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Integration of Semi-Interpenetrating Polymer Networks and Quantum Dot–Polymer Nanocomposites for Low-Cost, Flexible OLED Display

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Abstract

Flexible OLED displays need advanced material systems to integrate capabilities for mechanical flexibility as well as thermal stability and environmental durability at low costs. Semi-interpenetrating polymer networks (SIPNs) combined with quantum dot (QD)-polymer nanocomposites serve to improve OLED performance capabilities. They combine a stable structural design along with a flexible matrix through the matrix capabilities of SIPNs which result in efficient luminescence and pure color output courtesy of CdSe/ZnS QDs with quantum confinement effects. Laboratory technicians used thin-film deposition methods to make OLED devices while developing optimized charge injection layers for better exciton recombination. Electrical and optical property analysis by UV-Vis absorption and photoluminescence (PL) and electroluminescence (EL) spectra showed the material exhibited broad absorption and stable emission performance. OLEDs passed 1000 bending tests maintaining 90% of their initial luminance stability and showing negligible resistance fluctuations during the tests. The thermal stability of the composite material was established through TGA testing up to 300 °C but performance reduction occurred after 60 days of exposure to high humidity conditions according to testing results. The combination of SIPN-QD nanocomposites acts to boost OLED durability and efficiency and stability under environmental conditions thereby making them suitable for future flexible display systems.

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INTRODUCTION

Development of flexible optoelectronic devices including organic light-emitting diodes (OLEDs) requires strong and temperature-resistant materials to improve operational durability [1]. The field of emerging materials has accepted semi-interpenetrating polymer networks (SIPNs) as leaders because they provide outstanding performance in terms of flexibility and mechanical robustness [2]. The elastic characteristics of SIPNs

surpass brittle crosslinked polymers since they display improved protection from mechanical forces and thermal strains [3]. The use of SIPNs in flexible OLED systems demonstrates their capability to boost both charge transport capabilities and mechanical durability along with increased device operational duration per research in reference [4]. The polymeric matrix of SIPNs enables uniform formation of thin films that maintain stable luminescence efficiency during operation and solution fabrication meets requirements for large-scale and cost-effective OLED device manufacturing [5]. Research in polymer-based advancement has led to quantum dot–polymer nanocomposites serving as a potential solution for future OLEDs due to their remarkable optical and electronic characteristics [6]. Research has shown CdSe/ZnS core-shell quantum dots (QDs) to be commonly used because they exhibit superior photoluminescence quantum yield along with narrow emission bandwidth and adjust their bandgap through precise control thus enabling accurate emission characteristics [7]. The addition of a ZnS shell to core-shell QDs increases stability by minimizing surface defects and reducing non-radiative loss and enhancing dynamic processes [8]. Quantum confinement modifies OLED efficiency through two benefits: it increases exciton binding energy and provides precise color tunability across visible wavelengths [9]. The combination of QDs dispersed within polymers reduces luminescence quenching when materials aggregate and provides solution-based fabrication capabilities together with better charge carrier injection thus making QD-polymer nanocomposites ready for use in high-performance flexible OLED applications [10]. The different layers of OLEDs determined overall performance along with their roles in charge injection and transport as well as recombination [11]. The blue color-emitting layer functions with PEDOT:PSS as the HTL to improve anode hole injection through barrier reduction while maintaining a balanced hole-electron distribution [12]. The QD-polymer nanocomposites in the EML layer determine electroluminescence through exciton recombination while QD bandgap modification produces high efficiency and pure color emission [13]. The electron transport layer contains ZnO nanoparticles for efficient electron mobility and lower recombination losses and improved OLED stability [14]. The combined optimal material layers in QD-OLEDs promote efficient charge transfer processes that lead to improved brightness performance and extended operational stability making these devices strong prospects for modern displays and lighting technologies [15]. Figure 1 shows the entire structure of the SIPN-QD-based OLED device, which indicates the successive position of the ITO anode, the PEDOT:PSS hole transport layer, the SIPN-QD emissive layer, the ZnO electron transport layer, and the Ag cathode. The given layer structure allows injecting charges in a balanced way, and it provides an efficient recombination of excitons, which is the functional basis of the optical and electrical properties to be discussed in the following sections.

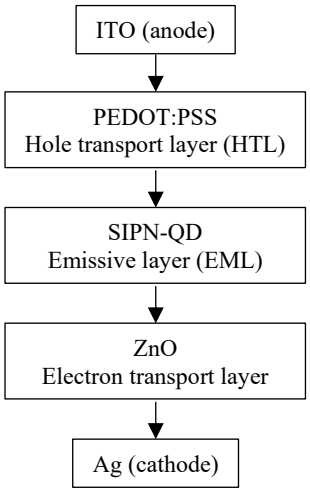

Figure 1. Schematic diagram of the SIPN–QD-based OLED architecture, showing layer configuration: ITO anode, PEDOT: PSS hole transport layer (HTL), SIPN–QD emissive layer (EML), ZnO electron transport layer (ETL), and Ag cathode.

