Australian National University

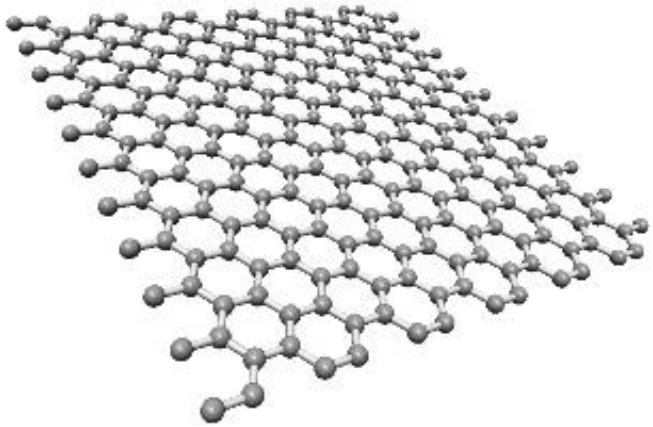
Graphene 2017
March 28-31
Barcelona (Spain)

Intensely illuminated Excitons and tightly bound Trions in 2-D Phosphorene by Optical Dimensional Transformation

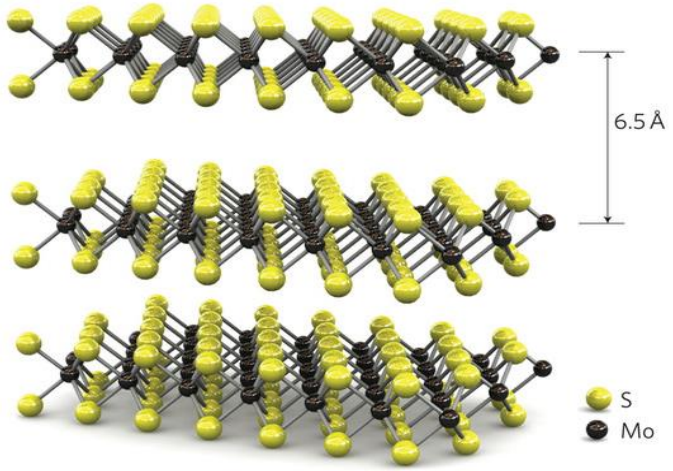
Ankur Sharma
PhD Student
Australian National University

Contents

2D semiconductors

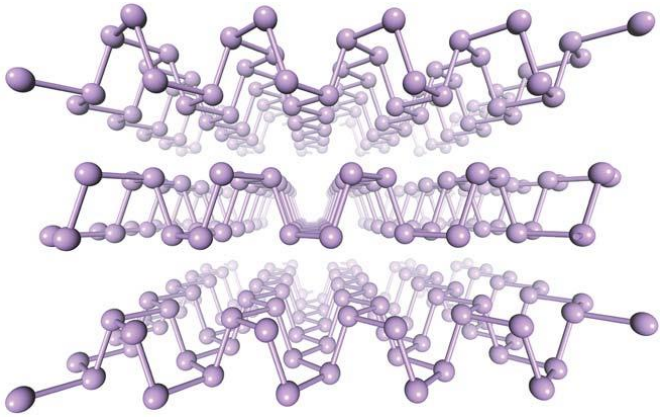


Graphene



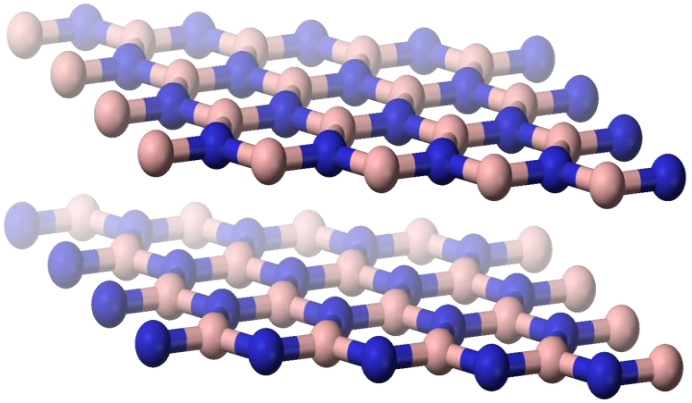
MX_2

Nat. Nanotechnol. **6**, 147 (2011).



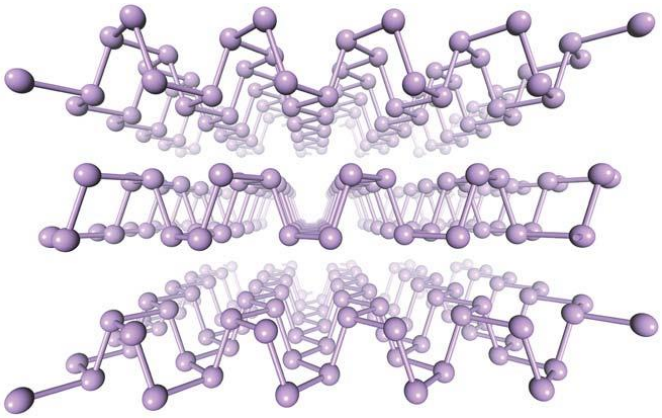
Phosphorene

Nat. Nanotechnol. **9**, 372 (2014).



