The FUTURE PHOTONICS Hub
Advancing manufacturing of next-generation light technologies

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2D MBE Activities in Sheffield

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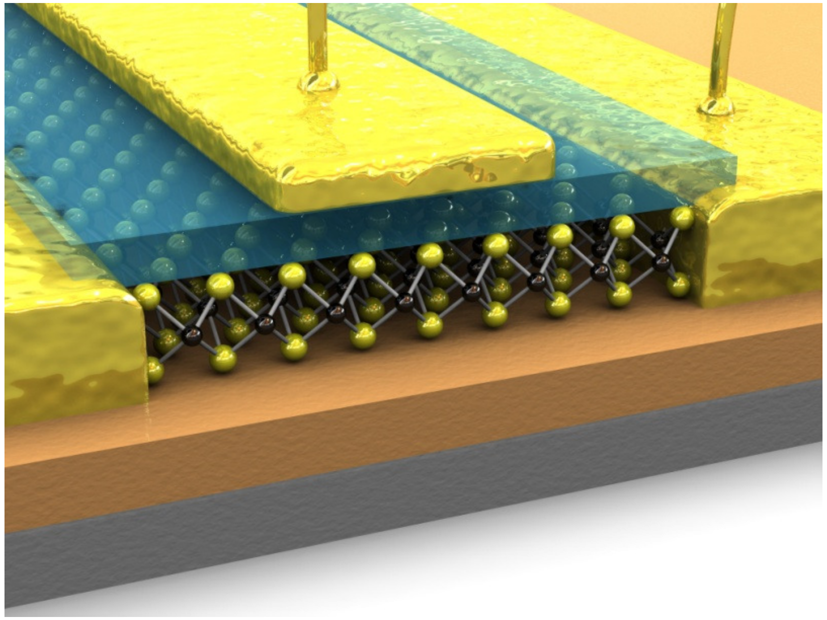
University of Southampton
The University Of Sheffield.

Outline

- Motivation
- Van der Waals crystals
- The Transition Metal Di-Chalcogenides (TMDCs)
- Conventional vs Van der Waals Epitaxy
- The novel materials MBE system in Sheffield
- Links within The Hub and other MBE Researchers in the UK

2D Materials – Attractive Properties

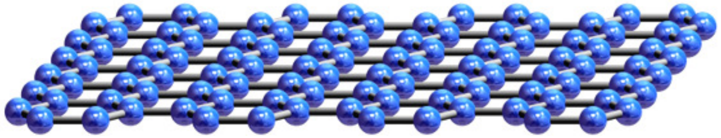


MoS_2 transistor, A. Kis group
Nat. Nano., 6, 147 (2011)

- Flexible and light-weight
- Low amount of raw material required
- Low cost and large-area production
- Adjustable optical transparency
- Very wide range of band-gaps
- Robust under optical excitation
- Good material quality (carrier mobility)
- Potential for building heterostructures
- Compatibility with a range of substrates

Van der Waals Crystals

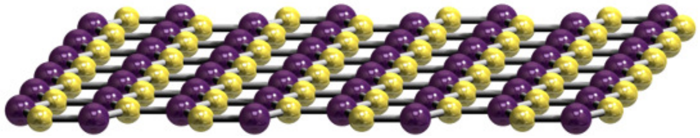
Graphene



Zero band gap, low intrinsic doping (10^9 cm^{-2})
Highly transparent (97 %)
High mechanical strength
High charge carrier mobility (~ 10^5 cm^2/Vs)

A. H. Castro Neto et al., Rev. Mod. Phys. 81, 109 (2009)

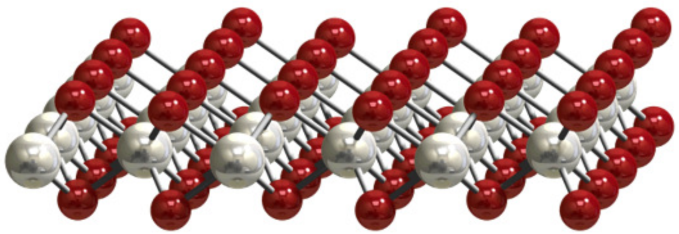
Hexagonal boron nitride



Wide band gap semiconductor (>6 eV)
High quality
Substrate for graphene electronics
Defect free tunnel Barrier.

