Black phosphorus-based van der Waals heterostructures for mid-infrared optoelectronics and silicon photonics

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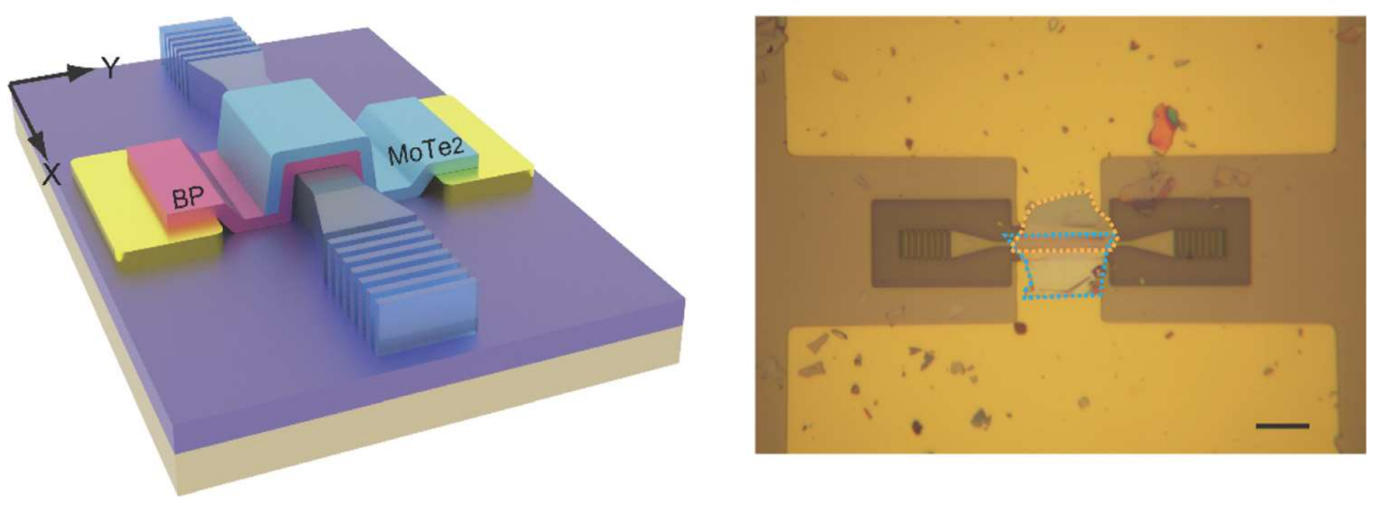
Introduction

