SCIENCE CHINA
Information Sciences

• LETTER •

July 2025, Vol. 68, Iss. 7, 179403:1–179403:2
https://doi.org/10.1007/s11432-025-4362-7

Dielectric metasurface enhanced performance in multilayer WS_2 photodetector

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Received 7 January 2025/Revised 2 March 2025/Accepted 24 March 2025/Published online 20 June 2025

Citation Zhao H J, Wang W Q, Ding H L, et al. Dielectric metasurface enhanced performance in multilayer WS_2 photodetector. Sci China Inf Sci, 2025, 68(7): 179403, https://doi.org/10.1007/s11432-025-4362-7

Two-dimensional transition metal dichalcogenides (2D TMDCs) have emerged as revolutionary materials for next-generation optoelectronics due to their atomic thickness, tunable bandgaps, and exceptional light-matter interactions. Among them, multilayer tungsten disulfide (WS_2) presents particular advantages including enhanced carrier mobility and mechanical stability compared to monolayer counterparts [1]. However, its indirect bandgap nature fundamentally limits light absorption efficiency—a critical drawback hindering practical photodetector applications [2]. Traditional enhancement strategies using plasmonic nanostructures or Fabry-Pérot cavities often suffer from intrinsic ohmic losses or complex fabrication requirements, while existing dielectric metasurface integrations mainly focus on conventional bulk semiconductors rather than 2D materials [3, 4]. To address this issue, we have developed a novel 2D dielectric metasurface photodetectors (2d-DMPs) by integrating soft-imprinted SU8 photonic structures with multilayer WS_2, as shown in Figures 1(a) and S1. Compared to pristine WS_2 devices, the 2d-DMP exhibits a 1400% increase in detectivity (D^*), 900% in external quantum efficiency (EQE), and 750% in responsivity (R). The device also demonstrates fast response times, with rise times of 17.3 µs ($\Gamma_{\rm rise1}$) and 590 µs ($\Gamma_{\rm rise2}$), and decay times of 7.9 µs ($\Gamma_{\rm decay1}$) and 372 µs ($\Gamma_{\rm decay2}$). This scalable and cost-effective approach of integrating dielectric metasurfaces with 2D materials enables the realization of high-sensitivity, fast-response photodetectors for advanced imaging, environmental monitoring, and next-generation optoelectronics.

Materials and method. Devices were fabricated on Si/SiO_2 substrates (285 nm oxide) pretreated with O_2 plasma (50 sccm, 30 W, 5 s) to enhance hydrophilicity. Mechanically exfoliated multilayer WS_2 was transferred via PDMS. Electrodes were prepared by micro-manipulation. (1) Gold bars (120 nm thick) were precisely cut to target lengths using a 1-µm needle tip under microscopic observation on a customized platform, and (2) adhered to WS_2 using adhesive-coated probes. SU8-2000 photoresist (1 : 1 cyclopentanone dilution) was spin-coated (4000 r/min, 300 r/s^2, 30 s) to form a 600 nm film. A PDMS mold was pressed onto SU8 for hot embossing (65°C/90°C, 1 min each), replicating nanocylinders. Surface roughness was introduced via O_2 reactive ion etching (RIE: 30 sccm, 30 W, 60 s), creating granular textures. The structured SU8 served dual roles as a light-trapping metasurface and protective encapsulation. Electrical characterization was performed using an FS-Pro source meter under irradiation with a 532 nm wavelength.

Results and discussion. In 2d-DMP, the nanocolumn structure of the metasurface can generate resonance modes to enhance the interaction between light and matter. The optimal structural parameters were determined through FDTD simulations, as illustrated in Figures 1(b) and S2. The smooth surface of direct nanoimprinted SU8 metasurfaces causes specular reflection losses, thus mitigated by introducing controlled surface roughness via RIE. This process generates a nanoscale texture with ∼30 nm granular features. Moreover, the structure of the roughened metasurface closely matches the ideal parameters. Figure 1(c) shows the cross-sectional view of the electric field distribution after roughening the structure by etching with RIE for 60 s, see Figure S3. The solid line represents the edge of the structure, while the part encircled by the dashed line denotes the target area of interest. Subsequent to roughening the structure, the maximum enhancement factor of the electric field intensity increases to 3.4. It is important to note that excessive etching will reduce the thickness of the SU8 microcavity, which in turn will lead to a destruction of the optimal electromagnetic field distribution that has been predicted by FDTD simulation, as shown in Figure S4. The thickness of the multi-layer WS_2 in 2d-DMP is mostly 5–15 nm, see Figures 1(d) and S5. The device characteriza-