K. Watanabe et al., Nature Materials, 3, 404-409 (2004)

Transition metal dichalcogenides

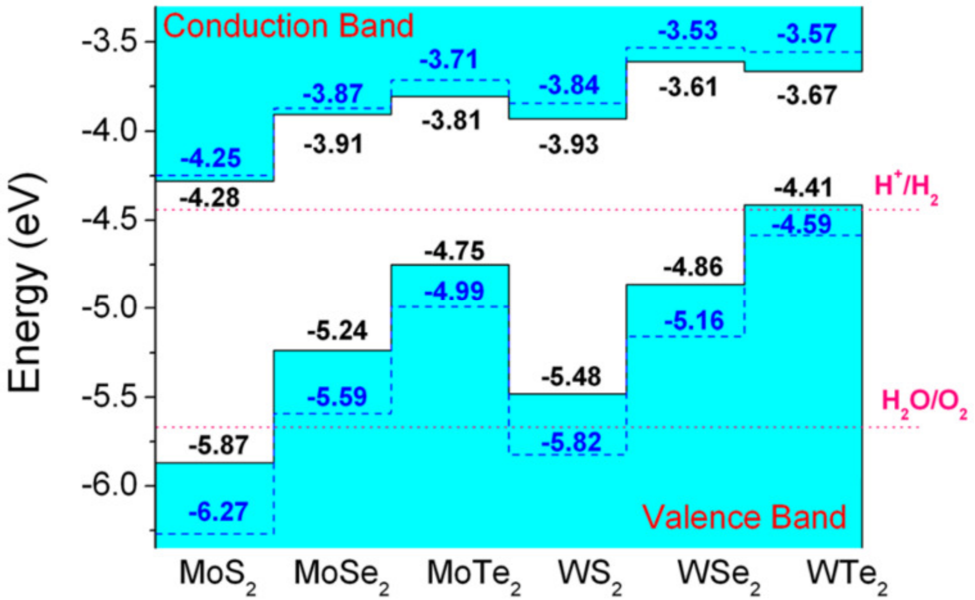


Semiconducting with excitonic resonances in the visible and near infra red
MoS_2, WS_2, $MoSe_2$, WSe_2

M. Chhowalla et al., Nature Chemistry (2013)

Also other layered materials such as GaSe, InSe, Bi_2Se_3 etc

Calculated band alignments



- Various hetero-structures are possible for applications in valleytronics, photovoltaics and optoelectronics covering a range of wavelengths

J. Kang et al. Appl. Phys. Lett., 102, (2013), 012111

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The Transition Metal Di-Chalcogenides

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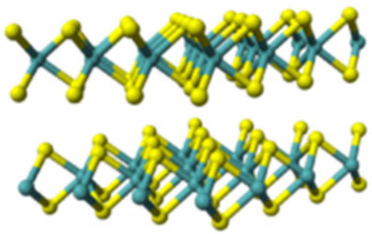

