Electronic Supplementary Material (ESI) for Nanoscale.


Supporting Information

# Deep-Ultraviolet-Light-Driven Reversible Doping of $WS_2$ Field-Effect Transistor

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We have measured the electronic transport properties of SL, BL and ML-$WS_2$ field effect transistor by sweeping the back gate voltage before and after DUV+$N_2$ treatment. Figures S1a, c and e show typical hysteresis curves observed in SL, BL and ML-$WS_2$ devices on $SiO_2$ substrate before exposing the devices to DUV+$N_2$ treatment, where the back gate voltage was swept continuously from −30 to +40 V and then from +40 V to −30 V. We note that threshold voltage ($V_{th}$) moves towards negative (positive) back gate voltage ($V_{bg}$) for the gate voltage sweep from −30 V (+40 V) to +40 V (−30 V). The hysteresis in threshold voltage ($V_{th}$) was around 6 - 8 V for SL, BL and ML-$WS_2$ devices on $SiO_2$ substrate in the pristine state, which is due to charge impurities. Similar transport measurement was done for SL, BL and ML-$WS_2$ devices after 30 min DUV+$N_2$ exposure as shown in Figure S1b, d and f, where the back gate voltage was swept continuously from −80 to +40 V and then from +40 V to −80 V. Almost no (very small) hysteresis in threshold voltage ($V_{th}$) was observed SL, BL and ML-$WS_2$ devices after DUV+$N_2$ treatment. The very weak hysteresis curves indicate that the number of charge impurities were reduced after DUV+$N_2$ exposure.

We have measured the transfer characteristics ($I_{ds}$-$V_{bg}$) of ML-$WS_2$ (32 nm thick) to confirm the similar effect as reported in the paper on $MoS_2$ films,[1] in which authors claimed that the mobility starts to decrease after a certain flake thickness. In our experiments a decrease of mobility and on/off ratio was observed for the 32-nm-thick ML-$WS_2$ device as compared to the 3.55-nm-thick ML-$WS_2$ device in our manuscript. Figure S2a shows the optical image of device used in our study. Figure S2b shows the transfer characteristics ($I_{ds}$-$V_{bg}$) of the 32-nm-thick ML-$WS_2$ device. The mobility of device was observed as 23 $cm^2$/Vs and the on/off ratio as ~$10^3$, which were much lower than the mobility of 90 $cm^2$/Vs and the on/off ratio of ~$10^5$ of the 3.55-nm-thick $WS_2$ device.

