Organic photosensors for detection of VUV scintillation light

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Motivation

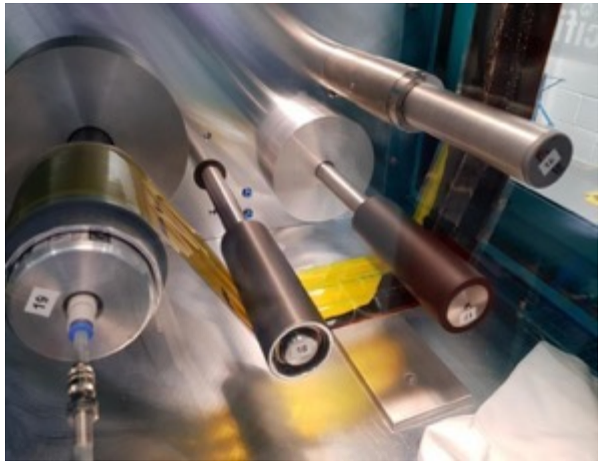
- Light collection for next-generation noble element detectors
  - Push for larger detector sizes means more areal coverage needed.
  - Need large areal coverage to up ~1000 m^2
  - Ideally, direct VUV sensitive
  - Simultaneous collection of light and charge helpful for pixelated TPC readout schemes

- *Need:*
  - Large-area ***low-cost*** VUV photosensors

- VUV detectors approaches
  - PMTs with WLS, VUV SiPMs, light traps, GaN, etc…
  - Amorphous selenium (See talk by Jonathan Assadi)
  - *Organic semiconductors* (This talk!)

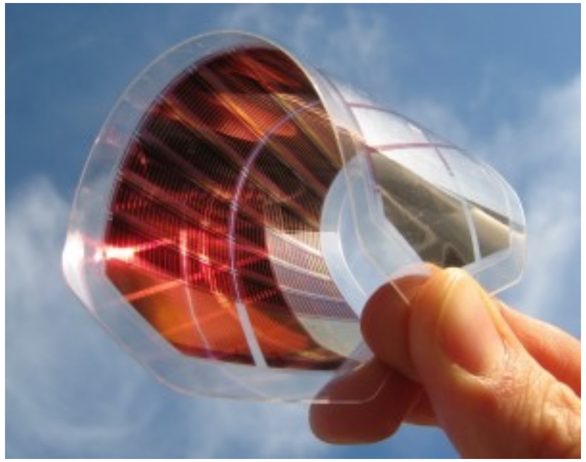
Collaborators:
- Sabrina Cheng (ORNL),
- Kate Hausladen (ORNL),
- Austin McDonald (UTA),
- Jonathan Asaadi (UTA)

Organic semiconductors for (VUV) photon detection?



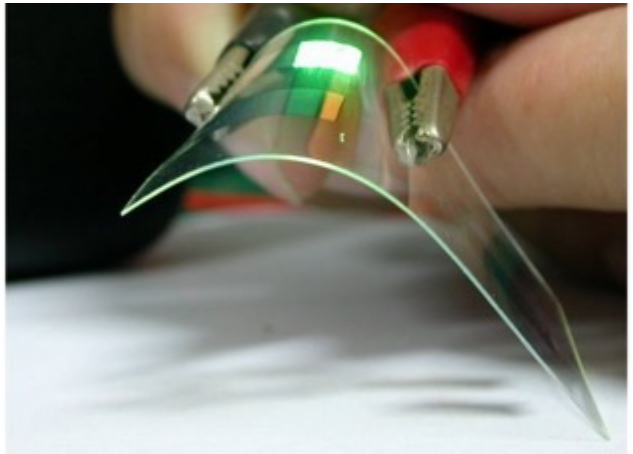
https://www.theengineer.co.uk/printed-perovskite-solar-cells/

Additive manufacturing



https://3dprint.com/1666/scientists-3d-print-new-solar-panels-which-work-best-when-cloudy/

Solar energy



https://www.evolving-science.com/matter-energy-materials/powering-future-one-step-closer-organic-electronics-our-homes-00165

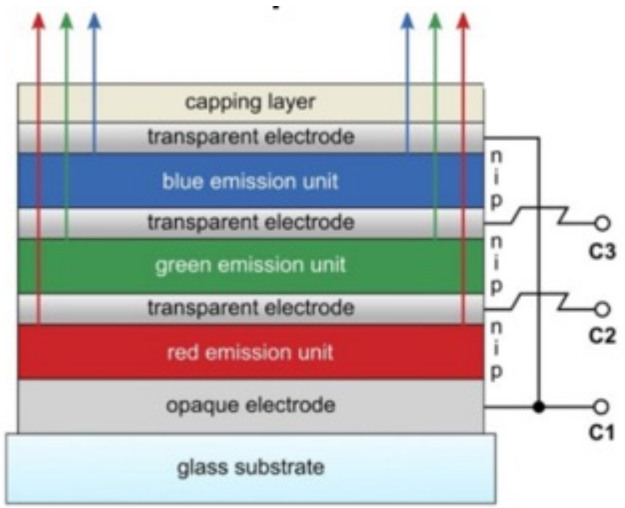
**Organic LEDS (OLEDs)
and organic photosensors**

Vast amount of knowledge exists – Can it be adapted for high energy physics experiments?

Interesting opportunities….

