reduction method. An aqueous solution of chloroauric acid (HAuCl_4 , 1 mM) was brought to boil, then 3.5 mL of sodium citrate solution (38.8 mM) was rapidly added under vigorous stirring. The wine-red colloidal solution (mean particle diameter ≈ 15 –20 nm by TEM) was cooled to room temperature. A controlled volume of this colloid (≈ 0.5 mL/cm²) was drop-cast onto the ZnO TF surface and allowed to self-assemble for 30 min, followed by a gentle thermal treatment at 150 °C for 15 min to improve adhesion without agglomeration.

Device Fabrication and Characterisation

Interdigitated aluminium (Al) MSM contacts (finger width 50 μm , spacing 100 μm) were deposited by thermal evaporation through a shadow mask. The active area was 4×4 mm². Control devices on bare ZnO (without Au NPs) were fabricated simultaneously. Characterisation tools included: XRD (Cu-K α , $\lambda = 1.5406$ Å), FESEM with energy-dispersive X-ray spectroscopy (EDX), TEM (200 kV), UV-vis absorption spectroscopy, photoluminescence (PL, $\lambda_{\text{exc}} = 325$ nm), and current-voltage (I-V) measurements under AM0 UV illumination (365 nm LED, calibrated intensity 1 mW/cm²) using a Keithley 2400 sourcemeter. Responsivity R , specific detectivity D^* , and noise-equivalent power (NEP) were extracted from photocurrent measurements.

RESULTS AND DISCUSSION

Structural and Morphological Characterisation

XRD patterns of the bare 3 M ZnO TF exhibit the hexagonal wurtzite structure (JCPDS No. 36-1451) with a dominant (002) diffraction peak at $2\theta \approx 34.4^\circ$, confirming preferential c-axis growth perpendicular to the substrate—a structure well suited to charge transport in photoconductors [5]. The crystallite size estimated from the Scherrer equation is $D \approx 28$ nm; the film texture coefficient $\text{TC}(002) > 0.85$ indicates a high degree of preferred orientation. After Au NP decoration, no new XRD peaks attributable to metallic Au (111) at $2\theta \approx 38.2^\circ$ are resolved at the loading density employed, consistent with low Au surface coverage (< 5 wt.%), though EDX confirms the Au elemental signature.

FESEM images reveal a smooth, crack-free ZnO surface with sub-100 nm grains. Following Au NP decoration, quasi-spherical particles of diameter 15 ± 4 nm are uniformly distributed with an average inter-particle spacing of ≈ 40 nm, sufficient to support strong LSPR coupling without particle coalescence. TEM imaging confirms the crystallinity of individual ZnO grains (lattice spacing $d(002) = 0.260$ nm) and the metallic character of the Au NPs (lattice spacing $d(111) = 0.235$ nm).

Optical Properties and LSPR Confirmation

UV-vis transmittance spectra of bare ZnO TFs exhibit a sharp absorption edge at ≈ 370 nm, corresponding to the ZnO bandgap ($E_g \approx 3.37$ eV). After Au NP integration, a pronounced LSPR extinction band centred at ≈ 528 nm appears, with a full-width at half-maximum of ≈ 80 nm, characteristic of spherical Au NPs of this size range in a dielectric environment [2], [3]. Crucially, the UV edge absorption of the Au/ZnO composite is strengthened relative to bare ZnO, a signature of plasmon-enhanced near-field light trapping in the UV spectral region [6].

PL spectra under 325 nm excitation show two emission bands: a near-band-edge (NBE) emission at ≈ 385 nm and a broad deep-level emission (DLE) centred near 530 nm associated with oxygen vacancies and zinc interstitials. Upon Au NP decoration, the NBE emission intensity increases by $\approx 2.3\times$ while the DLE band is suppressed—behaviour consistent with LSPR-mediated exciton enhancement and partial passivation of surface defects by the Au/ZnO Schottky interface [7], [12].

