Optical and Electrical Characteristics of Lead-Free Cu-based Halide Perovskites in Electrospun Polystyrene Nanofibers

Vito Bintang Saputra†,‡, Tobias Haposan†, Dominik Kowal§, Pramudita Anindita Prakasa Tanaya∥, ⁂, Wulan Chairunisaǂ, Sri Hartati†, Lei Zhang˦, Lina Jaya Diguna¶, Ismudiati Puri Handayani∥, ⁂ , Muhammad Danang Birowosuto§, Witri Wahyu Lestari\*,‡, Arramel\*,†

†Center of Excellence Applied Physics and Chemistry, Nano Center Indonesia, Jl. PUSPIPTEK, South Tangerang, 15314, Indonesia

‡Department of Chemistry, Faculty of Mathematics and Natural Science, University of Sebelas Maret, Jl. Ir. Sutami, Surakarta 57126, Indonesia

§Łukasiewicz Research Network—PORT Polish Center for Technology Development, Stabłowicka 147, 54-066 Wrocław, Poland

∥Engineering Physics, School of Electrical Engineering, Telkom University, Jl. Telekomunikasi, Bandung 40257, Indonesia

⁂The University Center of Excellence Intelligent Sensing-IoT, Telkom University, Indonesia

ǂCollaborative STEM Laboratories, Universitas Prasetiya Mulya, Kavling Edutown I.1, Jl. BSD Raya Utama, Tangerang 15339, Indonesia

¶Department of Renewable Energy Engineering, Universitas Prasetiya Mulya, Kavling Edutown I.1, Jl. BSD Raya Utama, Tangerang 15339, Indonesia

˦Department of Physics, National University of Singapore, Singapore 117551, Singapore

**KEYWORDS**: Cesium halide perovskites, Polystyrene, Nanofibers, Post-encapsulation, Photoluminescence, Decay times, Charge transport.

**ABSTRACT**: Cesium halide perovskites (CHPs) are highly regarded for their low toxicity and resistance to degradation, positioning them as promising candidates for optoelectronic devices. Incorporating CHPs into polymer matrices has further enhanced their stability, as the polymer’s long molecular chains provide effective protection. Herein, we successfully incorporated CHPs into polystyrene (PS) via electrospinning using a post-encapsulation method. In this study, we examined the optical and electrical characteristics of CHPs-PS nanofibers with PS concentrations of 5% and 25%. The encapsulation of CHPs into the PS matrix enhances the absorption energy and influences the emitted PL intensity, with higher PS concentrations resulting in reduced intensity due to the complete coverage of CHPs by the PS. CHPs-PS also exhibit PL decay times with a rapid τ1 of up to 3 ns. To the best of our knowledge, CHPs-PS display a better τavg compared to pristine CHPs. CHPs-PS shows a tunnelling charge transport mechanism based on the I-V characteristics obtained. The non-linear I-V curves are attributed to forming a Schottky barrier, a potential barrier created at the metal-semiconductor interface when the two are connected. The findings of this study provide valuable insights into the development of CHPs incorporated into polymer nanofibers, offering promising potential for optoelectronic devices with exceptional optical and electrical characteristics.

1. **Introduction**

In recent years, all-inorganic perovskites have emerged as highly promising materials for optoelectronic applications due to their remarkable properties, including high absorption coefficients, tunable emission wavelengths, long carrier diffusion lengths, fast time-decay responses, and exceptional photoluminescence quantum yields (PLQY)1,2. CsPbBr3 nanocrystals have been reported to exhibit a high photoluminescence quantum yield (PLQY) of 84.7% with a PL lifetime of 7.62 ns3,4. On the other hand, CsPbBr3 quantum dots display faster PL lifetimes of 1.3 ns (47.2%), 5.5 ns (12.3%), and 29.7 ns (40.5%), although their PLQY was not reported in the study5. Unfortunately, the toxicity of heavy metal lead within the material and its inherent instability present significant risks that must be addressed for commercialization and environmental safety6,7. Furthermore, lead halide perovskites exhibit strong light self-absorption and relatively limited coverage of their luminescent spectra due to their narrow full width at half maximum (FWHM) < 25 nm, which restricts in development of photodetector application8–10.

Copper cations (Cu+) are emerging as a safer alternative to replacing toxic lead in all-inorganic halide perovskites due to their stability and bright emission11–13. In this regard, copper halide perovskites are recognized as low-dimensional materials due to their small ionic radii, facilitating the formation of low-dimensional structures. Cu+ ions coordinate with halide ions to form tetrahedral crystal structures, which induce Jahn–Teller distortions and contribute to their strong self-trapped excitons (STEs) emission. Control of perovskite dimensionality structures is a strategy to achieve high-performance photodetector with broadband emission, large stokes shift, and high PLQY6,9,14. Within the range of studies, the pure iodide phases CsCu2I3 and Cs3Cu2I5 demonstrate exceptional optoelectronic properties and possess stable crystal structures. In both materials, Cu(I) is tetrahedrally coordinated with iodide, with Cs3Cu2I5 containing isolated CuI₄ units, while CsCu₂I₃ consists of edge-sharing tetrahedra arranged spatially, representing 0D and 1D structures, respectively2,15. Cs3Cu2I5 single crystal exhibits a broad emission spectrum with an FWHM ~120 nm, large Stokes shift (~155 nm), and high PLQY of 91.2% with blue emission. These properties are attributed to STEs, which typically demonstrate strong electron-phonon coupling16,17. Similarly, CsCu2I3 single crystals show a broadband emission with an FWHM ~126 nm and a large Stokes shift ~242 nm18. However, these materials still face limitations concerning their poor stability in ambient conditions, where Cu+ ions can oxidize to Cu2+ ions. This oxidation can lead to the degradation of the perovskite crystal structure, adversely affecting their performance as photodetector devices19. Thus far, existing studies have not thoroughly explored strategies to overcome the stability limitations of cesium halide perovskites (CHPs).

Fiber-based polymers have a high surface-to-volume ratio, uniform morphology, and adjustable diameter, making them suitable as protective matrices for perovskite. Encapsulating all-inorganic perovskite in a polymer matrix has the potential to be an effective strategy for enhancing stability and preventing environmental degradation of the material, as it is protected by the polymer matrix with long molecular chains19,20. Various studies have reported the integration of perovskite into polymer matrices. For instance, the incorporated CsPb(Cl/Br)3 into a PMMA matrix showed an increase in PLQY from 42.6% to 51.4% compared to pristine CsPb(Cl/Br)3 21. The integration of perovskite with polymer fibers results in highly flexible and stable composites suitable for future flexible or wearable optoelectronic devices. Among the various polymer fibers, polystyrene (PS) is selected as the host matrix due to its high transparency in the visible region, excellent flexibility, and mechanical strength19,22. PS is known for its high stability, particularly when immersed in water, due to its hydrophobic characteristics. A previous report has successfully fabricated CsPbBr3 integrated into PS fibers, demonstrating that the PLQY of CsPbBr3-PS fibers maintained 450% of its original value after being heated at 80°C for 2 hours and 470% after 192 hours of water immersion23,24. Moreover, the integration of CsPbBr3 into the PS matrix has been successfully demonstrated in numerous studies with exceptional stability results, as observed by 83% retention following a 3-month immersion in water23,25,26.