- Organic semiconductors
  - Low cost & highly scalable
    - Roll-to-roll printing production > 100 m scale
  - Industry driven technology
    - Cell phones, OLED displays, sensors for medical devices
- Can be made on rigid and flexible substrates
- Stackable geometry for spectroscopic (multicolor) readout
  - No loss of photosensor coverage
  - Cherenkov vs scintillation separation?

https://www.sammobile.com/news/samsungs-new-foldable-and-udc-panels-reveal-an-exciting-future/



https://www.nature.com/articles/s41598-018-27976-z

Stacked OLED

Stacked OPD

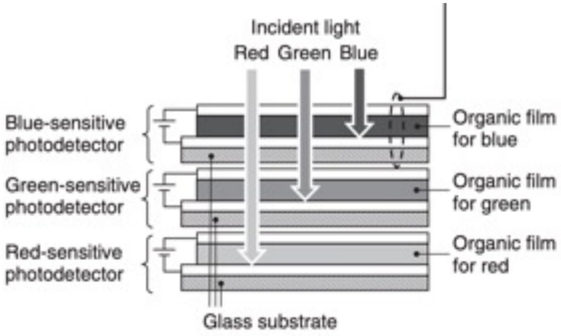


Fig. 1. Schematic diagram of stack structure and cross sectional view of a photodetector.

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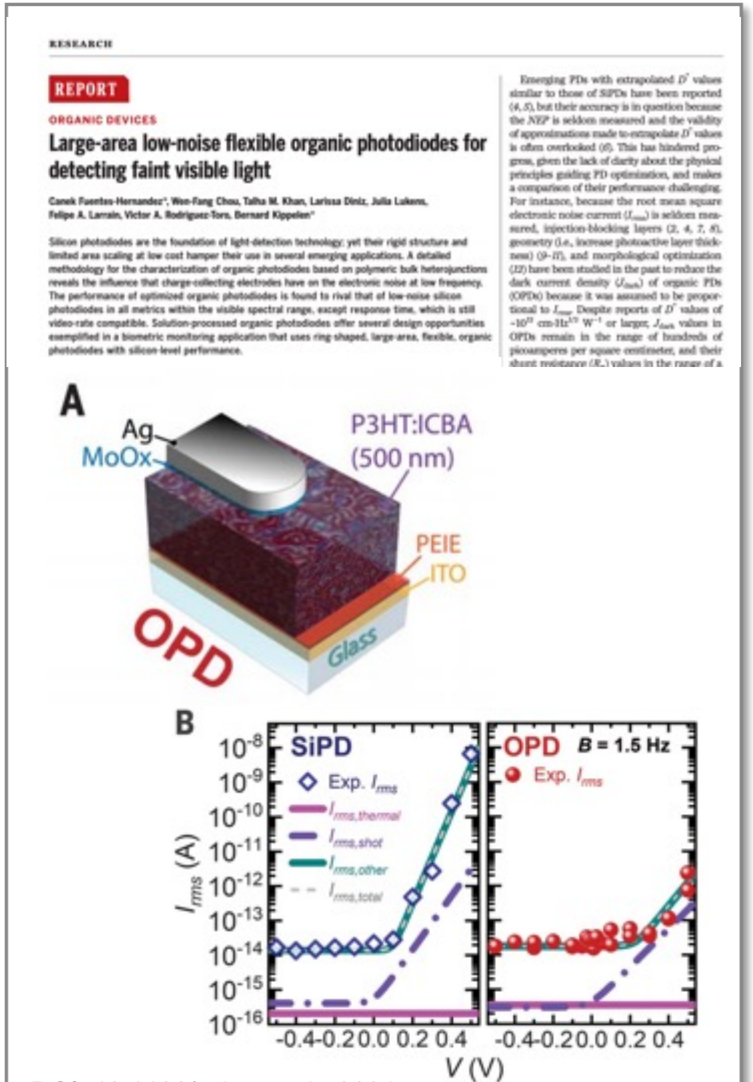
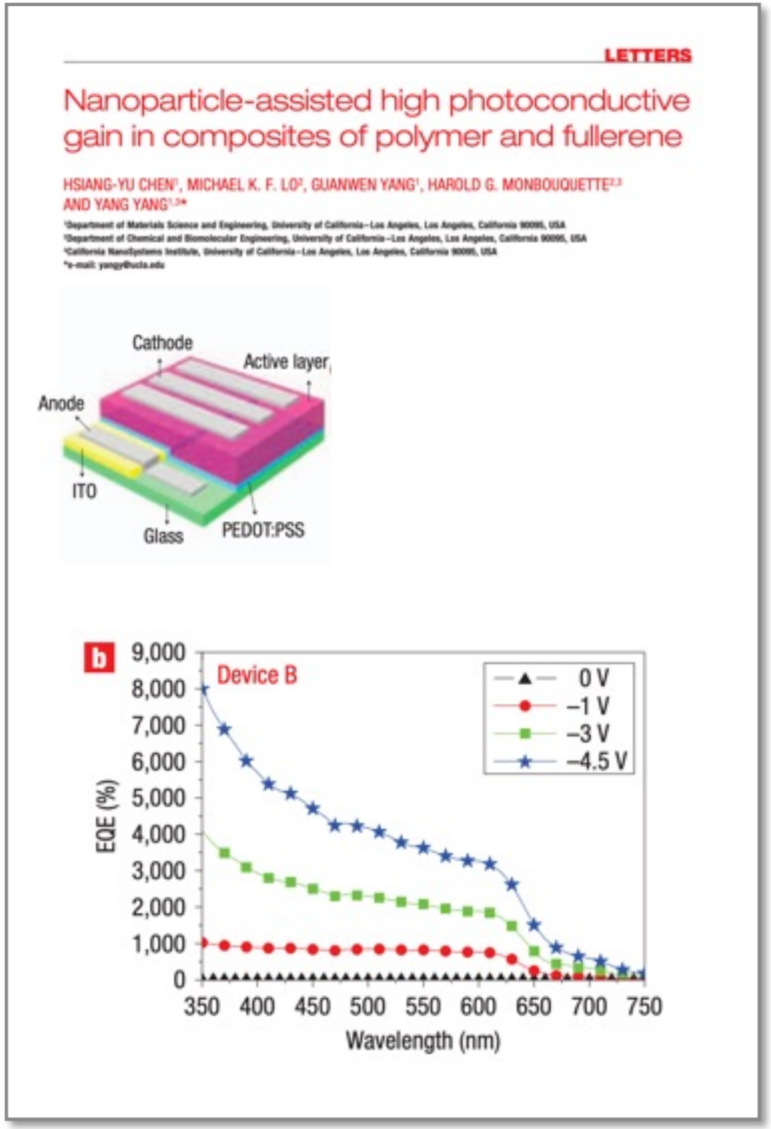
What about dark current and gain?

