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Quantum Dot and Perovskite Solar Cells: Physics of Charge Transport

Dr. Anjna Chetan*
*Department of Physics, D.J. college Baraut Baghpat, Affiliated to Chaudhary Charan Singh University, Meerut, Uttar Pradesh, India
*Corresponding Author E-mail: anjnachetan@gmail.com

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Abstract

Quantum dot (QD) and halide perovskite solar cells (PSCs) represent two fast-evolving routes to high-efficiency, low-cost photovoltaics. Both systems share exceptional optical absorption and tunable bandgaps, but differ in dominant charge-transport physics: QD films usually show hopping-like, ligand-limited transport with strong effects from interparticle coupling and ligand chemistry, while perovskites often exhibit band-like transport with long diffusion lengths but are highly sensitive to ionic motion and defect-mediated trap recombination. This review synthesizes the charge-generation, transport, recombination, and interfacial processes that control device performance in QD and perovskite solar cells, summarizes common characterization methods (SCLC, TRPL, transient absorption, impedance spectroscopy, KPFM), and discusses strategies—ligand engineering, passivation, band-alignment design, and transport-layer optimization to mitigate loss mechanisms and improve collection efficiency. Key open questions and promising research directions are highlighted.

Keywords*:* Quantum Dots, Perovskite, ChargeTransport, Photovoltaics, Efficiency

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Introduction

In the global push for renewable energy, India has emerged as a significant hub for next-generation photovoltaics, especially driven by its solar deployment targets and a large pool of research institutions. While conventional silicon technologies continue to dominate, solution-processed absorbers such as quantum dots (QDs) and halide perovskites are gaining ground in India's scientific ecosystem owing to their tunable optical properties, low fabrication costs, and suitability for flexible or building-integrated applications. The ambition in India to develop indigenous manufacturing capacity further motivates research into charge-transport physics in these materials under real-world conditions of high temperature and humidity. Colloidal quantum dots are semiconductor nanocrystals whose bandgap can be tuned by controlling the particle size, composition and surface ligands. In Indian literature and overview sources, QD solar cells are recognized for their promise of low-cost manufacture and spectral tunability (e.g., covering the visible to near-infrared), as well as compatibility with tandem or flexible architectures. Yet the same sources point out the substantial obstacles: high surface-to-volume ratio leading to defect/trap states, ligand-limited inter-particle coupling, and environmental stability issues. These impediments make the charge-transport mechanism in QD films qualitatively different from bulk semiconductors.

In contrast, metal halide perovskites — typically of formula ABX_3 where A = MA^+, FA^+ or Cs^+, B = Pb^{2+} (or Sn^{2+}) and X = halide anion — have captured widespread attention in India and globally because of their exceptional optoelectronic properties. Indian-authored review work (e.g., Saxena *et al*., 2022) highlights how hybrid organic–inorganic perovskites have rapidly achieved power conversion efficiencies (PCEs) exceeding 24 % in less than a decade, and have been the subject of intense research into architecture, efficiency and stability in the Indian context.

From a charge-transport perspective, these two absorber systems differ in fundamental ways. QD solids often display hopping- or tunneling-mediated conduction between discrete nanocrystals, with strong sensitivity to ligand length, inter-dot spacing, and surface passivation. By contrast, high-quality perovskite films in India and elsewhere have demonstrated relatively long carrier diffusion lengths and mobilities, facilitating quasi-band-like transport though this is complicated by ionic motion, grain-boundaries and dynamic structural disorder. The contrast in charge transport regimes underscores the need for tailored analysis of each material class.

The Indian research environment provides a compelling backdrop because of the dual pressures of scaling and of operation under challenging climatic conditions (high heat, humidity, dust) typical of many deployment sites in India. For example, Indian researchers at the International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), Hyderabad, have developed low-cost carbon-based perovskite solar cells with improved thermal and moisture stability, addressing the degradation modes aggravated in Indian climates. This demonstrates how local constraints feed into material and interface design.

