Synthesis and Characterization of Organic−Inorganic Perovskite Thin Films Prepared Using a Versatile Two-Step Dipping Technique

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A convenient two-step technique for preparing thin films of the organic−inorganic perovskites $(RNH_3)_2(CH_3NH_3)_{n-1}M_nI_{3n+1}$ (R = butyl, phenethyl; M = Pb, Sn; $n = 1, 2, \infty$) has been achieved. Films of the metal halide, MI_2, were first deposited onto ash glass or quartz disks using vacuum evaporation or spin-coating. By dipping these inorganic films, at room temperature, into an organic ammonium iodide solution for a short period of time (1−5 min for the layered perovskites), single-phase samples of the corresponding organic−inorganic perovskite thin films were formed. While a variety of solvents can be used for the dipping process, toluene/2-propanol mixtures have been shown to work well for many of the present compounds. The layered organic−inorganic perovskite films exhibited uniform surfaces and strong photoluminescence at wavelengths that were consistent with the corresponding materials made by single-crystal growth from solution. However, dipped organic−inorganic films made from evaporated PbI_2 exhibited a luminescent peak that was red-shifted approximately 10 nm relative to those prepared from spin-coated PbI_2, perhaps due to states induced near the band edge as a result of crystal defects or surface states. Films of the three-dimensional perovskites $CH_3NH_3MI_3$ (M = Pb, Sn) were also prepared by dipping MI_2 films into a methylammonium iodide 2-propanol solution. The resulting perovskite films were black, and their X-ray diffraction patterns were in good agreement with those of samples prepared from solid-state reactions or solution chemistry techniques. The present work demonstrates that the new dipping technique can be used as a generic method for synthesizing thin films of a variety of layered and three-dimensional organic−inorganic perovskites. It is expected to be particularly useful for preparing films of organic−inorganic systems in which the organic and inorganic components have incompatible solubility characteristics, or for systems in which the organic component is difficult to evaporate. The structural characterization and photoluminescence results all suggest that the perovskite films prepared using the title method are well-organized, making this method a promising technique to prepare thin films for a variety of potential device applications and scientific studies.

Introduction

Organic−inorganic perovskites have recently attracted much attention due to their unique electrical, magnetic, and optical properties, as well as their excellent film processability.[1−5] Layered perovskites, $(RNH_3)_2(CH_3NH_3)_{n-1}M_nI_{3n+1}$ (M = group IVB metal), naturally form a quantum-well structure in which a two-dimensional semiconductor layer of corner-sharing MI_6 octahedra and an organic ammonium layer are alternately stacked.[1,3,5,6] The excitons, resulting from the low dimensionality of these semiconductor sheets, have a binding energy of several hundred millielectronvolts, which enables strong emission even at room temperature.[6,7] Their strong room-temperature photoluminescence, along with significant photoluminescence wavelength tunability, make the organic−inorganic perovskites attractive candidates for emitter materials in electroluminescent devices.[8,9] Era[9] et al. have recently reported an electroluminescent device using the layered perovskite $(C_6H_5C_2H_4NH_3)_2PbI_4$ as an emitter material. At liquid nitrogen temperature, an electroluminescent intensity of 10 000 cd/m^2 was obtained at a current density of 2 A cm^{-2}, using an applied voltage of 24 V.

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Proper processing is essential in order to generate the material quality and morphology required to observe strong luminescence or to build devices. Single crystals and deposited thin films are two of the most useful forms for studies of optical and electrical properties. In general, when high-quality single crystals are required, crystal growth from the melt phase is often used. However, as a result of the organic ammonium cations, which decompose at relatively low temperature (<250 °C),[10] organic–inorganic perovskites are typically made using solution chemistry techniques.[1,5,11] Crystals resulting from solution methods are often, however, too small or of insufficient quality to be useful in device applications.

For the preparation of thin films, the spin-coating technique is suitable for processing many organic–inorganic perovskites because the components are often substantially soluble in conventional organic solvents. Spin-coating can be considered a special case of solution crystal growth. It allows the formation of perovskites on a substrate, while the solvent is evaporating off. Using this method, high-quality, highly oriented layered perovskite thin films can often be obtained.[12,13,14] However, control of film thickness, uniformity, and surface morphology is difficult using spin-coating. In addition, while simple organic ammonium salts are soluble in a range of organic solvents, including those that can dissolve the inorganic MI_2 salt, for more complex organic cations the choice of solvent becomes more limited. Furthermore, solvent techniques are not always compatible with the MI_2 salt, due to problems with solubility, strong solvent coordination, or the stability of the metal valence state.

Vacuum evaporation techniques have also recently been employed to grow oriented thin films of layered perovskites through a dual-source vapor deposition process.[15] The benefits of this technique are that it is possible to precisely control the thickness and smoothness of the thin-film surfaces. However, the preparation of various perovskites using different organic components is expected to be limited because each organic component easily contaminates the inside of the evaporation equipment. In addition, in some cases, the organic salt might not be thermally stable up to the temperatures required for evaporation, making this approach impractical for these systems. Even when it is possible to evaporate the organic salt, it is often difficult to balance the organic and inorganic rates, an important criterion for achieving the correct compositions of the resulting perovskite films. It is even more problematic that for each new organic–inorganic system, a reestablishment of the rates has to be carried out empirically.

In this work, we report a convenient two-step dipping technique for preparing high-quality thin films of a variety of perovskites. Thin films of MI_2 ($M = Pb, Sn$) were first prepared by vacuum-depositing MI_2 onto substrates, and these were subsequently dipped into a solution containing the desired organic ammonium cation for a short period of time. Using this technique, thin films of different layered organic–inorganic perovskites $(RNH_3)_2(CH_3NH_3)_{n-1}M_nI_{3n+1}$ (R = butyl, phenethyl; M = Pb, Sn; and $n = 1, 2$) and three-dimensional perovskites $CH_3NH_3MI_3$ (M = Pb, Sn; i.e., $n = \infty$) have been successfully prepared. The films were characterized by X-ray diffraction, atomic force microscopy (AFM), and absorption and fluorescence spectroscopies.

It is shown that the lattice constants of these dip-processed perovskites are very similar to those of the corresponding compounds prepared by solution-growth or by solid-state reactions. The layered perovskite thin films possess strong photoluminescence, distributed uniformly across the film areas. Similar results were achieved starting from spin-coated MI_2 films, which were dipped into appropriate solutions of the organic ammonium cations. This work demonstrates the simplicity and versatility of the dipping technique. It can be used for a variety of organics and inorganics, even if they have incompatible solubility characteristics. In addition, the sometimes problematic step of evaporation of the organic salt, necessary for the dual-source vapor deposition technique, can be replaced by a much simpler and controllable dipping step.

