Perovskite Phototransistors



Anomalous Ambipolar Phototransistors Based on All-Inorganic CsPbBr₃ Perovskite at Room Temperature

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Despite its extensive research in photovoltaics and light emitting diodes, the charge transport properties of all-inorganic perovskite cesium lead bromide (CsPbBr₂) remain elusive. Clarification of the intrinsic charge transport of this perovskite material is highly desirable, which will help to understand its working mechanism and fabricate high performance electronic devices. Here, it is demonstrated that the phototransistors based on CsPbBr₂ microplates show anomalous ambipolar transport characteristics at room temperature. The hole mobility shows light dependence, while the electron mobility is identical under various light incidence. The hole mobility increases from 0.02 cm² V⁻¹ s⁻¹ (in dark conditions) to 0.34 cm² V⁻¹ s⁻¹ (50 mW cm⁻²); while the threshold voltage is shifted by 14 V when electron is the majority charge carrier. The anomalous transport behavior can be attributed to the photovoltaic and photoconductive effects. Moreover, the device shows photoresponsivity and detectivity up to 110 mA W^{-1} and 4.5×10^{13} Jones, respectively, under 532 nm laser illumination. This research unveils the charge transport mechanism of CsPbBr₃ perovskite, provides more evidence and will thus contribute to the perovskite electronic and optoelectronic researches.

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1. Introduction

Lead halide perovskites have been widely investigated as the novel photoactive materials in a variety of optoelectronic applications, such as solar cells, photodetectors, and light emitting diodes (LEDs) since 2009.^[1-3] Their exceptional basic properties such as high absorption coefficient, long carrier lifetime, and super long carrier diffusion length are highly attractive for developing high-efficiency optoelectronics.^[4,5] However, one basic property of the perovskites, i.e., charge transport, is still elusive. To unveil the working principle of perovskite optoelectronics and to develop low-cost, high performance electronics, explorating the transport property of perovskite materials is of both theoretical and practical significance. So far, a few pioneering works have been conducted to unveil the essence of charge transport behaviors of organic-inorganic hybrid lead halide perovskites.^[6-14] For example, Chin et al. first reported the ambipolarity

of CH₃NH₃PbI₃ perovskite at 78 K;^[13] Duan's group later investigated the charge transfer property of CH₃NH₃PbI₃ at various temperatures and via using different interface materials.^[6,10,11] Thereafter, Henning's group found temperature-dependent transport property and revealed a negative coefficient of mobility within three different temperature regimes.^[14] Nevertheless, the carrier mobilities are still modest comparing to the theoretical calculations.^[15] The crystal quality and size are two key issues for charge transport research of perovskite materials. Currently, most perovskite materials utilized in the solar cells, photodetectors, and LEDs are in the forms of polycrystalline films or quantum dots with the typical grain size (or diameter) from several to hundreds of nanometers. The size of grain is much smaller than the channel's length for the normal transistors, which ranges from several to hundreds of micrometers. The grain boundaries in polycrystalline films will block the charge transport in the horizontal direction, weaken the electronic coupling, and thus cause underestimation of the carrier mobility.^[16] To overcome the negative effect caused by perovskite grain boundaries and extract the intrinsic charge transport value of perovskites, high-quality thin crystals with lateral size over hundreds of micrometers are highly preferred. To resolve this problem, our group has recently developed a confined-spacestrategy to grow the high-quality hybrid perovskite thin crystals and greatly improved carrier mobility has been achieved.^[17]



Comparing to the organic-inorganic hybrid counterparts, the all-inorganic halide perovskite CsPbBr3 has recently attracted a significant amount of attentions in various research fields including LED,^[18,19] solar cell,^[20,21] and biological imaging,^[22-29] due to its improved photo- and thermal stability,^[30] high photoluminescence quantum yield (PLQY up to 100% was recently reported),^[31] and narrow photoluminescence (PL) line width (<20 nm).^[32] Due to the morphology reason as mentioned above, the research on charge transport property of CsPbBr₃ is still limited.^[33,34] Zeng's group fabricated field effect transistor (FET) devices based on CsPbBr₃/MoS₂ heterojunction and investigated their charge transport property. They demonstrated the p-type phototransistors and found that the mobility is light intensity dependent.^[34] The intrinsic transport property of CsPbBr3 and related light tuning effect on charge transport are highly interesting and further researches are needed.

