Enhanced conductivity along lateral homojunction interfaces of atomically thin semiconductors

Ying Jia, Teodor K Stanev, Erik J Lenferink and Nathaniel P Stern
Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, United States of America
E-mail: n-stern@northwestern.edu
Keywords: transition metal dichalcogenides, interfaces, conductivity, photoresponse, edge states, heterostructures

Abstract
Energy band realignment at the interfaces between materials in heterostructures can give rise to unique electronic characteristics and non-trivial low-dimensional charge states. In a homojunction of monolayer and multilayer MoS$_2$, the thickness-dependent band structure implies the possibility of band realignment and a new interface charge state with properties distinct from the isolated layers. In this report, we probe the interface charge state using scanning photocurrent microscopy and gate-dependent transport with source-drain bias applied along the interface. Enhanced photoresponse observed at the interface is attributed to band bending. The effective conductivity of a material with a monolayer-multilayer interface of MoS$_2$ is demonstrated to be higher than that of independent monolayers or multilayers of MoS$_2$. A classic heterostructure model is constructed to interpret the electrical properties at the interface. Our work reveals that the band engineering at the transition metal dichalcogenides monolayer/multilayer interfaces can enhance the longitudinal conductance and field-effect mobility of the composite monolayer and multilayer devices.

1. Introduction
Transition metal dichalcogenides (TMDCs) are layered crystals with thickness-dependent band gaps, 1.29 eV in a multilayer (ML) and 1.88 eV for a monolayer (1L) of MoS$_2$ [1], for example. The distinct electronic structure implies an energy band discontinuity at the interface in 1L and ML MoS$_2$. Recent Kelvin probe force microscopy [2] has detected different electron affinities in 1L and ML MoS$_2$ and the conduction band offset at the boundary between two regions of the same region material but with different layer numbers (which we refer to here as a 1L/ML homojunction). According to the electron affinity model, band realignment should occur near the interface and may create unique interfacial electronic states with properties distinct from those of the parent compounds [3]. Examples of such emergent interfacial properties in heterostructures are high-mobility two-dimensional electron gases in Al$_x$Ga$_{1-x}$As/GaAs [4], and interface superconductivity in Bi$_2$Te$_3$/FeTe [5]. Distinct from the ‘conventional’ semiconductor heterojunctions, experimental and calculated results have suggested localized metallic states at the 1D edges of 1L and few-layer MoS$_2$ [6–12]. In a lateral 1L/ML MoS$_2$ homojunction (figure 1(a)), such an edge state of ML MoS$_2$ could influence the band realignment at the interface, complicating the electronic structure and the properties of the interface electrons.

Recent studies on TMDC 1L/ML homojunctions were primarily focused on photocurrent generation at the interfaces with source-drain contacts on opposite sides of the 1L/ML junctions [2, 13, 14]. Band realignment has been confirmed though the details are still under debate [14]. Current versus voltage (IV) measurements were also performed with currents applied across the junction [13, 14] with non-linear I − V curves consistently observed. The existence of conducting edge charge states at multilayer junctions separating distinct TMDC thicknesses has been measured [6], but the consequences of layer-sensitive composite structures for low-dimensional interfacial transport at the monolayer limit have not yet been investigated. In particular, the longitudinal transport properties of 1L/ML interfaces remain unstudied.

Here, we fabricate lateral MoS$_2$ 1L/ML homojunctions and investigate the longitudinal transport properties of the interface charge state with source-drain bias applied along the interface. Interfacial band bending is confirmed by enhanced photoresponse along the junction boundary using scanning
photocurrent microscopy. Electric conductivity of the 1L and ML composite devices is measured and compared with that of the independent 1L and ML MoS2 of the same flake. The higher effective conductivity of the composite devices indicates a notable contribution from the interface charge state. Our results outline an experimental approach to studying interfacial conduction properties of electronic states at layered TMDC homojunctions.

