Fabrication of Vertically-Stacked MoS_2-Based Thin-Film Photovoltaic Devices

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2D layered transition metal dichalcogenides (LTMDs) have been envisioned for making new ultra-thin-film photovoltaic (PV) devices with a unique combination of excellent photovoltaic performance, superior flexibility, long life time, and low manufacturing cost.[1, 2] Especially, a single semiconducting LTMD (*e.g.*, WSe_2, WS_2, and MoS_2) layer (~0.5 nm thick) can absorb as much sunlight as 50 nm of Si (or 12 nm of GaAs) and generate currents as high as 4.5mA/cm^2. Therefore, 2D LTMD films hold a significant potential to be used for making ultrathin flexible photovoltaic (PV) cells with 1-3 orders of magnitude higher power densities than the best existing thin-film solar cells.[1-2] In spite of such an optimistic anticipation, the current LTMD-based PV cells still exhibit relatively poor PV performance,[2-5] which is attributed to the lack of proper fabrication and doping processes for tailoring MoS_2 layers into optimized PV device architectures.

To address this challenge, we developed a fabrication route combining transfer-printing methods[6] and plasma-assisted doping processes,[7] which can create PV devices consisting of vertically stacked Au/p-type MoS_2/n-type MoS_2/ITO structures (**Fig. 1**). Such vertically stacked PV devices exhibit reasonably good (and promising further improved) PV performance, in terms of short-circuit photocurrent density (J_{sc}) up to 29 mA/cm^2 that is comparable to J_{sc} values of exquisite III-V semiconductor PV cells, power-conversion efficiencies (PCEs) up to 3.53% that is the highest PCE among LTMD-based thin-film PV cells (**Fig. 2**), and extrinsic quantum efficiencies (EQEs) > 40% over a broad wavelength range (300 to 800 nm) (**Fig. 3a**). In addition, such a vertically stacked ITO/plasma-doped MoS_2/metal structure can also be used for making thin-film photodetectors with a high responsivity (> 100 mA/W at zero bias for $\lambda = 300$ to 800 nm) (**Fig. 3b**) and a high light/dark current ratio (10^2 - 10^4 at negative biases) (**Fig. 3c**).

This work provided important scientific insights and materials processing methods for creating new thin-film photovoltaic devices and other relevant optoelectronic components based on emerging 2D materials.

[1] K. F. Mak, C. Lee, J. Hone and T. F. Heinz, Physical Review Letters, **105**, 136805/1-4 (2010)
[2] G. Eda and S. A. Maier, ACS Nano, **7**, 5660-5665 (2013)
[3] L. Britnell, R. M. Ribeiro, A Eckmann and A. H. C. Neto, Science, **340**, 1311-1314 (2013)
[4] M. Shanmugam, C. A. Durcan, B. Yu, Nanoscale, **4**, 7399-7405. (2012)
[5] M. Fontana, T. Deppe, A. K. Boyd, M. Rinzan and P. Barbara, Scientific Reports, **3** (2013)
[6] H. Nam, S. Wi, H. Rokni, M. Chen, G. Priessnitz, W. Lu, and X. Liang*, ACS Nano, 7, 7, 5870-5881 (2013)
[7] M. Chen, H. Nam, S. Wi, L. Ji, X. Ren, L. Bian, S. Lu, and X. Liang*, Applied Physics Letters, 103,14, 142110/1-142110/4 (2013)

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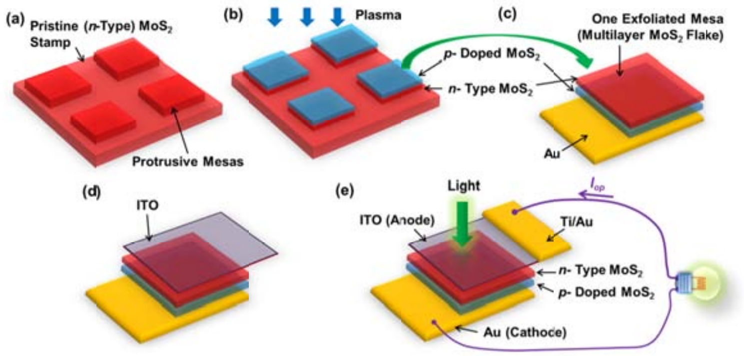

Fig. 1 Fabrication of PV devices consisting of vertically stacked Au/p-type MoS_2/n-type MoS_2/ITO structures by using transfer-printing in combination with plasma doping.

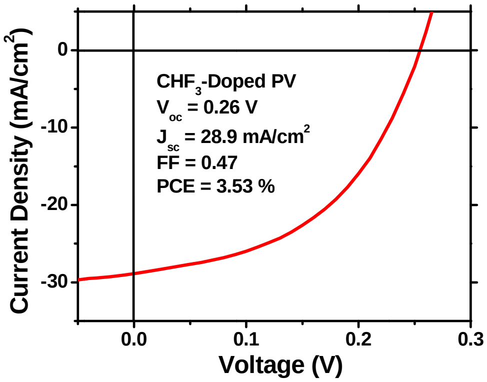

Fig. 2 J-V characteristic curve, measured under illumination of AM1.5G simulated sunlight (power density, 100 mW/cm^2), of a plasma-doped MoS_2 PV device.

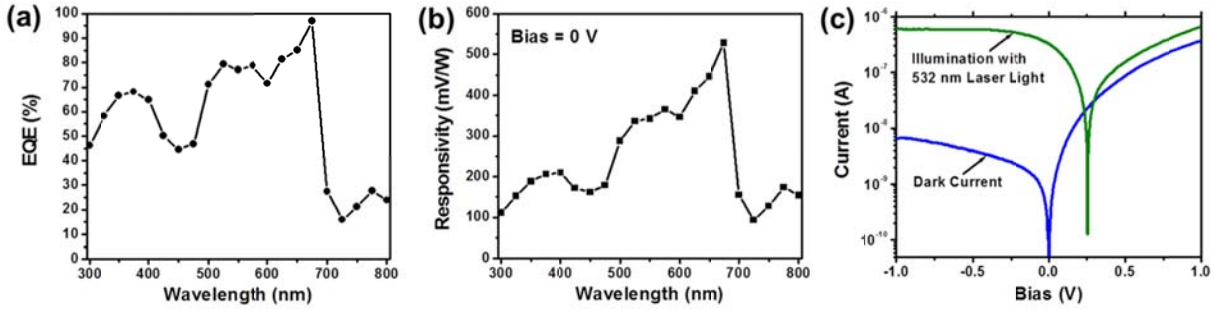

Fig. 3 EQE (a) and responsivity (b) values of a PV device with MoS_2 thickness of 120 nm measured at wavelengths λ = 300 to 800 nm. (c) shows the I-V characteristic curves under dark (blue curve) and illumination (532 nm laser light with excitation power of 203 mW/cm^2) (green curve) conditions. This PV diode exhibits high light/dark current ratios (10^2 to 10^4) at reverse biases, suitable for photodetector applications.

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