Experimental Section

Vacuum Deposited Metal Iodide Films. Vacuum evaporation of the MI_2 films (M = Pb, Sn) was performed using a homemade evaporation chamber. The MI_2 powder (PbI_2, Alfa Aesar, 99.999%; SnI_2, APL Engineered Materials, 99.999%) was loaded into a quartz crucible, and placed into the chamber, and the system was pumped down to a base pressure of about 4×10^{-7} Torr before beginning the evaporation. The metal iodide was evaporated and deposited onto ash glass or quartz substrates, which were maintained at room temperature, achieving a pressure of approximately 1×10^{-6} Torr during the deposition. During the deposition, the deposition rate and film thickness were monitored using a quartz crystal balance, with the deposition rates typically kept in the range 60–70 Å/min. The MI_2 films were immediately transferred into a nitrogen-filled drybox after deposition.

The resultant films were transparent, with the PbI_2 film having a light yellow color and SnI_2 a greenish-yellow color. The thin films were uniform and smooth, as indicated by the profiles measured on an Alpha-Step 200 and an AFM, and the final film thicknesses were in the range 2000–3000 Å. X-ray diffraction indicated that they consisted of grains that were primarily *c*-axis oriented with respect to the substrate.

Spin-Coated Metal Iodide Films. In addition to the evaporated metal(II) iodide films, spin-coated films were also used as a starting point for the dipping process. Spin-coating was performed in a nitrogen-filled drybox, and the spin rate was electronically controlled to be approximately 1600 rpm. Saturated methanol solutions of the metal(II) iodides were employed for the spin-coating process. As for the evaporated films, the spin-coated MI_2 films were primarily *c*-axis oriented.

Preparation of the Organic Salt Solutions. The solutions of organic ammonium iodides were prepared by dissolving 107 mg of butylammonium iodide or 268 mg of phenethylammonium iodide in 1 mL of 2-propanol (Aldrich, anhydrous). The 2-propanol solution was then diluted with 6 mL of toluene (Aldrich, anhydrous). The molar concentrations for the butylammonium iodide and the phenethylammonium iodide solutions were 38 and 77 mM, respectively. Due to the limited solubility in the above mixed solvent, 7 mL of pure 2-propanol

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was used to dissolve 140 mg of methylammonium iodide to prepare a 127 mM solution of this organic salt. A solution containing 2 equiv of butylammonium iodide and 1 equiv of methylammonium iodide was prepared by completely dissolving 80 mg of butylammonium iodide (0.40 mmol) and 32 mg of methylammonium iodide (0.20 mmol) in 5 mL of 2-propanol and then diluting this solution with 25 mL of toluene. All the solutions were kept in a nitrogen-filled drybox.

The butylammonium iodide used in the above solutions was prepared by bubbling hydrogen iodide (Matheson Gas Products) into a butylamine (Aldrich) chloroform solution. Phenethylammonium iodide and methylammonium iodide were previously prepared in this laboratory by mixing aqueous solutions of the organic amine and hydriodic acid and drying the product under vacuum.

Procedures for Dipping. In a nitrogen-filled drybox, each MI_2 thin film was immersed into a solution containing the desired organic ammonium iodide for a selected period of time. After the film was taken out from the dipping solution, it was immediately immersed in a rinse solution, which had the same composition as the dipping solution solvent (without the dissolved organic ammonium salt) for 5−10 s, to remove any excess organic ammonium salt. Before the thin film was transferred out of the drybox for measurements, it was pumped in the drybox loading lock for 10 min to ensure that any remaining solvent was removed. The specific films were prepared as follows:

$(C_4H_9NH_3)_2PbI_4$: Upon immersing an evaporated PbI_2 thin film into the 38 mM butylammonium iodide solution, it immediately turned an opaque yellow. Although there were no significant changes in appearances for the thin films prepared with different dipping duration, ranging from 5 s to 10 min, X-ray diffraction showed that it took about 1−3 min to complete the reaction of converting all the PbI_2 into the perovskite compounds. In terms of photoluminescence, it was of little benefit to extend the dipping duration beyond 2 min. In fact, it sometimes caused the formed perovskite films to partially come off the substrate if the immersion period was longer than 30 min, resulting in films with rough surfaces.

Spin-coated films of PbI_2 also formed $(C_4H_9NH_3)_2PbI_4$ when they were dipped into a butylammonium iodide solution. Typically, a period longer than 1 min was used for the dipping step. The films showed yellowish color after the dipping process and they were still transparent (in contrast to the films prepared from evaporated PbI_2). The absorption spectrum showed that a dipped spin-coated film of PbI_2 had an strong absorption peak at 524 nm, in accordance with the absorption peak associated with free excitons in single crystals of $(C_4H_9NH_3)_2PbI_4$.[10]

$(C_6H_5C_2H_4NH_3)_2PbI_4$: The procedure for dipping evaporated PbI_2 films into the phenethylammonium iodide solution was similar to that for the butylammonium iodide analogue. The resultant films of $(C_6H_5C_2H_4NH_3)_2PbI_4$ were yellow and not transparent. In the dipping process, a 1−3 min period was generally required to complete the reaction between the PbI_2 films and phenethylammonium iodide in the solution. Longer than 20 min of dipping duration usually led to rough films.

$CH_3NH_3PbI_3$: The three-dimensional perovskites were also formed when methylammonium iodide was used in the dipping solution. As soon as a PbI_2 film was introduced into a methylammonium iodide−2-propanol solution the film turned black, indicating the formation of a surface layer of $CH_3NH_3PbI_3$. To complete the transformation of the film into the three-dimensional perovskite required a period of 1−3 h, much longer than for the synthesis of the layered perovskite films. The resulting $CH_3NH_3PbI_3$ perovskite films were black and uniform.

$(C_4H_9NH_3)_2(CH_3NH_3)Pb_2I_7$: The preparation of thin films of the bilayer (i.e., $n = 2$) perovskite, $(C_4H_9NH_3)_2(CH_3NH_3)Pb_2I_7$, was carried out stepwise. First, a PbI_2 film was dipped into the 38 mM butylammonium iodide solution for 10 s, resulting in a film of $(C_4H_9NH_3)_2PbI_4$. It was then dipped for 3 min into the mixed solution containing 2 equiv of butylammonium iodide and 1 equiv of methylammonium iodide. The resulting film appeared bright red and was not transparent. Using these dipping parameters, no evidence for lower order (i.e., $n = 1$) or higher order ($n > 2$) members of the perovskite family could be detected using X-ray diffraction. The $(C_4H_9NH_3)_2(CH_3NH_3)Pb_2I_7$ film changed little for samples with dipping periods up to 3 h. However, a 12 h dipping duration eventually led to a dark gray film, which was identified by X-ray diffraction as primarily $CH_3NH_3PbI_3$.

