Enhanced photodetection with BP – organic hybrid

12th December 2022

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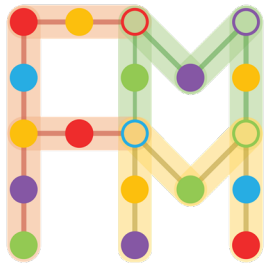
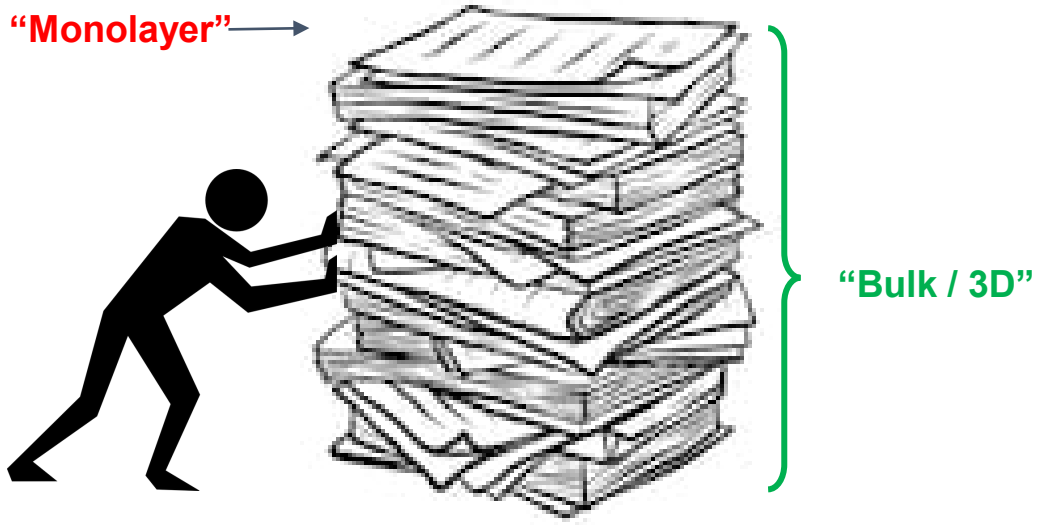
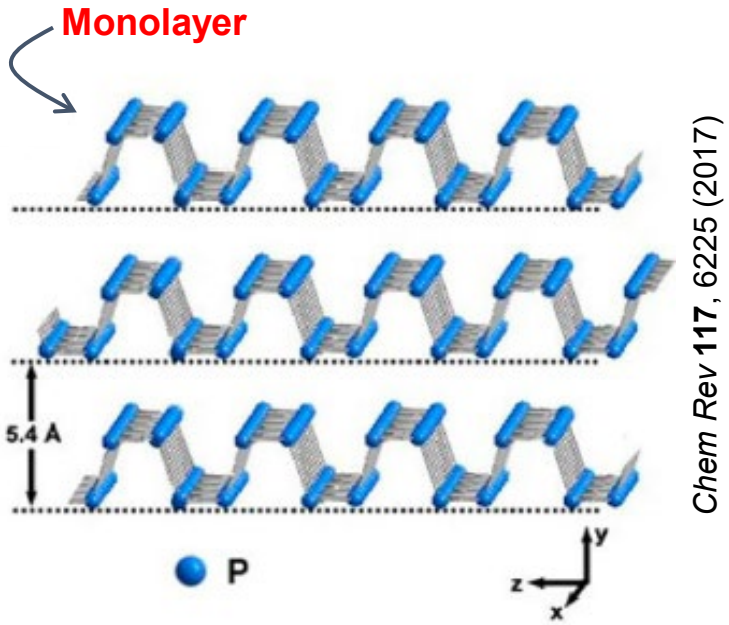


Two-dimensional (2D) Materials

- Layered materials, weak interlayer (van der Waals) forces
- Single layer of atoms / molecules



