University of Nottingham

UK China Malaysia

Fast UV-C Photonics: Sensing Laser Pulses on fs Timescales

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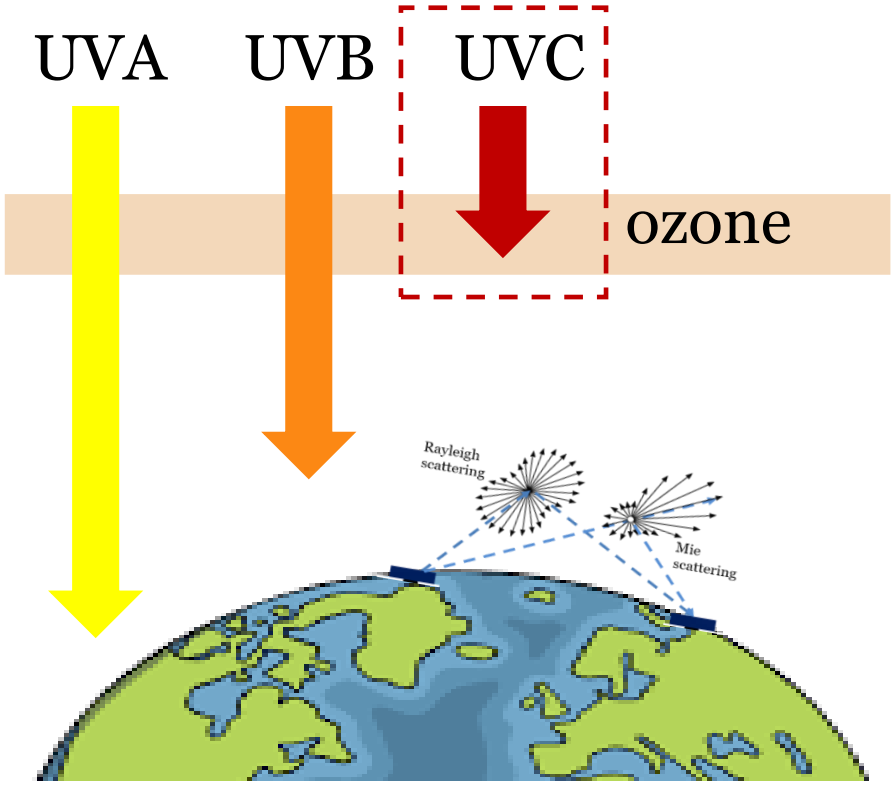
2D semiconductors, 2SEM

UV-C Photonics

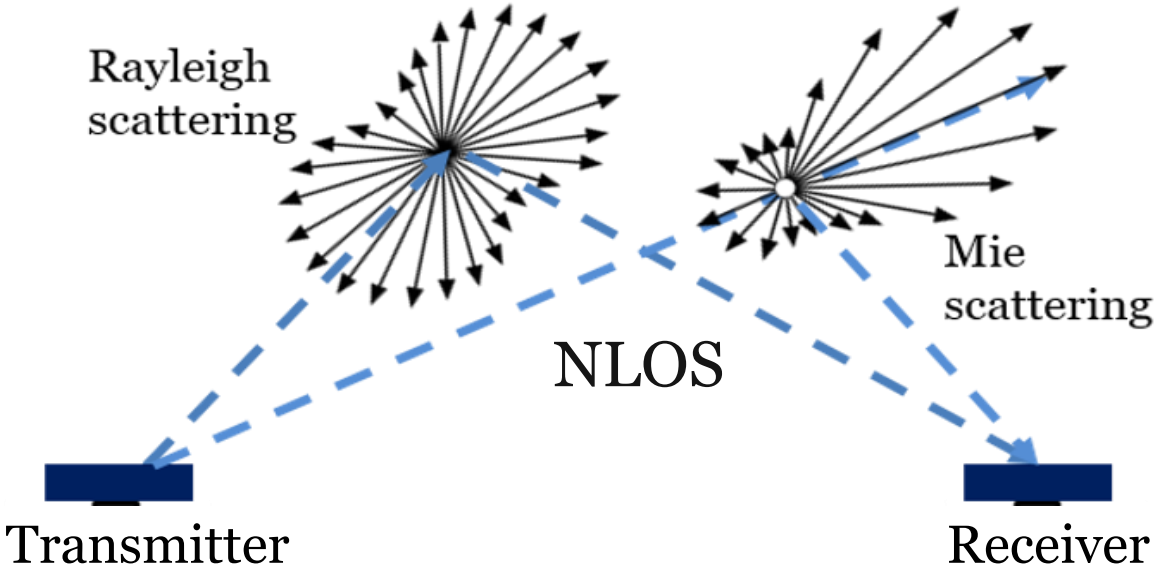
UV-Bands: UVA (320–400 nm), UVB (280–320 nm), **UVC (100–280 nm)**



UVC light is blocked by ozone

Free-Space Communication

Solar-blind detection in UVC range
Non -Line of Sight (NLOS)

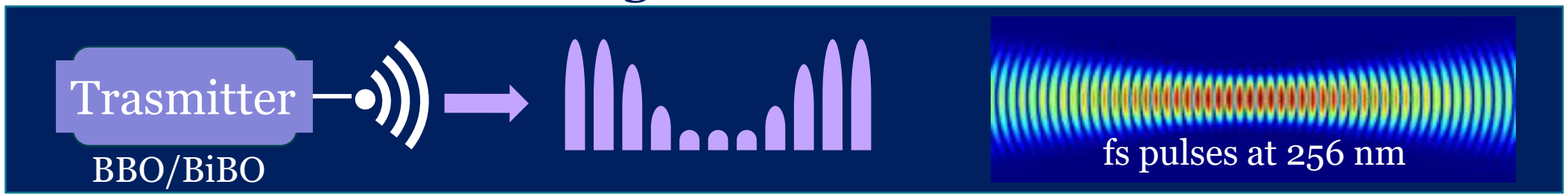


Sharma et al. *ACS Photonics* 2022
Kneiss et al. *Nat. Photonics* 2019

Funded by the Defence and Science Technology Laboratory

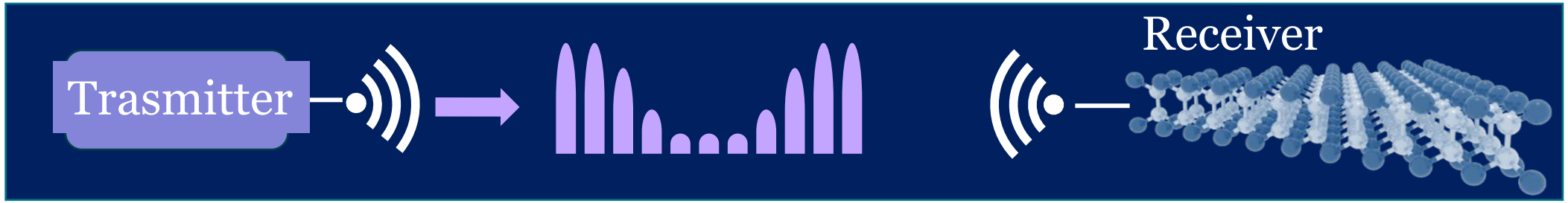
UV-C Transmitter/Receiver

Transmitter: UV-C Laser Light



- Harmonic generation in non-linear crystals (BBO-BiBO)
- 20% conversion power efficiency from 1024 nm to 256 nm
- Coding fs pulses for communication

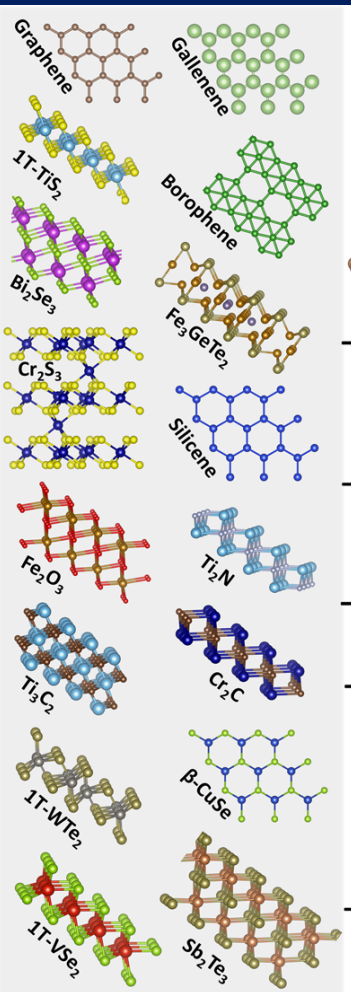
Receiver: 2D Semiconductor (2SEM) Planar Sensor



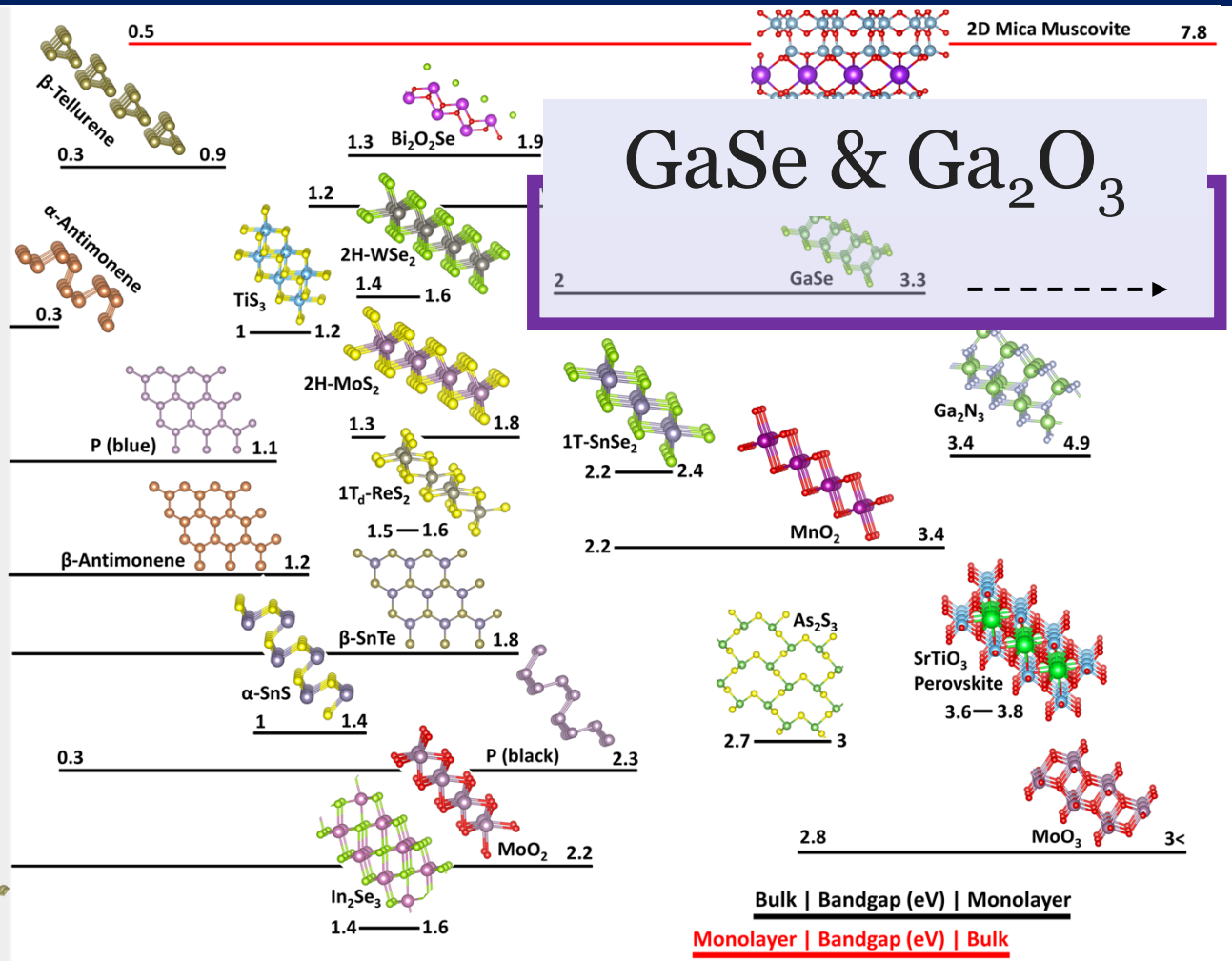
- Spectral selectivity in UV-C
- Detection of fs pulses
- Decoding fs pulses for communication

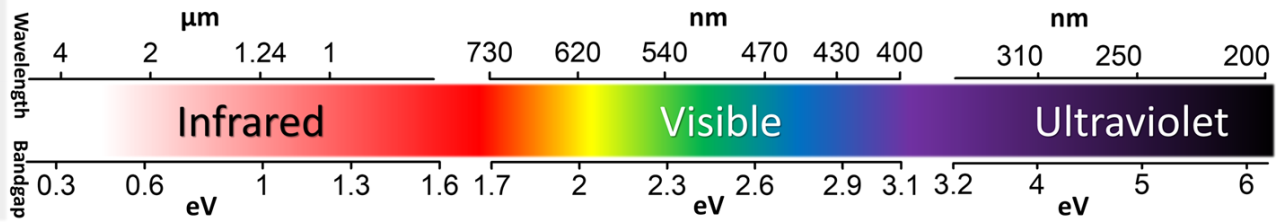
Funded by the Defence and
Science Technology Laboratory
[dstl]

2D Materials for Photonics



Terahertz & Microwave





2D Materials with band gap energies

tuneable via control of layers number, heterostructure, strain, chemical doping, alloying, intercalation, substrate engineering, *etc.*

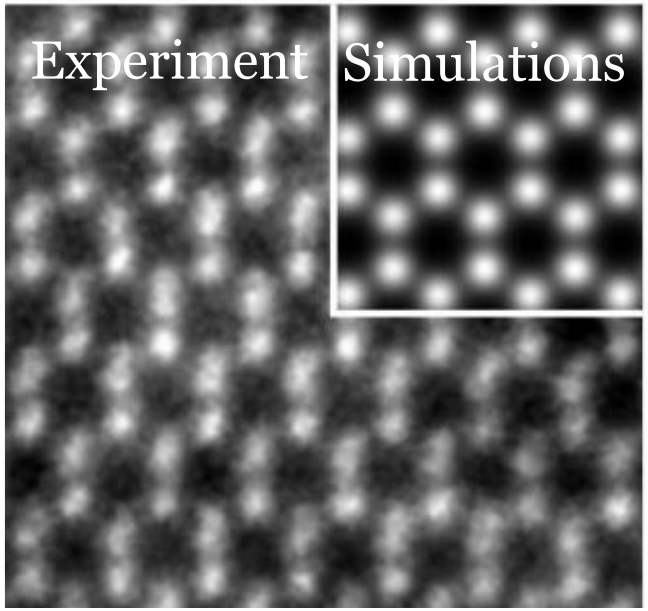
Chaves et al. *npj 2D Mat.&Appl.*2020

A few 2D materials for UV-C photonics

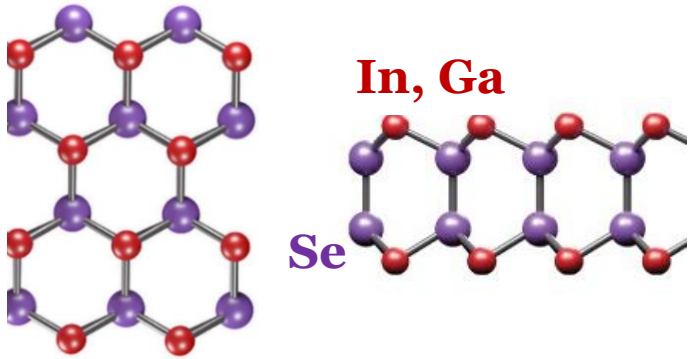
Felton et al. *ACS Photonics* 2025

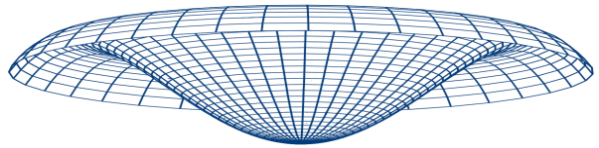
2D Semiconductors (2SEM) at Nottingham

Metal III: Ga, In **Chalcogen VI**: Se

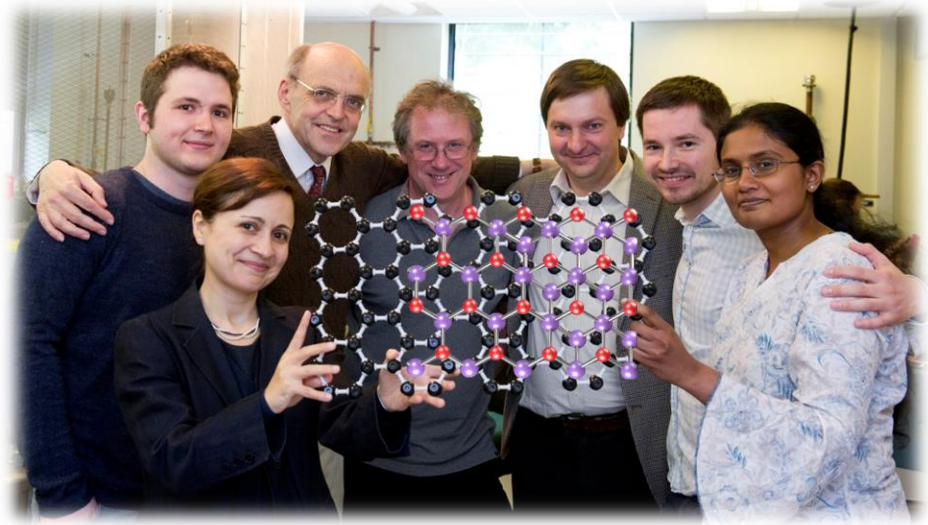


Hopkinson et al. *ACS Nano* 2019

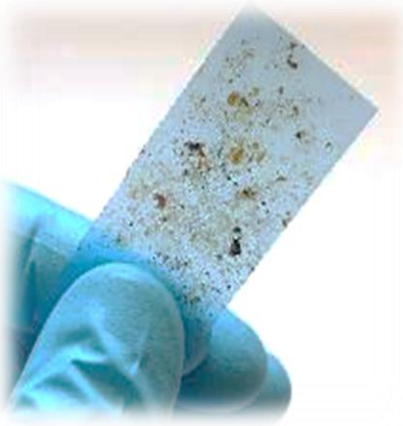


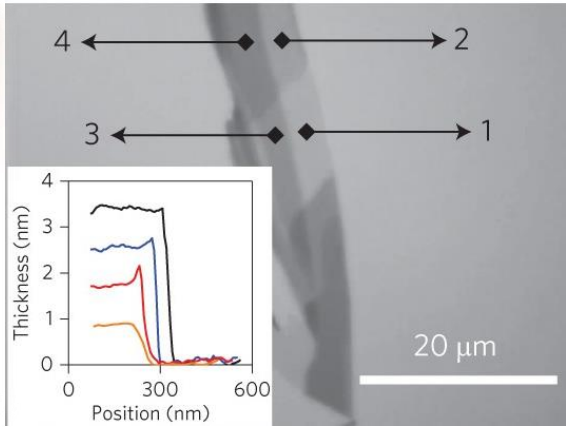


Inverted Mexican hat valence band



- Tuneable band structure
- Band gap energy from NIR to VIS
- High electron mobility
- Ferroelectricity, elasticity…



