Monocrystalline halide perovskite nanostructures for optoelectronic applications

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Single crystal perovskites are the simple structures to study perovskites to their most fundamental properties. In this chapter we varied the electric field applied to single crystals of methylammonium lead bromide and mapped changes in both their elemental composition and photoluminescence. Synchrotron-based nanoprobe X-ray fluorescence (nano-XRF) with 250 nm resolution revealed quasi-reversible field-assisted halide migration, with corresponding changes in photoluminescence (PL). We observed that higher local bromide concentration was correlated to superior optoelectronic performance in $\text{CH}_3\text{NH}_3\text{PbBr}_3$, while regions with lower bromide concentration showed decreased PL intensities. A lower limit on the electromigration rate is calculated from these experiments, and the motion is interpreted as vacancy-mediated migration based on nudged elastic band density functional theory simulations. The XRF mapping data provides direct evidence of field-assisted ionic migration in a model hybrid perovskite thin single crystal, while the link with photoluminescence proves that the halide stoichiometry plays a key role in the optoelectronic properties of the perovskite.
3 Halide migration and its effect on the PL of single crystal perovskites

3.1 Introduction

Halide perovskite materials have shown promise for a wide range optoelectronic applications including light-emitting diodes [114], photonic lasers [123], and solar cells [220, 221]. Despite their impressive potential demonstrated in laboratory devices, questions remain regarding many of the fundamental properties that govern their performance limits, especially their stability under hot [222], humid [223], illuminated [224] and biased operating conditions [225]. Understanding both the origin of this instability and its connection to performance is key to developing perovskite optoelectronic devices beyond the laboratory.

Many groups have suspected ionic migration under an electric field and illumination as an important limiting mechanism in hybrid perovskite devices, particularly in regard to current-voltage sweep hysteresis [97, 226–229]. Assuming thermal equilibrium and non-interacting defects, perovskites are predicted to have a high concentration of vacancies (10^{17} − 10^{20} cm^{-3} for CH_{3}NH_{3}PbI_{3}) [230]. Evidence of vacancy-mediated diffusion of X-site anions (in the ABX_{3} structure) with low activation energy through the conventional hopping mechanism along the anion octahedral edge has been determined for oxide [231] and inorganic halide perovskites [94]. In the analogous hybrid halide perovskites, extensive computational investigations, particularly in the methylammonium lead iodide (CH_{3}NH_{3}PbI_{3}) system, have shown that I^- is likely the most mobile ion because it exhibits a lower energy barrier to migration in comparison to Pb^{2+} and CH_{3}NH_{3}^+ [226, 228, 232]. Several groups have observed ionic migration of both organic cations and halide anions and in CH_{3}NH_{3}PbI_{3} and CH_{3}NH_{3}PbI_{3-x}Cl_{x} using techniques such as energy-dispersive X-ray spectroscopy (EDX) [233, 234], time-of-flight secondary-ion-mass spectrometry (tof-SIMS) [235], X-ray photoemission spectroscopy (XPS) [236] and IR microscopy mapping techniques [234]. These analytical techniques each have their own specific limitations. For instance, tof-SIMS involves sample fragmentation and physical destruction of the investigated area [237]; IR microscopy can detect bond stretches of the organic components in perovskite films but is generally not sensitive to the low-frequency vibrations of the inorganic components [238]; and XPS is sensitive only to the first few nanometers near the surface and requires high-vacuum conditions. EDS must be applied with caution to halide perovskites because of their sensitivity to electron beam damage [224, 239]. Finally, the nanoprobe X-ray fluorescence (nano-XRF) technique maps heavy elements throughout the bulk of the sample with higher spatial resolution and sensitivity than XPS, tof-SIMS, EDS, or IR microscopy.

