Hybrid Quantum Materials

Integrating Organic Semiconductor Nanocrystals into Renewable DNA Biopolymer Films

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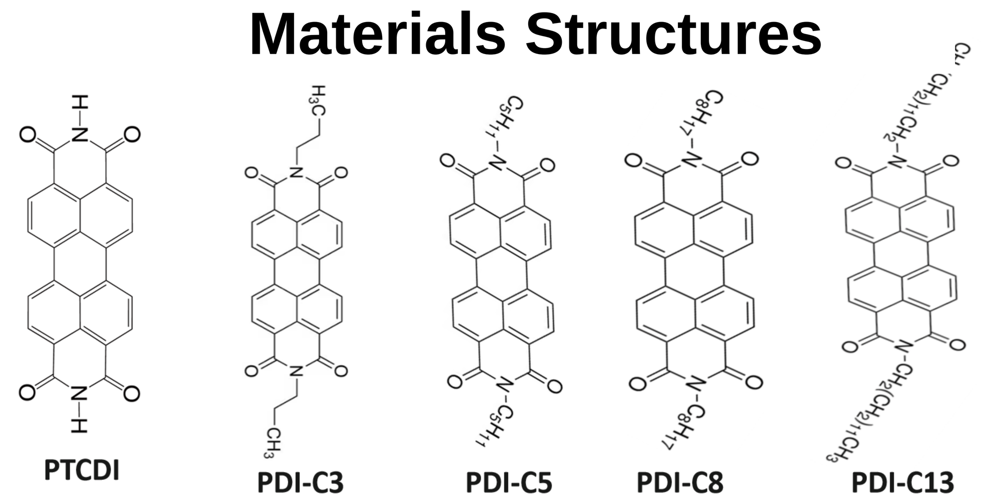
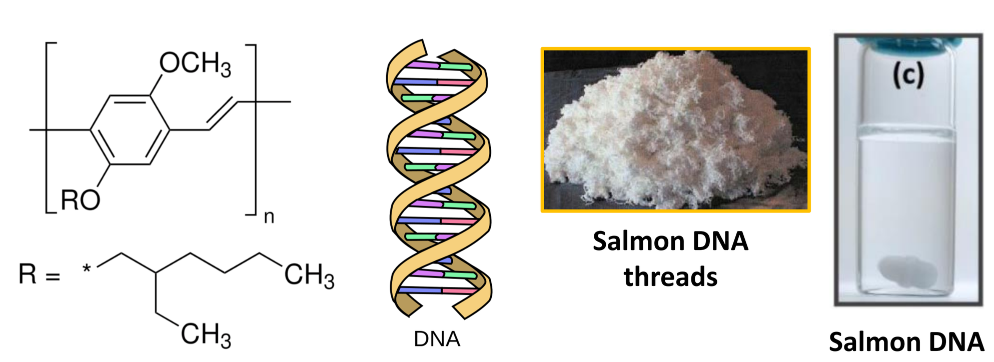
Introduction

DNA-based biopolymer films, such as those made from salmon DNA, are emerging as wide bandgap optoelectronic materials from renewable resources [1–3], and perylene diimide derivatives, known for their exceptional stability, can self-assemble into crystalline aggregates on the micro- and nanoscale, making them attractive building blocks for controlled quantum materials [4,5].

We are investigating the quantum properties of organic semiconductors using PPVs (MEH-PPV, BDMO-PPV), salmon DNA biopolymers, perylene diimide (PDI) derivatives, and PTCDA. Student researchers have fabricated devices and thin films, and analyzed experimental data to study their quantum optical properties. The material systems include DNA film-based quantum wells and micro- and nanoscale crystalline aggregates of PDIs [6–8].