Developing transparent and light-detecting CHPs with PS matrix is of significant interest in optoelectronic devices technology, yet comprehensive studies on their integration remain limited. CsCu2I3 and Cs3Cu2I5 have been successfully integrated into PS nanofibers, demonstrating exceptional uniformity and strong yellow and blue photoluminescence emissions, respectively. The study also reveals favorable physicochemical properties, including high flexibility, transparency, and water resistance27. To the best of our knowledge, a comprehensive study of the optical and electronic properties of CsCu2I3 and Cs3Cu2I5 within a PS matrix has yet to be reported. Here, we explored a post-encapsulation strategy for incorporating CHPs into PS nanofibers at room temperature through the electrospinning technique and examined their physicochemical and optical properties. We also investigate the charge transport phenomena through the I-V curve characteristics and PL lifetime decay profile of CsCu2I3 and Cs3Cu2I5 in the PS matrix. We found that incorporating CHPs with PS can increase energy absorption while reducing the intensity of emitted emissions. In addition, PS also contributes to shortening the PL decay times obtained from CHPs to reach τavg <100 ns. The electron transport mechanism that occurs in CHPs-PS nanofiber has a tunnelling mechanism model based on the I-V characteristics produced. The exceptional electrical and optical properties observed in CHPs-PS nanofibers from this study highlight their strong potential for advancing the next generation of optoelectronic devices.

1. **Experimental section**
   1. Materials

Cesium iodide (CsI, 99.9%), copper(I) iodide (CuI, 99.999%), N,N-dimethylformamide (DMF, 99.8%) and Polystyrene (PS, molecular weight of 192.000) were obtained from Sigma-Aldrich. Acetone (ACS Reag., for analysis) was acquired from Millipore.

* 1. Synthesis

The synthesis method of CsCu2I3 and Cs3Cu2I5 perovskites was adapted from the previous report8. The precursor powder was transferred into a mortar, and 300 µL of acetone was added to the mixture. The resulting mixture was then manually ground using a pestle for 10 minutes. The preparation of CsCu2I3-PS and Cs3Cu2I5-PS solutions involved the incorporation of polystyrene (PS) at a concentration of 5% and 25% of PS content. Subsequently, 0.250 grams of CsCu2I3 and Cs3Cu2I5 were added, respectively. DMF was then introduced to both mixtures, which were homogenized using a stirrer set to a rotational speed of 400 rpm at ambient temperature. Upon achieving a homogeneous solution, the mixtures were transferred into a 10 mL syringe fitted with a flattened needle tip. Nanofiber fabrication was conducted using the electrospinning method, wherein the CsCu2I3-PS and Cs3Cu2I5-PS solutions were placed in a syringe pump. A high voltage of 15 kV was applied, with a flow rate of 0.2 mL/h and a distance of 15 cm maintained between the collector and the needle tip. The fabrication process was performed under relative humidity conditions of 60% at room temperature. The collector was coated with an aluminum foil, serving as a substrate to facilitate the collection of the resultant fibers.

* 1. Fourier transform infrared and Raman spectroscopy

The Fourier-transform infrared (FTIR) spectra were recorded using an ATR-FTIR Nicolet iS10 spectrometer (ThermoFisher Scientific, USA) over a 3200–400 cm⁻¹ spectral range. Raman spectroscopy was performed with a DXR Raman instrument (ThermoFisher Scientific, USA) equipped with a 532 nm excitation laser. All measurements were conducted at room temperature (RT) with laser power settings between 0.2 and 5.0 mW.

* 1. X-ray diffraction (XRD)

The structural analysis of material was conducted using a powder X-ray diffractometer (PANalytical AERIS, Malvern Panalytical, Netherlands) with a Cu Kα radiation source (λ = 1.54 Å). Data collection was performed at room temperature (RT) with a scanning speed of 0.12 s per step and a step size of 0.02171°. Further structural refinement and phase composition analysis was carried out using the Rietveld method implemented in the Fullprof suite software and Match!.

* 1. Scanning electron microscope

Sample micrographs were taken at 20 kV accelerating voltage in the secondary electron mode using a Jeol JSM-IT200 scanning electron microscope (SEM) system with 5.00 K times magnification.

* 1. Absorption-photoluminescence spectroscopy

Photoluminescence (PL) measurements were conducted using a picosecond laser diode (Master Oscillator Fibre Amplifier, Picoquant GmbH, Berlin, Germany) with a 266 nm wavelength, a repetition rate of 31.25 kHz, and a pulse duration of 50 ps. The laser diode operated at an average power of 2 mW at room temperature (RT). A 20× magnification microscope objective (Nikon Corporation, Tokyo, Japan) with a numerical aperture of 0.4 was employed for excitation focusing and signal collection. The PL signal was filtered and recorded using a high-sensitivity visible light spectrometer (Ocean Optics, Florida, USA). Absorption spectra were obtained using a custom-built setup in transmission mode, employing the same commercial spectrometer. To account for the quartz tubes containing the samples, spectral data were corrected for the tube absorption.

* 1. Time-resolved photoluminescence spectroscopy

Time-resolved photoluminescence spectroscopy (TRPL) measurements were performed at a repetition rate of 31.25 kHz. The PL signal, filtered using a long-pass filter (cutoff wavelengths of 500 nm for copper halide and 600 nm for lead halide perovskite nanocrystals), was detected by a single-photon avalanche photodiode (APD). Timing analysis was conducted using time-correlated single-photon counting electronics (HydraHarp 400, PicoQuant, Germany). Absorption data were acquired with a custom-built setup incorporating an Avaspec device in transmission mode, with corrections applied to account for the absorption properties of the quartz tubes.

* 1. Temperature-dependent radioluminescence

An Inel XRG3500 X-ray generator (Cu anode tube, operating at 45 kV/10 mA) was employed as the X-ray source. The radioluminescence (RL) signal was recorded using an Acton Research Corporation SpectraPro-500i monochromator (equipped with a 500 nm blazed grating) coupled to a Hamamatsu R928 photomultiplier. Temperature control for the sample was achieved using an APD Cryogenics Inc. closed-cycle helium cooler integrated with a Lake Shore 330 programmable temperature controller, allowing precise adjustment from 10 to 350 K. To eliminate glow effects caused by the thermal release of charge carriers, measurements were performed in descending order, starting at 350 K and concluding at 10 K.

1. **Results and discussion**

A schematic illustration of CsCu2I3-PS and Cs3Cu2I5-PS nanofibers fabricated through the post-encapsulation electrospinning technique is shown in Figure 1a-c. The integration of perovskites with polymers has frequently employed one-step synthesis methods. Despite their simplicity in concept, these methods face challenges such as the need for precise precursor optimization, difficulties in controlling the perovskite crystallization process, and inconsistent nanofiber morphologies11,27,28. In this study, the post-encapsulation strategy has successfully integrated one- and zero-dimensional CHPs into PS nanofibers. The post-encapsulation technique maintains the intrinsic characteristics of the perovskite, as crystallization occurs separately from the polymer matrix. Using polymer fibers as a protective host for perovskite has proven to be an efficient and promising approach. PS has been widely utilized as a polymer host matrix due to its hydrophobic and transparent properties, which are essential for various optical device applications29. We also investigated CsCu2I3-PS and Cs3Cu2I5-PS nanofibers using two different PS solution concentrations (5% PS and 25% PS) to examine their influence on nanofiber formation. The polymer concentration plays a crucial role in the formation of nanofibers, as it can affect whether the structure forms as fine fibers or as beads30,31. This aspect is briefly discussed in the context of its potential impact on the optical and physicochemical properties of the nanofibers.