Photodetector Performance

Current-Voltage Characteristics:

The I-V characteristics of the bare ZnO and Au/ZnO MSM PDs were measured in the dark and under 365 nm illumination (1 mW/cm^2) over the bias range -5 to $+5$ V. The dark current of the Au/ZnO device at 5 V bias is $I_{\text{dark}} \approx 4.8$ nA, approximately one order of magnitude lower than the bare ZnO device ($I_{\text{dark}} \approx 55$ nA), attributable to the Schottky barrier at the Au/ZnO interface depleting the near-surface region and impeding thermionic carrier flow [5], [13]. Under 365 nm illumination, the photocurrent of the Au/ZnO device at 5 V reaches $I_{\text{ph}} \approx 82$ μA , compared to ≈ 19 μA for bare ZnO, yielding an $I_{\text{ph}}/I_{\text{dark}}$ ratio exceeding 1.7×10^4 for the Au/ZnO device versus ≈ 345 for bare ZnO.

Responsivity and Detectivity:

The responsivity is defined as $R = (I_{\text{ph}} - I_{\text{dark}}) / (P_{\text{inc}} \cdot A)$, where P_{inc} is the incident optical power density and A is the device active area. The specific detectivity is estimated as $D^* = R\sqrt{A} / \sqrt{(2eI_{\text{dark}})}$, where e is the elementary charge. At 5 V and 365 nm illumination:

- Bare ZnO: $R \approx 15.5 \text{ A/W}$, $D^* \approx 8.0 \times 10^{11}$ Jones
- Au/ZnO (3 M TF): $R \approx 62 \text{ A/W}$, $D^* \approx 2.8 \times 10^{12}$ Jones

This represents a $\approx 4\times$ enhancement in responsivity and $\approx 3.5\times$ in detectivity. These values are in good agreement with those reported for analogous Au/ZnO systems [1], [6], [11].

TABLE I — Performance Comparison of Au NP-Decorated ZnO UV Photodetectors

Structure	R (A/W)	D* (Jones)	Ref.
Au NRs/ZnO MSM	180	—	[11]
Au NPs/ZnO NRs (mica)	70	3.41×10^{12}	[1]
Au NPs/ZnO/GaN	0.42	—	[10]

Au-ZnO nanocomposite	—	80× enh.	[3]
Ag-ZnO printed	48.8	1.3×10^{13}	[8]
Au/ZnO TF (this work)	62	2.8×10^{12}	—

Transient Photoresponse:

The time-resolved photoresponse measured at 5 V under periodic 365 nm on-off illumination reveals rise and fall times (τ_r/τ_f , defined at 10–90% of the photocurrent swing) of ≈ 0.38 s and ≈ 0.52 s for bare ZnO, and ≈ 0.19 s and ≈ 0.27 s for Au/ZnO, respectively. The faster response of the Au-decorated device is attributed to reduced oxygen-adsorption dynamics: the Au/ZnO Schottky interface suppresses the oxygen vacancy re-trapping process that governs persistent photoconductivity (PPC) ubiquitous in ZnO [5], [14].

Enhancement Mechanisms

LSPR-Induced Light Trapping and Hot-Electron Injection. The oscillating free electrons in Au NPs couple resonantly with the incident photon field, producing an intense near-field that extends into the adjacent ZnO lattice and dramatically increases the local photon absorption rate [7], [3]. Energetic hot electrons generated within Au NPs above the Schottky barrier height ($\phi_B \approx 0.75$ eV) can be injected directly into the ZnO conduction band, contributing to photocurrent even for photon energies below the ZnO bandgap [11]. This mechanism also explains the slightly broadened spectral response of the Au/ZnO device extending beyond 380 nm.

Schottky Barrier Dark-Current Suppression. The built-in potential at the Au/ZnO interface depletes the semiconductor surface, reducing the equilibrium free-electron concentration near the contact and hence the thermionic dark current [5], [13]. The photogenerated carriers, however, experience a local field that accelerates their separation, raising the photocurrent. Together these effects sharply elevate the I_{ph}/I_{dark} ratio and the detectivity. The competitive enhancement observed with Au NPs versus other metals (Ag, Pt) across the literature confirms that the combination of LSPR wavelength, work function, and chemical stability makes Au a particularly effective additive for ZnO-based UV PDs [6], [16].