- Organic photodiodes (OPD) have reached the dark current of Si photodiode technologies
  - P3HT:ICBA based OPD have reach dark currents $I_{rms} < 0.1$ pA
- Ongoing research exploring gain-mechanisms in photo photodiodes
  - External quantum efficiencies > 100%
    - Photons in → electrons out
- Challenges with OPDs
  - *Slow response time*
  - *Cryogenic operation?*
  - *Long term stability?*

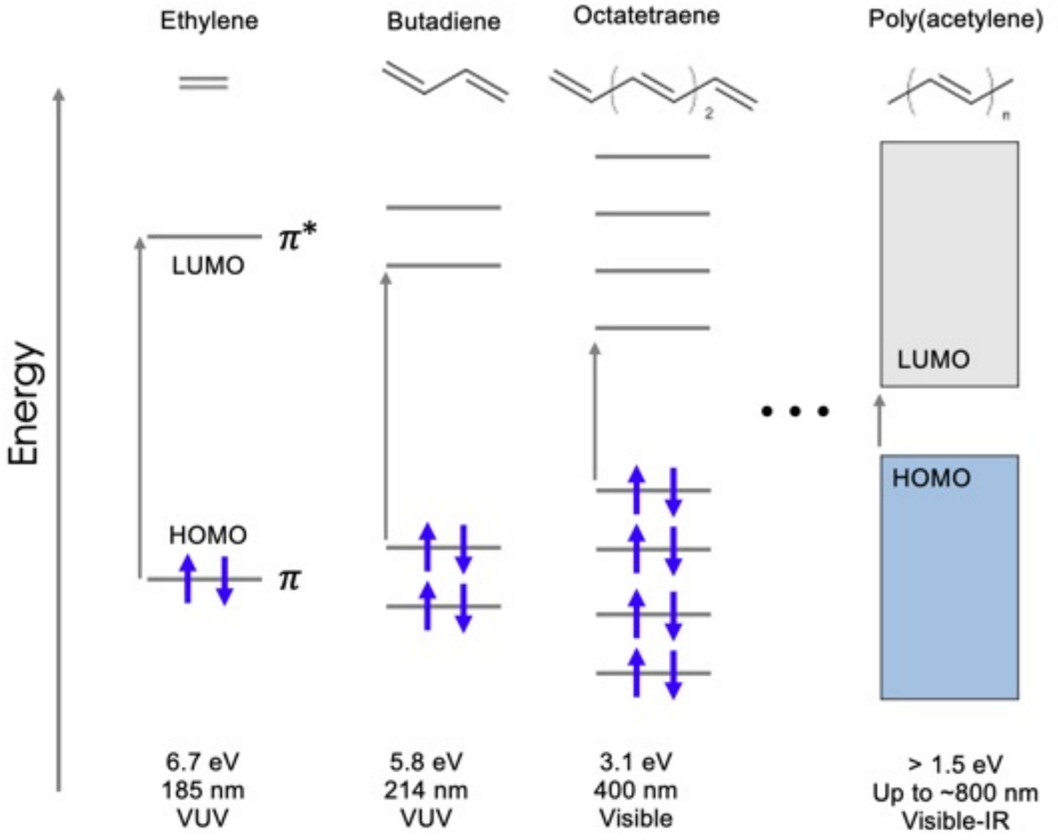


DOI: 10.1126/science.aba2624

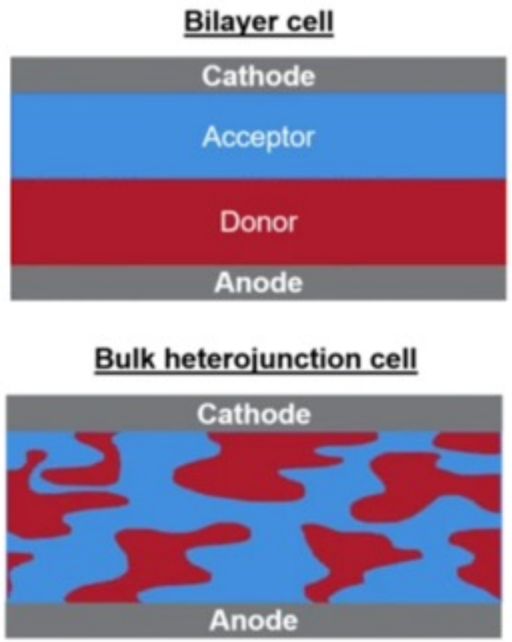


Organic semiconductors?