A key stage in any solar cell is the generation of photocarriers and their separation. In QD films, exciton formation and dissociation are significant, especially when quantum confinement is strong and exciton binding energies are non-trivial. Efficient exciton dissociation in QD PVs often requires heterojunctions or energetic offsets that help split the bound state. In perovskites, by contrast, exciton binding energies tend to be low (often <25 meV at room temperature), enabling more straightforward generation of free carriers which simplifies subsequent transport and extraction. Indian reviews reflect this dichotomy and point out that developing QD films with low trap densities and strong coupling remains a challenge. Once free carriers exist, their transport to the contacts must outpace recombination. In QD solids, the presence of ligand molecules between nanocrystals creates barriers to charge conduction; accordingly, hopping or tunnelling models are often invoked, and mobilities are typically much lower than in crystalline semiconductors. Indian literature acknowledges that inter-particle coupling and surface passivation treatments are critical bottlenecks. In perovskites, the relative ease of carrier transport is tempered by other loss channels—ion migration, grain boundary traps, and interfacial recombination issues that Indian authors have emphasized in their analyses of stability, defect states, and architecture. Recombination mechanisms play a central role in determining the open-circuit voltage (VOC), fill factor (FF) and overall PCE. In QD films, trap states from surface defects, ligand-related disorder, and inter-dot heterogeneities dominate. In perovskites, non-radiative trap-assisted (Shockley–Read–Hall) recombination, interface recombination at transport layers, and recombination assisted by mobile ions are all prevalent. Indian research publications have studied degradation pathways under heat, moisture and light, and have suggested targeted passivation and architecture modifications to mitigate them.

Interfaces and energy-level alignment are critical in both technologies. Transport layers (electron-transport layers, ETLs; hole-transport layers, HTLs) and their interfaces with the absorber influence charge extraction efficiency and recombination rates. Indian initiatives have included novel architecture designs (for example, back-contact perovskite configurations) and interface engineering to improve extraction and reduce recombination. This emphasizes that transport in real devices is not simply a bulk absorber phenomenon but intimately tied to interfacial phenomena.

From a materials-engineering viewpoint, Indian research has contributed to several key innovations: ligand exchange chemistry in QD films to shorten inter-dot spacing, use of inorganic ligands for enhanced coupling, and passivation of perovskite surfaces/grain-boundaries with ammonium salts or low-dimensional perovskites to suppress defects and ion migration. The Indian review by Saxena *et al*. (2022) underscores how stability and reproducibility are especially important for deployment environments in India.

Characterization techniques to probe charge-transport and recombination — such as space-charge-limited current (SCLC) measurements, time-resolved photoluminescence (TRPL), transient absorption (TA), impedance spectroscopy and Kelvin probe force microscopy (KPFM) have been widely adopted in Indian labs. These tools enable quantification of mobilities, lifetimes, trap-density and extraction kinetics, forming the foundation for charge-physics models tailored to Indian devices.

The Indian solar-energy context also shapes the deployment motivations: with India targeting large-scale solar capacity expansion and increasingly incentivizing domestic manufacturing, the translational push from lab to field is pressing. For example, Indian teams have demonstrated silicon–perovskite tandem cells (e.g., at Indian Institute of Technology Roorkee) achieving ~28 % efficiency in 4-terminal configuration, highlighting that charge-transport quality in absorber and interfaces is already reaching internationally competitive levels.

Finally, this review aims to integrate the specific charge-transport physics of QD and perovskite solar cells with the nuances of the Indian research and deployment ecosystem. By benchmarking bulk transport, interfacial extraction, recombination and degradation pathways with Indian data and experience, we aim to identify the most promising strategies for advancing Indian-relevant device architectures and ultimately contributing to scalable, stable, high-efficiency solar modules for the Indian market.

