PHOTONICS **Research**

Golden hour for perovskite photonics

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Halide perovskite semiconductors have emerged as promising candidates for the next-generation low-energy consumption, high-flexibility photonics and optoelectronic devices thanks to their superior optical and excitonic properties as well as fabrication convenience. This special issue, including three review papers and six original research papers, focuses on the studies of both fundamentals and applications of perovskite photonics, covering materials, excitonic properties, nonlinear optics, strong light–matter interactions, and optoelectronic devices.

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In 2009, metal halide perovskites that combine both advantages of inorganic and organic semiconductors revived as sensitizers in solar cells (SCs) with a power conversion efficiency of 3.8%, which opened a booming decade for perovskite photonics and optoelectronics [1–6]. Up to now, the conversion efficiency of perovskite SCs has increased dramatically to over 25% [7]. The outstanding excitonic and optical properties of perovskites, including the large absorption/emission efficiency, high defect tolerance, long-distance carrier diffusion, and the low-cost fabrication process, also make them promising for light source and detector applications. The perovskite light-emitting diodes (LEDs) can be traced back to the 1990s [8]. In 2014, a room-temperature perovskite LED was realized by Tan *et al.* with an external quantum efficiency of only 0.1% [9], and until now the efficiency has been promoted to over 20% in green and red bands [10,11]. In 2014, the first room-temperature microlaser was realized using organic–inorganic hybrid perovskite nanoplatelets [12], and then perovskite lasers including polariton lasers, vortex lasers, and plasmonic lasers were developed rapidly thanks to the high optical gain [13–19]. Lately, the continuous-wave optically pumped perovskite microlasers and distributed feedback lasers have been reported [20–23]. Perovskites are also employed as active layers in high-efficiency, polarization-sensitive photodetectors [24,25] and X-ray detectors [26,27], which is benefitted from large absorption coefficients for both visible and X-ray spectral ranges as well as high carrier mobilities. Meanwhile, the perovskite nanocrystals can be used for a single-photon light source [28]. For example, a coherent single-photon source was recently reported with a coherence time as long as 80 ps [29], which is very promising for quantum communication applications based on large-scale solution-processed single-photon sources. In particular, perovskites have been an ideal platform to investigate the strong light–matter interactions toward room-temperature polaritonic devices working within a wide band spectrally covering from the ultra-violet to the visible range [17,20,21,30–34]. In 2017, Su *et al.* reported the first room-temperature polariton lasing in a planar perovskite cavity [17], and later in 2019, they observed the room-temperature exciton polariton condensation in a perovskite lattice [32]. In 2018, Zhang *et al.* reported the exciton polariton in low-dimensional $CH_3NH_3PbBr_3$ nanowires with a Rabi splitting energy of 390 meV [33], which was then promoted to 564 meV by Shang *et al.* through adopting the metal–insulator–semiconductor hybrid structure [34]. The studies on exciton polaritons of perovskites have benefitted from the development of low-threshold perovskite microlasers [20,21]. Given the complex framework of the whole perovskite photonics, this special issue aims to provide a journey throughout the fundamentals and applications in this field, and to present the prospects of this future semiconductor material.

Parameter verification is the first step to exploit a material. Excitons, one type of photoexcitation near the optical band edge, play an important role in the core physical processes of semiconductor photonic devices, such as optical transition, charge transfer, and strong exciton–photon coupling [35,36]. For three-dimensional perovskite materials with organic–inorganic hybrid characteristics, the long-standing controversy regarding exciton parameters, especially exciton binding energy ranging from a few meV to nearly 100 meV, has promoted scientists to carry out relevant researches from an in-depth and comprehensive perspective [37,38]. A new report conducted by Baranowski *et al.* has measured the exciton parameters of $CsPbCl_3$ through high magnetic field spectroscopy at 2 K, including exciton binding energy (64 ± 1.5 meV) and effective mass (0.202 ± 0.010 of the free electron mass) [39]. The measured results are consistent with the theoretical calculations, showing that the exciton binding energy and effective mass increase with decreasing halide atomic number. In addition, the permittivity decreases with lighter metal and halide atoms. These results prove the promising future for $CsPbCl_3$ as optoelectronic and polaritonic devices, especially in the violet and ultra-violet spectral ranges.