Recently, synchrotron-based nanoprobe X-ray fluorescence (nano-XRF) mapping has been shown to be an effective probe of local composition in CH_{3}NH_{3}PbI_{3-x}Cl_{x} devices without affecting the elemental distribution[240]. During nano-XRF mea-
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surement, a focused X-ray beam excites core-shell electrons from the atoms in the sample. When a core-hole is filled by relaxation of an outer shell electron, a fluorescent photon is emitted, and its energy identifies the element from which it came due to the characteristic energy of electronic transitions. As a photon-in, photon-out process, nano-XRF is dose efficient, critical for radiation-sensitive materials like the hybrid perovskites and enables nanoscale elemental mapping with part per million sensitivity for elements heavier than sodium [241]. The many-millimeter working distance at hard X-ray energies also facilitates in situ and in operando studies [242]. More details of XRF technique is discussed in the Supplementary Information (SI) (see Section 3.6).

The best way to provide a direct link between composition and performance is to combine spatially-resolved elemental or chemical detection methods with techniques that probe the material’s local optoelectronic properties. Luminescence spectroscopy and imaging are versatile techniques to probe recombination mechanisms and dynamics in semiconductors. For example, recently researchers have

![Figure 3.1: schematic of nanoprobe X-ray fluorescence and spatially resolved photoluminescence (PL) measurement.](image)

A 250 nm FWHM X-ray beam excites elemental fluorescence that reveals the local perovskite stoichiometry in single crystals bridging Pt-Pt electrodes. Subsequently, a laser beam excites optical luminescence to elucidate local optoelectronic quality. Note XRF and PL were not performed at the same time, but sequentially in a correlative microscopy approach.
used spatially-resolved luminescence to reveal the role of Cl in CH$_3$NH$_3$PbI$_{3-x}$Cl$_x$ [220], to correlate contact resistance with morphology [243, 244], and to understand the degradation of the perovskite layer [245] and its interfaces [244]. Despite the importance of ionic migration, open questions remain as to how stoichiometric changes affect to photoluminescence a property directly linked to device performance [78, 246].

In this study, we identify a direct relationship between halide migration and local optoelectronic quality. Direct elemental evidence of halide migration in a CH$_3$NH$_3$PbBr$_3$ single crystal is detected using nano-XRF. Thin single crystals of CH$_3$NH$_3$PbBr$_3$, which are tens of micrometers wide and \(~500\) nm thick, are used as a model system (fabricated according to the method presented in Chapter 2) to study the fundamental properties of ionic migration in hybrid perovskites, avoiding complications from grain boundaries that are present in perovskite thin films. In response to an applied electric field, local stoichiometric variations appear along the crystal, which are correlated to local changes in the PL intensity. PL intensity increases in halide-rich regions and decreases in halide-poor ones, with quasi-reversible variation observed over multiple voltage biasing cycles. Furthermore, nudged elastic band (NEB) density functional theory (DFT) computations confirm that Br$^-$ ions experience a low energy barrier to migration within the CH$_3$NH$_3$PbBr$_3$ structure. The direct link between local stoichiometry and optoelectronic quality also clarifies that halide migration is a challenge that is intrinsic to the absorber and one that may play a determining role in the ultimate performance limits of perovskite devices.

3.2 Nanoprobe X-ray fluorescence mapping

Nano-XRF mapping is used to identify the spatial distribution of elements within a CH$_3$NH$_3$PbBr$_3$ single crystal under applied bias. The crystals bridge Pt electrodes, and the voltage is applied laterally across the device as shown in Figure 3.1. Pt electrodes prevent any driving force from a difference in the work functions of two different metals and also minimize chemical reactions or diffusion [247] of metallic atoms at the metal/perovskite interface [101]. Although, some small variations due to slightly different surface of Pt, like surface roughness variations or impurities may exist. Prior to the XRF measurement, electrical contact between the perovskite crystal and Pt electrodes was confirmed by current-voltage (I-V) scans (Figure 3.2). Fluorescence spectra were collected at each point during the XRF mapping using a synchrotron X-ray beam with a 250 nm full-width half maximum. Figure 3.3a shows the corresponding optical micrograph of the CH$_3$NH$_3$PbBr$_3$ crystal studied by XRF. To check the stability of the crystals under the X-ray beam and also the reproducibility of the XRF experiment, first a repeated x-ray mapping was performed.
3.2 Nanoprobe X-ray fluorescence mapping

