Research Article

One-Dimensional $(\text{NH}=\text{CINH}_3)_3\text{PbI}_5$ 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 $(\text{NH}=\text{CINH}_3)_3\text{PbI}_5$ ((IFA)₃PbI₅) perovskite and related resistive memory properties are reported. The solution-processed 1D (IFA)₃PbI₅ 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)₃PbI₅ 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)₃PbI₅/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 instabil-

ity 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 $\text{CH}_3\text{NH}_3\text{PbI}_3$ [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 effective way 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 $(\text{NH}=\text{CINH}_3)_3\text{PbI}_5$ ($(\text{IFA})_3\text{PbI}_5$) crystals of a monoclinic crystal phase.

The well-crystallized $(\text{IFA})_3\text{PbI}_5$ owns a high decomposition temperature of $\sim 206^\circ\text{C}$ 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 $(\text{IFA})_3\text{PbI}_5$, we prepared $(\text{IFA})_3\text{PbI}_5$ 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 $\text{Au}/(\text{IFA})_3\text{PbI}_5/\text{ITO}$. The structure is no need to require any additional insulating layer or double metal electrodes, in which $(\text{IFA})_3\text{PbI}_5$ 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

$(\text{IFA})_3\text{PbI}_5$ is a new OIHP with 1D chain-shaped crystal structure, as characterized by X-ray single-crystal diffractometer. 1D $(\text{IFA})_3\text{PbI}_5$ 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 $(\text{IFA})_3\text{PbI}_5$ 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 (p2(1)/c space group) with $a = 6.430$ Å, $b = 20.129$ Å, and $c = 18.793$ Å. Besides, all the XRD peaks exhibit regular diffraction orientations, indicating that the prepared $(\text{IFA})_3\text{PbI}_5$ 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 $(\text{IFA})_3\text{PbI}_5$ by absorption spectrum, as displayed in the inset of Figure 1(d). The bandgap of $(\text{IFA})_3\text{PbI}_5$ 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 $(\text{IFA})_3\text{PbI}_5$, because the strong coordinate effect of DMSO helps to uniform crystal growth rates and promote crystallization of $(\text{IFA})_3\text{PbI}_5$ in solvents [29]. We fixed the DMF volume (160 μL) and $(\text{IFA})_3\text{PbI}_5$ (168 mg) and tuned the molar ratios of $(\text{IFA})_3\text{PbI}_5$ to DMSO to 1 : 1, 1 : 2, 1 : 3, 1 : 4, and 1 : 5, respectively, to find the optimized conditions for $(\text{IFA})_3\text{PbI}_5$ films.

FIGURE 1: Architecture and characterization of one-dimensional (IFA)₃PbI₅ crystal. (a) Schematic illustrations of the crystal structures along the axes of *a*, *b*, and *c*, respectively. (b) Thermal stability of (IFA)₃PbI₅ perovskite. The inset shows the needle-like shape of 1D crystal with a size of about 6 mm. (c) XRD spectrum of (IFA)₃PbI₅ film spin-coated on an ITO substrate. Inset: microscope picture of (IFA)₃PbI₅ perovskite. (d) The bandgap of (IFA)₃PbI₅ is about 3 eV, as determined by absorption spectrum (inset).

In a glove box with nitrogen atmosphere, (IFA)₃PbI₅ 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)₃PbI₅ 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)₃PbI₅ 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)₃PbI₅ 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)₃PbI₅ 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 ($R_q \sim 39$ nm, Figure 2(i)). These data clearly illustrate the 1D features of (IFA)₃PbI₅, 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 OIHPs that have not been reported. Here, ReRAM devices are constructed based on (IFA)₃PbI₅ films with a molar ratio of 1:4 of (IFA)₃PbI₅ to solvent DMSO. As shown in the inset of Figure 3(a), the thickness of the (IFA)₃PbI₅ layer is about 450 nm from the SEM cross-section view of a memristor cell. To research the intrinsic resistive switching properties of (IFA)₃PbI₅ perovskite, we fabricated the (IFA)₃PbI₅ film without any additional interface into the simplest sandwich structure of Au/(IFA)₃PbI₅/ITO, as further conveniently integrated into an 8 × 8 crossbar array memory (Figure 3(a)). Each unit cell area is 0.01 mm², of which electric properties were tested under ambient conditions. Figure 3(b) shows typical resistive switching (RS) behaviour of an Au/(IFA)₃PbI₅/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,

FIGURE 2: Fabrication and characterization of (IFA)₃PbI₅ films. (a) Schematic illustration of the fabrication process of (IFA)₃PbI₅ film on an ITO substrate. Representative SEM images of the (IFA)₃PbI₅ films prepared by the molar ratios of (IFA)₃PbI₅ to DMSO of (b) 1 : 1, (c) 1 : 2, (d) 1 : 3, and (e) 1 : 4; corresponding AFM images are shown in (f-i), respectively. The red arrows point to the agglomerates that have not been fully dissolved.