The order of the procedure is vital for the preparation of the $n = 2$ compound. If a PbI_2 thin film was directly immersed into a $C_4H_9NH_2{\cdot}HI-CH_3NH_2{\cdot}HI$ (2:1, molar ratio) solution, the reaction did not lead to the formation of $(C_4H_9NH_3)_2(CH_3NH_3)Pb_2I_7$. Instead, $CH_3NH_3PbI_3$ was primarily formed, as shown by the X-ray diffraction pattern. When a PbI_2 thin film was first immersed into a methylammonium iodide solution, the resulting $CH_3NH_3PbI_3$ material did not convert into $(C_4H_9NH_3)_2(CH_3NH_3)Pb_2I_7$ after dipping it into either the $C_4H_9NH_2{\cdot}HI-CH_3NH_2{\cdot}HI$ or the $C_4H_9NH_2{\cdot}HI$ 2-propanol solutions, even for periods of up to 12 h.

$(C_4H_9NH_3)_2SnI_4$: The dipping process for the $(C_4H_9NH_3)_2SnI_4$ films was similar to that for the lead(II) analogues, although the reactions were found to proceed at a faster rate. A SnI_2 film was first immersed into a 70 mM butylammonium iodide 2-propanol/toluene (1:16, v/v) solution for 2 s and then rinsed with toluene, yielding an opaque red-brown film. It emitted a nominally orange light under excitation from a 366 nm hand-held light.

$(C_6H_5C_2H_4NH_3)_2SnI_4$: The film of $(C_6H_5C_2H_4NH_3)_2SnI_4$ was prepared by first dipping a SnI_2 film into a saturated phenethylammonium iodide 2-propanol/toluene (1/16, v/v) solution for 3 s and then taking it out of the solution to dry in a nitrogen atmosphere. This procedure was repeated twice, and the resulting film was rinsed with the same mixed solvent in the absence of phenethylammonium iodide. The resulting film was red-brown and not transparent. An orange emission was seen when it was exposed to 366 nm light.

$CH_3NH_3SnI_3$: The films of $CH_3NH_3SnI_3$ were also black, similar to those of $CH_3NH_3PbI_3$. They were prepared by dipping the SnI_2 films into an 88 mM methylammonium iodide 2-propanol solution for 30 s. The resulting films were rinsed with 2-propanol. While the reaction between the SnI_2 films and methylammonium iodide was slower than for the corresponding two-dimensional butylammonium or phenethylammonium compounds, it was much faster than for the formation of the Pb analogue.

X-ray Diffraction. Room-temperature X-ray diffraction patterns were collected over the range of $2° \leqslant 2\theta \leqslant 60°$ for each MI_2 thin film and each perovskite thin film, using a Siemens D5000 diffractometer (Cu Kα radiation). All the samples were measured directly under ambient conditions, except the $CH_3NH_3SnI_3$ films, which were cut into 1 × 2 cm stripes and contained in an airtight cell filled with nitrogen from the drybox. The indexing of the diffraction peaks was performed for the perovskite films based on a comparison with the patterns from the corresponding materials prepared using a solution chemistry method or solid-state reactions. The lattice constants were refined using the Siemens WIN-METRIC program after removing the background and the Kα_2 component from the diffraction pattern.

Spectroscopic Measurements. Absorption spectra were recorded on a Hewlett-Packard UV−vis 8543 spectrophotometer. Excitation and emission spectra were taken on a Spex Fluorolog-2 spectrophotometer using a front-face geometry. The incident light was from a xenon arc lamp, which was passed through a SPEX 1680 0.22 m double spectrometer. The emission was detected using a SPEX 1911F detector, after it was passed through a similar double spectrometer.

The emission spectra of each sample were collected with three different excitation wavelengths (350, 385, and 480 nm, for example, for the $(C_4H_9NH_3)_2PbI_4$ films) to ensure that the emission spectra were independent of excitation wavelength.

AFM Measurements. The room-temperature AFM images of the various thin films were recorded on a Nanoscope III (DFM-5000, Digital Instruments, CA). The scan area was typically 10 × 10 μm for preliminary scans and 3 × 3 μm for more detailed scans.

Results and Discussion

Formation of Perovskite Structures. The selection of solvents for dissolving the organic ammonium iodides was found to be critical for obtaining high-quality thin films of the perovskites using the new dipping technique. The criteria for choosing the solvents are that they must be good solvents for the organic ammonium iodides, but poor solvents for the metal(II) iodides and the resulting perovskite compounds. While both hexane and toluene do not dissolve metal(II) iodides and the corresponding perovskites, they are not appropriate solvents because the organic ammonium salts used in this study are only slightly soluble in them. For example, PbI_2 thin films only minimally reacted after being immersed in a saturated butylammonium iodide/toluene solution for 12 h. In contrast, 2-propanol is a good solvent for organic ammonium salts as well as for the layered perovskites. When a PbI_2 thin film was dipped into a butylammonium iodide/2-propanol solution, it dissolved into the solution in a few seconds. To balance these two extremes, a mixed solvent was chosen, with a composition of 1 portion of 2-propanol to 6 portions of toluene by volume for A_2PbI_4, and 1 portion of 2-propanol to 16 portions of toluene for A_2SnI_4 ($A = C_4H_9NH_3$ and $C_6H_5C_2H_4NH_3$). The smaller ratio of 2-propanol for the A_2SnI_4 compounds was chosen because of the relatively higher solubility for the tin(II) compounds in this solvent. In the case where methylammonium iodide was used to yield the three-dimensional perovskites, pure 2-propanol was used, as methylammonium iodide was only slightly soluble in the above mixed-solvent system. More importantly, the resulting $CH_3NH_3MI_3$ perovskite films did not degrade during the synthetic process (a period of time up to 3 h), enabling the complete reaction of the MI_2 thin films.

The reaction between the organic ammonium iodides and the MI_2 films was very fast, especially for the layered perovskites. The formation of the perovskites was seen as soon as the MI_2 thin films were immersed into the organic ammonium solutions. In fact, a PbI_2 thin film, dipped in a butylammonium iodide solution for shorter than 5 s, had comparable photoluminescence intensity with the one that was dipped in the same solution for 5 min or longer. As X-ray diffraction patterns demonstrated, PbI_2 was sometimes detected in the perovskite films that were made using a dipping duration of less than 1 min. A 1−3 min period appeared to be necessary for all the lead(II) iodide in the films to be completely converted into perovskite. Tin(II) iodide thin films were found to react at a faster rate than the corresponding lead iodide films, with the reactions often being completed within a few seconds.