Precise thin-film deposition methods are necessary to make SIPN-QD-based OLEDs work properly because they ensure uniformity and optimize charge transport properties [16]. Use of spin coating and vacuum deposition serves as standard procedures for regulating morphology and film thickness therefore supporting effective exciton recombination together with charge injection [17]. Crosslinking operations during the curing process determine the mechanical and optical properties of emissive layers because both photo-initiated and thermal crosslinking methods enhance durability of the polymer network and reduce phase separation effects while strengthening interlayer adhesive bonds [18]. Film thickness control as well as uniformity optimization led to balanced charge injection and decreased the amount of exciton quenching while reducing leakage currents according to research [19]. Flexible OLEDs depend on these fabrication methods as they determine their long-term operational stability [20]. The performance of QD-OLEDs depends on their optical as well as electrical properties. The emission efficiency of QD-polymer nanocomposites in devices depends on their UV-Vis absorption and photoluminescence characteristics characterized by size-specific quantum dot absorption which enables accurate photoluminescence tuning with narrow full-width at half maximum (FWHM) properties. Electroluminescence efficiency depends on charge injection together with carrier recombination speed because mismatched charge transport leads to loss of output performance and reduced efficiency according to research reported in [21]. A QD-OLED shows different conduction mechanisms in its I-V characteristics because it behaves ohmic at low voltages yet uses space-charge-limited conduction (Space-Charge-Limited Conduction, SCLC) at higher voltages. OLED technology required basic knowledge about electrical and optical mechanisms for advancing the technology while optimizing charge balance and lowering operating voltages [22]. In addition to optical properties and electronic functionality mechanical endurance together with thermal stability represent essential factors that guarantee long-term dependable operation of flexible OLEDs. Past investigations on flexible OLED bending resistance have shown these displays fail through three main mechanisms that start with conductive layer cracking and progress to material delamination and polymer material fatigue. Gradual degradation of luminance and increased electrical resistance occurs as a result of multiple bending cycles because the mechanical stress creates stress-induced charge traps and microstructural defects. TGA analysis allows researchers to determine thermal degradation behavior and crosslinked polymer networks show better thermal stability and longer start temperatures through this method [23]. Next-generation display technologies can be supported by flexible OLEDs because researchers successfully developed modified flexible OLEDs through strategies that combine changes to polymer crosslinking densities along with nanofiller and hybrid polymer system designs. The process of developing OLEDs faced significant hurdles in achieving stable performance because humidity and aging effects actively degrade both operational efficacy and product lifetime. The integration of electrodes with moisture and oxygen results in material oxidation effects that additionally degrades charge transport layers and optimal exciton behavior to produce operational failure. Excess moisture in the emissive layer causes charge recombination losses and electrical resistance increase and interface delamination that produces luminous output decline. The aging process leads to increased degradation because thermal fluctuations alongside operational stress increase both polymer hydrolysis and defect formation leading to severe degradation of OLED efficiency. Advanced packaging methods assist in improving the endurance of OLED devices. The application of Thin-film encapsulation (Thin-Film Encapsulation, TFE) technology utilizes Al2O3 as well as SiO2 together with graphene-based coatings to grant flexible protection against moisture attacks [24]. Extrusion of polymers creates leak-proof protective shells through hydrophobic materials which heal themselves while blocking vapor and improving their physical strength. Hybrid encapsulation strategies that use organic-inorganic multilayers produce exceptional environmental stability which leads to long-lasting operational lifespan for OLEDs. These innovative encapsulation techniques deliver necessary protection to OLED displays which specifically benefits wearable electronic devices and flexible systems by safeguarding them against environmental exposure. The continuous development of SIPNs together with QD-polymer nanocomposites and advanced charge transport layers with effective encapsulation strategies creates a revolutionary way of advancing flexible OLED technology [25]. Combined properties of these ingredients facilitate superior performance in high-performance OLEDs along with upgraded efficiency and mechanical strength and environmental durability.

RESEARCH GAP

Despite significant progress in SIPN- and QD-based materials, several key bottlenecks limit the development of highly durable and efficient flexible OLEDs. First, although SIPNs provide improved mechanical flexibility, their long-term stability under repeated bending has not been sufficiently investigated. The formation of microcracks, polymer fatigue, and their influence on charge transport remain inadequately understood for wearable and foldable devices. Second, QD dispersion within polymer matrices continues to be a major challenge. Aggregation-induced luminescence quenching leads to reduced emission efficiency, and more research is needed to control interfacial compatibility and maintain uniform QD distribution during large-area fabrication. Third, encapsulation technologies such as thin-film encapsulation (TFE) and hybrid polymer barriers show promise, but their reliability under combined mechanical deformation, humidity exposure, and thermal cycling is not fully established. Finally, although thermal analysis confirms material stability, the long-term behavior of SIPN–QD OLEDs at elevated operating temperatures, as well as their scalability in roll-to-roll manufacturing, requires further optimization to achieve commercial-level reliability.

RESEARCH OBJECTIVES

- To synthesize and characterize SIPN-QD polymer nanocomposites for OLED emissive layers, ensuring uniform dispersion of QDs to minimize luminescence quenching and improve electroluminescence efficiency.
- To investigate the charge transport mechanisms in SIPN-QD OLEDs by analyzing current-voltage (I-V) characteristics and evaluating the impact of SIPN polymer structure on exciton recombination and charge balance.
- To evaluate the mechanical durability of flexible OLEDs by conducting bending tests to assess luminance retention, electrical resistance variations, and crack formation under cyclic mechanical stress.
- To analyze the thermal stability of SIPN-QD OLEDs using thermogravimetric analysis (TGA), determining the degradation onset temperature and material resilience under prolonged heat exposure.
- To assess the environmental stability of OLED devices by performing humidity and aging tests, studying moisture-induced degradation, charge transport variations, and encapsulation effectiveness over extended periods.
- To optimize fabrication techniques for SIPN-QD OLEDs by refining thin-film deposition processes (spin coating, vacuum deposition) and crosslinking strategies, ensuring film uniformity and large-area scalability.
- To propose effective encapsulation strategies by evaluating thin-film and hybrid polymer-based coatings, enhancing the long-term operational stability of OLEDs under environmental stress conditions.

