Supporting information

# Patterning and doping of Transition Metals in Tungsten Dichalcogenides

Yung-Chang Lin[1], Yao-Pang Chang[2], Kai-Wen Chen[3], Tai-Ting Lee[2], Bo-Jiun Hsiao[2], Tsung-Han Tsai[2], Yang, Yueh-Chiang, Kuang-I Lin[4], Kazu Suenaga[1,5], Chia-Hao Chen[3], and Po-Wen Chiu*[2,6]

[1]Nanomaterials Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba 305-8565, Japan

[2]Department of Electrical Engineering, National Tsing Hua University, Hsinchu 30013, Taiwan

[3]National Synchrotron Radiation Research Center, Hsinchu 30076, Taiwan

[4]Center for Micro/Nano Science and Technology, National Cheng Kung University, Tainan 70101, Taiwan

[5]The Institute of Scientific and Industrial Research (ISIR-SANKEN), Osaka University, Osaka 567-0047, Japan

[6]Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, 10617, Taiwan

*Correspondence to: pwchiu@ee.nthu.edu.tw

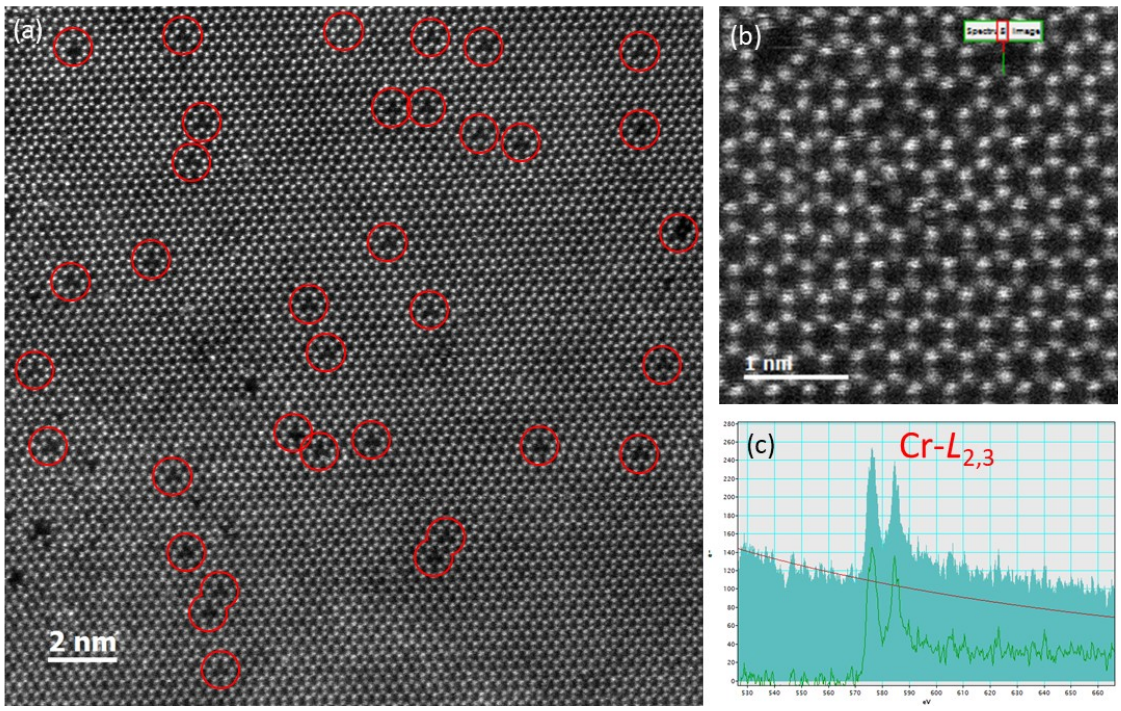


**Figure S1.** (a) STEM-ADF image of Cr:$WSe_{2-x}$ with Se flow to repair the Se vacancies through ORC reaction. The Cr substitutional dopants are highlighted by red circles. (b) Magnified STEM-ADF image of Cr:$WSe_2$. The atom-by-atom EELS line scan is performed along the green line. (c) EELS profile of Cr $L_2$, $L_3$ edges extracted from the EELS line scan.

