RESEARCH HIGHLIGHTS

Journal of Semiconductors
(2022) 43, 040203
doi: 10.1088/1674-4926/43/4/040203

Frontier applications of perovskites beyond photovoltaics

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Citation: L Y Mei, H R Mu, L Zhu, S H Lin, L X Zhang, and L M Ding, Frontier applications of perovskites beyond photovoltaics[J]. *J. Semicond.*, 2022, 43(4), 040203. https://doi.org/10.1088/1674-4926/43/4/040203

Perovskites have been widely utilized as active materials in various optoelectronic devices, e.g. light-emitting diodes (LEDs), photodetectors (PDs), and solar cells (SCs), etc., due to their facile processability and outstanding optoelectronic properties, like high optical absorption coefficients (~10^5 cm^{-1}), high carrier mobilities (~10–10^3 $cm^2/(V\cdot s)$), long carrier lifetime (~1–10 μs), long carrier diffusion length (1–100 μm) and tunable bandgaps (~1.17–2.88 eV), which enable them to deliver a comparable performance as traditional inorganic semiconductors. Perovskite LEDs offer 12.2%, 22.2%, 28.1% and 12.8% EQEs for white LEDs[1], near-infrared (NIR) LEDs[2], green LEDs[3] and blue LEDs[4], respectively. The efficiency for perovskite/Si tandem SCs reaches 29.8%, which is greater than that for silicon single crystal-based SCs (26.1%) and that for thin-film crystalline silicon-based SCs (21.2%)[5]. Moreover, the specific detectivity for Sn–Pb perovskite-based PDs reaches ~10^{12} Jones at 1000 nm, which is much greater than that for germanium-based PDs (~10^{11} Jones)[6]. Here, we highlight other applications in neuromorphic computing, synapse devices and ultrasound imaging[7–9].

The memory and central processing unit in traditional computers based on von Neumann architecture are separated, and the mismatch between the processing speed and data transmission speed causes difficulty in solving fast processing and storage of enormous data in face of the digital revolution[10]. The neuromorphic computing, inspired by biological neuromorphic system, is composed of devices that act as both storage and processing unit, and it can process large amounts of data in parallel and simultaneously deal with memory wall[11]. Various materials have been applied in plastic synapse-like devices to simultaneously perform memory and processing functions in neuromorphic computing, such as memristor, phase-change materials, perovskites, etc.[7, 12, 13]. Perovskite-based synapse devices have recently gained popularity due to low power consumption, fast response, optical/electrical tunability[7, 14–18]. Han *et al.* combined $CsPbBr_3$ quantum dots with pentacene to make a photonic memory (Fig. 1(a)). This device showed the characteristics of optical programming and electrical erasing (Fig. 1(b)). Multiple synaptic functions were demonstrated and could be further applied in image identification and classification[7]. Considering the practicality and accuracy of perovskite-based synapse devices, more efforts should focus on precise and linear tuning of synaptic resistance, co-optimization with algorithms, device stability, etc.

In addition to using photoelectrically-controlled variable resistance of perovskites to develop synaptic devices, perovskites also find applications in communication. High-performance storage and communication devices with high throughput, low power consumption and fast response are desired to meet the requirements of information explosion in modern society. Chang *et al.* verified a difunctional device composed of Ag/$CsPbBr_3$ QDs/ITO as both resistive random-access memory and light-emitting electrochemical cell by inverting the electrode (Fig. 1(c)), and then inversely connected two devices in series to achieve light-emitting memories, in which one as memory for coding and the other as light-emitting electrochemical cell for reading (Fig. 1(d))[8]. This design not only solves high signal transmission delay and power consumption present in separated devices, but also increases the capacity and privacy of signal transmission. Furthermore, multicast mesh network and composite device structures should be designed for further improving their usefulness.

Apart from optoelectronic properties, the photoacoustic properties of perovskites have been applied in photoacoustic transducers, which can transfer light signals to ultrasound pulses, and are applied in biomedical imaging, nondestructive testing, etc.[19]. Photoacoustic transducers possess advantages of high precision, fast response and simple device structure compared to traditional piezoelectric ultrasound transducers, which consist of a mass of cabling and suffer from electromagnetic interference. Normally, photoacoustic transducers consist of thermal expansion materials like PDMS and light absorption materials (e.g., carbon nanotubes, carbon nanofibers and perovskites)[9, 20, 21]. With the advantages of low heat capacity and high light absorption coefficient of CNTs, the bandwidth of CNTs-based photoacoustic transducers is much smaller than that of traditional transducers[20]. Perovskites with low specific heat capacity (~308 J/(kg·K)) and thermal diffusion coefficient (0.145 mm^2/s) can promise an effective thermal conduction with PDMS for high photoacoustic conversion efficiency[9]. Recently, Niu *et al.* combined $MAPbI_3$ with PDMS to make a photoacoustic transducer with high an acoustic pressure of 24.89 MPa and a record high –6 dB bandwidth of 40.8 MHz, and demonstrated an ultrasound imaging application under water by coating $MAPbI_3$ on fibers (Figs. 1(e) and 1(f))[9].

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Received 21 FEBRUARY 2022.