Materials Structures





Methods

Fluorescence Emission Anisotropy (r):

$$r = \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + 2I_{\perp}}$$

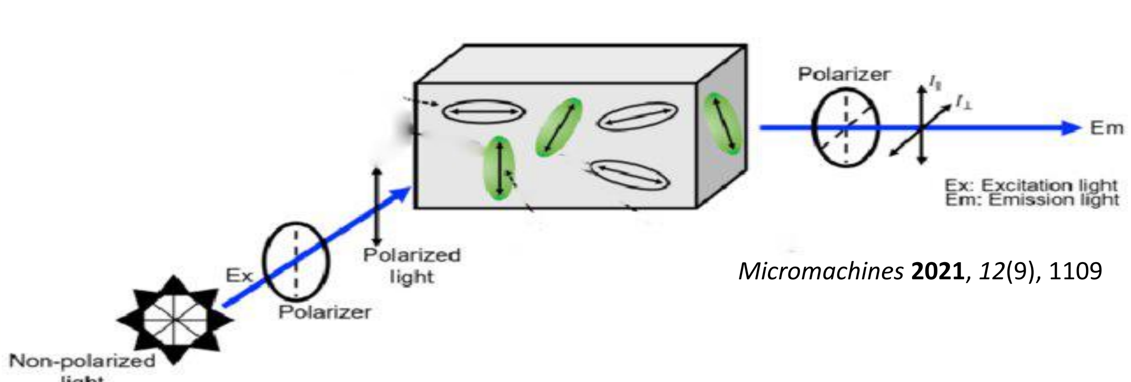
$I_{\parallel}$ = PL intensity of paralleled polarizer

$I_{\perp}$ = PL intensity of perpendicular polarizer

Fluorescence Emission Polarization (P), Modulation depth (M):

$$P = \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}} = \frac{3r}{2+r}, \quad M = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

$$Quantum\ Yield = \frac{Number\ of\ emitted\ photons}{Number\ of\ incident\ photons}$$



