Research Article

One-Dimensional (NH=CINH$_3$)$_3$PbI$_5$ Perovskite for Ultralow Power Consumption Resistive Memory

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Organic-inorganic hybrid perovskites (OIHPs) have proven to be promising active layers for nonvolatile memories because of their rich abundance in earth, mobile ions, and adjustable dimensions. However, there is a lack of investigation on controllable fabrication and storage properties of one-dimensional (1D) OIHPs. Here, the growth of 1D (NH=CINH$_3$)$_3$PbI$_5$ ((IFA)$_3$PbI$_5$) perovskite and related resistive memory properties are reported. The solution-processed (IFA)$_3$PbI$_5$ crystals are of well-defined monoclinic crystal phase and needle-like shape with the length of about 6 mm. They exhibit a wide bandgap of 3 eV and a high decomposition temperature of 206°C. Moreover, the (IFA)$_3$PbI$_5$ films with good uniformity and crystallization were obtained using a dual solvent of N,N-dimethylformamide (DMF) and dimethyl sulfoxide (DMSO). To study the intrinsic electric properties of this anisotropic material, we constructed the simplest memory cell composed of only Au/(IFA)$_3$PbI$_5$/ITO, contributing to a high-compacted device with a crossbar array device configuration. The resistive random access memory (ReRAM) devices exhibit bipolar current-voltage ($I$-$V$) hysteresis characteristics, showing a record-low power consumption of ~0.2 mW among all OIHP-based memristors. Moreover, our devices own the lowest power consumption and “set” voltage (0.2 V) among the simplest perovskite-based memory devices (inorganic ones are also included), which are no need to require double metal electrodes or any additional insulating layer. They also demonstrate repeatable resistance switching behaviour and excellent retention time. We envision that 1D OIHPs can enrich the low-dimensional hybrid perovskite library and bring new functions to low-power information devices in the fields of memory and other electronics applications.

1. Introduction

Organic-inorganic hybrid perovskites (OIHPs), which exhibit the advantage of tunable bandgap [1], high bipolar carrier mobility [2], long carrier diffusion length [3], and structural diversity [4], become one of the most promising materials in physical electronic applications [5], not just photovoltaic applications [6–8] and light-emitting diodes [9–11] (LEDs). The inherent ion migration of OIHPs easily causes current-voltage hysteresis, which leads to the instability and inefficiency of photovoltaic devices [12]. However, the sustainable current hysteresis phenomenon is a booming chance for applications in logic circuit [13], data storage [14], and resistance switching [15–17]. In recent years, resistive random access memory (ReRAM) devices based on OIHPs possess high integration density [18], good scaling capability [19], and multilevel information storage [20], which make them a promising candidate for the next-generation computing system. These excellent performances of ReRAM devices are mainly affected by the material
structure of synthesized OIHPs [21]. Apart from fine-tuning the component and thickness of OIHPs, their dimensionality modulation also helps to optimize the performances of ReRAM devices.

In recent years, three-dimensional (3D) perovskites (such as CH$_3$NH$_3$PbI$_3$ [22] and CsPbBr$_3$ [23]) have been applied to resistive random access memory (ReRAM) devices, which reflect reproducible resistive switching behaviour and flexible applications. The ReRAM devices based on two-dimensional (2D) Ruddlesden-Popper (RP) perovskites have better environmental stability and endurance properties owing to the protection of large organic cations on the surface [24]. The on/off ratio of memristor based on 2D OIHPs was dramatically increased due to much higher Schottky barrier between the metal electrode and active layer [25]. Moreover, compared with 3D OIHPs, 2D functional layer is anisotropic which significantly reduces the formation energy barrier of conductive filaments along the defect channels [26]. However, the research on ReRAM devices based on single 1D OIHPs is still in its infancy, with none study reported, which is a direct and efficient method to determine the intrinsic performance characteristics and applicable functional devices of new materials.