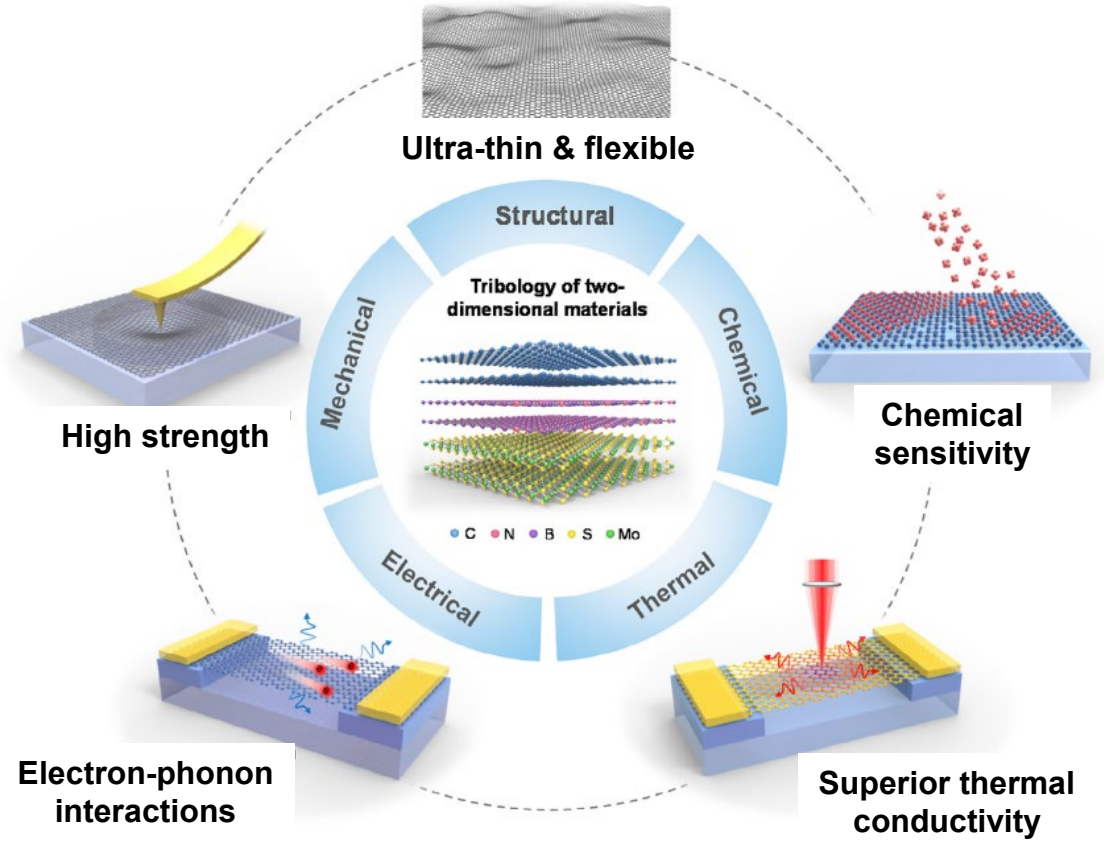


Chem Rev **117**, 6225 (2017)

Black Phosphorus (BP)

Two-dimensional (2D) Materials

- Exceptional physical, chemical, electronic properties
- Increased carrier mobility due to quantum confinement
- Applications
  - Optoelectronics, gas sensors, piezoeletronics, biosensors etc

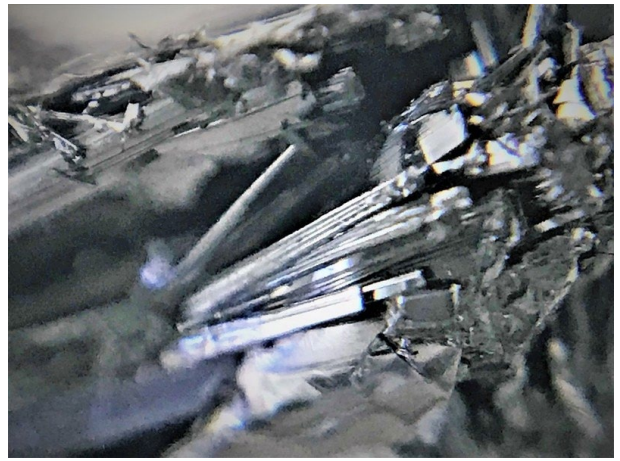


Materials Today **26**, 67 (2019)

Black phosphorus (BP)