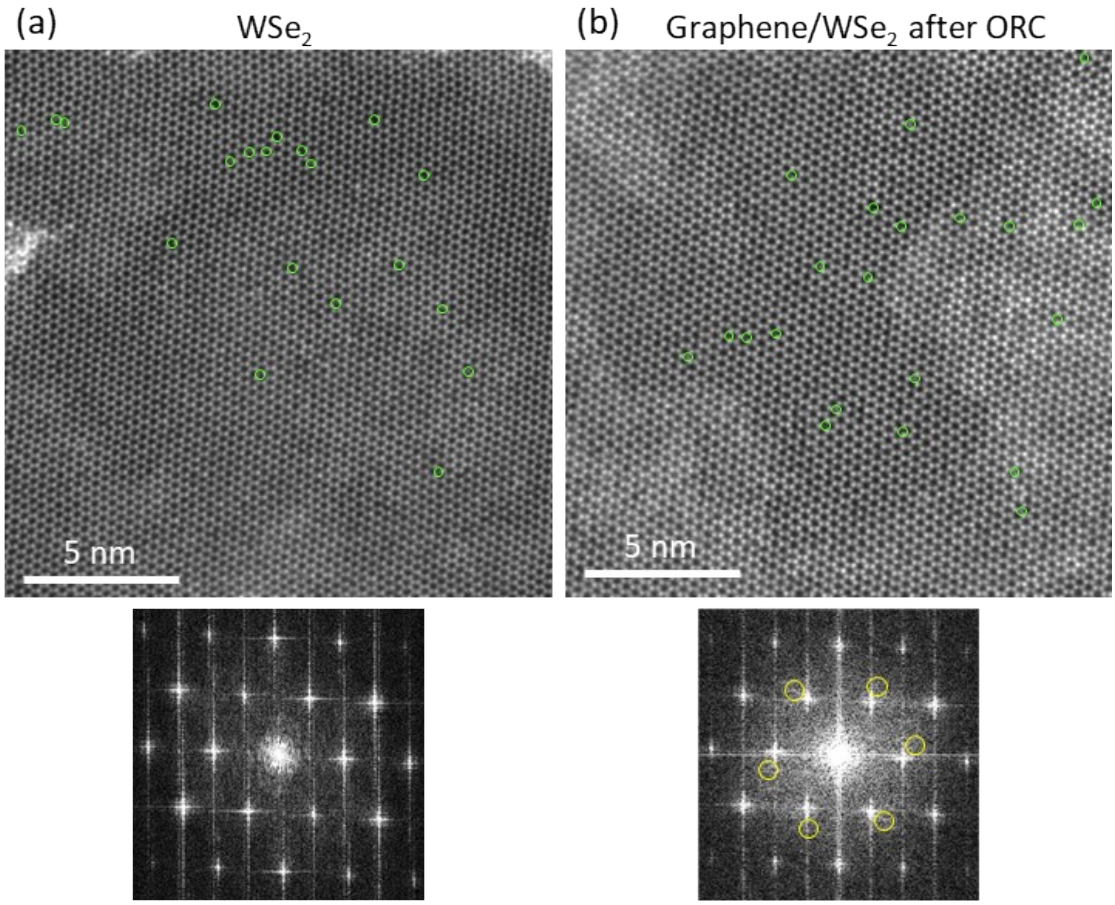


**Figure S2.** (a) STEM and corresponding FFT image of pristine $WSe_2$. Se vacancies are marked with green circles. (b) STEM and corresponding FFT image of $WSe_2$ covered with graphene after the ORC process. The yellow circles in the FFT image are contributed from the graphene lattice covered on $WSe_2$.