Here, we develop a solution-processed method to obtain high-quality, needle-like shape, and large-size (~6 mm in length) 1D (NH$_3$CINH$_2$)$_2$PbI$_6$ ((IFA)$_2$PbI$_4$) crystals of a monoclinic crystal phase.

\[
N \equiv CNH_3 + 2HI \rightarrow (NH = CNH_3)I \quad (1)
\]

\[
3(NH = CNH_3)I + PbI_2 \rightarrow (NH = CNH_3)_3PbI_5 \quad (2)
\]

The well-crystallized (IFA)$_2$PbI$_5$ owns a high decomposition temperature of ~206°C and a wide bandgap of ~3.0 eV, as compared with that of OIHPs in 2D and 3D. To explore the resistive switching characteristics of 1D (IFA)$_2$PbI$_5$, we prepared (IFA)$_2$PbI$_5$ films on ITO-coated glasses using a mixed solvent of N,N-dimethylformamide (DMF) and dimethyl sulfoxide (DMSO). The dual-solvent method helped us overcome the strong orientation and poor film-forming problem of low-dimensional OIHPs. Scanning electron microscope (SEM) and atomic force microscopy (AFM) analyses confirm that the large-area thin films possess high-quality crystallization and controllable uniformity, being well controlled by the molar ratio of DMF and DMSO. Then, we successfully manufactured ReRAM devices based on the simplest sandwich structure composed of Au/(IFA)$_2$PbI$_5$/ITO. The structure is no need to require any additional insulating layer or double metal electrodes, in which (IFA)$_2$PbI$_5$ film acts as the only insulating layer, benefitting facile device fabrication and intrinsic property study. In particular, the devices show the record-low power consumption of 0.2 mW among all OIHP-based memristors. Moreover, our devices have the lowest power consumption and “set” voltage (0.2 V) among all perovskite-based memristors that do not require double metal electrodes or any additional insulating layer. The fabricated 1D OIHPs provide a new opportunity for resistive switching applications, indicating that the material design of low-dimensional perovskites is of great potential in multifunctional electronic applications.

2. Results and Discussion

(IFA)$_2$PbI$_5$ is a new OIHP with 1D chain-shaped crystal structure, as characterized by X-ray single-crystal diffractometer. 1D (IFA)$_2$PbI$_5$ is a subclass of ABX$_3$ materials in which the A-site is replaced by carbamimidic iodide cations of IFA$^+$. The organic linker intersects and cuts along two special crystallographic planes of (110) and (010), breaking space constraints of conventional perovskites. Our 1D perovskite is formed by a large organic cation of IFA$^+$ alternating with a 1D inorganic chain of PbI$_5^{3-}$. As shown in Figure 1(a), structural illustrations of 1D perovskite on different planes show the case with five I atoms surrounding each Pb atom, in which one I atom in-chain is shared by two octahedrons, forming a 1D shape of PbI$_5^{3-}$. The negative charges are compensated by the large organic cation IFA$^+$ that caps the surface of 1D chains. The production of IFA$^+$ units is a precondition for forming the chain of 1D (IFA)$_2$PbI$_5$ perovskite. This production process requires breaking the carbon-nitrogen triple bond of cyanamide and then forming a carbon-iodine bond by adding iodine, thereby breaking the coulomb and hydrogen bonds in the 3D perovskite structure.

The crystal products display a needle-like shape (the inset of Figure 1(b)) and a large size with a representative length of about 6 mm. This crystal demonstrates good thermal stability with 5% weight loss at 206°C (Figure 1(b)) by using thermogravimetric analysis. The crystalline orientations could be detected by X-ray diffraction (Figure 1(c)), indicating a strong 2θ peaks at about 8.3° may be an XRD characteristic peak of 1D hybrid perovskite that is similar to the low-dimensional diffraction peaks of 2D OIHPs [27]. As shown in Table S1, all the XRD peaks are indexed to a monoclinic perovskite phase (p(2\(\|\))c space group) with \(a = 6.430 \text{ Å}, b = 20.129 \text{ Å}, \text{ and } c = 18.793 \text{ Å}\). Besides, all the XRD peaks exhibit regular diffraction orientations, indicating that the prepared (IFA)$_2$PbI$_5$ film is highly crystalline, consistent with the clear and regular 1D orientations of the bulk crystal observed using a microscope (inset of Figure 1(c)). We further studied the bandgap of 1D (IFA)$_2$PbI$_5$ by absorption spectrum, as displayed in the inset of Figure 1(d). The bandgap of (IFA)$_2$PbI$_5$ is about 3.0 eV, being wider than that of the perovskites with other dimensions [28]. We infer that the dimension could be an important parameter to control the band structure of hybrid perovskite.

