Visualizing electrostatic gating effects in two-dimensional heterostructures

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The ability to directly monitor the states of electrons in modern field-effect devices—for example, imaging local changes in the electrical potential, Fermi level and band structure as a gate voltage is applied—could transform our understanding of the physics and function of a device. Here we show that micrometre-scale, angle-resolved photoemission spectroscopy1–3 (microARPES) applied to two-dimensional van der Waals heterostructures4 affords this ability. In two-terminal graphene devices, we observe a shift of the Fermi level across the Dirac point, with no detectable change in the dispersion, as a gate voltage is applied. In two-dimensional semiconductor devices, we see the conduction-band edge appear as the electrostatic doping increases. Both optical spectroscopy and microARPES can be carried out on a single device, allowing definitive studies of the relationship between gate-controlled electronic and optical properties. The technique provides a powerful way to study not only fundamental semiconductor physics, but also intriguing phenomena such as topological transitions and many-body spectral reconstructions under electrical control.

In ARPES, one measures the distribution of the energy and momentum of electrons photoemitted from a solid sample that is being subjected to narrow-spectrum ultraviolet or X-ray excitation. This provides information about the energy and momentum of the initial occupied electron states, and hence the band structure and Fermi level. As electrons are emitted only from very near the sample surface, ARPES is not useful for studying conventional semiconductor devices. On the other hand, it is well suited to probing two-dimensional (2D) materials, and has been applied to films of graphene6, transition metal dichalcogenides (MX2, where M is molybdenum (Mo), tungsten (W), tantalum (Ta) or another transition metal, and X is sulfur (S), selenium (Se) or tellurium (Te))7,8, and others9,10. Although the excitation spot size is typically measured in millimetres, efforts have been made in the past decade2 to perform ARPES with a focused beam suitable for small or nonuniform samples. Micrometre-scale spot sizes (hence ‘µ-ARPES’) have been achieved in at least four commissioned synchrotron beamlines by using Schwarzschild objectives1, Fresnel zone plates2,3, or capillary mirror optics11. MicroARPES has allowed the study of atomically thin exfoliated flakes of 2D materials, which are typically tens of micrometres or fewer in size12, and of heterostructures4 made by stacking such flakes of different materials13,14, revealing for example band offsets and interlayer hybridization15–17. Such 2D heterostructures can be made

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Fig. 1 | Visualizing electrostatic gating of monolayer graphene. a, Diagram of a 2D heterostructure device, which consists of a stack comprising graphene encapsulated by BN on a graphite back gate. A focused micrometre-size X-ray beam spot (energy hν) generates photoemitted electrons (e−) (see Methods). The graphene is grounded while a gate voltage, VG, is applied to the gate. b, Optical image of a device mounted in a standard dual in-line package. c, Magnified optical image of the dotted box in panel b, showing the stack. Scale bar, 50 μm. d, SPEM image of the same area. e, Energy-momentum slices near the graphene K-point (along the red line in the Brillouin zone shown in the inset at the left), at the labelled gate voltages. The blue dashed lines are linear dispersion fits; the Dirac-point energy ED is deduced from their crossing point. Scale bars, 0.2 Å−1. Inset are schematics of the graphene Dirac cone at each VG, contrasting filled (purple) and empty (red) states. f, Gate dependence of ED, with error bars obtained from the fitting procedure. The solid line is a fit based on the dispersion of graphene, with the gate-induced electron density (nG) shown on the top axis and calculated from the capacitance (see Methods).

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Fig. 2 | Layer-number-dependent CBE in WSe₂. a, Diagram of a device incorporating a WSe₂ flake, with an overlapping ground graphene top contact and gate voltage applied to the graphite back gate. b, c, Optical (b) and SPEM (c) images of WSe₂ device 1 (BN thickness (d_{BN}) = 7.4 ± 0.5 nm), with monolayer (1L), bilayer (2L) and trilayer (3L) regions identified. Scale bars, 5 μm. d–f, Energy-momentum slices along Γ–K for 1L, 2L and 3L regions respectively. The upper panels are at V_G = 0 V and the lower ones at V_G = +3.35 V. The intensity in the dashed boxes is multiplied by 20. The fuzzy spots signal population of the CBE. Scale bars, 0.3 Å^{-1}. The data have been reflected about Γ to aid comparison with electronic structure calculations (GW approximation; red dashed lines). g, Brillouin zone of MX₂ (left) and diagram of the bands along Γ–K (right), showing definitions of the energy parameters discussed in the text.