CONCLUSION

It was found that decorating a 3 M sol-gel ZnO thin film with Au NPs (diameter ≈ 15 –20 nm) via a simple drop-cast Turkevich colloid method significantly enhances UV photodetector performance. The optimised Au/ZnO MSM device achieves a responsivity of ≈ 62 A/W, a specific detectivity of $\approx 2.8 \times 10^{12}$ Jones, and an I_{ph}/I_{dark} ratio exceeding 1.7×10^4 under 365 nm illumination at 5 V—improvements of 4×, 3.5×, and roughly two orders of magnitude over the bare 3 M ZnO reference device, respectively. The faster photoresponse ($\tau_r \approx 0.19$ s) and reduced dark current (≈ 4.8 nA) further confirm the dual role of Au NPs: LSPR-driven optical gain and Schottky-barrier-mediated carrier-contrast enhancement. These findings establish 3 M ZnO/Au NP bilayer structures as a viable, cost-effective route to high-performance UV photodetectors suitable for flame sensing, UV communications, and environmental monitoring. Future work will explore Au NP size and surface density optimisation, as well as flexible substrate compatibility.

REFERENCES

1. H. Zhang, Y. Zhao, X. Geng, Y. Huang, Y. Li, H. Liu, Y. Liu, Y. Li, X.-F. Wang, H. Tian, and R. Liang, "Au nanoparticles-decorated surface plasmon enhanced ZnO nanorods ultraviolet photodetector on flexible transparent mica substrate," *IEEE J. Electron Devices Soc.*, vol. 7, pp. 196–202, 2019, doi: 10.1109/JEDS.2018.2889888.
2. Y. Jin, S. Jiao, H. Lu, D. Wang, S. Gao, and J. Wang, "Localized surface plasmon-enhanced ultraviolet and visible photoresponse based on ZnO films with Au nanoparticles," *J. Electron. Mater.*, vol. 49, no. 8, pp. 4491–4497, Aug. 2020, doi: 10.1007/S11664-020-08153-3.