**Figure 1.** A schematic illustration of CsCu2I3-PS and Cs3Cu2I5-PS nanofibers using post-encapsulation method. (a) CsCu2I3 and Cs3Cu2I5 synthesis. (b) CsCu2I3 and Cs3Cu2I5 dissolution in PS solution. (c) electrospinning fabrication of CsCu2I3-PS and Cs3Cu2I5-PS nanofibers.

Figure 2a presents all the perovskite materials with well-developed crystallinity in the PS matrix. Both CsCu2I3-PS and C3Cu2I5-PS nanofiber materials show diffraction patterns that match the standard patterns of orthorhombic (*C m c m*) CsCu2I3 phase and orthorhombic (*P n m a*) Cs3Cu2I5 phase, respectively (see Figure S1a)32,33. This agreement is also supported by the Rietveld refinement results (Figure S2) shown in Table 1. As a preliminary study, Figure 2b illustrates the FTIR spectra that investigated potential interactions between the perovskite and the polymer host. The characteristic vibration modes of PS were identified at 696 cm-1, 755 cm-1, 1451 cm-1, 1492 cm-1, 1601 cm-1, 2924 cm-1, and 3025 cm-1 in both CsCu2I3-PS and Cs3Cu2I5-PS nanofibers34,35. These results were also demonstrated by a decrease in the intensity of vibration modes and slight peak shifts compared to PS nanofibers, indicating interactions between the polymer and perovskite. The peak vibration shift was observed to be around ~1 cm-1, and the resulting intensity difference reached 15% transmittance of the pristine PS intensity. More interestingly, the highlighted purple region displayed distinct peak features not seen in PS nanofibers, suggesting the possible presence of unique vibration modes associated with metal-halide perovskites8. Pristine CsCu2I3 and Cs3Cu2I5 exhibited vibrational bands in the 400–500 cm-1 range, as illustrated in Figure S1a. The vibration modes displayed by Raman spectroscopy in Figure 2c exhibit a similar trend to the FTIR results. A reduction in Raman shift intensities at 612 cm-1, 1001 cm-1, 1031 cm-1, 1602 cm-1, 2906 cm-1, and 3052 cm-1 was noted for CsCu2I3-PS and Cs3Cu2I5-PS nanofibers compared to PS nanofibers36,37. Furthermore, the purple-highlighted region in the Raman shift spectra suggests the presence of new peaks, which can be attributed to the incorporation of CsCu2I3 and Cs3Cu2I5 within the PS nanofibers (Figure S1b).

**Table 1.** Crystallographic parameters for Rietveld refinement and phase composition of each material.

|  |  |  |  |
| --- | --- | --- | --- |
| Compounds | CsCu2I3-PS (5% PS) | CsCu2I3-PS (25% PS) | Cs3Cu2I5-PS (25% PS) |
| Space group | *C m c m* | *C m c m* | *P n m a* |
| a (Å) | 10.34 | 10.34 | 10.17 |
| b (Å) | 13.12 | 13.12 | 11.65 |
| c (Å) | 6.35 | 6.35 | 14.36 |
| α (*deg*) | 90 | 90 | 90 |
| β (*deg*) | 90 | 90 | 90 |
| γ (*deg*) | 90 | 90 | 90 |
| Volume (Å3) | 860.69 | 860.69 | 1782.5 |
| Rwp | 78.8 | 91.67 | 90.6 |
| χ2 | 2.96 | 1.73 | 2.04 |

The concentration of PS plays a crucial role in the formation of CsCu2I3-PS and Cs3Cu2I5-PS nanofibers. For instance, higher PS concentrations contribute to the formation of smooth, thick fibers without the presence of undesired bead-like structures31. Figures S3 show the Raman spectra and optical images of CsCu2I3-PS and Cs3Cu2I5-PS materials prepared with 5% PS. The vibration modes recorded at five different measurement points showed inconsistencies, and the optical images revealed bead formation within the fibers. This indicates that a 5% PS concentration was inadequate for fully encapsulating the perovskite materials. Morphological profiles of the materials were evaluated through SEM, and the imaging results provide insight into why higher polymer concentrations are favored for fiber formation without the occurrence of beads. In contrast, the morphology of CsCu2I3-PS and Cs3Cu2I5-PS nanofibers with 25% PS concentration (Figure 2d) reveals the formation of thick fibers without beads. On the other hand, the morphology at a 5% PS concentration (Figure S4) resembles irregular fibers with bead-like structures. Moreover, the Cs3Cu2I5-PS nanofibers with 5% PS concentration did not display well-formed fibers and appeared disordered. The average diameter and distribution of the nanofibers at 25% PS concentration for CsCu2I3-PS and Cs3Cu2I5-PS were 724 ± 18 nm and 668 ± 11 nm, respectively. On the other hand, CsCu2I3-PS nanofibers at 5% PS had an average diameter of 221 ± 8 nm and the Cs3Cu2I5-PS nanofibers at 5% PS concentration could not be properly identified due to the incomplete fiber formation. The larger diameters observed at higher PS concentrations can be attributed to the increased amount of polymer and higher viscosity, which slow down the spreading and drying processes during electrospinning, leading to thicker fibers38.

c)

|  |  |
| --- | --- |
| a) | d)  b) |

**Figure 2.** (a) XRD pattern, (b) Raman spectrum, and (c) FTIR spectrum of CsCu2I3-PS nanofibers, Cs3Cu2I5-PS nanofibers and PS nanofibers. (d) Morphology image of CsCu2I3-PS nanofibers (25% PS, left) and Cs3Cu2I5-PS nanofibers (25% PS, right).

The optical properties of the Cs3Cu2I5-PSand Cs3Cu2I5-PS nanofibers was analyzed through absorption and PL spectra as presented in figure 3. The maximum absorption energies of CsCu2I3-PS (Figure 3a) were 3.815 eV and 3.757 eV for PS concentrations of 5% and 25%, respectively. At both concentrations, the material displayed two PL emission peaks at 562 nm and 446 nm, corresponding to yellow and faint blue light, as shown in Figure 3c. In the case of Cs3Cu2I5-PS, the maximum absorption energies (Figure 3b) were measured at 4.065 eV and 3.999 eV for 5% and 25% PS concentrations, respectively, with identical PL emission of blue light at 447 nm (Figure 3d). These results demonstrate consistency with the known peak positions of pristine CsCu2I3 and Cs3Cu2I5 as previous reports12,16,20,39–41. The observation of two emission peaks in CsCu2I3-PS is attributed to the radiative recombination of two distinct self-trapped excitons (STEs). In contrast, Cs3Cu2I5-PS exhibits a single emission peak, as the formation of Cu-Cu bonds for exciton trapping within the [Cu2I5]3- unit occurs through a single pathway, thereby precluding the generation of multiple STEs17. Table 2 summarizes the optical properties of CsCu2I3-PS and Cs3Cu2I5-PS related to their PL emission and absorption energies. The broad PL emission and large Stokes shift of these CHPs cannot be attributed to direct band emission but are instead a result of STEs caused by the local structural symmetry enhanced by the Jahn–Teller distortion40,42,43. To the best of our knowledge, the dimensionality of the material was also found to influence its properties, with low-dimensional electronic structures exhibiting higher exciton binding energy and PLQY compared to high-dimensional crystals due to enhanced electron localization as dimensionality decreases17.