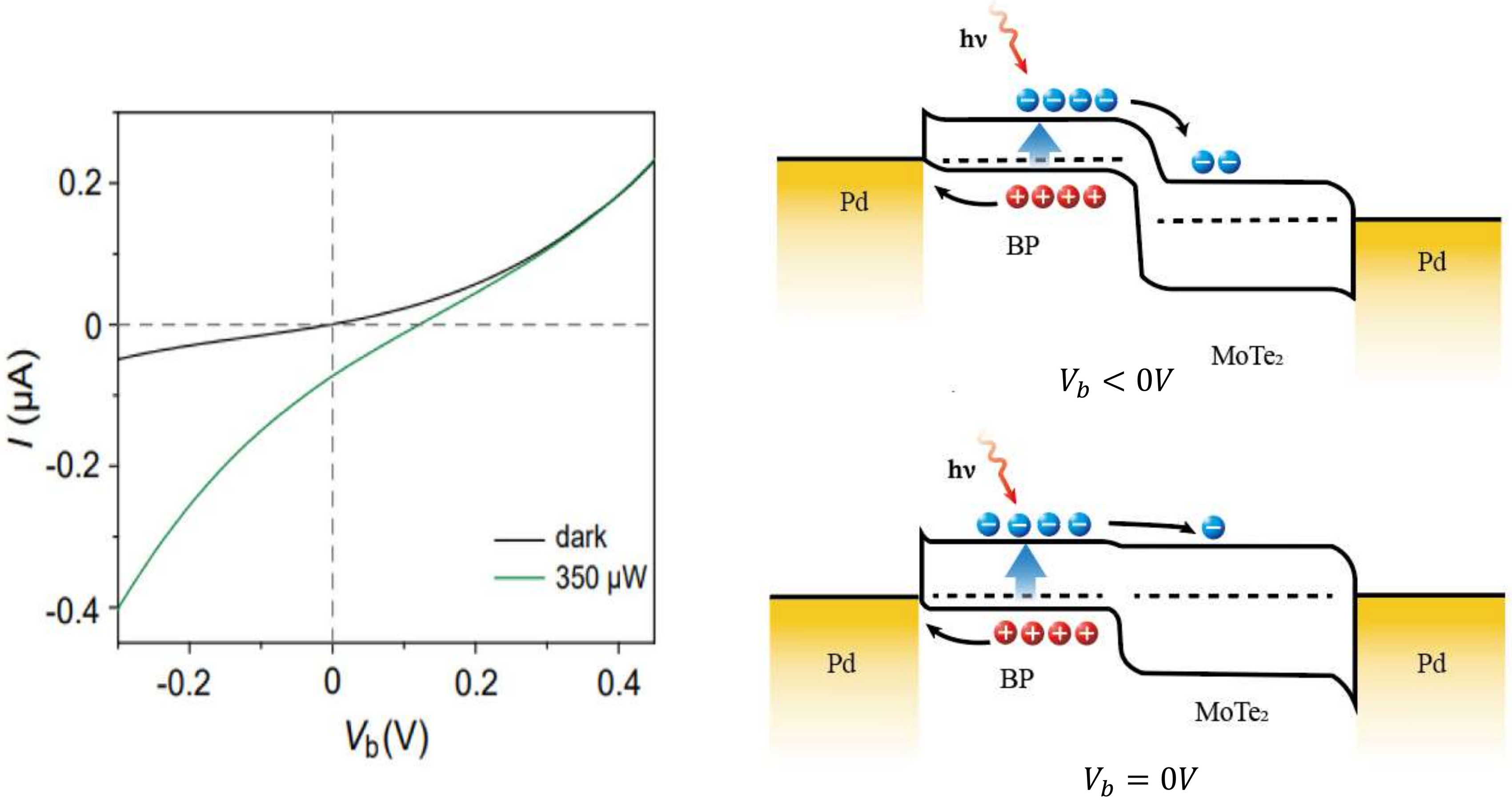
Extending the operation wavelength of silicon photonics to the mid-infrared (mid-IR) band will significantly benefit critical application areas, including health care, astronomy, and chemical sensing. However, a major hurdle for mid-IR silicon photonics has been the lack of high-performing photodetectors and light emitters. Here, we demonstrate multiple black phosphorus (BP)-based van der Waals heterostructures. We show they are useful for mid-IR optoelectronics and importantly can be integrated with silicon waveguides. These reported critical missing pieces in the silicon photonic toolbox will enable wide-spread adoption of mid-IR integrated photonic circuits.