- Increasing conjugation leads to formation of quasi-continuous 'bands'
- Short exciton diffusion length restricts thickness in planer geometry to ~10 nm
  - Thin thickness limits photo absorption in planer geometries
- Bulk heterojunction (BHJ) geometry
  - P-type & n-type semiconductor materials are blended together
  - Allows for thicker photosensor geometries



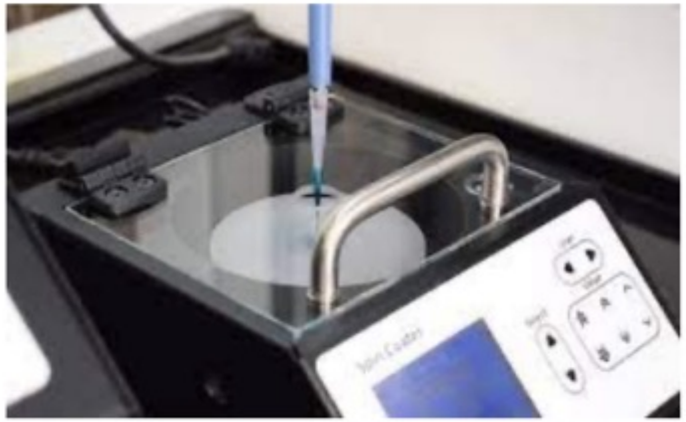
Optical band gap is highly tunable through molecular design

