Gallium Doping of Monolayer TMDs with Density and Spatial Control

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Doping offers a way of engineering two-dimensional (2D) materials for electronic, photonic, and spintronic applications. We show that 2D transition metal dichalcogenides (TMDs) can be variably doped with spatial and density control using an industry-standard 30 keV focused Ga^+ ion beam. Aberration-corrected scanning transmission electron microscopy (AC-STEM) and single-atom electron energy loss spectroscopy (EELS) provide direct evidence that transition metal atoms, Mo and W, are replaced with single Ga atoms up to a concentration of 2.4×10^{14} Ga/cm^2. Photoluminescence (PL) spectroscopy and density functional theory (DFT) show that variable Ga doping densities modify the electronic structure, shift the PL peak position, and induce n-type behavior in WS_2. We also show spatially-controlled doping of 2D flakes on Si/SiO_2 substrates. Finally, we perform simulations and atomic force microscopy to investigate potential doping mechanisms and study dynamical effects of Ga^+ irradiation on 2D materials. The methods presented here can be extended to other 2D materials and ion beam sources.

References

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[2] J.P. Thiruraman, K. Fujisawa, G. Danda, P. Masih Das, T. Zhang, A. Bolotsky, N. Perea-Lopez, A. Nicolai, P. Senet, M. Terrones, M. Drndić. *Nano Lett.* 18 (2018) 1651-1659.

Figures

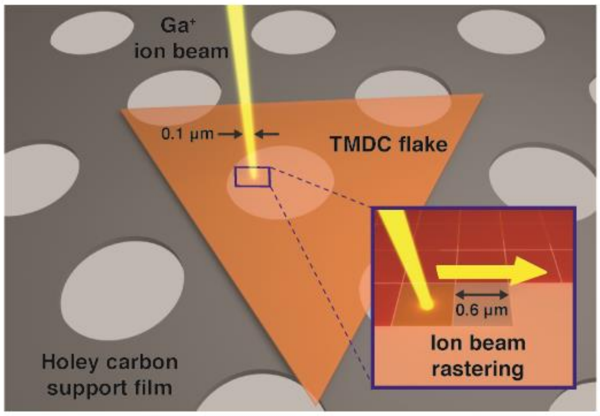

Figure 1: Graphic of the irradiation mechanism for monolayer TMDs (orange) suspended over 1-micron diameter holes using a focused Ga^+ ion beam (yellow). The inset illustrates the raster pattern of the FIB.

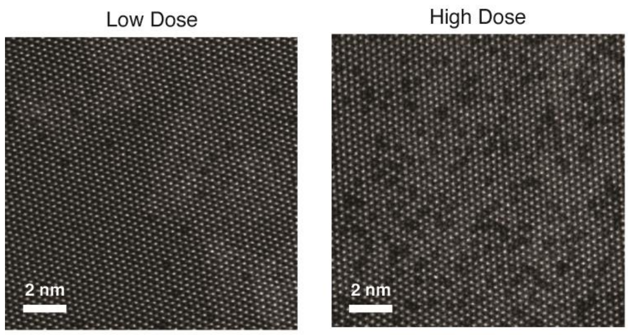

Figure 2: AC-STEM images of monolayer WS_2 exposed to ion beam irradiation with D = 5.1×10^{13} ions/cm^2 and D = 6.3×10^{14} ions/cm^2. Due to the Z-contrast behavior of HAADF imaging, the image intensity of Ga dopants is weaker compared to heavier W atoms.