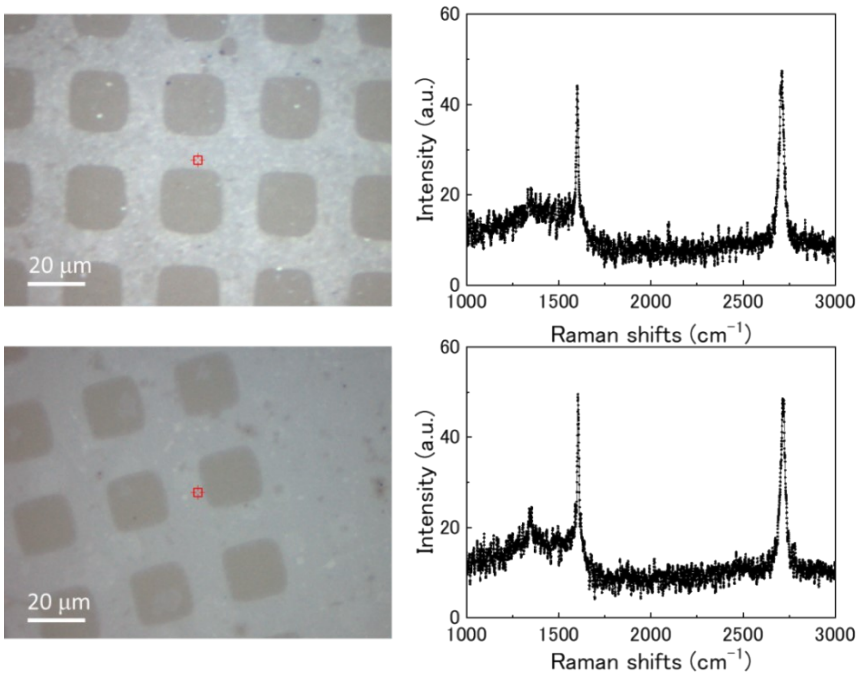


**Figure S3.** Optical images and corresponding Raman spectra of the single layer graphene mask after the ORC reaction.

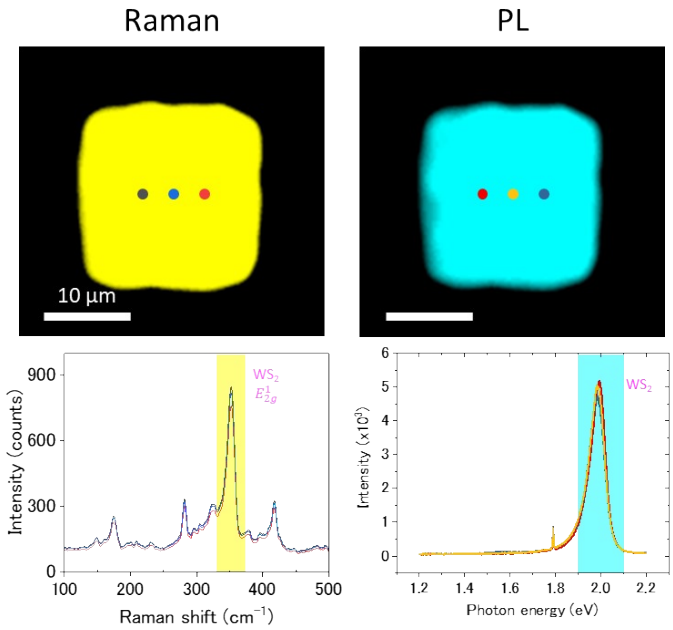


**Figure S4.** Raman and PL mapping of the unmasked region where the $WSe_2$ was transformed into Cr:$WS_2$ completely after the ORC reaction. The Raman and PL mappings were plotted regarded to the integrated $WS_2$ $E^1_{2g}$ peak (325~275 cm$^{-1}$) and the

$WS_2$ exciton peak (1.9~2.1 eV).