Figure 3.2: The I-V test under AM1.5G illumination of CH$_3$NH$_3$PbBr$_3$ crystals on Pt-Pt electrodes to ensure electrical contact and photoresponse prior to a) X-Ray exposure for XRF and b) laser exposure for PL measurements. Insets in both a and b show I-V curves under dark condition. Both IV curves show the crystals were electrically contacted to the electrodes and their current enhances by light illumination.

on a crystal without electrical contacts. As expected, the spatial distribution and elemental composition of the crystals are uniform on the 250-nm length scale of measurement during repeated X-ray mapping under the focused 13.6 keV X-ray beam with a flux of 2.37×10$^9$ photons/sec (Section 3.6.1). The same conditions then were used to map a crystal on the electrodes with and without electrical bias. Note that the light elements in the methylammonium cation are not detectable by XRF, but the major heavy elements Pb and Br are detectable with sensitivity down to parts per million.

The local Br:Pb stoichiometry within the CH$_3$NH$_3$PbBr$_3$ single crystal is initially homogeneous across the crystal, prior to applying the bias, but changes systematically during application of an external electric field (Figure 3.3b). The seven XRF maps of the Br:Pb atomic ratio in the 30 × 30 $\mu m^2$ crystal are arranged from left (Map 1) to right (Map 7) based on the chronological sequence of applied bias. Map 1 is the initial scan showing the Br:Pb atomic ratio. As expected, the initial area-averaged Br:Pb ratio across the crystal was 3.08±0.2. An arrow above each XRF map measured under bias indicates the direction of the electric field. In this experiment the left electrode is held at ground and the right electrode has the applied voltage bias $V_{app}$ (orange arrow ($V_{app} = -2V$) and blue arrow ($V_{app} = +2V$)). The Br:Pb ratio is plotted because it removes the effects of small spatial variations in thickness, but the shift in Br:Pb ratio seen in Figure 3.3 results entirely from a change in the Br distribution, as the Pb distribution remains constant throughout the XRF mapping (Figure 3.9).
Figure 3.3: anoprobe X-ray fluorescence (Nano-XRF) measurement of the changes in elemental distribution in a CH$_3$NH$_3$PbBr$_3$ single crystal under bias.  

a) An optical image of the CH$_3$NH$_3$PbBr$_3$ crystal characterized by nano-XRF. Regions A and B where the crystal covers the two different electrodes are indicated. The electrode under region A is grounded and the other electrode is biased. Scale bar is 15 μm.  

b) X-ray fluorescence maps of the Br:Pb elemental ratio with 250 nm step size and 100 ms dwell time per point under a sequence of +/-2V biases. The direction of the corresponding electric field for each map under bias is denoted by an arrow above the map (-2V orange and +2V blue).  

c) The mean Br:Pb ratio of Area A and Area B as measured by X-ray fluorescence during the bias sequence with the corresponding bias condition (top). Time spent at -2V is shaded in orange and +2V in blue.  

d) Average Br:Pb ratio with respect to time over the entire crystal.
3.2 Nanoprobe X-ray fluorescence mapping

To examine the migration of ions under electric field, the perovskite crystal under-went a total of three poling cycles, from unbiased to +/- 2V bias to unbiased. After collecting the initial unbiased map (left of Figure 2b), a -2V DC bias was applied. After 30 minutes of bias applied without X-ray irradiation, we collected an XRF map (25 min duration) with the bias still applied to observe the effect of the electric field. The change in the Br:Pb atomic ratio between Maps 1 and 2 clearly indicates depletion of Br above the electrode at lower potential (right Pt pad). This depletion is consistent with the direction that Br$^-$ anions would migrate. The bias was then removed, and after a 30 min relaxation period, a third XRF map was taken to visualize any diffusion along the Br concentration gradient. The Br concentration is then slightly depleted over the left-hand electrode as Br$^-$ diffuses back in the absence of bias.