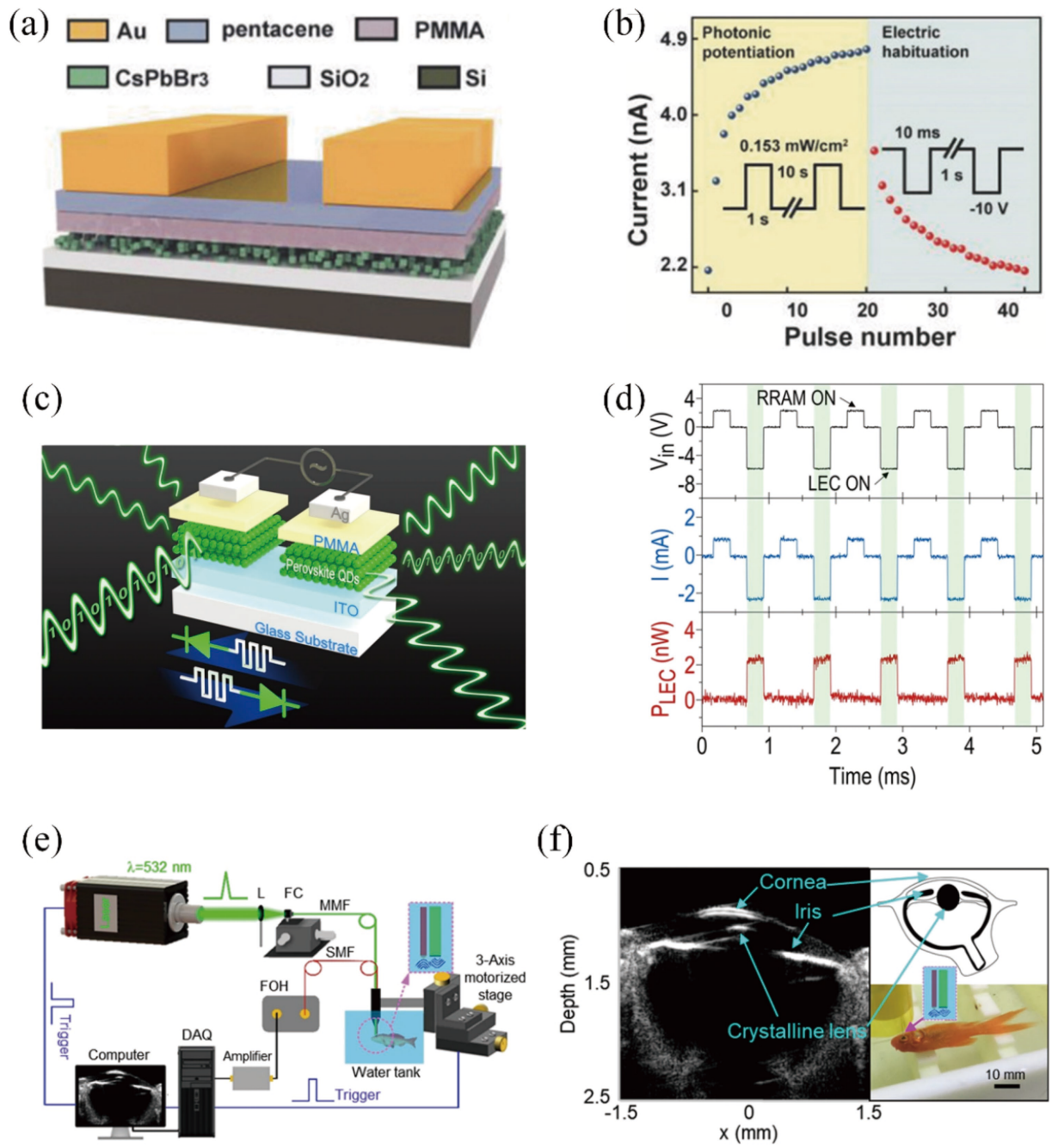

Fig. 1. (Color online) (a) Schematic of the synapse device based on $CsPbBr_3$ QDs. (b) Current modulation of $CsPbBr_3$ QDs-based synaptic device under the train of photonic pulses and negative electrical pulses. (c) Schematic of the light-emitting memory device. (d) Dual functions of $CsPbBr_3$ QDs-based device as both light-emitting electrochemical cell and resistive random-access memory by changing the bias direction. (e) High-resolution ultrasound imaging system based on fiber/perovskite device, where L, FC, MMF, SMF, FOH, DAQ represent lens, fiber coupler, multimode fiber, single-mode fiber, fiber-optic hydrophone and data acquisition card, respectively. (f) Ultrasonic imaging of fisheye based on fiber/perovskite device. (a) and (b), reproduced with permission[7]. Copyright 2018, Wiley-VCH. (c) and (d), reproduced with permission[8]. Copyright 2021, Springer Nature. (e) and (f), reproduced with permission[9]. Copyright 2021, Springer Nature.

In short, perovskites find some new applications in computing[7, 15, 16], communication[8, 9, 22], biomimetic retina[14, 23, 24], fingerprint recognition[25], etc. This article gives inspiration to researchers for further exploring perovskite materials.

Acknowledgements

L. Zhu thanks the financial support from Guangdong Basic and Applied Basic Research Foundation (2021A1515012198) and the Science and Technology Program of Guangzhou (202102021084). S. Lin thanks the support from Songshan Lake Materials Laboratory (Y0D1051F211) and the Key Project of the Joint Funds of Guangdong and Dongguan (2021B1515120034). L. Ding thanks the open research fund of Songshan Lake Materials Laboratory (2021SLABFK02), the National Key Research and Development Program of China (2017YFA0206600), and the National Natural Science Foundation of China (51773045, 21772030, 51922032, and 21961160720) for financial support.

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