hBN

Phosphorene

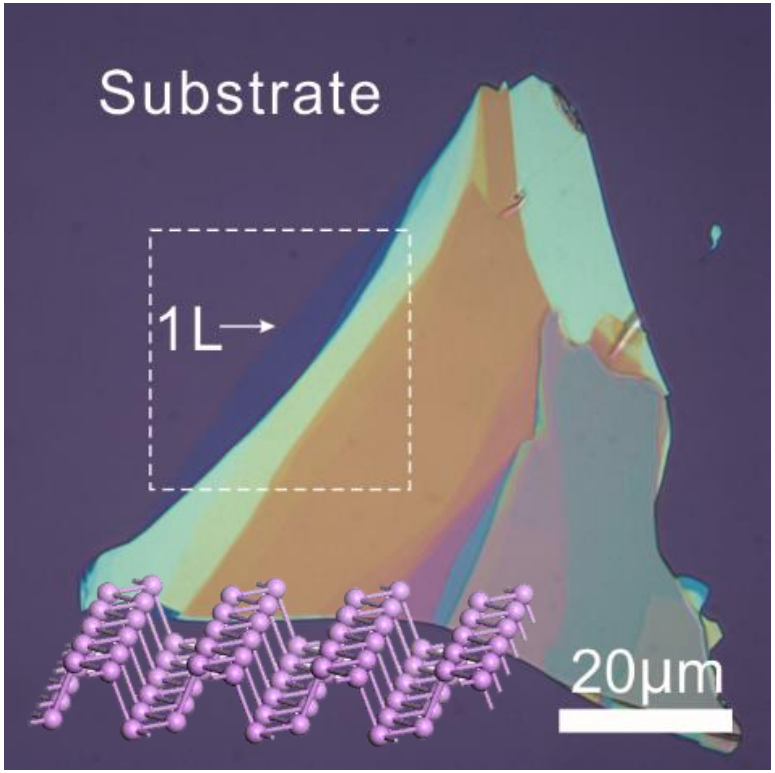


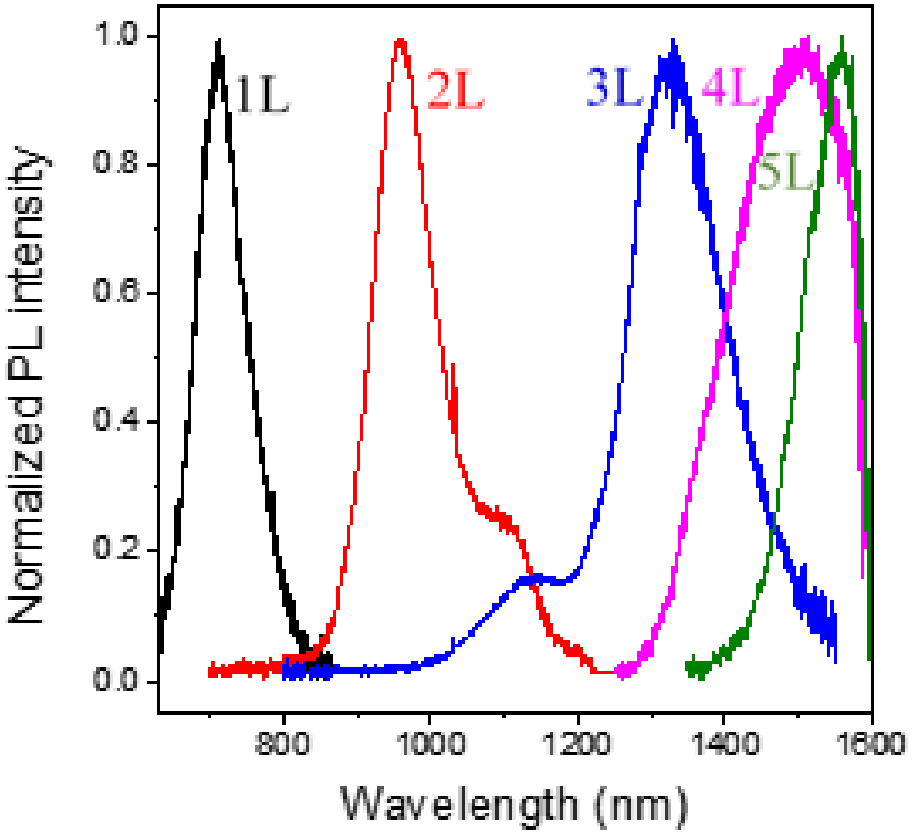
Nat. Nanotechnol. **9**, 372 (2014).

- Layer-dependent direct bandgap
  - ~2 eV for monolayer
  - ~0.3 eV for bulk
- Mobility ~1000 $cm^2V^{-1}s^{-1}$
- Drain current modulation ~10^5
- Optical, electrical and optoelectronic applications

PL spectra from phosphorene

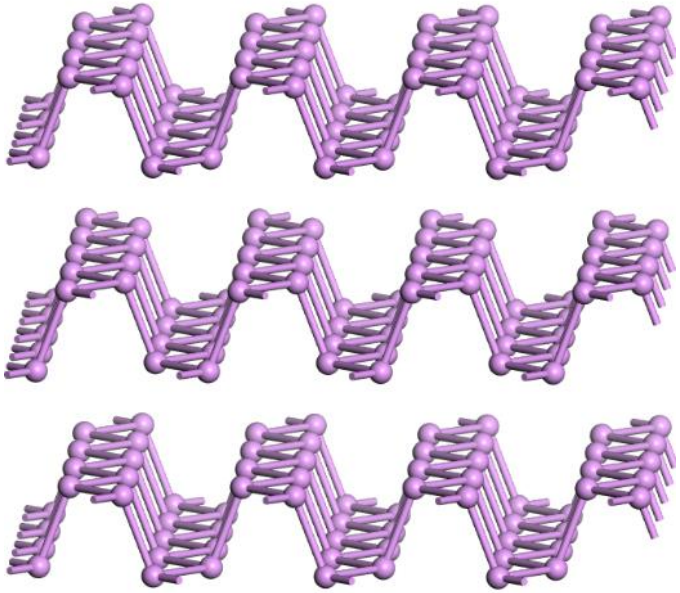
Yang, Jiong, et al. *Light Sci. Appl.* **4**.7 (2015): e312.

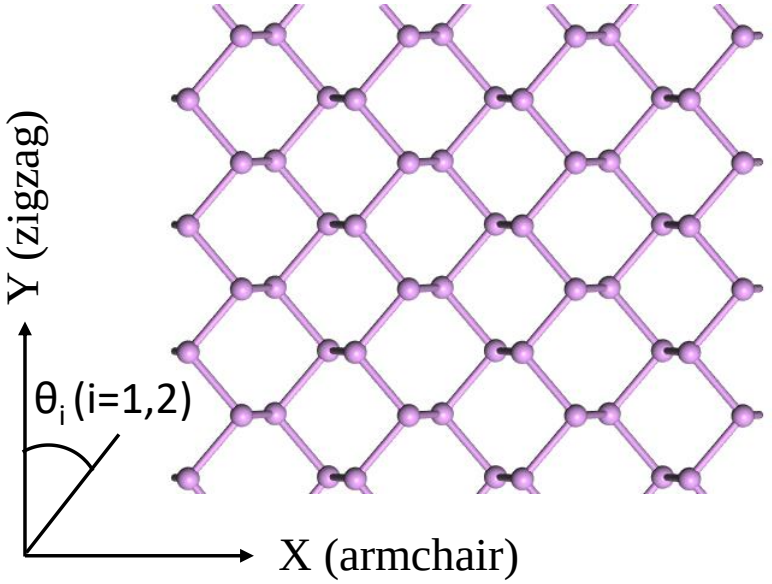




- Layer Dependent Optical band gap and PL emission

Anisotropic nature of phosphorene

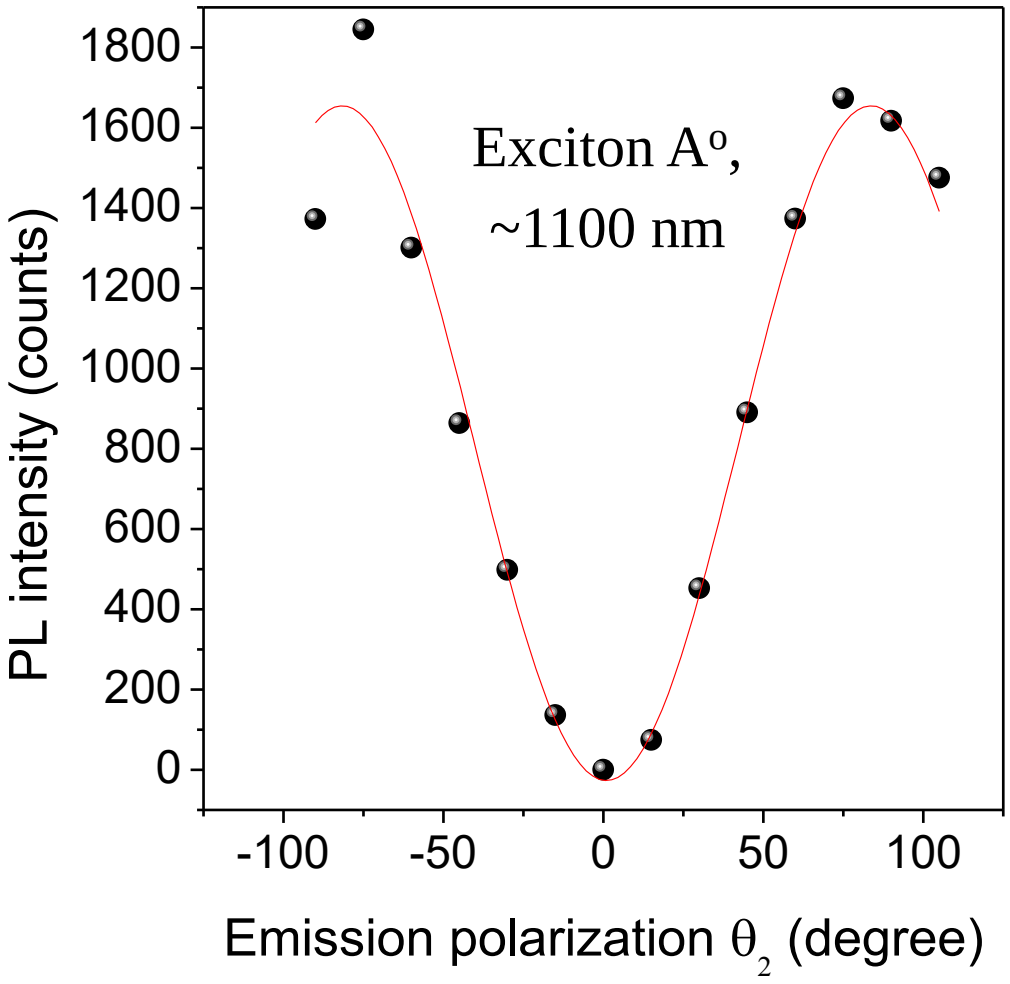


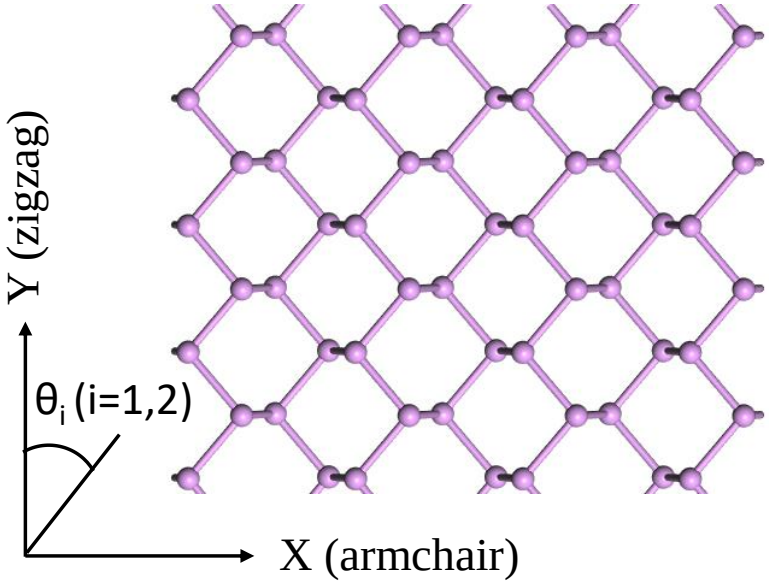


- Max. optical absorption along armchair direction
- Zero optical absorption along zigzag direction

Nat. Commun. **5** (2014).
Phys. Rev. B **89**, 235319 (2014).