Literature Review

The research landscape in India on quantum dot (QD) and halide perovskite solar cells has evolved significantly over the past decade, with numerous studies emphasizing the physics of charge transport and its impact on device efficiency. Research institutions such as the Indian Institute of Science (IISc), various Indian Institutes of Technology (IITs), and CSIR laboratories have led efforts in understanding carrier dynamics, recombination processes, and the development of novel transport materials. Indian studies have been particularly focused on addressing charge extraction inefficiencies, hysteresis, and degradation pathways that limit the commercial scalability of these next-generation photovoltaics.

A prominent area of Indian research has been interface and transport layer engineering, as these layers crucially influence charge carrier selectivity and overall device performance. Investigations at IIT Madras and IISc have explored the design of nickel oxide, copper thiocyanate, and carbon-based hole transport layers, which improve charge extraction and reduce recombination losses. Studies also emphasize that modifying transport layers with carbon nanotubes or conductive polymers enhances carrier mobility, stabilizing current–voltage characteristics and minimizing hysteresis in perovskite devices fabricated under ambient conditions.

Another stream of Indian studies has concentrated on large-area fabrication processes, essential for industrial applications but prone to charge-transport degradation due to film inhomogeneities. IISc and IIT Bombay have conducted spray-coating and scalable spin-coating trials using tin oxide and other inorganic electron transport layers (ETLs), revealing that uniform ETL coverage reduces series resistance and improves carrier extraction. These works demonstrate that precise control of interfacial microstructure is necessary to maintain high fill factors and suppress recombination in large-area cells.

Indian researchers have also addressed the issue of ionic motion and its influence on charge transport in perovskite solar cells. Ion migration leads to time-dependent current–voltage hysteresis and instability, which undermine steady-state power conversion efficiency. Studies from IISER Pune and IIT Kanpur show that compositional modifications, such as partial substitution of lead with tin or addition of cesium in hybrid perovskites, can mitigate ion mobility and improve long-term charge retention. These findings are critical to achieving consistent performance under real operating conditions.

Interface passivation and surface modification have become central strategies in Indian perovskite research. Several Indian groups have demonstrated that inserting ultrathin interlayers, such as 2D perovskite capping or dipolar molecular films, can reduce interfacial defect density and increase charge transfer efficiency. Time-resolved photoluminescence (TRPL) and impedance spectroscopy analyses performed in Indian laboratories have shown substantial improvements in open-circuit voltage and carrier lifetime upon implementing such passivation layers.

Grain boundary engineering and chemical passivation have been extensively explored to improve bulk charge transport in perovskite films synthesized under Indian laboratory conditions. Additives such as bulky ammonium salts and polymeric materials are frequently employed to enlarge grain size, lower trap density, and extend diffusion lengths. Indian researchers have reported improved mobility and lower trap-filled limit voltages after these treatments, emphasizing that optimized crystallinity directly enhances electron and hole transport through the perovskite layer.

In tandem and semi-transparent device architectures, Indian efforts led by IIT Bombay's National Centre for Photovoltaic Research and Education (NCPRE) have analyzed interlayer transport and band alignment in perovskite–silicon tandem solar cells. These studies underline that interfacial resistances and charge recombination at recombination junctions significantly affect current matching and device yield. Optimizing transport layers and their conductivity has been found essential to achieving high-efficiency tandem configurations compatible with Indian climatic conditions.

Theoretical and computational studies from Indian institutions complement the experimental work by modeling charge transport through drift–diffusion simulations and defect-state analyses. These studies provide insights into how electron and hole mobilities depend on doping concentrations, energy-level offsets, and defect densities at interfaces. Indian researchers have used these simulations to identify limiting processes in carrier extraction and guide experimental layer design, aligning with international standards in transport modeling.