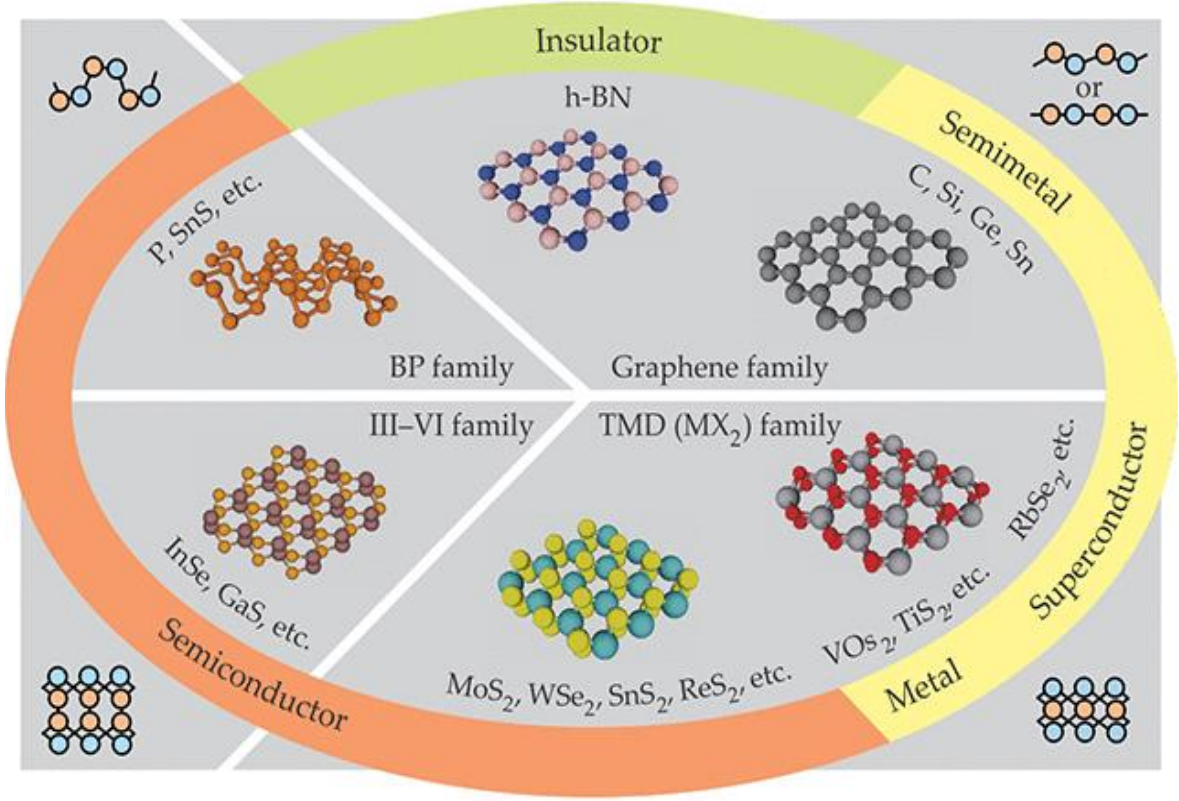


Mudd et al. *Adv. Mat.* 2013 & 2015
Bandurin et al. *Nature Nano.* 2017

What can we do with the right 2SEM?

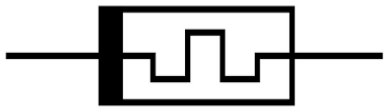
A wide range of functional devices

Ajayan et al *Phys. Today* 2016

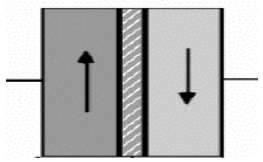


Quantum Hall Sensors
InSe/graphene
Kudrynskyi et al.
Phys.Rev.Lett. 2017

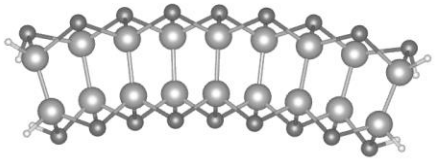
Exciton engineering
InSe/TMDs
Ubrig et al.
Nature Mat. 2020



Ferroeletricity
Ferroelectric In_2Se_3/graphene
Xie et al. *2D Mat.* 2021
Felton et al.Nature Com. 2025



Spin valves
2D Magnetic/TMD/MC
Zhu et al. *Adv. Mat.* 2021

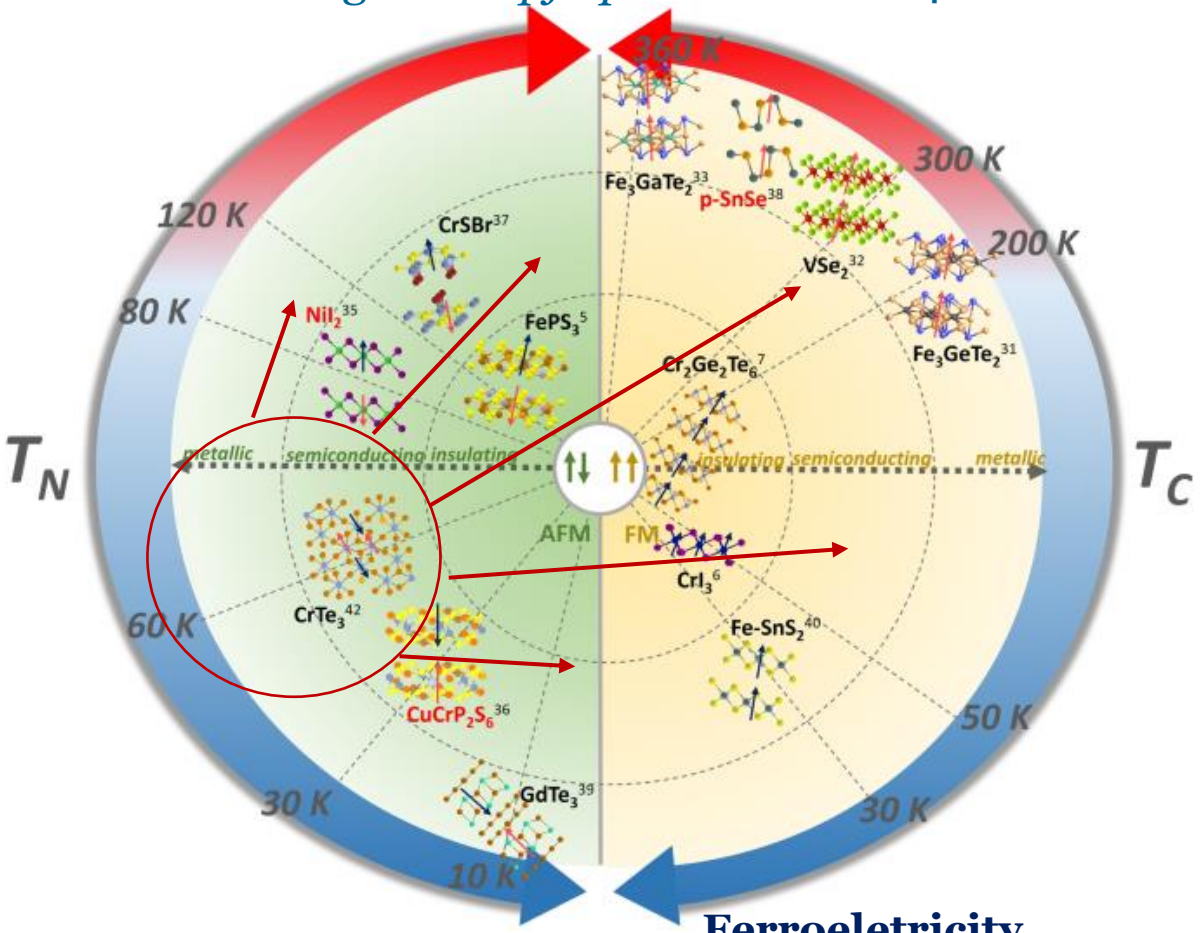


Flexible electronics
InSe/TMDs, GaSe
Blundo et al. *Nano Lett.* 2025
Barker et al. *npj Flex. El.* 2025

What can we do with the right 2SEM?

A wide range of functional devices

Zhang et al. *npj Spintronics* 2024



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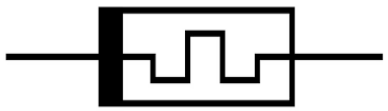
Nature Mat. 2020



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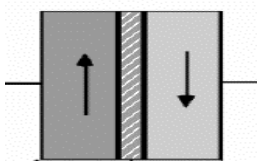
Xie et al. *2D Mat.* 2021
Felton et al.Nature Com. 2025



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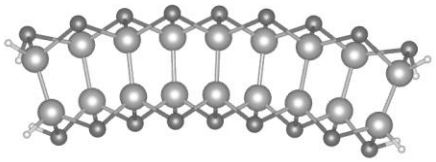
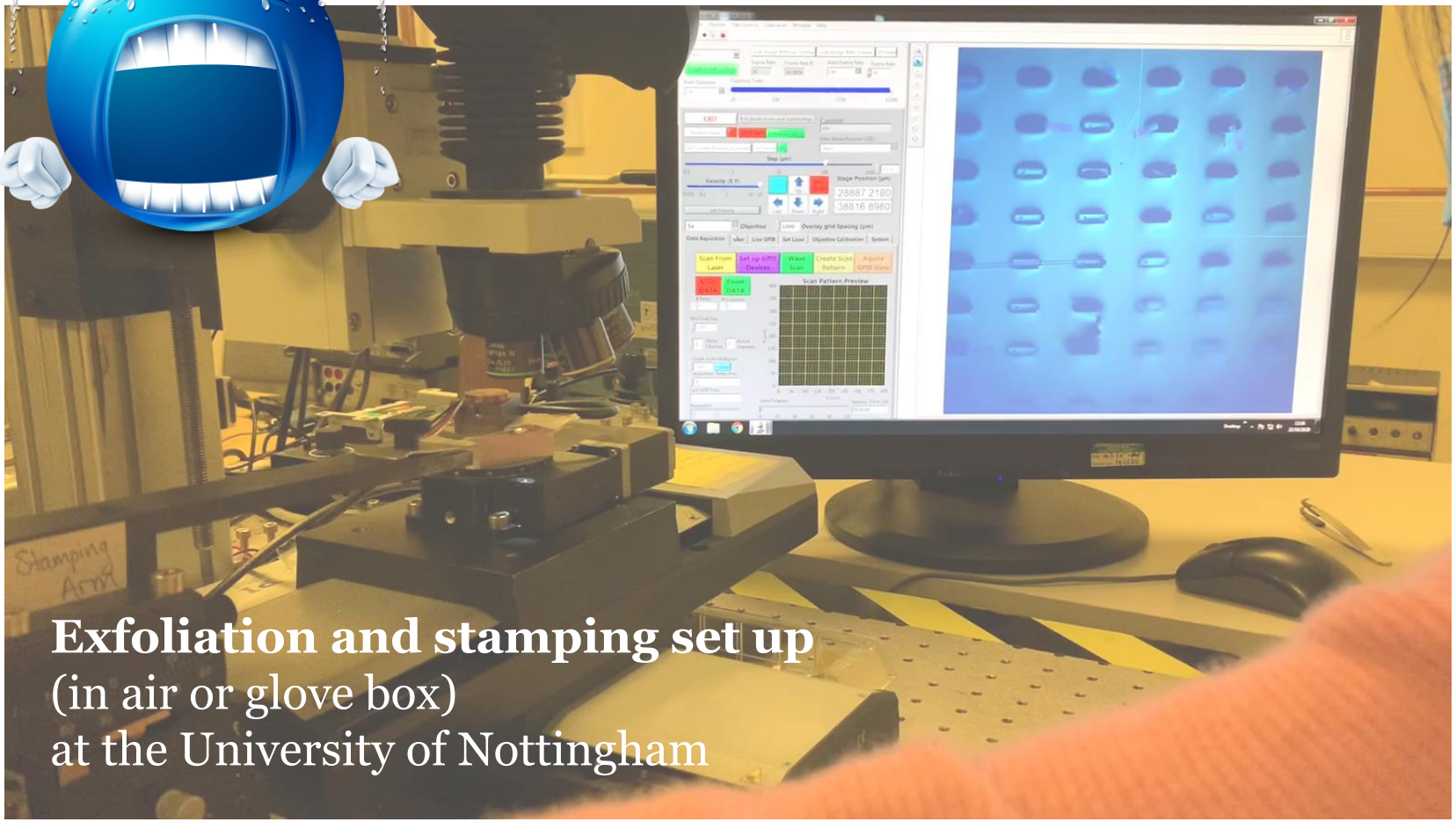
2D Magnetic/TMD/MC
Zhu et al. *Adv. Mat.* 2021



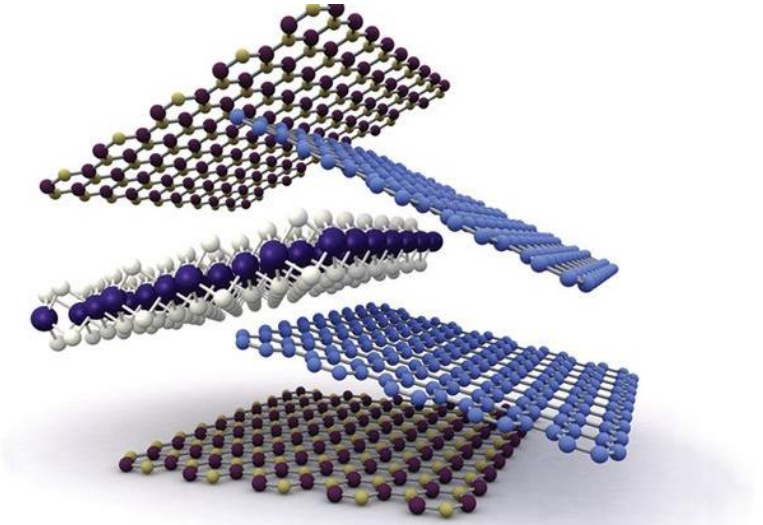
Flexible electronics
InSe/TMDs, GaSe
Blundo et al. *Nano Lett.* 2025
Barker et al. *npj Flex. El.* 2025

Making 2SEM

Mechanical exfoliation and stamping of 2SEM



Exfoliation and stamping set up
(in air or glove box)
at the University of Nottingham



Novoselov et al. *Science* 2016

- No scalability
- Contamination
- Limited control of size, composition, doping…

Epitaxial 2SEM

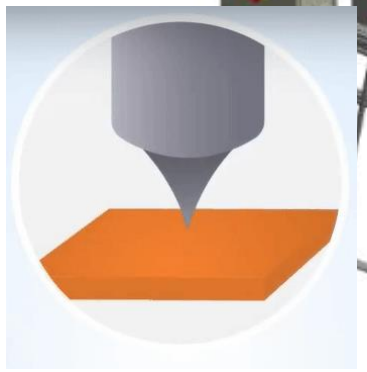
EPI2SEM: EPItaxial growth and In-situ analysis of 2SEM

2SEM: 2D semiconductors 3-chamber cluster in ultra high vacuum

Electron Spectroscopy for Chemical Analysis

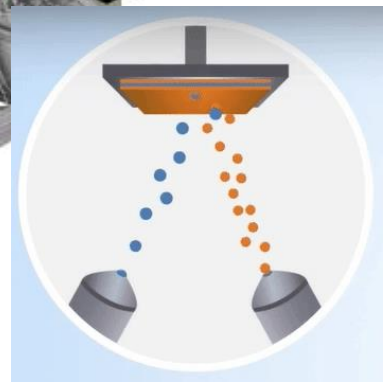
Probing bonds and band structures
XPS
XPEEM
PEEM
μ-ARPES

Scanning Probe Microscopy



Molecular Beam Epitaxy

Epitaxy in UHV (up to 3”wafers) for growth of 2SEM with atomic resolution
Focus on In, Se, Ga…



£3.2 m UKRI Strategic Equipment Award 2020-24 (with Scienta Omicron/MBE Komponenten)

