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BLUE SINGLE-LAYER LIGHT-EMITTING DIODES BASED ON A PEROVSKITE–POLYMER COMPOSITE

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Abstract. This study explores single-layer blue light-emitting devices based on a solution-processed hybrid perovskite–polymer composite. The emissive layer was formed from bromide precursors of an alkali metal and lead using a polymer matrix and organic additives. Thin films were deposited on transparent conductive substrates by spin-coating. Optical and electrical characteristics were evaluated at room temperature. The devices exhibit stable, narrow-band blue electroluminescence at relatively low operating voltages. Current–voltage analysis reveals distinct charge-transport regimes associated with carrier injection and recombination within the perovskite–polymer active layer. The results confirm the proof-of-concept of the proposed approach and indicate its potential for low-cost optoelectronic applications.

Keywords: blue light-emitting diode; electroluminescence; halide perovskites; perovskite–polymer composite; single-layer architecture; solution processing.

Perovskit–polimer kompozitiga asoslangan ko‘k bir qatlamli yorug‘lik chiqaruvchi diodlar

Annotatsiya. Mazkur ishda eritma asosidagi usulda olingan gibrid perovskit–polimer kompoziti asosida bir qatlamli ko‘k rangli diapazonda yorug‘lik chiqaruvchi qurilmalar imkoniyati o‘rganildi. Nurlantiruvchi qatlam ishqoriy metall va qo‘rg‘oshin bromid prekursorlaridan polimer matritsa hamda organik qo‘shimchalar ishtirokida hosil qilindi. Yupqa plyonkalar shaffof o‘tkazuvchan tagliklarga spin-coating usuli bilan surildi. Qurilmalarning optik va elektr xususiyatlari xona haroratida baholandi. Natijalar bir qatlamli strukturalarda nisbatan past ishchi kuchlanishlarda barqaror va tor spektrli ko‘k rangli elektroluminessensiya kuzatilishini ko‘rsatdi. Volt–amper tahlili zaryad tashuvchilarning injeksiyasi va rekombinatsiyasi bilan bog‘liq turli zaryad tashish rejimlarini aniqladi. Olingan natijalar taklif etilgan yondashuvning prinsipial amalga oshirilishini tasdiqlaydi va arzon optelektron qurilmalar uchun istiqbolli ekanini ko‘rsatadi.

Kalit so‘zlar: bir qatlamli arxitektura; eritma asosidagi usul; elektroluminessensiya; galogenid perovskitlar; ko‘k svetodiod; perovskit–polimer kompoziti.

Синие однослойные светодиоды на основе перовскит-полимерного композита

Аннотация. В работе исследована возможность создания однослойных светоизлучающих устройств синего диапазона на основе гибридного перовскит-полимерного композита, полученного растворным методом. Активный слой сформирован из бромидных прекурсоров щелочного

металла и свинца с использованием полимерной матрицы и органических добавок. Тонкие плёнки наносили на прозрачные проводящие подложки методом центрифугирования. Оптические и электрические характеристики устройств изучали при комнатной температуре. Показано, что однослойные структуры демонстрируют устойчивую узкополосную синюю электролюминесценцию при сравнительно низких рабочих напряжениях. Анализ вольт-амперных характеристик выявил характерные режимы переноса заряда, обусловленные инжекцией носителей и их рекомбинацией в перовскит-полимерном активном слое. Полученные результаты подтверждают принципиальную реализуемость предложенного подхода и его перспективность для низкозатратных оптоэлектронных приложений.

Ключевые слова: галогенидные перовскиты; однослойная архитектура; перовскит-полимерный композит; растворные методы; синий светодиод; электролюминесценция.

Introduction. The development of efficient and technologically simple blue light sources remains one of the key challenges in modern optoelectronics. The blue spectral region plays a crucial role in full-color display technologies, solid-state lighting, and optoelectronic sensing systems. However, the realization of stable and efficient blue light-emitting diodes (LEDs) is still associated with a number of fundamental and technological difficulties related both to material selection and device architecture.