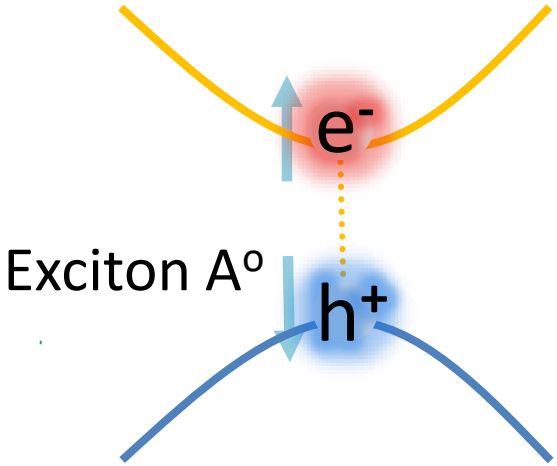
Quasi 1D Excitons in a 2D system

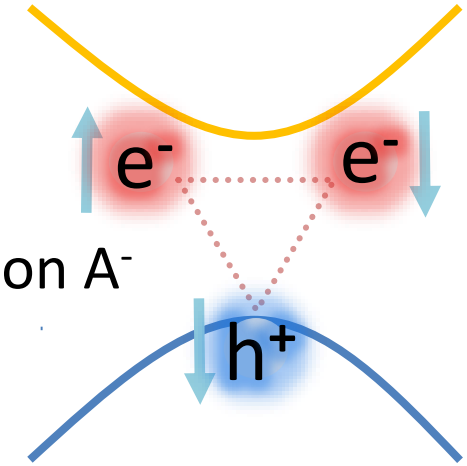


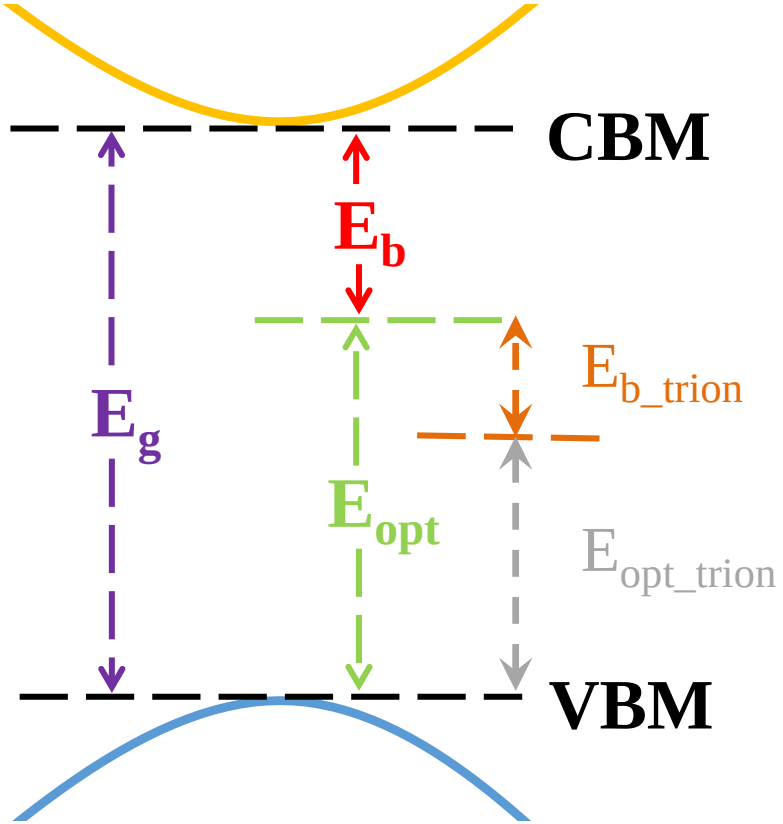


➢PL emission is polarized along the armchair direction.

Exciton and Trion

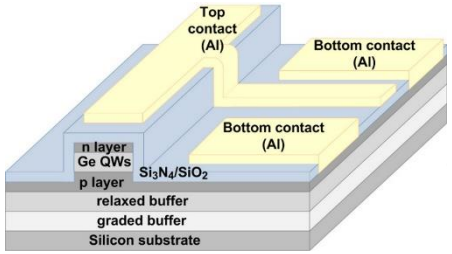






- With extra charge, non-zero spin
- Spintronics
- Tunable light sources

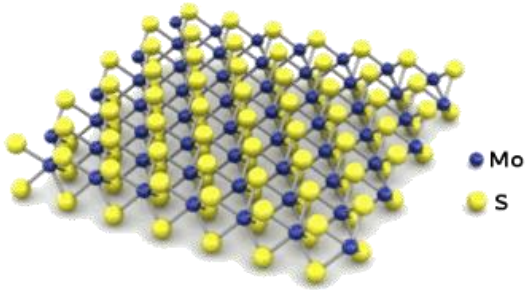
Trion Binding Energies



1-5 meV

quasi-2D

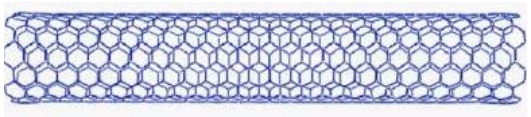
Phys. Rev. Lett. **71**, 1752 (1993).



~ 20 meV

2D

Nat. Mater. **12**, 207 (2013).

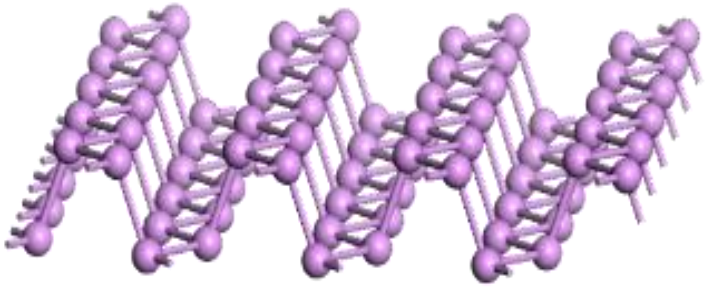


~ 200 meV

1D

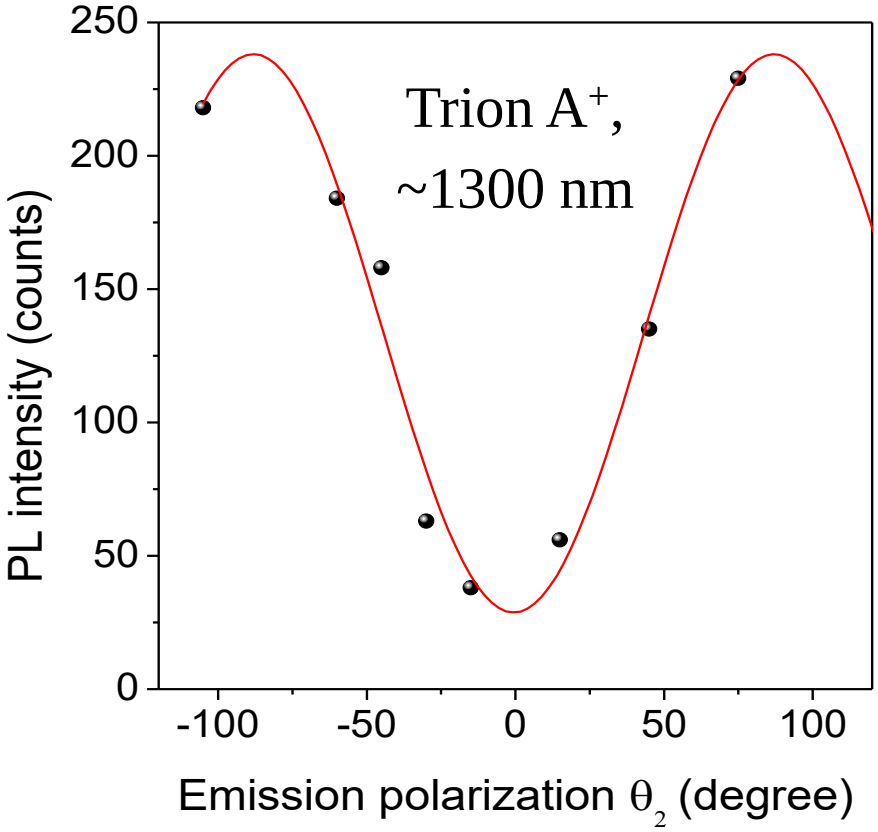
Phys. Rev. Lett. **106**, 037404 (2011)