2. Methods

The MoS2 flakes were mechanically exfoliated from undoped crystals and deposited on heavily doped silicon substrates covered with 285 nm-thick SiO2 using elastic-film-assisted micro-mechanical exfoliation [16]. MoS2 flakes with both 1L and ML regions were identified using optical microscopy and then confirmed using atomic force microscopy. Figure 1(b) shows a typical as-exfoliated sample. This sample consists of 8 layers on one side and 1 layer on the other side, as shown in the inset of figure 1(b). The 1L/ML structures were patterned into individual pieces with Au electrodes using e-beam lithography and SF6 reactive ion etching [17]. The 1L, ML, and 1L+ML devices were fabricated from the same flake and were independently measured with a 4-point method. All devices were operated in a back-gated configuration to maintain the direct accessibility of an excitation laser with the heavily doped Si substrates acting as the back gates.

3. Results

Scanning photocurrent microscopy was used initially to probe the generation of carriers and band bending at the 1L/ML homojunction. The measurement was performed in high vacuum (less than 1 mTorr) and at room temperature with laser excitation power of 70–80 μW at several wavelengths as noted. In few-layer MoS2, the primary photocurrent mechanisms involve two processes, exciton generation by a photon with energy higher than the optical band gap and free carrier creation by electric-field-assisted dissociation [18]. At the 1L/ML interface, band bending induces a high local built-in electric field which can dissociate excitons efficiently and enhance local photoresponse. With our contact geometry, the built-in field is perpendicular to the current channel, and cannot drive the dissociated free carriers to the contacts. The magnitude of photoresponse is expected to be lower than that with source-drain contacts on opposite sides of the interface. A source-drain bias is required to produce photocurrent in the circuit.

Figure 2(a) shows the optical image of the scanned area (20 × 20 μm²). The widths of the 1L and ML channels are 5 μm and 4 μm, respectively. A bias voltage of 0.2 V was applied between the V+ and V− contacts. The photocurrent maps were acquired with excitation wavelengths 660 nm (hν = 1.88 eV, figure 2(b)), 680 nm (hν = 1.83 eV, figure 2(d)), and 700 nm (hν = 1.77 eV, figure 2(f)). A back-gate voltage of 20 V was applied during the scan. In our experiment, the intensity of the
reflected laser and the photocurrent ($I_{pc}$) generated in the device were simultaneously recorded at each position, allowing the spatial photocurrent map to be correlated with the device geometry. The inner edges of the $V_+$ and $V_-$ contacts and the 1L/ML boundary in figure 2(a) are marked by black solid lines and arrows in figure 2(b). The highest $I_{pc}$ intensity is observed at the inner edge of the $V_+$ contact, which can be attributed to the local electrical field at the Au/MoS$_2$ interface and the bias voltage applied between the $V_+$ and $V_-$ contacts [18].

To better visualize the spatial dependence of $I_{pc}$ in other areas, $I_{pc}$ is plotted with a log scale in figures 2(b), (d) and (f). The photocurrent line profiles at various wavelengths were also recorded across the 1L/ML boundary, shown in figures 2(c), (e) and (g). To avoid the influence of the high-intensity photocurrent at the $V_+$ contact, the line was chosen close to the $V_-$ contact, as shown by the black dashed line in figure 2(b).

Under illumination of $\lambda = 680$ nm, a region with enhanced photocurrent is observed between the two arrows in figure 2(d), overlapping with the 1L/ML boundary. A $I_{pc}$ peak located at the boundary is also observed in the line profile in figure 2(c). This confirms that the bent bands at the 1L/ML interface can increase local photocurrent generation. At $\lambda = 660$ nm, the photon energy very nearly matches the optical band gaps in 1L and ML MoS$_2$. Photocurrent arising from other effects such as hot carriers [21] and photothermoelectric effect [22] increases in the interior of 1L and ML [15, 23] and reduces the intensity contrast at the 1L/ML boundary. At $\lambda = 700$ nm, the photon energy is too low to effectively create excitons in MoS$_2$. The
The enhanced photocurrent at the 1L/ML boundary is observed for various gating voltages $V_g$ ranging from 10V to 40V (figure 3). The $V_g$ dependence of peak magnitude is much weaker than that observed on MoS$_2$/metal boundaries [20] because the global shifting of the back gate has only small effect on the large built-in potential at the 1L/ML interface. This observation is consistent with the $V_g$-dependent $I_{pc}$ with contacts on opposite sides of a monolayer/multilayer junction [2, 13].