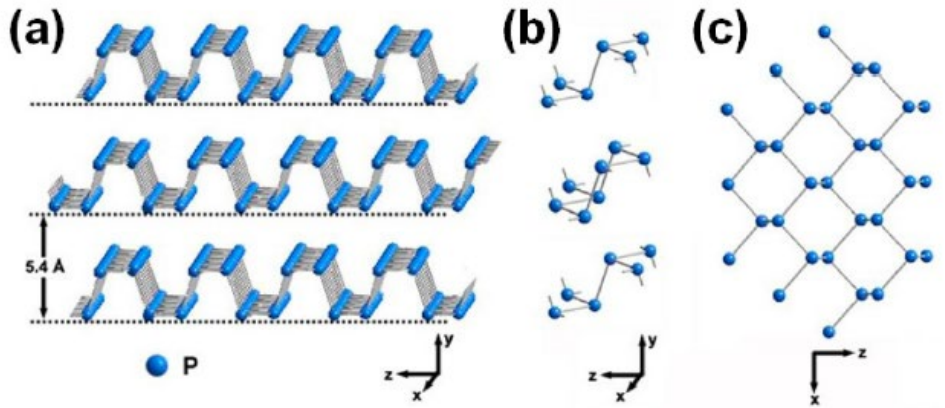
- Thickness dependent direct band-gap
  - 0.3 eV (bulk) → 2.0 eV (monolayer)
- High carrier mobility (> 10^3 cm^2 V^{-1} s^{-1})
- In-plane anisotropy
  - Electrical and optical
- Applications:
  - Optoelectronics, Humidity sensors
- Disadvantage → degrades at ambient conditions (passivation techniques available)

Bulk BP



2D Semiconductors, 2020

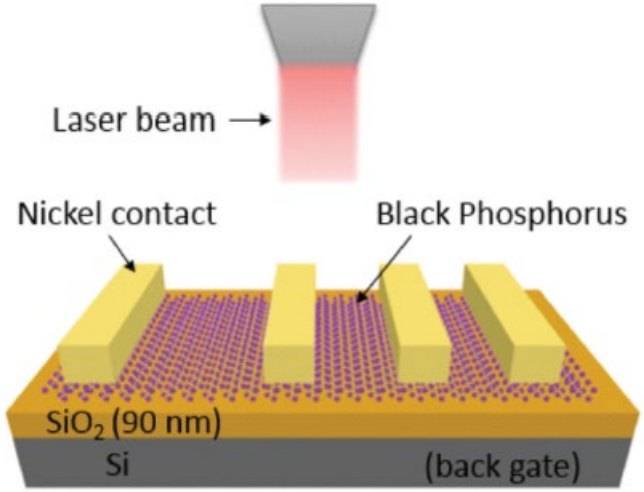
Side view **Top view**



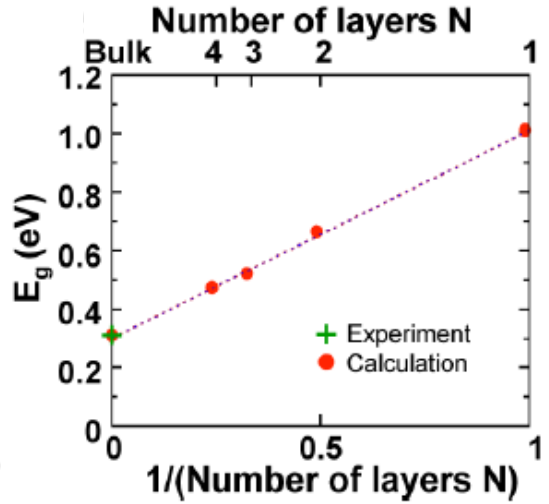
Chem Rev **117**, 6225 (2017)

Multilayer BP Photodetectors

- UV – visible or mid-IR photo absorption
  - 280 nm – 600 nm (UV-Vis), ~3 μm (mid-IR)
- Requires gating (external electric field) to achieve broadband photodetection > 600 nm
  - High power consumption
  - Non-gated devices → responsivity ~ 2 – 5 mA W^{-1} (visible: 532 nm – 640 nm)
- Thickness tuneable bandgap to manipulate optoelectronic properties
  - Difficulties in controlling thickness through mechanical and liquid exfoliation without introducing defects