It is somewhat remarkable that the reactions considered here are completed so quickly, even for relatively thick films. The reactions must occur through the organic ammonium iodides diffusing to the perovskite/metal(II) iodide interface, and subsequently reacting with the metal(II) iodides to form more of the perovskite. Layered perovskites consist of alternate inorganic layers and organic bilayers. This presumably allows organic ammonium iodide molecules to more easily diffuse into the structure along the van der Waals gap formed between organic layers of the structure.

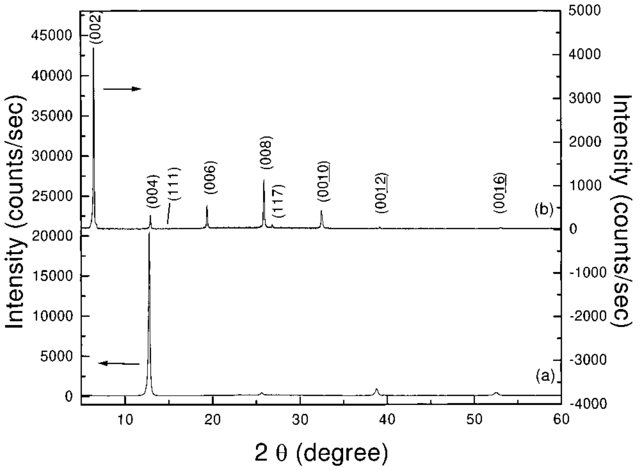

Figure 1. Room-temperature X-ray diffraction patterns for (a) a vacuum-deposited PbI_2 thin film, and (b) a $(C_4H_9NH_3)_2PbI_4$ thin film, prepared by dipping the PbI_2 thin film into a 38 mM butylammonium iodide 2-propanol/toluene solution for 1 min.

Compared to the layered perovskites, A_2MI_4, a much longer time is required to complete the reaction between metal(II) iodides and methylammonium iodide, which results in the formation of the three-dimensional perovskites, $CH_3NH_3MI_3$. In a methylammonium iodide solution, MI_2 rapidly reacts and forms a thin layer of the perovskite at the solution−film interface, as indicated by a color change for the film. In contrast to the layered perovskites, however, this surface layer does not aid in the diffusion of methylammonium iodide from the solution further into the interior of the film, since the three-dimensional structure lacks a van der Waals gap.

The importance of thermodynamics for the reactions between organic ammonium salts and PbI_2 was revealed by the formation process for the $(C_4H_9NH_3)_2(CH_3NH_3)Pb_2I_7$ films. Under the conditions examined, $CH_3NH_3PbI_3$ is found to be thermodynamically more stable relative to the other members of the layered perovskite family. This accounts for the fact that dipping a lead(II) iodide-based film into a $C_4H_9NH_2{\cdot}HI-CH_3NH_2{\cdot}HI$ (2:1, molar ratio) solution eventually gave rise to $CH_3NH_3PbI_3$, regardless of the starting film. $(C_4H_9NH_3)_2(CH_3NH_3)Pb_2I_7$ is apparently just an intermediate for the conversion of $(C_4H_9NH_3)_2PbI_4$ into $CH_3NH_3PbI_3$ in the presence of methylammonium iodide. Fortunately, the kinetics are slow enough to enable the $n = 2$ material to form as a metastable intermediate.

X-ray Diffraction from the Perovskite Thin Films. The vacuum-deposited PbI_2 thin films were mainly *c*-axis oriented, as indicated by the X-ray diffraction pattern shown in Figure 1a. Higher order [00l] diffraction peaks were detected, suggesting that the PbI_2 films were reasonably well-ordered. Upon dipping into the butylammonium iodide solution, the *c*-axis oriented PbI_2 films resulted in what appears to be predominantly *c*-axis oriented thin films of the layered perovskite, $(C_4H_9NH_3)_2PbI_4$, as shown in Figure 1b. It can be seen that the *c*-axis diffraction peaks overwhelmingly dominate the diffraction pattern, with seven observed [00l] peaks. The presence of higher order peaks indicates that the formed perovskite film is well-crystallized.

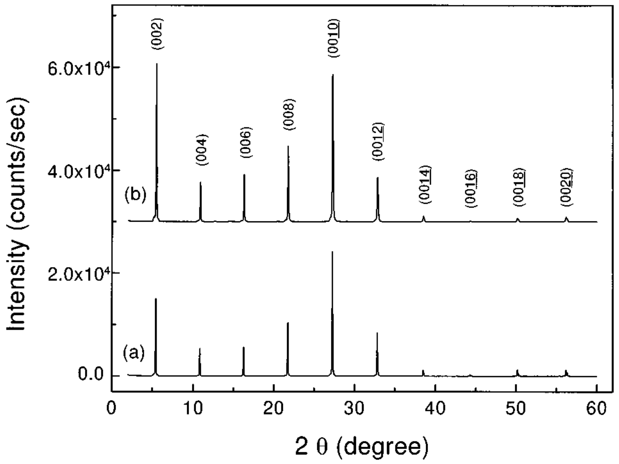

Figure 2. Room temperature X-ray diffraction patterns for (a) slightly ground $(C_6H_5C_2H_4NH_3)_2PbI_4$ crystals prepared using a solution chemistry technique and (b) a $(C_6H_5C_2H_4NH_3)_2PbI_4$ thin film prepared by dipping a PbI_2 thin film into a 77 mM phenethylammonium iodide 2-propanol/toluene solution for 10 min.

Although they are also *c*-axis oriented, the thin films of the layered perovskite $(C_6H_5C_2H_4NH_3)_2PbI_4$, prepared using dual-source vapor deposition, appeared to be less organized, as indicated by the absence of higher order diffraction peaks.[15]

While the strongest reflections from the thin films were [00l] peaks, several off-axis reflections (which tended to be weak but varied in intensity depending on preparation conditions) could also be detected for some of the films, enabling the determination of the lattice constants for the perovskite films. All of the 13 diffraction peaks for the $(C_4H_9NH_3)_2PbI_4$ film were successfully indexed (all of them were singly indexed), and the refined orthorhombic lattice parameters were a = 8.882(2) Å, b = 8.696(3) Å, c = 27.631(5) Å. This is in good agreement with the parameters, a = 8.886(2) Å, b = 8.698(2) Å, c = 27.637(5) Å, for samples prepared by a solid-state reaction between PbI_2 and $C_4H_9NH_2{\cdot}HI$ at 160 °C, and a = 8.863(2) Å, b = 8.682(1) Å, c = 27.570(2) Å, for single crystals prepared by a solution crystal growth technique.[10]

The diffraction patterns of the $(C_6H_5C_2H_4NH_3)_2PbI_4$ thin films showed that they were nominally *c*-axis oriented, as for $(C_4H_9NH_3)_2PbI_4$. Figure 2 demonstrates a good agreement between the diffraction pattern of a $(C_6H_5C_2H_4NH_3)_2PbI_4$ film made using the dipping method and that of ground crystals prepared by diffusing a methanol solution of $C_6H_5C_2H_4NH_2{\cdot}HI$ into an aqueous HI solution of PbI_2.