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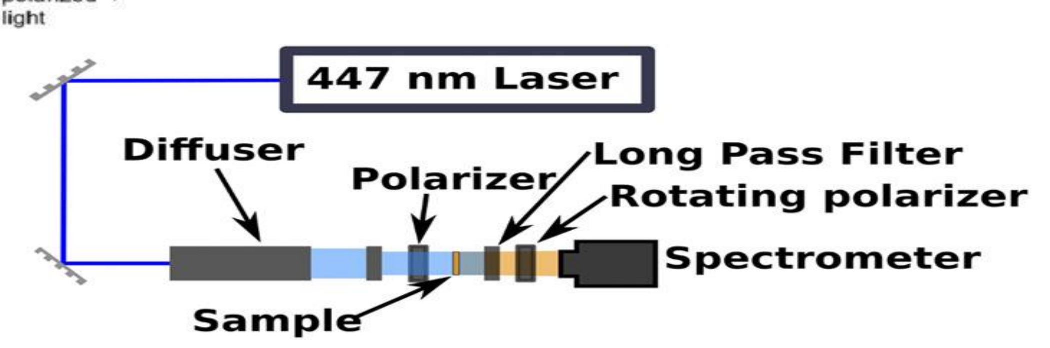
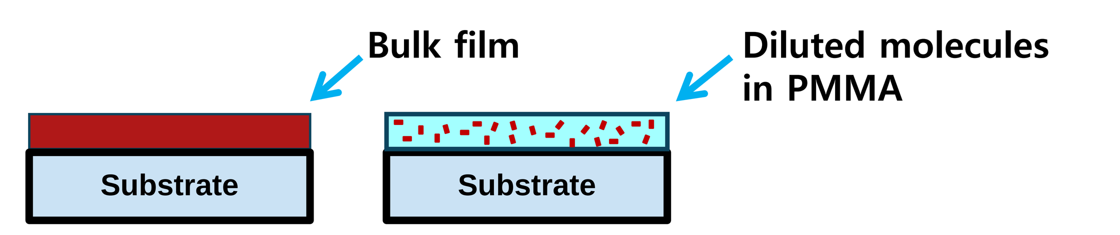
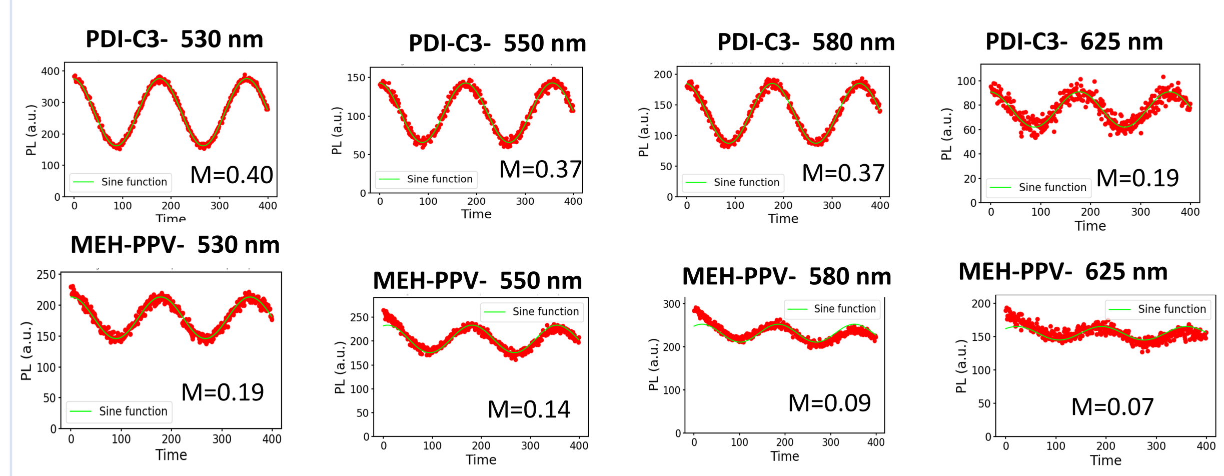
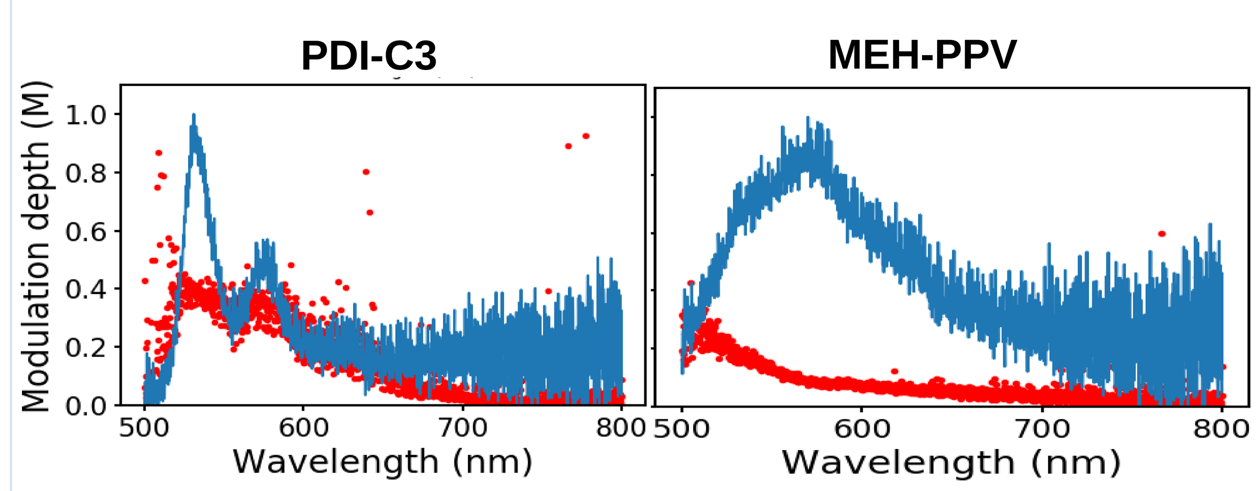


Results – Organic Semiconductors



Two sample structures
Bulk films for direct exciton migrations and interactions
Molecules and aggregates in PMMA films for quantum confinements