Modification and optimization are the second promotion. One of the origins of perovskite fever is the rich combination of cations and anions, where the cation candidates include various metal or organic cations while the halide anions can be easily tailored to obtain different bandgaps [40]. Furthermore, the emergence of layered perovskites with mixed dimensionality has combined valuable properties between those of two-dimensional and three-dimensional systems [41–43], featuring multiple quantum well nature and dielectric confinement. In addition to material, combining with cavity engineering also paves the way to fundamental photonics and practical devices. Four essays in this feature issue focus on mixed organic cations, mixed halide anions, two-dimensional perovskites, and perovskite-based plasmonic metasurface, respectively. Mixing halide anions has been an ordinary way for bandgap tuning and lattice stabilization in perovskites; however, the phase segregation under external stimuli (e.g., illumination) is detrimental to the device performance [44]. To provide an insight into this issue, Wang *et al.* review the phase segregation phenomena and possible mechanisms in inorganic mixed-halide perovskites, including thin films and nanocrystals [45]. In addition, the mitigation methods are also overviewed, i.e., compositional tuning, morphology engineering, and trap passivation. Another review by Zhang *et al.* focuses on the 2D counterpart, especially the cavity engineering and light–matter interaction in those 2D perovskite microcavities [46]. 2D perovskites are layered materials in which an inorganic metal-halide octahedron layer is sandwiched by two long-chain organic layers. Zhang *et al.* first introduced the unique properties of 2D perovskites that resulted from the inherent quantum well structure, and then summarized the fabrication methods, followed by exciton–photon coupling, photonics lasers, and a variety of other function devices in different cavity configurations. This review gives a general view of 2D perovskites and would promote the future development of this field. Zhang *et al.* studied the nonlinear effects in $MA_{1-x}FA_xPbI_3$ [$MA = CH_3NH_3^+$, $FA = CH(NH_2)_2^+$], i.e., two-photon absorption and saturable absorption. As the pump power increases from $1.0\ GW \cdot cm^{-2}$ to $3.0\ GW \cdot cm^{-2}$, a conversion from two-photon absorption to saturable absorption is observed from the Z-scan results, which is confirmed by transient absorption and power-dependent transmission spectra. With increasing x, i.e., the FA component, the nonlinear absorption coefficient decreases, accompanied by an increased saturation transmission intensity. The effect of organic cations results from weaker electron cloud distortion of Pb^{2+}, which is attributed to larger unit cell expansion and more hydrogen bonds for larger x [47]. Moreover, Lu *et al.* investigate the formation of exciton–photon polaritons and exciton–surface plasmon polaritons in perovskite-based subwavelength lattices with different thicknesses. From a theoretical discussion, the configuration sustaining strong light–matter interactions is considered to concurrently allow exceptional points with enhanced local density of states and a quasi-bound state in the continuum with negligible nonradiative losses of the dark mode [48].

Device applications in light harvesting and light source field have continuously fueled the rapid development of halide perovskite photonics and optoelectronics, in parallel with active research in the fundamental optical physics related to excitons and their dressed states with light. A wide range of devices have been demonstrated in solar cells, LEDs, lasers, amplifiers, displays, photodetectors, etc. [10,11,24,49–53]; nonetheless, there are still pending scientific and technological questions concerning large-area device fabrication, device stability, as well as the high-performance device. In this issue, Zhao *et al.* review the fabrication methods of large-area perovskite SCs (area larger than 1 cm^2) [54], such as spin-coating, blade-coating, and inject printing. In addition, they summarize the common strategies to improve the quality of large-area perovskite films, including engineering the precursor solvent and additives. Furthermore, the fabrication of the large-area charge transporting layer is also discussed, e.g., utilizing Bifluo-OMeTAD in place of Spiro-OMeTAD as HTL to circumvent the difficulty of large-area spin-coating. Although large-area SCs are harnessed by an efficiency lower than 20%, this review concludes with a clear direction ahead. Meanwhile, PTAA has been a conventional HTL in perovskite SCs. Its good hydrophobicity improves the device stability, but hinders the spin-coating process of perovskite precursors as well. Li *et al.* demonstrate a two-step solvent post-treatment to PTAA with DMF and toluene to improve the hydrophilicity and morphology of PTAA surface, on which the spin-coated perovskite layer shows better crystallinity [55]. As-fabricated inverted perovskite SCs exhibit a high efficiency of 19.13%, and a good stability of maintaining 88.4% of the initial PCE after 30 days in air. Beyond intrinsic photovoltaic properties, Mica *et al.* explore the potential of $Cs_{0.06}MA_{0.15}FA_{0.79}Pb(I_{0.85}Br_{0.15})_3$ SCs for visible light communication [56]. These triple-cation perovskite SCs exhibit great energy harvesting performance with PCE up to 21.4%. After the SCs are embedded into the circuit, the ability to collect data is measured for SCs with thicknesses from 60 to 965 nm, and a record high data rate of 56 Mbps for perovskite photodetectors is observed. A further discussion on bandwidth stresses the role of RC time constant, and the optimization of thickness is necessary considering the data rate and bandwidth concurrently. An extra emphasis by Liu *et al.* is placed on the upconversion lasing in $CsPb_2Br_5$ microplates with single-mode operation, high quality factor (~3551), and imperceptible color shift (<0.1 nm) [57]. The net optical gain of $CsPb_2Br_5$ microplates is quickly established in less than 1 ps and persists more than 30 ps, and the net gain for stimulated emission demonstrates a high characteristic temperature of 403 K, providing another all-inorganic platform for high-performance perovskite lasers beyond widely used $CsPbBr_3$.

In summary, this special issue presents some frontier works that give a glimpse of the inspiring advances in the field of perovskite photonics, including fundamental investigations, optimization explorations, and application achievements. Finally, we would like to thank the editorial team from *Photonics Research* for the opportunity to edit this special issue. We are also sincerely grateful to all the authors for their outstanding contributions and the referees for their valuable comments that helped to improve the articles in this special issue.

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