Fabricating high-quality and uniform films is an effective measure to scale up the size and enhance the properties of OIHP-based devices. A cosolvent of DMF and DMSO was applied to prepare films of 1D (IFA)$_2$PbI$_5$, because the strong coordinate effect of DMSO helps to uniform crystal growth rates and promote crystallization of (IFA)$_2$PbI$_5$ in solvents [29]. We fixed the DMF volume (160 \(\mu\text{L}\)) and (IFA)$_2$PbI$_5$ (168 mg) and tuned the molar ratios of (IFA)$_2$PbI$_5$ to DMSO to 1:1, 1:2, 1:3, 1:4, and 1:5, respectively, to find the optimized conditions for (IFA)$_2$PbI$_5$ films.
In a glove box with nitrogen atmosphere, (IFA)$_3$PbI$_5$ films were successfully fabricated on ITO-coated glasses (Figure 2(a)) by adding a trace of antisolvent (chlorobenzene) at the last five seconds of spin-coating for accelerating the film crystallization. We examined the products of this reaction by scanning electron microscope (SEM) and atomic force microscopy (AFM). Our films of 1D (IFA)$_3$PbI$_5$ show the same clear 1D needle-like shapes as the bulk crystals, which is different from the fuzzy surface morphology of other 1D perovskite films [30]. As shown in Figures 2(b)–2(e) and Figure S1(a), SEM images identify the full covering of needle-like perovskites on ITO substrates. The aggregates that have not been completely dissolved are indicated by red arrows (Figures 2(b) and 2(c)), describing that the solubility of (IFA)$_3$PbI$_5$ is well controlled by the dose of DMSO. The obvious pinholes are observed on the film surface, as shown by the yellow arrow in Figure S1(a), suggesting poor film is prepared using high dose of DMSO. As the molar ratio of (IFA)$_3$PbI$_5$ to DMSO increases from 1:1 to 1:5, the average size of the needle shape increases from ~286 nm to ~895 nm (Figure S2). The above data suggest that crystallization of (IFA)$_3$PbI$_5$ film can be precisely controlled by the dual-solvent method. AFM images in Figures 2(f)–2(i) and Figure S1(b) further verify the good control effect of DMSO on crystal solubility and further reveal that DMSO produces a good effect in film uniformity that the large-size needle shapes have a relatively small roughness ($R_g$ = ~39 nm, Figure 2(i)). These data clearly illustrate the 1D features of (IFA)$_3$PbI$_5$, in which the films present relatively lower roughness, larger crystal grains, and higher quality when the molar ratio of 1D crystal to DMSO is of 1:4 during film production (Figure S2(d)).

Storage properties are important to evaluate the quality of synthesized films, especially the storage properties of 1D OHHPs that have not been reported. Here, ReRAM devices are constructed based on (IFA)$_3$PbI$_5$ films with a molar ratio of 1:4 of (IFA)$_3$PbI$_5$ to solvent DMSO. As shown in the inset of Figure 3(a), the thickness of the (IFA)$_3$PbI$_5$ layer is about 450 nm from the SEM cross-section view of a memristor cell. To research the intrinsic resistive switching properties of (IFA)$_3$PbI$_5$ perovskite, we fabricated the (IFA)$_3$PbI$_5$ film without any additional interface into the simplest sandwich structure of Au/(IFA)$_3$PbI$_5$/ITO, as further conveniently integrated into an 8×8 crossbar array memory (Figure 3(a)). Each unit cell area is 0.01 mm$^2$, of which electric properties were tested under ambient conditions. Figure 3(b) shows typical resistive switching (RS) behaviour of an Au/(IFA)$_3$PbI$_5$/ITO device under the DC voltage sweep sequence of 0 V→3 V→0 V→−3 V→0 V, which exhibits nonvolatile resistive storage (NVRS) behaviour. The overlap of three successively measured I-V loops reflects the good reliability and forming-free properties of the device. From the virgin state, the first voltage sweep (as the red curve shown in Figure 3(b)) was performed by applying a positive bias on the Au top electrode, until a positive bias was applied to switch the device to LRS, which is commonly referred to as a “set” process. During this process, the device displays the conversion bias of “set” which is about 0.2 V,
possessing an ultralow power consumption of about 2 mW (note that power consumption is equal to LRS current multiplied by set voltage). Then, LRS maintains until a large negative bias voltage was used, and the I-V curves are converted to HRS at about -2.1 V, which is known as the ”reset” process. The switching characteristics at opposite polarity indicate that the memristor exhibits bipolar switching. The negative conversion voltage is significantly greater than the ”set” bias, which is related to the conduction mechanism of the Au/(IFA)\textsubscript{3}PbI\textsubscript{5}/ITO device, as explained below.