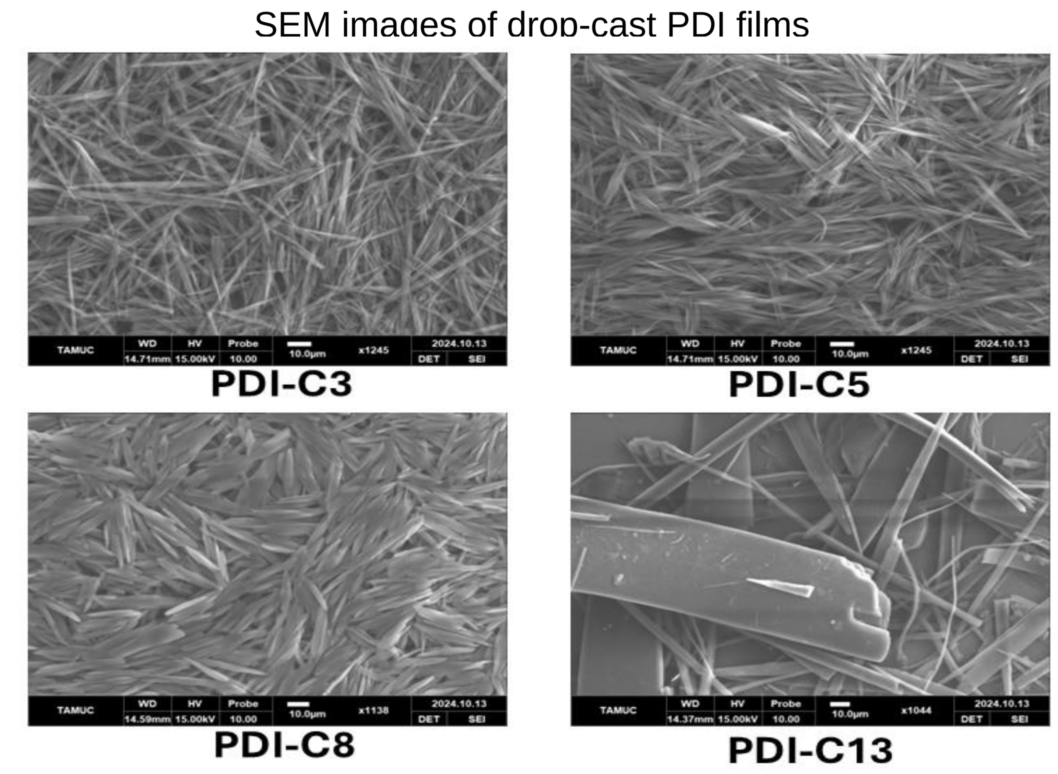




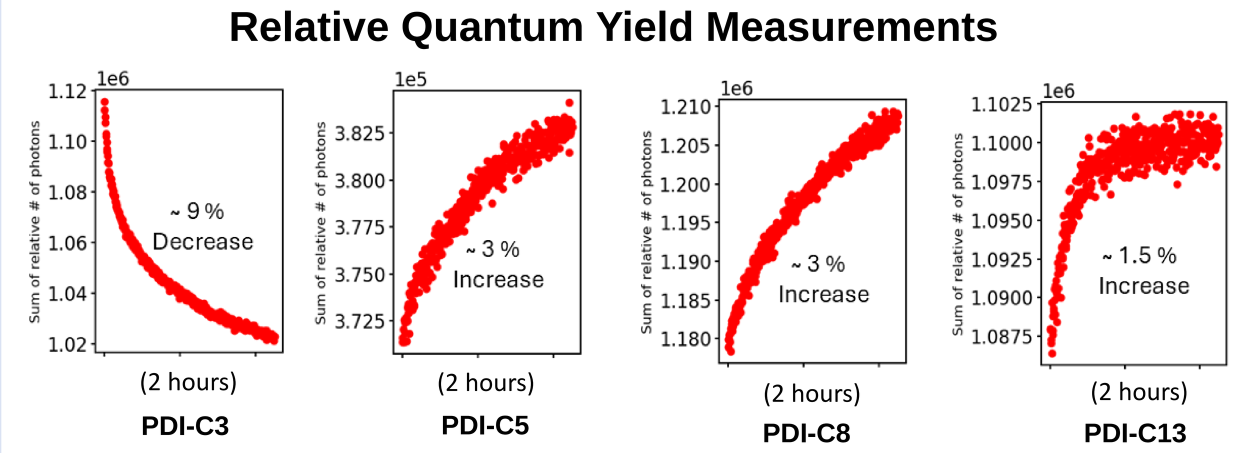
Emission modulation depth/polarization measurements (red) for immobilized PDI-C3 & MEH-PPV ensembles. (blue: PL spectra)