EPI2SEM: "Cooking and Tasting"

P. Beton

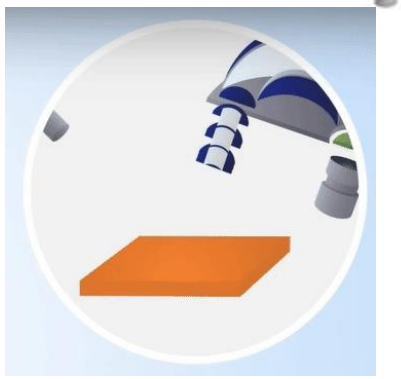
J. Bradford

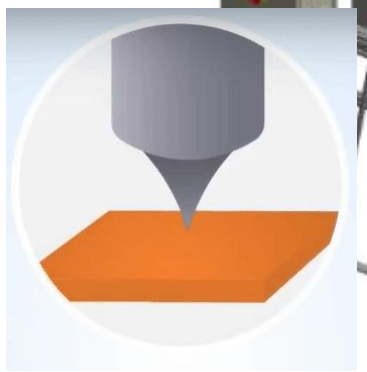
J. O'Shea

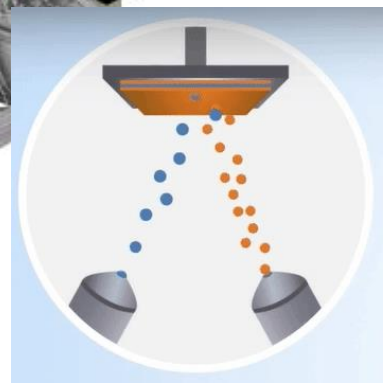
S. Novikov

T. Cheng

Link to other facilities by UHV suitcase



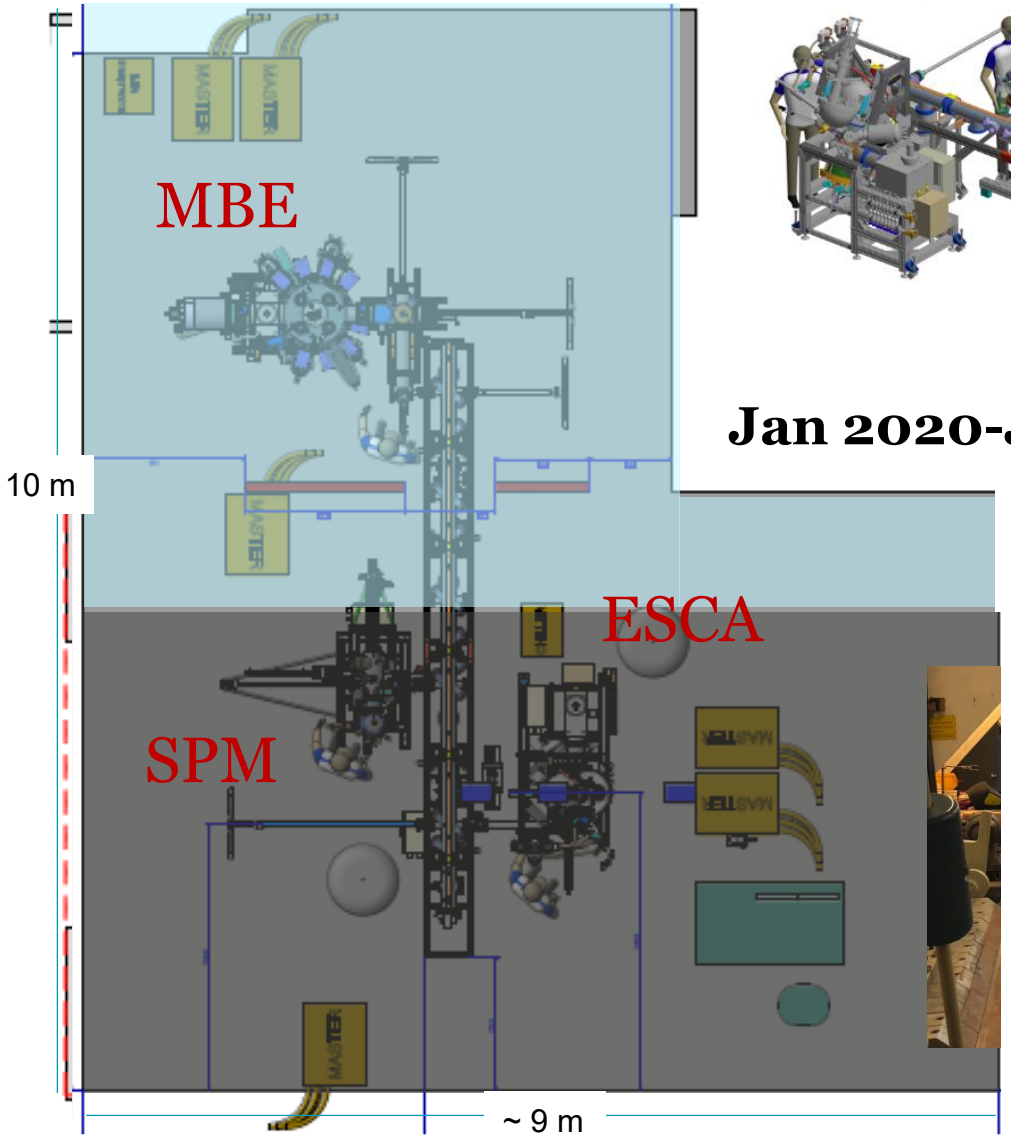


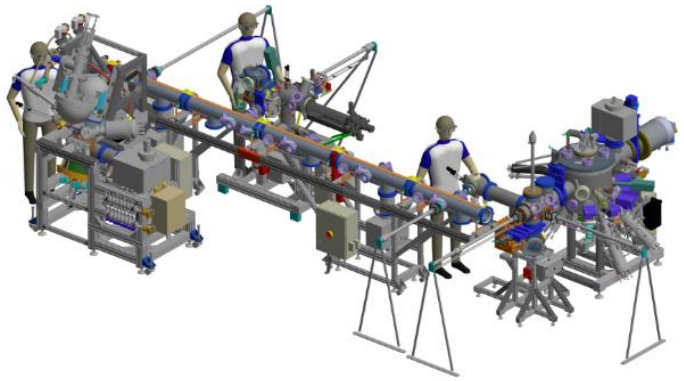


£3m UKRI Strategic Equipment Award 2020-24 (with Scienta Omicron/MBE Komponenten)

2020 Designing EPI2SEM

B-floor, School of Physics and Astronomy





Jan 2020-June 2021

Approval: Jan. 2020-Jan 2021
Works: March-June 2021

2021-22
Delivery/installation

July 2023 Upgrades
Prep-chamber
LEED
Optical microscope
Evaporators...

June 2021 Delivery in Nottingham

2021-22 Installation of EPI2SEM

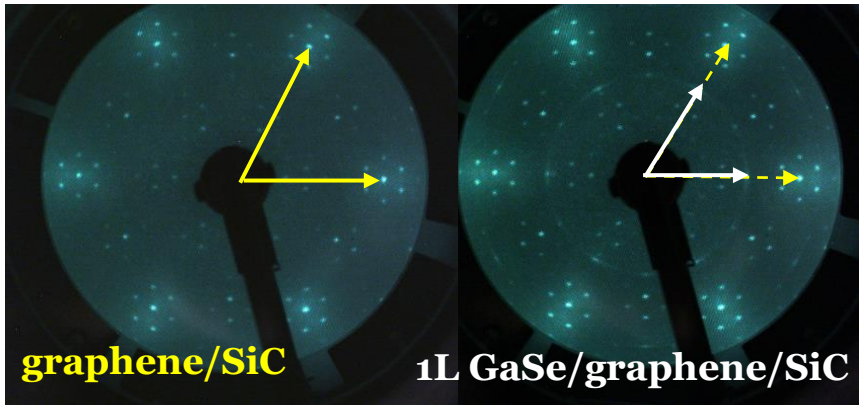
https://www.youtube.com/watch?v=mtXWhMOs9D4

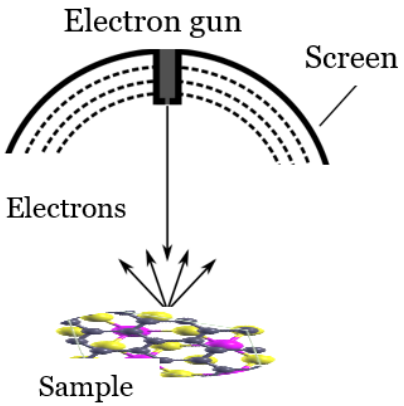
https://www.youtube.com/watch?v=GHCxEDMh3Ro

2D GaSe on Graphene

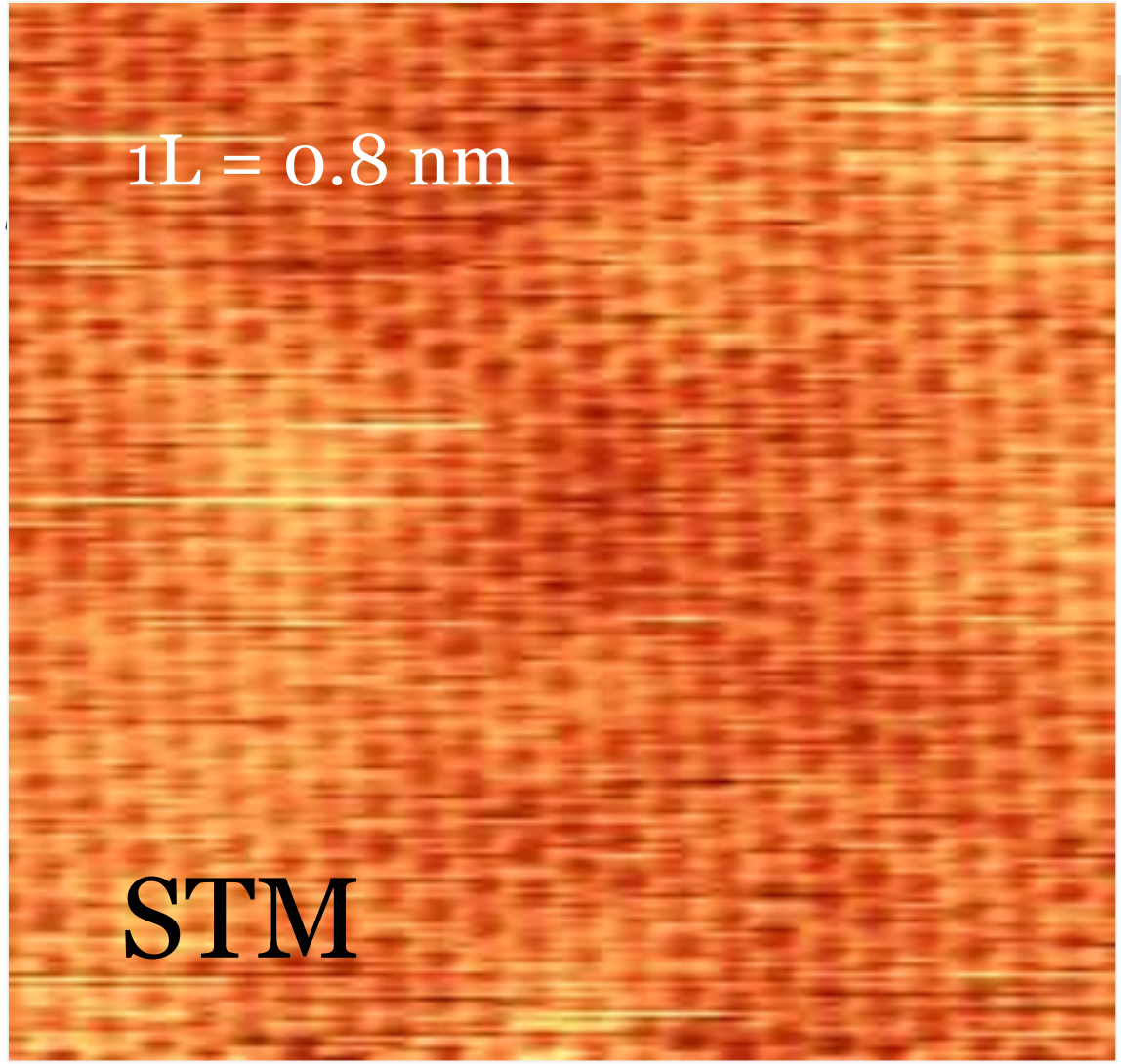
Epitaxy of 2D GaSe on epitaxial graphene

Low-energy electron diffraction (LEED)





Crystallinity and
in-plane alignment of
1 layer (1L = 0.8 nm) GaSe
with graphene

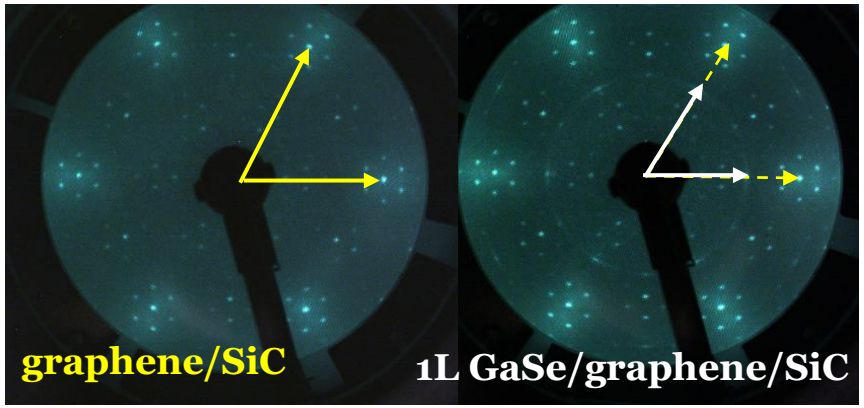


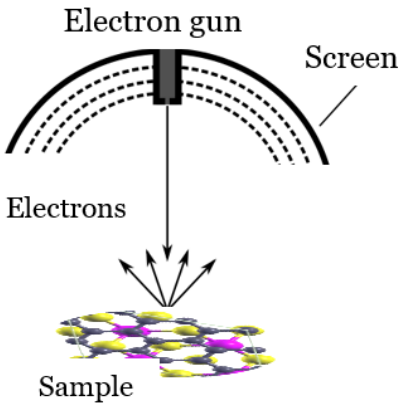
Bradford et al. *Small* 2024

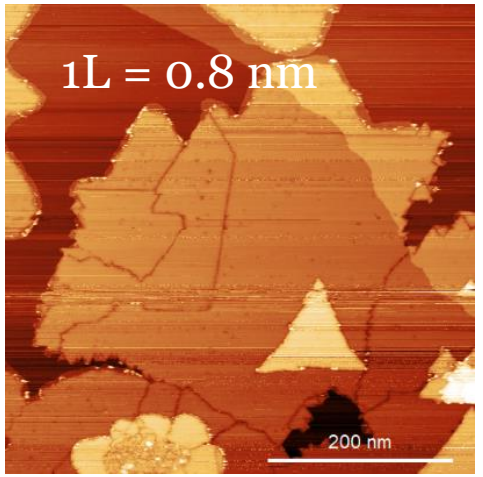
2D GaSe on Graphene

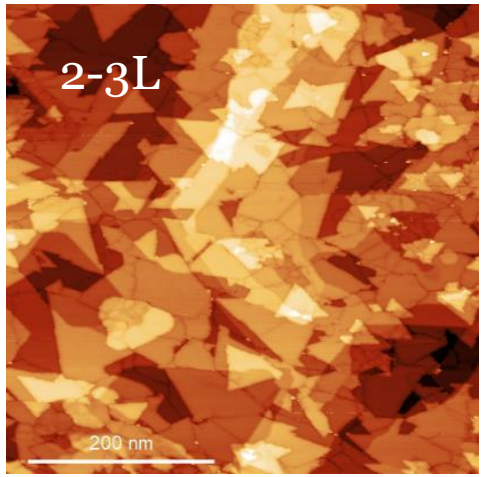
Epitaxy of 2D GaSe on epitaxial graphene

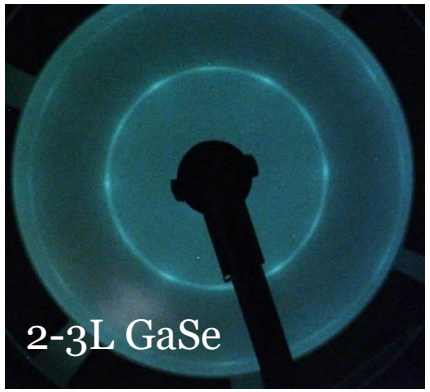
Low-energy electron diffraction (LEED)

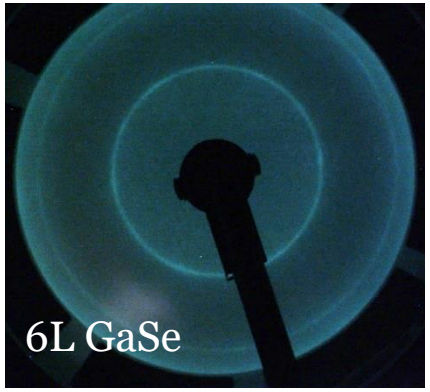


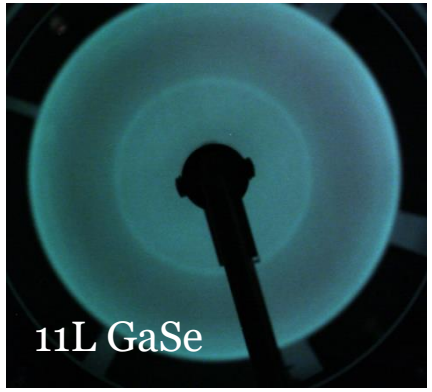












Orientation-disorder in thick layers

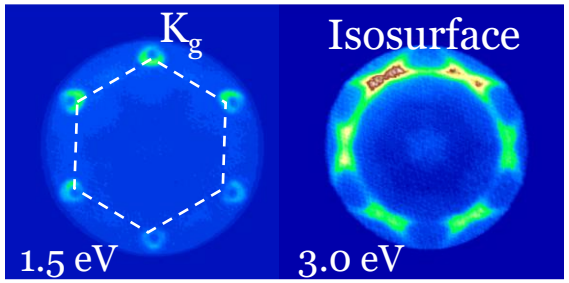
In-plane alignment not detected in thicker (> 3L) GaSe due to the small penetration depth of the electron beam and grains with smaller (100 nm) lateral dimensions.