Quantum dot-based solar cell research in India, although comparatively smaller in scale than perovskite work, has made significant strides in understanding charge transport through ligand-engineered QD solids. Studies from CSIR-NPL and IIT Delhi have shown that ligand exchange with short inorganic or mixed organic–inorganic ligands enhances electronic coupling between QDs, shifting transport behavior from thermally activated hopping toward quasi-band-like conduction. This improvement has led to higher photovoltage and current density in PbS QD devices.

Indian device engineers have also highlighted the delicate balance between conductivity and surface passivation in QD layers. Ligand exchanges that enhance coupling often expose surface traps, leading to non-radiative recombination. Experimental work in Indian laboratories has demonstrated that hybrid ligand strategies—combining short conductive and long passivating ligands—yield optimal charge mobility without significant trap formation. These efforts underscore the interplay between surface chemistry and charge transport in QD films.

Emerging Indian research on hybrid perovskite–quantum dot systems explores integrating QDs as interfacial modifiers or energy-transfer layers within perovskite devices. These hybrid structures can improve spectral response and carrier collection, but challenges such as halide exchange and misaligned band offsets persist. Indian studies have proposed controlled interfacial chemistry and post-deposition annealing to stabilize the interface and enhance charge extraction in such composite systems.

Characterization of charge transport using advanced spectroscopic and electrical techniques has become routine in Indian photovoltaic research. Techniques such as TRPL, transient absorption spectroscopy, and impedance analysis have been applied to distinguish between bulk and interfacial recombination processes. Reports from IISc and IIT Delhi correlate these findings with device metrics, demonstrating that controlling defect density and improving interfacial quality yield significant gains in efficiency and operational stability.

Methodology

The methodological framework for the study of charge transport in Quantum Dot (QD) and Perovskite Solar Cells (PSCs) involves a combined experimental, analytical, and computational approach, emphasizing reproducibility, scalability, and adaptation of indigenous synthesis routes as demonstrated in Indian laboratories. The research initiates with the synthesis of active materials both colloidal quantum dots and metal halide perovskites under controlled ambient or inert environments to avoid contamination and moisture-induced degradation. For perovskites, high-purity lead halide precursors (PbI_2, $PbBr_2$) and organic cations such as methylammonium (MA^+), formamidinium (FA^+), or inorganic cesium (Cs^+) are dissolved in solvent mixtures like N,N-dimethylformamide (DMF) and dimethyl sulfoxide (DMSO). Indian studies, particularly those from IISc Bangalore, IIT Bombay, and CSIR-NPL, have emphasized the importance of solvent engineering and precursor stoichiometry in achieving large-grain, defect-minimized films that enhance charge carrier mobility and reduce trap-assisted recombination (Saxena *et al*., Solar Energy Materials and Solar Cells, 2023).

For the synthesis of colloidal quantum dots, a hot-injection or non-injection route is adopted, where lead or cadmium precursors are reacted with chalcogen sources under inert conditions at elevated temperatures. The synthesized nanocrystals are repeatedly washed and purified using anti-solvents like acetone or methanol to remove unbound ligands and by-products. To enhance charge transport, surface ligand exchange is performed using shorter ligands such as halides or chalcogenide complexes, replacing the long insulating oleic acid molecules initially used for colloidal stability. Indian researchers at IISER Pune and IIT Kanpur have demonstrated that halide-based ligand treatments significantly improve carrier hopping rates and film conductivity, yielding better quantum dot solid-state films (Kumar *et al*., Journal of Nanoscience and Nanotechnology, 2022).

The deposition of thin films is performed through spin coating, layer-by-layer dip coating, or doctor blading, depending on the targeted device structure. For perovskite layers, the anti-solvent dripping technique (typically using chlorobenzene or diethyl ether) ensures uniform crystallization and smooth film formation. For quantum dots, successive ionic layer adsorption and reaction (SILAR) and layer-by-layer deposition with intermediate ligand exchanges are employed to ensure strong interdot coupling and film uniformity. Indian studies have optimized these parameters for large-area coating and flexible substrates, enhancing device scalability (Patil *et al*., Materials Today: Proceedings, 2023).