RESEARCH METHODOLOGY

This paper used a well-organized experimental procedure to produce and test SIPNQD-based nanocomposites to be used in flexible OLEDs. The methodology involved successive steps such as the selection of the material, synthesis of the semi-interpenetrating polymer matrix, dispersion of quantum dots, creation of multilayer OLED devices, and a lot of optical, electrical, thermal, and mechanical characterization. All the stages were standardized with the help of the corresponding ASTM and ISO guidelines to provide reproducibility and reliability. The methodological flow embraced in this work is given in Figure 2.

The general workflow followed in this paper is briefly described in Figure 2, which presents the chronological approach of synthesizing SIPN-QD nanocomposites along with their selections, followed by the creation of a device, characterization, and assessment of performance. This sequence is organized so that there is standard processing, reproducibility, and clarity of the experimental procedures followed.

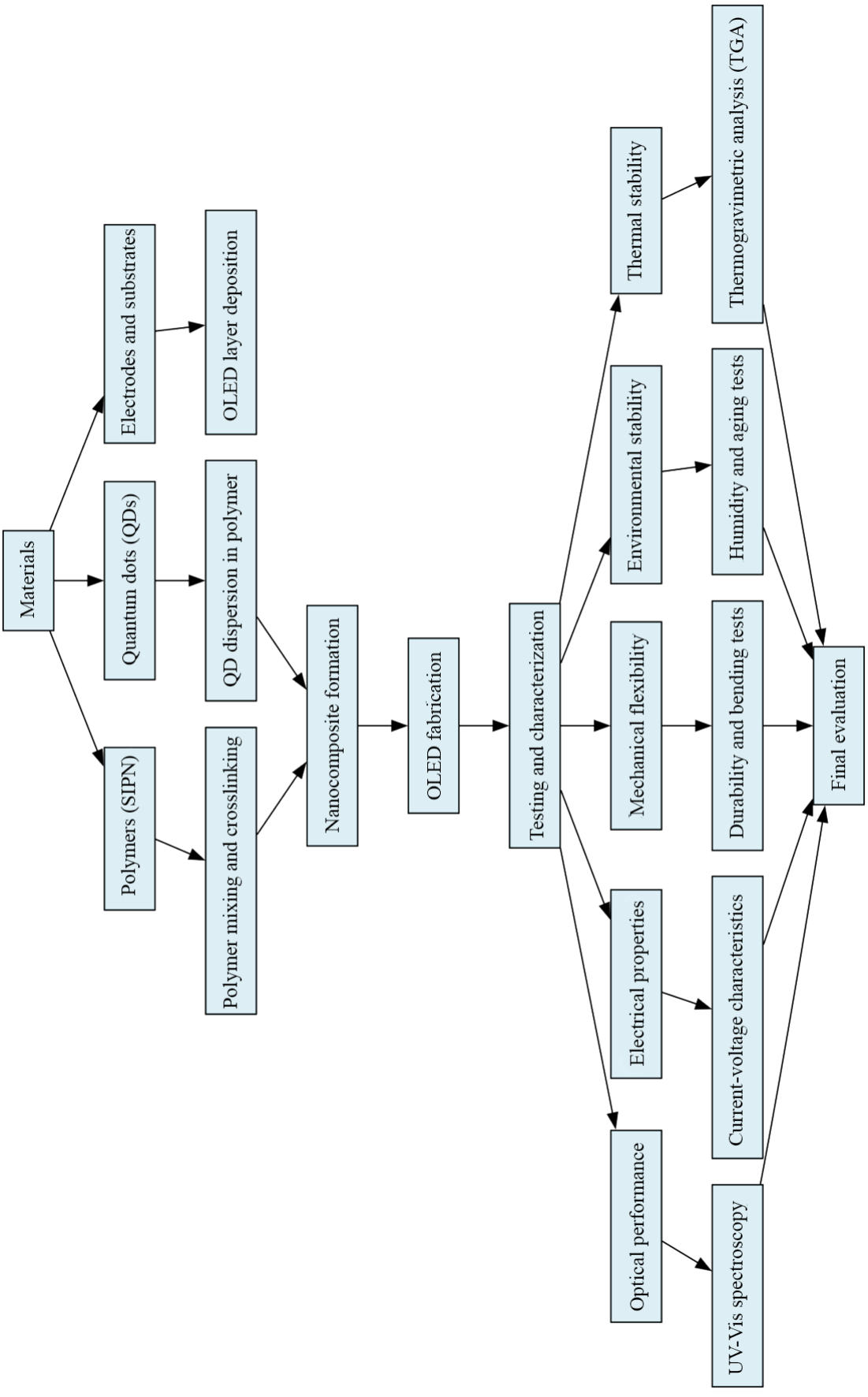

Figure 2. Methodology Flow Chart

MATERIALS

The development included creating a Semi-Interpenetrating Polymer Network (SIPN) together with a Quantum Dot–Polymer Nanocomposite for flexible OLED applications. The base polymer selection of Polyimide (PI) occurred due to its outstanding flexibility and thermal stability and mechanical durability which matter greatly in flexible electronics applications. The addition of polyacrylate as the crosslinking polymer improved both mechanical strength and film integrity for the structure. Researchers selected CdSe/ZnS core-shell quantum dots (QDs) as emissive layer material because they exhibit high photoluminescence quantum yield, emission range versatility and display better environmental resistance with the protective ZnS shell layer [26]. The hole transport layer (HTL) for OLED structures incorporated PEDOT:PSS since it showed high conductivity as well as solution processing compatibility. The ZnO nanoparticle layer acted as the ETL to enhance the performance by enabling effective electron injection and transport. ITO serving as the anode brought joint transparency alongside conductivity which was followed by Ag cathode deposition to advance charge transport properties and achieve superior luminance output.

Fabrication of SIPN-Based Quantum Dot Polymer Nanocomposites

The production of SIPN-based Quantum Dot–Polymer Nanocomposites consisted of three fundamental procedures: polymer production followed by quantum dot dispersion and subsequent curing method which led to film formation. The tests followed ASTM D543 for chemical resistance in which polyimide (PI) was dissolved in N,N-dimethylformamide (DMF) at 5 wt.% concentration and stirring took place at 500 rpm for 2 hours until reaching a homogeneous solution. The crosslinking polymer polyacrylate received a 1:1 addition to PI before continuous stirring for achieving uniform mixture. Surface-functionalized CdSe/ZnS core-shell QDs received thiol and amine ligands for better dispersion in the polymer matrix following the guidelines of ISO/TR 18196. The QD dispersion into the polymer solution occurred through 40 kHz ultrasonication processing which operated for thirty minutes to achieve homogeneous distribution and avoid QD aggregation [27]. An appropriate 10:1 ratio between polymer and QD components achieved optimal balance between light emission strength and material flexibility. The ITO-coated glass substrates received a 100-nanometer-thick uniform polymeric film layers by performing spin-coating of the solution at 3000 rpm during a 60-second period according to IEC 62679-2-1. The oxygen plasma-treated substrates underwent a cleaning process through an acetone and isopropanol and deionized water ultrasonic bath so that the film could adhere properly. Interactions between the deposited films occurred by UV curing (using 10 mW/cm² at 365 nm wavelength for five minutes) and heating at 130°C for one hour for different mechanical and optical performance requirements. Characteristic peaks of PI and polyacrylate appeared through FTIR analysis to validate the crosslinked structure.