Structure of Hybrid Mid-IR Photodetector



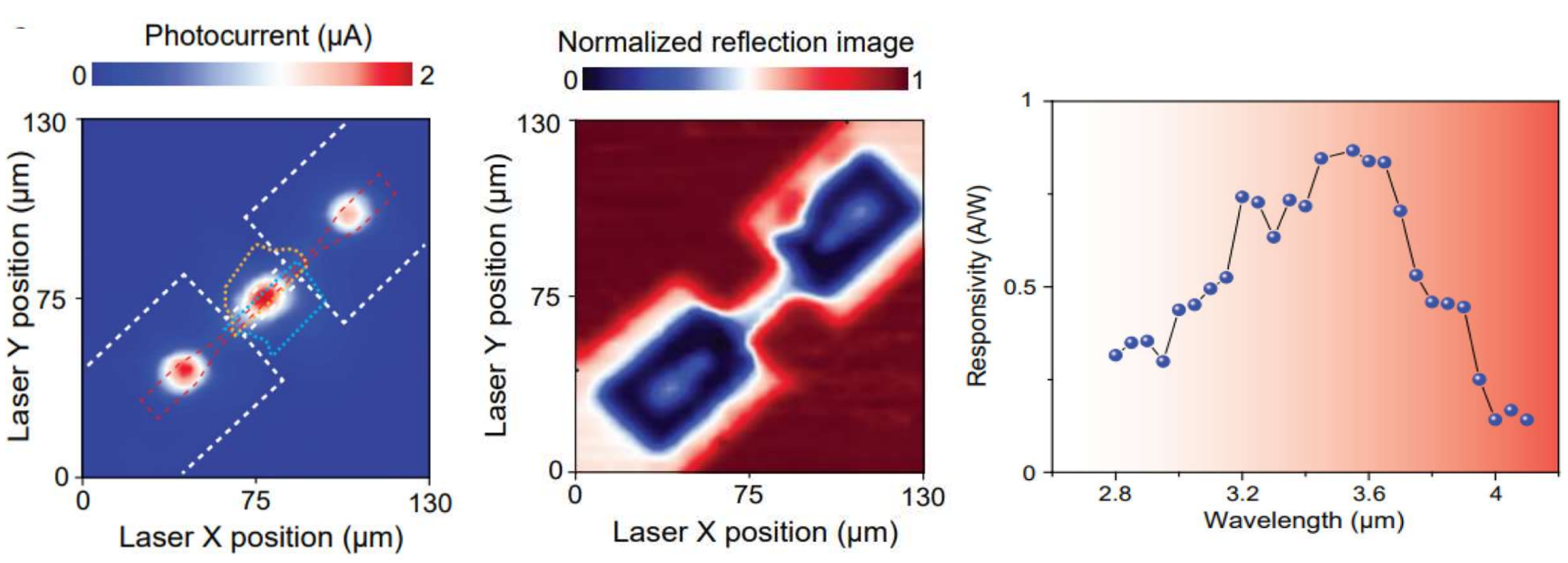
- The hybrid photodetector is composed of BP/$MoTe_2$ van der Waals heterostructure integrated with a silicon waveguide.
- 25-nm-thick BP is chosen as the light absorbing layer, and it could couple with the guided wave.
- The BP/$MoTe_2$ heterointerface forms a type II heterostructure and enables the efficient separation of electron-hole pairs in BP.

Device Operation Principle



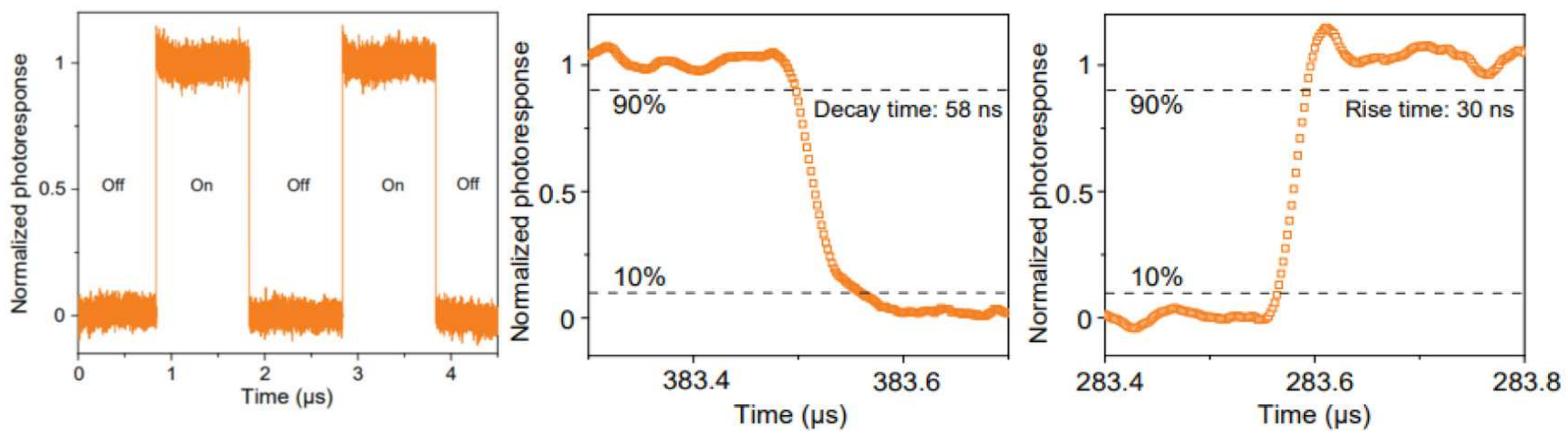
- *I-V* characteristic of the device under the dark and λ = 3.7 um illumination.
- The result shows that photocurrent increases dramatically when an external bias voltage is applied.
- Band diagrams illustrate the mechanisms of photocurrent generation.