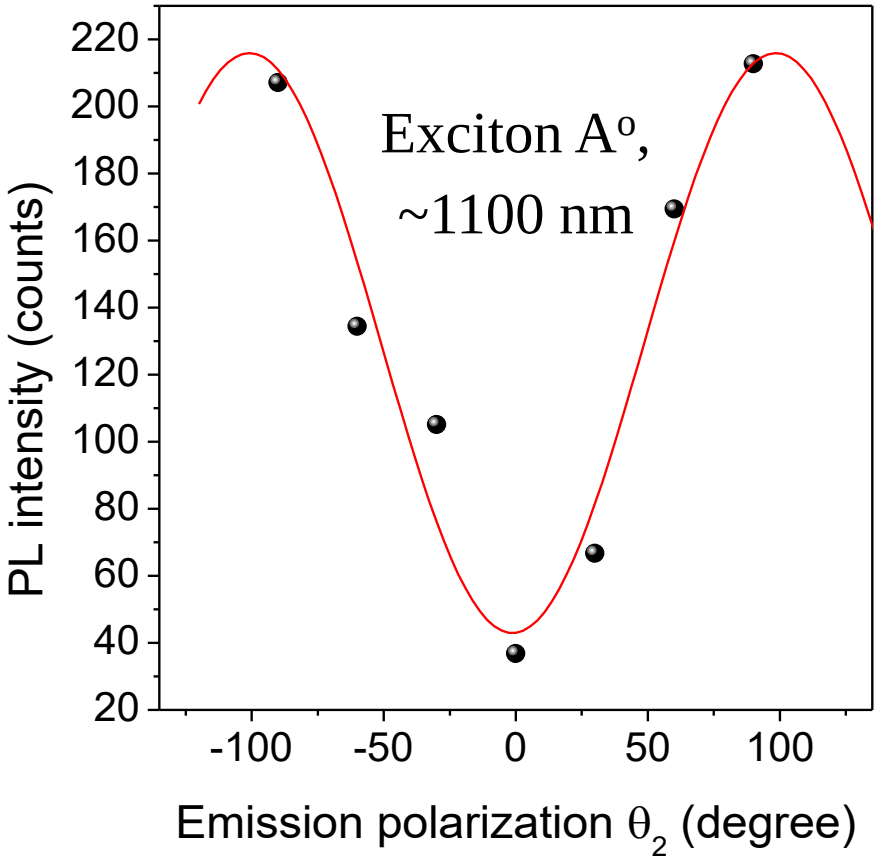
How to get high trion binding energy in a 2D system?



1D excitons in 2D system

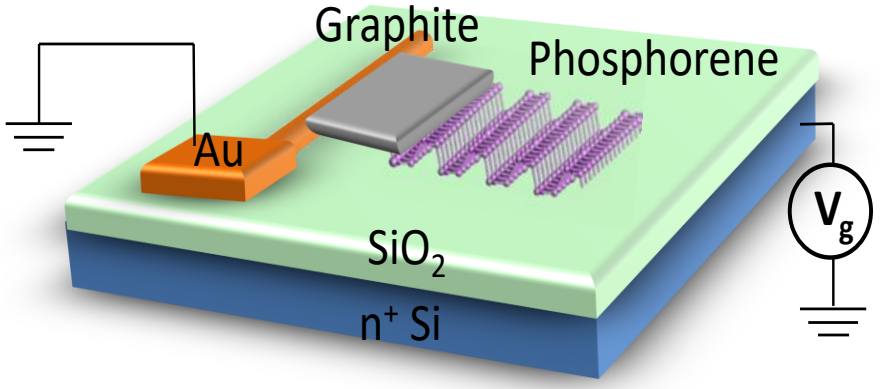
Quasi 1D Excitons/Trions



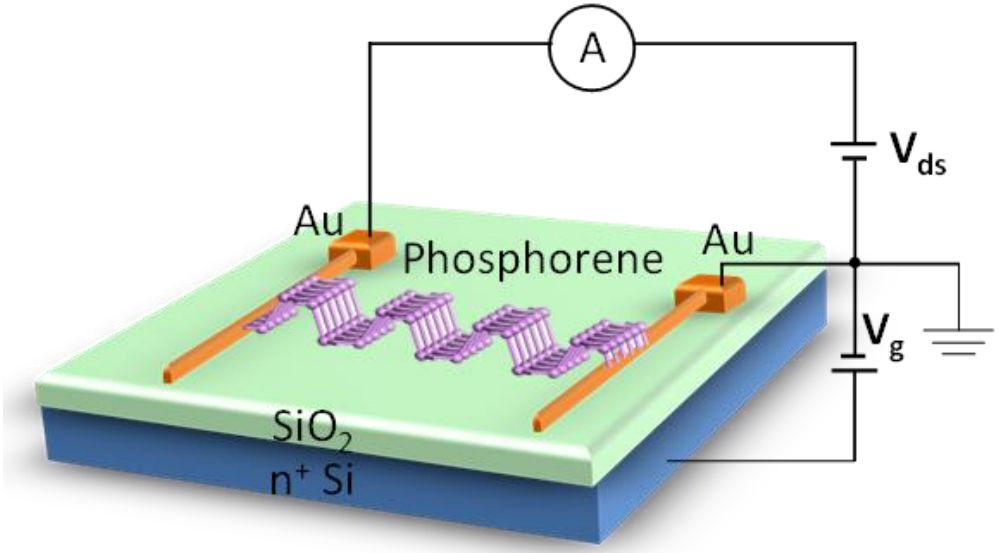


- PL emission from both excitons and trions is polarized along the armchair direction
- Quasi 1D nature of excitons/trions.