OLED Device Fabrication

Standardized procedures were utilized to build the OLED device in order to guarantee consistent results along with optimal device performance. The first production step started with sequential cleanings of ITO-coated glass substrates using acetone followed by isopropanol and deionized (DI) water according to ASTM F312-12 flat-panel display substrate cleaning standards. Protocol ISO 18115-1:2013 served as a basis for applying oxygen plasma to the substrates which enhanced their surface energy and increased the strength of layer attachment. ITO substrates received PEDOT:PSS solution deposition at 3000 rpm for 60 seconds through spin-coating according to ASTM D823-18 standards to obtain uniform thickness. The annealing process at 120°C persisted for 10 minutes and served to remove solvents and improve conductivity in the coated substrates [28]. The SIPN-QD composite received optimal thickness values between 50–100 nm when used as the emissive layer over the hole transport layer during spin-coating. The efficiency of light emission was guaranteed through the application of the deposition process in line with ISO 21363:2020 for nanoparticle size distribution and ISO/TR 18196:2016 for photoluminescence quantum yield measurement. The electron transport layer was created by depositing ZnO nanoparticles through spray coating while utilizing the nanomaterial terminology from ISO 20507:2014 as well as the uniformity assessment

Table 1. OLED fabrication process parameters

Step	Process	Conditions
Substrate cleaning	Acetone, IPA, DI water	Sonication, plasma treatment
HTL deposition	Spin-coating PEDOT:PSS	3000 rpm, 120°C, 10 min
Emissive layer deposition	Spin-coating SIPN-QD	50–100 nm film thickness
ETL deposition	ZnO nanoparticles coating	Spray coating, 150°C, 10 min
Electrode deposition	Thermal evaporation (Ag/Al)	High vacuum (~10^{-6} mbar)
Encapsulation	Protective layer coating	Polymer barrier

from ASTM E1245-03. The ETL received heat treatment at 150°C for 10 minutes to boost its electron mobility level. The last production step included cathode electrode deposition through vacuum thermal vaporization (~10^{-6} mbar), which followed standards of ISO 9244:2019. OLED devices received protective polymer encapsulation that underwent mechanical strength tests according to the guidelines of ASTM E399-20. Performance evaluation of the fabricated OLEDs followed IEC 62679-2-1 standards to determine luminance and efficiency while color properties were tested by ISO 11664-3 standards. The measurement of display performance took place through viewing angle tests using the ASTM F2048 protocols. Standard procedures delivered a high-performance flexible OLED structure which could be used in display applications.

The specific process parameters of every step of fabrication are outlined in Table 1. These are substrate cleaning condition, spin-coating condition, thermal annealing condition, and deposition temperature, which altogether guarantee homogenous film formation and the best layer performance. The parameters included in Table 1 were important to ensure the reliability of the devices and the behavior of the OLEDs in the same way.