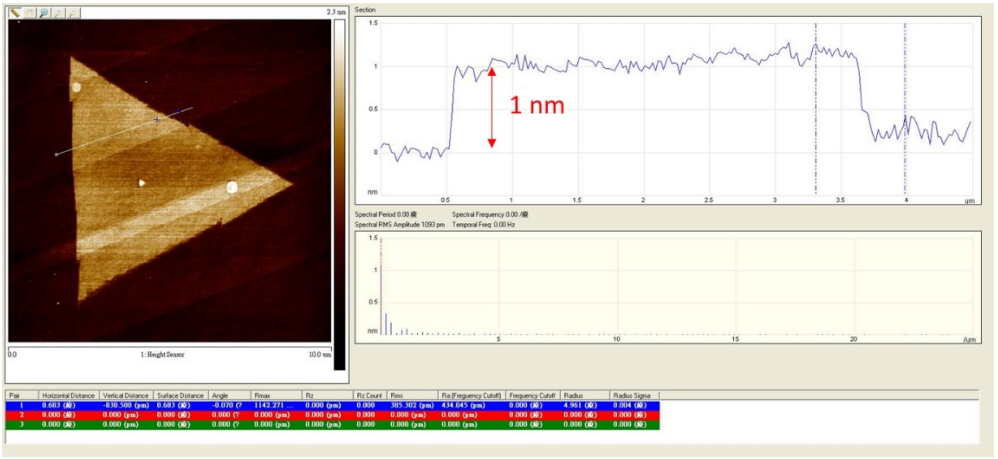


**Figure S5.** AFM image of Cr:$WS_2$. The height of the Cr:$WS_2$ is about 1 nm and the surface is uniform without extra layer grown on the surface after the ORC reaction.