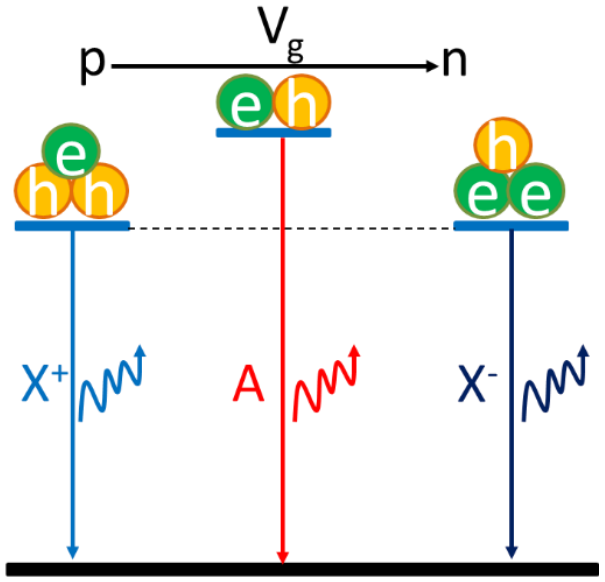
MOS device for Trion Modulation



Phosphorene MOS device



Phosphorene FET device



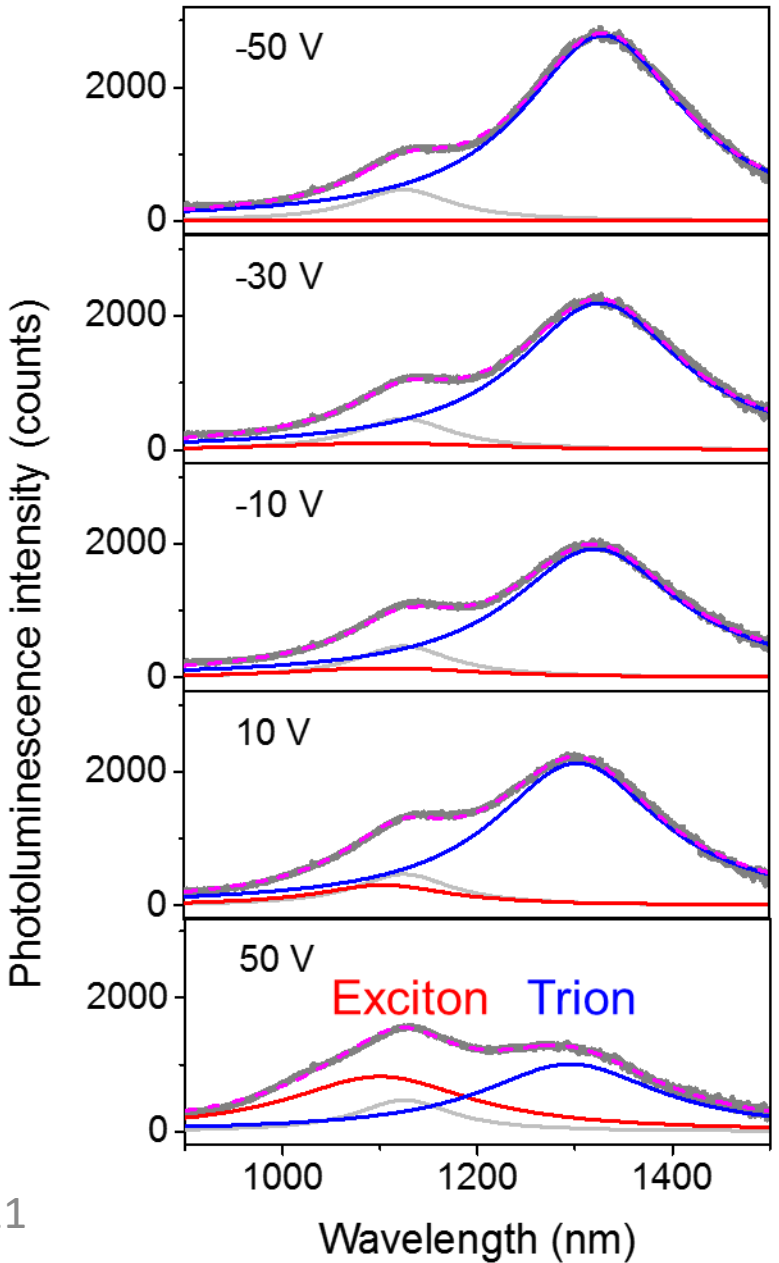
$$A + e \rightarrow X^-$$

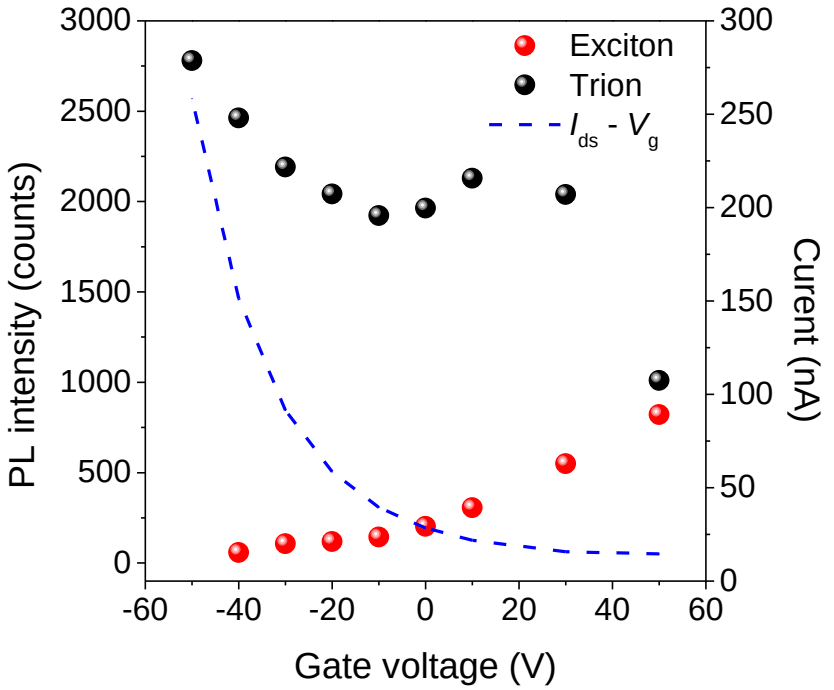
$$A + h \rightarrow X^+$$

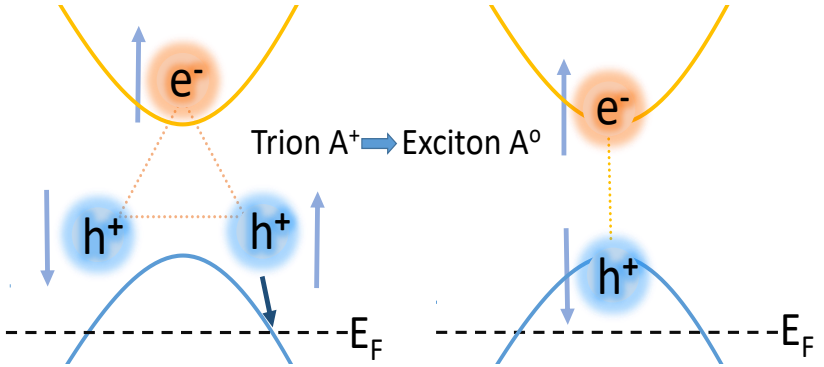
Back gate modulated PL emission

Australian National University

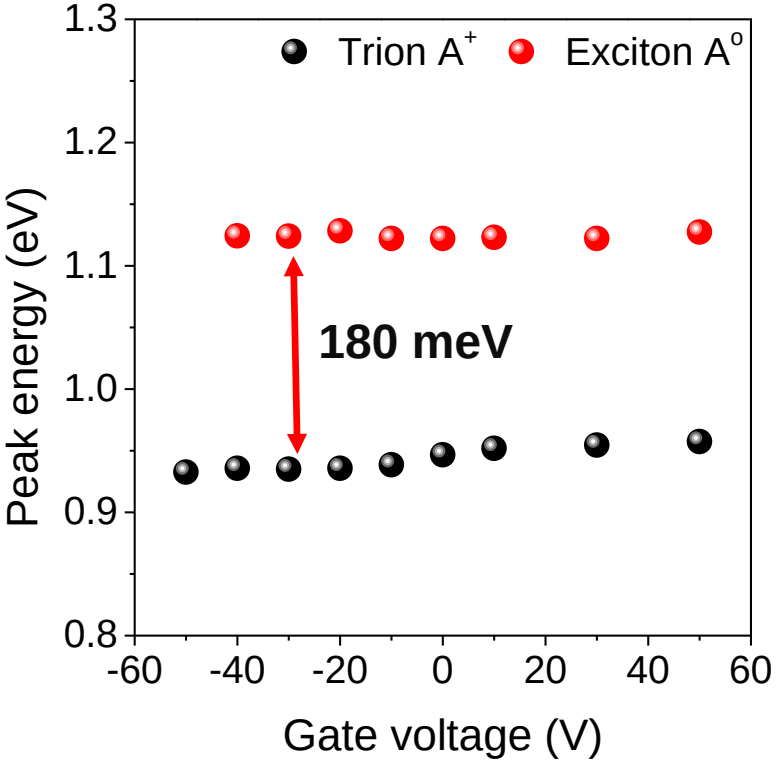
ACS Nano doi:10.1021/acsnano.5b06193 (2015)