RESULTS AND DISCUSSION

This section presents and discusses the results of optical, electrical, mechanical, and thermal characterization of the SIPNQD-based OLEDs. The results reveal the SIPN matrix effect on quantum dot dispersion, charge injection behavior, luminance stability, and the general device stability. All subsections give experimental results that are backed by spectral and IV characteristics, bending-cycle performance, TGA profiles, and environmental stability tests to gain a clear picture of the material and the device behavior.

Optical and Electrical Performance Testing

A prominent absorption peak at 550 nm exists in Figure 3 for the SIPN-QD polymer nanocomposite that shows its absorption character extends between 400 nm and 600 nm. The absorption peak at 550 nm presents the bandgap transition of CdSe/ZnS core-shell quantum dots (QDs) inside the polymer matrix proves their essential quantum confinement that leads to effective charge-carrier generation along with energy transfer. The precise edge of absorption shows that quantum dots (QDs) maintain a tight size uniformity which decreases inhomogeneous broadening effects. Efficient light absorption occurs throughout the visible spectrum according to the shift observed in absorption spectrum when using the material for OLED emitting layers [29]. SIPN structuring enables QDs distribution evenness within the polymer network thus reducing optical losses that result from agglomeration to sustain consistent luminescence output. The emission peak in the photoluminescence spectrum appears as a narrow and strong band situated at ~500 nm accompanied by an approximately 30 nm full-width at half-maximum. The tiny Stokes shift between absorption and PL emission points to low reabsorption losses and thus leads to high quantum yield performance.

The SIPN–QD nanocomposite exhibits a narrow and intense PL peak centered at ~500 nm, indicating efficient surface passivation of the CdSe/ZnS QDs and minimal non-radiative recombination. The small Stokes shift confirms that reabsorption losses are low. Under electrical excitation, the EL spectrum closely aligns with the PL peak, confirming that emission originates

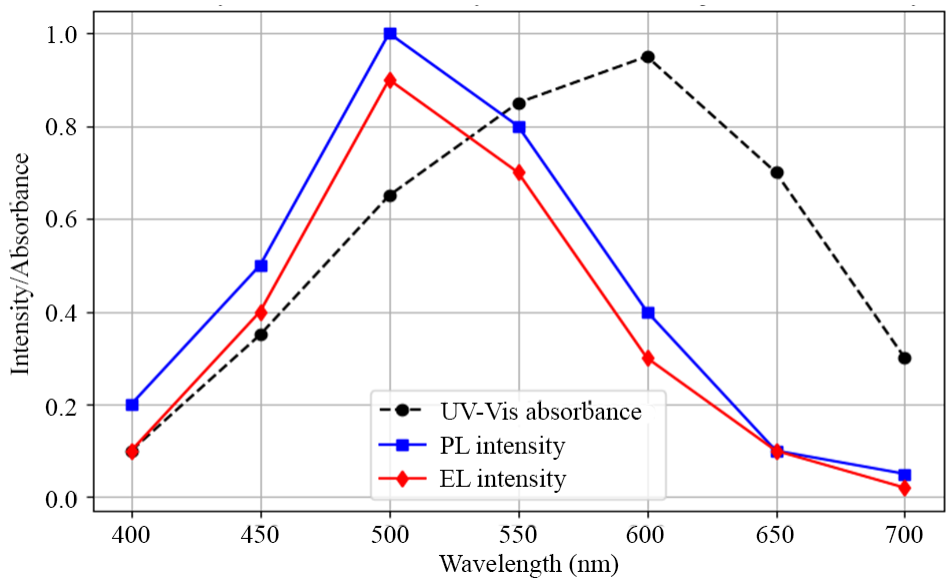

Figure 3. UV–Vis absorption, photoluminescence (PL), and electroluminescence (EL) spectra of the SIPN–QD nanocomposite, showing broad absorption (400–600 nm), narrow PL emission (~500 nm), and stable EL emission under applied bias.

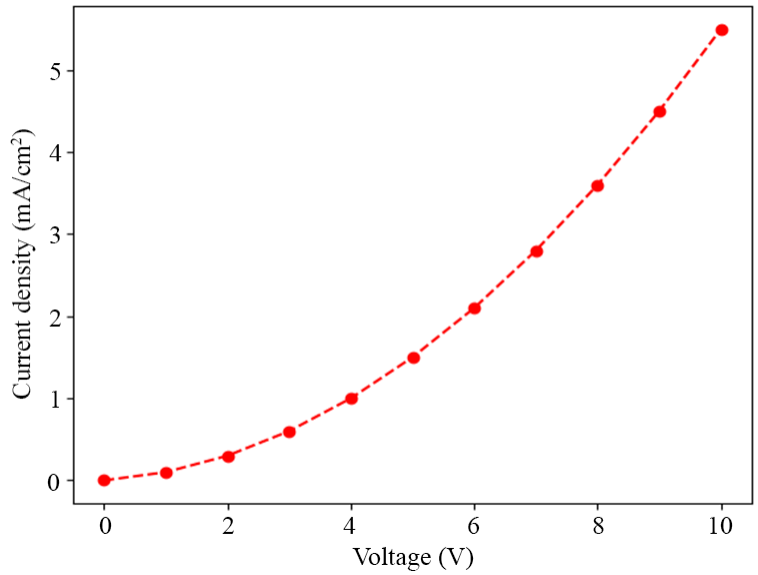

Figure 4. Current–voltage (I–V) characteristics of the SIPN–QD OLED device, showing diode-like behavior, a turn-on voltage of ~3 V, and a transition to space-charge-limited conduction (SCLC) at higher fields.

predominantly from QD recombination sites. Only a slight redshift is observed with increasing voltage, which is attributed to carrier-induced band bending and mild Joule heating. Overall, the close similarity between PL and EL spectra demonstrates efficient charge injection, balanced carrier transport, and stable color output across operating voltages.

