

Advancing the Frontiers of Near-Infrared Optoelectronics

Innovative approaches advance NIR emission technologies by improving their quantum efficiency, energy transfer, and thermal stability.

The field of near-infrared (NIR) optoelectronics has emerged as a critical area of innovation driven by the increasing demand for high-performance materials and devices across diverse applications, from bioimaging and sensing to advanced communication systems. Researchers have actively striven to overcome fundamental challenges such as low quantum efficiencies, energy loss, and thermal instability. The development of novel materials and device architectures has emerged as a cornerstone of progress in this domain. This highlight presents two pioneering studies that exemplify the synergy of materials sciences, photophysics, and engineering in advancing NIR technologies.

Traditional organic light-emitting diodes (OLEDs) in the NIR range have faced challenges related to low external quantum efficiencies (EQEs). This issue is caused by the emission energy gap law, which results in significant nonradiative losses as emission wavelengths extend into the infrared spectrum. This limitation often leads to inefficiencies that hinder the practical implementation of NIR OLEDs in fields such as bioimaging, data communication, and advanced sensing. To overcome these barriers, a collaborative research group led by Yun Chi (City University of Hong Kong, China) and Pi-Tai Chou (National Taiwan University) has introduced an innovative bilayer device architecture incorporating Pt(II) complexes and fluorescent dyes such as BTP-eC9.¹ The components of the architecture are engineered to form a synergistic donor-acceptor system. By leveraging interfacial energy-transfer mechanisms, this architecture achieves hyperfluorescence with peak emissions at 925 nm and EQEs of 2.24%, setting a new benchmark in the field. Additionally, the integration of a transfer printing method preserves the integrity of delicate molecular assemblies, ensuring efficient energy transfer and device stability. A grazing-incidence wide-angle X-ray scattering (GIWAXS) analysis performed at **TLS 13A1** revealed that the Pt(II) complexes in the OLED architecture exhibited highly ordered edge-on π - π stacking, which is crucial for efficient energy transfer. The BTP-eC9 fluorescent dye displayed lamellar-type face-on π - π stacking, which is also important for its function as an energy acceptor and emitter, facilitating the interfacial energy transfer mechanisms. Thus, the Pt(II) complexes act as highly efficient energy donors, transferring triplet-state energy to the singlet-state acceptors (BTP-eC9) *via* a Förster resonance energy transfer (FRET) mechanism, as demonstrated in **Fig. 1**. This process bypasses nonradiative loss channels, enhancing fluorescence intensity. A bilayer architecture with precise control over material interfaces minimizes back energy transfer and maintains structural order. The implementation of transfer printing addresses the challenge of assembling self-organized layers while maintaining their molecular arrangement, demonstrating the potential for large-scale manufacturing. This research not