We further check the reliability and reproducibility of our devices. With a reading voltage (\(V_{\text{read}}\)) of -0.5 V, we measured the data retention characteristics of HRS and LRS values and the cycling endurance, as shown in Figures 3(c) and 3(d), respectively. A constant on/off ratio of \(10^3\) is maintained for up to \(10^4\) s. Both LRS and HRS are relatively stable showing excellent repeatability between HRS and LRS for nearly 200 cycles. Moreover, we statistically calculated these basic characteristics from other 40 unit cells. Figure 3(e) presents the histograms of voltage distribution for the set (red) and reset (blue). The average voltage values of the set and reset are 0.2 and -2.1 V, respectively. Figure 3(f) shows the statistical resistance values of HRS and LRS of these 40 cells, respectively, with a stable value of the on/off ratio around \(10^3\).

Table 1 summarizes the performance comparison between our work and other good demonstrations of perovskite-based RS devices reported in recent years [15, 31–37]. The memristors based on 1D (IFA)\textsubscript{3}PbI\textsubscript{5} in our work own the record-low power consumption among all OIHP-based memristors [15, 31–33]. It is also worth noting that most memristors own low power consumption with the
setting of compliance current, normally lower than the current that the device can reach if without setting [31–37]. Also, (IFA)$_3$PbI$_5$-based memristors work normally without installing the compliance current, which show the robustness of our devices. Moreover, compared to the devices with the simplest device structure, such as Au/CH$_3$NH$_3$PbI$_3$/ITO [32], Au/CH$_3$NH$_3$PbI$_{3-x}$Cl$_x$/FTO [33], and Al/CsBi$_3$I$_{10}$/ITO [37], which do not require double metal electrodes or any additional insulating layer, our devices own the lowest power consumption and “set” voltage (0.2 V). The simplest device structure...
structure is advantageous for simplifying device fabrication process and studying material intrinsic properties.

For investigating the conduction mechanism in detail, we plot the $I-V$ curves for the set process with a double log-arithmic (see Figure 4(a)). The HRS data in the voltage region of 0-0.15 V is fitted well by a linear relationship with a slope of ~0.99, indicating a good Ohmic conduction [38]. This suggests that intrinsic thermally generated free carriers inside the (IFA)$_3$PbI$_5$ films are predominant over the injected carriers by electrical field. With the positive voltage rising from 0.15 V to 0.2 V, the injected carriers exceed thermally generated carriers that make a trap-controlled space charge limit current (SCLC) behaviour [39] ($I-V^2$). When voltage is larger than 0.2 V, all of the traps are filled by charge carriers and the conductive paths are formed in (IFA)$_3$PbI$_5$ films [40], setting the device from HRS to LRS. For the whole LRS range, the slope of $I-V$ curves remains ~0.99, demonstrating an Ohmic conduction mechanism. Moreover, the fitting results of $I-V$ curves exhibit the similar mechanism for the reset process, as shown in Figure 4(b), suggesting the reverse formation and rupture of conduction paths.

Inspired by the analysis of electric properties on a logarithmic scale, we further investigate the possible switching mechanism of our 1D (IFA)$_3$PbI$_5$-based devices. Halide perovskite structure is advantageous for simplifying device fabrication process and studying material intrinsic properties.

<table>
<thead>
<tr>
<th>Device structure</th>
<th>Power consumption</th>
<th>Set voltage</th>
<th>On/off ratio</th>
<th>Retention time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic-inorganic hybrid perovskites based devices</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Ag/FAPbI$_3$/Pt [31]</td>
<td>0.22 mW</td>
<td>0.22 V</td>
<td>$10^5$</td>
<td>$3 \times 10^3$</td>
</tr>
<tr>
<td>Au/CH$_3$NH$_3$PbI$_3$/ITO [32]</td>
<td>0.7 mW</td>
<td>0.7 V</td>
<td>$10^2$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Ag/CH$_3$NH$_3$PbI$_3$/Pt [15]</td>
<td>0.75 mW</td>
<td>0.15 V</td>
<td>$10^6$</td>
<td>$1.1 \times 10^4$</td>
</tr>
<tr>
<td>Au/CH$_3$NH$_3$PbI$<em>3$xCl$</em>{3-x}$/FTO [33]</td>
<td>14.7 W</td>
<td>1.47 V</td>
<td>$10^4$</td>
<td>$4.32 \times 10^4$</td>
</tr>
<tr>
<td>Inorganic perovskite - based memory devices</td>
<td></td>
<td></td>
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<tr>
<td>Au/Cs$_3$Bi$_2$I$_5$/Pt [34]</td>
<td>0.1 mW</td>
<td>0.1 V</td>
<td>$10^7$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Ag/PMMA/AgBiI$_4$/ITO [35]</td>
<td>0.16 mW</td>
<td>0.16 V</td>
<td>$10^4$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Ag/PMMA/CsPbI$_3$/Pt [36]</td>
<td>0.18 mW</td>
<td>0.18 V</td>
<td>$10^6$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Al/CsBi$<em>3$I$</em>{10}$/ITO [37]</td>
<td>1.7 mW</td>
<td>1.7 V</td>
<td>$10^3$</td>
<td>$10^4$</td>
</tr>
</tbody>
</table>