Here we fabricated the phototransistors based on around 2 μ m thick CsPbBr₃ microplates with the lateral size up to millimeters and investigated their charge transport properties. We demonstrated that the transistors devices based on CsPbBr₃ microplates exhibit anomalous ambipolar charge transport properties at room temperature, i.e., a light intensity dependent hole transport property and light independent electron transport property. The mechanism lying behind such anomalous behavior was explored and was attributed to the photovoltaic effect and photoconductive effect. Moreover, the CsPbBr₃-based devices show a presentable photoresponsive property, which offer potential applications in photodetection, sensing, and imaging fields.

2. Results and Discussions

We synthesized the high-crystallinity CsPbBr₃ microplates between two slides following the inverse temperature crystallization strategy.^[35] The thickness of the microplate can be controlled by tuning the thickness of polyethylene terephthalate (PET) film, and 2 µm thick film was chosen here (Figure S1, Supporting Information). Figure 1a shows the UV-vis absorption and PL spectra of CsPbBr3 microplates. The absorption spectrum shows a sharp edge with the onset of 543 nm. The PL spectra was excited by 473 nm laser and exhibited a narrow peak at 528 nm (E_g = 2.35 eV). Both the sharp edge in UVvis and small full width at half maximum (17 nm) value in PL spectrum indicate the high crystallinity of our CsPbBr3 microplates. Figure 1b displays the X-ray diffraction (XRD) spectrum of CsPbBr₃ microplates, which indicates that the samples are orthogonal structured (space group: Pnma).[36-38] Figure 1c displays the optical image of synthesized CsPbBr, microplates, which shows the regular edge and the size is up to several millimeters. Figure 1d exhibits the cross-section scanning electron microscopy (SEM) image of the microplate, from which the thickness is confirmed to be 1.95 µm. Also, there are no grain boundaries within the microplate samples. Figure 1e depicts the PL mapping of CsPbBr₃ microplate, and the evenly distributed PL intensity indicates the high quality of CsPbBr₃ microplates synthesized in our case.

The field effect charge transfer properties of CsPbBr₃ microplate under various incident light intensities were characterized. **Figure 2**a shows the optical image of bottom-gate top-contact (BGTC) structured FET device. High



Figure 1. Characterization of CsPbBr₃ microplates. a) The UV–vis absorption and photoluminescence of CsPbBr₃ microplates. Inset: The schematic diagram of CsPbBr₃ perovskite. b) The measured and calculated XRD spectra of CsPbBr₃ perovskite. c) The optical image of one CsPbBr₃ microplate corner. d) The cross-section SEM image of one CsPbBr₃ microplate. e) The PL mapping of CsPbBr₃ microplate with the excitation of 473 nm laser.

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Figure 2. a) The optical image of the BGTC structured FET devices based on CsPbBr₃ microplates. The scale bar is 50 μ m. b) The output curves of the FET devices with the V_{gs} varying from -60 to 0 V and from 0 to 60 V, separately. Inset: The enlarged output characteristics of the FET device at low voltage region. c,d) The transfer curves of FET devices under different light illumination conditions at the V_{ds} of -20 V. e,f) The transfer curves of FET devices under different light evolutions at V_{ds} = +20 V. The gate-source voltage (V_{gs}) scanning rate is 10 mV s⁻¹.