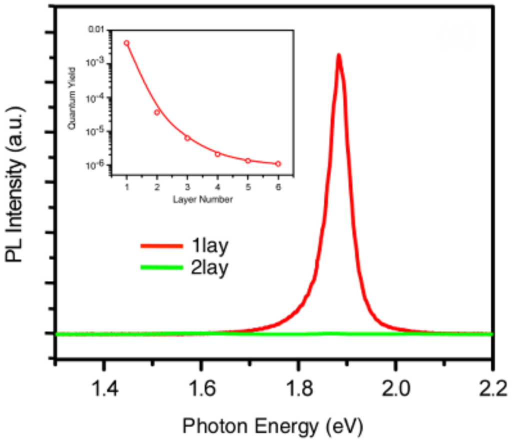

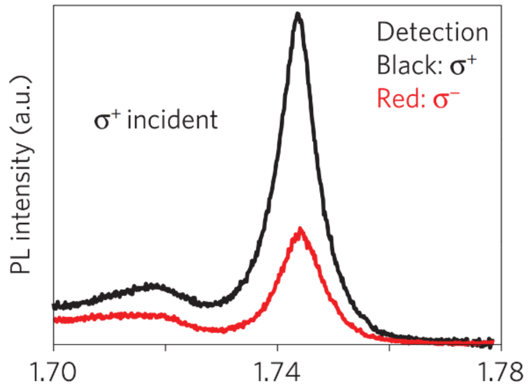

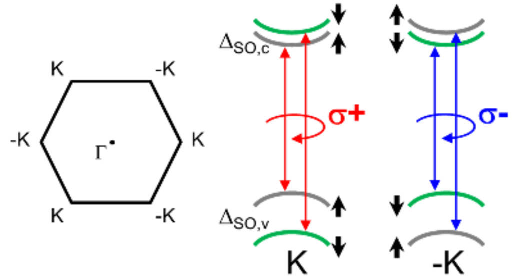

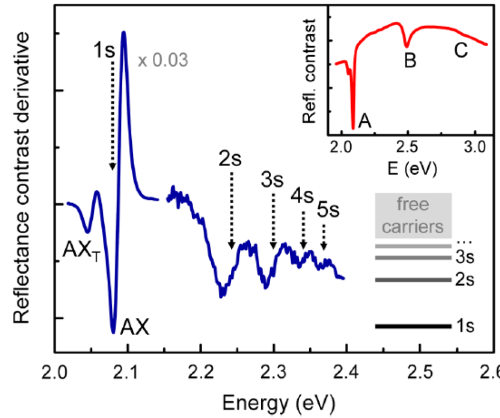

- Transition from indirect to direct band-gap semiconductor
- Strong spin-orbit and electron-hole exchange
- Valley polarisation effects
- Large exciton binding energies (0.2-0.5 eV)
- Large exciton oscillator strength (~40 times larger than in GaAs)

Mak et al. Phys. Rev. Lett., 105, (2010), 136805 Xu et al. Nature Phys., 10, (2014), 343 Chernikov et al. Phys. Rev. Lett., 113, (2014) 076802

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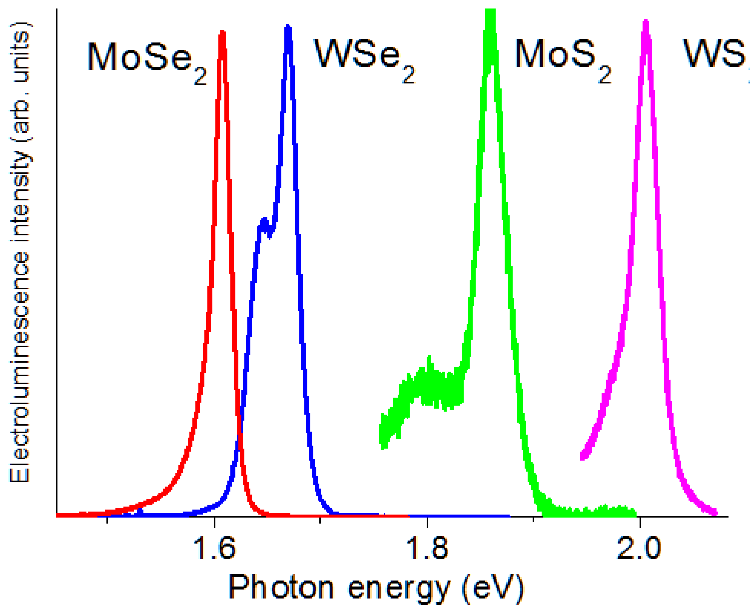
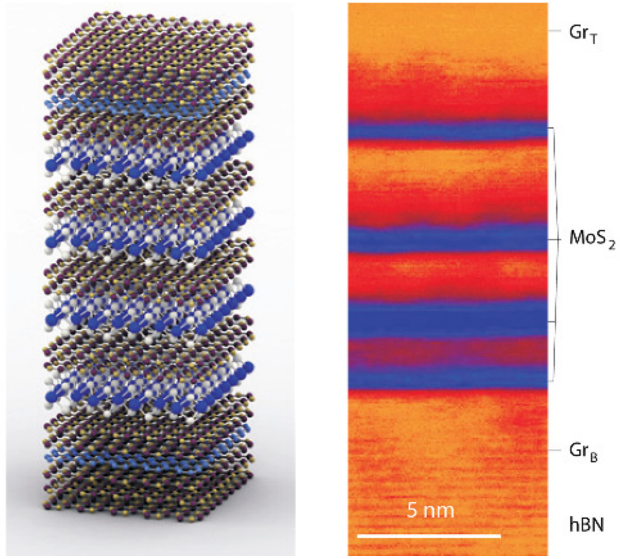
Optical properties