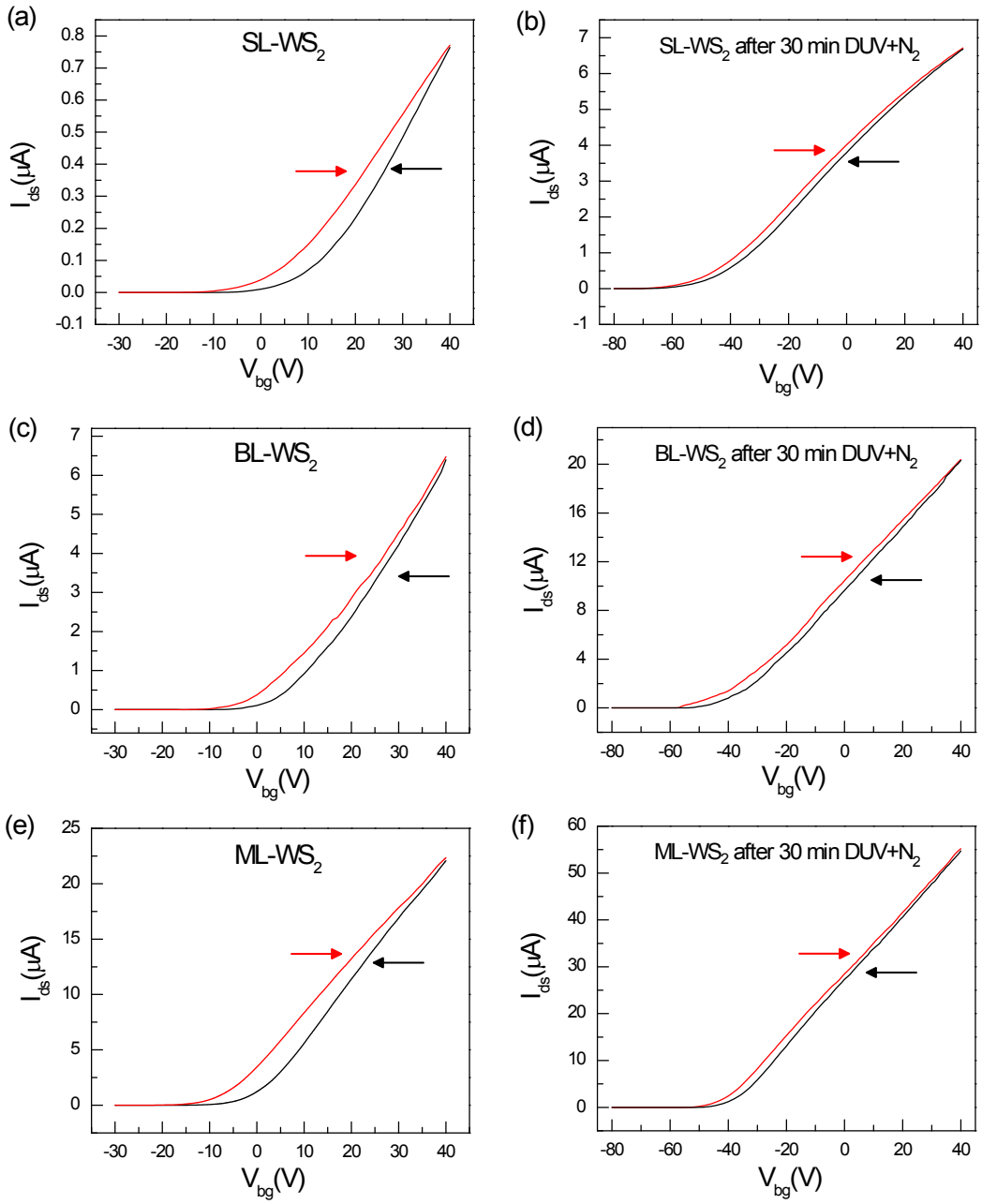


**Figure S1.** (a) Transfer characteristics ($I_{ds}$-$V_{bg}$) of the SL-$WS_2$ FET on $SiO_2$ substrate before DUV+$N_2$ exposure, where the back gate voltage was swept continuously from −30 to +40 V and then from +40 V to −30 V. (b) Transfer characteristics ($I_{ds}$-$V_{bg}$) of the SL-$WS_2$ FET on $SiO_2$ substrate after 30 min DUV+$N_2$ exposure, where the back gate voltage was swept continuously from −80 to +40 V and then from +40 V to −80 V. (c) Transfer characteristics of the BL-$WS_2$ FET on $SiO_2$ substrate before DUV+$N_2$ exposure. (d) Transfer characteristics of the BL-$WS_2$ FET on $SiO_2$ substrate after 30 min DUV+$N_2$ exposure. (e) Transfer characteristics of the ML-

$WS_2$ FET on $SiO_2$ substrate before DUV+$N_2$ exposure. (f) Transfer characteristics of the ML-$WS_2$ FET on $SiO_2$ substrate after 30 min DUV+$N_2$ exposure. All the measurements were performed in vacuum at room temperature.