The $(C_4H_9NH_3)_2(CH_3NH_3)Pb_2I_7$ (n = 2) films also exhibited an X-ray diffraction pattern suggesting primarily *c*-axis orientation, as seen in Figure 3. The long cell dimension along the *c*-axis was 39.37 Å, an increase of 11.78 Å from the n = 1 structure, $(C_4H_9NH_3)_2PbI_4$. For the tin(II) counterpart, the long unit-cell dimension perpendicular to the perovskite sheets increased from 27.576(2) Å for $(C_4H_9NH_3)_2SnI_4$ (n = 1) to 39.395(5) Å for $(C_4H_9NH_3)_2(CH_3NH_3)Sn_2I_7$ (n = 2), an increase of 11.819 Å.[1] The increase observed in both of these systems is the result of inserting two more $CH_3NH_3MI_3$ perovskite layers per unit cell.

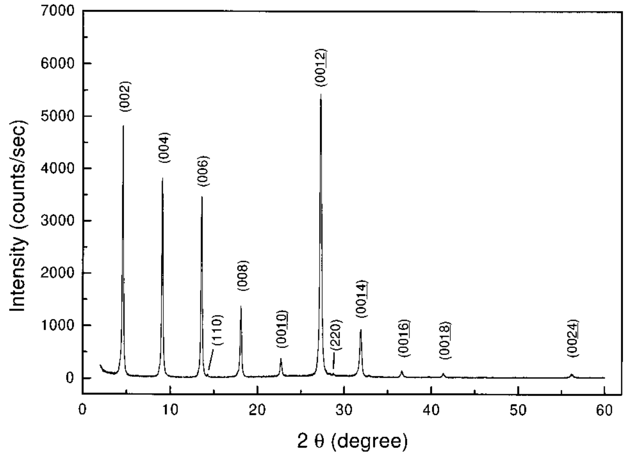

Figure 3. Room-temperature X-ray diffraction pattern for a $(C_4H_9NH_3)_2(CH_3NH_3)Pb_2I_7$ thin film synthesized by first dipping a PbI_2 thin film into a 38 mM butylammonium iodide 2-propanol/toluene solution for 10 s and then into an 2-propanol solution containing 2 equiv of butylammonium iodide and 1 equiv of methylammonium iodide for 3 min.

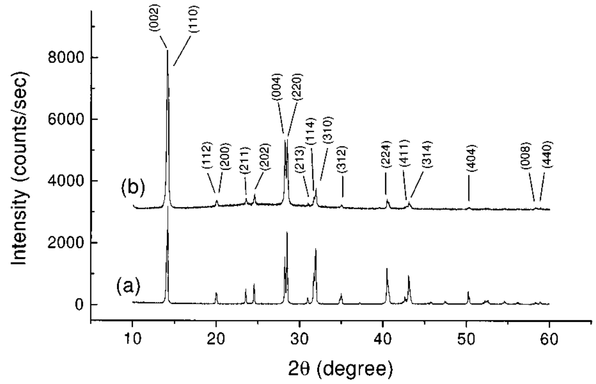

Figure 4. Room-temperature X-ray diffraction patterns for (a) a powder sample of $CH_3NH_3PbI_3$ prepared using a solid-state reaction and (b) a thin film of $CH_3NH_3PbI_3$, prepared by dipping a PbI_2 thin film into a 127 mM methylammonium iodide 2-propanol solution for 3 h.

Dip-processed $CH_3NH_3PbI_3$ thin films exhibited very similar diffraction patterns to those of $CH_3NH_3PbI_3$ prepared by a solid-state reaction, as shown in Figure 4. The refined tetragonal lattice parameters, a = 8.874(1) Å and c = 12.670(3) Å, are virtually identical with the values, a = 8.874 Å and c = 12.669 Å, for a sample prepared by solid-state synthesis.[16]

For the dip-processed tin(II) systems, the X-ray diffraction patterns of the $(C_4H_9NH_3)_2SnI_4$ and $(C_6H_5C_2H_4NH_3)_2SnI_4$ films were similar to those of corresponding crystals obtained by solution chemistry. Higher order [00l] peaks were observed, indicating the preferential *c*-axis orientation and reasonable crystalline order of the films. The diffraction peaks for the $CH_3NH_3SnI_3$ film reflected a cubic unit cell, with the refined lattice parameter a = 6.239(1) Å (compared to a = 6.2397(5) Å for samples prepared by precipitation from an aqueous hydriodic acid solution).[4]

Morphology of the Thin Films. Two-dimensional AFM topology and phase images from the surfaces of a thermally deposited PbI_2 film and several $(C_4H_9NH_3)_2PbI_4$ films, prepared using dipping times varying from 10 to 180 s, are shown in Figure 5. The surface of the evaporated PbI_2 film had small grains evenly distributed

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(16) Mitzi, D. B., unpublished results.