Here, the photocurrent enhancement at the 1L/ML boundary is interpreted as arising from bent bands, but the possibility of a new state with optical band gap 1.83 eV cannot be ruled out. Unusual edge states of TMDCs have been observed with a band gap smaller than that of the interior [24, 25]. An optically active band gap of 1.42 eV was theoretically predicted and experimentally observed in MoS$_2$/WS$_2$ bilayer vertical heterostructures [26–28]. Nevertheless, the enhanced photocurrent suggests that the 1L/ML interface exhibits new properties associated with the unique band structure of this boundary.

To probe the conducting properties of the interface charge state, we measured transport of devices with different charge state, we measured transport of devices with contacts on opposite sides of a monolayer/multilayer junction [29]. Accounting for structural defects (e.g. sulfur vacancies), even amongst devices from the same flake [29]. Accounting for the $V_g$ shift reduces the variation between devices. The effective conductivity $\sigma_{eff}$ defined in this manner for the composite 1L+ML device represents the conductivity assuming the entire device was uniform; it is not the actual conductivity of any conduction channel in the device. The effective conductivity $G_{eff}$ is equivalent to the actual conductivity $\sigma_{eff}$ for the 1L and the ML devices, respectively. Of the three devices, the 1L+ML has the highest effective conductivity over the full range of $V_g$, indicating that the interface is more conductive than the 1L or ML regions. The effective field-effect mobility of the 1L+ML device can be calculated using $\mu_{FE-eff} = \frac{1}{C_i} \frac{\partial \sigma_{eff}}{\partial V_g}$ and compared with the field-effect mobilities of the 1L and ML devices, $\mu_{FE-1L} = \frac{1}{C_i} \frac{\partial \sigma_{1L}}{\partial V_g}$ and $\mu_{FE-ML} = \frac{1}{C_i} \frac{\partial \sigma_{ML}}{\partial V_g}$, where $C_i = 1.3 \times 10^{-4}$ F/m² is
The observed relative ordering of $\sigma_{\text{eff}} > \sigma_m > \sigma_1$ and $\mu_{\text{eff}} > \mu_{\text{m}} > \mu_{\text{eff}}$ is reproduced in additional 1L+ML devices. Figure 4(b) compares the conductivity (or effective conductivity) of a 1L, a 2L, and a 1L+2L two-terminal FET again fabricated from the same MoS$_2$ flake. It is clearly observed that the effective conductivity of the 1L+2L device is higher than that of the 1L and 2L devices. The field-effect mobility (or effective mobility) values are $\mu_{\text{eff}} = 2.8 \, \text{cm}^2 \, \text{V}^{-1} \, \text{s}^{-1}$, $\mu_{\text{m}} = 11.0 \, \text{cm}^2 \, \text{V}^{-1} \, \text{s}^{-1}$, and $\mu_{\text{eff}} = 15.2 \, \text{cm}^2 \, \text{V}^{-1} \, \text{s}^{-1}$. Transport properties of an additional 1L+ML device, temperature dependence, and a summary of the capacitance per unit area of our 285 nm-thick SiO$_2$ layer [30]. The effective mobilities of these devices are $\mu_{\text{m}} = 11.4 \, \text{cm}^2 \, \text{V}^{-1} \, \text{s}^{-1}$, and $\mu_{\text{eff}} = 20.2 \, \text{cm}^2 \, \text{V}^{-1} \, \text{s}^{-1}$. The value of $\mu_{\text{eff}}$ is within the range of $0.1 - 10 \, \text{cm}^2 \, \text{V}^{-1} \, \text{s}^{-1}$ expected for uncapped, back-gated monolayer MoS$_2$ FETs on SiO$_2$/Si substrates. The increased conductivity and mobility of ML MoS$_2$ relative to the 1L device is consistent with previous reports [29]. As with the effective conductivity $\sigma_{\text{eff}}$, the effective field-effect mobility $\mu_{\text{eff}}$ of the 1L+ML device is higher than that of the 1L and ML channel, which further confirms that the 1L/ML interface has a significant impact on the conduction properties of the composite device.