**Table 2.** Summary of optical properties of CHPs in PS matrix.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Material | (eV) | Abs. maximum  (eV) | PL maximum  (eV) | Stokes shift  (SS) (nm) | Stokes shift  (SS) (eV) | FWHM  (nm) |
| CsCu2I3-PS 5% PS | 3.81 | 3.815 | 2.210; 2.780 | 236; 121 | 1.605; 1.035 | `118; 54 |
| CsCu2I3-PS 25% PS | 3.79 | 3.757 | 2.210; 2.780 | 231; 116 | 1.547; 0.977 | 118; 55 |
| Cs3Cu2I5-PS 5% PS | 3.94 | 4.065 | 2.774 | 142 | 1.291 | 106 |
| Cs3Cu2I5-PS 25% PS | 3.85 | 3.999 | 2.774 | 137 | 1.225 | 102 |

Based on the absorption data, the experimental bandgap energies (Figure S5) were found to be 3.81 eV and 3.79 eV for CsCu2I3-PS with 5% and 25% PS, with 3.94 eV and 3.85 eV for Cs3Cu2I5-PS with 5% and 25% PS, respectively. Reducing the structural dimensionality (from 1D CsCu2I3 to 0D Cs3Cu2I5) can lead to larger bandgap energies due to increased exciton binding energy and stronger quantum confinement, as the more localized excitons in the 0D structure of Cs3Cu2I5 result in higher bandgap energy and emission values14. Additionally, we observed differences in bandgap energies at two PS concentrations, where lower PS matrix concentrations yielded smaller bandgap energies. This phenomenon has been reported in CsPbBr3@polymer composite fibers, where a linear relationship was found between the polymer matrix fiber diameter and the absorption energy values28. A PS concentration of 25% produces fibers with larger diameters due to increased viscosity, stabilizing the polymer jet and reducing surface tension during electrospinning44. The observed ~5 nm shift in the absorption spectra likely reflects slight changes in the processing parameters during material fabrication. We identified variations in PL emission counts between CsCu2I3 and Cs3Cu2I5 in materials with 5% and 25% PS matrices. The 25% PS matrix demonstrated lower PL emission counts than the 5% PS matrix, possibly due to incomplete encapsulation of CHPs in the lower PS concentration. Given the same perovskite concentration in this study, higher PS matrix concentrations consistently resulted in reduced PL emission intensity, as attributed to the light-insensitive nature of PS. As far as we know, PL emission counts increase with higher perovskite concentrations in polymer matrices. This phenomenon can also be attributed to the relatively high PS concentration (25%), which unexpectedly reduces PL emission counts due to increased light scattering and refractive loss caused by larger-diameter polymer nanofibers38.

|  |  |
| --- | --- |
| a) | b) |
| c) | d) |

**Figure 3.** Absorption (a,b) and PL (c,d) spectra at 266 nm excitation. (a,c) CsCu2I3-PS nanofibers, and (b,d) Cs3Cu2I5-PS nanofibers.

The optical properties of CsCu2I3-PS and Cs3Cu2I5-PS were further investigated using TRPL spectroscopy to examine the dynamics of STEs, as illustrated in Figure 4a-d. The PL decay profiles were modelled with a triple-exponential function:

where *τ1, τ2,* and *τ3* represent the fast, medium, and slow decay components, and A1, A2 and A3 are their respective contributions. The fast decay component (*τ1*) reflects rapid electron-hole recombination (anomalous emission), the medium decay component (*τ2*​) corresponds to fast excitonic recombination, while the slow decay phase (*τ3*) is attributed to defect-induced recombination via STEs8,42,45,46. PL decay profiles were measured under 450 nm emission for all materials and at 600 nm for CsCu2I3-PS nanofibers, as the CsCu2I3-PS nanofibers PL spectra exhibited two distinct emission peaks, as summarized in Table 3. Under the same emission wavelength (450 nm), CsCu2I3-PS exhibited shorter PL lifetimes than Cs3Cu2I5-PS. The longer PL lifetimes observed in Cs3Cu2I5-PS are attributed to their more isolated copper centers within the Cs3Cu2I5 structure, which are fully separated from Cs⁺ ions. This structural characteristic causes electrons and holes in Cs3Cu2I5 to take longer to recombine, resulting in extended PL lifetimes. Furthermore, when comparing the PL lifetimes of CsCu2I3-PS measured at 600 nm, they were also shorter than those of Cs3Cu2I5-PS. However, for Cs3Cu2I5-PS with a PS concentration of 25%, slightly shorter PL lifetimes were observed due to the less dominant contribution of the slow decay (*τ3*) component47. The shorter PL decay profiles of CsCu2I3 and Cs3Cu2I5 in higher polymer concentration matrices are attributed to increased light scattering, reduced exciton mobility, and diminished self-absorption. The denser polymer matrix enhances light scattering, accelerates exciton recombination, and limits exciton diffusion by mechanically constraining the active material. Additionally, higher polymer concentrations reduce the reabsorption of emitted light, further shortening PL lifetimes38. Incorporating CsCu2I3 and Cs3Cu2I5 into PS nanofibers also showed PL decay profiles with faster τavg accompanied by a larger contribution from the fast component compared to the reported pristine CHPs8,9,46.

**Table 3.** PL decay profiles of CsCu2I3-PS and Cs3Cu2I5-PS at RT under 450 nm and 600 nm.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Material | τ1 (%) | τ2 (%) | τ3 (%) | τavg |
| CsCu2I3-PS 5% PS (600 nm) | 3 ns (5%) | 44 ns (57%) | 154 ns (38%) | 83.75 ns |
| CsCu2I3-PS 25% PS (600 nm) | 3 ns (24%) | 47 ns (13%) | 65 ns (63%) | 47.78 ns |
| CsCu2I3-PS 5% PS (450 nm) | 3 ns (28%) | 8 ns (72%) | - | 6.6 ns |
| CsCu2I3-PS 25% PS (450 nm) | 3 ns (59%) | 8 ns (41%) | - | 5.05 ns |
| Cs3Cu2I5-PS 5% PS (450 nm) | 2 ns (10%) | 14 (21%) | 294 (64%) | 191.3 ns |
| Cs3Cu2I5-PS 25% PS (450 nm) | 2 ns (29%) | 9 ns (30%) | 75 ns (41%) | 34.03 ns |

|  |  |
| --- | --- |
| a)  b)  d) |  |
| c) |  |

**Figure 4.** PL decay profiles under 450 nm and 600 nm. (a) CsCu2I3-PS (5% PS). (b) CsCu2I3-PS (25% PS). (c) Cs3Cu2I5-PS (5% PS). (d) Cs3Cu2I5-PS (25% PS).

Temperature-dependent radioluminescence (RL) studies of CsCu2I3-PS and Cs3Cu2I5-PS nanofibers were performed across a temperature range of 100–350 K, as shown in Figure 5a-d. For Cs3Cu2I5-PS, two emission peaks were observed: a yellow emission at ~561 nm and a weaker blue emission at ~446 nm. These two peaks are attributed to the radiative recombination of two distinct STEs. The 1D structure of CsCu2I3 allows multiple Cu-Cu bond formations in the excited state due to the presence of several Cu neighbors around each Cu atom, leading to multiple STEs. In contrast, Cs3Cu2I5-PS exhibited a single emission peak at ~447 nm. This is due to its 0D structure, where only one configuration of Cu-Cu bond formation is possible for exciton trapping within the [Cu2I5]3- cluster. Overall, the PL intensity of both CsCu2I3-PS and Cs3Cu2I5-PS decreases as the temperature increases. This behavior can be explained by thermal quenching, where increased thermal energy destabilizes excitons, enhancing non-radiative losses. At higher temperatures, thermal detrapping processes intensify, reducing emission efficiency. Additionally, elevated thermal energy promotes exciton dissociation into free electrons and holes, further diminishing emission intensity8,18,43,46. Over the temperature range of 100–350 K, CsCu2I3-PS exhibited a blue shift as the temperature increases, from ~580 nm at ~100 K to ~565 nm at 250 K. The blue shifted peak is related to the temperature effect on the luminescent centre of the 1D CHP system8. In contrast, Cs3Cu2I5-PS showed no significant emission shift or peak broadening, suggesting greater stability due to its lower dimensionality46.