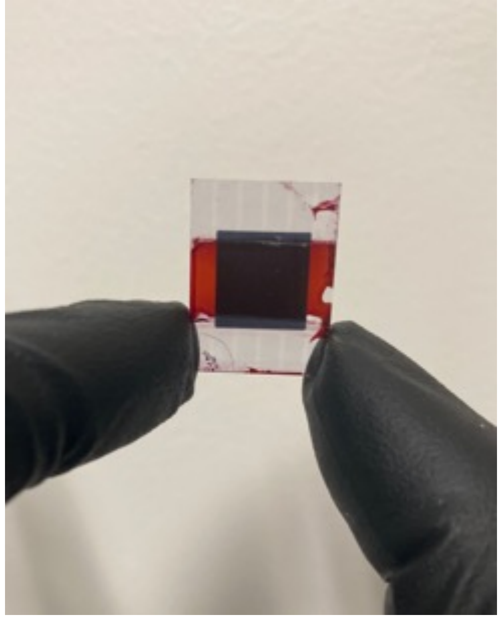


https://www.ossila.com/pages/organic-photovoltaics-introduction

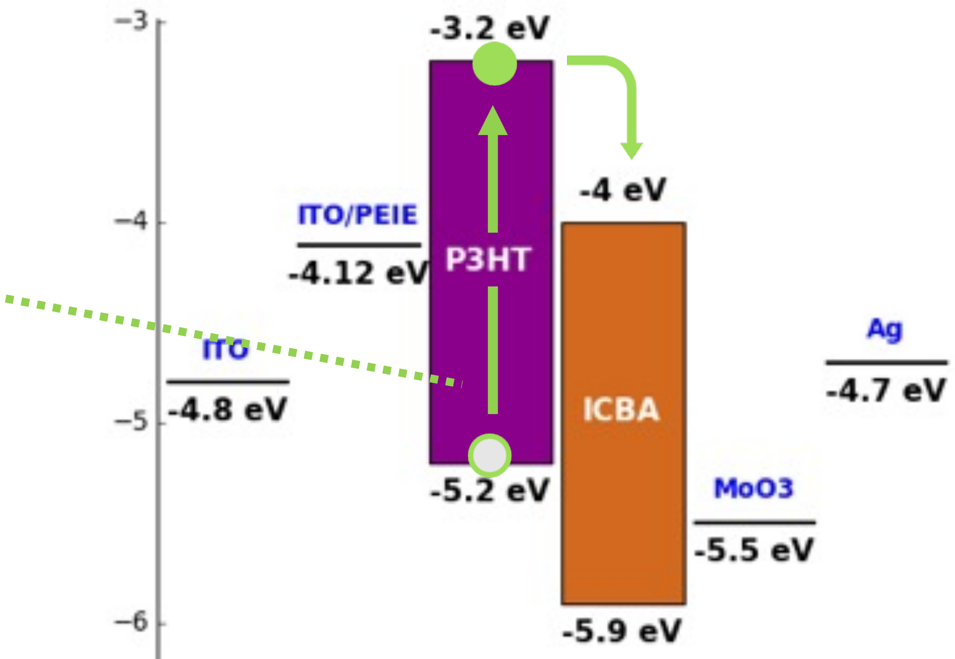
Fabrication of organic photodiodes

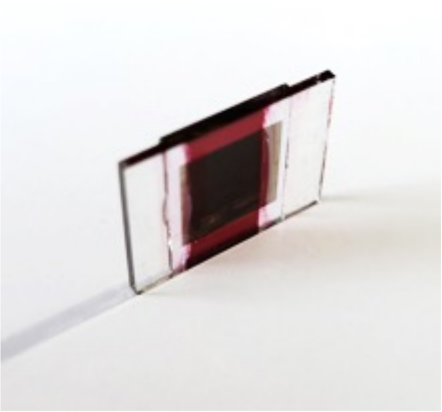
- Sputter coating of ITO anode layer
  - Transparent electrical conductor
- Cleaning of substrates
  - Sonicate and UV-ozone treatment
    - Improves wettability
- Apply photoactive layer
  - Spin coating
  - Can also use slot die for roll-to-roll
    - Applicable to *100+ meter scale production*
- Thermal evaporation of metallic cathode

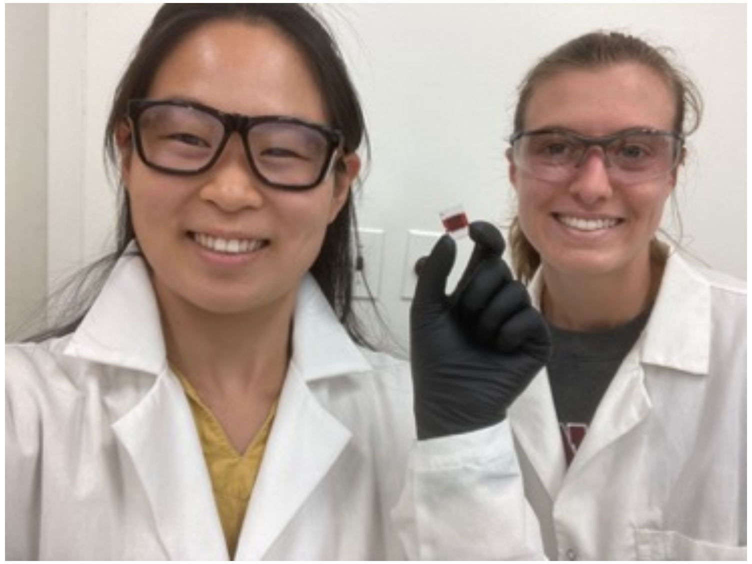




Organic photodiode

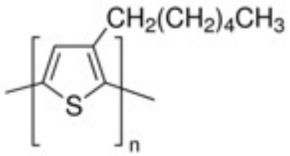




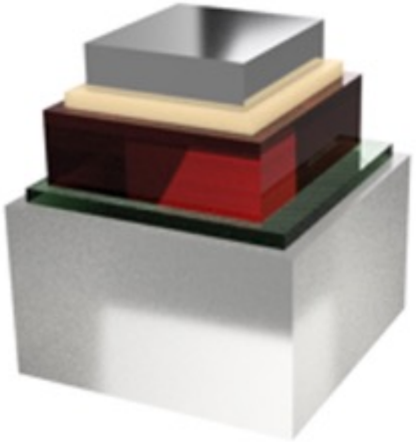


ORNL Summer Interns – Sabrina Cheng & Kate Hausladen hold their first functional OPD

P3HT
Electron donor
(n-type)



ICBA
Electron acceptor
(p-type)



*Nominal P3HT:ICBA thickness.
Thickness measurements in progress

Substrate – glass
Anode – ITO / PEIE
Photoactive layer – P3HT:ICBA
Cathode –Ag / MoO_x