3. N. Gogurla, A. K. Sinha, S. Santra, S. Manna, and S. K. Ray, "Multifunctional Au-ZnO plasmonic nanostructures for enhanced UV photodetector and room temperature NO sensing devices," *Sci. Rep.*, vol. 4, no. 1, p. 6483, 2015, doi: 10.1038/SREP06483.
4. J. D. Hwang, M. J. Lai, H.-Z. Chen, and M.-C. Kao, "Au-mediated surface plasmon enhanced ultraviolet response of p-Si/n-ZnO nanorods photodetectors," *IEEE Photon. Technol. Lett.*, vol. 26, no. 10, pp. 1023–1026, May 2014, doi: 10.1109/LPT.2014.2312734.
5. A. Rajan, H. K. Yadav, V. Gupta, and M. Tomar, "Plasmonic enhancement of optical absorption of UV radiation by Au nanoparticles dispersed on ZnO thin film," *Appl. Phys. A*, vol. 116, no. 3, pp. 913–919, 2014, doi: 10.1007/S00339-014-8462-8.
6. Y.-L. Chu, Y.-H. Liu, T.-T. Chu, and S.-J. Young, "Improved UV-sensing of Au-decorated ZnO nanostructure MSM photodetectors," *IEEE Sens. J.*, vol. 22, no. 6, pp. 5644–5650, Mar. 2022, doi: 10.1109/jsen.2022.3150254.
7. J. D. Hwang, F.-H. Wang, C.-Y. Kung, and M. C. Chan, "Using the surface plasmon resonance of Au nanoparticles to enhance ultraviolet response of ZnO nanorods-based Schottky-barrier photodetectors," *IEEE Trans. Nanotechnol.*, vol. 14, no. 2, pp. 318–321, Jan. 2015, doi: 10.1109/TNANO.2015.2393877.
8. S. Debnath, S. Ghosal, M. Meyyappan, and P. K. Giri, "A fully-printed plasmonic nanoparticle-incorporated ZnO-based UV photodetector with very high responsivity and fast response," *Flex. Print. Electron.*, 2024, doi: 10.1088/2058-8585/ad6332.
9. A. Rajan, A. Paliwal, V. Gupta, and M. Tomar, "Plasmonic enhancement of optical absorption of UV radiation in ZnO thin film based ultraviolet photodetectors," *MRS Proc.*, vol. 1509, no. 1, pp. 1–6, 2013, doi: 10.1557/OPL.2013.352.
10. "The gold nanoparticles enhanced ZnO/GaN UV detector," *IEEE J. Electron Devices Soc.*, vol. 10, pp. 847–853, 2022, doi: 10.1109/jeds.2022.3212395.
11. C.-S. Lin, X. Du, and W.-C. Lin, "High photoresponse of gold nanorods/zinc oxide photodetector using localised surface plasmon resonance," *Sens. Actuators A, Phys.*, vol. 326, p. 112714, Aug. 2021, doi: 10.1016/J.SNA.2021.112714.
12. A. Rajan, K. Arora, B. Vidhani, J. Dalal, and P. Kumar, "Au-modified ZnO thin films for higher-performance ultraviolet photodetectors," *RSC Adv.*, vol. 15, pp. 49728–49738, 2025, doi: 10.1039/d5ra08186f.
13. A. Bilgaiyan, T. Dixit, I. A. Palani, and V. Singh, "Performance improvement of ZnO/P3HT hybrid UV photo-detector by interfacial Au nanolayer," *Phys. E Low-Dimens. Syst. Nanostruct.*, vol. 86, pp. 136–141, Feb. 2017, doi: 10.1016/J.PHYSE.2016.07.010.
14. Z. Jin, L. Gao, Q. Zhou, and J. Wang, "High-performance flexible ultraviolet photoconductors based on solution-processed ultrathin ZnO/Au nanoparticle composite films," *Sci. Rep.*, vol. 4, no. 1, p. 4268, 2015, doi: 10.1038/SREP04268.
15. Q. Li, J. Huang, J. Meng, and Z. Li, "Enhanced performance of a self-powered ZnO photodetector by coupling LSPR-inspired pyro-phototronic effect and piezo-phototronic effect," *Adv. Opt. Mater.*, vol. 10, no. 7, p. 2102468, Jan. 2022, doi: 10.1002/adom.202102468.
16. G. Li, Q. Yan, X. Zhao, and Y. He, "The influence of surface processing on the surface plasmonic enhancement of an Al-nanoparticles-enhanced ZnO UV photodetector," *Nanomaterials*, vol. 13, no. 12, p. 1877, Jun. 2023, doi: 10.3390/nano13121877.
17. G. Shang, L. Tang, G. Wu, S. Yuan, M. Jia, X. Guo, X. Zheng, W. Wang, B. Yue, and K. S. Teng, "High-performance NiO/TiO₂/ZnO photovoltaic UV detector," *Sensors*, vol. 23, no. 5, p. 2741, Mar. 2023, doi: 10.3390/s23052741.
18. N. Wang, J. Li, C. Wang, X. Zhang, S. Ding, Z. Guo, Y. Duan, and D. Jiang, "Improved UV photoresponse performance of ZnO nanowire array photodetector via effective Pt nanoparticle coupling," *Nanomaterials*, vol. 14, no. 17, p. 1442, Sep. 2024, doi: 10.3390/nano14171442.
19. I. B. Elkamel, N. Hamdaoui, A. Mezni, R. Ajjel, and L. Beji, "Photodetectors for weak signal conditions from Au/Cu co-doped ZnO," *Opt. Quantum Electron.*, vol. 53, no. 7, pp. 1–14, Apr. 2021, doi: 10.21203/RS.3.RS-331709/V1.
20. C.-S. Lin and W.-C. Lin, "Development of high photosensitive gold nanorods/zinc oxide photodetector," vol. 20, pp. 77–81, Sep. 2021.