Conventional thin-film LEDs typically possess a multilayer structure comprising separate electron-transport layers, hole-transport layers, and an emissive layer. The fabrication of such devices requires complex technological processes, including vacuum deposition, the use of expensive materials, and strict control over deposition conditions. These factors significantly increase production costs and limit the scalability of the technology for widespread practical applications.

In this context, single-layer LED architectures fabricated via solution-based methods have attracted increasing attention in recent years. The simplified device structure allows a substantial reduction in the number of fabrication steps and overall manufacturing costs. Nevertheless, the implementation of single-layer LEDs, particularly those emitting in the blue spectral region, remains a challenging task due to issues related to inefficient charge injection, recombination losses, and instability of the active layer.

Halide perovskites based on alkali metals and lead have emerged as promising materials for optoelectronic applications owing to their high absorption coefficients, pronounced excitonic photoluminescence at room temperature, and relatively high tolerance to crystallographic defects. At the same time, blue-emitting perovskites often exhibit increased sensitivity to defects, phase instability, and degradation of optoelectronic properties under an applied electric field.

One promising strategy to address these challenges involves the formation of hybrid perovskite–polymer composites. The incorporation of a polymer matrix enables stabilization of the perovskite phase, limitation of crystallite growth, and partial passivation of surface defects. In addition, the polymer component can participate in charge and ion redistribution under an electric field, which is particularly important for single-layer devices lacking dedicated charge-transport layers.

In the present work, the feasibility of realizing a single-layer blue-emitting LED based on a hybrid perovskite–polymer composite formed from bromide precursors of an alkali metal and lead using solution-processing techniques is investigated. Special attention is devoted to the study of the electroluminescent and electrical characteristics of the fabricated devices, as well as to the analysis of their operation in terms of charge transport and recombination mechanisms within the active layer. The obtained results aim to demonstrate the proof-of-concept of the proposed approach and to evaluate its potential for the further development of low-cost perovskite-based light-emitting technologies.

Literature review. The intensive development of optoelectronics over recent decades has stimulated growing interest in new classes of semiconductor materials capable of providing efficient emission in the visible spectral range. Particular attention has been focused on materials that combine high optical performance with the possibility of low-temperature and solution-based processing, which significantly reduces device fabrication costs [1-3].

Lead halide perovskites based on alkali metals are currently regarded as one of the most promising material systems for light-emitting and photonic applications due to their high photoluminescence quantum efficiency, narrow emission bandwidth, and pronounced excitonic nature of optical transitions [4,5]. Numerous studies have demonstrated that the bandgap and spectral characteristics of perovskites can be finely tuned by varying the halide composition, nanocrystal size, and synthesis conditions [6–8].

A substantial contribution to the understanding of the optical properties of perovskite nanocrystals has been made by studies focused on controlling their shape, size, and surface chemistry. It has been shown that surface passivation and ligand engineering can significantly enhance the photoluminescence quantum yield and reduce the density of defect states [9,10]. At the same time, surface and grain-boundary defects remain among the key factors limiting emission efficiency and long-term stability of perovskite materials [11,12].

Fully inorganic perovskites based on $CsPbX_3$ (X = Cl, Br, I) are of particular interest due to their improved thermal stability compared to hybrid organic–inorganic analogues [13-15]. Nevertheless, achieving stable blue emission in such systems remains challenging because of the phase instability of mixed-halide compositions and their tendency toward halide segregation under illumination or applied electric fields [16,17].

To overcome these limitations, various approaches aimed at modifying the perovskite lattice have been actively explored, including ionic doping, anion exchange, and the incorporation of foreign cations [18-20]. While these strategies allow for spectral tuning, they often lead to increased synthesis complexity and reduced reproducibility of material properties.

An alternative and increasingly attractive strategy involves the formation of hybrid perovskite–polymer composites, in which the polymer matrix serves as a stabilizing medium, limits crystallite growth, and passivates defects [20-22]. It has been demonstrated that polymer incorporation improves film morphology, enhances mechanical stability, and reduces long-term degradation of the perovskite phase.