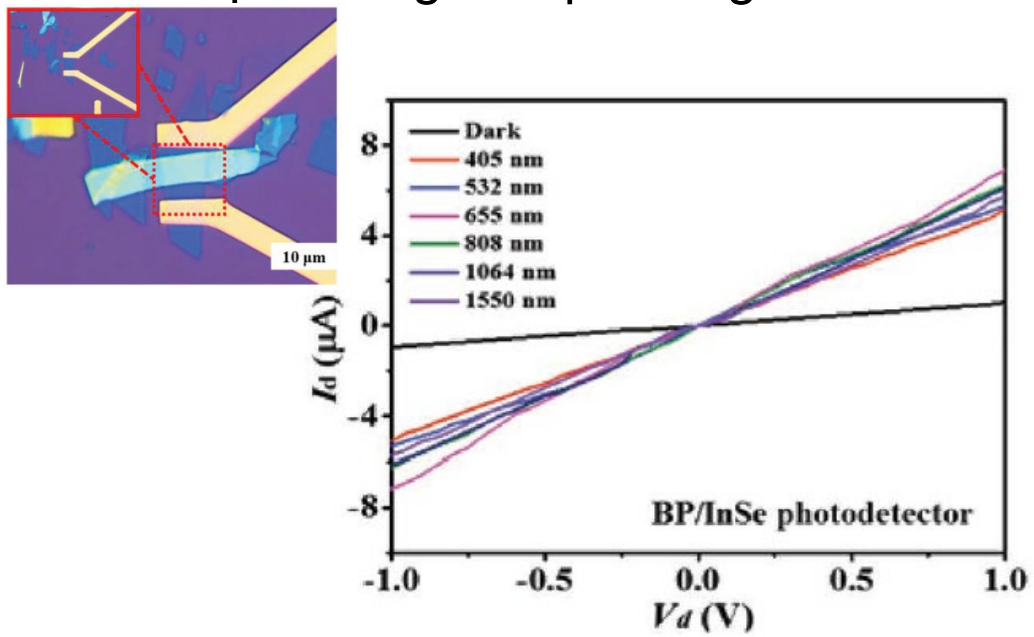
Advanced Materials **28**, 3481 (2016)



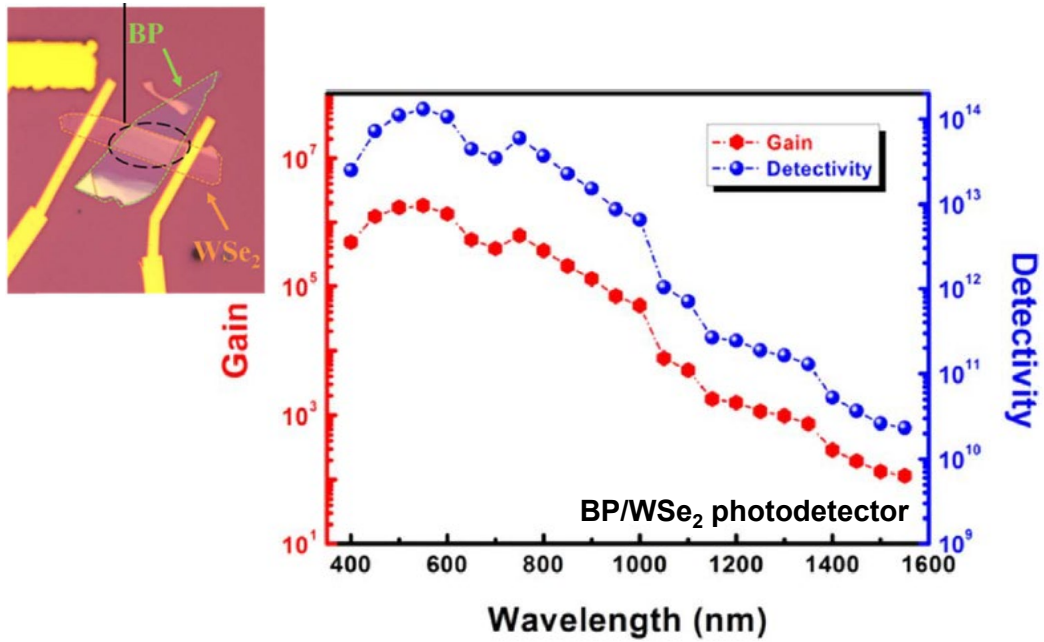
ACS Nano **8**, 4033 (2014)