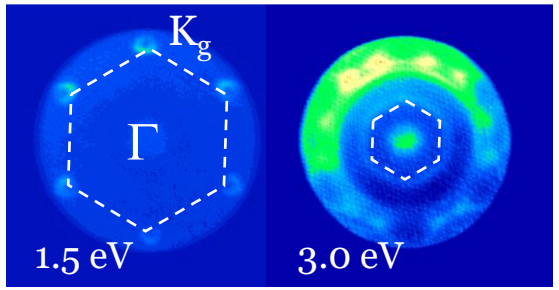
Bradford et al. *Small* 2024

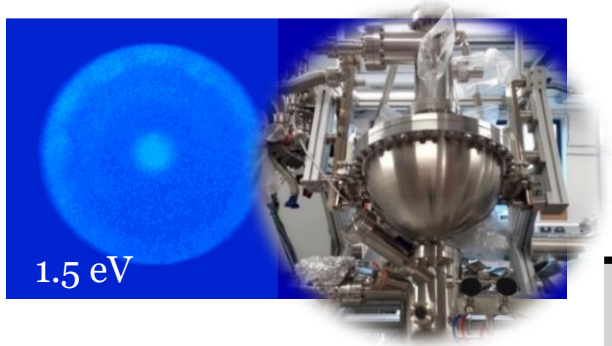
Band Structure and Symmetry

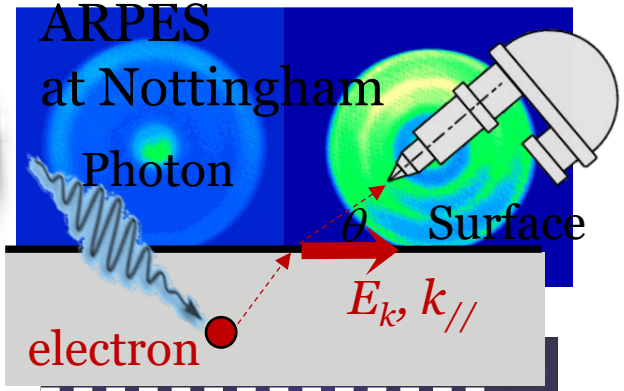
Angle Resolved Photoemission Spectroscopy, ARPES

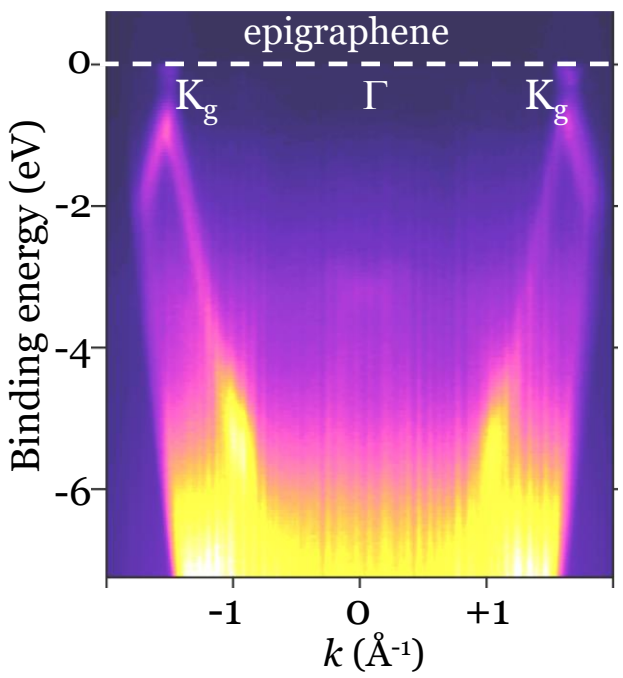
graphene | **1L GaSe** | **2L GaSe** | **6L GaSe**

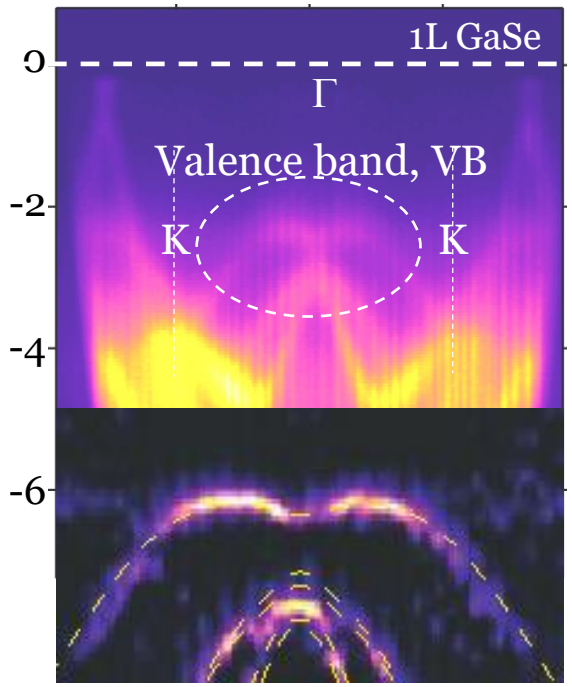


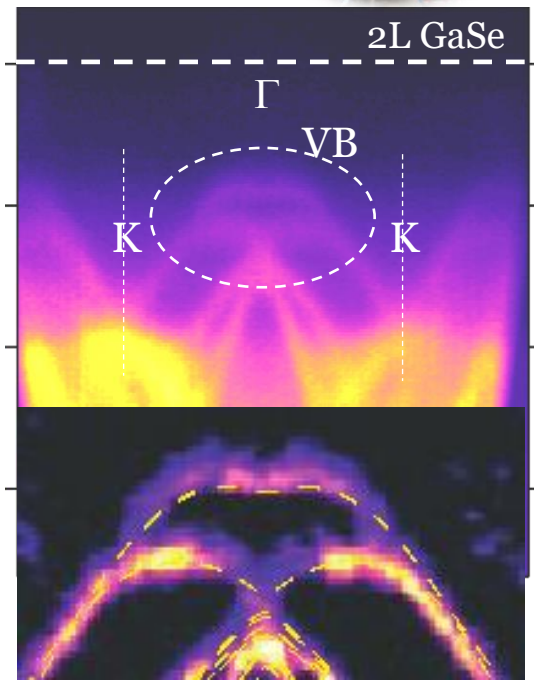


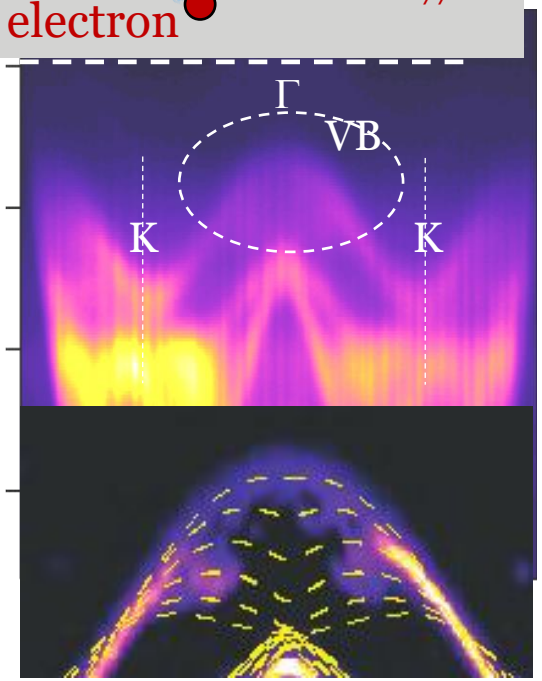










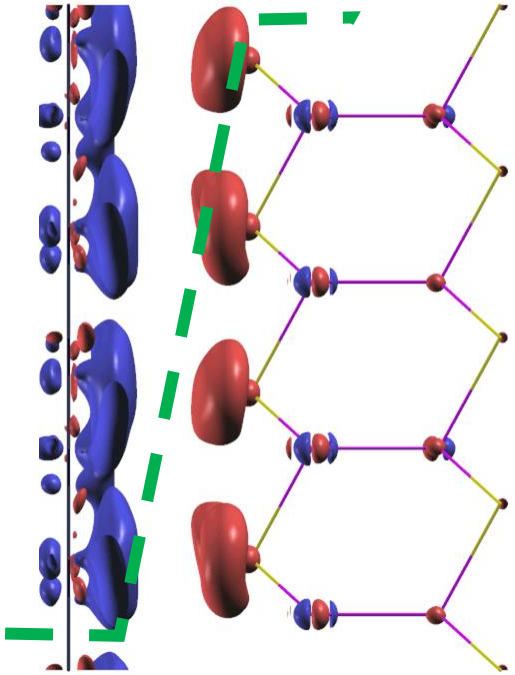


Mexican Hat VB | Mexican Hat VB | Parabolic VB

He I excitation ($h\nu$ = 21.219 eV); microscope operated in energy filtered mode: pass energy = 25 eV; slit width= 0.5 mm (resolution = 0.05 eV)

Interfacial Charge Dipole

Charge Dipole

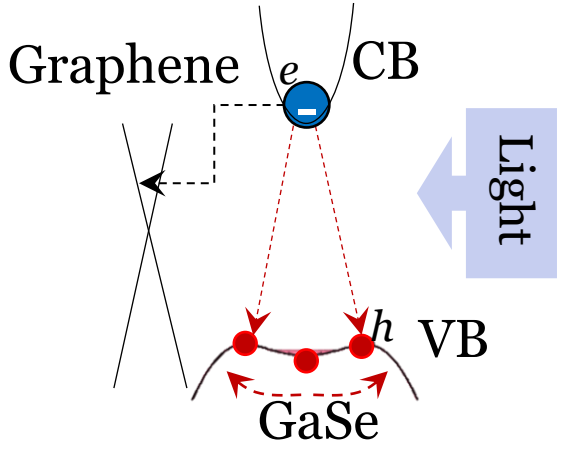


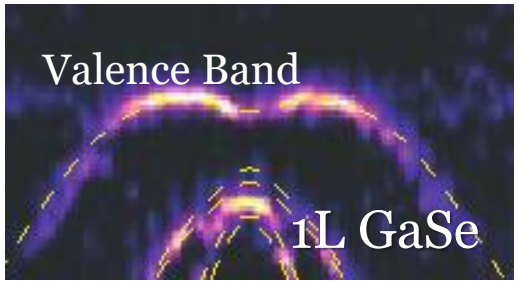
Graphene GaSe

Blue = fewer electrons | Red = more electrons

Built in potential
$\Delta\phi =$ 0.25 eV
Modelled by DFT
Measured by UPS

Effects of Light on graphene

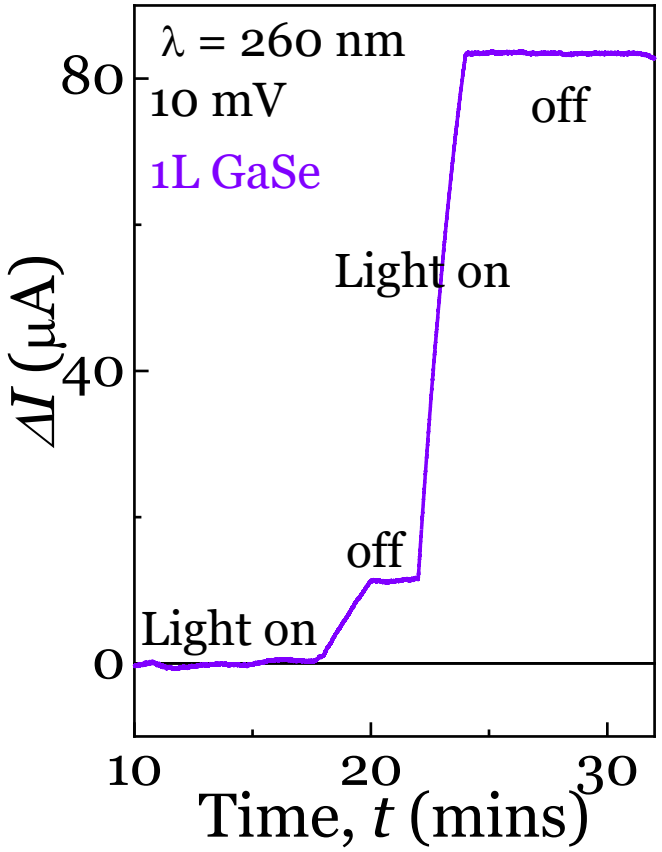




- e-h created in GaSe
- Electrons transfer to graphene
- Holes localized in GaSe

Photo-memory

Persistent photocurrent in graphene



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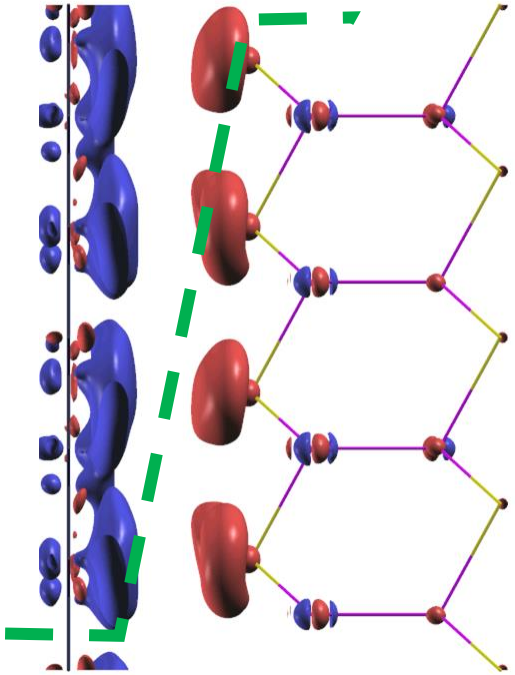
Interfacial Charge Dipole

Charge Dipole

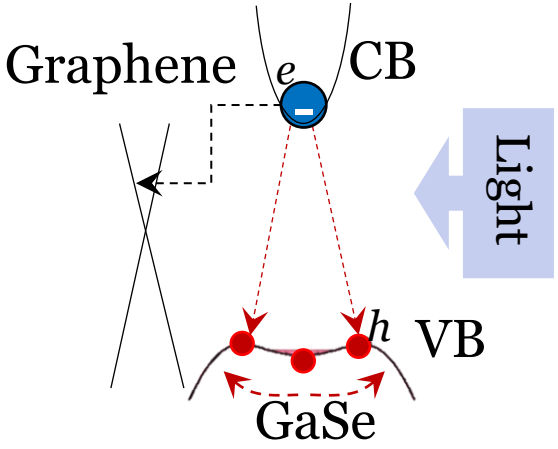


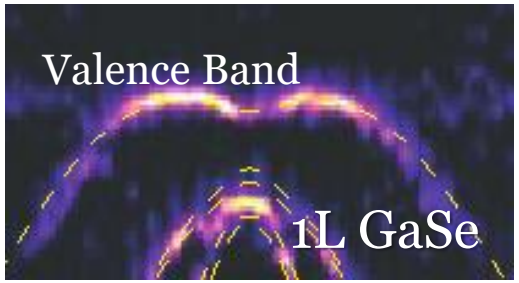
Graphene GaSe

Blue = fewer electrons	Red = more electrons

Built in potential
$\Delta\phi =$ 0.25 eV
Modelled by DFT
Measured by UPS

Effects of Light on graphene





- e-h created in GaSe
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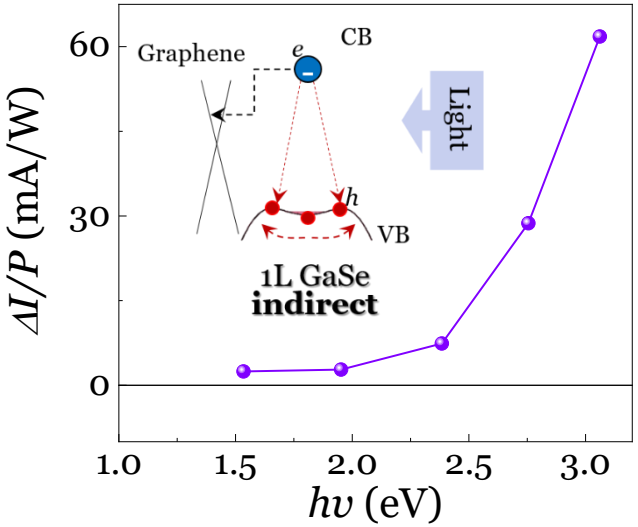
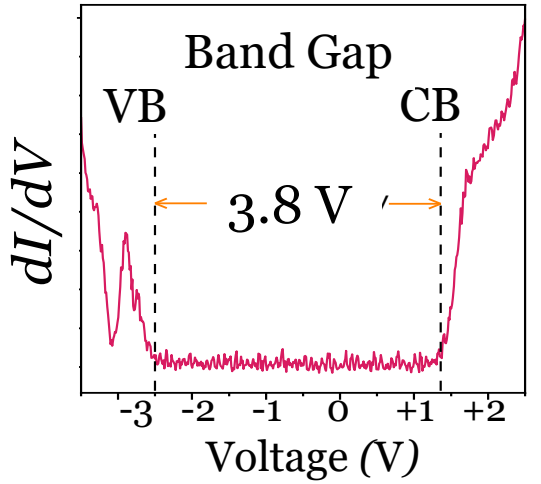
Photo-memory