Several studies have reported the successful realization of single-layer perovskite light-emitting diodes in which the polymer component contributes not only to structural stabilization but also to charge transport and internal electric field formation [23,24]. Such devices exhibit simplified architectures and can be fabricated using solution-based methods without the need for vacuum technologies.

Of particular importance are investigations focused on the electroluminescent properties of perovskite systems and the mechanisms of charge carrier recombination. It has been shown that at low excitation levels, radiative excitonic recombination dominates, whereas at higher voltages the contribution of defect-assisted and nonlinear recombination processes increases [25]. These effects strongly influence spectral stability and the operational lifetime of light-emitting devices.

A significant contribution to the development of perovskite-based materials has been made by the authors of the present work. In particular, the optical properties and potential applications of $KPbBr_3$ perovskite have been investigated, demonstrating the possibility of controlling spectral characteristics through variation of stabilizer ratios and temperature [26,27]. In addition, the potential of perovskite nanocomposites for sensing applications has been demonstrated, and the temperature dependence of photoluminescence in $CsPbBr_3$ has been systematically studied [29].

Furthermore, results obtained in related studies on the synthesis and properties of polymeric materials and composites confirm the effectiveness of organic matrices in stabilizing functional inorganic phases [30]. Taken together, these studies highlight the relevance of developing hybrid perovskite–polymer systems with simplified architectures and tunable optoelectronic properties.

Thus, analysis of the current state of research indicates that despite significant progress in the field of perovskite light-emitting devices, the challenge of creating stable single-layer blue-emitting LEDs has not yet been fully resolved. This underscores the relevance of the present study, which is

focused on investigating the electroluminescent properties of hybrid perovskite–polymer composites and evaluating their potential for application in low-cost optoelectronic devices.

Materials and methods. Potassium bromide (KBr) and lead bromide ($PbBr_2$) were used as inorganic precursors for the formation of the perovskite phase. Dimethyl sulfoxide (DMSO) was employed as the solvent, polyethylene oxide (PEO) served as the polymer matrix, while oleic acid (OA) and OAc were used as stabilizing and defect-passivating additives. All reagents were of analytical grade and were used without further purification.

The precursor solution for the active layer was prepared by dissolving KBr and $PbBr_2$ in a molar ratio of 1:1 in 10 mL of DMSO under continuous stirring until a homogeneous and transparent solution was obtained. After complete dissolution of the inorganic components, polyethylene oxide was added to the solution, followed by the introduction of oleic acid and OAc in volumes of 3 mL each. The resulting mixture was further stirred until full homogenization, ensuring the formation of a hybrid perovskite–polymer composite.

Thin-film active layers were deposited by spin-coating onto glass substrates coated with a transparent conductive layer of indium tin oxide (ITO). After deposition, the films were subjected to thermal annealing on a heated platform to remove residual solvent and to complete the crystallization of the perovskite phase. Based on the obtained films, single-layer light-emitting diode structures with a simplified architecture of ITO / perovskite–PEO / top contact were fabricated.

Electroluminescence spectra of the fabricated devices were recorded at room temperature using a Shimadzu RF-6000 spectrofluorimeter in the visible wavelength range under the application of a constant bias voltage. Electrical characteristics were measured using a source-measure unit capable of recording current–voltage (J–V) characteristics and calculating current density. Visual confirmation of device operation and emission uniformity was performed by digital photography.

Results and discussion. Figure 1 presents the normalized electroluminescence (EL) spectra of the single-layer perovskite–polymer LED recorded at applied voltages of 2.6 V and 4.0 V, along with a photograph of the operating device. At an applied voltage of 2.6 V, an intense emission maximum is observed in the blue spectral region at a wavelength of approximately 478 nm. The narrow shape of the emission band indicates the dominance of excitonic radiative recombination within the perovskite grains and a relatively low contribution from defect-related states under moderate electrical excitation conditions.

