



Figure 2 | Multi-junction lateral heterostructures based on MoS₂ and WS₂.

a, Optical image of a heterostructure composed of three MoS₂–WS₂ junctions. **b**, SEM image of the region of the heterostructure within the dashed box in **a**. **c**, **d**, Raman (**c**) and photoluminescence (**d**) spectra at points 1, 2, 3, 4, and at the junctions 1–2, 2–3 and 3–4 indicated in **b**. **e**, Normalized photoluminescence colour contour plot along a direction perpendicular to the interfaces, where the white arrow indicates the growth direction. **f**, Composite Raman intensity map of the heterostructure.

g, Photoluminescence intensity map of the MoS₂ domains, at 1.84 eV. **h**, Photoluminescence intensity map of the WS₂ domains, at 1.97 eV. **i**, Composite photoluminescence map of the heterostructure. **j**, Electron diffraction pattern of the heterostructure. **k–m**, Atomic-resolution HAADF-STEM images of a MoS₂–WS₂ interface (**k**), pure WS₂ (**l**) and pure MoS₂ (**m**) regions. **n**, Atomic ball model superimposed on the HAADF-STEM image of the interface. **o**, Electron intensity profile of the region along white box in **k**. Scale bars, 10 μm (**a**, **b**, **f–i**); 1 nm (**k–m**).

We further extended the use of the one-pot approach to produce sequential lateral heterostructures of sulfide monolayers (MoS₂–WS₂) (Extended Data Figs 6, 7). Figure 2a shows the optical image of a three-junction heterostructure (MoS₂–WS₂–MoS₂–WS₂). Its corresponding scanning electron microscopy (SEM) image (Fig. 2b) reveals the coexistence of alternating MoS₂ (dark contrast) and WS₂ (bright contrast) domains. The Raman spectra acquired at different positions (Fig. 2c), as well as the Raman maps (Fig. 2f), also confirm the sequential formation of MoS₂ and WS₂ domains. Regions 1 and 3 exhibit phonon modes at 384 cm^{−1} (E_{2g}) and 405 cm^{−1} (A_{1g}) that are consistent with monolayer MoS₂ (ref. 23), whereas the WS₂ regions (2 and 4) present the characteristic first-order (E_{2g}¹ at 355 cm^{−1} and A_{1g} at 418 cm^{−1}) and second-order (most intense at 350 cm^{−1} (2LA(M)) Raman peaks²⁴. At the interfaces (1–2, 2–3 and 3–4), the Raman spectra are mostly composed of a superposition of the vibrational modes of both MoS₂ and WS₂ domains (Supplementary Table 1). Single photoluminescence peaks associated with direct excitonic emissions from monolayers were observed for MoS₂ (1.84 eV) and WS₂ (1.97 eV) domains (Fig. 2d). The corresponding photoluminescence intensity maps at 1.84 eV (Fig. 2g), 1.97 eV (Fig. 2h) and composite image (Fig. 2i) show that, within each domain, the photoluminescence emission is homogeneous. The photoluminescence line scan across the junctions (Fig. 2e) also displays the modulation of the optical bandgap along the heterostructure with sharp discontinuities at the junctions. At the interfaces, the photoluminescence spectra show the superposition of two well-resolved peaks corresponding to the simultaneous excitation of MoS₂ and WS₂ domains. For the MoS₂→WS₂ interfaces 1–2 and 3–4, and around the MoS₂ domain, these photoluminescence peak positions are slightly blue-shifted by 25 meV and by 10 meV, respectively. Photoluminescence shifts were not observed at the WS₂→MoS₂ interface (2–3), which is consistent with the results obtained for selenide-based junctions. Z-contrast images from the inner regions of each domain (Fig. 2l, m) confirm the high purity of the individual MoS₂ and WS₂ domains. The high quality and single-crystalline nature of these interfaces produced by lateral epitaxy was also verified by electron diffraction (Fig. 2j) and Z-contrast STEM imaging (Fig. 2k–o).

The morphology of the sulfide-based heterostructures involves MoS₂ cores with a truncated triangular geometry containing two types of zig-zag edge: metal-terminated (Mo-zz) and chalcogen-terminated (S-zz). The WS₂ domains grow preferentially along one of these MoS₂ edges, leading to WS₂ sections with a convex isosceles trapezoid shape. The consecutive MoS₂ growth follows the same pattern. The shape of the two-dimensional TMD crystal is determined by the relative growth rates of the different edges. Experimental²⁵ and theoretical²⁶ studies have shown that edge stability in MX₂ TMDs depends on the gas environment, the M:X atomic ratio and the growth temperature. A chalcogen-deficient environment promotes the formation of M-zz edges, while chalcogen-rich environments favour the stability of the X-zz edges. The distinct geometries observed in selenide- and sulfide-based heterostructures could originate from the different vaporization rates of selenium and sulfur, as well as the stability of the supply of the chalcogen atom during growth. This hypothesis is discussed in more detail in Methods.

TMD ternary alloys have received increasing attention owing to their composition dependent electronic properties and their potential to further expand the range of available two-dimensional materials beyond the four primary binary compounds (MoS₂, MoSe₂, WS₂ and WSe₂) (refs 27, 28). However, integrating different ternary alloys into a single crystal heterostructure has not yet been achieved. The versatility of the one-pot approach allowed us to fabricate sequential multi-junction heterostructures based on ternary alloys (MoS₂(1−x)Se_{2x}–WS₂(1−x)Se_{2x}). To this effect, solid sources containing combinations of either MoSe₂ + WS₂ or MoS₂ + WSe₂ were used. Figure 3a, b shows optical images of two distinct alloy-based lateral heterostructures (ALH1 and ALH2) with three junctions (Extended Data Figs 8–10). The corresponding photoluminescence maps (Fig. 3c, d) are consistent with different S:Se ratios. MoS₂(1−x)Se_{2x} and WS₂(1−x)Se_{2x} domains in ALH1 exhibit single photoluminescence peaks at 1.61 eV and 1.71 eV, respectively, whereas for ALH2 the Mo-rich and the W-rich domains have photoluminescence emissions at 1.67 eV and 1.8 eV, respectively. The photoluminescence line scan across ALH2 (Fig. 3e) shows that the position of the photoluminescence peak for each domain remains