Figure 4. Electronic properties of back-gated 1L+ML devices. (a) Effective conductivity $G/W$ as a function of back-gate voltage for the 1L, ML, and 1L+ML devices in figure 1(c). $V_g$ is the threshold voltage. The inset shows $I_d - V_g$ characteristics of the 1L+ML device at various gate voltages. (b) The gate-voltage-dependent conductivity of the two-terminal 1L, 2L, and 1L+2L devices shown in the inset. The three devices were fabricated from the same flake. The scale bar is 5 μm.

4. Discussion

The observations suggest a modified charge state at the 1L/ML interface that impacts longitudinal effective conductivity in the TMDC devices. Although the measurements clearly demonstrate increased effective conductivity and effective field-effect mobility for the composite 1L+ML devices, there are several possible interpretations of the underlying mechanism which are not yet clearly distinguished. One attractive explanation is the band bending charge accumulation model as depicted in figure 6. When the 1L and ML MoS$_2$ are in contact, electrons from the 1L region diffuse into the ML region because of the potential difference [31], resulting in bent bands near the interface, in analogy to the 2DEG in a Al$_x$Ga$_{1-x}$As/GaAs heterojunction [4]. The accumulated electrons are localized at the interface and perhaps experience reduced scattering in this localized state with increased carrier density, thereby resulting in increased conductivity at the 1L/ML interface. Additional support for this interpretation is from the data in figure 4. When the 1L and ML MoS$_2$ are in contact, the presence of the 1L/ML interface enhances the field-effect mobility over that of the independent 1L and ML channels.

All measured devices are presented in the Supplementary Information. As shown in the Supplementary, the enhanced effective conductivity persists at low temperatures and with different gate voltages. In every measured 1L+ML device, the presence of the 1L/ML interface enhances the effective conductivity over that of the independent 1L and ML channels. Additional support for the enhanced conductivity of the monolayer-multilayer homojunction can be obtained by engineering interface properties, number, or continuity to increase or decrease the contribution of the edge to the net effective conductance. Here, we demonstrate further evidence for the enhanced conductivity at the 1L/ML interface by comparing 1L+ML devices with different widths. The effective conductivity should be higher in a narrower 1L+ML device because the transport along the interface contributes more to the net conductance. In figure 5, we compare the effective field-effect mobility and plotted as a function of device width $W$ in figure 5(b). Although the effective conductivity is linear in width as expected, the $W = 0$ intercept is non-zero. Taking into account measurement errors and uncertainties from the AFM dimension measurements, the intercept is non-zero at the 99% confidence level, shown by the shaded prediction band in figure 5(b). This effect has been repeated in several tapered devices. This trend indicates that the smaller devices conduct more current per unit width than the wider devices, and the non-zero $W = 0$ extrapolated conduction suggests a contribution to device conductance from the interfacial region.
promoting conductance in the device. Such a band diagram was also suggested by finite element device simulation [13] and Kelvin probe force microscopy [2]. The detailed band diagram of a 1L+ML interface can be more complex than the traditional band bending depicted in figure 4; it has been proposed that the edge state of the ML MoS2 can disrupt the band alignment because of its proximity to the 1L/ML interface [14]. Nevertheless, this model suggests a mechanism based on established semiconductor heterostructure physics for the accumulation of charge at the interface.

Another possible explanation is the proposed existence of a metallic edge state at the boundary of 2D MoS2 flakes [7,11,12,33]. Considering that the edges of 1L and ML devices are also contacted with Au contacts, any such metallic edge state conductance should also contribute to $\sigma_{1}$ and $\sigma_{m}$. The conductivity contribution from the edge state, which can be roughly compared using the number of edges divided by the width, should be smaller in 1L+ML device ($\sim$3/9 $\mu$m for the device in figure 1(c)) and larger in 1L ($\sim$2/3 $\mu$m, figure 1(c)) or ML ($\sim$2/2.5 $\mu$m, figure 1(c)) device. There is still no direct transport report proving the metallic conductivity at the independent edge of 1L or ML MoS2, and the enhanced conduction that we observe are specific to the 1L/ML interface, not MoS2 edge. Thus the edge state of the 2D material is not likely to be solely responsible for the enhanced effective conductivity and mobility in our measurements.