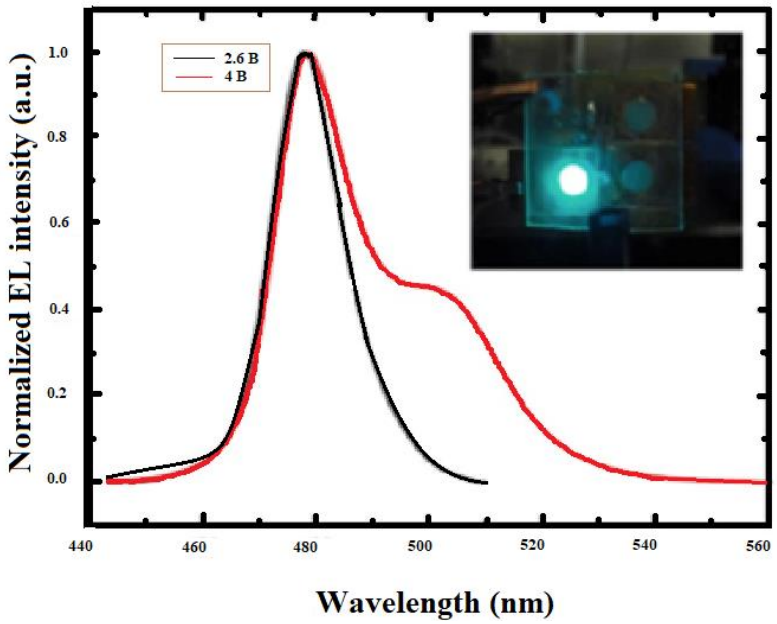


Figure 1. Normalized electroluminescence spectra of a single-layer perovskite–polymer LED recorded at different applied voltages, along with a photograph of the operating device (adapted from [28])

Upon increasing the applied voltage to 4.0 V, the electroluminescence spectrum exhibits noticeable broadening accompanied by the appearance of an additional long-wavelength contribution.

This behavior can be attributed to the activation of defect states and local structural inhomogeneities arising in the mixed-halide perovskite under a strong electric field. Despite this spectral broadening, the main emission peak remains located in the blue region, indicating the stability of the dominant radiative recombination mechanism.

The photograph of the operating device confirms uniform blue emission over the entire active area, suggesting homogeneous charge injection and effective carrier recombination throughout the perovskite–0polymer layer.

Figure 2 shows the current density–voltage (J–V) characteristic of the single-layer perovskite–polymer LED plotted in semi-logarithmic coordinates. Three distinct regions of charge transport corresponding to different conduction regimes can be clearly identified on the curve and are schematically indicated in the figure.

In the low-voltage range from 0 to approximately 2.0 V, the current density increases almost linearly with increasing applied voltage. At V ≈ 0.5 V, the current density is on the order of 0.1–0.2 mA/cm², while at V ≈ 2.0 V it reaches approximately 1 mA/cm². This behavior is characteristic of an ohmic conduction regime, in which charge transport is governed by leakage currents and carrier recombination at defect-related states within the active layer. In this regime, the contribution of radiative recombination is minimal, which is consistent with the absence of detectable electroluminescence.