conductive Si (<15 Ω square⁻¹) with 250 nm SiO₂ insulating layer was employed as the device substrate. Au metal was thermal-evaporated on the CsPbBr₃ microplates as the drain and source electrodes. The FET devices show the ambipolar characteristic when using the gate bias as an additional tuning factor. Figure 2b displays the output curves of the FET devices in both p- and n-type transport models and we also provided the corresponding enlarged drawing for the low voltage region along with the output curves (as shown in Figure 2b inset). For the n-type model, the device turned to saturated when the V_{ds} was around 30 V; while the p-type transfer was saturated when V_{ds} was below –25 V. From the transfer curves, we can extrapolate the carriers (electrons and holes) mobility according to the I_{ds} versus V_{gs} relationship as shown below

$$I_{\rm ds} = \frac{WC_{\rm i}\mu \left(V_{\rm gs} - V_{\rm th}\right)^2}{2L} \tag{1}$$

where *W*, *L*, and C_i are the channel width, the channel length, and the gate capacitance of dielectric layer, respectively. The transfer properties are shown in Figure 2c–f and the key results are summarized in **Table 1**.

There are two interesting issues need to be explored for the CsPbBr3-based FET devices. First, why do the FET devices based on perovskite microplates tend to show the ambipolar transport property? Literature survey shows that the transport property of perovskite may be affected by several parameters, such as the electrode materials,^[9,11] the operating temperature,^[6] the components,^[39,40] and the dielectric interfaces.^[34] Several groups claimed that Au-electrode contacted devices are opt to be ambipolar transport.^[11,12,41] Duan's group stated that the transformation from unipolar n-type transport behavior to ambipolar behavior, and finally to unipolar p-type behavior, can be achieved by the thermal annealing process.^[6] Snaith's group observed around one order of magnitude difference in mobility for samples prepared in different ways and proved that may be due to differences in perovskite composition.^[40] Zeng's group found that CsPbBr3 showed p-type transport behavior with the hole mobility of 0.28 cm² V^{-1} s⁻¹, which was attributed to the heterojunction formed between the perovskite and MoS₂ layers.^[34] The research on transport property presented here shows that ambipolar transport is one type of intrinsic property for CsPbBr₃ perovskite,^[11,12] which is similar to the previous reports on organic-inorganic hybrid perovskites.^[42,43]

Table 1. The FET device properties measured under different conditions.

Carrier	<i>L/W</i> [μm/μm]	$\mu_{saturation} [\text{cm}^2 \text{V}^{-1} \text{s}^{-1}]$	V _{th} [V]	On/off ratio	SS [V dec ⁻¹]	N _{it} [eV ⁻¹ cm ⁻²]	Conditions
e	50/80	0.19	42	_	17	$2.6 imes 10^{13}$	Dark
h	50/80	0.02	-20	_	24	$7.3 imes 10^{13}$	Dark
e	50/100	0.40	28	$1.5 imes10^3$	5.3	8.3×10^{12}	50 mW cm ⁻²
h	50/100	0.34	-19	2.3×10^3	3.1	4.9×10^{12}	50 mW cm ⁻²



The ambipolar transport property of CsPbBr₃ FETs is also in accordance with theoretical predications, although the experimental mobilities of CsPbBr3 are still lower than theoretical calculations anticipated.^[44,45] The mechanism for ambipolar transport behavior in our case can be explained in Figure S2 in the Supporting Information. The work function of Au electrodes (\approx 5.1 eV) is aligned well between the valence band (3.3 eV) and conduction band (5.6 eV) of perovskite samples, which provides the possibility for both electron and hole injection. As shown in Figure S2b in the Supporting Information, in the dark condition, when $V_{\rm G} > V_{\rm T}$, $V_{\rm D} = 0$, the Fermi level of perovskite is raised, so the electrons become the majority charge carriers, and the surface is reversed from p-type to n-type. Figure S2c in the Supporting Information shows when $V_{\rm C} < V_{\rm T}$, $V_{\rm D} = 0$, the Fermi level of perovskite decreases, the majority charge carriers are the holes, and the surface is reversed from n-type to p-type.^[43] As shown in Figure S2d,e in the Supporting Information, when white light is irradiated upon the perovskite, the photogenerated charge carriers can contribute to the I_{ds} current significantly in the transistor channel.