⇨ Goal: Fundamental understanding of exciton creation and migration

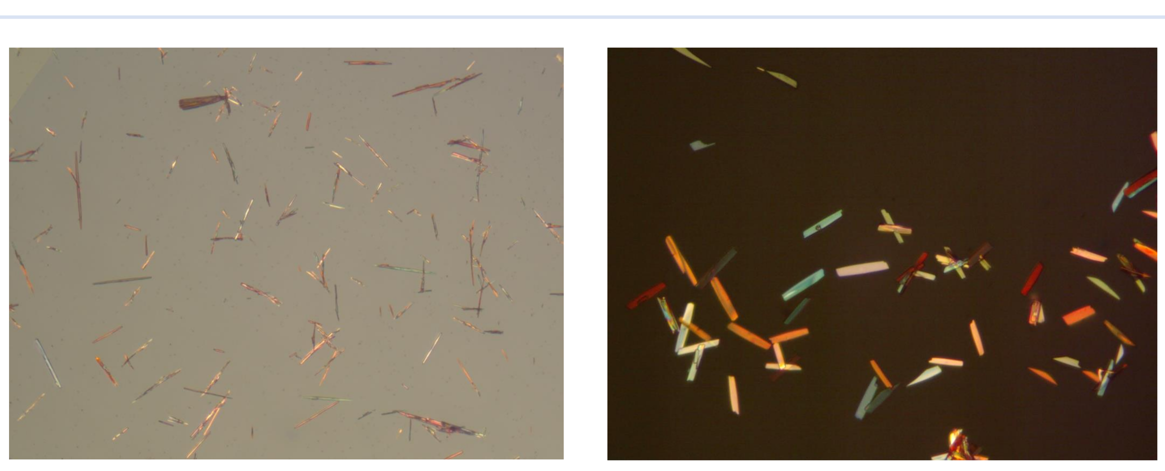
SEM images of drop-cast PDI films



Relative Quantum Yield Measurements



⇨ Goal: Controlled and enhance quantum yield/efficiency



Optical microscope images of PDI aggregates from a diluted PDI solution

Polarized light microscope images of highly crystalline PDI aggregates

⇨ Goal: Controlled quantum confinements in crystalline aggregats

Results – DNA Biomaterials

DNA biomaterials can be dopants, active semiconductors, and host matrices for quantum materials. They enable wide bandgap properties, renewable processing, and hybrid systems with nanocrystals or aggregates, making them versatile components for advanced organic electronics and quantum optoelectronic applications.

