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Efficiency enhancement in quantum dot-color-converted micro-LED full-color displays via nonradiative resonant energy transfer

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Micro-light-emitting diodes (micro-LEDs) have established themselves as a leading candidate for next-generation display technologies owing to their superior properties such as ultra-high resolution, fast-response, low power consumption, and exceptional brightness.[1] However, the realization of full-color micro-LED displays faces two long-standing bottlenecks: (1) Mass transfer of red, green, and blue (RGB) micro-LED chips is technically complex and costly, a challenge that even leading manufacturers struggle to address economically. (2) Quantum dots (QDs) based down conversion solution, though bypassing the mass transferring and being able to prepare super fine pixels, suffers from excitation blue/UV light leakage. The insufficient absorption and conversion of excitation light from micro-LED chips lead to transmission of excitation light though the green and red color conversion pixels, which results in severe distortion of the color fidelity of full-color micro-LED display device.

Beyond improving the PLQY of color-conversion QDs, enhancing their excitation-light absorption is equally vital to minimize optical leakage in thin pixel architectures. Current micro-LED displays still suffer from low conversion efficiency and weak red emission, mainly due to two bottlenecks: (1) the quantum well (QW)-QD separation in conventional planar structures often exceeds the effective energy-transfer range; (2) red QDs show poor blue excitation efficiency owing to large energy mismatch and defect-induced nonradiative recombination, which further reduces emission and increases blue light leakage.

Recently, nonradiative resonant energy transfer (NRET) at the QW-QD and QD-QD interfaces have emerged as a promising strategy to address these limitations. The NRET mechanism enables highly efficient energy transfer while circumventing secondary photon reabsorption and scattering losses. This Commentary examines the pivotal role of NRET in QD-based color-converted micro-LED displays, and posits that incorporating NRET at both QW-QD and QD-QD interfaces will be essential for realizing next-generation, high-performance full-color micro-LED displays (Figure 1).

FUNDAMENTALS OF NRET: MECHANISM AND TUNABILITY

NRET, predominantly manifested as Förster resonance energy transfer (FRET), requires three key conditions: substantial spectral overlap between the donor emission and acceptor absorption spectra, favorable dipole-orientation alignment, and donor–acceptor separations below 10 nm. Unlike Dexter energy transfer (1-2 nm ranges), FRET operates via long-range dipole-dipole coupling, affording greater flexibility for practical device integration. The FRET rate (k_{FRET}) is governed by the spectral overlap integral (J), donor photoluminescence quantum yield (ϕ_D), donor lifetime (τ_D), and donor-acceptor distance (r_{DA}), as described by the Förster equation:

$$k_{FRET} = \frac{\phi_D \kappa^2}{\tau_D} \frac{9000(\ln 10)}{128\pi^5 N n^4} \frac{1}{r_{DA}^6} J(\varepsilon_A) \quad (1)$$

where κ^2, J, r_{DA}, N, n, and ε_A represent dipole orientation factor, spectral overlap integral, donor-acceptor distance, Avogadro's number, refractive index, and acceptor extinction coefficient, respectively. κ^2 (typically 0-4) describes alignment between donor emission and acceptor absorption dipoles and is