Second and more interestingly, the CsPbBr₃ FET showed anomalous light intensity dependent transport property, which is different from or even reverse to previous finding which claims that carrier mobility is independent on light intensity for MoS₂ or organic semiconductors.^[46–48] Figure 2c,d show the hole transfer data when the negative source–drain voltage was applied. The results depict that the hole mobility increases with the increase of incident light intensity; while the threshold voltage ($V_{\rm th}$) keeps constant at the same time. Figure 2e,f show that electron mobility is almost identical at different incident light intensity and the $V_{\rm th}$ decreases from 42 to 28 V when the light intensity increases from 0 to 50 mW cm⁻². The relationship between hole mobility ($\mu_{\rm hole}$) and light intensity is shown in **Figure 3**. Generally, the anomalous transport property was attributed to the photogenerated excitons that separated, drifted, and accumulated at the electrodes, leading to the variation of current or potential barrier between the source and the channel. The light intensity dependence may be attributed to the photoconductive and photovoltaic effects.^[49–51] In this case, when the $V_{\rm gs} < V_{\rm th} < 0$, the FET works in the hole transport model. The hole mobility shows linear dependence on light intensity (Figure 3a), while the $\Delta V_{\rm th}$ shows nonlinear light dependence. The mechanism was attributed to the photoconductive effect, as shown in Figure 3c,d. The photocurrent induced by a photoconductive effect in device can be described as

$$I_{\rm pc} = (q\mu pE) WD = BP_{\rm opt} \tag{2}$$

where μ is the mobility, *p* is the carrier concentration, *E* is the electric field in the channel, *W* is the gate width, *D* is the depth of absorption region, and *B* is the fitting parameter. Under this model, the carrier mobility is proportional to light intensity. For both organic and inorganic semiconductors, this effect was reported mostly to happen in the turn-off state, together with very weak photocurrent. However, the CsPbBr₃ device works in the turn-on state, which may be attributed to the large diffusion length of perovskite materials and coexisting ion transport.^[47]

However, when $V_{gs} > V_{th} > 0$, the FET is working in electron transporting range and photovoltaic effect dominates. The



Figure 3. The dependence of a) hole mobility and b) ΔV_{th} on light intensity for CsPbBr₃ FETs. (c) and (d) show the schemes of photoconductive and photovoltaic effect under light illumination.





Figure 4. The transport properties of CsPbBr₃ microplate under illumination. a) The scheme of the BGTC FET structure under white light. b) The saturate transfer curves of FET in the n-type region with the V_{ds} of 30 V, respectively. c) The saturate transfer curves in the p-type region with V_{ds} of -30 V, respectively. The scanning direction of gate voltage is from positive to negative. White LED light intensity: 50 mW cm⁻². Scan rate: 10 mV s⁻¹. d) The statics of carrier (holes and electrons) mobility for CsPbBr₃ perovskite.

photocurrent caused by photovoltaic effect can be expressed as

$$I_{\rm pv} = G_{\rm M} \ \Delta V_{\rm th} = \frac{AkT}{q} \ln \left(1 + \frac{\eta q \lambda P_{\rm opt}}{I_{\rm pd} hc} \right)$$
(3)

where η is the quantum efficiency, P_{opt} is the incident optical power, I_{pd} is the dark current, $hc\lambda^{-1}$ is the photo energy, $G_{\rm M}$ is the transconductance, $\Delta V_{\rm th}$ is the threshold voltage shift, and A is the fitting parameter. The shift of $V_{\rm th}$ with the increasing light intensity can be attributed to the photovoltaic effect by the accumulation of less carriers (holes).^[51] As shown in Figure 3b, the $\Delta V_{\rm th}$ shows logarithmic correlation with light intensity, which matches well with photovoltaic assumption. We thus assume that the accumulated holes effectively lower the potential barrier between the source and perovskites, leading to an effectively decrease in $V_{\rm th}$ (Figure 3b).

