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Efficient photovoltaic and electroluminescent perovskite devices

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Planar diode structures employing hybrid organic-inorganic methylammonium lead iodide perovskites lead to multifunctional devices exhibiting both a high photovoltaic efficiency and good electroluminescence. The electroluminescence strongly improves at higher current density applied using a pulsed driving method.

Hybrid organic-inorganic methylammonium lead iodide perovskites (CH$_3$NH$_3$PbI$_3$) have recently been used to prepare very efficient solar cells.\textsuperscript{1,2,11} Previously, these materials have been used to prepare light-emitting diodes (LEDs).\textsuperscript{12,13} Electroluminescence was first shown at very low temperatures,\textsuperscript{14} and later by incorporating an organic emitter also at room temperature.\textsuperscript{12} These devices, however, were not obtained with the same material used in recent efficient solar cells, i.e. the methylammonium lead iodide which adopts the 3D perovskite structure. The LEDs were fabricated using 2D layered lead iodide and chloride perovskites containing longer alkylammonium salts. Recently, it was demonstrated that also the 3D CH$_3$NH$_3$PbI$_3$ perovskite exhibits strong photoluminescence quantum yield (PLQY) up to 70% at high excitation intensity,\textsuperscript{15} and were incorporated into LEDs.\textsuperscript{16} Hence, this opens up the possibility to prepare a multi-functional device that shows simultaneously efficient photocurrent generation and electroluminescence.\textsuperscript{12} Such devices were shown previously, albeit with rather low photovoltaic efficiency (< 1%).\textsuperscript{18-20}

Two main types of architectures for CH$_3$NH$_3$PbI$_3$ based photovoltaic devices have been demonstrated so far, either using mesoporous metal oxide scaffolds or planar structures.\textsuperscript{3,4,21} In the latter either a metal oxide or an organic hole blocking layer is employed, resulting in the transparent bottom electrode being the electron or hole collector, respectively. Recently, we showed a device architecture in which the perovskite layer is sandwiched in between an organic hole and electron blocking layer leading to photovoltaic efficiencies close to 15%.\textsuperscript{5,22} Such a structure is frequently used in organic light-emitting diodes (OLEDs) to confine electrons and holes in the light-emitting layer.\textsuperscript{23} In a similar device layout and using CH$_3$NH$_3$PbBr$_3$ perovskite nanoparticles bright green electroluminescence was observed.\textsuperscript{24} Thin films based on these perovskite nanoparticles exhibited PLQY’s above 20% at low excitation intensity. Therefore, the planar architecture with the hole and electron blocking layers is also expected to lead to efficient light-emission in view of the high PLQY’s observed in thin films of CH$_3$NH$_3$PbI$_3$. However, a high work function electrode, Au, was used in the solar cell configuration. Even though it works well to extract electrons, it is not ideal for their injection into the lowest unoccupied molecular orbital (LUMO) of the electron transporting layer. Therefore, we have adapted the architecture by employing a thicker electron transporting/hole blocking layer and a low workfunction top electrode. Using this architecture the device exhibits simultaneously a high photovoltaic efficiency and good electroluminescence.

Fig. 1 a) Device layout. b) Simulated and experimental grazing incidence x-ray diffraction (GIXRD) pattern for a CH$_3$NH$_3$PbI$_3$ perovskite thin film.

The device layout is shown in Fig. 1a and consists of a 80 nm poly(3,4-ethylenedioxythiophene):poly(styrene sulfonic acid) (PEDOT:PSS) layer and a thin layer (20 nm) of poly[N,N'-bis(4-
butylphenyl)-N,N'-bis(phenyl)benzidine (polyTPD) as the electron blocking layer. On top of this, the CH$_3$NH$_2$PbI$_3$ was thermally evaporated to a thickness of 320 nm, using a protocol described previously, followed by a hole blocking layer of [6,6]-phenyl C$_{61}$-butyric acid methyl ester (PCBM) (100 nm). The device was completed by the evaporation of a Ba (10 nm) top electrode covered with Ag (100 nm). Both the polyTPD and the PCBM layers were deposited using a meniscus coating process to ensure high quality films. The X-ray diffraction pattern of the CH$_3$NH$_2$PbI$_3$ layer is shown in Fig. 1b demonstrating a good match with the calculated one and ensuring the formation of the perovskite structure.