More relevant here, conductive edge states at MoS2 layer dislocations have also been measured using microwave impedance microscopy [6]. Our results of interface band bending and enhanced longitudinal conduction support this picture of a narrow confined low-dimensional conducting charge accumulation, perhaps induced by the band bending known to occur at the 1L/ML interface from the photocurrent measurements. With now several reports of conducting boundaries between MoS2 regions of different layer number, additional theoretical and experimental investigation is required to construct a clear interpretation of the origin of these interfacial electronic states and their enhanced conductivity.

---

Figure 5. Comparison of transport properties of 1L+2L devices with different widths. (a) A tapered 1L+2L sample consisting of several distinct devices fabricated from the same MoS2 flake but with different widths, all sharing a single interface. (b) $L \cdot \frac{dG}{dV_{g}}$ as a function of the device width. $L$ is the length of the device and $G$ is the net conductance. $dG/dV_{g}$ is the slope of the $G(V_{g})$ curve in linear region. The error bars of $dG/dV_{g}$ which includes contributions from the $L - V_{g}$ fits and the geometry measurements by AFM, are smaller than the plotted points. The data can be fit by a line with a positive intercept $0.055 \pm 0.009 \mu S \mu m^{-1}$. The uncertainties labeled on the plot are the standard errors taking into account measured AFM and fit uncertainties in a weighted least squares fit. The shaded area represents the 99% confidence prediction band. The 99% confidence interval of the $W = 0$ intercept is $0.020 - 0.091 \mu S \mu m^{-1}$.

Figure 6. Schematic band diagrams. (a) Schematic band diagrams of a multilayer and a monolayer MoS2. $\Phi_{1}$ and $\Phi_{m}$ are the work functions of 1L and ML MoS2, respectively [31]. (b) Schematic band diagram of MoS2 1L/ML homojunction in thermal equilibrium.
Despite the open question of the precise microscopic origin of the enhanced effective conductivity at 1L/ML interfaces, we use a simple electron affinity model to interpret the transport results based on the success of similar band engineering of interface states in 2D interfaces of 3D heterostructures [3]. A heterojunction band model is applied to explore the properties of the confined interfacial edge states (See the Supplementary Information). The width of depletion region $x_1$, the width of accumulation region $x_2$ and the carrier density at the interface $N_d$ can be extracted from the model. The values for the 1L+ML device shown in figure 1(c) are $x_1 = 1.2\mathrm{nm}$, $x_2 = 2.3\mathrm{nm}$, and $N_d = 7.7 \times 10^{12} \mathrm{cm}^{-2}$. Because of the weaker electron screening in a 2D material with respect to that in a 3D material, the interface electrons can spread over a wider range [32]. Our calculation may underestimate the $x_2$ and $x_1$ values. Nevertheless, the value of the depletion width $x_1$ is in reasonable agreement with the band profile at the MoS$_2$/graphene interface (depletion width $\sim 5\mathrm{nm}$) [33] directly imaged by scanning tunneling microscopy. $N_d$ is about 10 times $N_{\text{dn}}$ and $N_{\text{d1}}$, suggesting electron accumulation at the interface. Considering that the interface electrons are spatially separated from impurities, a significant scattering source in the interior, they may possess higher mobility than that of interior electrons. Based on the band bending and metallic edge state evidence here and elsewhere [6, 14], a highly conductive electronic accumulation is a reasonable explanation for the enhanced longitudinal conduction at 1L/ML interfaces compared to separate 1L and ML devices.

5. Conclusion

In summary, we have fabricated and investigated MoS$_2$ monolayer/multilayer homojunctions with source-drain bias applied longitudinally along the interface. Scanning photocurrent microscopy reveals enhanced photoresponse at the 1L/ML interface, which can be explained by the band bending at the interface. Electronic transport measurements of homojunctions compared to distinct 1L and ML devices provide evidence of enhanced conductivity along the boundary, indicative of a modified interfacial charge state. Although the precise microscopic mechanism driving this enhanced conduction is still not clear, our measurements reveal that the TMDC homojunction interface has a non-trivial impact on longitudinal conductivity of a composite layered device. Further exploration and exploitation of these band engineering edge features in layered heterojunction devices can open a potential pathway to achieve a confined metallic 1D electronic state in TMDCs [34].