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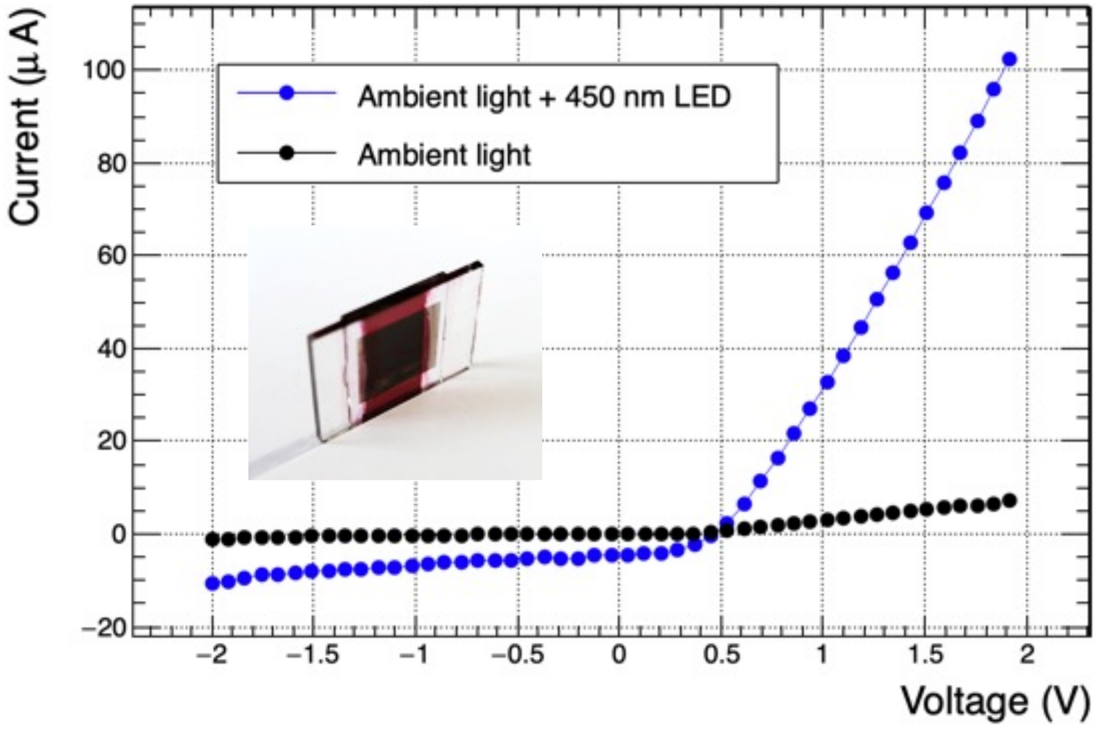
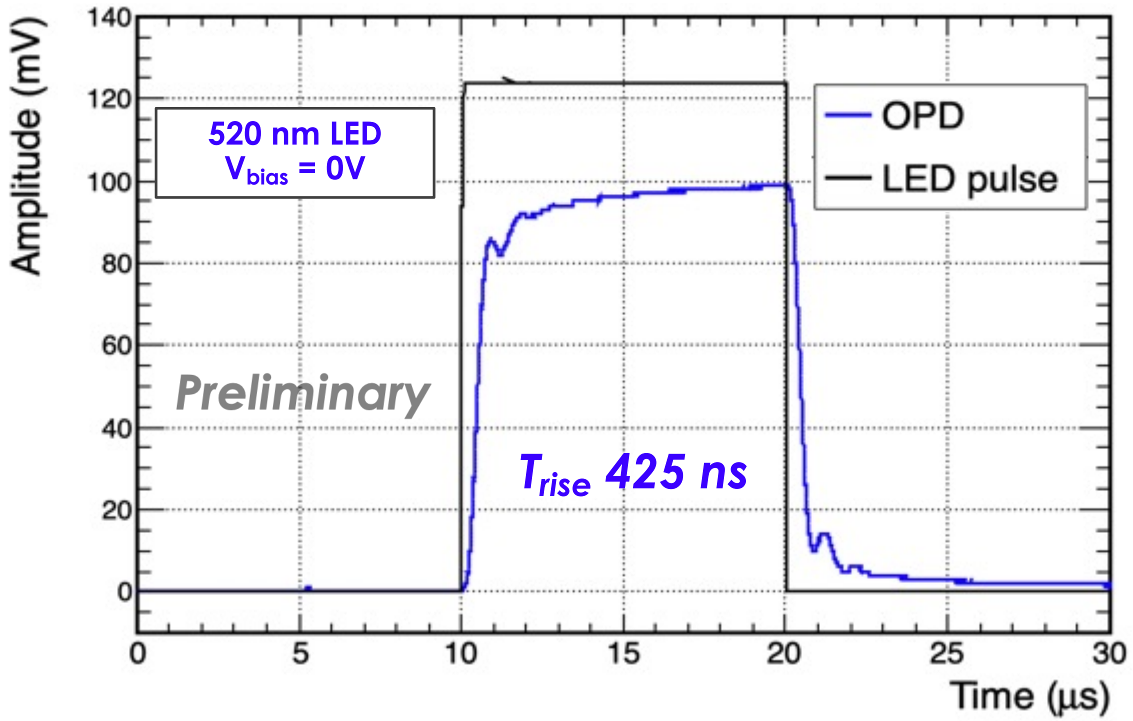
Results

- First batch of P3HT:ICBA OPDs ***It works!***

I-V curve



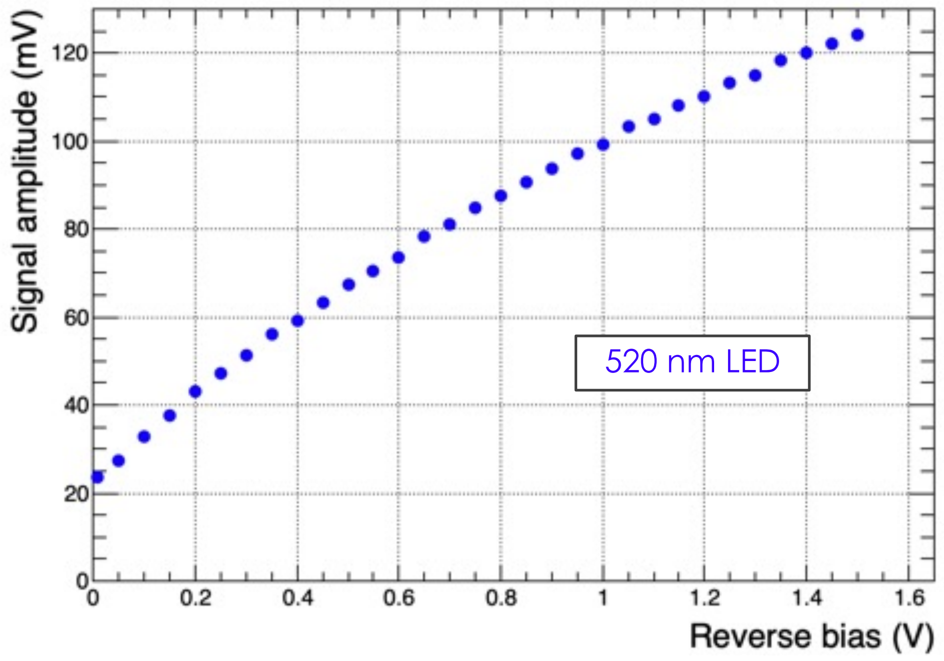
Timing response



Slower response time compared to SiPM or PMTs. For fast timing applications, OPDs can be used in combination with faster detectors