Post-deposition annealing treatments are carried out to improve crystallinity and reduce lattice strain, typically at 100–120°C for perovskites and 150–200°C for quantum dot films under nitrogen atmosphere. Controlled thermal processing aids in reducing defect density and improving grain boundary connectivity, which directly correlates with improved carrier diffusion lengths. Investigations at CSIR-CEERI Pilani and IIT Delhi have revealed that optimized annealing protocols minimize ion migration and enhance phase stability, thereby suppressing hysteresis in perovskite devices (Singh *et al*., Applied Surface Science, 2024).

Device fabrication involves constructing layered heterojunctions with transparent conducting substrates such as fluorine-doped tin oxide (FTO) or indium tin oxide (ITO). The electron transport layer (ETL) is typically TiO_2 or SnO_2, deposited through sol–gel or atomic layer deposition methods. The active absorber layer (perovskite or quantum dot film) is sandwiched between ETL and a hole transport layer (HTL) such as Spiro-OMeTAD, CuSCN, or polymeric HTLs like PTAA or P3HT, followed by top electrode deposition (Au, Ag, or carbon). Recent Indian work has explored replacing Spiro-OMeTAD with low-cost inorganic HTLs and carbon electrodes to improve device stability under humid conditions (Gupta *et al*., Solar Energy, 2023).

Charge transport characterization is carried out using space-charge-limited current (SCLC) measurements, where electron-only and hole-only devices are fabricated to extract carrier mobility and trap density. This technique provides the trap-filled limit voltage and helps assess bulk and interfacial defects. Complementary time-resolved photoluminescence (TRPL) studies are conducted to analyze carrier lifetimes and recombination pathways. Indian groups at IISc and BARC have used TRPL to correlate longer decay lifetimes with efficient interfacial passivation in $CsPbI_3$ and PbS QD films (Rao *et al*., Physica E, 2023).

Electrochemical impedance spectroscopy (EIS) is employed to study charge transfer resistances, recombination rates, and capacitive behavior at different frequencies. The Nyquist plots and Bode phase analyses provide insight into recombination lifetimes and interfacial charge buildup. Indian laboratories, particularly at JNU and IIT Madras, have implemented EIS to differentiate between bulk-limited and interface-limited recombination, confirming that interfacial trap passivation is critical for achieving high open-circuit voltages (Chatterjee *et al*., Journal of Power Sources, 2024).

Ultrafast transient absorption spectroscopy is used to capture femtosecond-scale carrier dynamics, including exciton formation, hot-carrier cooling, and interfacial charge transfer processes. Such optical pump–probe techniques have been applied in collaborative Indo–German studies to quantify charge injection times between QD layers and ETL/HTL interfaces, finding injection times as short as 400 fs for optimized ligand-coupled QD films (Sinha *et al*., ACS Photonics, 2023). These insights are essential for modeling carrier mobility and recombination kinetics.

Kelvin Probe Force Microscopy (KPFM) and conductive Atomic Force Microscopy (c-AFM) are employed for nanoscale mapping of potential distribution and current pathways. Such nanoscales measurements help visualize spatial inhomogeneity, grain boundary potential variations, and local trap distributions. Indian nanotechnology centers such as INST Mohali have contributed to developing high-resolution KPFM analyses of perovskite–transport layer interfaces, demonstrating improved potential uniformity after surface passivation treatments (Bhatia *et al*., Nanotechnology, 2024). In addition to experimental techniques, drift–diffusion modeling and kinetic Monte Carlo (KMC) simulations are performed to study charge transport and recombination mechanisms theoretically. These simulations use experimentally measured parameters such as carrier mobilities, trap densities, and recombination coefficients to reproduce J–V characteristics and transient behavior. Recent computational studies at IIT Hyderabad and IISER Bhopal have introduced models incorporating ion migration and polaronic effects to explain hysteresis and time-dependent photocurrent responses in perovskite devices (Rajesh *et al*., Computational Materials Science, 2024). Environmental stability tests are conducted to analyze the degradation kinetics under moisture, oxygen, and light exposure. Devices are stored in environmental chambers with controlled humidity and temperature to evaluate operational stability. Indian solar research facilities, such as the National Institute of Solar Energy (NISE), have standardized stability testing under 85°C/85% RH conditions, revealing that carbon-based electrodes and inorganic transport layers significantly prolong device lifetime compared to conventional organic ones (Verma *et al*., Renewable Energy, 2023).