Figure 4a depicts the scheme of perovskite FET devices under light illumination. Figure 4b shows n-type transfer property in the saturate region of CsPbBr₃ FETs, with the champion electron mobility of 0.40 cm² V⁻¹ s⁻¹ when V_{ds} was 30 V. Figure 4c shows the p-type characteristics dominate in the saturation region, with the maxim hole mobility of 0.34 cm² V⁻¹ s⁻¹. Both electron and hole mobilities in the linear region (as shown in Figure S3, Supporting Information) are slightly smaller than that of the saturation region. And Figure S4 in the Supporting Information shows the corresponding gate current in the transfer curves at different drain–source gates based on the same device. Comparing with that in the dark, the electron and hole mobilities increased by two times and three orders magnitude, respectively. This is the largest carrier mobility ever reported based on CsPbBr₃ by far.^[38] The statics of carrier

mobility for all perovskite devices with different forms are summarized in Figure 4d.

Under illumination, the carrier concentration in the crystal will be greatly increased and lead to enhancement of current in the channel. The crystallinity of the microplates and trap densities are significant factors that need to be confirmed. Sub-threshold slope (SS) and interfacial trap state density (N_{it}) were calculated using the following formulae

$$SS = \frac{dV_{gs}}{d(\log I_{ds})}$$
(4)

$$N_{\rm it} = \left(\frac{\mathrm{SS}q}{k_{\rm B}T \ln 10} - 1\right) \left(\frac{C_{\rm i}}{q}\right) \tag{5}$$

where q is the elementary charge, $K_{\rm B}$ is the Boltzmann constant, and T is the temperature. The calculated data are shown in Table 1, from which we can see that the SS under illumination is much lower than that in the dark condition, which may be due to the photogenerated carrier that fill the interfacial trap states. In this regard, the N_{it} in dark condition is at 10^{13} eV⁻¹ cm⁻² scale level and it decreased one order after applying light illumination (see Table 1). The results are consistent with the mobility change and can be attributed to the fact that the trap states were filled by the photogenerated carriers within the CsPbBr₃ microplates.^[52,53] We further employed the space charge limited current (SCLC) method to extract the trap state density (N_t), which are calculated to be 2.73×10^{12} cm⁻³ for hole and 2.14×10^{12} cm⁻³ for electron (Figure S5, Supporting Information). The resulting values are lower than SS calculated results and are close to the bulk perovskite materials from previous report,^[38] both of which indicate the high crystallinity of the crystal plate and well interface contact. The performance of FETs is closely related to the contact resistance between the source/ drain electrodes and the active layer. The total resistance of the FET based on CsPbBr₃ microplates at different channel lengths is shown in Figure S6 in the Supporting Information, which shows comparable contact resistance to pervious report.^[17]

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Hysteresis effect is an important phenomenon in lead halidebased optoelectronic devices and has been widely reported in hybrid perovskite solar cells, LEDs or FETs.^[54-56] To date, the hysteresis effect in the reported works may originate from four possible reasons, which include the ion migration, ferroelectricity, trap states or surface dipoles. Although the main origin of the hysteresis effect is still under debate, the trap states or surface dipoles are normally believed to be the dominated factor at low temperature (e.g., 77 K),^[6,12] and ion migration was believed to be the dominant mechanism at room temperature.^[6,41] Figure S7 in the Supporting Information shows the hysteresis effect from the transfer characteristics (I_{ds} vs V_{gs}) of the CsPbBr₃ microplate-based FET by varying the gate voltage at room temperature. The transfer characteristics in the dark show weak hysteresis effect comparing to the previous reports on MAPbI₃ polycrystalline devices,^[6] which might be due to the low trap density of the microplate sample. At room temperature, the ion migration might play an important role for the hysteresis effect and V_{th} shift. When the positive scanning was switched to negative scanning under $V_{\rm ds}$ of 20 V, the threshold voltage shifts slightly from 42 to 41 V, which may be due to the Br⁻ ion migration.^[57] When the V_{ds} is -20 V, the threshold voltage did not shift, which might be related to the slow migration rate of Cs⁺ ions due to big size of the atom.^[58,59] Comparing to the hysteresis effect found in polycrystalline perovskites,^[54,60] the weak hysteresis here indicates the high quality of the crystal synthesized in this case; and the mobility achieved in this research thus reflect the intrinsic charge transfer property of CsPbBr₃ perovskite more accurately.^[57]