Figure 4: Resistive switching mechanisms. Analysis of Au/(IFA)$_3$PbI$_5$/ITO on the logI-logV curves and their fitting results of (a) "set" and (b) "reset" under voltage sweep. (c–e) Schematic diagrams of the process of switching mechanism, and the iodine ions and iodide vacancies (V’s) are represented by the green and white balls, respectively.
as an active layer in NVRS is generally regarded as relatively soft ionic solids, which is prone to contain point defects, vacancies, interstitials, cations, and antisite substitutions [41]. Previous work demonstrated that iodide vacancies (V$_I$’s) have much lower activation energy (0.1-0.6 eV) compared with other point defects [42]. Therefore, we think V$_I$’s conductive filament is very possibly responsible for the conductive mechanism in our 1D (IFA)$_3$PbI$_5$-based memristors. As shown in Figure 4(c), many thermally generated iodine ions and their corresponding vacancies are randomly distributed in (IFA)$_3$PbI$_5$ films before applying a voltage bias. As shown in Figure 4(d), when a positive voltage bias is applied to a memristor, V$_I$’s conductive filament paths begin to create after the iodine ions and their vacancies migrate toward the opposite directions. The conductive filaments grow along V$_I$ defect channels from the bottom electrode to the top electrode, facilitating the injected carriers following trap-to-trap hopping, thereby prompting the memory device from HRS to LRS. Afterwards, in the negative voltage region, the redistribution of iodine ions and their vacancies brings the collapse of V$_I$’s channels, and the device was recovered from LRS to HRS (Figure 4(e)).

As a functional layer, 1D (IFA)$_3$PbI$_5$ owns obvious anisotropic characteristics, which has natural 1D channels for the orderly migration of ions in the dark field, thereby greatly reducing the energy barrier for the formation of conductive paths. Therefore, it is possible that the V$_I$’s conductive filaments can easily formed under an extremely low electric field in (IFA)$_3$PbI$_5$ perovskite with native 1D crystal structure, leading to the device low operating voltage and ultrapower consumption. Meanwhile, the high-density 1D ion channels in the active layer provide convenience for the growth of multiple conductive filaments with robust features. It is difficult to break these robust conductive channels, thus requiring a large negative voltage to convert the device from LRS to HRS.

3. Conclusions

In summary, we show the controllable fabrication and storage properties of 1D (IFA)$_3$PbI$_5$ formed by carbamimidic iodide cations. The large-size crystals with needle-like shapes own good thermal stability and wide bandgap. We also produce (IFA)$_3$PbI$_5$ films using a dual-solvent method. The morphology structure of the films was readily controlled by the solvent ratio of DMF to DMSO. Our films possess good crystallization and uniformity, allowing the first investigation of resistive switching properties of 1D perovskite. We apply the simplest ITO-based sandwich device structure with a single metal electrode, in which (IFA)$_3$PbI$_5$ is used as the only insulating layer, to simplify the fabrication process and reveal the intrinsic storage characteristics. The memristors possess bipolar nonvolatile resistive switching behaviour, particularly with a record-low power consumption of about 0.2 mW among all OIHP-based memories. Also, our devices own the lowest power consumption and “set” voltage (0.2 V) among the perovskite-based memristors without double metal electrodes or additional insulating layer. Future explorations of 1D OIHP devices, which can combine the light-detection, resistive memory, and logic calculation, are highly expected. We are optimistic that by the simple fabrication and fascinating attributes of 1D OIHP materials, their electronic and optoelectronic devices could be pushed more for the development of flexible, low-power, and multifunctional applications.