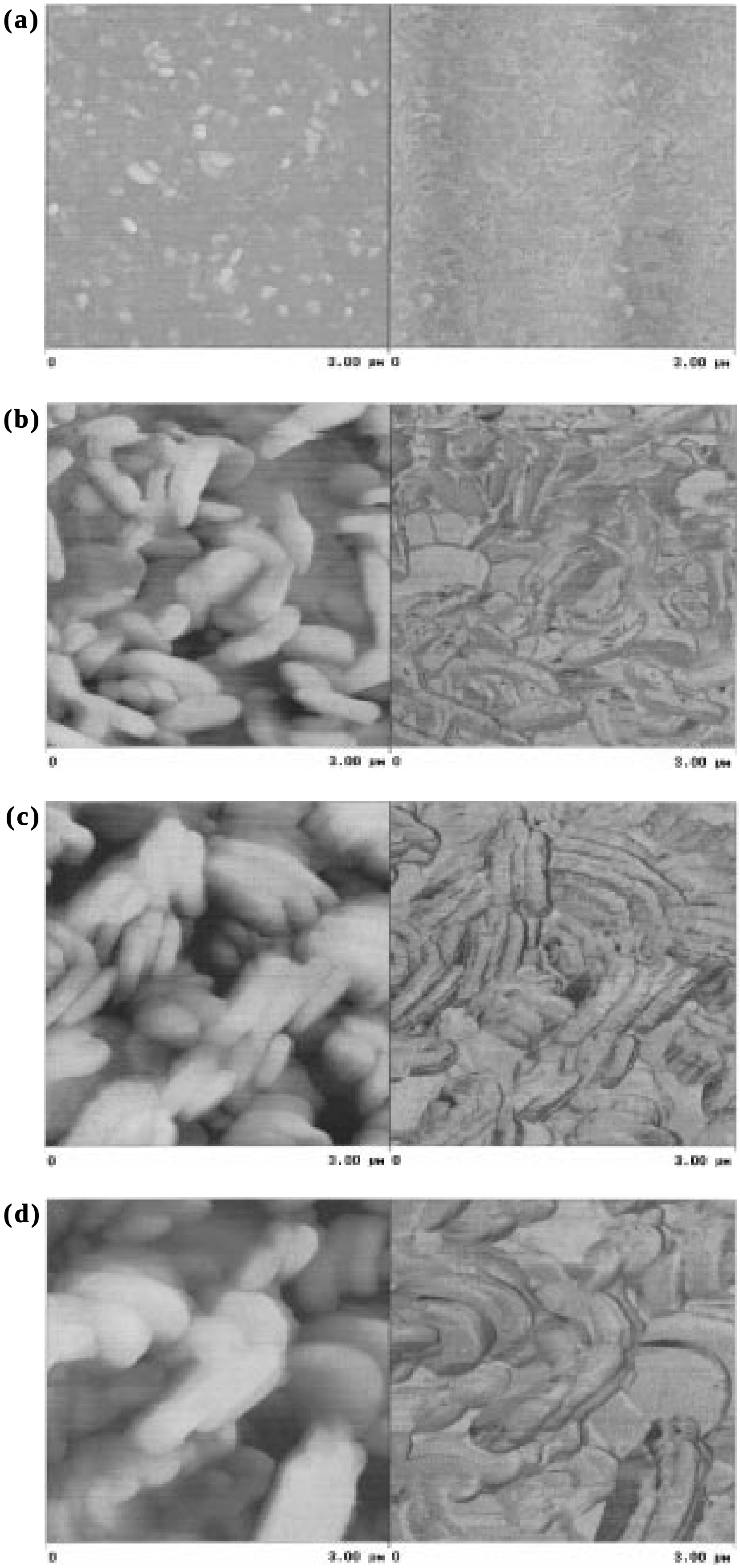

Figure 5. AFM images: The left frames are topology images and the right frames are phase images for (a) a film of vacuum evaporated PbI_2; (b), (c), and (d) films of $(C_4H_9NH_3)_2PbI_4$, prepared by dipping evaporated PbI_2 films into the butylammonium iodide solution for 10, 60, and 180 s, respectively.

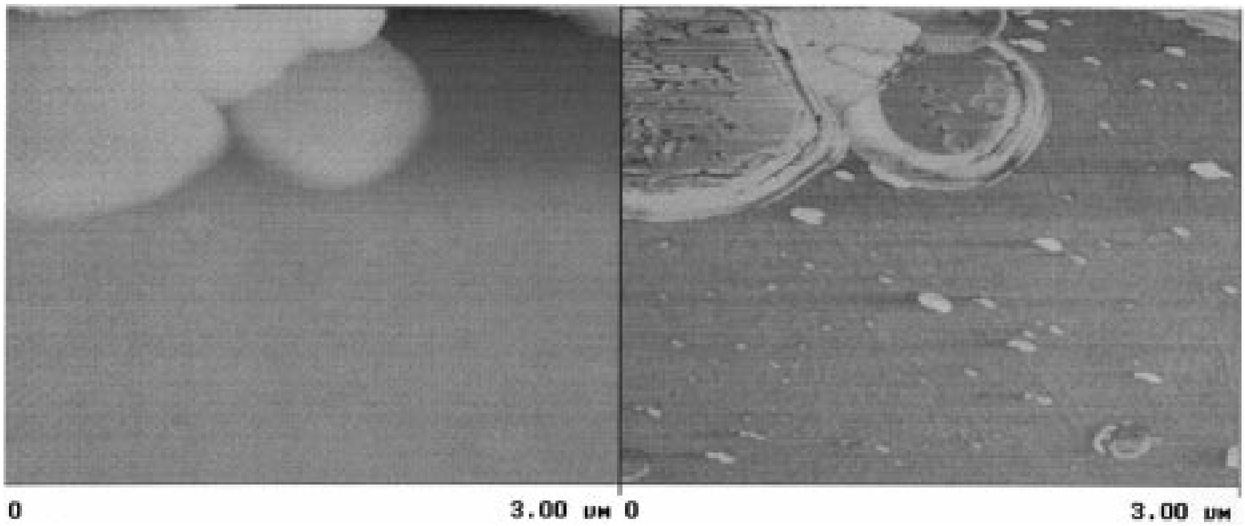

Figure 6. AFM topology (left) and phase (right) images of a film of $(C_4H_9NH_3)_2PbI_4$, prepared by dipping a spin-coated PbI_2 film into the butylammonium iodide solution for 1 min.

over the film area and had a mean roughness of 9 nm. After this film had been dipped in a butylammonium iodide solution, the surface morphology dramatically changed. As shown in Figure 5b, small, well-defined, randomly distributed grains were observed for a film prepared by dipping for 10 s. The grains appeared to be platelike, and the mean roughness of the film was about 97 nm. Compared to the undipped lead iodide film, the grains appeared to be substantially larger, with typical in-plane dimensions on the order of 0.6(2) μm and an average thickness of around 0.2(1) μm. X-ray diffraction indicates that a substantial fraction of the PbI_2 remained unreacted in this sample. For a film with a dipping duration of 60 s, in which most of the PbI_2 had reacted to form the corresponding perovskite, the grain size appeared larger and the mean roughness of the film increased to 121 nm. However, the most interesting change was in the arrangement of the grains. Although macroscopically the clusters were still randomly distributed, they were now often composed of two or three platelike grains which were packed together in parallel, as shown in both the topology and phase images (Figure 5c). Figure 5d shows the images of a film dipped for 180 s in a butylammonium iodide solution. In this case the PbI_2 had completely reacted, as indicated by its X-ray diffraction pattern. The mean roughness of this film (113 nm) changed little relative to that for the 60 s dipping duration. However, the platelike grains appeared to have grown further relative to the shorter dipping duration samples, with many grains having in-plane dimensions larger than 1 μm. These results indicate that the arrangement and size of the perovskite grains strongly depends upon the dipping duration.

The structure of the layered perovskites is highly anisotropic, and crystal growth tends to occur most easily along the plane of the perovskite sheets and more slowly along the perpendicular direction to the sheets. Consequently, crystals of these materials generally grow as plates, with the in-plane dimension corresponding to the plane of the perovskite sheets. In examining Figure 5, the platelike crystals appear to be approximately randomly oriented with respect to the substrate. This would suggest some *a*–*b* orientation to the films, rather than pure *c*-axis orientation. These observations need to be understood in the context of the X-ray data, which for most films suggest primarily *c*-axis orientation.