- Demonstrations of Photoluminescence and Electroluminescence from a number of materials to date including room temperature operation
- LED Devices fabricated by "peel and lift" process

Withers et al, Nature Materials (2015), Nano Letters (2015)

Conventional vs van der Waals Epitaxy

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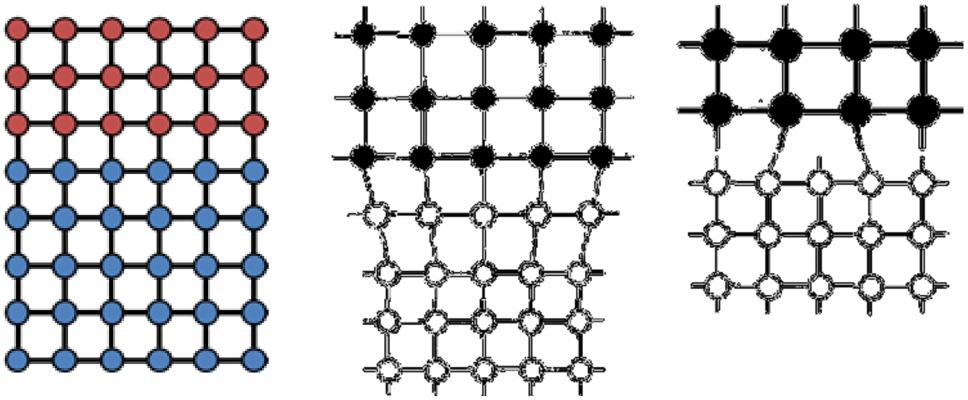
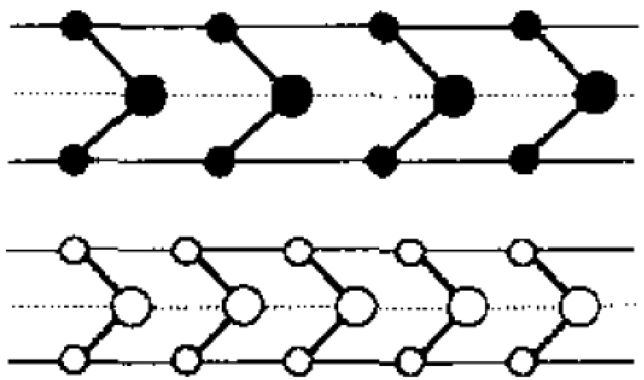


- Dangling bonds at clean surfaces of conventional materials
- Small amounts of strain can be accommodated
- Defect free growth challenging for large lattice mismatches or materials with different crystal structures



- Weak bonding between layers in VdW epitaxy relaxes the requirement on material choice
- Allows creation of heterostructures or use of VdW layers as ultra thin buffer layers