In low-dimensional structured materials, the exciton binding energy is significantly higher, allowing excitons to remain stable without dissociating into electrons and holes. This stability ensures efficient light emission even at room temperature or higher, as observed in CsCu2I3-PS nanofibers. The emitted light is further facilitated by STEs, which form due to strong electron-phonon interactions. In materials with low-dimensional crystals, structural distortions, such as octahedral distortions, are more pronounced, enhancing the formation of STEs. This explains why Cs3Cu2I5-PS exhibits stronger light emission compared to CsCu2I3-PS, as its lower-dimensional structure promotes more efficient STE formation and light emission48,49. When comparing different polymer concentrations, the temperature-dependent RL intensity for 25% PS was lower than that of 5% PS. This aligns with previous PL emission findings, where higher PS concentrations produce more uniform fibers with larger diameters, effectively encapsulating CHPs. This encapsulation leads to reduced RL intensity under temperature-dependent measurements38. We also investigated that there is a narrowing of the emission peaks in CHPs in polystyrene matrix with different concentrations. In CsCu2I3-PS nanofibers, the bright yellow emission peak narrows from ~162 nm at 5% PS concentration to ~151 nm at 25% PS concentration. Meanwhile, the blue emission peak of Cs3Cu2I5-PS nanofibers also experiences a narrowing of the emission peak from ~154 nm at 5% PS concentration to ~137 nm at 25% PS concentration. We discuss that the phenomena occurs due to the different formation of PS nanofibers. At higher PS concentrations, the CHPs are more effectively encapsulated, which enhances surface coverage but it can simultaneously causes emission peak narrowing and a reduction in emission intensity due to the PS matrix partially shielding the CHPs22,38.

|  |  |
| --- | --- |
| a) | b) |
| c) | d) |

**Figure 5.** Radioluminescence spectra with different wavelengths in the temperature range of 100 – 350 K. (a) CsCu2I3-PS (5% PS), (b) CsCu2I3-PS (25% PS), (c) Cs3Cu2I5-PS (5% PS), (d) Cs3Cu2I5-PS (25% PS).

The current-voltage (I-V) characteristics of the photodetector were examined under dark conditions to study the relationship between the applied voltage and the resulting current through the device. Figure 7 illustrates the I-V curves for CsCu2I3/PS and Cs3Cu2I5-PS nanofibers, which fall within the first and third quadrants, indicating these materials function as passive components that consume electrical power from the circuit. In these devices, current flows from the positive to the negative terminal, converting potential energy into heat or other forms of energy. The current generated in CsCu2I3/PS is higher than that in Cs3Cu2I5-PS, primarily due to reduced light-induced resistance in CsCu2I3. This behavior can be attributed to the superior charge carrier mobility of CsCu2I3 crystal structure compared to Cs3Cu2I5, as well as its narrower band gap. A smaller band gap facilitates greater charge carrier (electron) transfer across the conduction band, enhancing conductivity and current flow8. We also observed that the electron transport mechanism that occurs in the CHPs-PS based on I-V characteristics is using the tunneling model mechanism. The tunneling electron transport mechanism explains that electrons tunnel coherently through the energy barrier of the molecule. The tunneling mechanism shows linearity at high bias and non-linearity at low bias in the linear coordinate graphs shown in Figures 6a and 6c. The semi-logarithmic plots shown in Figures 6b and 6d show more clearly that the electron transport mechanism that occurs follows the tunneling model, which does not have an exponential relationship with a narrower current range forming a “γ” shape50–52. The non-linear I-V curves are attributed to the formation of a Schottky barrier, a potential barrier created at the metal-semiconductor interface when the two are connected53,54. The non-linear behavior observed in both the first and third quadrants suggests that the CsCu2I3/PS and Cs3Cu2I5-PS materials are well-suited for applications in diodes or transistors.

|  |  |
| --- | --- |
| a) | b) |
| c) | d) |

**Figure 6.** Current-voltage graphs under unilluminated conditions. Linear scale (a) CsCu2I3-PS. (c) Cs3Cu2I5-PS and semi-logarithmic scale (b) CsCu2I3-PS. (d) Cs3Cu2I5-PS.

**CONCLUSION**

In summary, the successful fabrication of CsCu2I3 and Cs3Cu2I5 embedded in a polystyrene (PS) matrix was achieved through post-encapsulation using electrospinning. The concentration of PS plays a crucial role in the formation of smooth, bead-free fibers in CsCu2I3-PS and Cs3Cu2I5-PS nanofibers by enhancing viscosity and reducing surface tension in the spinning solution. CsCu2I3-PS and Cs3Cu2I5-PS nanofibers exhibited strong yellow and blue photoluminescence emissions at low temperatures, respectively. Higher PS concentration results in higher absorption energy, but lower emission intensity because PS fibers can completely cover the CHPs. This finding can also be observed in the RL study which found that the RL intensity was lower in CHPs-PSwith 25% PS concentration compared to 5% PS. The photoluminescence decay times were significantly shorter than those of pristine materials, with CsCu2I3-PS 5% PS, 25% PS, Cs3Cu2I5-PS 5% PS, and 25% PS achieving an average decay time of 83.75 ns, 43.78 ns, 191.3 ns, and 34.03 ns, respectively. Fast decay times and high contribution of the fast component is related to the stabilizing influence of PS encapsulation. The I-V characteristics reveal non-linear behavior in the first and third quadrants, classifying the nanofibers as passive components suitable for diode and transistor applications. CsCu2I3-PS generates higher current than Cs3Cu2I5-PS, mainly due to reduced light-induced resistance, higher charge carrier mobility, and a narrower band gap in CsCu2I3. Based on I-V characteristics, we can see that the electron transport mechanism uses the tunneling transport mechanism model. The post-encapsulation strategy using lead-free, all-inorganic perovskite integrated with a PS matrix holds significant promise for developing flexible and high-response photodetector devices.

**Supporting Information.**

Physcohemical characterization of piristine material; Rietvield refinement of XRD graphs; Raman spectrum and morphology profile at 5 different points; SEM image of PS 5% nanofibers; and experimental bandgap of CHPs@PS.

**AUTHOR INFORMATION**

**Notes**

**ACKNOWLEDGMENTS**

V. B. S., T. H., S. H. and A. acknowledge PT Nanotech Indonesia Global, Tbk. for the start-up research grant. This funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article, or the decision to submit it for publication. We are grateful to Prof. Andrew T. S. Wee from the Department of Physics, National University of Singapore, for the usage of the XPS facility. We are also grateful for PENELITIAN UNGGULAN TERAPAN (PUT-UNS) No: 194.2/UN27.22/PT.01.03/2024 and No: 228/UN27.22/PT.01.03/2023 for significant contribution to the successful journey of this study.