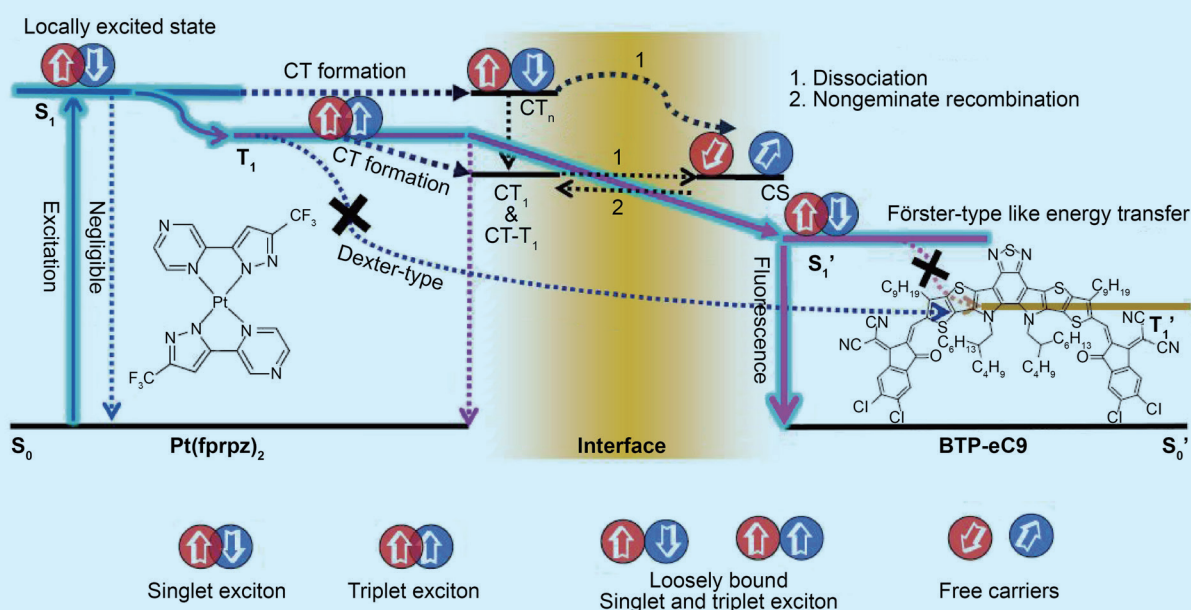


Fig. 1: An overview of the interfacial energy transfer dynamics that underpin NIR OLED functionality: the solid sky-blue pathway illustrates the interfacial energy-transfer process, which facilitates FRET. In this context, the S₀ and S₁ states represent the ground and excited states, respectively, of the singlet manifold, and the T₁ state denotes the triplet state. [Reproduced from Ref. 1]

only demonstrates a leap in device performance but also establishes a robust framework for tackling the inherent limitations imposed by the emission energy gap law.

The second significant research contribution comes from Sebastian Mahlik of the University of Gdansk, Poland, focusing on inorganic materials, specifically, Ga–In oxides doped with Cr^{3+} ions.² This study investigates the dual-purpose functionality of these materials as NIR phosphors for light-emitting diodes (LEDs) and ultraviolet photodetectors. The research examines the intricate interplay between radiative and nonradiative processes, emphasizing luminescence-quenching mechanisms. Cr^{3+} -activated materials have attracted significant attention for their ability to emit broadband NIR light, positioning them as ideal candidates for phosphor-converted LEDs. However, traditional interpretations of luminescence quenching often fail to explain the unique thermal behaviors observed in these systems. This study presents a novel perspective by attributing luminescence quenching to hole-based thermal ionization rather than electron transfer to the conduction band—a paradigm shift in understanding transition-metal-doped luminescent materials. High-resolution synchrotron X-ray diffraction (XRD) data, obtained at **TPS 19A**, revealed that Ga–In oxide samples predominantly exhibit a monoclinic $\beta\text{-Ga}_2\text{O}_3$ structure. Increasing indium (In^{3+}) doping levels led to the coexistence of two phases: the monoclinic $\beta\text{-Ga}_2\text{O}_3$ phase and the cubic In_2O_3 phase. This phase separation underscores the limited solubility of In^{3+} in the Ga_2O_3 host lattice and the structural changes induced by In^{3+} substitution. Greater indium concentrations introduced more disorder into the crystal lattice, as evidenced by the broadening of peaks in diffraction patterns and the appearance of mixed phases at higher doping levels. This disorder affected the local crystal field around Cr^{3+} dopants, significantly influencing their optical and photoelectric properties.

The study presents a groundbreaking hole-based thermal quenching mechanism, which challenges the conventional focus on electron transfer. This mechanism accounts for the material's luminescence behavior at elevated temperatures. The $\text{Ga}_{1.98-x}\text{In}_x\text{O}_3:0.02\text{Cr}^{3+}$ system exhibits tunable NIR emission and efficient photocurrent generation, rendering it suitable for both light emission and detection applications. By combining high-resolution synchrotron XRD with photoluminescence analysis, the research links In-induced structural modifications to enhanced optical performance. The substitution of In^{3+} ions alters the crystal field environment, optimizing energy level alignments for NIR emission and expanding the material's functionality in optoelectronic applications.

Together, these studies provide a comprehensive exploration of the challenges and solutions shaping the future of NIR optoelectronics. The meticulous research on OLEDs emphasizes the importance of molecular precision and device architecture, whereas the insights into Cr^{3+} -activated materials highlight the interplay between structure, energy dynamics, and multifunctionality. By connecting organic and inorganic systems, this compilation highlights the shared principles that underpin success in the field: innovation in material design, rigorous characterization, and a vision for translational impact. (Reported by Yu-Jong Wu)

This report features the work of Yun Chi, Pi-Tai Chou and their collaborators published in Nat. Commun. 15, 4664 (2024), and the work of Sebastian Mahlik and his collaborators published in JACS 146, 22807 (2024).

TPS 19A High-resolution Powder X-ray Diffraction

TLS 13A1 X-ray Scattering

- GIWAXS, XRD
- Materials Science, Inorganic Chemistry, Solid-state Chemistry, Photoluminescence

References

1. C.-M. Hung, S.-F. Wang, W.-C. Chao, J.-L. Li, B.-H. Chen, C.-H. Lu, K.-Y. Tu, S.-D. Yang, W.-Y. Hung, Y. Chi, P.-T. Chou, Nat. Commun. 15, 4664 (2024).
2. N. Majewska, M.-H. Fang, Sebastian Mahlik, JACS 146, 22807 (2024).