Even in nominally unoriented powders of the layered perovskites, prepared by solid-state synthesis, the dominant peaks in the X-ray diffraction pattern are the [00l] reflections, as a result of the strong scattering arising from the heavy atoms making up the inorganic sheets. Nevertheless, this factor is not enough to explain the overwhelming dominance of the *c*-axis reflections, compared to the off-axis reflections, for the dip-processed films. It is possible that the ordering along the *c*-axis of the structure is better than the ordering in the *a*–*b* plane of the structure, perhaps as a result of disordering of the organic cations. It is also possible that while on the surface of the film some crystallites are oriented with the *a*–*b* planes nominally perpendicular to the substrate, underneath this surface layer the film might be primarily *c*-axis oriented. Finally, if the grains that are not *c*-axis oriented with respect to the substrate are also preferentially oriented, but with an orientation that has a weak X-ray scattering cross section, then the *c*-axis reflections might appear to be by far the strongest reflections, despite a substantial percentage of the grains not having this orientation. Clearly, orientation effects for these highly anisotropic materials are very important for potential device fabrication and therefore more work needs to be done to clarify these issues.

The images of spin-coated PbI_2 films from a methanol solution show that they were smooth and homogeneous, with a mean roughness of 1.7 nm. After it had been dipped in a butylammonium iodide solution for 1 min, the X-ray diffraction pattern showed that all the PbI_2 had reacted, and the surface roughness increased, with platelike domains forming on the surface (Figure 6). Notice that while the surface of the dip-processed sample from the evaporated PbI_2 film was uniformly rough, with crystallites sticking out of the surface over the entire area of the film, the film resulting from the spin-coated PbI_2 had a substantial amount of smooth area, with however sizable crystals growing out of the surface over some interval. This difference in surface morphology presumably at least partially accounts for

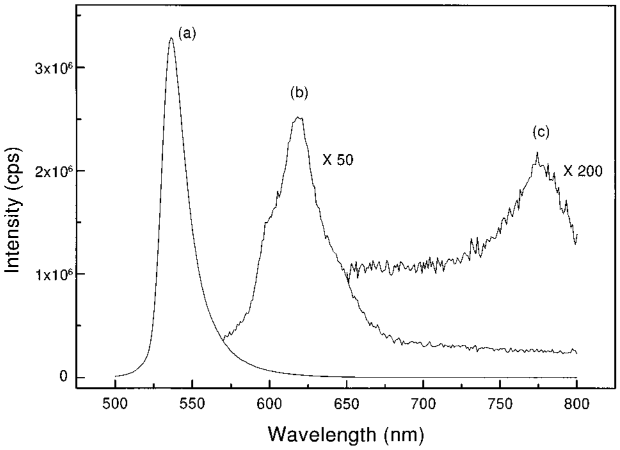

Figure 7. Emission spectra of perovskite thin films prepared using the dipping technique, with an excitation wavelength of 480 nm, for (a) $(C_4H_9NH_3)_2PbI_4$, (b) $(C_4H_9NH_3)_2(CH_3NH_3)Pb_2I_7$, and (c) $CH_3NH_3PbI_3$.

the difference in optical transparency between the organic–inorganic films prepared from spin-coated PbI_2 as opposed to those prepared from evaporated PbI_2.

In contrast to the films prepared from the two-step dipping process, the thin films prepared by spin-coating from an acetonitrile solution of $(C_4H_9NH_3)_2PbI_4$ yielded a much smoother film, with mean roughness of only 1.1 nm. There were small dark spots homogeneously distributed over the film surface. Presumably these are tiny crystals of $(C_4H_9NH_3)_2PbI_4$ formed in the course of spin-coating. While the dip-coated films appear substantially rougher, the surface morphology is expected to depend on the choice of the solvent system used during the dipping process. The full range of potential solvents has only begun to be explored. Furthermore, we have seen preliminary evidence that it may be possible to control the orientation of the perovskite films using the dipping process. Finally, it should be easier to control thickness uniformity over larger areas using dip-processing.

Photoluminescence of the Perovskite Thin Films. Single crystals of organic–inorganic layered perovskites, $(RNH_2)_2MI_4$ ($M = Pb$, Sn) exhibit strong exciton absorption and sharp exciton emission in the visible range at room temperature. The luminescence originates from electronic transitions within the inorganic perovskite layer. Due to their natural quantum-well structure, it is possible to tailor optical properties by varying either the organic or the inorganic components of the structure.

When the thin films of $(C_4H_9NH_3)_2PbI_4$, prepared using the dipping method, were exposed to a hand-held ultraviolet light (366 nm), they emitted strong green luminescence, which was evenly distributed across the film surface ($\sim$1.5 cm^2). Figure 7a shows the emission spectra for this sample. A strong, sharp peak was observed at 537 nm, with full width at half-height of 20 nm, when the film was excited at 480 nm. The emission peak position was independent of the excitation wavelength. It was found that there was no explicit relation between the emission spectrum and the dipping duration. Both the peak profile and width were virtually the same in all thin films with dipping duration ranging from 5 s to 10 min.

Compared to the emission spectra of single-crystal samples,[10] the spectra of $(C_4H_9NH_3)_2PbI_4$ films prepared from evaporated PbI_2 were red-shifted by about 10 nm. While it was not possible to measure the absorption spectra of these films since they were not transparent, the excitation spectrum did show a sharp peak at 523 nm, which corresponds to the absorption of the exciton state within the inorganic perovskite sheets. For comparison, the absorption spectrum of a thin film of $(C_4H_9NH_3)_2PbI_4$, prepared from a spin-coated PbI_2 film (which was transparent), exhibited a sharp exciton peak at 524 nm. The luminescence peak in these films was at 525 nm, which matches the results from the solution-grown crystals. Because the emission peak arises from an exciton state in the inorganic sheets of the layered perovskite structure, it is possible that subtle changes in the crystal lattice of these films relative to the single-crystal samples (perhaps due to organic cation disordering) may significantly impact the luminescence properties and account for the 10 nm red-shift for the films produced from the evaporated PbI_2 films. It is also possible that differences in grain size and crystallographic orientation in these films, as suggested from the AFM results, could contribute to the shift in wavelength. Perhaps the most likely explanation arises from states near the band edge of the perovskite layer, which could be due to defects in the crystal structure or surface states.