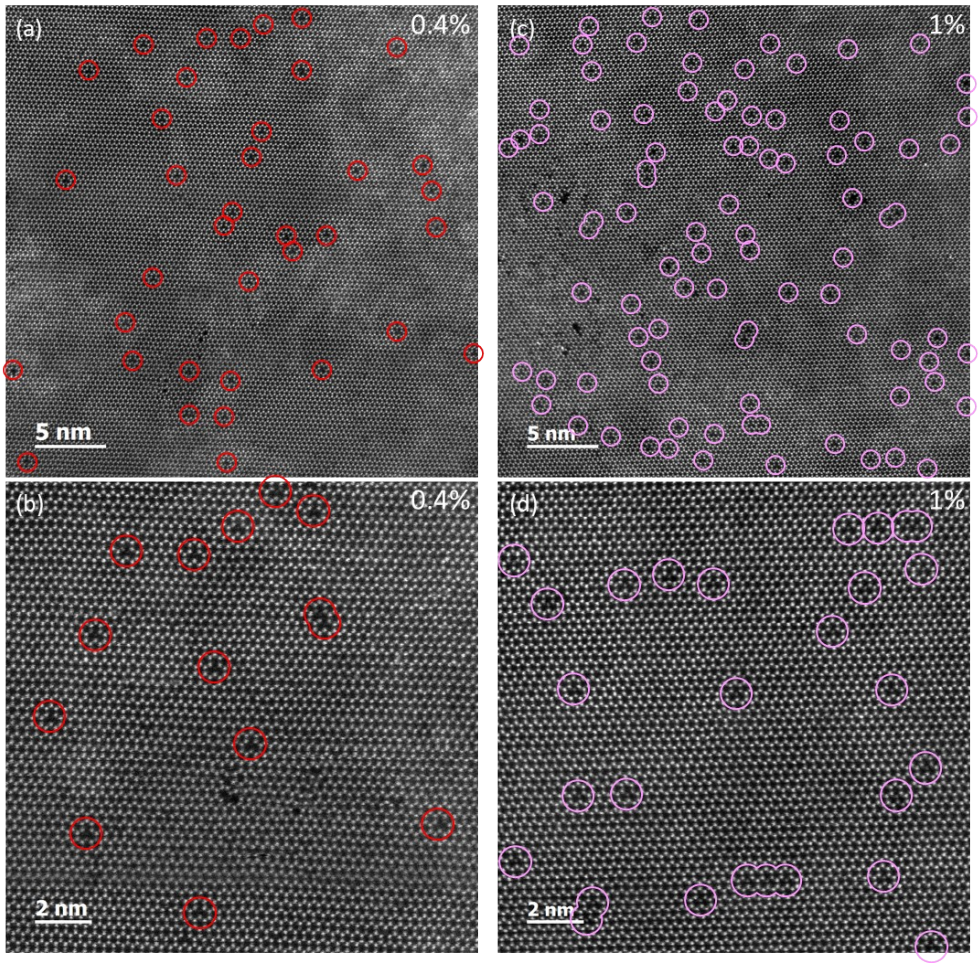


**Figure S6.** (a,b) STEM images of 0.4% Cr-doped $WSe_2$ at different magnifications. (c,d)

STEM images of 1% Cr-doped $WSe_2$ at different magnifications.

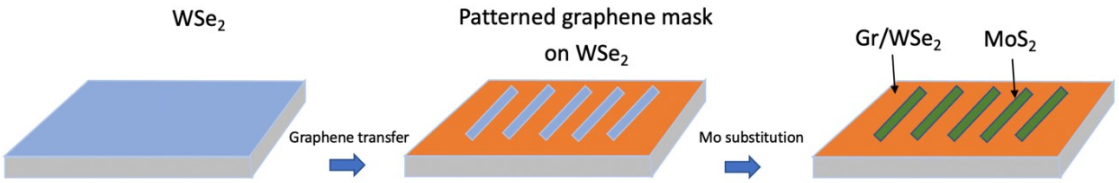


**Figure S7.** To make lateral heterostructures, graphene is used as the mask and transferred onto a monolayer $WSe_2$ film. The exposed $WSe_2$ areas allow for ORC reaction. After the ORC reaction with the supply of Mo and S precursors, the exposed $WSe_2$ stripes can be nearly converted into $MoS_2$.

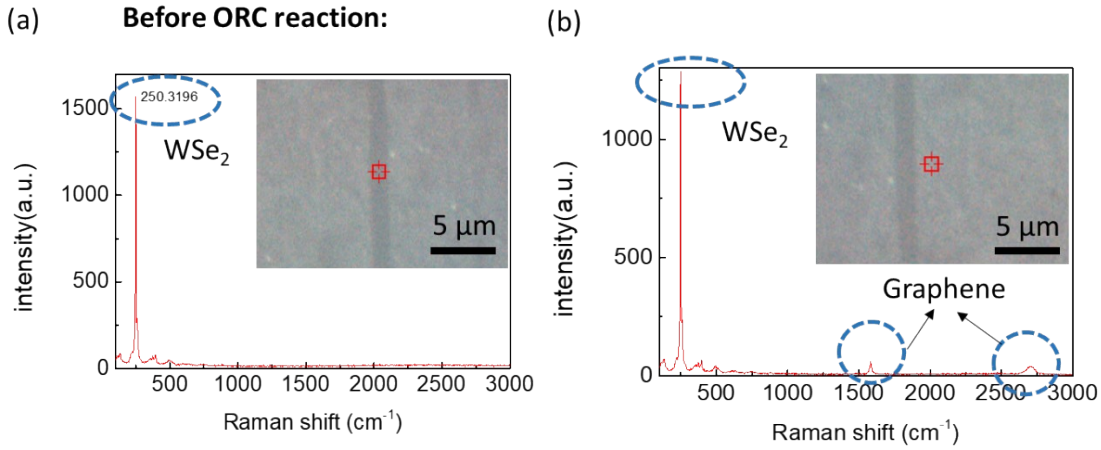


**Figure S8.** Raman spectra before the ORC reactions with the supply of Mo and S precursors. (a) Raman spectrum acquired on the area of exposed $WSe_2$. (b) Raman spectra acquired on the area of $Gr/WSe_2$. The figure insets in (a) and (b) show the optical microscopy image of the patterned Gr mask on $WSe_2$.