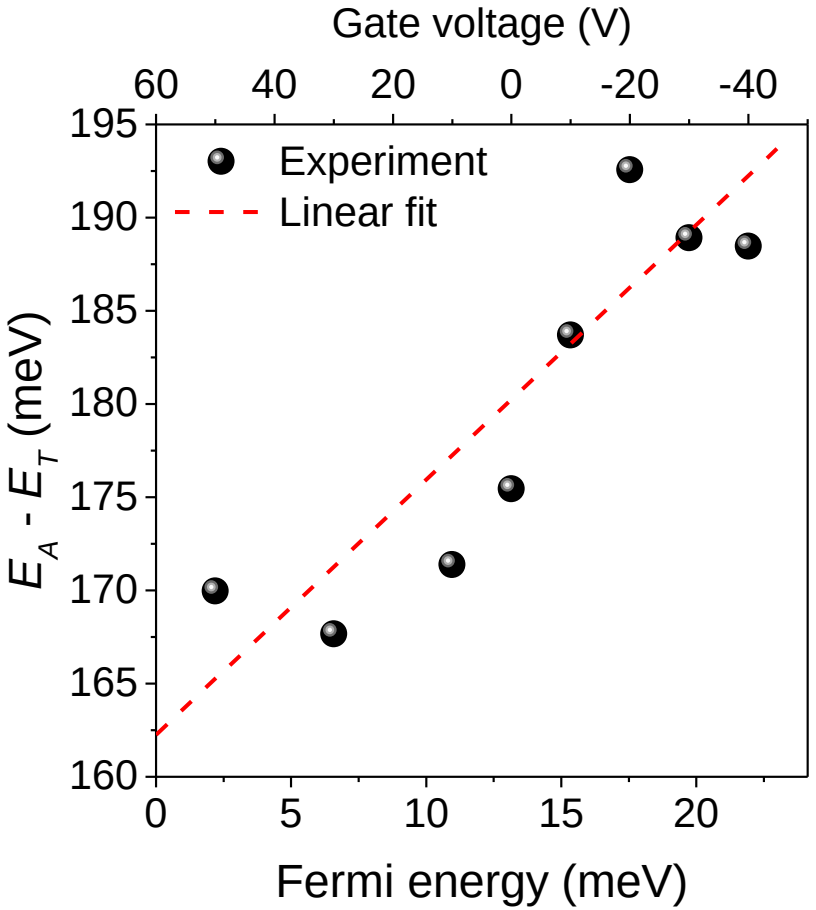






Binding energy of Trions





$ne = CV_g$ *(Nat. Commun.* ***5.*** *2014)*

Back gate capacitance (C) = 1.2x10^{-8} Fcm^{-2}

$E_F = \frac{\hbar^2 \pi n}{2 m_h e^2}$ *(Nat. Commun.* ***12.*** *2014)*

$$m_h = \sqrt{m_x^* m_y^*} = 0.41 m_0$$

m_0 is the mass of free electron.

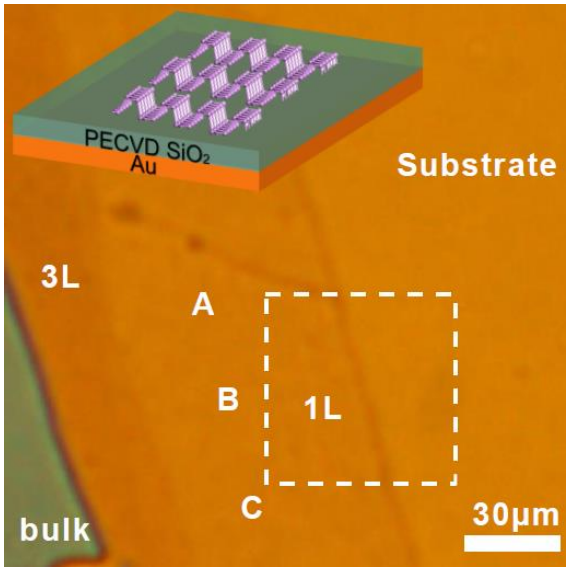
Quasi 1D Excitons in Phosphorene

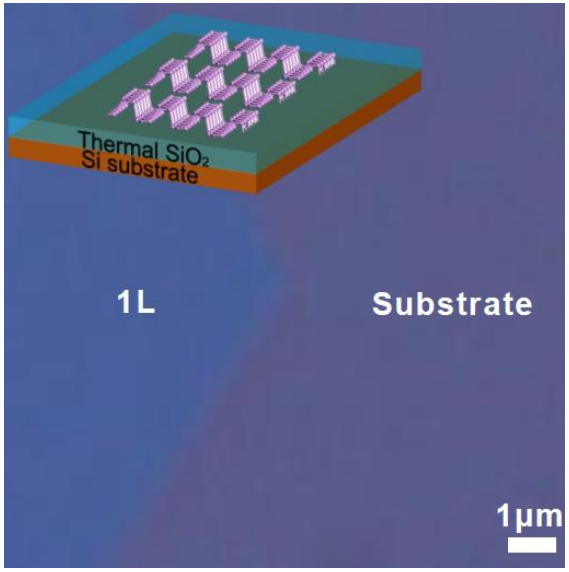
- Limited luminescence quantum yield due to quasi 1D nature of excitons.
- Quenching of mobile excitons by rapid collision with local quencher states/defects.
- This defect quenching was improved to an extent by using 1D carbon nanotubes (CNT).
- CNTs have small optical cross sectional areas.

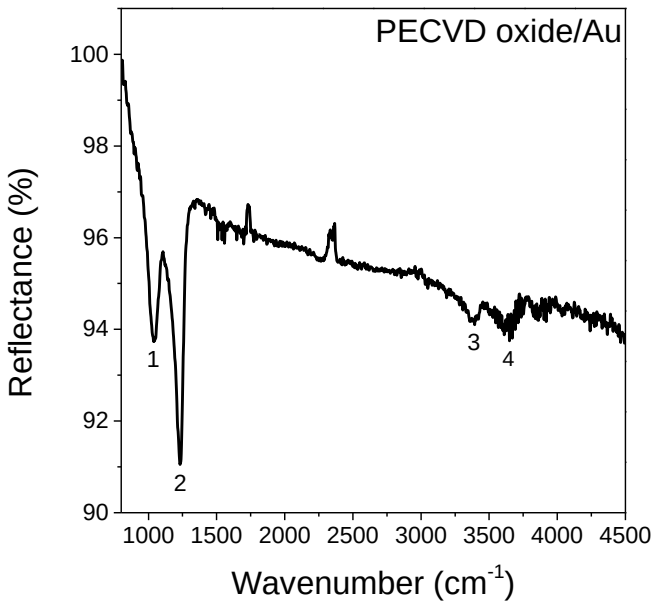
Motivation

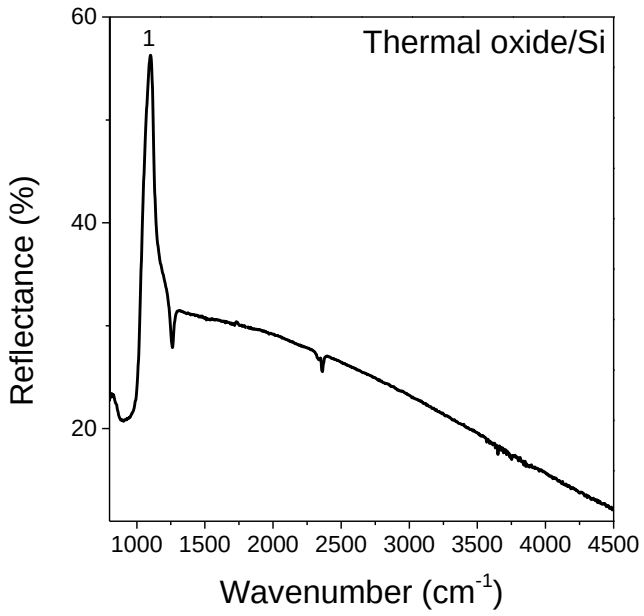
- Reverse use of local states as 0-D photoluminescence centres.
- Capture mobile excitons and convert into photons with high radiative relaxation rate.
- Embedding 0-D like localised states might enhance exciton emission.
- Possible through irradiation, oxidation and physical absorption.
- Puckered Configuration of BP might lead to extrinsic point defects including surface adatoms.