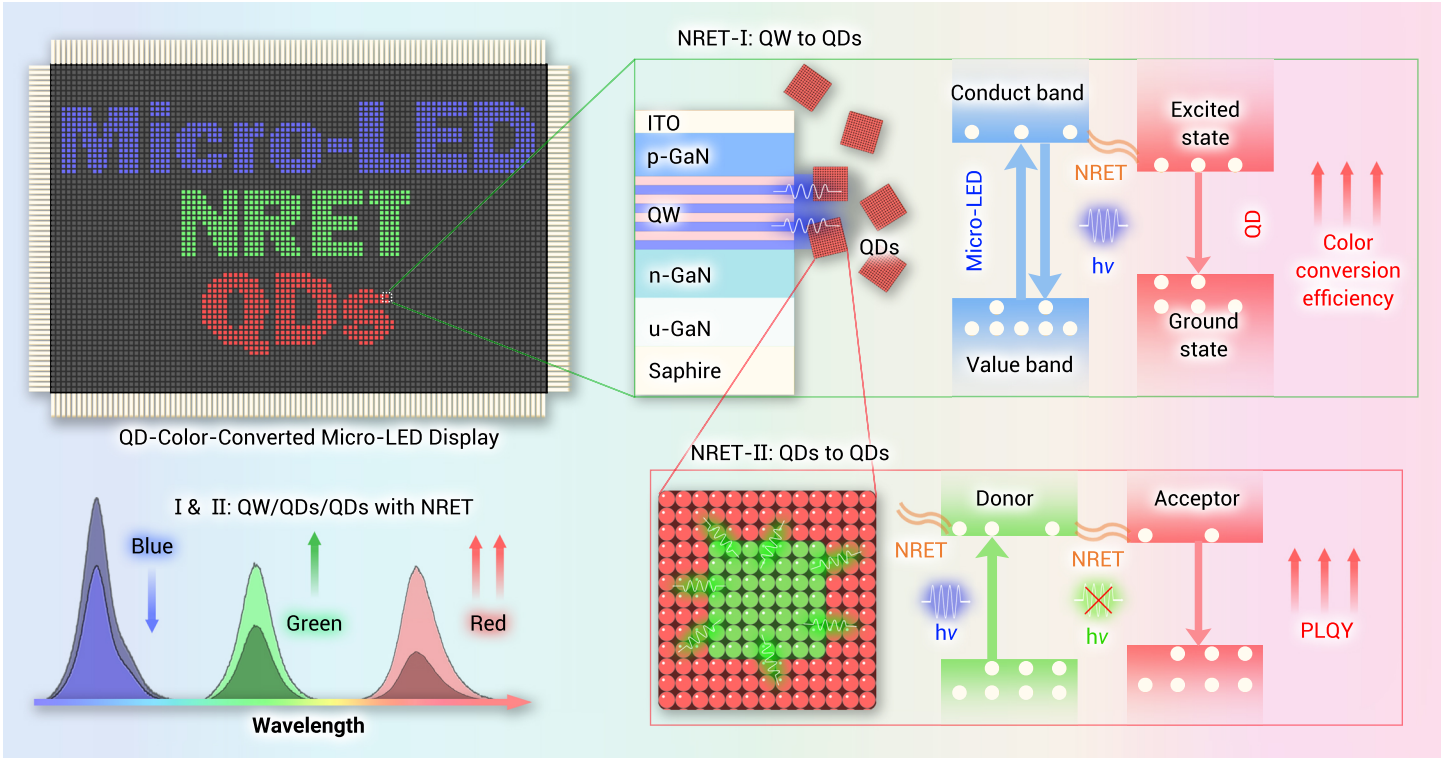

Figure 1. Schematic diagram of NRET in QW-QD interfaces and QD-QD interfaces in color conversion Micro-LED displays.

often taken as 2/3 for randomly oriented solution processed QD films. J quantifies donor-acceptor spectral resonance and a larger J promotes a higher FRET rate. In micro-LED displays, QD heterostructure engineering aims to maximize J, while device nanostructuring minimizes r_{DA} and optimizes dipole coupling.

NRET AT QW-QD INTERFACES

To maximize NRET efficiency at the QW-QD interface, micro-LED architecture must be carefully optimized. Wu et al. deposited red QDs via inkjet printing onto nano ring micro-LED arrays, ensuring close contact with the blue emitting QWs.[1] By using an atomic layer deposited SiO_2 interlayer to reduce the QW-QD separation to ~1 nm, this structure achieved a record NRET efficiency of 53.6% and a color gamut of 104.8% NTSC, highlighting that device engineering is as critical as QD design for efficient energy transfer.

Beyond structural engineering, strategies such as epitaxial growth of QDs directly on the QW surface have been explored to enhance NRET efficiency at the QW-QD interface. For instance, GaAs QDs grown by droplet epitaxy approach on AlGaAs barriers exhibit high symmetry and reduced fine structure splitting, which are advantageous for efficient and deterministic energy transfer.[2] Such epitaxial integration shortens the donor-acceptor separation and improves spectral overlap, offering a complementary route to ligand engineering for optimizing NRET efficiency and providing additional pathways for device optimization.

NRET AT QD-QD INTERFACES

Red-emitting QDs exhibiting high PLQY and robust blue/UV-light absorption are essential for efficient color conversion in full-color micro-LED displays. To mitigate the pronounced energy mismatch between blue excitation light and red QDs, engineering QD-QD interfaces via NRET has emerged as a compelling strategy. As depicted in the "NRET-II: QDs to QDs" schematic of Figure 1, such interfaces not only amplify excitation efficiency but also bolster structural stability through effective surface passivation.

Chen et al. developed bicomponent perovskite QD nanocomposites with $CsPbBr_3$ cores, γ-$CsPbI_3$ shells, and a ~2 nm amorphous SiO_2 interlayer that suppresses halide migration while maintaining an optimal NRET spacing.[3] Through core-to-shell NRET, the nanocomposites achieved a 2.1 fold enhancement in red emission intensity under 460 nm blue excitation and a PLQY of 99.9%, simultaneously boosting blue light absorption and reducing leakage in micro-LED displays.