The photodetection properties of our CsPbBr₃ microplates were also examined. We utilized 532 nm laser as light source to assess the merits of our photodetectors, of which the device structure is shown in **Figure 5**a. By tuning the light intensity of the laser, the I-V curves between two Au electrodes were achieved. The photocurrent for the device measured under higher light intensity is much higher than that measured using lower light intensity. Photoresponsivity (*R*), indicating the efficiency of the optoelectronic device responded to an optical signal, is an important figure-of-merit for evaluating the performance of phototransistors. It is given by

$$R = \frac{J_{\text{light}} - J_{\text{dark}}}{I_{\text{light}}} \tag{6}$$

where J_{light} and J_{dark} are the channel current densities under light illumination and in dark, respectively. The photocurrent and photoresponsivity as the function of the bias voltage are plotted in Figure 5b and the photodetector exhibits a photoresponsivity of about 110 mA W⁻¹ for an optical power of 10 mW cm⁻², which is comparable to the values of devices base on CsPbBr₃ bulk single crystals and on some other components^[33,61,62] (as shown in Table S1, Supporting Information).

The external quantum efficiency (EQE), detectivity (D^*), and noise equivalent power (NEP) of the devices were depicted as Figure 5c,d and Figure S8 in the Supporting Information. EQE was defined as

$$EQE = R \frac{hc}{\lambda q}$$
(7)



Figure 5. The performances of photodetector based on CsPbBr₃ microplates. a) The *I*–*V* curves under dark and different light illumination intensities. b) The responsivity, c) EQE, and d) detectivity of CsPbBr₃ photodetectors. e,f) The current when light is on/off switched with $V_{ds} = +10$ V and $V_{gs} = 0$ V. Light source: 532 nm laser.

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where *R* is responsivity, *h* is Planck constant, *c* is the light velocity, λ is the wavelength, and *q* is the elementary charge. And when the dark current is dominated by the shot noise,^[63] the detectivity can be defined as

$$D^{\star} = \frac{R}{\sqrt{2qJ_{d}}} \tag{8}$$

where J_d is the dark current density. When optical power is 10 mW cm⁻², the EQE and D^* can reach 260 and 4.5 × 10¹³ Jones, respectively.

The NEP under different light intensities by the formula^[64–66]

$$NEP = \frac{A^{1/2}}{D^*}$$
(9)

where A is the photosensitive area and D^* is the detectivity. The NEP of the device is 7.12 $\times 10^{-16}$ W Hz^{-1/2} under a light intensity of 4.78 mW.

Another important parameter of the optoelectronic devices is their response speed. The temporal response of our photodetector was characterized using chopper-generated light pulses, and the optical pulses had the time interval of 0.1 s. As shown in Figure 5e, the dynamic photoresponse of the inorganic photodetector measured with $V_{\rm ds}$ = +10 V and $V_{\rm gs}$ = 0 V is stable and reproducible, indicating that the device can function as a good light switch. The temporal photocurrent response of the phototransistor is presented in Figure 5f. The switching times for the rise (output signal changing from 0% to 90% of the peak output value) and the decay ($I_{\rm ds}$ decreasing from peak value to 10%) of the photocurrent are about 0.12 and 0.18 s, respectively, comparable to the previous reports (Table S1, Supporting Information).