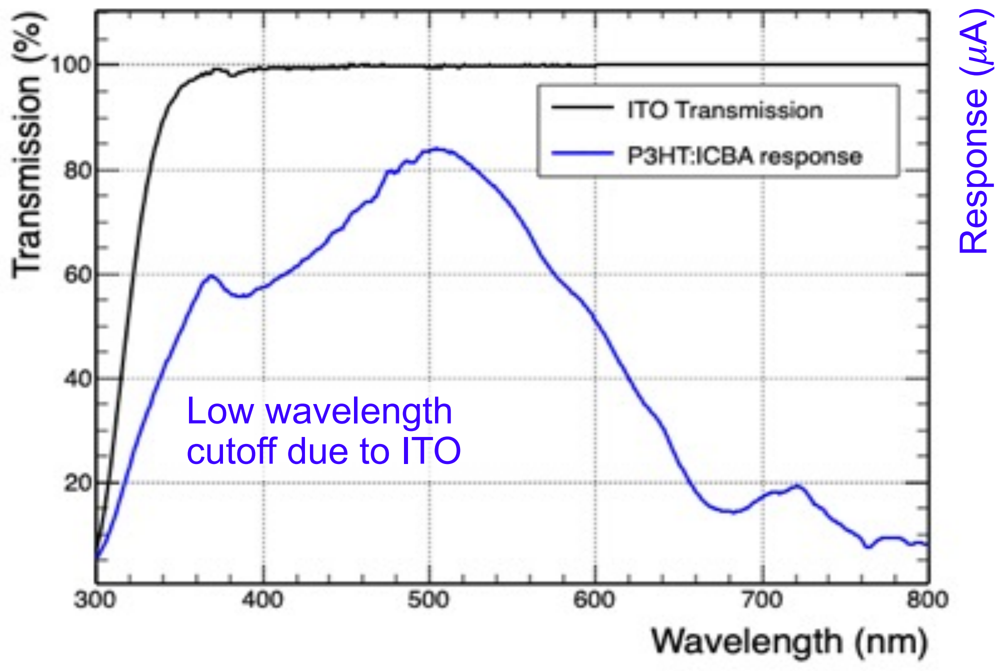
Results

Signal Amp vs bias



Can operate in reversed bias mode or photoconductor mode

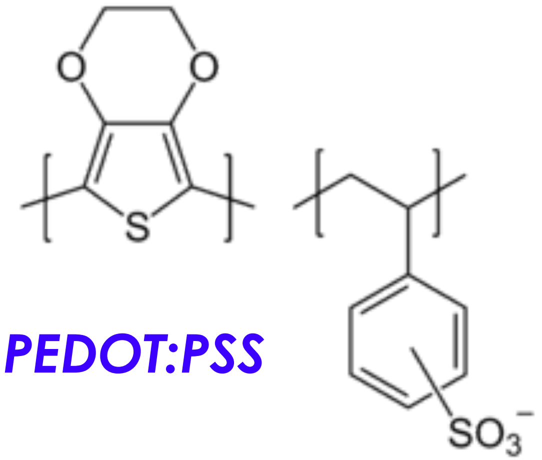
Spectral sensitivity



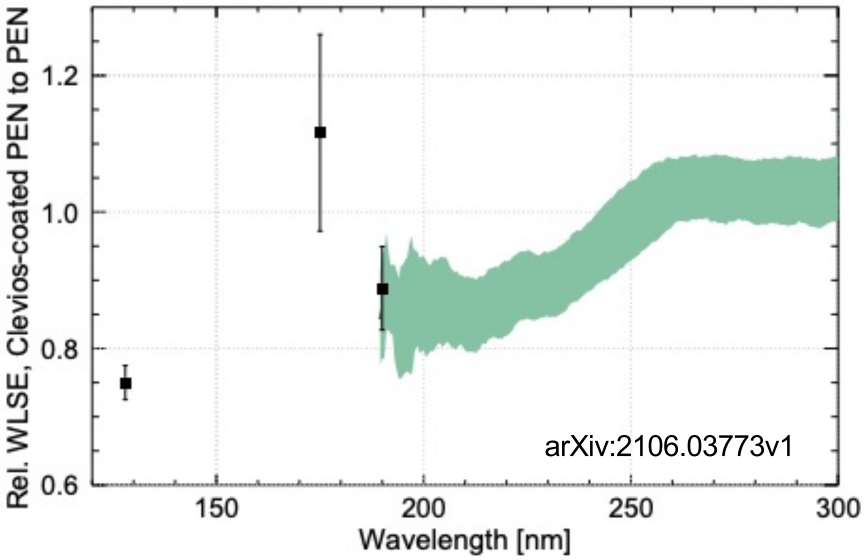
ITO limits the lower wavelength of OPD!