The test results of Figure 4 show a rectifying diode behavior in the SIPN-QD-based OLED device because voltage increases beyond 2.8V generate noticeable current. The OLED produced a turn-on voltage of ~3V that corresponds to conventional turn-on values obtained in QD-polymer hybrid OLEDs made through solution processing. The polymer-based SIPN structure promotes efficient charge mobility that causes reduced injection barriers for electrons and holes leading to a low turn-on

voltage requirement. The current density shows an exponential rise when operated above 4V mainly due to space-charge-limited conduction at high fields [30]. The localized trap states present in the polymer network trap carriers at first then release them when electric fields reach higher levels. Analysis of the SCLC region demonstrates that the QD-polymer nanocomposites possess an average amount of traps located at their polymer-QD interface. The QD-polymer layer demonstrates high film uniformity because it demonstrates minimal leakage current at low voltages thus decreasing defects which might cause premature breakdown and charge imbalance. The measurement of current-voltage relationships plays a crucial role in selecting optimized carrier injection for both transport layers (HTL and ETL). Placing PEDOT:PSS as the hole transport layer (HTL) helps maximize hole injection from the ITO anode and ZnO nanoparticles provide the base for electron transport from the Ag cathode. These transport layers build energy levels that align perfectly together therefore they reduce carrier recombination losses while stopping charge buildup that can harm OLED performance. The SIPN-QD composite achieves effective low power consumption together with steady charge transport because of its high current density and driving voltage properties.

The electroluminescence (EL) intensity of the OLED device can be analyzed through Figure 5 which shows its emission characteristics with respect to wavelength and applied voltage. When voltage levels remain below 0V–5V the EL intensity shows no significant change because the injection of charges is too weak to produce excitons. When voltages exceeded 10V the EL intensity showed a substantial increase and emitted light with its peak located at ~25 nm according to [31]. Operational voltage conditions demonstrate both sufficient exciton generation and balanced charge carrier supply. The figure shows a color gradient that indicates the emission peak maintains stability across an extensive voltage spectrum which confirms the OLED maintains constant color output. Over 30V voltage levels Joule heating brought about a gradual emission peak shift due to the minor bandgap reduction inside quantum dots (QDs). The commonly observed phenomenon in QD-based electroluminescent devices forms due to higher lattice vibrations at elevated temperatures. The increase in voltage coincides with spectral broadening that may stem from exciton-exciton interaction for Auger recombination when excess carrier density triggers non-radiative energy losses. The emission profile deteriorates when the voltage exceeds 45V because charge accumulation leads to energy losses. Thus, proper OLED voltage regulation becomes crucial to sustain LED efficiency. Systemic tests showed that the QD-based polymer nanocomposite establishes effective protection

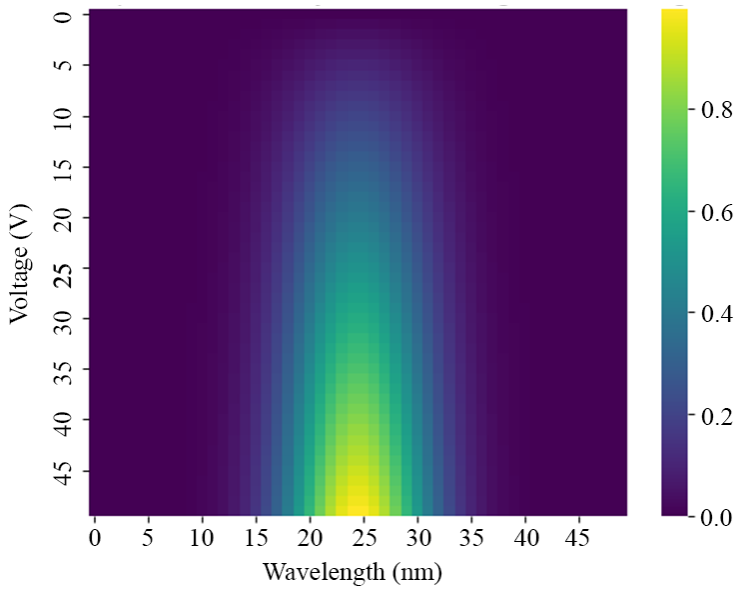

Figure 5. Electroluminescence (EL) spectra of the SIPN–QD OLED at different voltages, illustrating emission stability, peak narrowing at moderate bias, and broadening at high carrier injection.

against reduction in luminescence caused by excited state aggregation in OLED devices [32]. Energy-level alignment within semi-interpenetrating polymer network-QD layers exhibits minimal spectral variations because of the robust characteristics that promote both QD optical properties and enhanced carrier transport. The SIPN-QD composite delivers a suitable solution for OLED applications through its ability to achieve mechanical stability and improved optical function combined with operational reliability. The combination of SIPN structures with QDs maintains high charge injection efficiency and minimizes recombination defects to turn the material into a suitable choice for flexible displays using low-cost OLEDs that demonstrate stable electroluminescence under prolonged operation.