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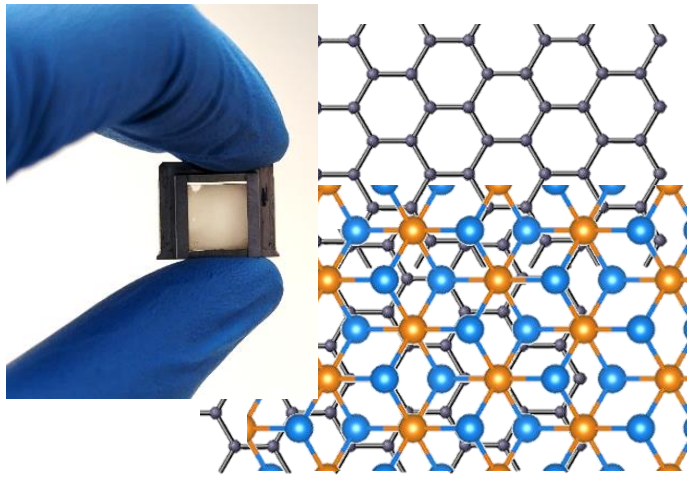
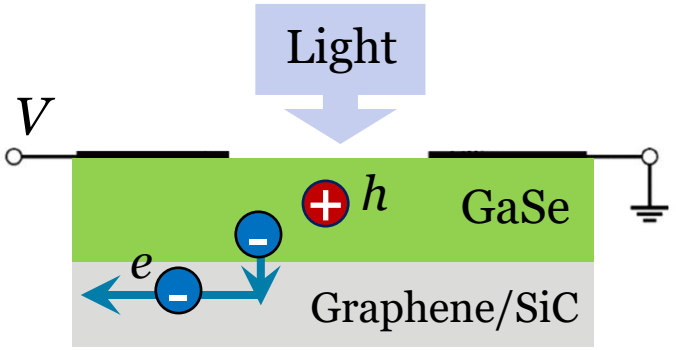
Platforms for UV-C Photonics

GaSe/graphene/SiC





GaSe: Optical channel

Graphene: Transport channel

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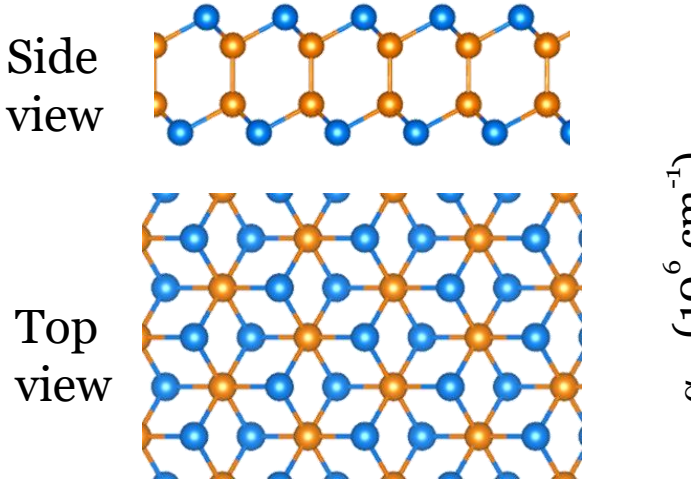
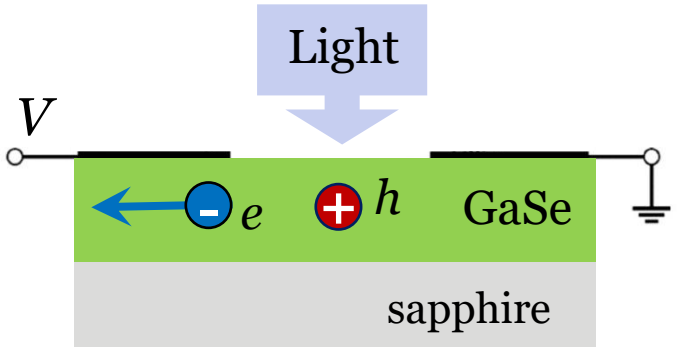
GaSe/sapphire





GaSe: Optical & Transport channel

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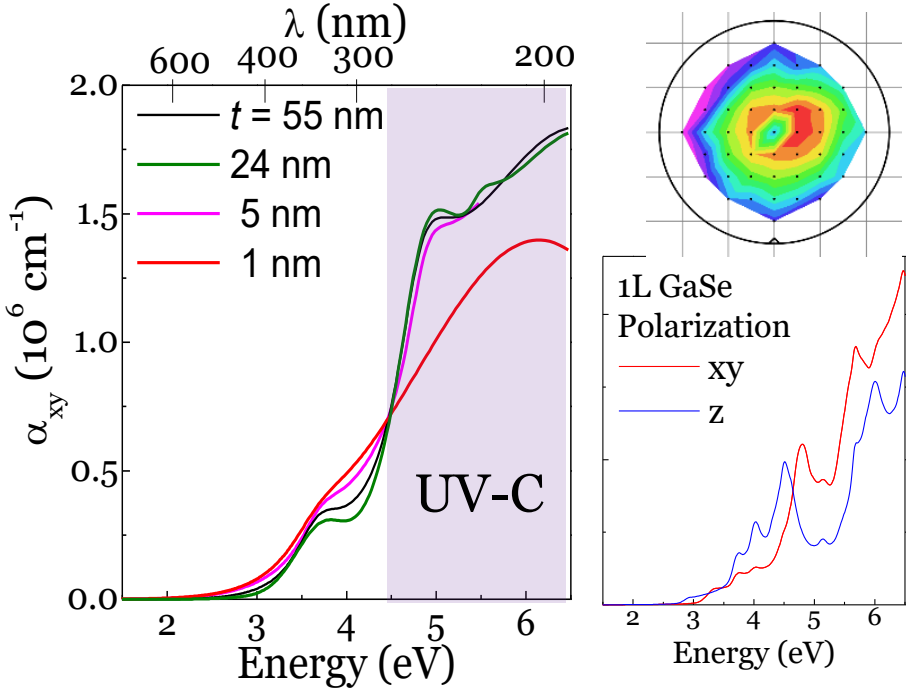
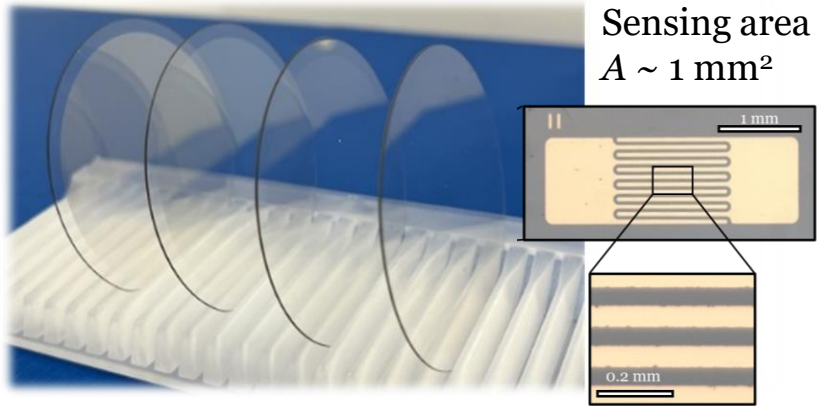
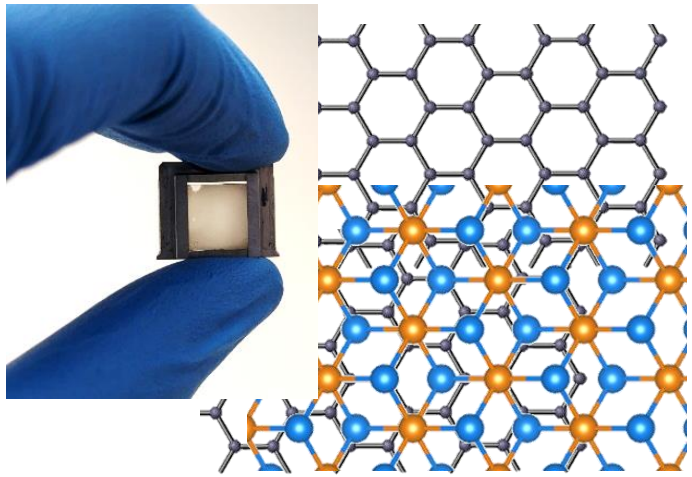
Ellipsometry: Absorption

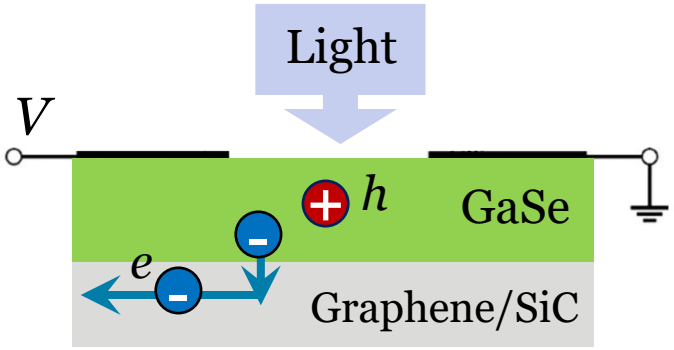




Platforms for UV-C Photonics

GaSe/graphene/SiC





GaSe: Optical channel

Graphene: Transport channel

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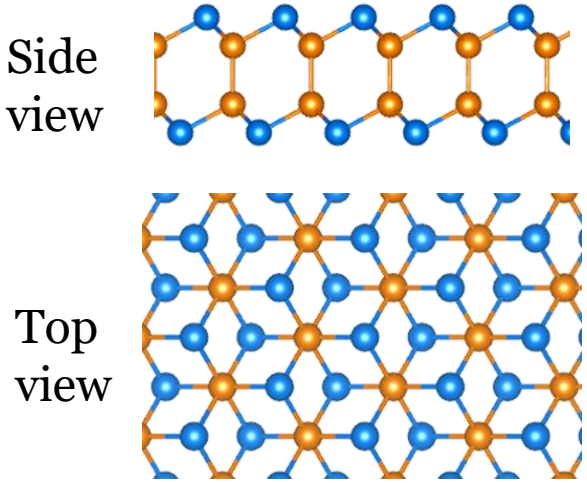
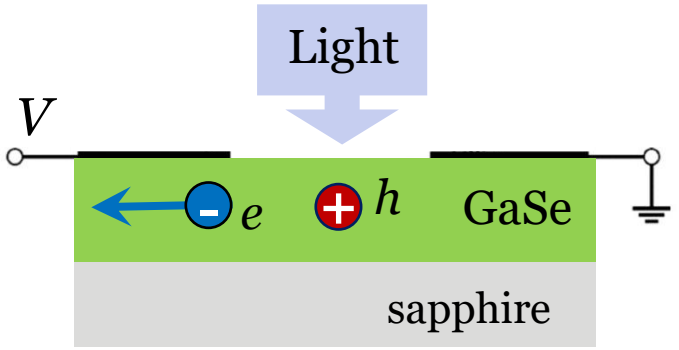
GaSe/sapphire





GaSe: Optical & Transport channel

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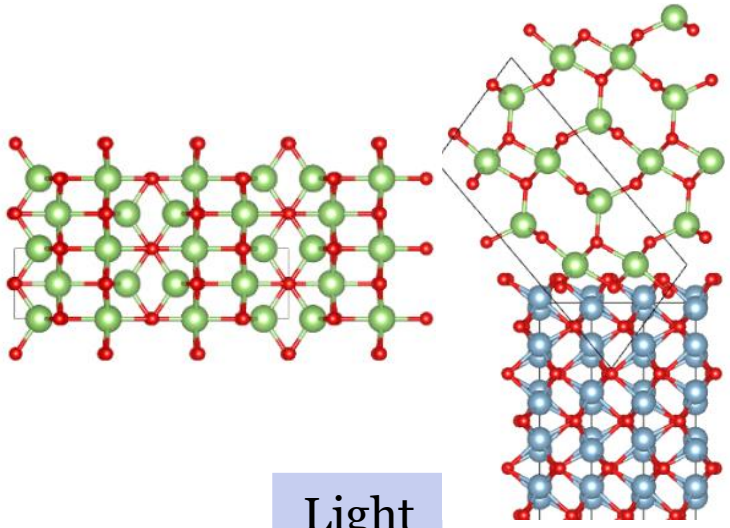
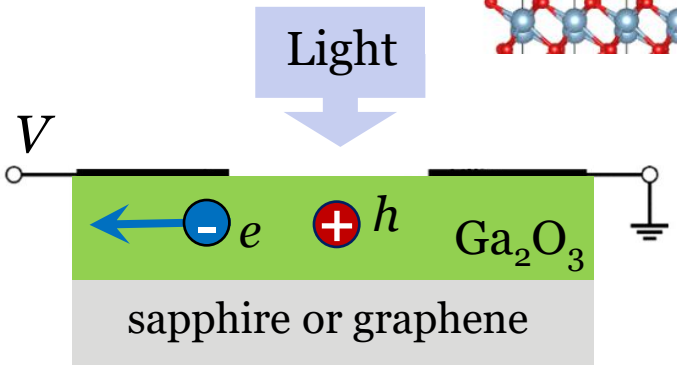
Ga_2O_3 on sapphire or graphene





Ga_2O_3: Optical & Transport channel

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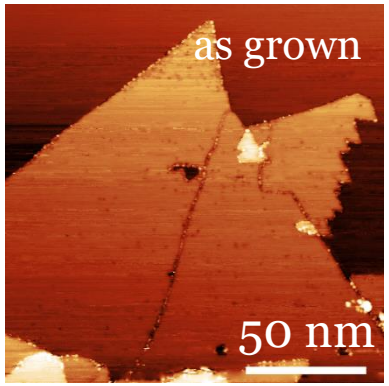
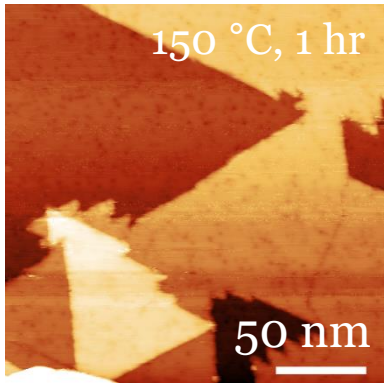
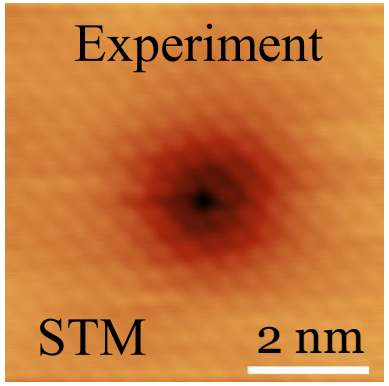
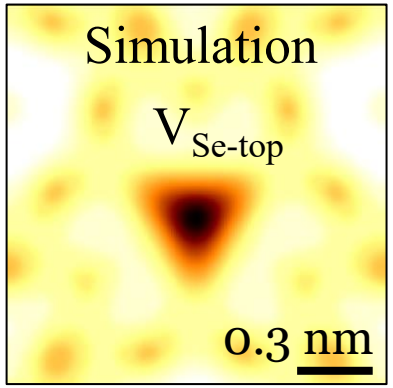
Cottam et al. *ACS Photonics* 2025

Se-vacancies in GaSe

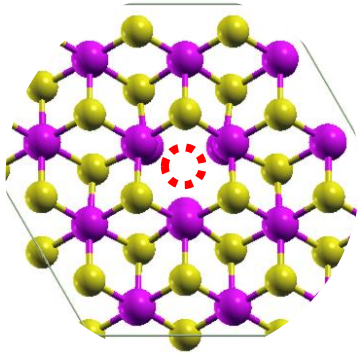




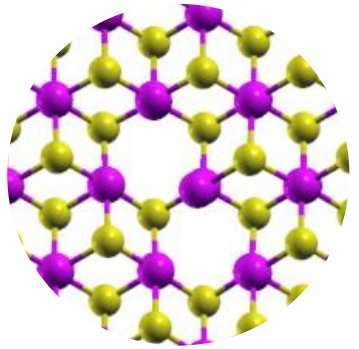


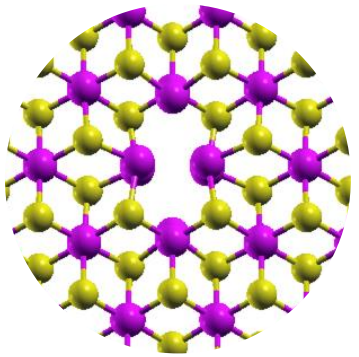


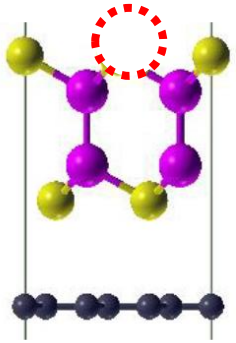
Se-vacancy



Multiple Se-vacancies





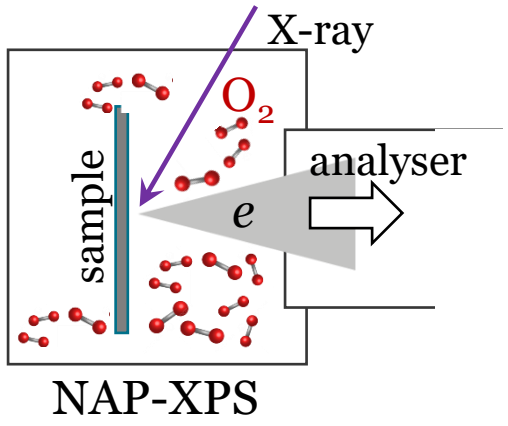


2D defect density of 8×10^{11} cm^{-2} in as-grown GaSe. Defects consist of single **Se-vacancies**, which have the lowest formation energy.