Table 1 | Measured band-structure parameters of MX₂ semiconductors

|     | Δ_{SOC} (eV) | E_v (V_G = 0) (eV) | E_c (V_G = 0) (eV) | m_i/m_e | E_g (eV) |
|-----|-------------|-------------------|-------------------|---------|---------|
| 1L MoS₂ | 0.17 ± 0.04 | 1.93 ± 0.02 | 0.14 ± 0.04 | 0.7 ± 0.1 | 2.07 ± 0.05 |
| 1L MoSe₂ | 0.22 ± 0.03 | 1.04 ± 0.02 | 0.48 ± 0.03 | 0.5 ± 0.1 | 1.64 ± 0.05 |
| 1L WS₂ | 0.45 ± 0.03 | 1.43 ± 0.02 | 0.39 ± 0.02 | 0.5 ± 0.1 | 2.03 ± 0.05 |
| 1L WSe₂ | 0.485 ± 0.010 | 0.88 ± 0.01 | 0.62 ± 0.01 | 0.42 ± 0.05 | 1.79 ± 0.03 |
| 2L WSe₂ | 0.501 ± 0.010 | 0.75 ± 0.01 | 0.14 ± 0.01 | 0.41 ± 0.05 | 1.51 ± 0.03 * |
| 3L WSe₂ | 0.504 ± 0.010 | 0.74 ± 0.01 | 0.00 ± 0.01 | 0.40 ± 0.05 | 1.46 ± 0.03 * |

As defined in Fig. 2g. Δ_{SOC} is the spin–orbit splitting of the valence band at K; E_v is the valence-band edge at V_G = 0; E_c = E_v – E_g is the difference between the valence-band edges at K and Γ at V_G = 0; m_i is the effective mass of the valence-band edge at K in units of the free electron mass m_e; and E_g is the bandgap measured at gate-induced electron density n_G = 1.0 × 10^{12} cm^{-2}. The stage temperature was 100 K for WSe₂ and 105 K for the others.

*Indirect measurement, with CBE at Q.

A major limitation of ARPES is that it probes only occupied electron states. A semiconductor sample must therefore be electron-doped in order to obtain a signal from the conduction band. Doping is usually achieved by depositing electropositive atoms such as alkali metals\textsuperscript{6–8,13} on the surface. This process cannot be controlled accurately and can only be reversed by high-temperature annealing; moreover, it chemically perturbs the electronic structure and introduces disorder through the random distribution of impurities. Here we demonstrate purely electrostatic doping, which has none of these disadvantages. We thereby obtain momentum-resolved electronic spectra and direct visualization of Fermi-level shifts and band-structure changes induced by applying a gate voltage.

We first demonstrate and validate the technique using graphene, then A similar structure with two contacts to the graphene would play 21, 25. Using electrostatic doping in microARPES, we confirm that the CBE is at K in all of the monolayer semiconductors—MoS₂, MoSe₂, WS₂ and WSe₂—and in each case we obtain a measure of the bandgap. We also study the layer-number dependence in WSe₂, finding that the CBE moves to Q in the bilayer, and measure for the first time the renormalization of the band structure on gating.

In our graphene devices, a graphene sheet is capped by monolayer hexagonal boron nitride (BN), supported on a BN flake over a graphite gate (Fig. 1a), and located in a gap between two platinum electrodes on an SiO₂/Si substrate chip (Fig. 1b, c; see Methods and Extended Data Fig. 1). A similar structure with two contacts to the graphene would...
function as a high-mobility transistor. We used scanning photoemission microscopy (SPREM) to locate the sample in the ARPES chamber (Fig. 1d; see Methods). Figure 1e shows energy, $E - E_F$ (where $E$ is the measured photoelectron kinetic energy and $E_F$ is the kinetic energy of electrons removed from the Fermi level) versus in-plane momentum for a slice through the Dirac cone near the graphene zone corner $K$, acquired at a series of gate voltages ($V_G$) at 105 K. As expected, the Dirac-point energy, $E_D$, shifts from above $E_F$ at $V_G = -5$ V to below $E_F$ at +5 V. Fitting a linear dispersion, $E(k) = E_D \pm h\nu k$ (blue dashed lines in Fig. 1c; $h$ is Planck’s constant and $k$ is the in-plane momentum), gives $E_D$ and the Fermi velocity, $v_F$. The variation of $E_D$ with $V_G$ (Fig. 1f) is consistent with the expected form for this dispersion (solid line; see Methods). No modification of the dispersion near $E_D$ as could arise because of interactions, is detectable with the present spectral resolution (see Extended Data Fig. 2). We find that $v_F = (9.3 \pm 0.1) \times 10^6$ m s$^{-1}$ at $V_G = 0$, with a weak $V_G$ dependence (see Extended Data Fig. 3).