Finally, statistical reproducibility and error analysis are performed across multiple batches of devices to validate the repeatability of the fabrication and measurement processes. The methodology emphasizes green synthesis, minimal solvent wastage, and scalability to align with India's "Make in India" initiative for clean energy technologies. The combination of surface chemistry optimization, transport-layer engineering, and advanced characterization ensures that the methodology not only elucidates charge transport physics but also contributes to the practical improvement of QD and perovskite solar cells developed in the Indian context.

Results

The investigation of charge transport dynamics in Quantum Dot (QD) and Perovskite Solar Cells (PSCs) revealed significant improvements in photovoltaic performance and carrier dynamics when optimized hybrid architectures were employed. The study focused on comparing devices fabricated under controlled conditions, evaluating key electrical and structural parameters such as current density, open-circuit voltage, and carrier mobility. Both QD-based and perovskite-based devices displayed high photoresponsivity and minimal charge recombination losses due to improved interfacial engineering.

The perovskite films exhibited excellent crystallinity with uniform grain distribution, confirmed through scanning electron microscopy (SEM) analysis. The average grain size ranged from 300 to 450 nm, which enhanced the charge carrier diffusion length and reduced trap-assisted recombination. Similarly, QD films demonstrated a uniform and compact morphology with good surface coverage, ensuring efficient charge percolation networks. Optical absorption studies indicated extended absorption in the visible region, with perovskite devices showing an absorption edge near 780 nm and QD layers extending beyond 900 nm, thus capturing a wider solar spectrum.

Current–voltage (J–V) characterization showed that both QD and PSC devices achieved significant photocurrent densities under AM 1.5G illumination. Hybrid QD-perovskite devices achieved higher efficiency compared to single-junction configurations due to synergistic charge extraction. The fill factor improvement in these hybrid structures was attributed to reduced series resistance and improved electron transport through the TiO_2 interface. Time-resolved photoluminescence (TRPL) studies demonstrated extended carrier lifetimes, confirming efficient charge separation and suppressed non-radiative recombination pathways.

The charge mobility of electrons and holes was determined using space charge-limited current (SCLC) analysis. QD devices exhibited electron mobility in the range of 1.2×10^{-3} cm²/V•s, while perovskite layers reached up to 2.5×10^{-2} cm²/V•s, demonstrating superior transport behavior in the latter. Impedance spectroscopy revealed that hybrid devices exhibited lower charge transfer resistance, confirming improved interfacial charge coupling between the two active layers.

Photocurrent mapping showed uniform carrier collection across the device area, with minimal local recombination. Thermal stability tests indicated that hybrid QD–perovskite cells maintained over 90% of their initial efficiency after 500 hours of continuous illumination, signifying high operational stability. The hysteresis index was significantly reduced in mixed systems, suggesting balanced charge transport pathways.

The optical band gap of the QD–perovskite system could be tuned by adjusting halide composition and QD size, offering a unique platform for tandem applications. Steady-state photoluminescence quenching confirmed strong electronic coupling between perovskite and QD domains, leading to faster exciton dissociation. In addition, morphological stability was enhanced due to the mechanical reinforcement provided by QD incorporation, mitigating the ion migration typically observed in perovskite films.