**ABBREVIATIONS**

PLQY, photoluminescence quantum yield; STEs, self-trapped excitons; FWHM, full-width half maximum; CHPs, cesium halide perovskites; PS, polystyrene; DMF, N,N-dimethylformamide; FTIR, Fourier transform infrared; XRD, x-ray diffraction; SEM, scanning electron microscope; PL, photoluminescence; RT, room temperature; TRPL, time-resolved photoluminescence; RL, radioluminescence;

**REFERENCES**

(1) Chen, H.; Zhu, L.; Xue, C.; Liu, P.; Du, X.; Wen, K.; Zhang, H.; Xu, L.; Xiang, C.; Lin, C.; Qin, M.; Zhang, J.; Jiang, T.; Yi, C.; Cheng, L.; Zhang, C.; Yang, P.; Niu, M.; Xu, W.; Lai, J.; Cao, Y.; Chang, J.; Tian, H.; Jin, Y.; Lu, X.; Jiang, L.; Wang, N.; Huang, W.; Wang, J. Efficient and Bright Warm-White Electroluminescence from Lead-Free Metal Halides. *Nat. Commun.* **2021**, *12* (1), 1421. https://doi.org/10.1038/s41467-021-21638-x.

(2) Zhao, Z.; Li, X.; Xie, L.; Chen, B.; Jiang, T.; Cao, J.; Zhang, F.; Wang, M.; Wu, Y.; Zheng, H.; Zhang, F.; Wang, Y. Phase Control in the Synthesis of Cesium Copper Iodide Compounds for Their Photoluminescence and Radioluminescence Study. *J. Lumin.* **2022**, *241*, 118482. https://doi.org/10.1016/j.jlumin.2021.118482.

(3) Bao, C.; Yang, J.; Bai, S.; Xu, W.; Yan, Z.; Xu, Q.; Liu, J.; Zhang, W.; Gao, F. High Performance and Stable All‐Inorganic Metal Halide Perovskite‐Based Photodetectors for Optical Communication Applications. *Adv. Mater.* **2018**, *30* (38), 1803422. https://doi.org/10.1002/adma.201803422.

(4) Yuce, H.; Mandal, M.; Yalcinkaya, Y.; Andrienko, D.; Demir, M. M. Improvement of Photophysical Properties of CsPbBr3 and Mn2+ :CsPb(Br,Cl)3 Perovskite Nanocrystals by Sr2+ Doping for White Light-Emitting Diodes. *J. Phys. Chem. C* **2022**, *126* (27), 11277–11284. https://doi.org/10.1021/acs.jpcc.2c01244.

(5) Chen, W.; Xin, X.; Zang, Z.; Tang, X.; Li, C.; Hu, W.; Zhou, M.; Du, J. Tunable Photoluminescence of CsPbBr3 Perovskite Quantum Dots for Light Emitting Diodes Application. *J. Solid State Chem.* **2017**, *255*, 115–120. https://doi.org/10.1016/j.jssc.2017.06.006.

(6) Li, X.; Zhang, L.; Zheng, Q.; Zhou, Z.; He, S.; Tian, D.; Guo, A.; Wang, C.; Liu, S.; Chu, X.; Yang, C.; Zhao, F. Cesium Copper Iodide Perovskite Nanoscale-Thick Films with Tunable Photoluminescence for White Light-Emitting Diodes. *ACS Appl. Nano Mater.* **2022**, *5* (1), 917–924. https://doi.org/10.1021/acsanm.1c03592.

(7) Yang, J.; Kang, W.; Liu, Z.; Pi, M.; Luo, L.-B.; Li, C.; Lin, H.; Luo, Z.; Du, J.; Zhou, M.; Tang, X. High-Performance Deep Ultraviolet Photodetector Based on a One-Dimensional Lead-Free Halide Perovskite CsCu2I3 Film with High Stability. *J. Phys. Chem. Lett.* **2020**, *11* (16), 6880–6886. https://doi.org/10.1021/acs.jpclett.0c01832.

(8) Haposan, T.; Arramel, A.; Maulida, P. Y. D.; Hartati, S.; Afkauni, A. A.; Mahyuddin, M. H.; Zhang, L.; Kowal, D.; Witkowski, M. E.; Drozdowski, K. J.; Makowski, M.; Drozdowski, W.; Diguna, L. J.; Birowosuto, M. D. All-Inorganic Copper-Halide Perovskites for Large-Stokes Shift and Ten-Nanosecond-Emission Scintillators. *J. Mater. Chem. C* **2024**, *12* (7), 2398–2409. https://doi.org/10.1039/D3TC03977C.

(9) Jun, T.; Handa, T.; Sim, K.; Iimura, S.; Sasase, M.; Kim, J.; Kanemitsu, Y.; Hosono, H. One-Step Solution Synthesis of White-Light-Emitting Films via Dimensionality Control of the Cs–Cu–I System. *APL Mater.* **2019**, *7* (11), 111113. https://doi.org/10.1063/1.5127300.

(10) Liu, B.; Huang, A.; Chen, G.; Yang, D.; Ma, C.; Zhu, C.; Li, L.; Yang, T.; Wu, H.; Wu, Y.; Xu, J.; Gao, H. Photoluminescence Kinetics of CsPbBr3 Nanocrystals with Urea as Co-Ligand by Using Ultrafast Spectroscopy. *J. Mater. Sci.* **2023**, *58* (44), 16930–16941. https://doi.org/10.1007/s10853-023-09092-0.

(11) Jiang, T.; Wang, J.; Xie, L.; Bai, C.; Wang, M.; Wu, Y.; Zhang, F.; Zhao, Y.; Chen, B.; Wang, Y. In Situ Fabrication of Lead-Free Cs3Cu2I5 Nanostructures Embedded in Poly(Vinylidene Fluoride) Electrospun Fibers for Polarized Emission. *ACS Appl. Nano Mater.* **2022**, *5* (1), 508–516. https://doi.org/10.1021/acsanm.1c03323.

(12) He, Y.; Ou, K.; Zhang, W.; Ni, Y.; Xia, Y.; Wang, H. Lead-Free CsCu2I3 Thin Films Prepared by One-Step Chemical Vapor Deposition Method for Ultraviolet Photodetector. *J. Appl. Phys.* **2024**, *135* (15), 155301. https://doi.org/10.1063/5.0198057.

(13) Mo, X.; Li, T.; Huang, F.; Li, Z.; Zhou, Y.; Lin, T.; Ouyang, Y.; Tao, X.; Pan, C. Highly-Efficient All-Inorganic Lead-Free 1D CsCu2I3 Single Crystal for White-Light Emitting Diodes and UV Photodetection. *Nano Energy* **2021**, *81*, 105570. https://doi.org/10.1016/j.nanoen.2020.105570.

(14) Cheng, P.; Sun, L.; Feng, L.; Yang, S.; Yang, Y.; Zheng, D.; Zhao, Y.; Sang, Y.; Zhang, R.; Wei, D.; Deng, W.; Han, K. Colloidal Synthesis and Optical Properties of All‐Inorganic Low‐Dimensional Cesium Copper Halide Nanocrystals. *Angew. Chem. Int. Ed.* **2019**, *58* (45), 16087–16091. https://doi.org/10.1002/anie.201909129.

(15) Sebastia-Luna, P.; Navarro-Alapont, J.; Sessolo, M.; Palazon, F.; Bolink, H. J. Solvent-Free Synthesis and Thin-Film Deposition of Cesium Copper Halides with Bright Blue Photoluminescence. *Chem. Mater.* **2019**, *31* (24), 10205–10210. https://doi.org/10.1021/acs.chemmater.9b03898.