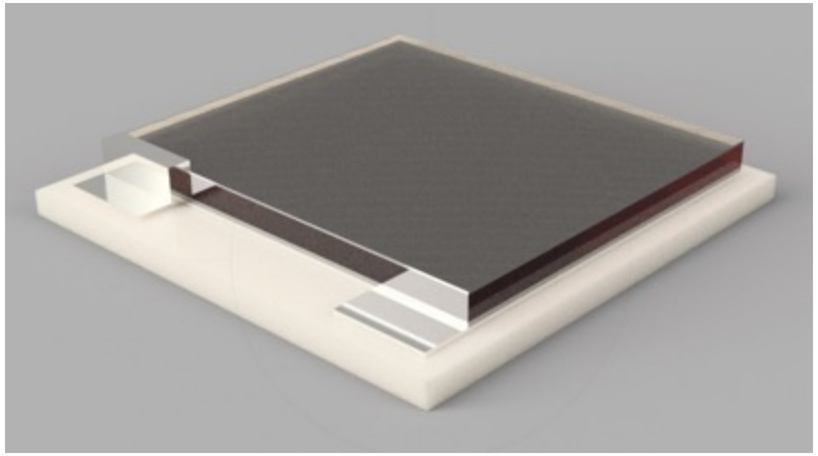
R&D on VUV transparent conductors

- Challenge for VUV sensors is requirement to have a VUV transparent conductor
  - Critical component for planer geometry VUV sensors
  - Functions as a VUV window and electrode
- Recent results indicate PEDOT:PSS may function as a transparent conductor for VUV light.
- Possible solution – invert assembly procedure with transparent conductor material such as PEDOT:PSS



PEDOT:PSS





PEDOT:PSS
PEIE
P3HT:ICBA
Ag/MoO_x

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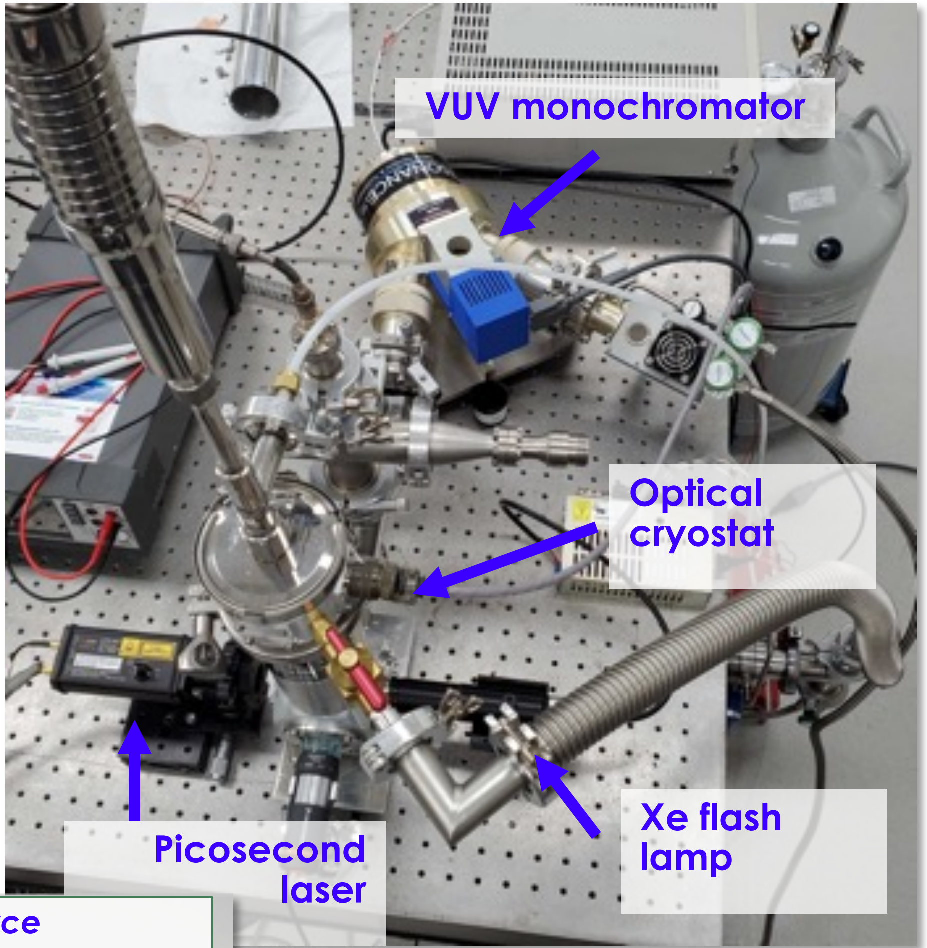
Conclusion and next steps…

- Organic photodiodes may serve as an attractive option for next-generation experiments
  - Low-cost, scalable technology
  - Ability to create stackable spectroscopic photosensors
- Low temperature & VUV wavelength testing in progress
- Newly developed VUV sensor evaluation platform
  - Wavelength range: 58 – 3200 nm
  - Temperature range: 5 – 500 K
- Light sources
  - Windowless plasma lamp
  - *Newly developed 128 nm pulsed light source*
    - Adjustable intensity – ~10k to single photon level
    - ***See talk by Austin McDonald on Friday!***



VUV pulsed light source

VUV photons on demand!

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Thank you