The density of Se-vacancies can be increased by **an annealing in UHV**.

Bradford et al. *2D Materials* 2025

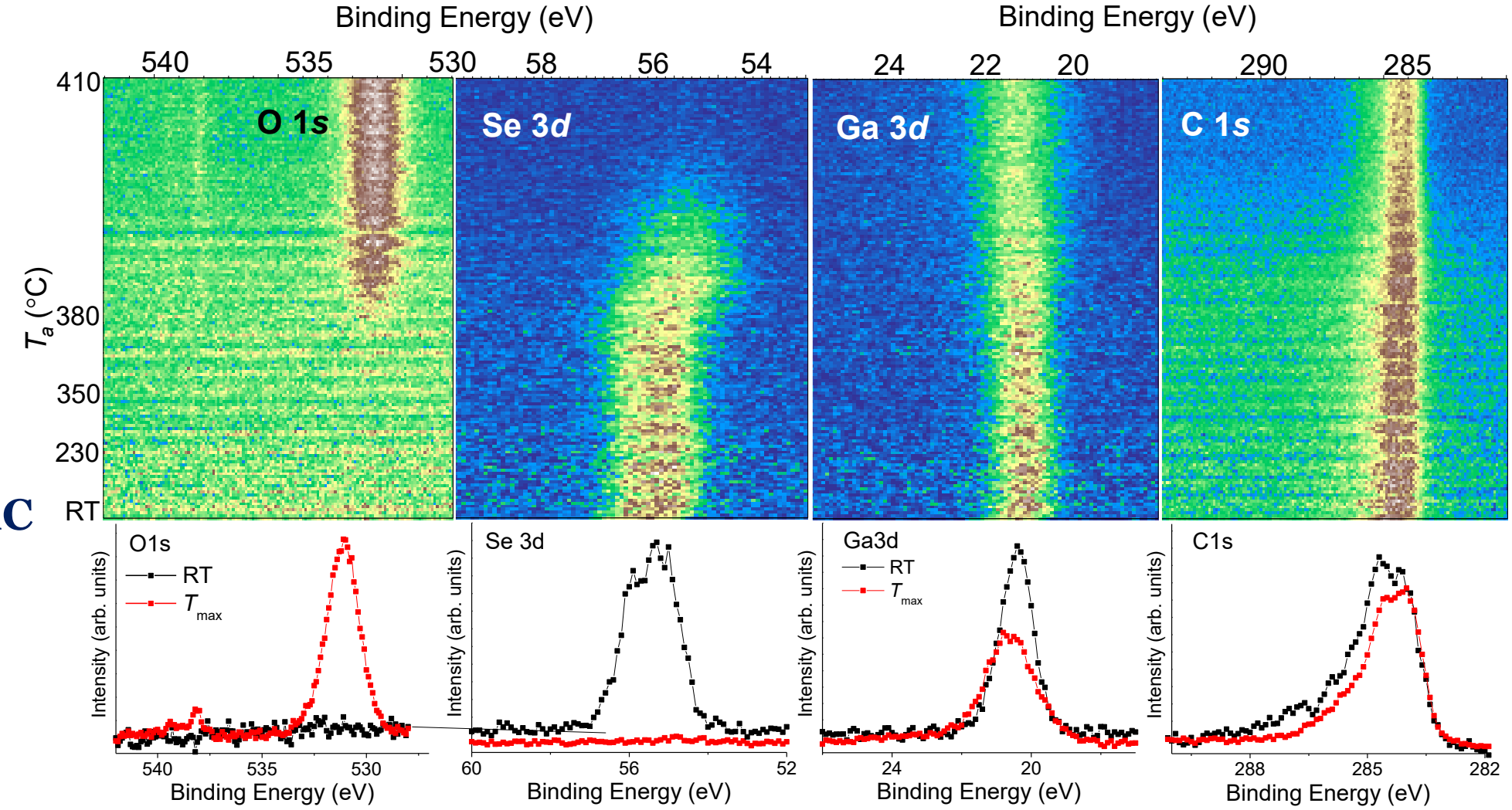
Conversion of $GaSe$ into Ga_2O_3



Near-Ambient Pressure (NAP) XPS

Thermal oxidation of **GaSe/graphene/SiC** by formation of Se-vacancies and Ga-O bonds

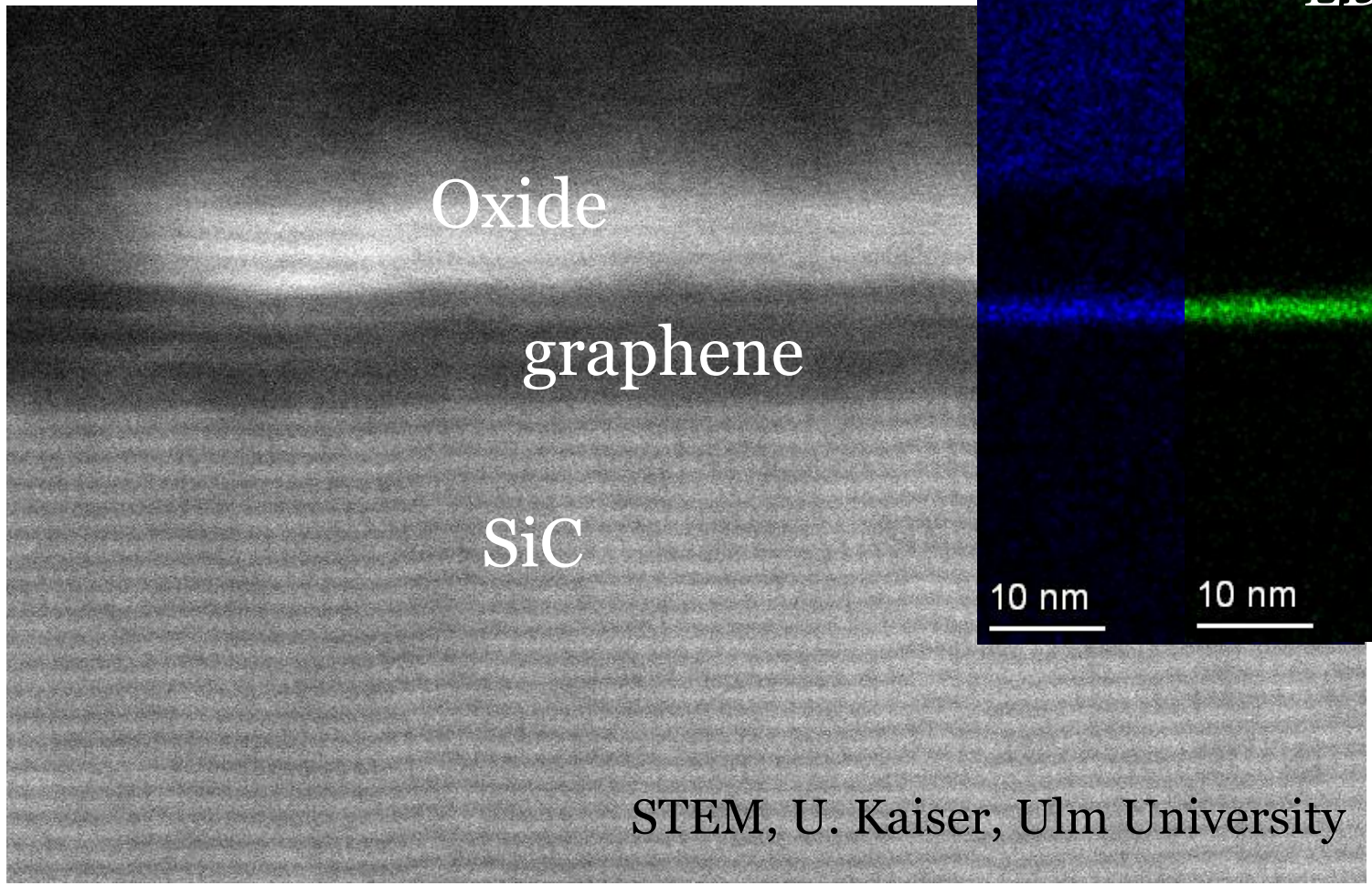
XPS signal of core electrons



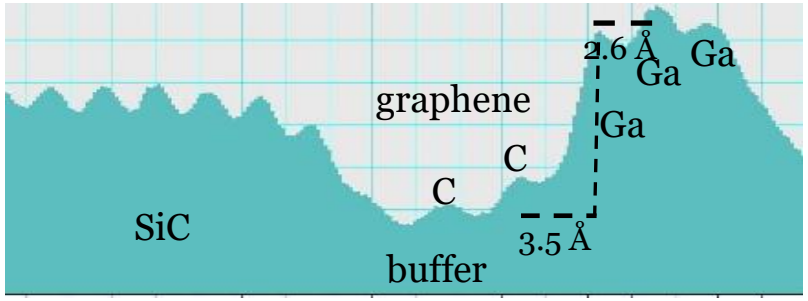
2D Oxide, 2DO

Electron Transmission Microscopy of Ga_2O_3

- Atomically thin oxide
- Crystalline oxide
- High-quality interface with graphene

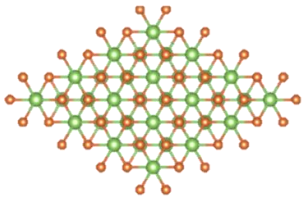


STEM profile

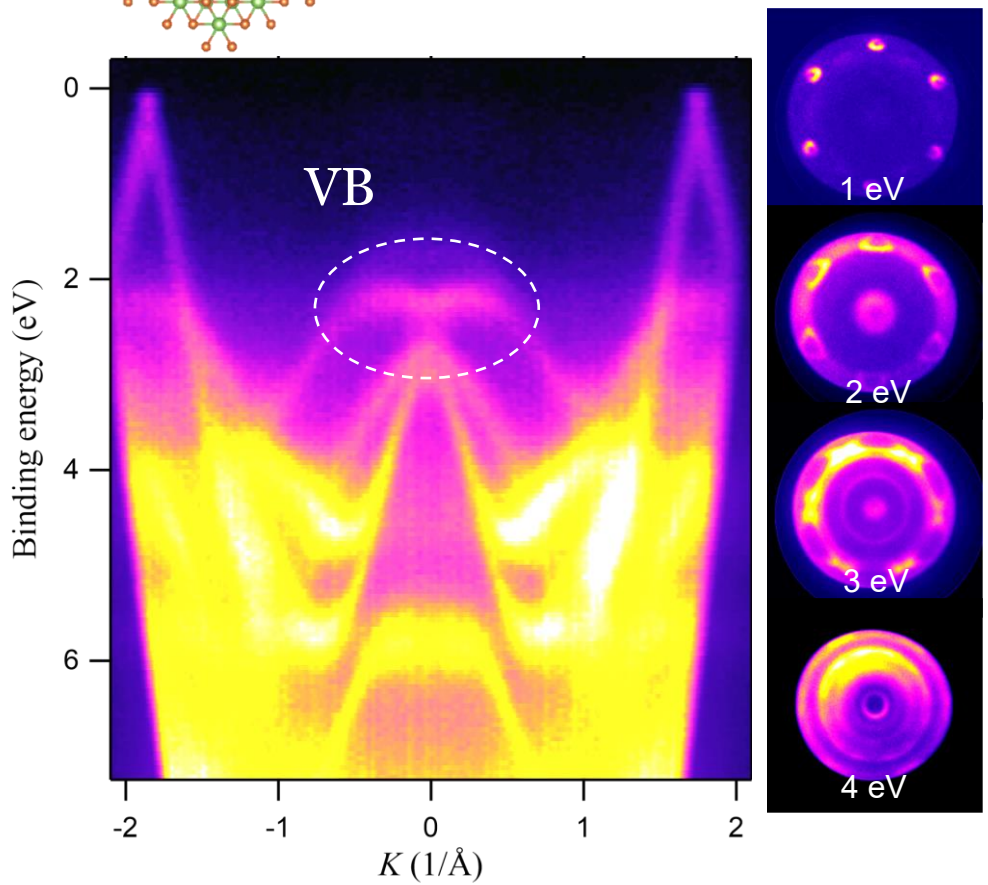


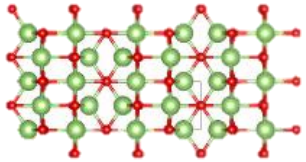
2DO: Band Structure

Weakly dispersed valence band
Large band offset (> 1.5 eV) and band gap energy (~ 4.5 eV)