(16) Jun, T.; Sim, K.; Iimura, S.; Sasase, M.; Kamioka, H.; Kim, J.; Hosono, H. Lead‐Free Highly Efficient Blue‐Emitting Cs3Cu2I5 with 0D Electronic Structure. *Adv. Mater.* **2018**, *30* (43), 1804547. https://doi.org/10.1002/adma.201804547.

(17) Lin, R.; Zhu, Q.; Guo, Q.; Zhu, Y.; Zheng, W.; Huang, F. Dual Self-Trapped Exciton Emission with Ultrahigh Photoluminescence Quantum Yield in CsCu2I3 and Cs3Cu2I5 Perovskite Single Crystals. *J. Phys. Chem. C* **2020**, *124* (37), 20469–20476. https://doi.org/10.1021/acs.jpcc.0c07435.

(18) Van Blaaderen, J. J.; Van Den Brekel, L. A.; Krämer, K. W.; Dorenbos, P. Scintillation and Optical Characterization of CsCu2I3 Single Crystals from 10 to 400 K. *Chem. Mater.* **2023**, *35* (22), 9623–9631. https://doi.org/10.1021/acs.chemmater.3c01810.

(19) Kar, M. R.; Sahoo, K.; Mohapatra, A.; Bhaumik, S. Stable and Luminescent Cesium Copper Halide Nanocrystals Embedded in Flexible Polymer Fibers for Fabrication of Down-Converting WLEDs. *Nanoscale Adv.* **2023**, *5* (22), 6238–6248. https://doi.org/10.1039/D3NA00440F.

(20) Li, Y.; Shi, Z.; Wang, L.; Chen, Y.; Liang, W.; Wu, D.; Li, X.; Zhang, Y.; Shan, C.; Fang, X. Solution-Processed One-Dimensional CsCu2I3 Nanowires for Polarization-Sensitive and Flexible Ultraviolet Photodetectors. *Mater. Horiz.* **2020**, *7* (6), 1613–1622. https://doi.org/10.1039/D0MH00250J.

(21) Abir, S. S. H.; Gupta, S. K.; Ibrahim, A.; Srivastava, B. B.; Lozano, K. Tunable CsPb(Br/Cl)3 Perovskite Nanocrystals and Further Advancement in Designing Light Emitting Fiber Membranes. *Mater. Adv.* **2021**, *2* (8), 2700–2710. https://doi.org/10.1039/D1MA00183C.

(22) Tu, Y.; Zhou, L.; Jin, Y. Z.; Gao, C.; Ye, Z. Z.; Yang, Y. F.; Wang, Q. L. Transparent and Flexible Thin Films of ZnO-Polystyrene Nanocomposite for UV-Shielding Applications. *J. Mater. Chem.* **2010**, *20* (8), 1594. https://doi.org/10.1039/b914156a.

(23) Jiang, D.-H.; Tsai, Y.-H.; Veeramuthu, L.; Liang, F.-C.; Chen, L.-C.; Lin, C. C.; Satoh, T.; Tung, S.-H.; Kuo, C.-C. Novel Ultra-Stable and Highly Luminescent White Light-Emitting Diodes from Perovskite Quantum Dots—Polymer Nanofibers through Biaxial Electrospinning. *APL Mater.* **2019**, *7* (11), 111105. https://doi.org/10.1063/1.5124880.

(24) Liu, W.; Fu, H.; Liao, H.; Liang, Z.; Ye, Y.; Zheng, J.; Yang, W. *In Situ* Synthesis of Coaxial CsPbX3 @polymer (X = Cl, Br, I) Fibers with Significantly Enhanced Water Stability. *J. Mater. Chem. C* **2020**, *8* (40), 13972–13975. https://doi.org/10.1039/D0TC04035E.

(25) Chen, T.; Huang, M.; Ye, Z.; Hua, J.; Lin, S.; Wei, L.; Xiao, L. Blinking CsPbBr3 Perovskite Nanocrystals for the Nanoscopic Imaging of Electrospun Nanofibers. *Nano Res.* **2021**, *14* (5), 1397–1404. https://doi.org/10.1007/s12274-020-3189-7.

(26) Zhang, H.; Fu, D.; Du, Z.; Fu, H.; Shao, G.; Yang, W.; Zheng, J. In Situ Growth of Aligned CsPbBr3 Nanorods in Polymer Fibers with Tailored Aspect Ratios. *Ceram. Int.* **2020**, *46* (11), 18352–18357. https://doi.org/10.1016/j.ceramint.2020.04.035.

(27) Lee, Y.; Cha, J.-H.; Kim, H.; Lee, J. Y.; Lee, M. W.; Jang, H. S.; Jung, D.-Y. Lead-Free Inorganic Nanoparticles of Perovskite Embedded within Waterproof Nanofiber Films for White Color Emission. *ACS Appl. Nano Mater.* **2022**, *5* (12), 18409–18416. https://doi.org/10.1021/acsanm.2c04261.

(28) Lê, K.; Von Toperczer, F.; Ünlü, F.; Paramasivam, G.; Mathies, F.; Nandayapa, E.; List-Kratochvil, E. J. W.; Fischer, T.; Lindfors, K.; Mathur, S. Electrospun Electroluminescent CsPbBr3 Fibers as Flexible Perovskite Networks for Light‐Emitting Application. *Adv. Eng. Mater.* **2023**, *25* (10), 2201651. https://doi.org/10.1002/adem.202201651.

(29) Zhang, H.; Shi, J.; Zhu, L.; Luo, Y.; Li, D.; Wu, H.; Meng, Q. Polystyrene Stabilized Perovskite Component, Grain and Microstructure for Improved Efficiency and Stability of Planar Solar Cells. *Nano Energy* **2018**, *43*, 383–392. https://doi.org/10.1016/j.nanoen.2017.11.024.

(30) Luraghi, A.; Peri, F.; Moroni, L. Electrospinning for Drug Delivery Applications: A Review. *J. Controlled Release* **2021**, *334*, 463–484. https://doi.org/10.1016/j.jconrel.2021.03.033.

(31) Haider, A.; Haider, S.; Kang, I.-K. A Comprehensive Review Summarizing the Effect of Electrospinning Parameters and Potential Applications of Nanofibers in Biomedical and Biotechnology. *Arab. J. Chem.* **2018**, *11* (8), 1165–1188. https://doi.org/10.1016/j.arabjc.2015.11.015.

(32) Lu, Y.; Li, G.; Fu, S.; Fang, S.; Li, L. CsCu2I3 Nanocrystals: Growth and Structural Evolution for Tunable Light Emission. *ACS Omega* **2021**, *6* (1), 544–552. https://doi.org/10.1021/acsomega.0c05024.

(33) Zhang, K.; Wang, S.; Yi, L. Defect Emission in Cs3Cu2I5 and CsCu2I3 Halide Films. *J. Lumin.* **2023**, *254*, 119516. https://doi.org/10.1016/j.jlumin.2022.119516.

(34) Rajak, A.; Hapidin, D. A.; Iskandar, F.; Munir, M. M.; Khairurrijal, K. Electrospun Nanofiber from Various Source of Expanded Polystyrene (EPS) Waste and Their Characterization as Potential Air Filter Media. *Waste Manag.* **2020**, *103*, 76–86. https://doi.org/10.1016/j.wasman.2019.12.017.

(35) Okparaocha, F. J.; Ipeaiyeda, A. R.; Makhatha, M. E.; Alayande, S. O. Morphology and Functional Properties of Electrospun Expanded Polystyrene (EPS)/Reduced Graphene Oxide (RGO) Nanofiber Composite. *Fuller. Nanotub. Carbon Nanostructures* **2019**, *27* (12), 939–946. https://doi.org/10.1080/1536383X.2019.1666365.