Tuning BP Characteristics (Hybridization)

- Achieving broadband (UV – IR) photodetection with hybridization
  - Heterostructuring with other 2D materials
    - Accurate positioning needed and not scalable
  - Requires higher operating bias to overcome barrier



Advanced Optical Materials **7**, (2019)

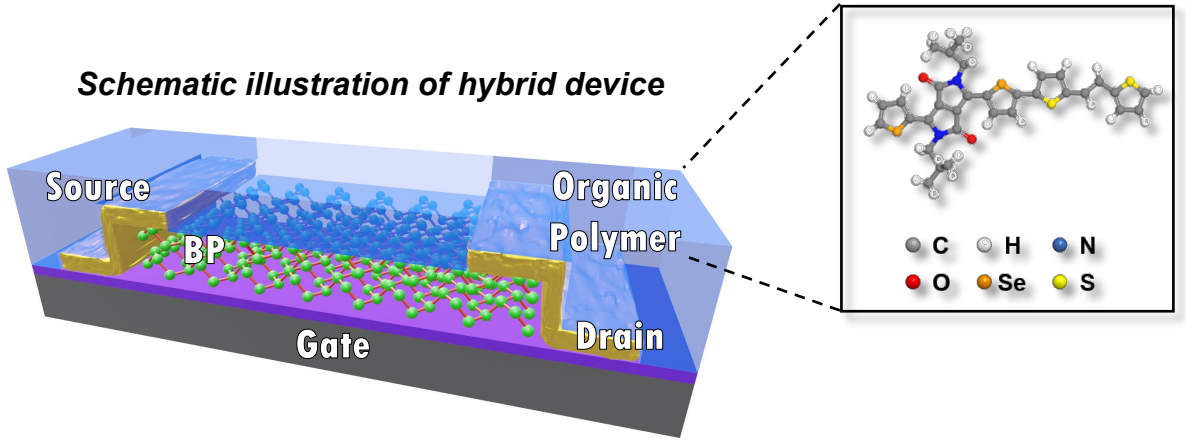


Nano Energy **37**, (2017)

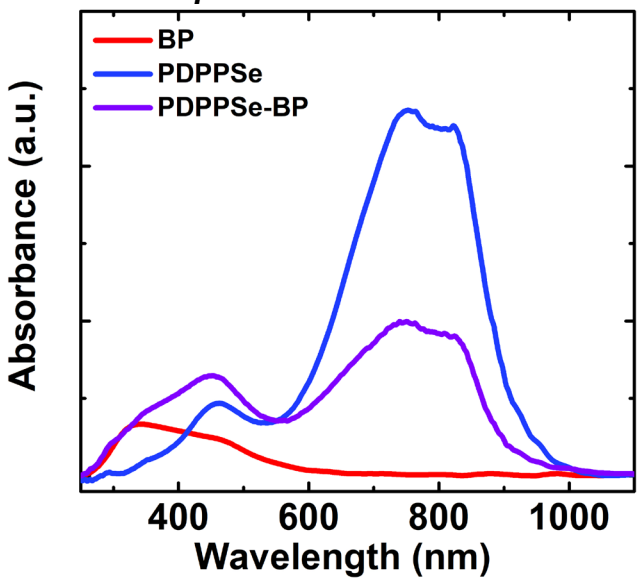
BP – Organic Hybrid

- DPP semiconducting polymer
  - High optical absorption in Visible-IR
  - Low band-gap
- Inorganic (BP) + organic (DPP) semiconductor hybrid
  - Simple scalable hybridization process
  - Combined optical absorbance of both materials
    - UV to near-IR