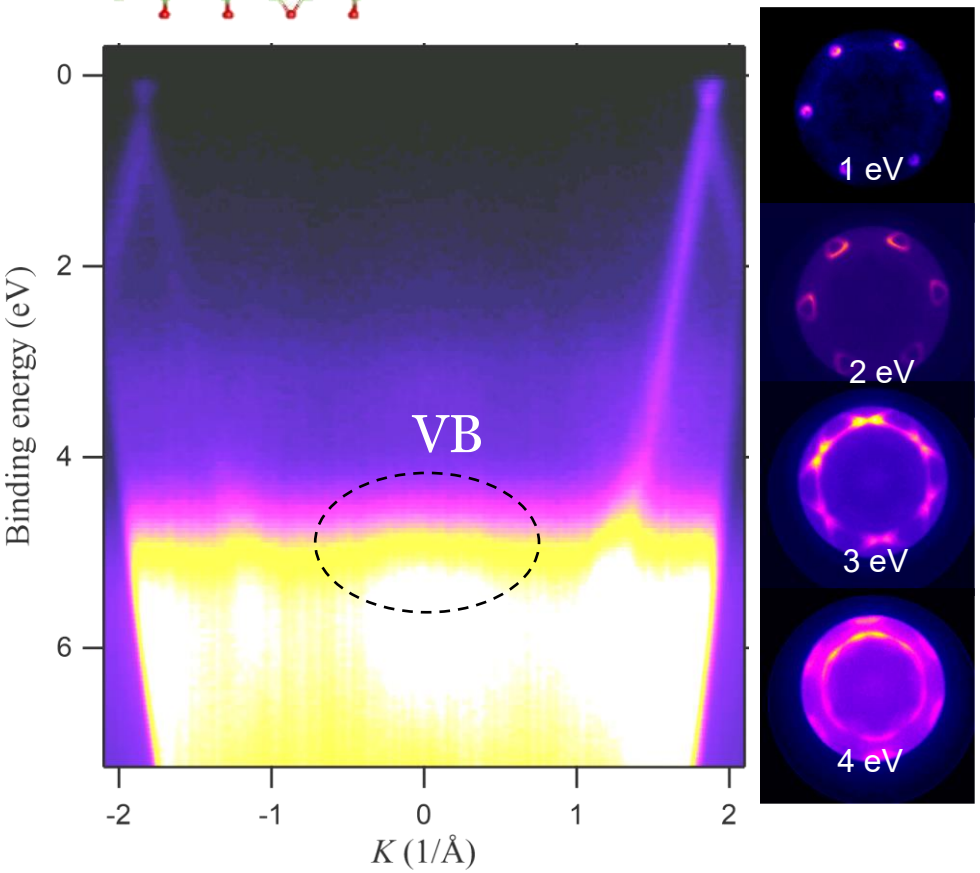


GaSe/graphene



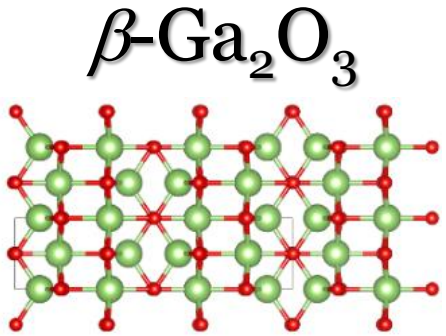


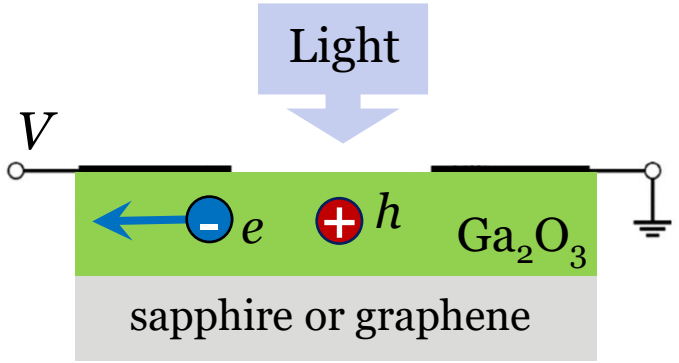
Ga_2O_3/graphene



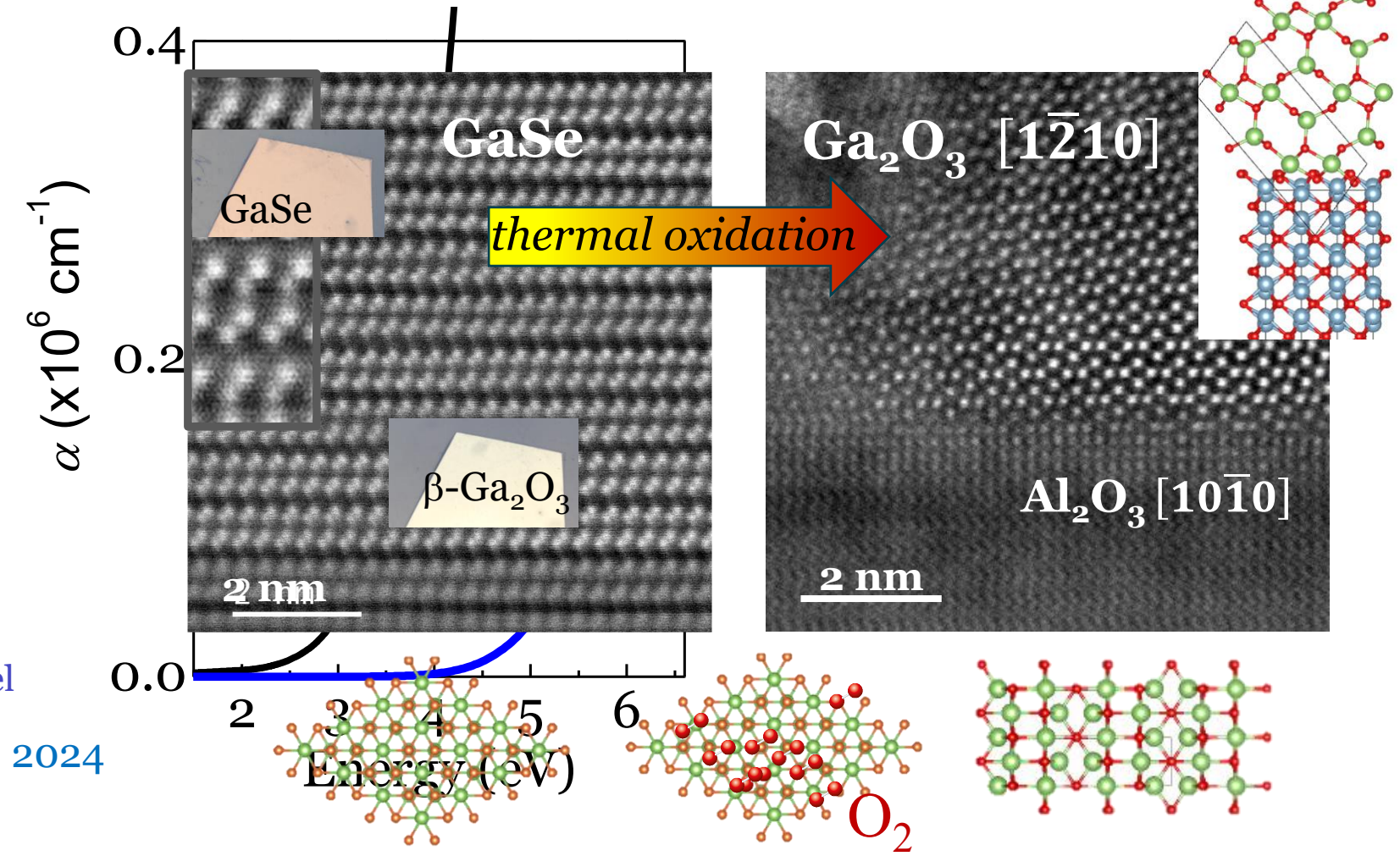
Platforms for UV-C Photonics

UV-C Selectivity in Ga_2O_3





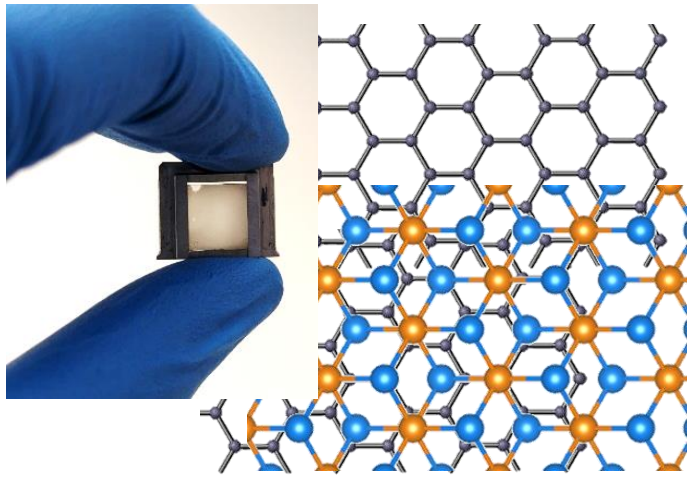
Ga_2O_3: Optical & Transport channel

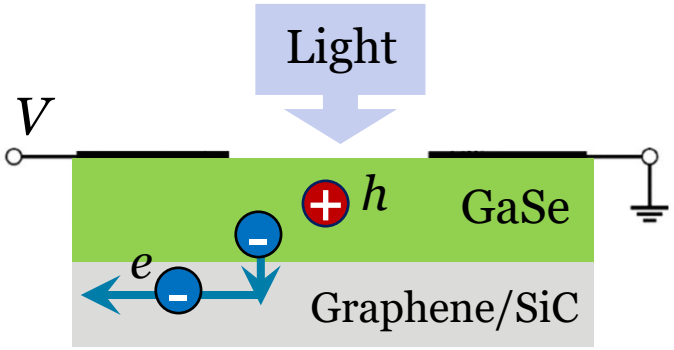


Cottam et al. *ACS Appl. Nano. Mat.* 2024
Cottam et al. *ACS Photonics* 2025

Platforms for UV-C Photonics

GaSe/graphene/SiC





GaSe: Optical channel

Graphene: Transport channel

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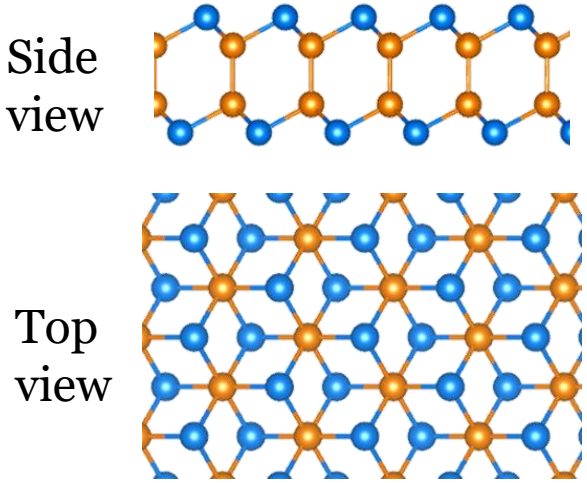
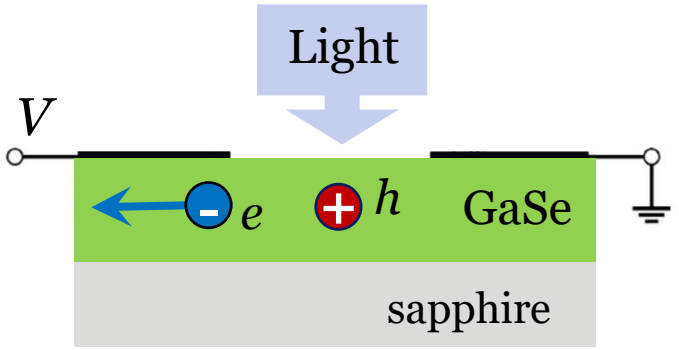
GaSe/sapphire

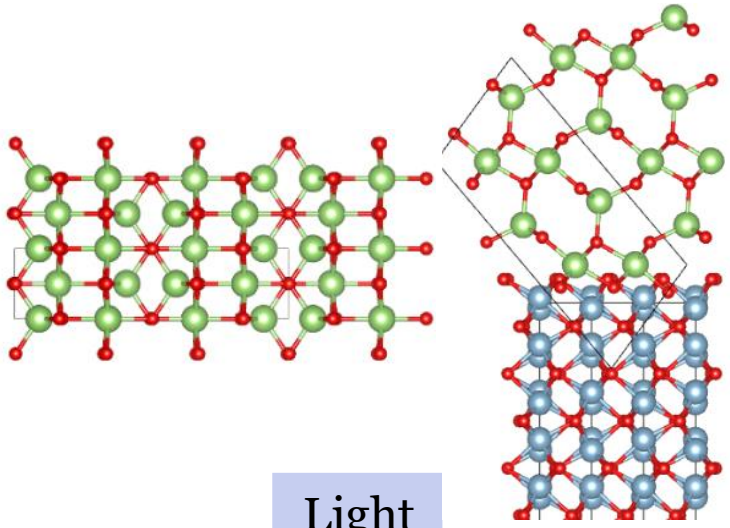


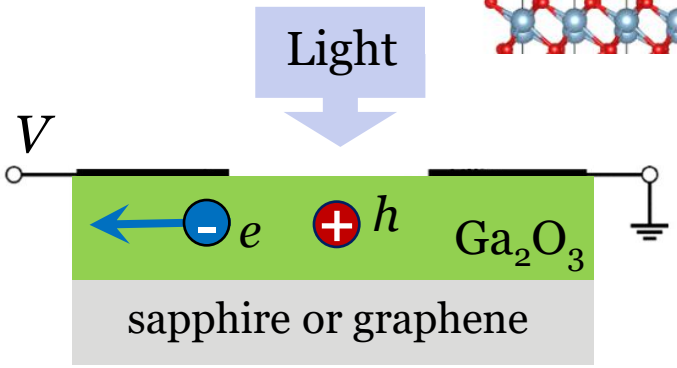


GaSe: Optical & Transport channel

Shiffa et al. *Small* 2024

Ga_2O_3 on sapphire or graphene



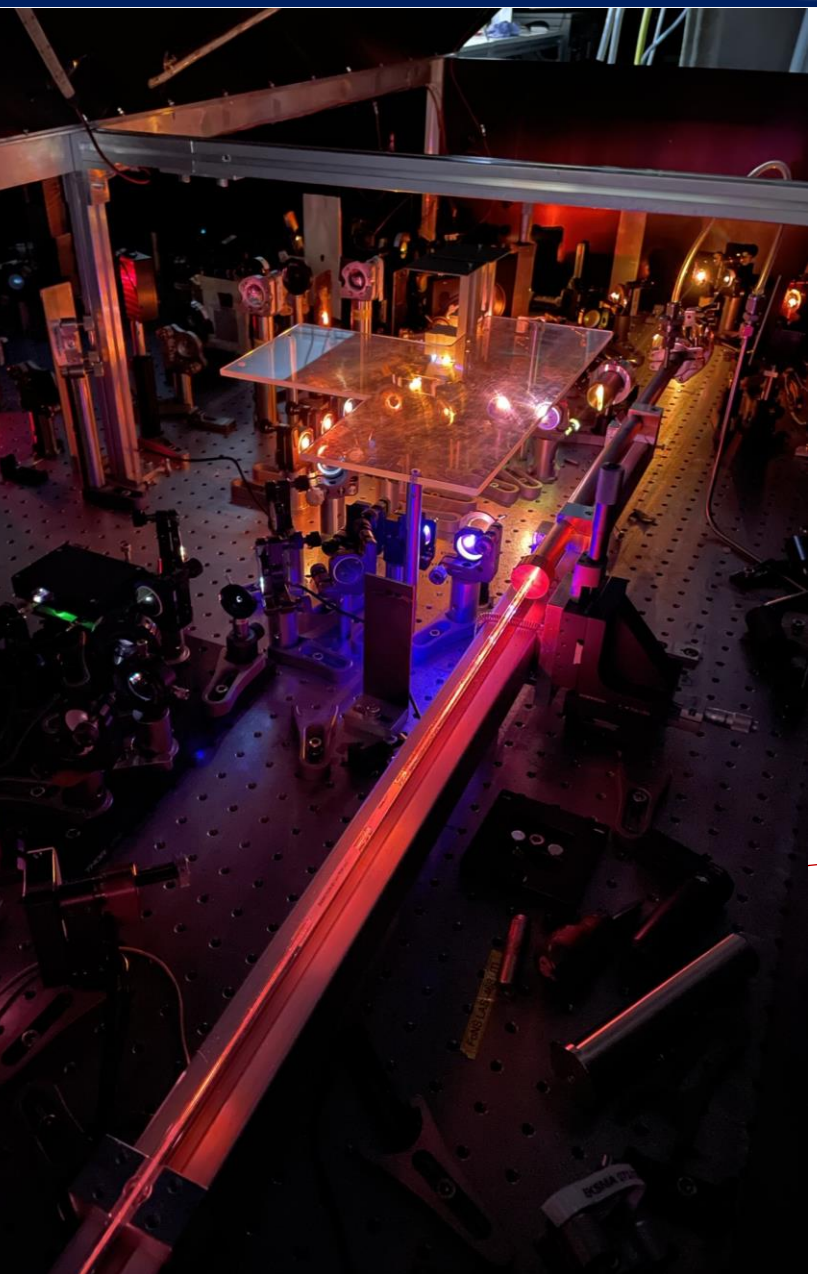


Ga_2O_3: Optical & Transport channel

Cottam et al. *ACS ANM* 2024

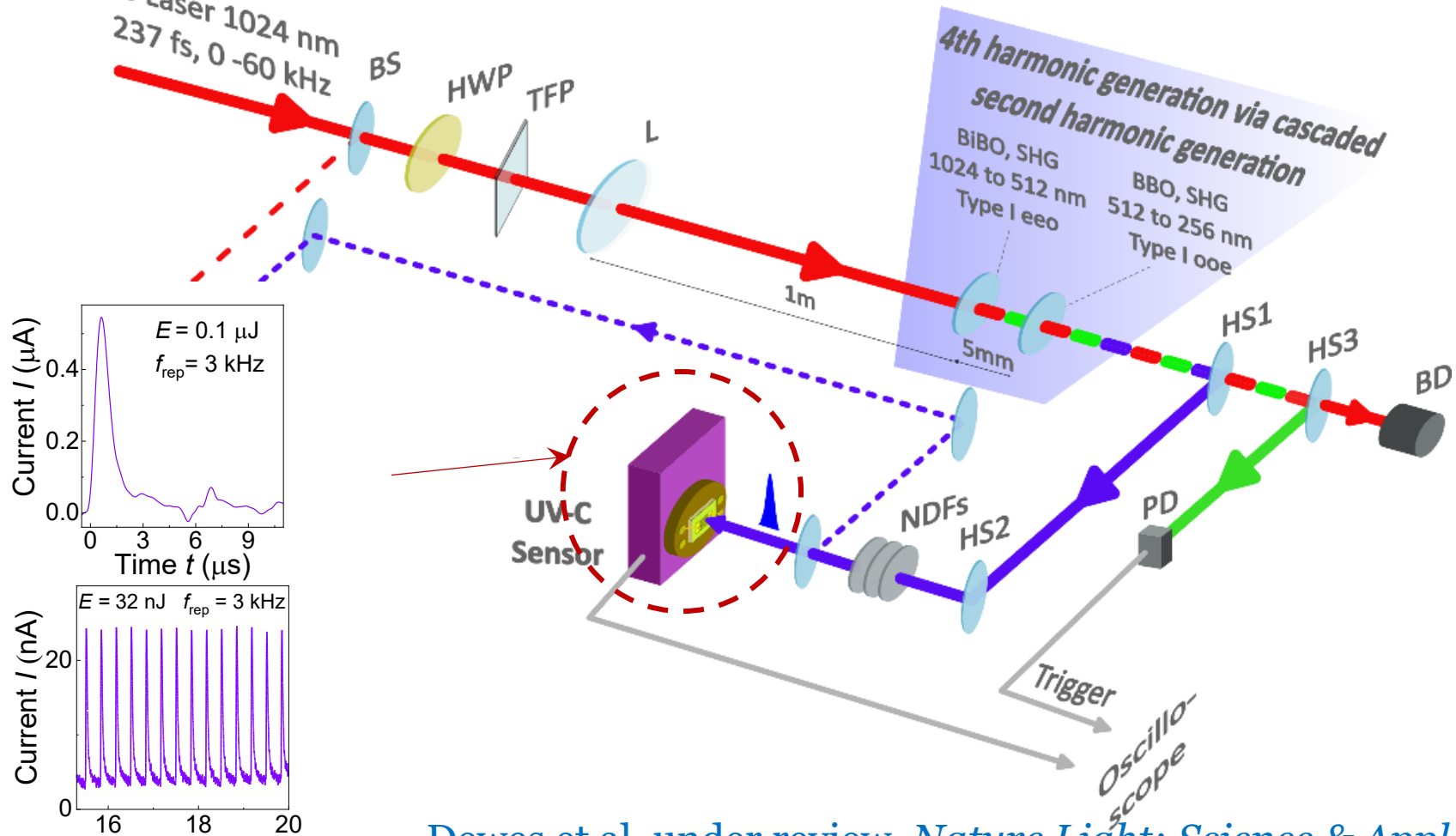
Cottam et al. *ACS Photonics* 2025

Sensing UV-C fs Laser Pulses



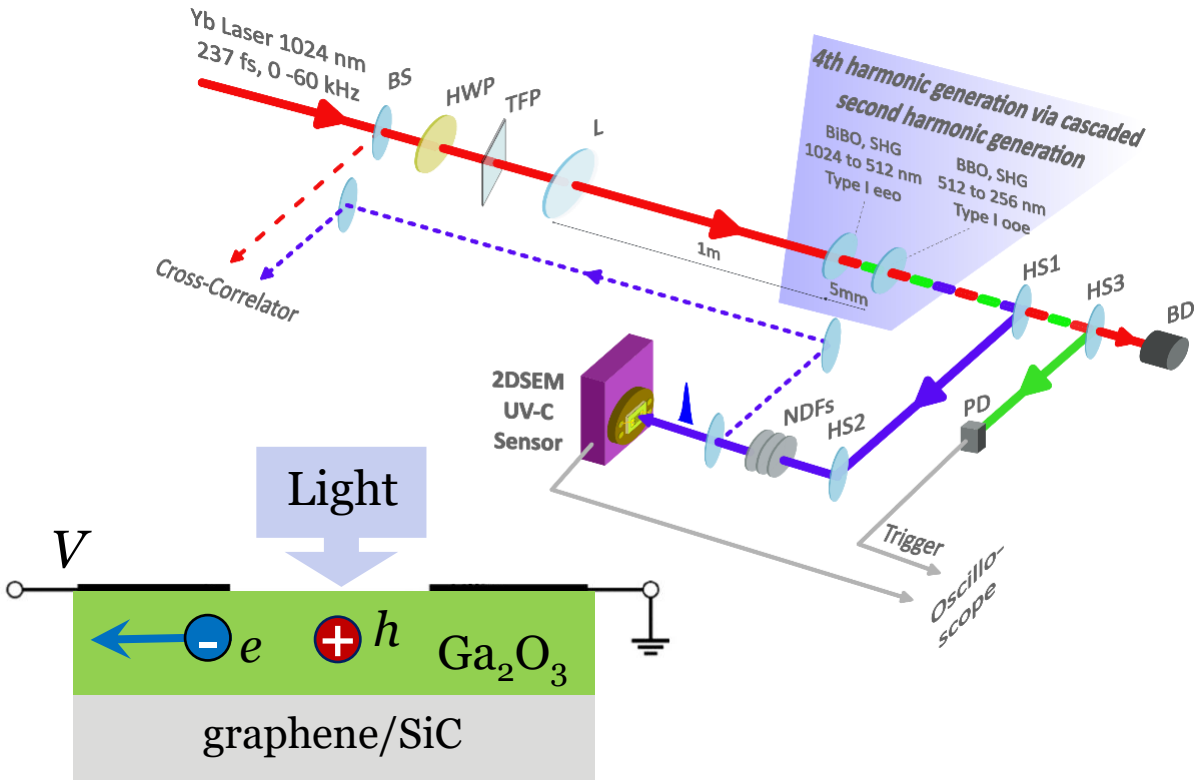
Integration Source/Sensor

- Sensing at 256 nm (UV-C)
- Sensing single fs pulses and pulse trains



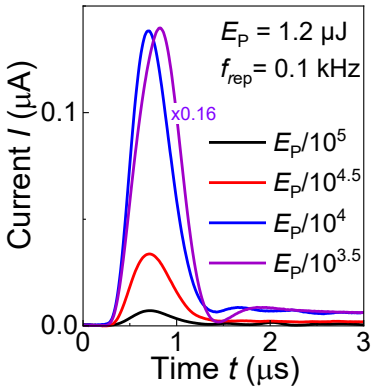
Dewes et al. under review *Nature Light: Science & Appl.*