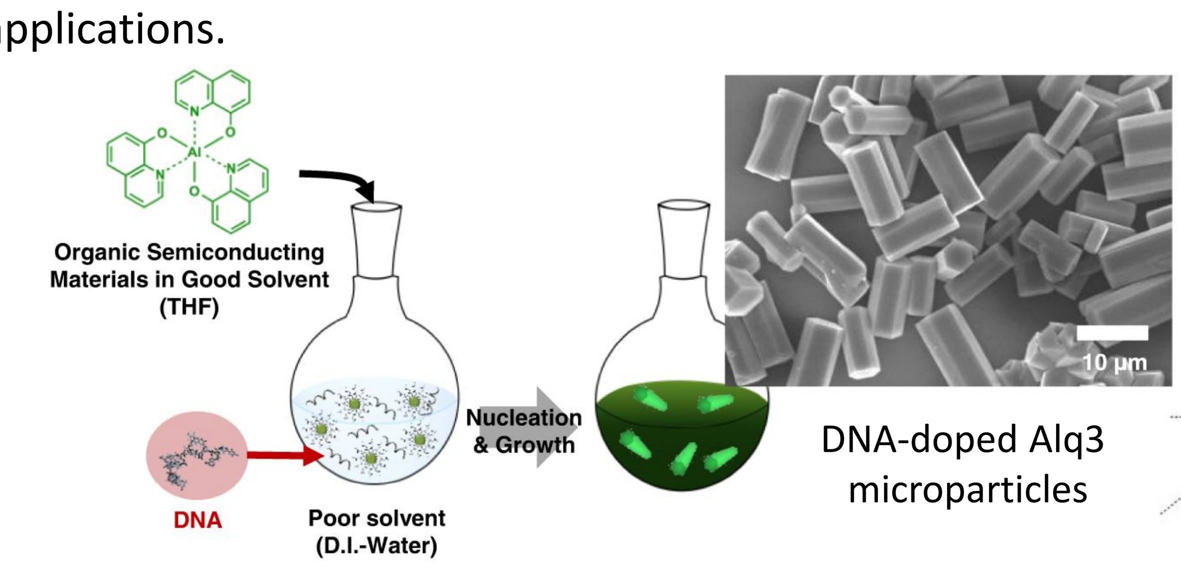
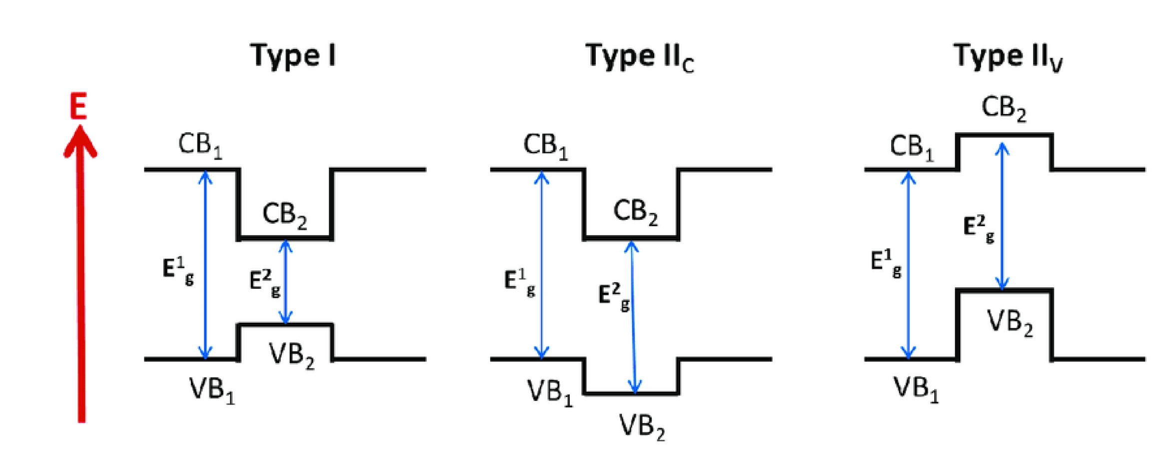
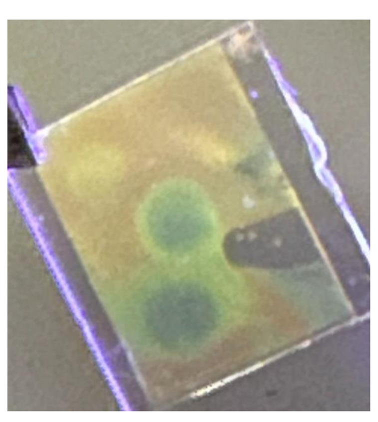


Fig. DNA as a molecular dopant in light-emitting organic crystals [1]



Quantum well types

Salmon DNA film (~100 nm) on Si wafer



A prototype of salmon DNA quantum well DNA/PPV/DNA
Excitation light-induced degradations (green dots) and imperfect PPV films are shown.

⇨ Goal: Band offset characterization and stability enhancement, and embedding crystalline PDI aggregates into DNA films for controlled quantum confinements

Future Plans

The research group at East Texas A&M University will experimentally fabricate and characterize type-I and type-II organic semiconductor quantum wells. The group will also develop hybrid materials by embedding quantum dots and crystalline PDI aggregates into DNA thin films, aiming to achieve tunable and stable luminescence. The work will include studies on size-dependent PDI aggregate crystals, ordered crystalline PDI aggregate arrays, and electric field induced quantum confinement effects (Fall 2025).

References

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[5] W. Ni, L. Sun, G.G. Gurzadyan, Ultrafast spectroscopy reveals singlet fission, ionization and excimer formation in perylene film, Sci Rep 11 (2021) 5220.
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