Vighnesh et al. demonstrated efficient NRET in $CsPbI_3$/ZnSe heteronanostructures via in-situ epitaxial growth, where the ultralow lattice mismatch (< 3.2%) and Type-I band alignment enhanced energy transfer and exciton confinement, yielding a PLQY of 96% alongside improved stability.[4] Similarly, Li et al. engineered CdSe/ZnS-$CsPb(Br_{1-x}I_x)_3$ heterostructure QDs, in which NRET from the donor to the acceptor shifted the excitation peak into the UVA/blue range, ensuring compatibility with micro-LED backlights.[5] These QDs were formulated into inks for electrohydrodynamic printing, producing red conversion pixels as small as 8 μm with 26.6% conversion efficiency, and enabling a full-color display with a color gamut of 131.3% NTSC.

Moreover, the NRET strategy is not limited to perovskite or CdSe-based QDs. It is equally applicable to other emerging QD systems, such as InP QDs, which are commercially attractive due to their cadmium-free composition and environmental friendliness. By designing appropriate donor-acceptor pairs within InP-based core-shell or heterostructures, NRET can similarly enhance blue absorption and red emission efficiency, broadening the material choices for sustainable and high-performance micro-LED displays.

EXISTING CHALLENGES

Practical implementation of NRET also faces challenges such as maintaining sub-10 nm donor-acceptor distances uniformly across large-area displays, mitigating spectral drift due to QD size dispersion or micro-LED wavelength variation, and ensuring NRET stability under prolonged high-flux excitation. Furthermore, the integration of NRET QDs with high-resolution patterning techniques like electrohydrodynamic printing must achieve high yield and reproducibility for commercial adoption.

Long-term reliability under operational conditions-including thermal drift, high excitonic loading, and material degradation-also must be addressed to ensure stable NRET efficiency and consistent device performance over the display lifespan. Future efforts should therefore focus on improving the thermal and photostability of NRET-optimized QDs and device architectures.

From an industrial perspective, integrating NRET-engineered QDs into existing micro-LED manufacturing workflows-such as mass transfer or color-filter-free processes-poses challenges in terms of material compatibility, process tolerance, and cost. Ensuring that NRET QD inks are compatible with high-throughput patterning techniques and that device structures are scalable will be critical for successful commercialization.

FUTURE OUTLOOK

These advancements delineate two synergistic NRET paradigms: QW-QD interfacial transfer for superior color-conversion efficiency and QD-QD interfacial transfer for augmented optoelectronic characteristics and environmental durability. The next developmental frontier entails their synergistic fusion to surmount lingering barriers to full-color micro-LED commercialization, as conceptualized in the "I & II" integration of Figure 1. A viable pathway forward encompasses: (1) Utilizing advanced core-shell QDs as color converters to harness inherent NRET-boosted performance. (2) Depositing these QDs onto nanostructured micro-LEDs to optimize QW-QD NRET via ultrashort separations. (3) Leveraging high-resolution QD patterning for scalable, uniform RGB color-conversion pixel arrays. This holistic strategy would concurrently tackle deficiencies in conversion efficiency, longevity, and manufacturability.

Several refinements are imperative to actualize this blueprint. First, core-shell QD architectures must be fine-tuned to align with nano-structured micro-LED emissions-for instance, by customizing core emission for maximal spectral overlap with shell absorption while confining core-shell spacing to the NRET regime. Second, nano-ring micro-LED geometries should incorporate light-management features, such as distributed Bragg reflectors (DBRs), to redirect lateral emissions vertically and thereby amplify display luminance. DBRs can effectively reflect unconverted blue light back into the color conversion layer, increasing the photon recycling chance and thus boosting the overall color conversion efficiency and luminance. This approach complements NRET by minimizing optical losses and enhancing light extraction, which is particularly beneficial for high-brightness display applications. Third, NRET-embedded QD inks warrant formulation enhancements to optimize compatibility with diverse patterning modalities.

The NRET mechanism inherently reduces blue leakage and enhances color saturation by improving red emission efficiency, which directly benefits color gamut and purity in full-color displays. Ultimately, this orchestrated convergence of strategies charts the most efficacious route to full-color micro-LEDs that satisfy the exacting demands of next-generation augmented/virtual reality, large-format, and ultrahigh-resolution displays-poised to expedite commercialization and revolutionize the display sector.

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DECLARATION OF INTERESTS

The authors declare no competing interests.