When the direction of the bias is reversed (+2V), the Br shifts toward the positively biased electrode, also consistent with migration of Br$^-$. A significant Br shift away from the left-hand negative electrode is observed in Map 4, while the Br concentration recovers slightly on the right-hand electrode (Map 2 vs 4). Upon subsequent relaxation in Map 5, a small recovery in the Br distribution is again seen. The last cycle seen in Maps 6 and 7 repeats the same -2V and 0V bias condition as Maps 1 and 2, respectively. It confirms that the observed changes in the Br:Pb distribution are partially repeatable.

The lower bound for mobility of Br ions is estimated at room temperature using Equation (3.1).

$$\mu = \frac{\nu}{E}$$

where $\mu$ is the mobility, $\nu$ is the velocity and $E$ is the applied electric field. The applied electric field is 2000 V/cm given the applied voltage of 2V and the gap space between electrodes of 10 $\mu$m. Knowing the 1800s duration of applied bias, the drift velocity ($\nu$) is calculated to be $5.56 \times 10^{-7}$ cm/s. This estimates the lower bound of Br drift mobility at room temperature as $2.78 \times 10^{-10}$ cm$^2$/V.s.

To assess the migration of Br$^-$ within the crystal more quantitatively, the changes in average Br:Pb atomic ratio above each of the two electrodes are presented in Figure 3.3c. The average ratio is plotted with respect to time and applied bias. As Br:Pb increases on one electrode, a decreasing ratio is seen on the other, providing additional support for an ion migration mechanism. The largest Br concentration change occurs above the lower potential electrode (Electrode B) right after the first bias is applied, when the Br:Pb ratio drops from 3.0$\pm$0.03 to 2.6$\pm$0.07. All subsequent changes are smaller, and the Electrode B area never recovers fully its initial Br concentration. On the other hand, Electrode A exhibits a more reversible response to applied bias and largely recovers from the smallest Br:Pb ratio near 2.8$\pm$0.09 to...
2.9±0.06 after final relaxation. Small, severely Br deficient regions evidenced by localized dark spots in Figure 3.3 develop above both electrodes over time. These regions indicate local degradation of the perovskite phase and possible formation of PbBr₂. After biasing the crystal for 4 hours, the area-averaged Br:Pb ratio in the last XRF map (rightmost) is 2.69. The loss of Br occurs predominantly during the first negative bias of each electrode, after which the total average concentration of Br was fairly stable (Figure 3.3d). Given what appears to be nanoscopic local formation of PbBr₂ in some regions, one could speculate that trace amounts of CH₃NH₃Br leaves the sample in an electrochemical reaction in regions of negative bias under X-ray irradiation. On the other hand, little change of the Br:Pb ratio away from 3.0 is observed between the electrode gap throughout the biasing cycles. Overall, the Br:Pb distribution shifts in the direction opposite the applied field at all time points.

![Image](image.png)

**Figure 3.4: Photoluminescence mapping of CH₃NH₃PbBr₃ crystal.** a) Optical image of a hybrid perovskite crystal on Pt electrodes with labeled regions of interest A and B. b) and c) Overlaid photoluminescence spectra in Areas A and B after -2V and after +2V biasing, respectively. Black curves in each figure represent the initial PL intensity before any biasing in areas A and B. Plots with empty and filled markers correspond to average PL spectra of areas A and B, respectively. The corresponding spatially-resolved relative PL intensity maps are shown in (d) for -2V bias and (e) for 2V bias relative to the initial unbiased PL map. Scale bars are 15 μm.
3.3 Photoluminescence mapping

A fresh CH$_3$NH$_3$PbBr$_3$ microcrystal, (optical image shown in Figure 3.4, I-V scan in Figure 3.2b), from the same sample chip is used to explore how the local optoelectronic properties vary in response to similar bias sequences as were used in the nano-XRF experiments. The crystal was excited using a 15 $\mu$W, 405 nm continuous-wave violet laser while performing PL mapping before, during, and after bias as presented in Figure 3.5a-g. Each map took $\sim$30 min to be collected. PL emission spectra were collected for each point of the crystal by moving the stage in the X and Y directions by 333 nm steps, and PL maps were constructed from the integration of the total emission intensity over the wavelength 500-580 nm.