Responsivity and Broadband Detection



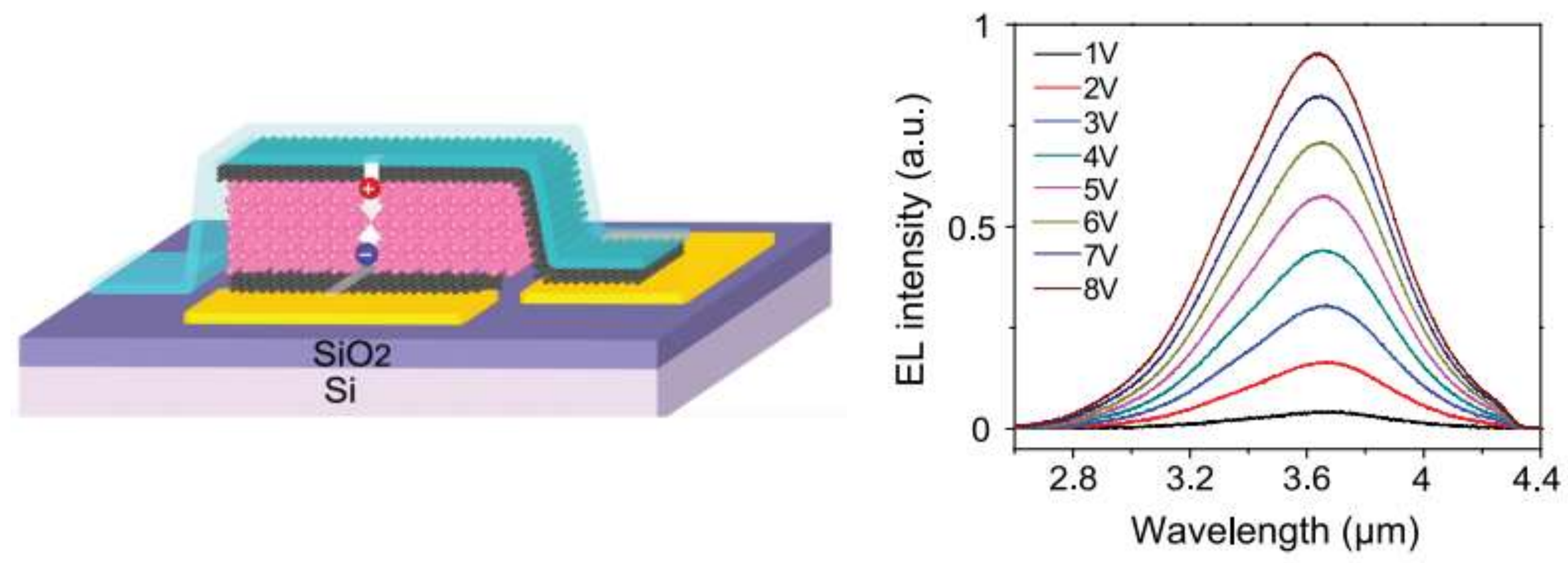
- Photocurrent can be generated at the BP/$MoTe_2$ heterostructure and two silicon grating couplers. This indicates the guided light can propagate to the heterostructure photodetector and effectively interact with the stacked BP flake through the evanescent field.
- Photoresponsivity exceeds 0.4 A/W for 3 μm to 3.9 μm, and the peak photoresponsivity reaches 0.85 A/W, suggesting our BP detector is applicable to mid-IR silicon photonics.