Schematic illustration of hybrid device



Optical absorbance curve

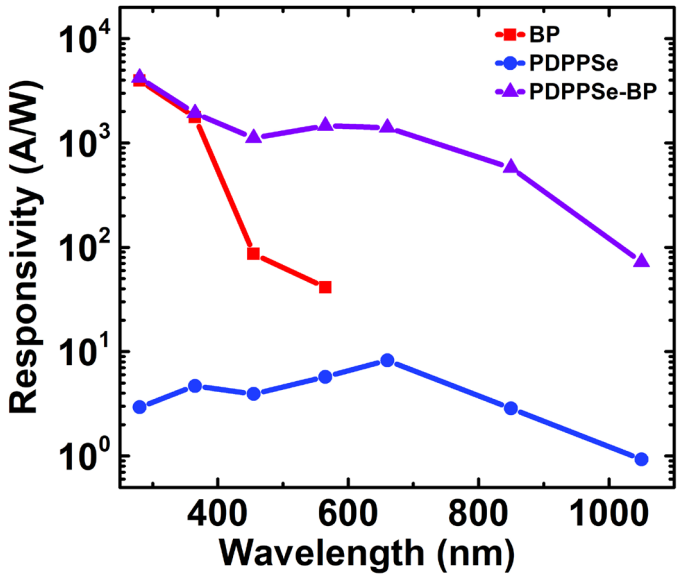


DPP: Diketopyrrolopyrole

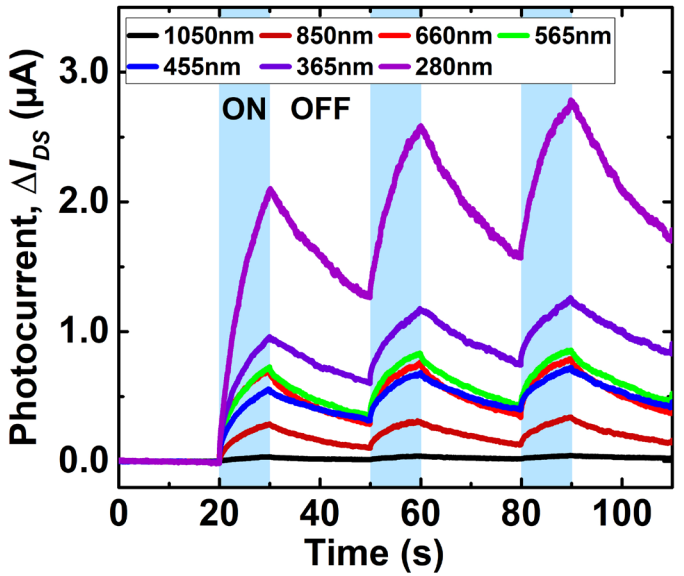
BP – Organic Hybrid

- Substantial enhancement in photoresponsivity, especially in Vis – near IR
  - No gating required (typically requires V_G of > 15 V in literature)
  - Low operation voltage (V_{DS}) of 50 mV
  - Responsivities up to 4 × 10^3 A W^{-1} without external gating

Photoresponsivities



Transient photoresponse of hybrid

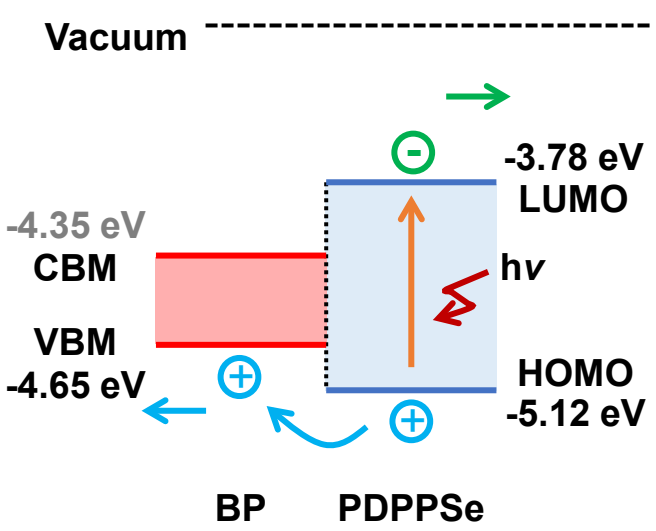


M.X. Low, S. Kuriakose, Q. Liu, P. Sonar, S. Walia, et. al., Advanced photonics research, 2021, 2 (11), 2100150