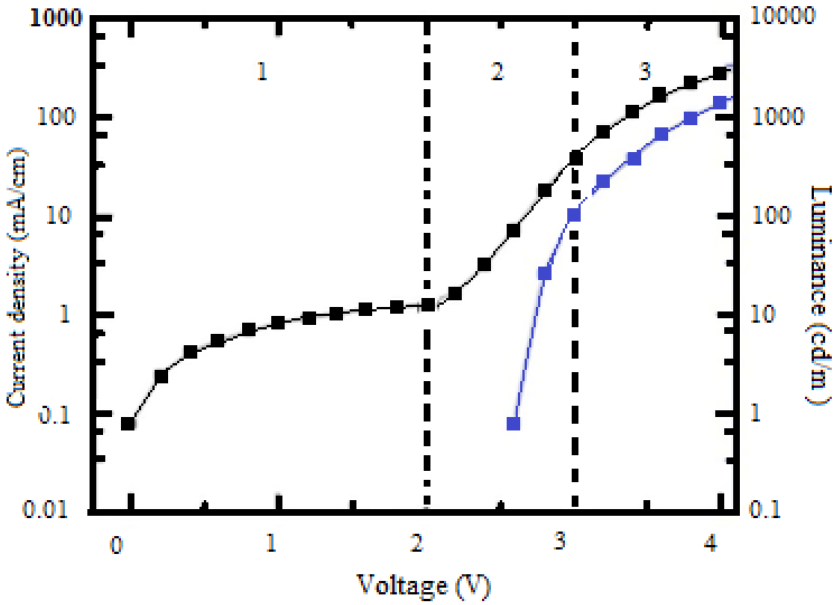


Figure 2. Current density–voltage (J–V) and luminance–voltage (L–V) characteristics of a single-layer perovskite–polymer light-emitting diode (adapted from [28])

Upon increasing the applied voltage above approximately 2.0 V, a transition to a nonlinear conduction regime is observed. In the voltage interval from 2.0 to 3.0 V, the current density increases by more than one order of magnitude, rising from ~1 mA/cm² to ~10–30 mA/cm². This region is associated with enhanced injection of electrons and holes from the electrodes into the perovskite–polymer active layer. Stable electroluminescence emerges in this voltage range, which is in good agreement with the appearance of blue emission in optical images and the corresponding electroluminescence spectra.

At voltages exceeding approximately 3.0 V, the current density exhibits a steep increase and reaches values on the order of 100–200 mA/cm² at V ≈ 4.0 V. This behavior indicates a transition to a regime close to space-charge-limited current (SCLC), where charge transport is governed by carrier accumulation in the active layer and internal electric fields. In this region, the electroluminescence intensity reaches its maximum; however, further voltage increase may lead to enhanced defect-assisted processes and potential structural degradation of the device.

Figure 3 shows a photograph of the LED device operating under electrical bias. The observed bright blue emission confirms the successful realization of electroluminescence in the single-

layer perovskite–polymer structure. The uniformity of the emitted light across the active area indicates a homogeneous electric field distribution and the absence of pronounced local defects that could lead to non-uniform charge injection. The visual observations are in good agreement with the results of the spectral and electrical measurements.

Overall, the obtained results demonstrate the feasibility of achieving stable blue electroluminescence in a simplified single-layer architecture based on a hybrid perovskite–polymer composite. Despite the manifestation of defect-assisted processes at elevated voltages, the device exhibits narrow-band blue emission, a relatively low turn-on voltage, and uniform emission from the active layer. The presented data confirm the promise of the proposed approach and indicate significant potential for further optimization of the material composition and device structure aimed at improving the efficiency and operational stability of electroluminescent characteristics.



Figure 3. Photograph of the operating single-layer perovskite–polymer LED under applied bias voltage (reproduced from [28])

Conclusions. In this work, an important scientific and technological challenge related to the development of simplified blue-emitting LED structures based on halide perovskites was addressed. In contrast to conventional multilayer architectures that require dedicated electron- and hole-transport layers as well as complex vacuum-based processing, we propose an approach based on forming a single-layer hybrid perovskite–polymer emissive layer prepared via solution processing.

1. It was demonstrated that bromide precursors of an alkali metal and lead, combined with a polymer matrix, enable stable blue electroluminescence at relatively low operating voltages. Experimental investigation of the electroluminescent and electrical characteristics confirmed the reproducible device operation and revealed distinct charge-transport regimes associated with carrier injection and recombination within the perovskite–polymer active layer.
2. The incorporation of polyethylene oxide and organic additives was found to play a key role in stabilizing the perovskite phase, forming uniform thin films, and creating conditions favorable for efficient charge injection in a single-layer architecture. Despite the manifestation of defect-assisted processes at elevated voltages, the structure maintains a dominant radiative recombination pathway, providing stable blue electroluminescent emission.
3. Overall, the obtained results confirm the proof-of-concept of the proposed strategy for single-layer perovskite–polymer LEDs and demonstrate its potential as an alternative to more complex multilayer systems. Further optimization of the active-layer composition, defect passivation, and electrode interfaces may lead to improved device efficiency and long-term operational stability, thereby expanding the prospects for low-cost optoelectronic and light-emitting technologies.

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