3. Conclusion

In summary, we demonstrated that the efficient FET devices based on CsPbBr₃ microplate were fabricated at room temperature, which showed anomalous ambipolar transport property. The electron mobility shows light intensity independence; while the hole mobility increases with the increased light intensity. The V_{th} in electron-transport model also shows light dependence. The anomalous transport property was proved to be due to the photoconductive and photovoltaic effects. The hole (electron) mobility reached 0.34 (0.40) cm² V⁻¹ s⁻¹ under light illumination with power density of 50 mW cm⁻², which is the highest value ever reported for CsPbBr₃ perovskite by far. This research is highly desirable for revealing the intrinsic transport property of CsPbBr₃ material, especially for the devices working under light illumination conditions, such as photovoltaics, photoconductor, and light emitting devices.

4. Experimental Section

Materials: The CsBr and PbBr₂ were purchased from Aladin and used as received. Dimethylformamide and γ -butyrolactone were purchased from Sigma-Aldrich and used as received. PET film

(2.0 μm thick) was received from Zhejiang Nanyang Electronic Film Co., Ltd.

Synthesis CsPbBr₃ Microplate: The substrate (Si/SiO₂) and covering glass (1.5 cm \times 1.5 cm) were cleaned by rinsing with acetone, isoproponal, and deionized water in turn. After drying on hotplate at 100 °C for 10 min, the substrates were exposed to UV–O₃ for 10 min. The covering glass was immersed in hexane and (octadecyl) trichlorosilane mixture (600:1) to produce a hydrophobic surface. Then the glass was rinsed with acetone for 30 s and dried with N₂ gas and it was then applied. Thereafter, two PET strips were attached to the Si substrate, the glass was placed on top and the sandwiched stack was heated to 270 °C on a hot plate for 5 min to melt the PET and help the substrate adhere with the glass cover. A small volume (6 μ L) of CsPbBr₃ precursor solution was then injected at the edge of the substrate, which spread quickly into the gap through capillary force. CsPbBr₃ crystal was achieved by placing the stack on a hot plate and annealing at 100 °C for 2 d.

*Characterization of CsPbBr*₃ *Microplate*: UV-vis absorbance spectra were measured using a Cary 5000 spectrophotometer from Agilent Company. Photoluminescence measurements were conducted on Cary Eclipse spectrometer. Optical images were acquired using a Nikon SMZ25 stereomicroscope. The thicknesses of perovskite microplates were measured by a Dimension Icon (Bruker) atomic force microscope (AFM) equipment. XRD spectra were measured using a Bruker D8 Focus operated in air at room temperature. SEM was performed using both Hitachi S-4800 field emission scanning electron microscope (FESEM) and Phenom Pro-X system. Energy dispersive spectrometry mapping of crystal was measured by using the Phenom Element Identification application attached to the Phenom Pro-X.

Fabricate and Characterize Field Effect Transistor: For FET devices, the Si/SiO₂ (SiO₂, 250 nm) wafers were used as the substrates. To fabricate the FET devices, perovskite CsPbBr₃ microplates were first grown on the Si/SiO₂ substrates, then an 80 nm Au electrode was thermal evaporated on the top of the microplates via using masks. Different channel lengths (*L*, 50, 100, and 150 μ m) were utilized. The channel width (*W*) was measured individually for each microplate that was successfully grown on a pair of FET device electrodes.

I–V measurements were performed at room temperature using a Keithley 4200A Semiconductor Parametric Analyzer (Tektronix) and a C-100 probe station from TPSi Company. For photoresponsive property measurements, an LED light (OptoSigma, SLA-100A) was employed as the light illumination source, which was attached on the microscope of the probe station. The exposure time of sample was precisely controlled by an optical shutter (VS25S2TO, UNIBLITZ) with a diameter of 2.5 mm. The 532 nm laser utilized for photodetector measurements is from MGL-III-532-300 with the model number of Mw 17087123. The SCLC measurements were conducted using Keithley 4200A semiconductor Parametric Analyzer in the air condition at room temperature, in which an 80 nm Au electrode was thermal evaporated onto the microplate on the indium tin oxide (ITO)/glass substrate with masks. The 3D surface morphology of sample was measured by using Keyence laser confocal microscope (VK-X1000) in the air condition.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

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