Koma, Thin Solid Films 216 p72 (1992)

Molecular Beam Epitaxy of TMDCs

TABLE 1. Materials grown with van der Waals epitaxy (here TX_2 denotes transition metal dichalcogenide)

Material group	Materials grown with van der Waals epitaxy	References
Quasi-one dimensional	Se/Te	8
	Te/Se/Te	
Quasi-two dimensional	TX'_2/TX_2	3–5
	TX_2/SnS_2	10
	TX_2/mica	12, 13
Quasi-two dimensional on three-dimensional	TX_2/S–GaAs(111)	15
	$TX_2/CaF_2(111)$	20
	GaSe/Se–GaAs(111)	16, 17
	GaSe/H–Si(111)	
Organic	Phthalocyanines/TX_2	
	Coronene/TX_2	
	C_{60}/MoS_2	21

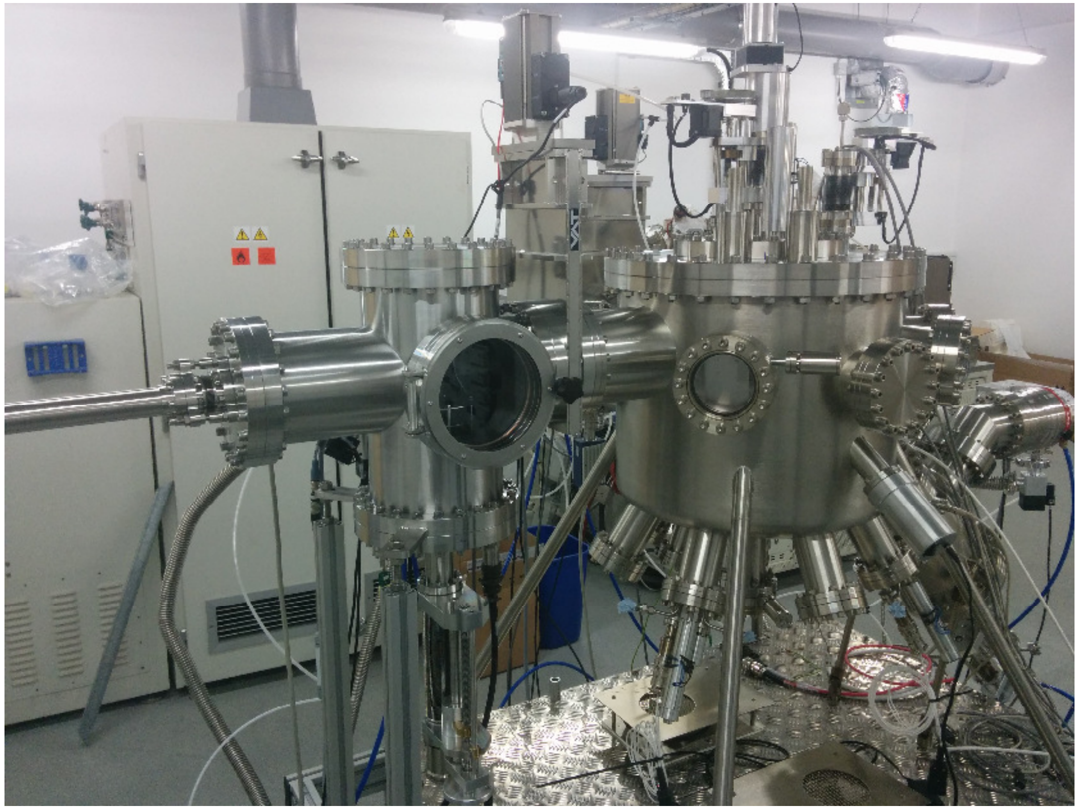
- Group of Koma and Ueno performed experiments on a wide range of materials in the 1990s using Molecular Beam Epitaxy

- The field has seen a resurgence in recent years including demonstrations of
  - GaAs on Silicon using a graphene buffer layer
  - $MoSe_2$ on AlN(0001)/Si(111) substrates