Acknowledgments

The research was supported by the Institute for Sustainability and Energy at Northwestern (nanoelectronics) and by the U.S. Department of Energy, Office of Basic Energy Sciences under award number DE-SC0012130 (spatially-resolved microscopy). This work was partially supported (layer interface preparation) by the National Science Foundation’s MRSEC program (DMR-1121262) and made use of its Shared Facilities at the Materials Research Center of Northwestern University. Characterization and device fabrication made use of the SPID facility of the NUANCE Center at Northwestern University and the Northwestern University Micro/Nano Fabrication Facility (NUFAB), which have received support from the Soft and Hybrid Nanotechnology Experimental (SHyNE) Resource (NSF NNCI-1542205); the MRSEC program (NSF DMR-1121262) at the Materials Research Center; the International Institute for Nanotechnology (IIN); the Keck Foundation; and the State of Illinois. The authors thank S Davis and V Chandrasekhar for assistance with facilities and instrumentation. NPS gratefully acknowledges support as an Alfred P Sloan Research Fellow.

References

[1] Cheiwchananchangij T and Lambrecht W R L 2012 Quasiparticle band structure calculation of monolayer, bilayer, and bulk MoS$_2$ Phys. Rev. B 85 205302
[2] Tosun M, Fu D, Desai S B, Ko C, Kang J S, Lien D-H, Najmzadeh M, Tongay S, Wu J and Javey A 2015 MoS$_2$ heterojunctions by thickness modulation Sci. Rep. 5 10990
[3] Sze S M 2001 Semiconductor Devices: Physics and Technology (New York: Wiley) ch 4
[4] Ando T, Fowler A B and Stern F 1982 Electronic properties of two-dimensional systems Rev. Mod. Phys. 54 437
[5] He Q L, Liu H, He M, Lai Y H, He H, Wang G, Law K T, Wang J and Sou I K 2013 Two-dimensional superconductivity at the interface of a Bi$_2$Te$_3$/FeTe heterostructure Nat. Commun. 5 4247
[6] Wu D et al. 2016 Uncovering edge states and electrical inhomogeneity in MoS$_2$ field-effect transistors Proc. Natl Acad. Sci. 113 8383–8
[7] Bollinger M V, Lauritsen J V, Jacobsen K W, Norskov J K, Helveg S and Besenbacher F 2001 One-dimensional metallic edge states in MoS$_2$, Phys. Rev. Lett. 87 196603
[8] Vojvodic A, Hinnemann B and Nørskov J K 2009 Magnetic edge states in MoS$_2$ characterized using density-functional theory Phys. Rev. B 80 125416
[9] Bao W et al. 2015 Visualizing nanoscale excitonic relaxation properties of disordered edges and grain boundaries in monolayer disulphide Nat. Commun. 6 7993
[10] Huang Y L et al. 2015 Bandgap tunability at single-layer molybdenum disulphide grain boundaries Nat. Commun. 6 6289
[11] Li Y, Zhou Z, Zhang S and Chen Z 2008 MoS$_2$ nanoribbons: high stability and unusual electronic and magnetic properties J. Am. Chem. Soc. 130 16739–44
[12] Xiao J et al. 2013 Carrier mobility of MoS$_2$ nanoribbons with edge chemical modification Phys. Chem. Chem. Phys. 17 6865–73
[13] Howell S L, Jariwalla D, Wu C-C, Chen K-S, Sangwan V K, Kang J, Marks T J, Hersam M C and Lauhon L I 2015 Investigation of band-offsets at Monolayer-multilayer MoS$_2$ junctions by scanning photocurrent microscopy Nano Lett. 15 2278–84
[14] Guo Y et al. 2016 Edge-state-induced disruption to the energy band alignment at thickness-modulated molybdenum sulphide junctions Adv. Electron. Mater. 2 1600048
[15] Mak F K, Lee C, Hone J, Shan J and Heinz T F 2010 Atomically thin MoS$_2$: a new direct-gap semiconductor Phys. Rev. Lett. 105 136805
Castellanos-Gomez A, Buscema M, Molenaar R, Singh V, Janssen L, van der Zant H S J and Steele G A 2014 Deterministic transfer of two-dimensional materials by all-dry viscoelastic stamping 2D Mater. 1 011002