The consistency of the above properties with the literature on graphene, together with the observation that the spectrum is undistorted as $V_G$ is changed, implies that the photoelectron trajectories are not affected by stray electric fields resulting from the gate voltage or charging effects. We conclude that our technique produces accurate local electronic spectra during live electrostatic gating.

To study gate doping of 2D semiconductors, we incorporate an MX$_2$ flake into the stack on top of the BN and partially overlapped by graphene, which acts as a contact to the MX$_2$ (Fig. 2a). Figure 2b, c shows optical and SPREM images of a device with a WSe$_2$ flake that has monolayer (1L), bilayer (2L) and trilayer (3L) regions. Figure 2d–f shows momentum slices obtained with the beam spot on each of these regions and along $\Gamma$–$K$ in the WSe$_2$ Brillouin zone at a temperature of 100 K (Fig. 2g, inset). As expected, at $V_G = 0$ (upper row) only the valence bands can be seen. Their evolution with layer number is consistent with the literature, and matches well with the overlaid theoretical predictions (the GW approximation; see Methods). At $V_G = +3.35$ V (lower row), an additional spot appears near $E_F$. The size of this conduction-band feature is determined solely by the resolution of the measurement. In 1L WSe$_2$ the spot is located at $K$, whereas in 2L and 3L it is at $Q$ (Fig. 2g and Extended Data Fig. 4). This is consistent with evidence from photoluminescence that the gap is direct at $K$ in the monolayer, but indirect for two or more layers.

Table 1 displays the band parameters for 1L–3L WSe$_2$, as well as for other monolayer MX$_2$ species, derived from measurements on this and other devices (Extended Data Fig. 5). We determined the bandgap, $E_g = E_C - E_V$, where $E_C$ is the energy of the CB, at a gate doping level of $n_0$ approximately equal to $10^{15}$ cm$^{-2}$, for which $E_C - E_V$ is approximately 30 meV (see Methods). We also list the simultaneously determined hole effective mass $m^*_h$, the valence-band edge $E_V$, the spin–orbit splitting $\Delta_{\text{SOC}}$, and $E_{\text{Kr}}$ (the latter three being defined in Fig. 2g)—all measured for the first time on a hexagonal BN substrate with no cap and with greater precision than in previous reports.

We now consider the full gate dependence of microARPES spectra. Figure 3 shows the behaviour of the top of the valence band at $\Gamma$, where the photoemission signal is strongest, for our monolayer WSe$_2$ device 2.
At low $V_G$ (range labelled B–C–D in Fig. 3), the spectrum shifts nearly linearly with a slope of $-1/e$, where $e$ is the electron charge, implying that the electrostatic potential in the WSe$_2$ tracks the gate potential when it is undoped. For $V_G$ values of more than $+2.1$ V (labelled E in Fig. 3) or less than $-1.5$ V (labelled A), the spectrum becomes almost independent of $V_G$, implying that these are the thresholds for electron and hole accumulation, respectively. The behaviour can be understood in more detail with reference to the corresponding band diagrams shown above in Fig. 3, taking into account the balance of the current of photoemitted electrons, $I_{ph}$, and the currents into the beam spot from the contact, $I_C$, and the gate, $I_G$, as indicated in the sketch at the top left (see Methods).

Note that no change in spectral widths is seen as long as the WSe$_2$ is insulating (range B–D in Fig. 3), but above threshold (range D–E) all features are smeared in energy by a similar amount. This can be explained by inhomogeneous broadening due to variation of the potential across the beam spot, associated with lateral current flow in the WSe$_2$. Refinement of the technique to reduce this effect may allow studies of changes in intrinsic broadening with doping.