BP over PECVD oxide Substrate

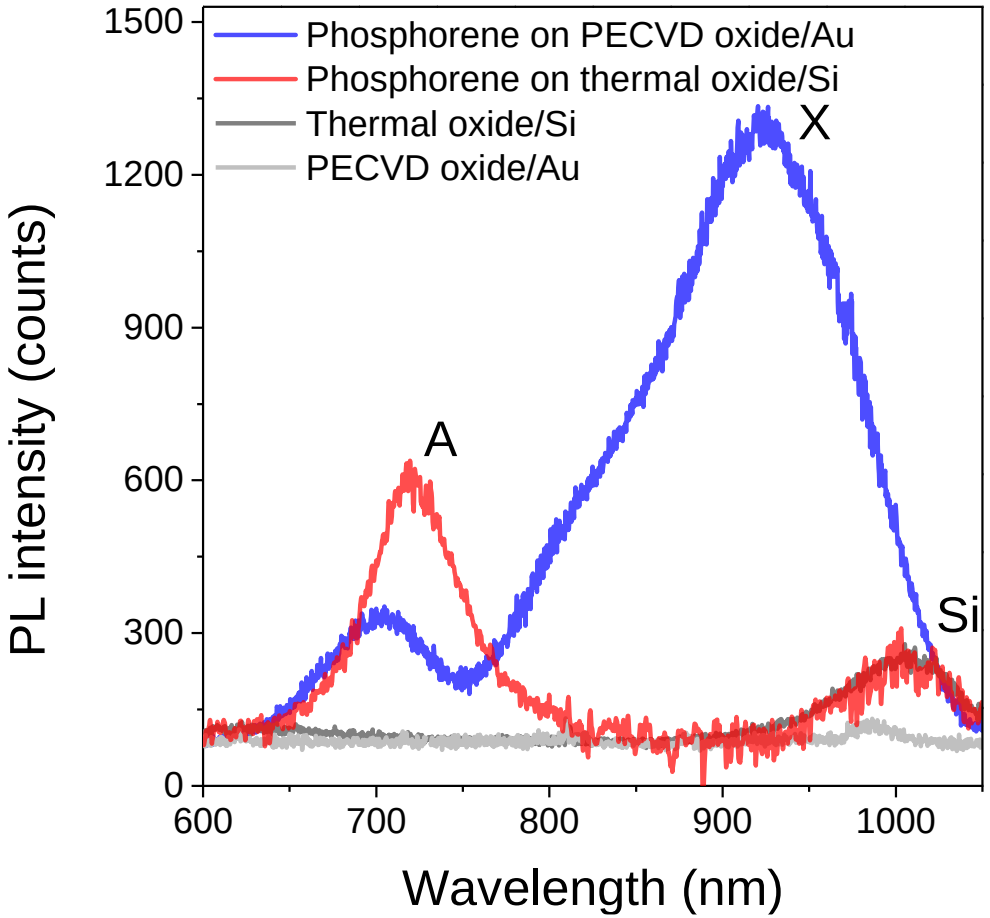


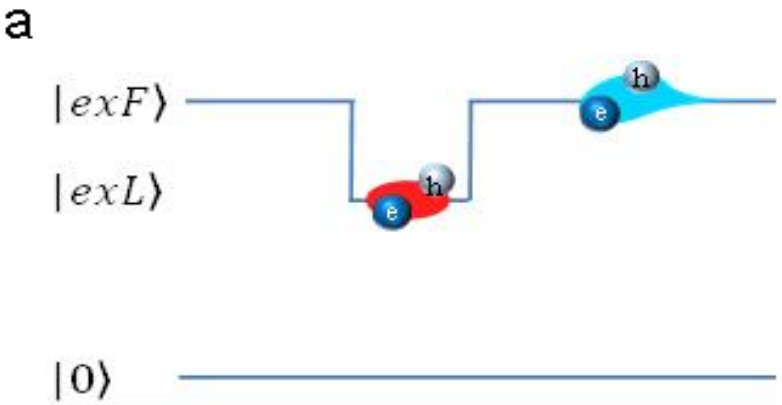


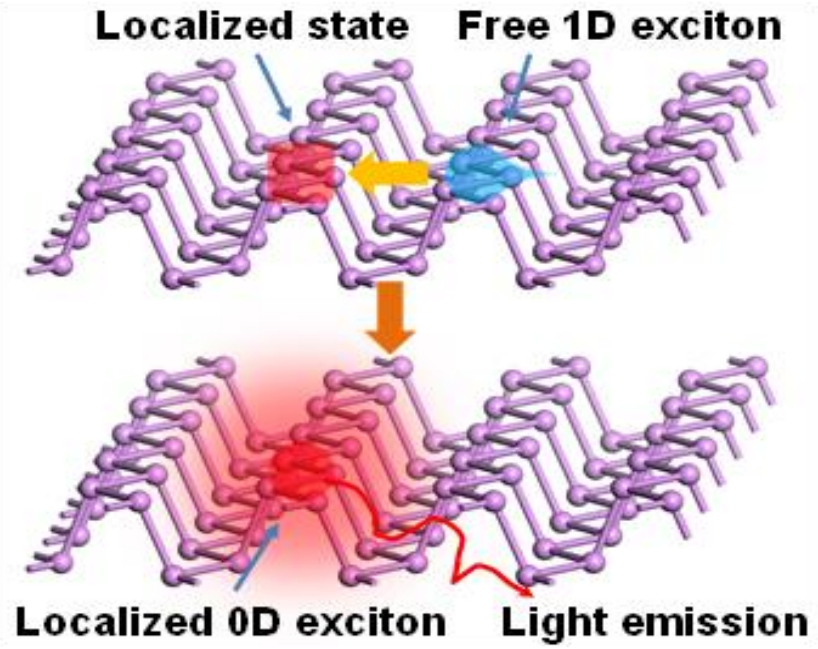




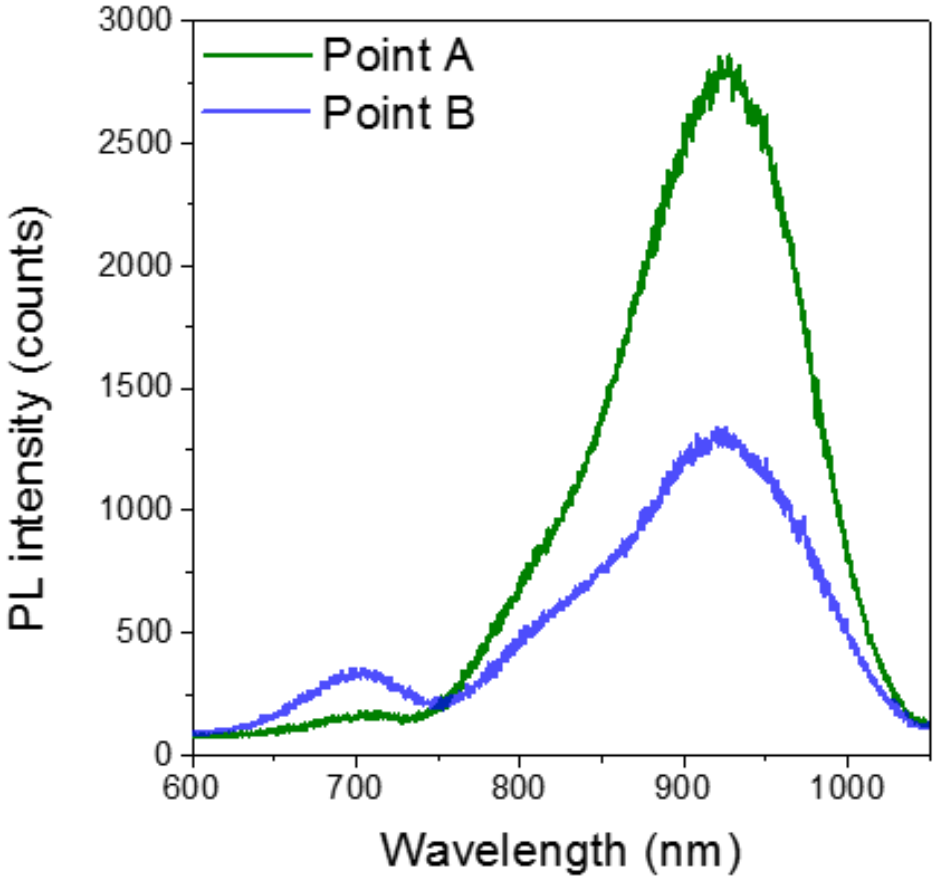
Bright 0-D Excitonic emissions

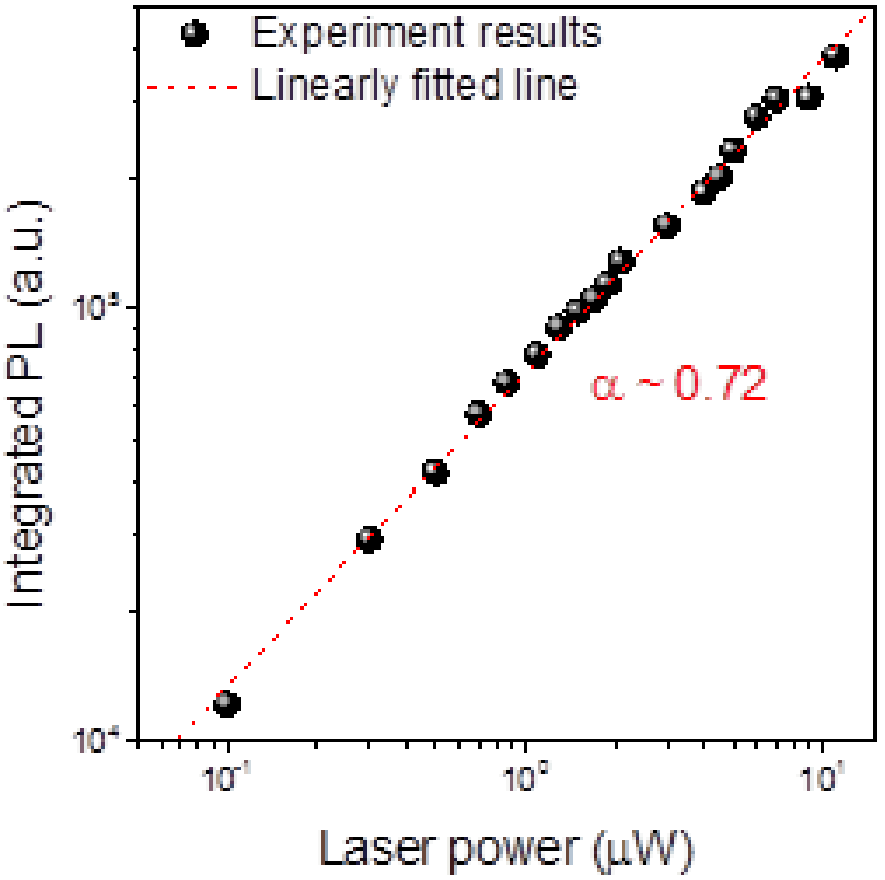






Experimental Observations

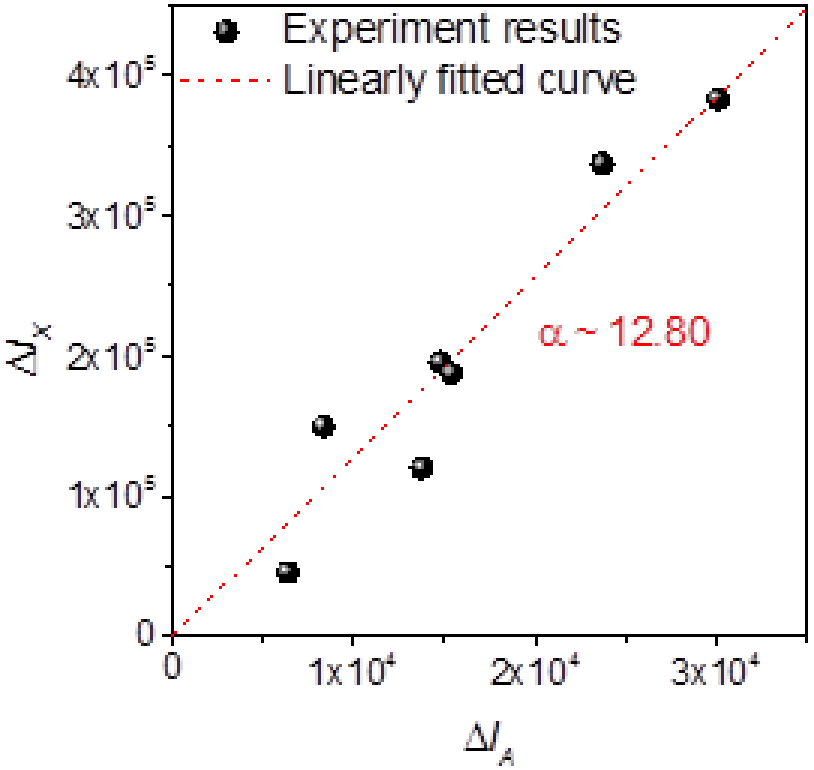




Enhanced Quantum yield

Australian National University

Adv. Mat., doi:10.1002/adma.201505998 (2016).



$$\frac{\Delta I_X}{\Delta I_A} \leq \frac{1}{2}\left(\frac{\eta_X}{\eta_A}\right)\left(\frac{E_X}{E_A}\right)$$

$$\frac{\eta_X}{\eta_A} \geq \approx 33.6$$

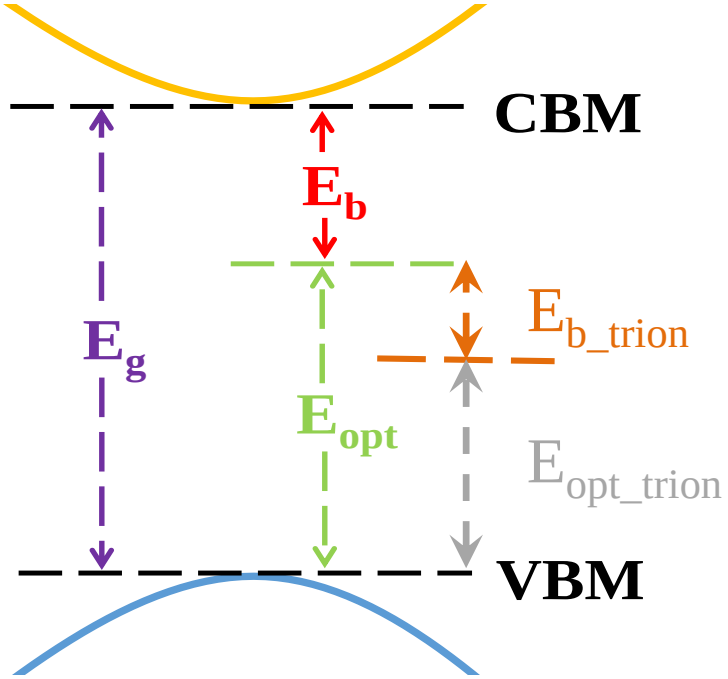
- 2D-1D-0D Hybrid system
- Phosphorene: 0D excitons at RT

while TMDs: 0D excitons at cryogenic T.

Conclusion