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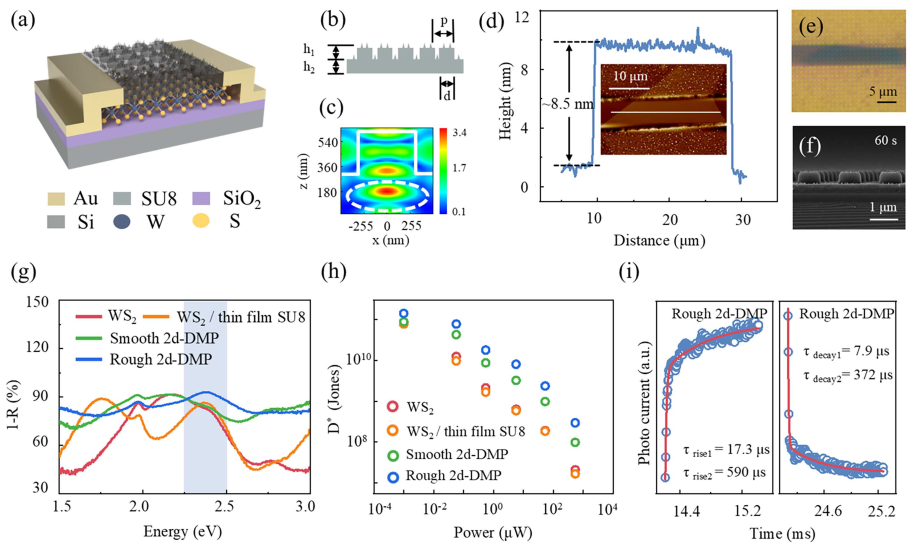

Figure 1 (Color online) (a) Illustrates the structured SU8 metasurface on a WS_2 photodetector (2d-DMP). (b) The SU8 cylinders have a diameter of d (620 nm) and periodicity of p (1020 nm), where h_1 (330 nm) represents the height of the nanocylinders, and h_2 (300 nm) indicates the thickness of the underlying SU8 layer. (c) FDTD simulation of the electric field distribution after 60 s of RIE treatment. (d) AFM characterization of multilayer WS_2. The height profile indicates a thickness of approximately 8.5 nm. (e) An optical microscope image at 100× magnification showing WS_2 after structuring with SU8. (f) SEM of the metasurface after 60 s of RIE treatment. The actual roughened metasurface exhibits structural parameters $d \approx 610$ nm, $p \approx 1020$ nm, $h_1 \approx 340$ nm, $h_2 \approx 290$ nm. (g) Approximate assessment of absorption by $1 - R$. (h) D^* of multi-layer WS_2, WS_2/thin film SU8, smooth 2d-DMP, and rough 2d-DMP. (i) The transient photoresponse of the rough 2d-DMP.

tion of 2d-DMP is shown in Figures 1(e) and (f). Absorption comparison shows structured devices enhance WS_2 light absorption by ∼12% at 2.3–2.5 eV (blue spectral region). The enhancement between 2.5 and 3.0 eV is as high as 50%, as illustrated in Figure 1(g). To quantify the exact enhancement at the 532 nm detection wavelength, the roughened SU8 metasurface exhibits a 46% reduction (from 15.6% to 8.1%) in reflection and resulting in a significantly enhanced absorption. Therefore, by carefully controlling the cavity dimension and surface morphology of the nanostructures, we have achieved an optimal balance, thereby maximizing the device's optoelectronic performance. It was demonstrated that the photoluminescence (PL) intensity of both WS_2/SU8 metasurface and WS_2/roughened SU8 metasurface was effectively enhanced, as shown in Figure S6. In multilayer WS_2 photodetectors, the indirect bandgap inherently induces high carrier recombination, limiting photoresponse efficiency. For 2d-DMP devices incorporating SU8 metasurfaces, the enhanced localized electric field provides an additional driving force for carrier separation. This promotes rapid separation of photogenerated carriers, accelerating electron migration to the conduction band and hole return to the valence band, thereby suppressing recombination probability and improving photoresponsivity. 2d-DMP achieves enhanced specific detectivity (D^*) over reported WS_2-based photodetectors, matching MoS_2/WS_2 heterostructure performance (Figures 1(h) and S7). The performance of the 2d-DMP is significantly enhanced at multiple light intensities after nanostructured SU8 metasurface integration, especially at high light intensities. The 2d-DMP's response speed remains unaffected by the soft nanoimprinting process, maintaining a consistent rate of microseconds, as evidenced in Figures 1(i) and S8, and is comparable to those heterostructured devices. The reproducibility-tested enhancement factors for D^*, EQE, and R each demonstrate approximately an order of magnitude improvement (see Figure S9).

Conclusion. This study integrated a nanostructured SU8 metasurface onto a multilayer WS_2 photodetector to construct the 2d-DMP device, enhancing light absorption and photodetector performance. Controlled surface defects introduced via RIE optimized localized electric field concentration, boosting light trapping/scattering effects to further increase absorption while maintaining microsecond-scale response speeds. It also provides a scalable approach for designing low-cost, high-efficiency optoelectronic devices with 2D materials in the future.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 62375139, 62288102, 62104112, U24A20295), National Key Research and Development Program of China (Grant No. 2021YFA1202904), Jiangsu Province Key R&D program (Grant No. BK 20232044), Natural Science Research Start-up Foundation of Recruiting Talents of Nanjing University of Posts and Telecommunications (Grant No. NY223181), Project of State Key Laboratory of Organic Electronics and Information Displays (Grant Nos. GDX2022010007, GZR2024010024), Natural Science Foundation of Jiangsu Province (Grant No. BK20240643), and Natural Science Foundation of the Jiangsu Higher Education Institutions of China (Grant No. 24KJB510027).

Supporting information Figures S1–S9. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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