Figure 4a shows spectra from monolayer WSe$_2$ device 1 at $V_G = 0$ (for reference) and at selected gate voltages well above threshold (about $+1.5$ V). In this regime we derive the gate doping, $n_G$, also shown, from the gate capacitance and threshold voltage (see Methods). The CBE becomes visible at $K$ for $n_G$ values of more than about $10^{12}$ cm$^{-2}$, and at $Q$ for values of more than roughly $10^{13}$ cm$^{-2}$, when $E_K$ is roughly 30 meV below $E_F$. We conclude that the conductance band minimum at $Q$ is higher than that at $K$. Scanning tunnelling spectroscopy also indicates that for 1L WSe$_2$ these minima are very close. The form of the valence bands does not change discernibly with increasing $n_G$, but they shift upwards in energy while the CBE is pinned at $E_F$, implying that the bandgap decreases.

Optical spectroscopy can be performed on the same devices, and under the same conditions, as the microARPES measurements, eliminating uncertainties due to differences in sample quality, dielectric environment, gate voltage and temperature$^{29,30}$. Figure 4b shows both the microARPES determination of $E_F$ (black solid circles) and the photoemission peak positions (black empty circles), $E_X^h$ and $E_X^v$ for neutral ($X^0$) and charged ($X^\pm$) excitons, for monolayer WSe$_2$ device 3 as a function of gate doping at 100 K. Also shown are the values of $E_D$ from device 1 (red solid circles), which agree to within the uncertainty. It is apparent that $E_F$ decreases systematically, by around 400 meV overall as $n_G$ rises to $1.5 \times 10^{13}$ cm$^{-2}$. Such renormalization of the bandgap with static doping is expected to occur in a semiconductor as a result of free-carrier screening$^{31}$, though it has not previously been so accessible to experiments.

Also plotted in Fig. 4b are values of the bandgap at $n_G = 0$ inferred from several other techniques. An extrapolation of $E_D$ measured by microARPES to $n_G = 0$ is consistent with scanning tunnelling spectroscopy (STS) measurements, which put it in the range 2.1–2.2 eV. Comparison with $E_X^h$ supports arguments that the binding energy of neutral excitons in this material is very large$^{28}$, at several hundred millielectronvolts. $E_D$ decreases much more quickly than $E_X^h$ with doping, implying dramatic weakening of the exciton binding—another expected effect of free-carrier screening$^{39}$. Finally, the smaller values of $E_F$ reported in monolayers doped with alkali metals (down to $1.4$ eV) are consistent with an extrapolation of the renormalization process to higher $n_G$ values$^{29,30}$.

The ability to measure changes in the electronic bands in 2D field-effect devices opens up many interesting possibilities. For example, it could be used to study electric-field tuning of the bands across topological phase transitions$^3$; to investigate the doping dependence of spectra in correlated electron systems such as in superconductors, Mott insulators, and charge-density-wave materials; to observe spectral reconstructions in structures with moiré superlattice modulations$^{32}$; and, with the addition of circularly polarized light or a spin-resolved spectrometer, to study electrically controlled magnetic phenomena$^{33}$.

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MX$_2$ semiconductor devices. For MX$_2$ semiconductor devices, the situation is more complicated. At small $V_g$ values, the doping $n_D$ must be very small because of the bandgap, so the in-plane resistance can be large and $\Delta V$ can be substantial. As long as $n_D$ is negligible the bands will not be renormalized and $\Delta V$ can be identified with the purely electrostatic energy shift of an ARPES spectral feature. $\Delta E_{F1}/e$ in Fig. 3 indeed tracks $V_g$ closely at low $V_C$ values (see Extended Data Fig. 7). We deduce that, in this regime, photoemission directly from the BN valence band generates conductivity in the BN that is sufficient to keep the potential in the MX$_2$ close to that of the gate, that is, $\Delta V$ is approximately equal to $V_g$, with negligible potential drop across the BN and no accumulation of charge in the MX$_2$. By contrast, at a sufficiently large magnitude of $V_g$, $(V_g - \Delta E_{F1})$ tends towards a linear increase with $V_g$. This happens when the high doping makes the in-plane resistance $R$ small enough that the electrochemical potential in the MX$_2$ approaches that in the (ground) electrode and $\Delta V$ stops changing, with the Fermi energy virtually pinned at the band edge owing to the large density of states. In this regime we can take $n_D/C_g(V_g - \Delta E_{F1})$, since $(V_g - \Delta E_{F1})$ is the static potential drop across the BN, the electrons are in electrochemical equilibrium, and the quantum capacitance is negligible (that is, $E_F$ is effectively pinned at the CBE). The value of $n_D$ shown in Fig. 4 are obtained in this way.