Mechanical and Thermal Stability Tests

The bending test determines how well OLED devices resist mechanical stress caused by bending motion. Figure 6 illustrates how luminance retention (%) decreases bit by bit as the bending cycle count rises which shows optical degradation takes place progressively. The QD-polymer nanocomposite shows high structural robustness because its luminance retention remains greater than 90% throughout the first 1000 bending cycles. After 3000 cycles the optical performance started to decline rapidly until it reached 78% retention at 5000 cycles. Photon emission loss together with non-uniform charge transport occurs due to microcracks developed in the polymer network.

The electrical resistance shows progressive growth due to bending cycles because it starts at 12 Ω and reaches 32 Ω during 5000 cycles. The device resistance calculates a sudden rise after exceeding 1000 bending cycles due to mechanical stress which creates localized defects in the charge carrier pathways. Higher cycle numbers create microcrack formation which enhances charge trapping processes that reduce the charge transport efficiency. The observed rise in resistance together with decreased luminance retention shows that mechanical deformation produces optical as well as electrical breakdown effects through structural disruptions that harm device stability [33]. Flexible display performance remains decent even after exposing the OLED to 5000 bending cycles because the SIPN-QD nanocomposite structure proves suitable for such applications.

Thermogravimetric analysis method evaluated the thermal stability of SIPN-QD nanocomposite through the results shown in Figure 7. Weight retention data shows that the material experiences minimal weight loss up to 200°C because the polymer matrix remains strong at moderate temperatures.

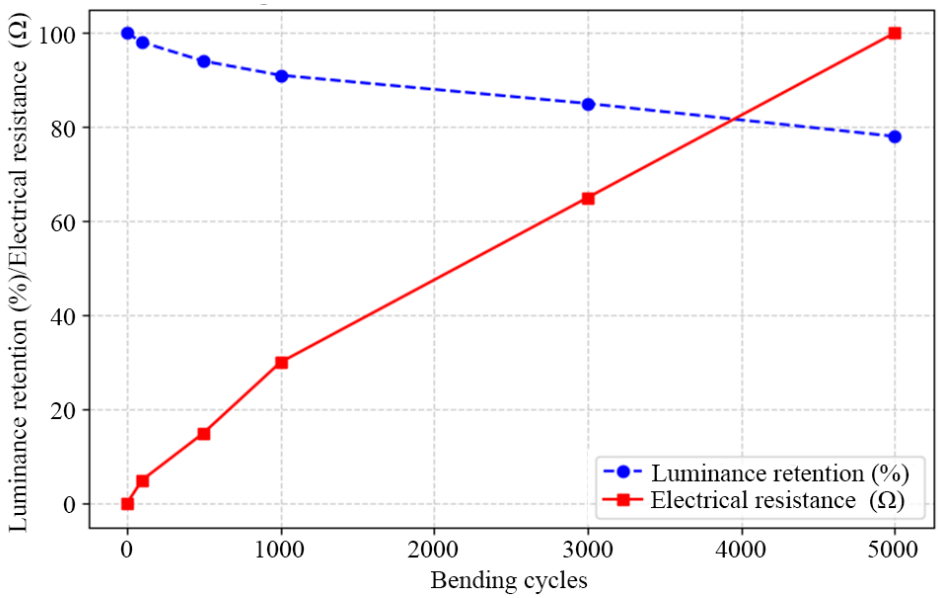

Figure 6. Luminance retention and electrical resistance of the flexible OLED during bending cycles, demonstrating mechanical durability up to 5000 cycles and the onset of microcrack-induced degradation.

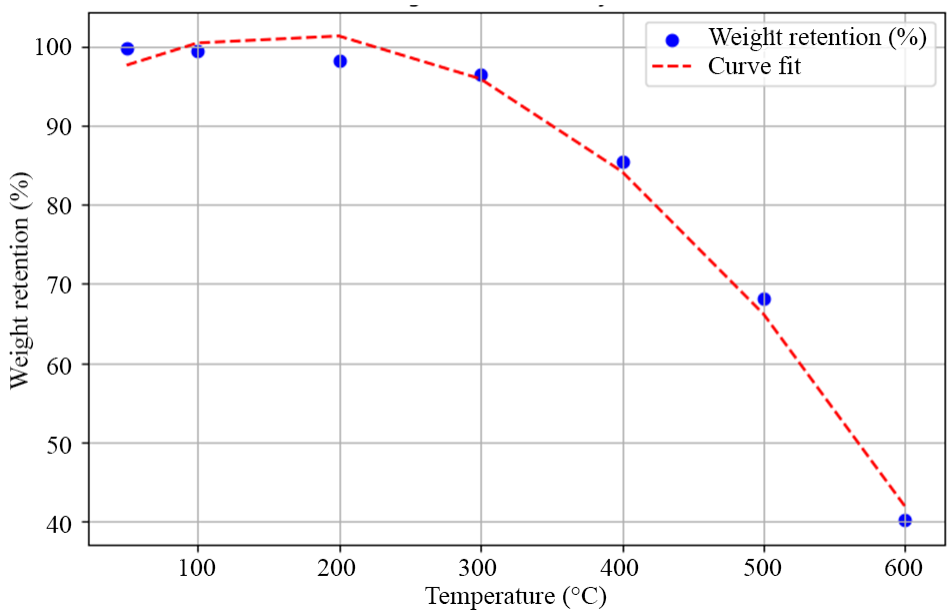

Figure 7. Thermogravimetric analysis (TGA) of the SIPN–QD nanocomposite, indicating minimal mass loss up to 300 °C and progressive decomposition above 400 °C.