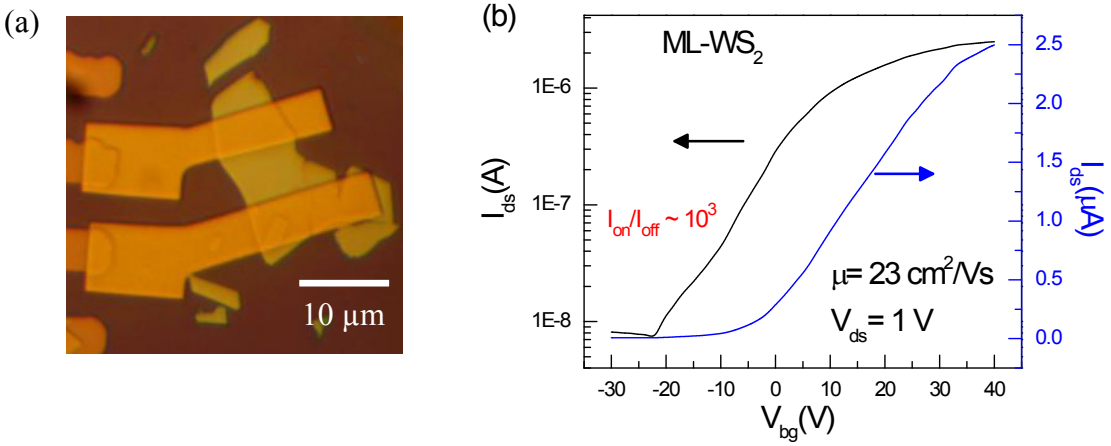


**Figure S2.** (a) Optical image of the 32-nm-thick ML-$WS_2$ FET. (b) Transfer characteristics ($I_{ds}$-$V_{bg}$) of the 32-nm-thick ML-$WS_2$ FET. The mobility of device was observed as 23 $cm^2$/Vs and the on/off ratio as ~$10^3$.