4. Materials and Methods

4.1. Synthesis and Material Preparation. 1D (IFA)$_3$PbI$_5$ crystals were synthesized by adding lead iodide (99.999%) powder (1.844 g, 4.0 mmol) into aqueous hydroiodic acid (57% by weight, 24 mL) at 75°C. In a flowing argon atmosphere, 0.168 g (4.0 mmol) amount of cyanamide was added to the solution and kept stirring for 30 min. Then, the mixed solution was cooling to precipitate (IFA)$_3$PbI$_5$ crystals. (IFA)$_3$PbI$_5$ solution was prepared by magnetic stirring at room temperature for 2 h by dissolving (IFA)$_3$PbI$_5$ (168 mg) in a dual solvent of dimethyl sulfoxide (DMSO) and N,N-dimethylformamide (DMF, 160 μL). Keeping DFM unchanged at 160 μL, we configured solutions with four concentrations, in which the DMSO volumes were 8.5 μL, 17 μL, 25.5 μL, 34 μL, and 42.5 μL, corresponding to the molar ratios of (IFA)$_3$PbI$_5$ to DMSO of 1:1, 1:2, 1:3, 1:4, and 1:5, respectively.

4.2. Device Fabrication. Indium tin oxide- (ITO-) coated glass substrates were sequentially cleaned in acetone, isopropanol, and ethanol for 15 min and then dried using nitrogen gas. The clean substrates were treated in UV-ozone for 30 min before being transformed into a nitrogen-filled glove box for device fabrication. To obtain highly uniform and smooth (IFA)$_3$PbI$_5$ film, the preprepared solution was spin-coated on the ITO surface with a spin-coating rate of 3000 rpm for 30 s. Then, the chlorobenzene was quickly dropped onto the center of the substrate during spin-coating. Subsequently, the film was annealed on a hot plate at 100°C for 5 min. Then, (IFA)$_3$PbI$_5$ film was cooled to room temperature. To complete the device fabrication, the top metal electrodes (Au, 60 nm) were deposited on the (IFA)$_3$PbI$_5$ film by thermal evaporation at pressure of 5 × 10$^{-4}$ Torr using a shadow mask.

4.3. Characterization. The crystal structure was characterized by X-ray diffraction (XRD) with Cu Kα radiation (Bruker AXS D8) and X-ray single crystal diffraction meter (BRUKER D8 QUEST). The decomposition temperature was measured using the Thermal Gravimetric Analyzer (METTLER TOLEDO TGA2). Bandgap was confirmed by absorbance spectra using a UV–vis spectrophotometer (SHIMADZU UV-1750). Atomic force microscope (AFM, Park XE-70) and scanning electron microscope (SEM, JEOL JSM-7800F) were used to characterize the morphologies and uniformity. The thickness of (IFA)$_3$PbI$_5$ was measured by step profiler (KLA Tencor). Typical current-voltage (I-V) characteristic curves of memory cells were measured in the atmosphere using a semiconductor parameter analyzer (Keithley 4200-SCS).
**Data Availability**

All data needed to evaluate the conclusions in the paper are presented in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

**Conflicts of Interest**

The authors declare no competing financial interest.

**Authors’ Contributions**

T. Q., L. W., and W. H. conceived the project. F. S., H. Y., and Q. C. designed and performed the experiments. Y. Q., C. L., H. M., X. Z., C. I., Y. F., and Z. C. assisted in the material characterization and device test. H. Y., F. S., and L.W. contributed to the paper writing. All authors discussed and reviewed the manuscript. Xuefen Song, Hao Yin, and Qing Chang contributed equally to this work.

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**Supplementary Materials**

Table S1: single crystal data of 1D (IFA)$_3$PbI$_5$. Fig. S1: surface morphology and resistive switching property of 1D (IFA)$_3$PbI$_5$ prepared with a molar ratio of (IFA)$_3$PbI$_5$ to DMSO of 1:5. Fig. S2: surface morphology of 1D (IFA)$_3$PbI$_5$. Table S1: single crystal data of 1D (IFA)$_3$PbI$_5$. Fig. S1: surface morphology and resistive switching property of 1D (IFA)$_3$PbI$_5$ prepared with a molar ratio of (IFA)$_3$PbI$_5$ to DMSO of 1:5. Fig. S2: surface morphology of 1D (IFA)$_3$PbI$_5$. (Supplementary Materials)

**References**