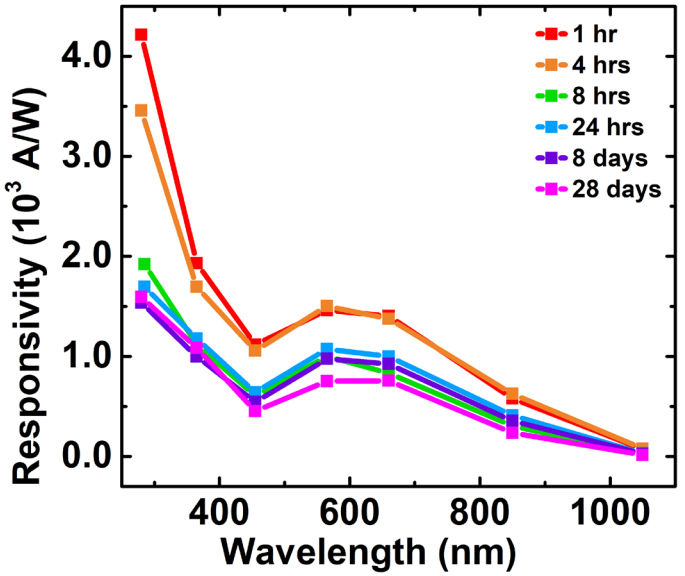
BP – Organic Hybrid

- Type-I band alignment
  - Allows photogenerated carriers in polymer to flow into high mobility BP
- Organic polymer also serves as passivation layer
  - Remains stable > 28 days in ambient (BP typically degrades within 7 days)

Band alignment structure



BP – organic hybrid device after 28 days



M.X. Low, S. Kuriakose, Q. Liu, P. Sonar, S. Walia, et. al., Advanced photonics research, 2021, 2 (11), 2100150

BP – Organic Hybrid (Comparison)

Material	Substrate	Spectral Range (nm)	R (A/W)	λ_{LED} (nm)	P_{LED} (mW/cm^2)	Testing Condition	V_{DS} (V)	V_G (V)	Ref
13 nm BP + PDPPSe	SiO_2/Si	280 – 1050	72.2 4.22×10^3	1050 280	3	Ambient	0.05	0	This work
7 nm BP + WSe_2	SiO_2/Si	400 – 1550	1×10^3	637	1	Ambient	0.5	0	12
16 nm BP + InSe	SiO_2/Si	405 – 1550	53.7	655	50	Ambient	1.0	-20	11
8 nm BP	SiO_2/Si	400 – 940	0.0048	640	16	Vacuum	0.2	0	10
120 nm BP	SiO_2/Si	532 – 1550	0.0005 0.002	1550 532	3.1×10^6	-	0	0	27
28 nm BP	SiO_2/Si	1550	1.55	1550	9270	Ambient (h-BN)	0.5	0	28
4.5 nm BP	SiO_2/Si	310 – 950	1.82 9×10^4	950 310	2 - 31	Vacuum	0.1	-80	4
8 nm BP	SiO_2/Si	400 – 900	1×10^3 5.6×10^4	900 633	0.5	Vacuum	-1.0	-15	9
7 nm BP	SiO_2/Si	532 – 940	0.003 0.028	940 532	$0.26 – 3.03 \times 10^{-3}$	Vacuum	0	7 – 12	29
30 nm BP	SiO_2/Si	570 – 1700	5	570	1	Ambient (Al_2O_3)	0.05	-20	30
10 nm BP	PI/PET	830	53	830	16.5	Ambient (Al_2O_3)	0.3	-4	31

Summary

- Multilayer BP – organic hybrid broadband photodetectors
  - Simple hybridization process
  - Broadband spectral detection range: 280 nm (UV) to 1050 nm (near-IR)
  - High responsivities → up to 4×10^3 A W^{-1}
  - No external gating needed ($V_G = 0$)
  - Low operating voltages ($V_{DS} = 50$ mV)
  - Stable in ambient conditions > 28 days
- Applications
  - Colour imaging
  - Optical communications

Connect With Us!

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