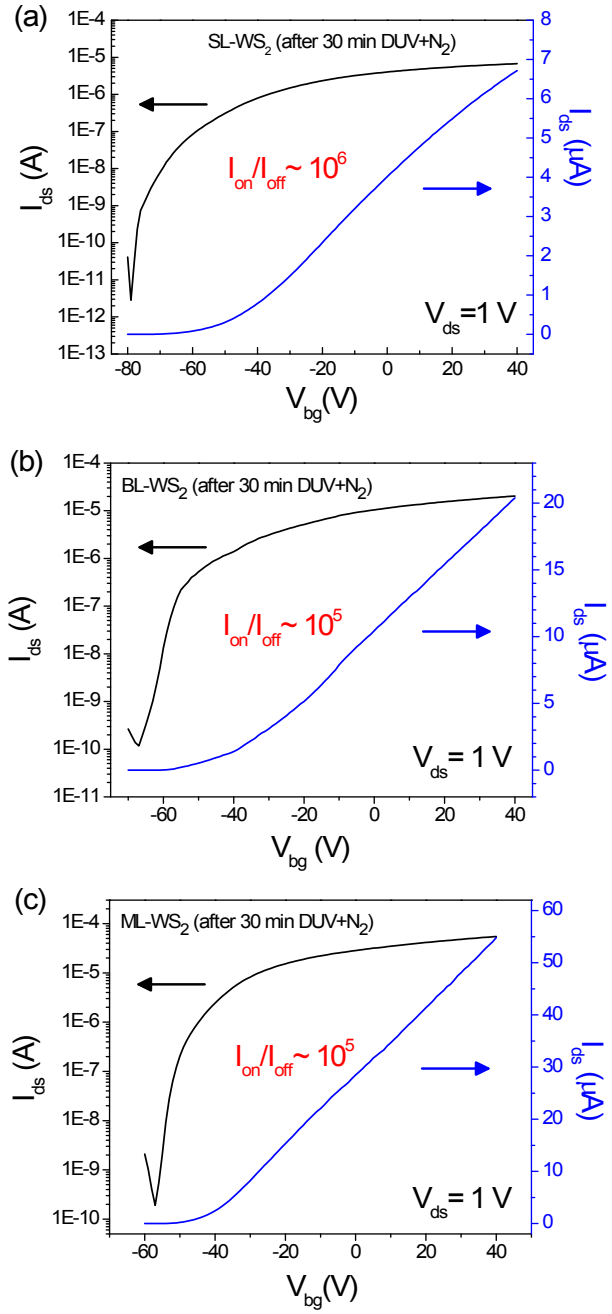


**Figure S3.** (a) Transfer characteristics ($I_{ds}$-$V_{bg}$) of SL-$WS_2$ FET after the 30 min DUV+$N_2$ treatment. On/Off ratio of the device is ~$10^6$. (b) Transfer characteristics ($I_{ds}$-$V_{bg}$) of BL-$WS_2$ FET after the 30 min DUV+$N_2$ treatment. On/Off ratio of the device is ~$10^5$. (c) Transfer characteristics ($I_{ds}$-$V_{bg}$) of ML-$WS_2$ FET after the 30 min DUV+$N_2$ treatment. On/Off ratio of the device is ~$10^5$. All measurements were performed in vacuum at T = 300 K.

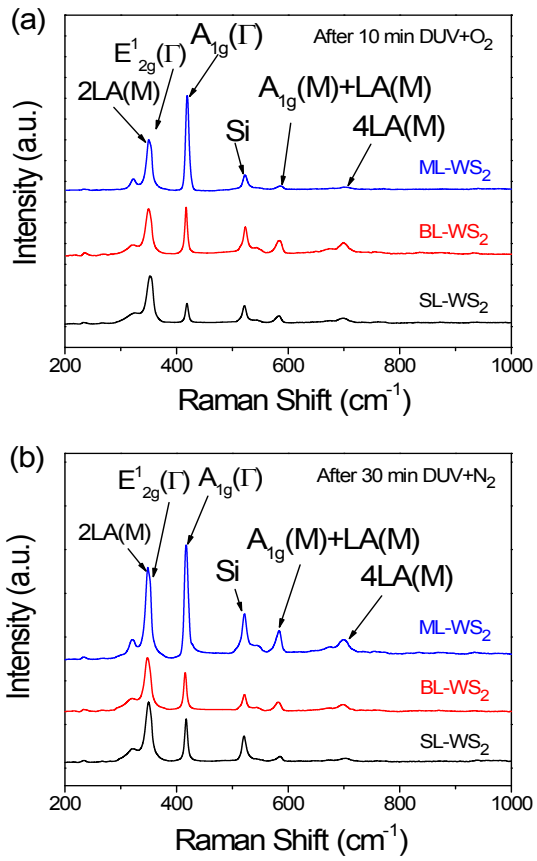


**Figure S4**. (a) Raman spectra for SL-$WS_2$, BL-$WS_2$, and ML-$WS_2$ films after the 10 min DUV+$O_2$ treatment. (b) Raman spectra for SL-$WS_2$, BL-$WS_2$, and ML-$WS_2$ films after the 30 min DUV+$N_2$ treatment. These Raman spectra reveal that additional ionic chemical bonds are not created in $WS_2$ films during DUV+$O_2$ and DUV+$N_2$ treatments.

**Table S1.** Oxygen amount detected through energy-dispersive X-ray spectroscopy for SL-$WS_2$, BL-$WS_2$, and ML-$WS_2$ before and after the 30 min DUV+$N_2$ treatment.

| Device | Device No. | Before DUV+$N_2$ treatment | After DUV+$N_2$ treatment |
|---|---|---|---|
| SL-$WS_2$ | 1 | 24.60±0.011% | 22.30±0.013% |
| | 2 | 24.65±0.014% | 22.37±0.015% |
| BL-$WS_2$ | 1 | 24.42±0.015% | 22.32±0.013% |
| | 2 | 24.35±0.011% | 22.23±0.012% |
| ML-$WS_2$ | 1 | 24.50±0.015% | 22.60±0.012% |
| | 2 | 24.55±0.013% | 22.63±0.014% |

## References

1. S. Das and J. Appenzeller, *physica status solidi (RRL)-Rapid Research Letters*, 2013, **7**, 268-273.