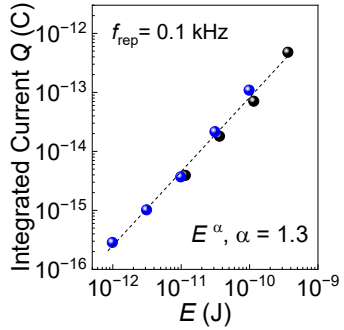
Sensing fs Laser Pulses

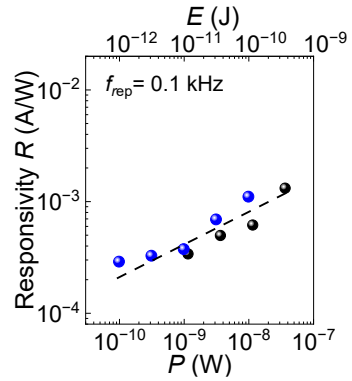


- Detection of fs pulses is not limited by slow trapping on defects.
- Increase of responsivity with E, P and pulse repetition rates f_{rep} due to photo-thermionic emission from SiC

Dependence on pulse energy E

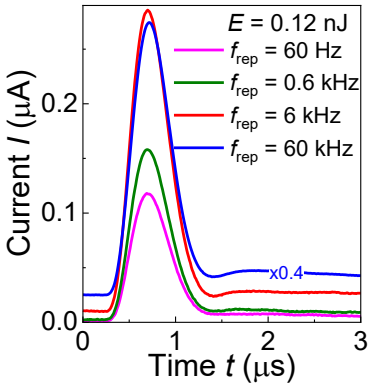


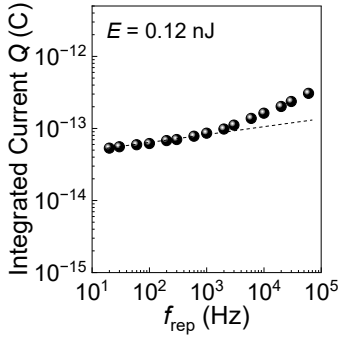


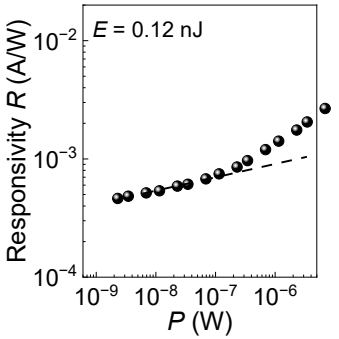


Average photocurrent $I = Qf_{rep}$
Q = integral of I over $T = 1/f_{rep}$ $\quad R = Q/E = I/P$

Dependence on repetition rate f_{rep}



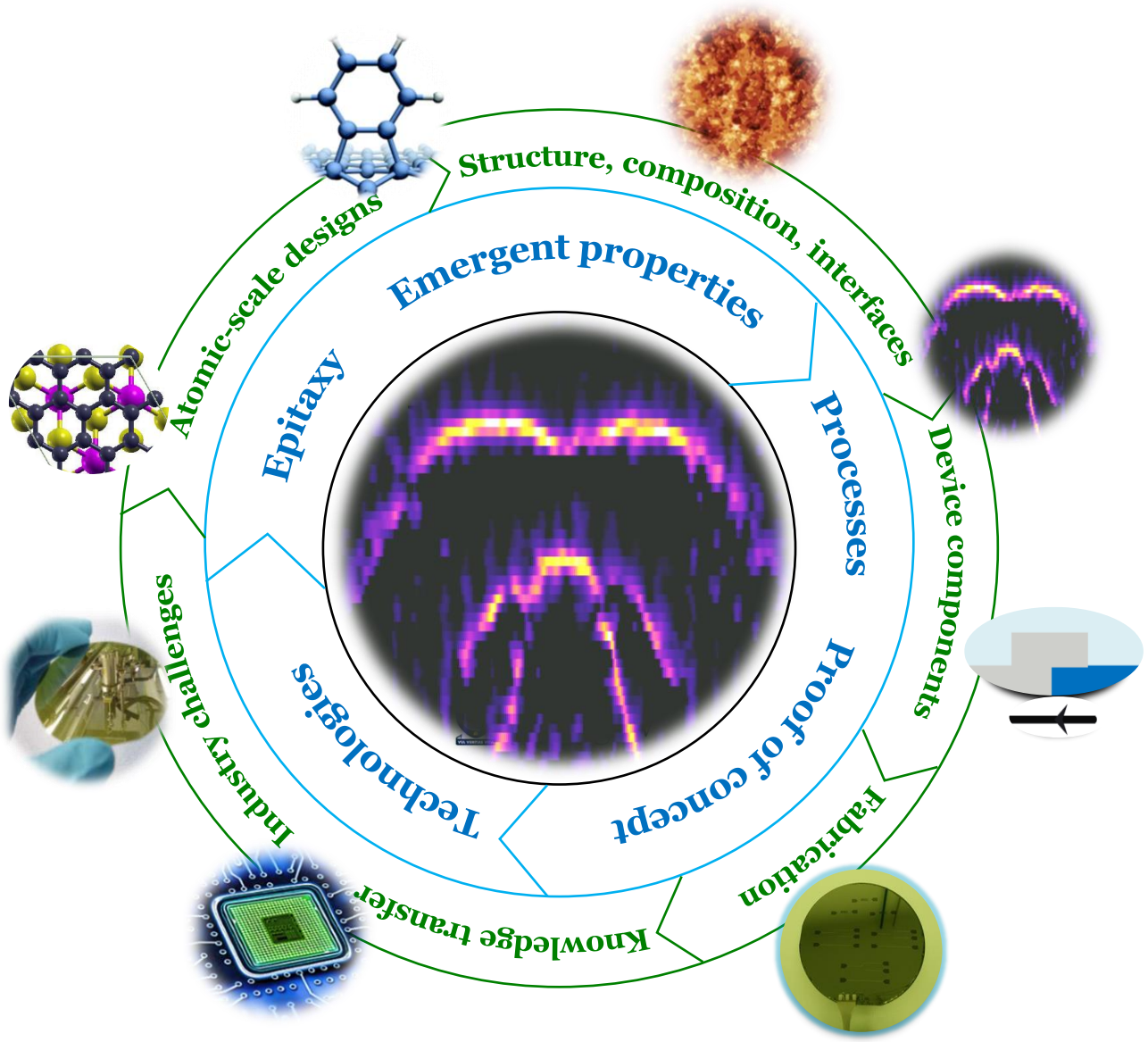




Low-Power Electronics

EPSRC Programme Grant
2025-30, £6M

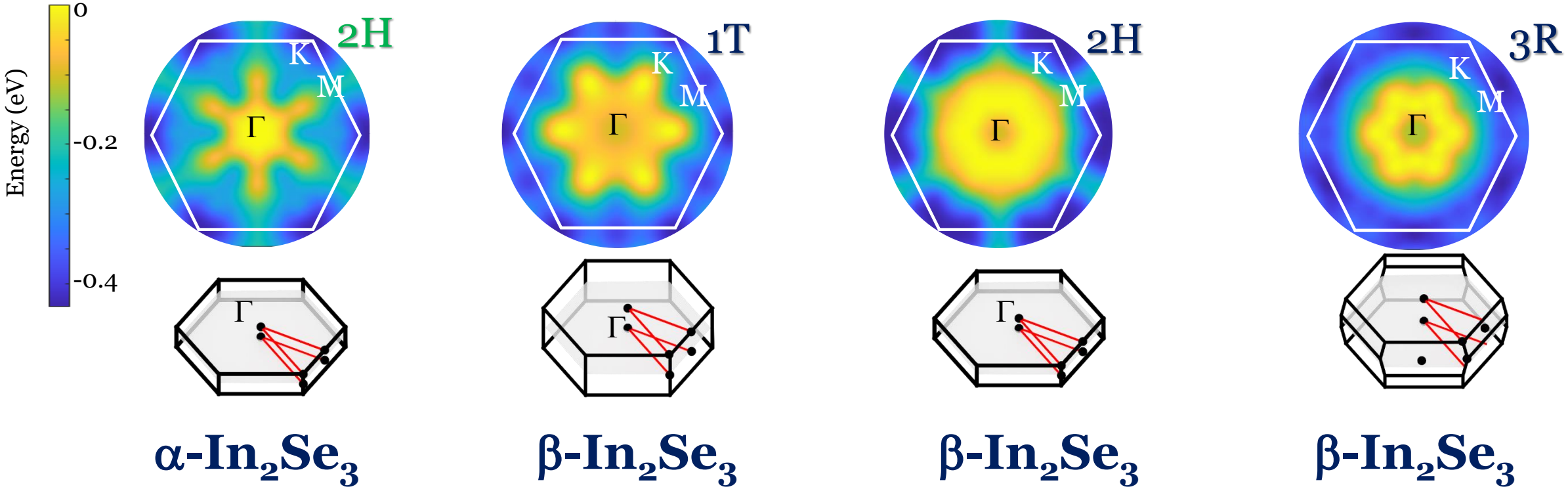
- Queen Mary University of London, University of Glasgow and University of Nottingham will develop 2SEM for prototype low-energy consumption electronic devices that will reduce electricity demand from data centres/high-performance computing
- 2SEM produced at wafer-scale
- > 20 partners in academia/industry (Paragraf)



"Zoo" of 2D Bands

Inverted "Mexican Hat" valence band

in GaSe, InSe, and ferroelectric In_2Se_3

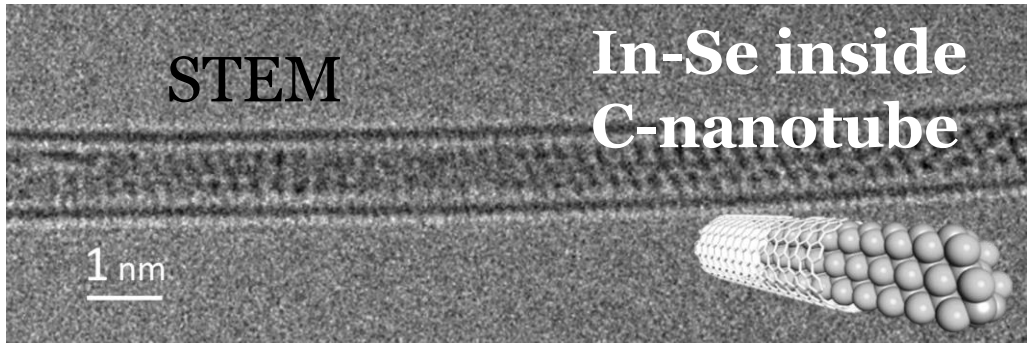


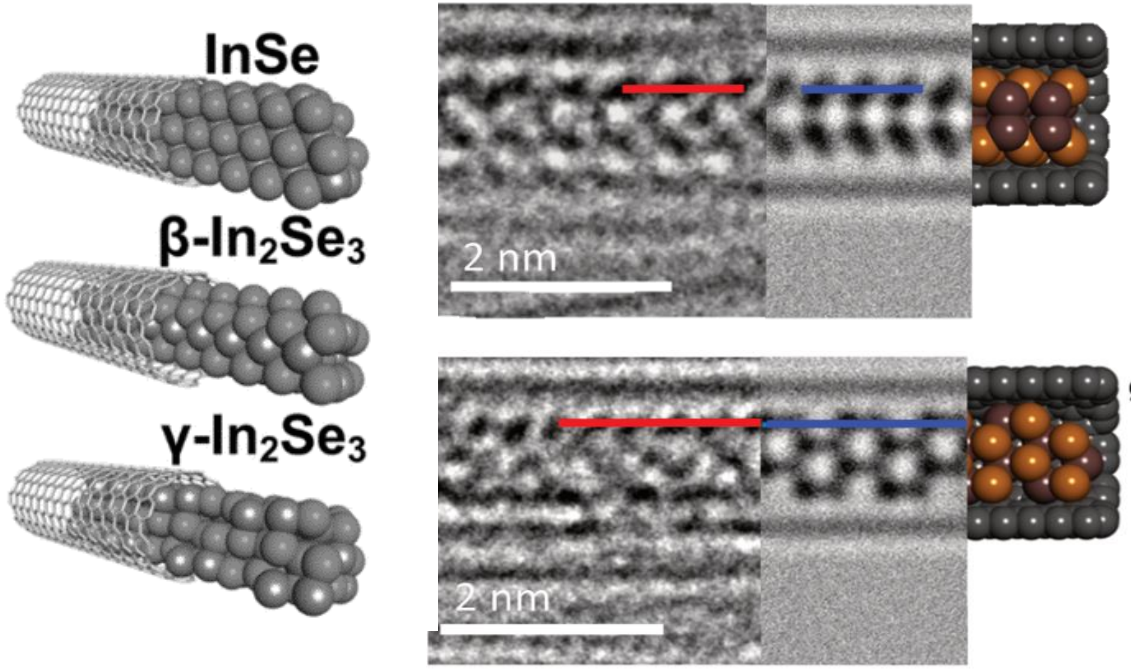
α-In_2Se_3 **β-In_2Se_3** **β-In_2Se_3** **β-In_2Se_3**

Felton et al. *Nature Com.* 2025

Hybrid Systems

Encapsulation of 2SEM within C and BN-nanotubes

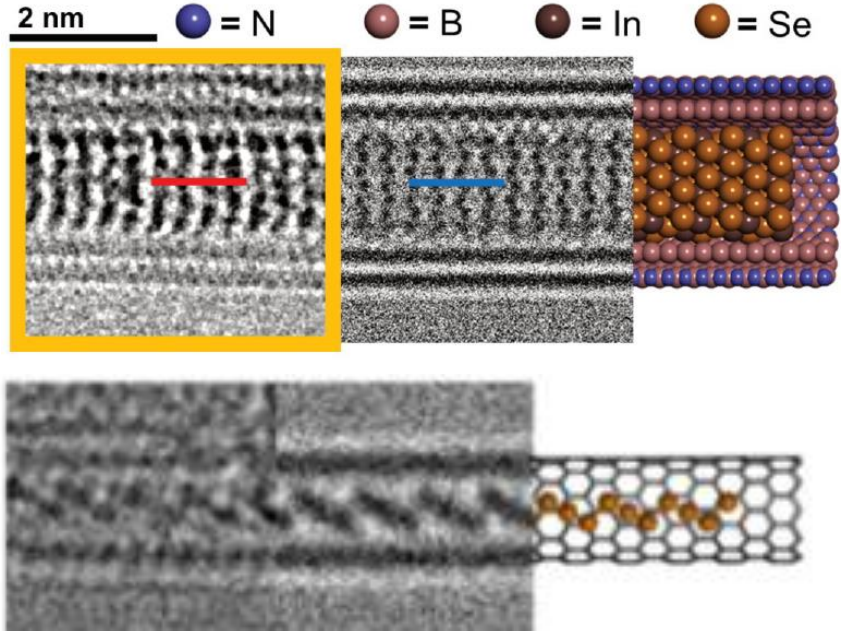




Cull et al. *ACS Nano* 2023

A wide range of polymorphs and nanostructures

In-Se/Se inside a BN-nanotube



Cull et al. *Adv. Mat.* 2025

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S Novikov, T Cheng, PH Beton, CJ Mellor, J O'Shea, L Eaves, O Makarovsky…

…

EMFL European Magnetic Field Laboratory

NPL National Physical Laboratory

dstl

UKRI

The Leverhulme Trust

Partners

GRAPHENE FLAGSHIP