The thin films of the perovskite, $(C_6H_5C_2H_4NH_3)_2PbI_4$, prepared from evaporated PbI_2, showed similar photoluminescence to the butylammonium analogue. Upon exciting at 480 nm, an emission peak at 537 nm, with full width at half-height of 14 nm was observed. This emission was also red-shifted about 10 nm relative to the emission of single crystals of $(C_6H_5C_2H_4NH_3)_2PbI_4$, similar to the case for $(C_4H_9NH_3)_2PbI_4$. The photoluminescence characteristics of $(C_4H_9NH_3)_2PbI_4$ and $(C_6H_5C_2H_4NH_3)_2PbI_4$ were very similar, presumably because they have similar structures within the inorganic sheets. Furthermore, this similarity suggests that the interactions between adjacent inorganic sheets are insignificant in $(C_6H_5C_2H_4NH_3)_2PbI_4$ and $(C_4H_9NH_3)_2PbI_4$, because the former has a substantially longer distance between adjacent inorganic sheets (16.316 Å for $(C_6H_5C_2H_4NH_3)_2PbI_4$ vs 13.794 Å for $(C_4H_9NH_3)_2PbI_4$).

The red films of $(C_4H_9NH_3)_2(CH_3NH_3)Pb_2I_7$ emitted at 618 nm when excited at 480 nm (Figure 7b), with full width at half-height of approximately 30 nm. The emission wavelength was red-shifted by about 83 nm relative to that of $(C_4H_9NH_3)_2PbI_4$. Although the absolute efficiency was not determined, the photoluminescence from the $n = 2$ thin films was significantly weaker than for the $(C_4H_9NH_3)_2PbI_4$ films. In contrast to $(C_4H_9NH_3)_2PbI_4$, the inorganic sheets of $(C_4H_9NH_3)_2(CH_3NH_3)Pb_2I_7$ have a bilayer structure. It has been previously reported that in the family, $(C_6H_5C_2H_4NH_3)_2(CH_3NH_3)_{n-1}Pb_nI_{3n+1}$, the bandgap energy, the lowest exciton energy, and the exciton binding energy all decrease with increasing sheet thickness (increasing n) as a result of quantum confinement or dimensionality effects.[17] As a consequence, the exciton state in layered perovskites with thicker sheets is progressively less stable, and the emission associated with this exciton

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[17] Ishihara, T. *J. Lumin.* **1994**, *60* & *61*, 269.

state correspondingly red-shifts. This accounts for the red-shifted emission and relatively low emissive efficiency for the thin films of $(C_4H_9NH_3)_2(CH_3NH_3)Pb_2I_7$, relative to the $n = 1$ member of the $(C_4H_9NH_3)_2(CH_3NH_3)_{n-1}Pb_nI_{3n+1}$ family. As the $n = \infty$ member, the thin film of $CH_3NH_3PbI_3$ emitted even more weakly, with a further red-shift of the emission peak to 780 nm (Figure 7c). The emission peak was broad, with full width at half-height of approximately 40 nm. The absorption spectrum of these films had a step-shaped profile with the absorption edge at approximately 1.6 eV, which is in good agreement with the reported bandgap of $CH_3NH_3PbI_3$.[17]

The films of $(C_4H_9NH_3)_2SnI_4$ and $(C_6H_5C_2H_4NH_3)_2SnI_4$ emitted at 639 and 629 nm, respectively. Qualitatively, their emissions were weaker relative to their Pb counterparts, which is in agreement with the conclusion drawn from a comparison with the corresponding solution-grown crystals. The $CH_3NH_3SnI_3$ films, however, were not emissive under similar conditions at room temperature.

The emission intensities of thin films of the layered perovskites were comparable to those of the corresponding single-crystal samples.[10] It has been found that the luminescence of these layered perovskites is very sensitive to defects in the structure.[18] For $(C_4H_9NH_3)_2PbI_4$, poorly crystallized samples, finely ground crystals, or pressed pellets prepared by solid-state synthesis, exhibit very little, if any, photoluminescence at room temperature.[18] The fact that thin films of the layered perovskites made by the dipping technique have strong photoluminescence indicates that they are well-crystallized and have few nonradiative decay centers for the excitons.

Conclusion

As a potential emitter material for electroluminescent devices, organic−inorganic layered perovskites offer many potential advantages over conventional organic or inorganic materials. In addition to their strong photoluminescence, they have higher mobility relative to pure organic emitter materials, and much more processing flexibility and luminescence tunability compared to inorganic emitter materials. For luminescent devices, high-quality films are required, as characterized by (among other factors) uniform thickness, single-phase composition, well-crystallized grains, and strong, uniform luminescence across the film area. Spin-coating enables simple processing of well-crystallized thin films, which can locally be very smooth. However, control over film thickness and uniformity over large areas is difficult, and this technique would not be suitable for inorganic and organic constituents that have incompatible solubility characteristics. Vacuum deposition is another promising technique that allows precise control of the thickness and smoothness of the films but involves the often difficult to control process of evaporating the organic salt.

In this work, a two-step dipping technique has been demonstrated that can be considered a hybrid between the vacuum deposition and solution chemistry techniques. It not only takes advantage of the vacuum deposition technique with respect to managing the film thickness and uniformity but also retains the benefits of the solution chemistry methods in the sense that well-crystallized films can be generated without heating the organic component for evaporation. In addition to using evaporated MX_2 films as a first step, spin-coated films can also be used if this is more compatible with the system under consideration.

The convenience of this technique lies in its stepwise nature. The MX_2 films can be prepared in advance and can then be used to form the desired perovskites just before they are needed. The fact that only the evaporation of MX_2 is required significantly simplifies the preparation process and furthermore enables syntheses in which two organic salts are used. In addition, single-source evaporation of MX_2 helps to maintain a clean deposition environment. For the dipping technique, the main factors influencing the quality of the films are the choices of solvent for dissolving organic ammonium salts and the dipping duration. These two factors are relatively easy to control. As a consequence, good-quality thin films can be conveniently prepared. For applications that require patterning, the dipping technique may also provide a promising pathway, since prior to the dipping step the surface of the film can be coated with a resist so that only selected areas are exposed to the organic cation in solution.

The versatility of the dipping technique has also been demonstrated in this work by preparing a variety of perovskites, $(RNH_3)_2(CH_3NH_3)_{n-1}M_nI_{3n+1}$, with $n = 1$, 2, and ∞, using virtually the same dipping procedures. For a given metal, “M”, the family of perovskites can be prepared by simply varying the organic ammonium cations or by using mixed cations in the dipping solution. While we have considered here the tin(II) iodide and lead(II) iodide based systems with relatively simple organic cations, a variety of other perovskites, with various metals, halogens, or more complex organic molecules are expected to form by dipping MX_2 (X = Cl, Br, I) thin films into the corresponding organic ammonium halide solutions. These might include the divalent rare-earth metal and transition metal halides (chloride, bromide, iodide), and a variety of primary organic ammonium cations.

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(18) Mitzi, D. B.; Liang, K. *Chem. Mater.* **1997**, *9*, 2990.