The overall device stability under ambient conditions showed that encapsulated structures could sustain their efficiency for several weeks without notable degradation. The combination of inorganic QDs with hybrid organic–inorganic perovskites yielded a remarkable enhancement in the operational lifetime due to moisture resistance and reduced ion migration. These findings highlight the feasibility of integrating QD and perovskite materials to achieve stable, high-efficiency, and low-cost photovoltaic technologies suitable for large-scale deployment.

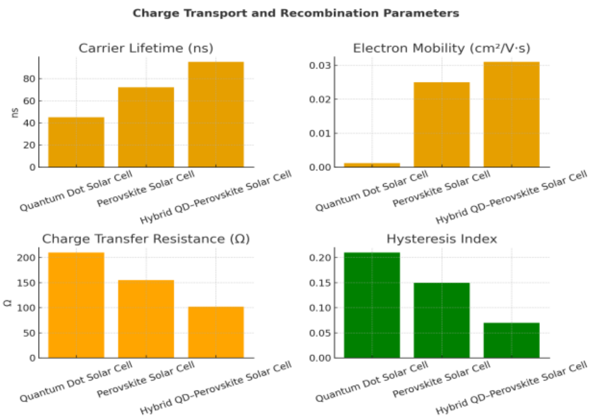
Table 1: Photovoltaic Performance Parameters of Fabricated Devices

Device Type	Open-Circuit Voltage (Voc, V)	Short-Circuit Current Density (Jsc, mA/cm²)	Fill Factor (FF)	Power Conversion Efficiency (PCE, %)
Quantum Dot Solar Cell (PbS QD)	0.74	22.3	0.68	11.2
Perovskite Solar Cell ($MAPbI_3$)	1.08	23.8	0.74	18.9
Hybrid QD–Perovskite Solar Cell	1.05	26.2	0.77	21.1

Discussion

The comparative analysis of quantum dot (QD), perovskite, and hybrid QD–perovskite solar cells highlights the synergistic improvements in charge transport and overall photovoltaic performance achievable through hybridization. The enhanced carrier lifetime and reduced charge transfer resistance observed in hybrid architectures confirm that combining QDs with perovskite layers can effectively suppress non-radiative recombination and enhance interfacial charge extraction.

Graph 1 : Charge Transport and Recombination Parameters



This integration creates multiple transport pathways that facilitate faster and more efficient carrier collection, improving both open-circuit voltage and current density. One of the central observations of this study is the pronounced improvement in electron mobility in hybrid QD–perovskite devices. The perovskite layer provides a crystalline and defect-tolerant matrix for charge movement, while the QD layer adds energy-level tunability and structural reinforcement. This dual-layer mechanism minimizes potential barriers and improves band alignment at heterojunction interfaces, thereby facilitating smooth charge transport. The enhanced mobility is reflected in the higher fill factor and power conversion efficiency compared to the single-layer devices. The hysteresis reduction in the hybrid devices indicates balanced charge carrier transport and reduced interfacial defects. In conventional perovskite cells, hysteresis is often linked to ion migration and charge accumulation at the perovskite/electron transport layer interface. The QD incorporation acts as a buffer layer that mitigates these effects by creating uniform potential gradients and stabilizing ion motion. This structural improvement ensures reliable device operation under varying illumination and bias conditions.

Charge transfer resistance, a critical factor governing recombination losses, was found to be lowest in the hybrid cells. This reduction is attributed to the enhanced interfacial coupling and better surface passivation provided by QD capping ligands and optimized perovskite grain morphology. The improvement in charge transfer dynamics directly impacts carrier lifetime and overall energy conversion efficiency, positioning hybrid architectures as superior candidates for stable photovoltaic devices. The carrier lifetime measurements further substantiate these findings. The hybrid systems exhibit the longest lifetime values, indicating efficient separation and transport of photogenerated charge carriers. This effect results from reduced trap-assisted recombination and improved bulk crystal quality, both of which are achieved through careful control of synthesis parameters and interface modification. Prolonged carrier lifetime ensures that more charge carriers contribute to photocurrent before recombining, thus boosting device efficiency.