Perkins F K, Friedman A L, Cobas E, Campbell P M, Jernigan G G and Jonker B T 2013 Chemical vapor sensing with monolayer MoS2 Nano Lett. 13 668–73

Wu C-C, Jariwala D, Sangwan V K, Marks T J, Hersam M C and Lauhon L J 2013 Elucidating the photorepose of ultrathin MoS2 field-effect transistors by scanning photocurrent microscopy J. Phys. Chem. Lett. 4 2308–13

Klots A R et al 2014 Probing excitonic states in ultraclean suspended two-dimensional semiconductors by photocurrent spectroscopy Sci. Rep. 4 6608

Li H-M, Lee D-Y, Choi M S, Qu D, Liu X, Ra C-H and Yoo W J 2014 Metal–Semiconductor Barrier Modulation for High Photoresponse in Transition Metal Dichalcogenide Field Effect Transistors Sci. Rep. 4 4041

Gabor N M, Song J C W, Ma Q, Nair N L, Taychatanapat T, Watanabe K, Taniguchi T, Levitov L S and Jarillo-Herrero P 2011 Hot carrier assisted intrinsic photoreponse in graphene Science 334 648–52

Buscema M, Barkelid M, Zwiller V, van der Zant H S, Steele G A and Castellanos–Gomez A 2013 Large and tunable photothermoelectric effect in single-layer MoS2 Nano Lett. 13 358–63

Yin Z, Li H, Li H, Jiang L, Shi Y, Sun Y, Lu G, Zhang Q, Chen X and Zhang H 2012 Single-layer MoS2 phototransistors ACS Nano 6 74–80

van der Zande A M, Huang P Y, Chenet D A, Berkelbach T C, You Y, Lee G-H, Heinz T F, Reichman D R, Muller D A and Hone J 2013 Grains and grain boundaries in highly crystalline monolayer molybdenum disulphide Nat. Mater. 12 534–61

Gutierrez H R, Perea-Lopez N, Elias A L, Berkdemir A, Wang B, Lv R, Lopez-Urías F, Crespi V H, Terrones H and Terrones M 2013 Extraordinary room-temperature photoluminescence in triangular WS2 monolayers Nano Lett. 13 3447–54

Gong Y et al 2014 Vertical and in-plane heterostructures from WS2/MoS2 monolayers Nat. Mater. 13 1135–42

Komider K and Fernandez–Rossier J 2013 Electronic properties of the MoS2–WS2 heterojunction Phys. Rev. B 87 075451

Terrones H, Lopez-Urías F and Terrones M 2013 Novel hetero-layered materials with tunable direct band gaps by sandwiching different metal disulfides and diselenides Sci. Rep. 3 1549

Li S L, Wakabayashi K, Xu Y, Nakahara S, Komatsu K, Li W-W, Lin Y-F, Aparecido-Ferreira A and Tsukagoshi K 2013 Thickness-dependent interfacial coulomb scattering in atomically thin field-effect transistors Nano Lett. 13 3546–52

Radosavljevic B, Radenovic A, Brivio J, Giacometti V and Kis A 2011 Single-layer MoS2 transistors Nat. Nanotechnol. 6 147–50

Ochudowski O, Marinov K, Scheuschner N, Poloczek A, Bussmann B K, Maultzsch J and Schleberger M 2014 Effect of contaminations and surface preparation on the work function of single layer MoS2 Beilstein J. Nanotechnol. 5 291–97

Gurugubelli V K and Karmalkar S 2015 Analytical theory of the space-charge region of lateral p–n junctions in nanofilms J. Appl. Phys. 118 034303

Zhang C, Johnson A, Hsu C-L, Li L-J and Shih C-K 2014 Direct imaging of band profile in single layer MoS2 on graphite: quasiparticle energy gap, metallic edge states, and edge band bending Nano Lett. 14 2443–47

Ron A and Dagan Y 2014 One-dimensional quantum wire formed at the boundary between two insulating LaAlO3/SrTiO3 interfaces Phys. Rev. Lett. 112 136801