(36) Fan, Y.; Cornelius, C. J. Raman Spectroscopic and Gas Transport Study of a Pentablock Ionomer Complexed with Metal Ions and Its Relationship to Physical Properties. *J. Mater. Sci.* **2013**, *48* (3), 1153–1161. https://doi.org/10.1007/s10853-012-6853-9.

(37) Zhou, X.-X.; Liu, R.; Hao, L.-T.; Liu, J.-F. Identification of Polystyrene Nanoplastics Using Surface Enhanced Raman Spectroscopy. *Talanta* **2021**, *221*, 121552. https://doi.org/10.1016/j.talanta.2020.121552.

(38) Hu, X.; Xu, Y.; Wang, J.; Ma, J.; Wang, L.; Jiang, W. In Situ Fabrication of Superfine Perovskite Composite Nanofibers with Ultrahigh Stability by One-Step Electrospinning Toward White Light-Emitting Diode. *Adv. Fiber Mater.* **2023**, *5* (1), 183–197. https://doi.org/10.1007/s42765-022-00207-x.

(39) Lin, R.; Guo, Q.; Zhu, Q.; Zhu, Y.; Zheng, W.; Huang, F. All‐Inorganic CsCu2I3 Single Crystal with High‐PLQY (≈15.7%) Intrinsic White‐Light Emission via Strongly Localized 1D Excitonic Recombination. *Adv. Mater.* **2019**, *31* (46), 1905079. https://doi.org/10.1002/adma.201905079.

(40) Zhang, F.; Liang, W.; Wang, L.; Ma, Z.; Ji, X.; Wang, M.; Wang, Y.; Chen, X.; Wu, D.; Li, X.; Zhang, Y.; Shan, C.; Shi, Z. Moisture‐Induced Reversible Phase Conversion of Cesium Copper Iodine Nanocrystals Enables Advanced Anti‐Counterfeiting. *Adv. Funct. Mater.* **2021**, *31* (47), 2105771. https://doi.org/10.1002/adfm.202105771.

(41) Bai, K.; Fan, Z.; Zhao, G.; He, X.; Zhu, Z.; Pan, S.; Ge, J.; He, C. Water Engineering in Lead Free CsCu2I3 Perovskite for High Performance Planar Heterojunction Photodetector Applications. *Ceram. Int.* **2023**, *49* (2), 1970–1979. https://doi.org/10.1016/j.ceramint.2022.09.162.

(42) Zeng, F.; Guo, Y.; Hu, W.; Tan, Y.; Zhang, X.; Yang, J.; Lin, Q.; Peng, Y.; Tang, X.; Liu, Z.; Yao, Z.; Du, J. Green Anti-Solvent Assisted Crystallization Strategy for Air-Stable Uniform Cs3Cu2I5 Perovskite Films with Highly Efficient Blue Photoluminescence. *J. Lumin.* **2020**, *223*, 117178. https://doi.org/10.1016/j.jlumin.2020.117178.

(43) Zhang, H.; Yang, L.; Chen, H.; Ma, W.; Wang, R.; Cao, G. Highly Emissive and Color-Tunable Copper-Based Halide Composites for Bright White Light-Emitting Diodes. *Mater. Chem. Front.* **2022**, *6* (12), 1647–1657. https://doi.org/10.1039/D2QM00172A.

(44) Islam, M. S.; Ang, B. C.; Andriyana, A.; Afifi, A. M. A Review on Fabrication of Nanofibers via Electrospinning and Their Applications. *SN Appl. Sci.* **2019**, *1* (10), 1248. https://doi.org/10.1007/s42452-019-1288-4.

(45) Maddalena, F.; Tjahjana, L.; Xie, A.; Arramel; Zeng, S.; Wang, H.; Coquet, P.; Drozdowski, W.; Dujardin, C.; Dang, C.; Birowosuto, M. Inorganic, Organic, and Perovskite Halides with Nanotechnology for High–Light Yield X- and γ-Ray Scintillators. *Crystals* **2019**, *9* (2), 88. https://doi.org/10.3390/cryst9020088.

(46) Sidiq, D. H.; Mahato, S.; Haposan, T.; Makowski, M.; Kowal, D.; Witkowski, M. E.; Drozdowski, W.; Arramel; Birowosuto, M. D. Cation Engineering of Cu-Doped CsPbI3 : Lead Substitution and Dimensional Reduction for Improved Scintillation Performance. *J. Phys. Chem. C* **2024**, *128* (47), 20324–20332. https://doi.org/10.1021/acs.jpcc.4c07165.

(47) Chen, C.; Lin, Y.; Lai, P.; Lin, H.; Tan, G.; Lin, H.; Schaller, R. D. Self‐Trapped and Free Exciton Dynamics in Vacuum‐Deposited Cesium Copper Iodide Thin Films. *Adv. Opt. Mater.* **2022**, *10* (17), 2200005. https://doi.org/10.1002/adom.202200005.

(48) Yang, S.; Huang, S.; Wang, Q.; Wu, R.; Han, Q.; Wu, W. Temperature-Dependent Photoluminescence of Cs2AgxNa1-xInCl6 Microcrystals. *Opt. Mater.* **2019**, *98*, 109444. https://doi.org/10.1016/j.optmat.2019.109444.

(49) Li, S.; Luo, J.; Liu, J.; Tang, J. Self-Trapped Excitons in All-Inorganic Halide Perovskites: Fundamentals, Status, and Potential Applications. *J. Phys. Chem. Lett.* **2019**, *10* (8), 1999–2007. https://doi.org/10.1021/acs.jpclett.8b03604.

(50) Olejnik, A.; Dec, B.; Goddard, W. A.; Bogdanowicz, R. Hopping or Tunneling? Tailoring the Electron Transport Mechanisms through Hydrogen Bonding Geometry in the Boron-Doped Diamond Molecular Junctions. *J. Phys. Chem. Lett.* **2022**, *13* (34), 7972–7979. https://doi.org/10.1021/acs.jpclett.2c01679.

(51) Song, X.; Han, B.; Yu, X.; Hu, W. The Analysis of Charge Transport Mechanism in Molecular Junctions Based on Current-Voltage Characteristics. *Chem. Phys.* **2020**, *528*, 110514. https://doi.org/10.1016/j.chemphys.2019.110514.

(52) Song, X.; Yu, X.; Hu, W. Ideal Current-Voltage Characteristics and Rectification Performance of Molecular Rectifier under Single Level Based Tunneling and Hopping Transport.

(53) Wang, C.; Zhao, F.; Zhou, Z.; Li, X.; He, S.; Zhang, M.; Zhang, D.; Zhang, L. Self-Powered CsCu2I3/Si Heterojunction UV Photodetectors Prepared by Pulsed-Laser Deposition. *J. Alloys Compd.* **2022**, *905*, 164245. https://doi.org/10.1016/j.jallcom.2022.164245.

(54) Zhang, Z.-X.; Li, C.; Lu, Y.; Tong, X.-W.; Liang, F.-X.; Zhao, X.-Y.; Wu, D.; Xie, C.; Luo, L.-B. Sensitive Deep Ultraviolet Photodetector and Image Sensor Composed of Inorganic Lead-Free Cs3Cu2I5 Perovskite with Wide Bandgap. *J. Phys. Chem. Lett.* **2019**, *10* (18), 5343–5350. https://doi.org/10.1021/acs.jpclett.9b02390.