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)₃PbI₅/ITO device, as explained below.

We further check the reliability and reproducibility of our devices. With a reading voltage (V_{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)₃PbI₅ 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

FIGURE 3: Resistive switching properties of (IFA)₃PbI₅-based memristors. (a) Schematic and circuit diagram of a ReRAM device with crossbar array configuration. The measurement unit cell with a sandwich structure composed of Au/(IFA)₃PbI₅/ITO is indicated by a red circle. Inset: SEM cross-section image of a memristor cell. (b) Typical *I-V* curves with three sweeps of an Au/(IFA)₃PbI₅/ITO memory device. DC switching of (c) the retention time test and (d) nearly 200 consecutive cycles; the currents were read at -0.5 V. (e) Histogram statistics of set/reset voltage distributions. (f) The resistance statistics of 40 representative unit cells.

setting of compliance current, normally lower than the current that the device can reach if without setting [31–37]. Also, (IFA)₃PbI₅-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/CH₃NH₃PbI₃/ITO [32], Au/CH₃NH₃PbI_{3-x}Cl_x/FTO [33], and Al/CsBi₃I₁₀/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

TABLE 1: Comparison of 1D (IFA)₃PbI₅-based memristor (our work) with previous works.

Device structure	Power consumption	Set voltage	On/off ratio	Retention time
Our work	0.2 mW	0.2 V	10³	10⁴
Organic-inorganic hybrid perovskites based devices				
Ag/FAPbI ₃ /Pt [31]	0.22 mW	0.22 V	10 ⁵	3 × 10 ³
Au/CH ₃ NH ₃ PbI ₃ /ITO [32]	0.7 mW	0.7 V	10 ²	10 ⁴
Ag/CH ₃ NH ₃ PbI ₃ /Pt [15]	0.75 mW	0.15 V	10 ⁶	1.1 × 10 ⁴
Au/CH ₃ NH ₃ PbI _{3-x} Cl _x /FTO [33]	14.7 W	1.47 V	10 ⁴	4.32 × 10 ⁴
Inorganic perovskite - based memory devices				
Au/Cs ₃ Bi ₂ I ₉ /Pt [34]	0.1 mW	0.1 V	10 ⁷	10 ³
Ag/PMMA/AgBiI ₄ /ITO [35]	0.16 mW	0.16 V	10 ⁴	10 ⁴
Ag/PMMA/CsPbI ₃ /Pt [36]	0.18 mW	0.18 V	10 ⁶	10 ³
Al/CsBi ₃ I ₁₀ /ITO [37]	1.7 mW	1.7 V	10 ³	10 ⁴

FIGURE 4: Resistive switching mechanisms. Analysis of Au/(IFA)₃PbI₅/ITO on the $\log I$ - $\log V$ 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_I ’s) are represented by the green and white balls, respectively.

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 logarithmic (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)₃PbI₅ 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] ($I \sim V^2$). 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)₃PbI₅ 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)₃PbI₅-based devices. Halide perovskite

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)₃PbI₅-based memristors. As shown in Figure 4(c), many thermally generated iodine ions and their corresponding vacancies are randomly distributed in (IFA)₃PbI₅ 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)₃PbI₅ 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)₃PbI₅ 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)₃PbI₅ formed by carbamimidic iodide cations. The large-size crystals with needle-like shapes own good thermal stability and wide bandgap. We also produce (IFA)₃PbI₅ 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)₃PbI₅ 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 cal-

culuation, 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)₃PbI₅ 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)₃PbI₅ crystals. (IFA)₃PbI₅ solution was prepared by magnetic stirring at room temperature for 2 h by dissolving (IFA)₃PbI₅ (168 mg) in a dual solvent of dimethyl sulfoxide (DMSO) and N,N-dimethylformamide (DMF, 160 μ L). Keeping DFM unchanged at 160 μ L, we configured solutions with four concentrations, in which the DMSO volumes were 8.5 μ L, 17 μ L, 25.5 μ L, 34 μ L, and 42.5 μ L, corresponding to the molar ratios of (IFA)₃PbI₅ 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)₃PbI₅ 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)₃PbI₅ film was cooled to room temperature. To complete the device fabrication, the top metal electrodes (Au, 60 nm) were deposited on the (IFA)₃PbI₅ 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 K α radiation (Bruker AXS D8) and X-ray single crystal diffractometer (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)₃PbI₅ 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. X. S., H. Y., and Q. C. designed and performed the experiments. Y. Q., C. L., H. M., X. Z., C. L., Y. F., and Z. C. assisted in the material characterization and device test. H. Y., X. 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)₃PbI₅. Fig. S1: surface morphology and resistive switching property of 1D (IFA)₃PbI₅ prepared with a molar ratio of (IFA)₃PbI₅ to DMSO of 1:5. Fig. S2: surface morphology of 1D (IFA)₃PbI₅. (*Supplementary Materials*)

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