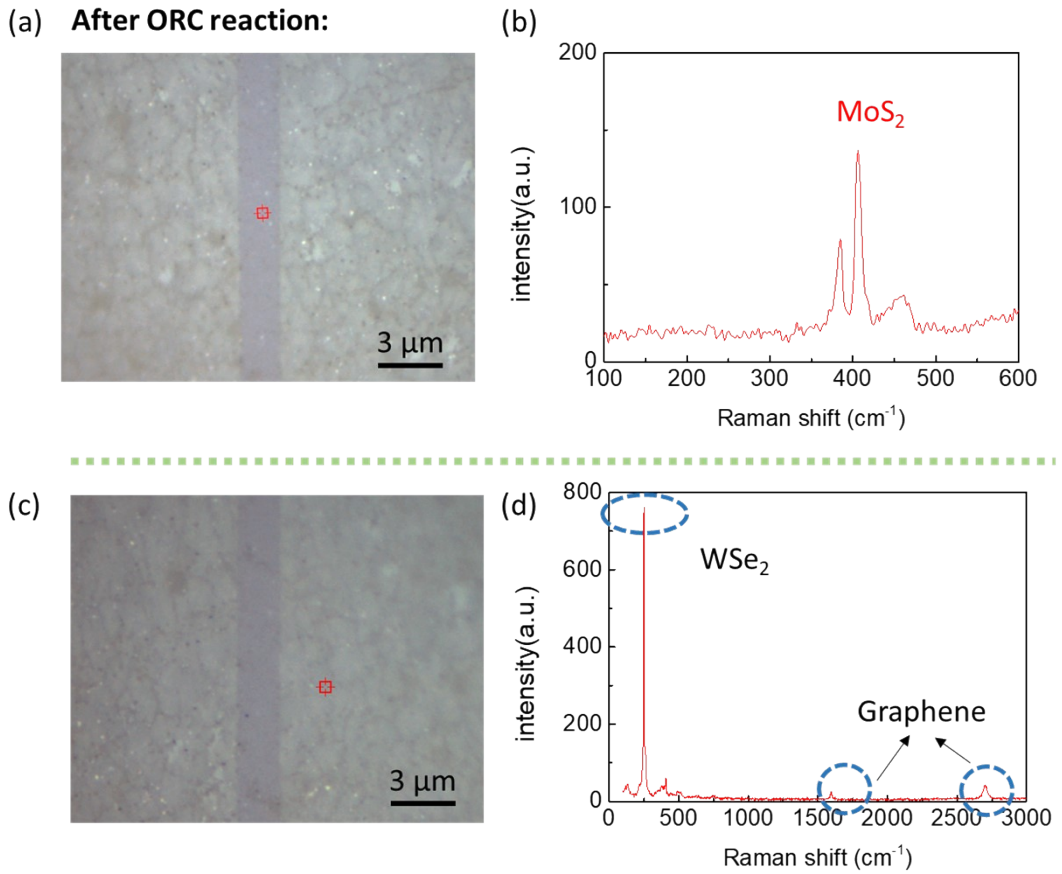


**Figure S9.** Raman spectra and optical microscopy images of the patterned Gr mask on $WSe_2$ after the ORC reactions with the supply of Mo and S precursors. (a) and (c) show the optical microscopy images of the area where Raman spectra were acquired. (b) and (d) show, respectively, the Raman spectrum acquired on the exposed and masked areas of Gr/$WSe_2$. On the exposed area, the Raman characteristic peaks of $WSe_2$ vanish and is replaced by those of $MoS_2$ after the ORC reaction. On the contrary, the Raman characteristic peaks of $WSe_2$ on the Gr-masked areas remain unchanged after the ORC reaction.