First, the photovoltaic effect of these devices was examined. The incident photon to electron conversion efficiency (IPCE, Fig. 2a) was determined as a function of wavelength and the current density versus voltage characteristics (J-V, Fig 2b) were determined in dark and under 1 sun illumination. The key performance data are similar versus voltage characteristics (J-V, Fig 2b) were determined in dark and under 1 sun illumination. The key performance data are similar. The spread of performances for a series of devices is depicted in Figure S1.

![Fig. 2 a) Typical IPCE spectrum for the solar cells. b) J-V curves in the dark (gray line) and under 1 sun illumination using forward and reverse scan directions (black and red line, respectively).](image)

The external quantum efficiency (EQE$_{EL}$) of the device reaches a maximum of approximately 0.04% (Fig. S2). This is similar to the EQE$_{EL}$ previously reported by us for the devices using a gold top electrode (0.012%). The spread of performances of the EQE$_{EL}$ for different devices is shown in Figure S3. Such efficiencies are approximately 2 orders of magnitude lower than the most efficient thin film near infrared emitting devices. The PLQY of a similar perovskite material, the so-called mixed halogen perovskites CH$_3$NH$_2$Pb$_{1-x}$Cl$_x$, is strongly dependent on the excitation intensity in the range from 25 to 2000 mW cm$^{-2}$. In our devices the CH$_3$NH$_2$PbI$_3$ is prepared from only the iodide precursors and we were unable to detect a photoluminescence signal using a (C920-02, Hamamatsu Photonics) with a Xe lamp as the excitation source and a multichannel spectrometer (Hamamatsu PMA-11) as the optical detector. Using the same setup for a film containing CH$_3$NH$_2$PbBr$_3$ perovskite nanoparticles we observed a PLQY of 23%. Only when the CH$_3$NH$_2$PbI$_3$ is excited with a CW laser (at 405 nm) a photoluminescence signal could be observed. In the multifunctional device employing CH$_3$NH$_2$PbI$_3$, the electroluminescence increases with increasing current density (Figure 4a). Holes and electrons are confined to the CH$_3$NH$_2$PbI$_3$ layer due to the efficient electron and hole blocking materials adjacent to it. This therefore leads to a strong increase in excitons formation and thus electroluminescence in that layer. This effect is remarkable, as in most OLEDs the emission decreases with increasing current density due to various quenching effects related with high exciton and polaron densities. Hence, a similar behavior as was observed for the CH$_3$NH$_2$Pb$_{1-x}$Cl$_x$ perovskite might take place. In order to increase the excitation intensity, the devices were driven with pulsed current using a periodic square waveform, with duty cycle of 50% at a frequency of 100 Hz. This allows for much higher current densities while avoiding rapid degradation as the device is allowed to relax (dissipate excess heat) in the off state. Average current densities up to 1150 mA cm$^{-2}$ (Fig. 4a), corresponding to 2300 mA cm$^{-2}$ in the on phase of the pulse (Fig. 4b), were obtained. The resulting irradiance
increases steadily, exceeding $330 \mu\text{W cm}^{-2}$ at the maximum current density. The radiance meter integrates the emitted photons over a period of 100 ms and as such records the average emission. Hence, the light output was also measured using a Si-photodiode coupled to an oscilloscope enabling the visualization of the on/off cycles in correspondence to the applied current pulses (Fig. 4b). Intense electroluminescence up to $770 \mu\text{W cm}^{-2}$ is reached in the pulse peak with a rising time (time to reach 90% of the maximum signal) of approximately 4 ms. This slow response can be ascribed either to a low exciton formation rate or to a slow depletion of the exciton quenching sites, or both.

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