Fast temporal Response



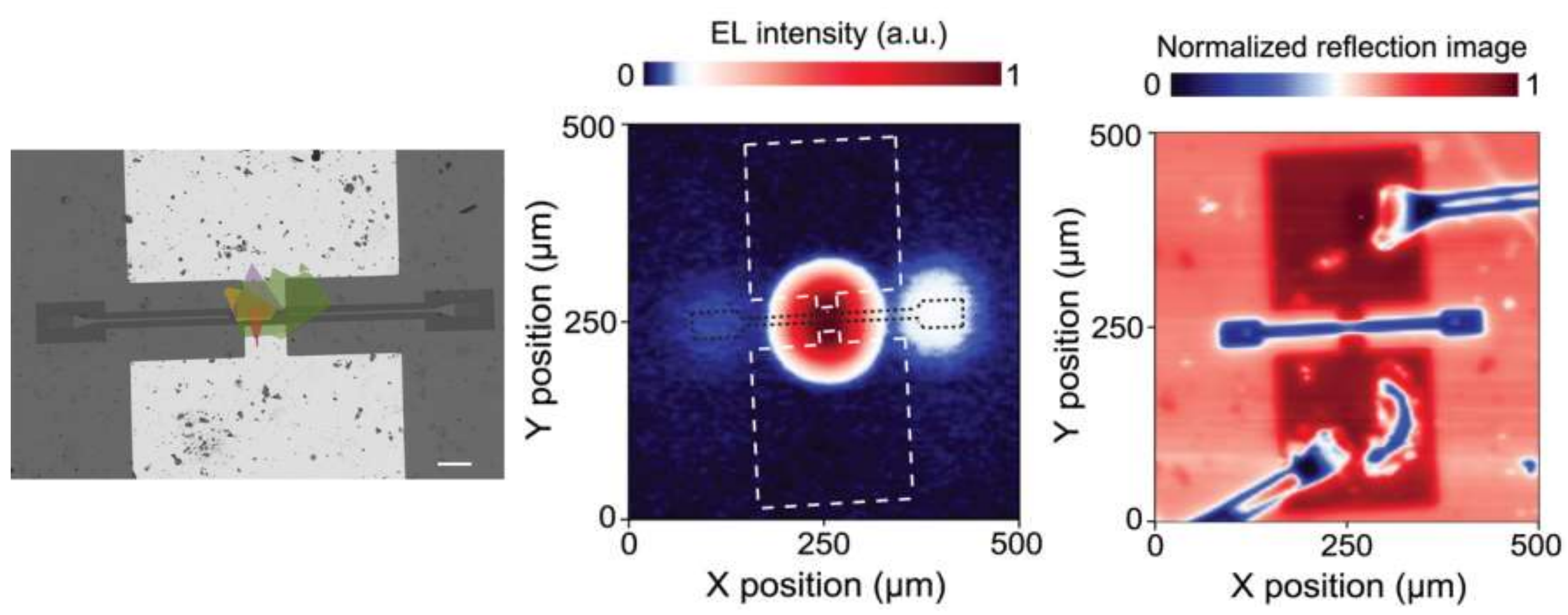
- The demonstrated hybrid detector has ultrafast rise (30 ns) and fall (58 ns) times.
- Our device exhibits a repeatable and stable mid-IR photoresponse, as the variations of currents in the light-on and dark states are both less than 10%.

Structure of Light-Emitting Diodes



- The light emitting diode is composed of the vertically stacked hBN/Gr/BP /Gr.
- When applying bias voltage across two graphene contacts, we could find mid-IR emission from BP with the peak wavelength ~3.64 um.

Waveguide-integrated BP emitter



- A false-color SEM image of the waveguide-integrated BP LED.
- Three bright spots can be observed from the scanning electroluminescence map. The central brighter spot corresponds to the position of BP LED, while the two extra emission spots are located at the grating couplers.
- The result indicates the emission of BP LED can be evanescently coupled into waveguide, and then propagate to the grating couplers, which redirect the emission out of the free space, showing its potential for on-chip mid-IR source applications.

Conclusions

In summary, we demonstrate high-performing mid-IR optoelectronics based on BP. Our developed hybrid BP photodetector exhibits broadband and ultrafast responses with high responsivity. The developed BP-based LED has peak emission wavelength of 3.64 μm, which lies within atmospheric transmission windows. Moreover, these BP heterostructures can be integrated with silicon waveguides, offering tremendous opportunities for mid-IR silicon photonics applications.

Acknowledgements & References

- This work was supported by the Ministry of Science and Technology of Taiwan under grant MOST 107-2112-M-007-002-MY3 & MOST 110-2124-M-007-002.
- Nano Lett. 2020, 20, 9, 6824–6830
- ACS Applied Materials & Interfaces (Accepted)

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