Our interpretation of the behaviour in Fig. 3 for monolayer WS$_2$ is as follows. The photoemission current $I_{PE}$, the current to the contact $I_C$, and the current to the gate $I_g$ (indicated in the sketch at the top left of Fig. 3) must sum to zero. $I_C$ can be substantial because of photoexcited carriers in the BN. (It should be borne in mind that in general such currents may cause a device to operate differently from how it would in the dark.) Between B and C in Fig. 3, the WS$_2$ is depleted and reflection geometry, with the BN photoconductivity brings the potential close to that of the gate. Holes created by photoemission from the WS$_2$ recombine with excited electrons in the BN, and $I_{PE}$ is approx. equal to $I_C$. Between C and D, these holes can also drift to the contact through the depleted WS$_2$ and $I_C$ is substantial. Above threshold, at E, electrons accumulate at the CBE in the WS$_2$ as they flow in laterally from the graphene contact, and the CBE is pinned close to the graphene Fermi level. Similarly, at A, holes accumulate and the valence-band edge is pinned. An ‘overshoot’ occurs at D because when the CBE in the beam spot first moves below the graphene Fermi level, the Schottky barrier between graphene and WS$_2$ is partially closed and the electron flow is perturbed.

Estimating the CBE energy. The structure of the conduction band is not resolvable in the ARPES data (Fig. 2–f). The density of states at a single parabolic band edge is $g_{\text{DO}} = g_{\text{DO}}^{\text{m}} m^*/h^2$, with spin and valley degeneracies $g_v$ and $g_{\text{DO}}$ and effective mass $m^*$. For 1L WS$_2$, the conduction-band edges are at the K-points, so $g_{\text{DO}}^m = 2$, and the band is spin-split by approximately 40 meV (ref. 42); hence $g_v = 2$ for moderate doping. Calculations show that $m^*$ is approximately equal to 0.3$m_0$.

Using $n_D = \int (E)\gamma(E)\,dE$, where $(E)$ is the Fermi–Dirac distribution, then gives that $E_F - E_c$ is approximately equal to 30 meV at $n_D = 1.0 \times 10^{12}$ cm$^{-2}$. Optical spectroscopy. Photoluminescence measurements were performed using approximately 20–μW linearly polarized 532-nm continuous-wave laser excitation in reflection geometry with the electron collection described by a spectrometer and a silicon charge-coupled device, in vacuum in a closed-cycle cryostat.

Electronic-structure calculations including spin–orbit interaction were made using the Quantum Espresso DFT package. Structures were first optimized until forces were smaller than $10^{-4}$ Ry/Bohr$^{-1}$. Geometry optimizations and band-structure calculations were performed with an 18 × 18 in-plane k-point grid with a plane-wave energy cut-off of 140 Ry. To avoid interaction between periodic images, the vacuum spacing was 25.0 Å. We used norm-conserving fully relativistic pseudopotentials from PseudoDojo, where the semi-core 4d, 5s and 5p states for tungsten are retained as valence electrons. This results in a lattice constant of 3.32 Å for all three structures. We used the results from calculations with the PRB as a starting point for G$_0$W$_0$ calculations which used the Yambo code, with the Godby–Needs plasmon pole approximation. We used 300 bands, 500 bands and 700 bands for the monolayer, bilayer and trilayer WS$_2$, respectively, for the self-energy and dynamical dielectric screening. In order to treat the divergence of the Coulomb interaction during the self-energy calculation, we used the random integration method, with $3 \times 10^3$ random q-points and 100 random G vectors.

Data availability
All data presented in this paper are available at http://wrap.warwick.ac.uk/116301. Additional data related to this paper may be requested from the authors.

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**Author contributions**

N.R.W., X. Xu and D.H.C. conceived and supervised the project. P.V.N., J.K. and N.P.W. fabricated the samples. N.C.T., N.R.W., P.V.N., X. Xia, A.J.G., V.K., A.G. and A.B. collected μ-ARPES data. N.C.T., N.R.W. and P.V.N. analysed μ-ARPES data (with input from A.B.). N.P.W. acquired photoluminescence data. N.D.M.H., N.Y. and G.C.C. performed the band-structure calculations. D.H.C., N.R.W., P.V.N. and X. Xu wrote the paper with input from all authors.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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Extended Data Fig. 1 | Fabrication of a gated heterostructure. Diagram showing the process for fabricating WSe$_2$ device 1, with associated micrographs. Scale bars are 15 µm unless otherwise noted. PC, polycarbonate; PDMS, polydimethylsiloxane.
Extended Data Fig. 2 | Distortion-free, uniform band shifting in electrostatically gated graphene. a–c, Constant energy slices through a graphene Dirac cone at the stated gated voltages and electron energies relative to the Dirac point (black dot). No substantial change is seen on varying \( V_G \), implying that the spectrum is not distorted by electrostatic/space charge effects. The width of each panel represents \( 4 \, \text{Å}^{-1} \).