- High Binding energy of trions (≈162 meV) can be observed in 2D, few layer phosphorene , only shown earlier in 1D CNTs.

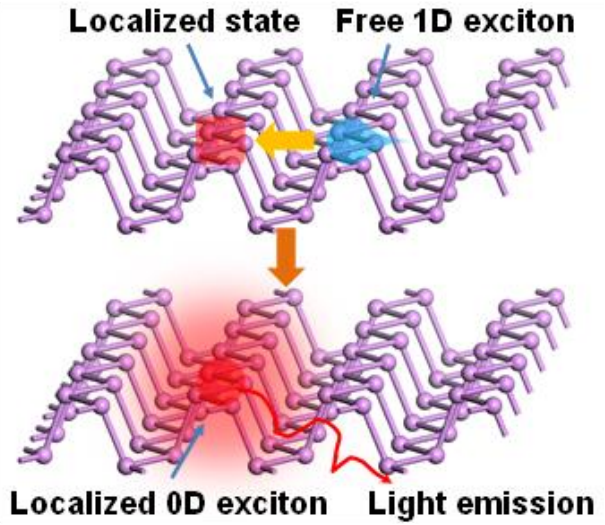
- This is possible due to quasi 1D nature of excitons/trions in phosphorene along the armchair direction of crystal.



Conclusion

- Quantum yield of excitons (Quasi 0-D) can be enhanced significantly by inducing localised oxygen defects.

- PECVD substrates can be used for such defects induction as puckered structure of phosphorene helps inducing surface defects.



Acknowledgements

A/Prof. Yuerui (Larry) Lu
Prof. Daniel MacDonald
Prof. Chennupati Jagadish AC

ANU VC HDR Travel Grant
Graphene 2017 Travel Grant
Australian Govt. IPRS Scholarship
ANU HDR Scholarship

All NEMS Lab Members

Thank You!