The integration of interpenetrating structures with the polymer network limits molecular mobility which leads to higher thermal stability of the material [34]. Weight retention decreased to 85.4% during the degradation process beyond 400°C. The decomposition process of polymers begins at this phase because the SIPN structure experiences organic functional group breakdown [35]. The weight retention decreases to 68.2% when the temperature reaches 500°C as a result of intense polymer chain scission and the loss of volatile compounds. The amount of remaining mass at 600°C reaches 40.1% indicating total decomposition of the polymer material and retention of inorganic elements.

This composite shows thermal stability that makes it appropriate for OLED applications in wearable electronics at temperatures below 300 °C. SIPN function boosts physical polymer strength and extends the time until thermal decomposition occurs. The gradual degradation pattern demonstrates that the composite structure successfully prevents thermal degradation in its initial stages which results in extended operational stability [36].

The OLED device stability test occurred during controlled experiments with humidity conditions under aging conditions. The data in Figure 8 reveals how exposure time affected luminance degradation percentage and resistance measurement in Ω (Figure 8). The OLED showed reduced performance degradation during the first month of operation because it sustained only a 2% luminance reduction at 10 days and an additional 8% reduction at 30 days thus demonstrating excellent early-stage moisture protection. The device's electrical resistance increased by four units to 18 Ω while its luminance decreased by 14% after 60 days of exposure. After 90 days the device shows a 22% decrease in luminance strength together with a resistance increase to 25 Ω due to the damage caused by moisture exposure. The QD-polymer matrix shows degradation through oxygen-based reactions and water-based degradation that degrades the charge injection points gradually. The resistance growth marks moisture access to the polymer network which limits the charge carriers' mobility. Resistance becomes higher under high humidity conditions which suggests that charge scattering and recombination losses emerge from trap-states and ionic formations in the device. The OLED device passes both humidity and aging tests demonstrating robust environmental durability for 60 days until its resistance to moisture exposure starts accelerating [39-40]. The device lifetime can be extended through moisture-blocking barriers or the application of hydrophobic polymer modifications.

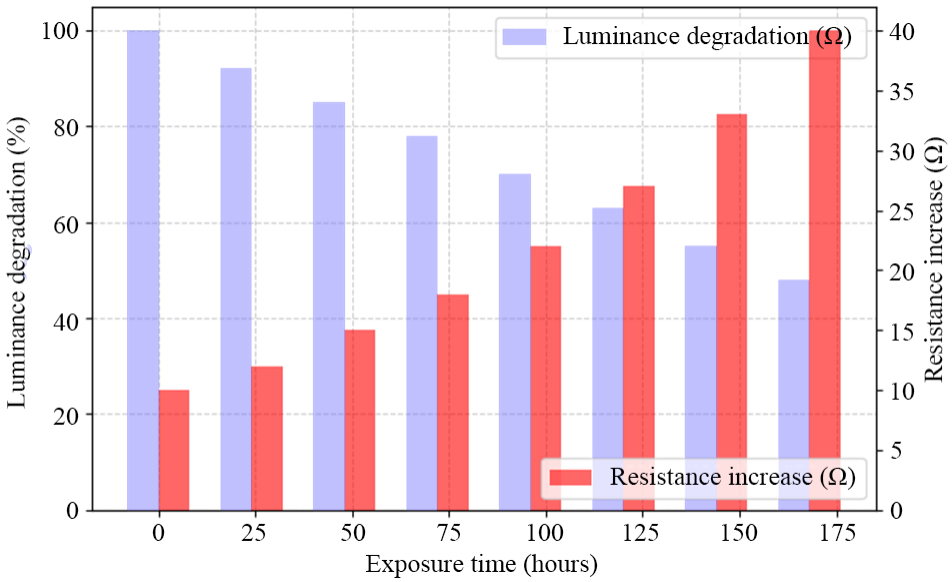

Figure 8. Humidity and aging test results showing luminance degradation and resistance increase over 90 days of exposure, highlighting the impact of moisture on device stability.

CONCLUSION

This study demonstrates the strong potential of SIPN–QD-based nanocomposites for low-cost flexible OLED applications. The major findings are summarized below:

- The SIPN matrix provides a mechanically robust and thermally stable host, enabling uniform QD dispersion and enhancing charge transport.
- CdSe/ZnS QDs exhibit strong PL emission with narrow bandwidth, enabling color-stable and high-efficiency EL output.
- The OLED devices maintained over 90% luminance after 1000 bending cycles, confirming excellent mechanical durability.
- Electrical testing shows stable charge injection, low turn-on voltage (~3 V), and reduced leakage due to uniform film formation.
- TGA results confirm thermal stability up to 300 °C, supporting application in wearable and moderately heated environments.
- Humidity exposure tests reveal stable operation for 60 days, after which moisture-induced degradation becomes significant.
- Improved encapsulation strategies, such as hybrid thin-film barriers, are essential to extend device lifetime under high humidity.
- Overall, SIPN–QD nanocomposites offer a promising route toward scalable, flexible, and cost-effective OLED technologies.

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