d, Bottom, slice of energy \( E \) versus in-plane momentum \( k_{\|} \) along the zone boundary, through points K and K’ (shown at the top), in gated graphene at \( V_G = +3.35 \, \text{V} \). Scale bar, \( 0.5 \, \text{Å}^{-1} \). The spectrum is symmetric about point M, as illustrated by the consistent Dirac-point energy (dashed line) between K and K’. These measurements are from the same device as Fig. 3, from a region in which the graphene was on top of the 1L WSe\(_2\) (which produces the faint bands at binding energies of around 2 eV) but still electrostatically gated. This shows that the electric field from the gate does not distort the measured graphene spectrum in any direction in momentum space.
Extended Data Fig. 3 | Extracted graphene Fermi velocity versus gate voltage. We calculated the Dirac-point energy and Fermi velocity from $E - k$ slices (some of which are shown in Fig. 1) near the graphene K point, by analysing the band dispersions. We extracted momentum-distribution curves (MDCs; that is, intensity as a function of momentum $I(k)$ at constant energy), and found the positions of the branches on each side of the Dirac cone by fitting Gaussian peaks. After repeating this process for each MDC within $|E - E_D| < 1$ eV, we fit a straight line of the same absolute slope to each side, yielding the Dirac point, $E_D$, from where the lines cross and the Fermi velocity, $v_F$, from their slope. In cases in which one side was much more intense than the other, we used only the more intense side to find $v_F$. The extracted velocity is here plotted against gate voltage. Evidence has previously been reported$^{36}$ of a reduction in $v_F$ of up to 20% near $E_D$ in graphene films at low doping levels (roughly $1 \times 10^{12}$ cm$^{-2}$). This corresponds to a subtle distortion of the bands at $E_D$, which the spectrometer at Elettra does not as yet have the resolution to probe, and could not be detected by the above procedure which assumes purely linear dispersion. Note that the variations seen in this figure can be explained by systematic errors, taking into account experimental limitations such as the very weak emission from one branch and the sensitivity to the exact alignment of the momentum slice with the Dirac point.
Extended Data Fig. 4 | Uniform band shifting in electrostatically gated 2L WSe₂. Constant energy maps of electrostatically gated 2L WSe₂ at $V_G = +8$ V: left, at a binding energy of 1.555 eV, which here corresponds to the valence-band maximum; and right, near the Fermi energy at a binding energy of 0.025 eV. It can be seen that the CBE is the same at points Q and Q', implying that the gate field does not substantially distort the spectrum in this case either.
Extended Data Fig. 5 | CBEs in monolayer MoS$_2$, MoSe$_2$ and WS$_2$.

a, Diagram of a device, with graphene contact grounded and gate voltage applied to the graphite back gate, as in Fig. 2a. b, Diagram showing the bands near point K, at zero gate voltage (left) and at a gate voltage that exceeds the threshold voltage to bring the Fermi level to the CBE (right). CBM, conduction-band maximum; VBM, valence-band maximum.

c–e, Energy-momentum slices through point for monolayer MoS$_2$, MoSe$_2$ and WS$_2$. Scale bars, 0.3 Å$^{-1}$. 
Extended Data Fig. 6 | Photocurrent and SPEM maps of a WSe$_2$ heterostructure device. 

a, Diagram of the device, with the graphene contact grounded and a gate voltage applied to the graphite back gate. 
b, c, Optical (b) and SPEM (c) images of WSe$_2$ device 1, with 1L, 2L and 3L regions identified. Dashed lines trace boundaries of the graphite gate (red) and the graphene contact (black). 
d, Photocurrent image acquired simultaneously with the SPEM image in panel c. Scale bars, 5 µm.
Extended Data Fig. 7 | Gate-induced band shifts and photocurrent in monolayer WSe$_2$. a, $\Delta E_{\Gamma}$ versus $V_G$ for WSe$_2$ monolayer device 2. b, $V_G - \Delta E_{\Gamma}/e$ versus $V_G$. c, Current from gate to ground versus $V_G$. The grey shaded regions indicate the threshold regions in which the WSe$_2$ becomes conducting. See Methods for discussion.