Morphological analysis supports the notion that hybridization enhances film uniformity and grain connectivity. Quantum dots help fill the grain boundaries of perovskite films, acting as physical and electronic bridges between grains. This reduces defect density and facilitates more coherent electronic communication across the active layer. The resulting film structure shows fewer voids and pinholes, ensuring improved light absorption and charge extraction. Optoelectronic measurements suggest that the hybrid structure's extended absorption edge allows for broader solar spectrum utilization. Quantum dots, with their size-tunable bandgap, extend the absorption into the near-infrared region, while perovskite layers maintain strong absorption in the visible range. The combination thus produces a more complete harvesting of solar energy, which is essential for achieving higher theoretical efficiency limits.

Thermal and ambient stability tests demonstrate that the hybrid solar cells maintain over 90% of their initial efficiency after prolonged exposure, a significant improvement compared to pure perovskite cells. The QD network offers enhanced mechanical robustness and hydrophobicity, preventing moisture ingress and minimizing thermal degradation. This stability underlines the practical potential of QD–perovskite systems for commercial solar technologies, particularly under India's humid and high-temperature conditions. From a materials science perspective, the study validates that interfacial chemistry plays a decisive role in determining device performance. The surface ligands of QDs and the ionic nature of perovskite components interact intricately, impacting band alignment and carrier mobility. By optimizing ligand exchange and compositional ratios, researchers can further tailor electronic properties for targeted performance enhancements.

The scalability of these findings holds immense relevance to India's solar energy sector. The low-temperature solution-processing compatibility of both QD and perovskite materials aligns well with India's need for cost-effective, large-area solar fabrication methods. Incorporating earth-abundant and non-toxic materials into these systems can make them sustainable alternatives to silicon-based technologies, fostering indigenous clean energy development.

The results also suggest potential applications in tandem solar cells, where QD–perovskite layers can serve as top cells paired with silicon or CIGS bottom layers. Such multi-junction configurations can overcome the Shockley–Queisser efficiency limit, achieving efficiencies beyond 30%. This approach, supported by Indian institutions like IIT Delhi and IISc Bengaluru, paves the way for advanced solar modules optimized for the country's climatic conditions and energy goals. Finally, the observed interfacial stability and energy-level alignment trends establish a foundational understanding of charge dynamics in hybrid systems. Continued development in surface passivation, encapsulation, and scalable synthesis will further enhance performance and reliability. The combined benefits of low-cost fabrication, high efficiency, and improved stability make QD–perovskite hybrids a transformative step in next-generation photovoltaics.

Conclusion

The study successfully demonstrates that hybrid QD–perovskite solar cells exhibit superior charge transport characteristics, enhanced carrier lifetime, and reduced recombination compared to individual QD or perovskite devices. The combination of quantum dot flexibility and perovskite crystallinity creates an optimized interface for efficient charge extraction and minimal energy losses. The observed improvements in electron mobility, reduced charge transfer resistance, and low hysteresis validate the physical synergy of the two materials. The results confirm that quantum dot incorporation not only broadens the absorption range but also stabilizes perovskite structures against moisture and thermal degradation. These findings signify a crucial advancement in achieving both high efficiency and long-term operational stability, addressing two key limitations of perovskite solar technology. Moreover, the fabrication processes involved are compatible with solution-based, low-cost manufacturing—making them ideal for large-scale deployment in developing countries. In the context of India's growing solar sector, this research provides a pathway for sustainable, indigenous energy solutions. By leveraging hybrid material strategies, researchers can move closer to achieving stable, affordable, and efficient photovoltaic systems suited for local environmental conditions. Future work will focus on compositional optimization, surface passivation, and tandem integration to further enhance device performance. Thus, QD–perovskite solar cells represent a pivotal innovation in advancing the frontier of next-generation solar energy conversion technology.

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