Koma, Thin Solid Films 216 p72 (1992)

Arafin et al. Adv. Func. Mater. (2014)
Xenogiannopoulou et al, Nanoscale (2015) 7, 7896

The "Novel Materials" MBE at Sheffield



- System from Mantis Deposition Ltd installed in August 2016
- Deposition chamber plus load lock for up to 4 samples
- High temperature substrate manipulator (1000˚C)
- Up to 2 inch substrate size
- 4-pocket electron beam evaporator for high melting point materials (Mo, W, Hf, Nb)
- 3 k-cells for lower temperature materials (Zinc, Selenium, Indium?)

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Space for expansion

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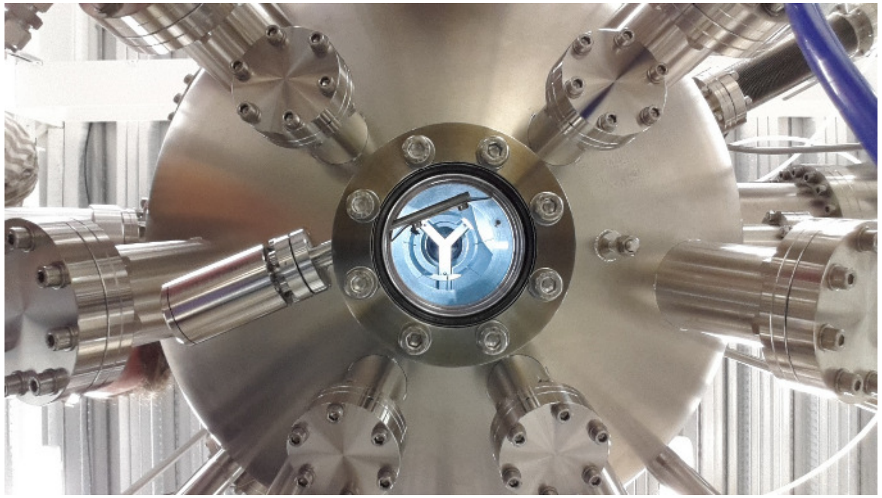
- Three large ports available for
  - Nitrogen Plasma source
  - Te, Sb, Bi, Ga ….
  - Additional TM sources ….
- Four smaller ports for
  - Gas injectors/crackers - H_2
  - dopants etc.
- Also have optical access to the substrate surface for
  - RHEED studies
  - Reflectivity measurements



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Aims

- In-situ study/confirmation of TMD growth via RHEED
  - XRR/XRD, Room Temperature optical/electrical testing
- Heterostructure and compositional growth studies
  - Eg. $MoSe_2/WSe_2$ or $Mo_xW_{1-x}Se_2$
- Provide material to other users for more detailed optical/electrical characterisation including Liquid Helium
  - Low Dimensional Semiconductor Devices group in Physics at Sheffield performing world leading experiments on exfoliated samples
- TMD or TI interlayers for Van der Waals epitaxy
  - eg. GaN on GaAs (111)B, GaAs on Si (111) and then (110),(100)
- Fabrication of devices
  - Transistors, LEDs, Sensors

Links within the Hub and UK

- MBE is a complementary technique to CVD being used in Southampton
  - Broadens the range of materials available
  - Use of large area CVD growth as templates in MBE process
- University of Nottingham
  - Dual chamber MBE system to develop graphene and h-BN growth
- University of Oxford
  - MBE system for the growth of Topological Insulator layered materials such as Bi_2Se_3
- Heriot Watt
  - Only research group in the UK performing II-VI epitaxy, wealth of experience on the source technology and material quality

Summary

- Important technological properties of 2D materials
- Van der Waals crystals
- The Transition Metal Di-Chalcogenides (TMDCs)
- Conventional vs Van der Waals Epitaxy
- The novel materials MBE system in Sheffield
- Links within The Hub and MBE research groups in the UK

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Thank you for your attention

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