Enhancement of PL intensity under bias at the forward biased electrode and its reduction at the reverse biased electrode area is attributed to the change of the depletion region width at each contact. Similar changes in PL emission intensity with the variation of DC bias were reported in other semiconductors such as InP, GaAs, and CuGaSe$_2$ [248–250]. To compare crystals at the same bias condition, the PL emission spectra averaged over the area of each electrode (area A and B) were collected at zero bias after applying and removing the electric field as shown in Figure 3.4b-c. An increase in PL intensity relative to its initial value was observed in the region above the electrode previously held at higher potential. A decrease was observed over the contact at lower potential. According to the XRF maps in Figure 3.3, the contact with the higher potential is where the Br concentration is higher; therefore, the Br$^-$ rich regions exhibit enhanced PL after removal of the electric field.

Figure 3.4d-e show the spatial variation of PL intensity across the crystal in response to biasing as the percentage change of PL intensity ($\Delta$PL, %). Each map represents the percentage change of PL after removing the electric field and returning the crystal to the initial 0V condition. (Details of the calculation are in Section 3.6.)

Figure 3.5: Spatially-resolved PL intensity maps. Each pixel of each map is the integration of PL intensity at 500-580 nm. The bias condition is indicated above each map, and the direction of the electric field is indicated below with arrows if applicable. Scale bar is 15 $\mu$m.
The orange and blue arrows on figures 3d and 3e, respectively, show the electric field that the crystal experienced before collecting the PL maps. Comparing the relative changes with the direction of the electric field, one sees that the PL intensity increases in the region that experienced higher potential (see the red regions at left side Figure 3.4d and right side Figure 3.4e), and decreases in the region that was previously at lower potential (see the blue regions at right side Figure 3.4d and left side Figure 3.4e). This anti-correlation between electrodes A and B after bias mirrors the trend seen in XRF. The bias-dependence of the local photoluminescence is confirmed in CH₃NH₃PbBr₃ crystals deposited onto different electrodes (Au-Au and Au-Ti electrodes) as shown in the SI (Figure 3.11), indicating that the changes in PL are independent of the particular metal/perovskite interface. In all cases, the peak of the PL spectrum does not shift in energy significantly (less than 2 nm) between the Br-rich and Br-poor regions (see SI, Figure 3.12).

The changes in PL intensity may be explained by vacancy-mediated halide migration. Initially, the PL intensity was inhomogeneous across the single crystal as seen in Figure 3.5 suggesting that surface or bulk defects dominate the PL response. Upon applying bias across the crystal, it is observed that Br⁻ moves opposite to the direction of the electric field and the local PL increases where Br increases. This enhanced PL in bromide-rich regions may originate from three distinct but related mechanisms, triggered by the ionic migration as seen in the XRF maps (schematic of mechanisms in Section 3.3). First, bromide migration will lead to local changes in

![Figure 3.6: Schematic of mechanisms that can explain the observed PL intensity variation.](image)

At the positive (negative) electrode, Br⁻ migration may a) reduce (increase) a vacancy-related, recombination active point-defect concentration, or b) passivate (expose) surface states at the contact interface. Alternatively, c) the remnant field due to slow ionic back-diffusion after the electric field is removed may leave a narrower (wider) depletion region.
the bromide vacancy concentration, which has been proposed to play an important role in the photoluminescence quantum yield \cite{104, 233, 251}. Crystal point defects such as vacancies may act as non-radiative recombination centers; therefore, a higher Br$^-$ vacancy concentration could lead to lower radiative recombination efficiency, causing the band-to-band PL intensity to decrease. Second, bromide stoichiometry may play a role in the density of interface states at the contacts. The migration of the bromide away from the contact interface at the lower potential electrode may lead to a higher density of interface states, and at the other contact, the higher Br content may passivate interface states. Finally, ionic migration will cause some residual change in the potential at the perovskite/metal contact interface even after the electric field is removed, due to slow ionic diffusion. At the lower-potential contact the perovskite/metal interface behaves as in reverse bias: the residual change in potential increases the depletion region, which helps to split the photogenerated carriers and prevents them from recombining radiatively, suppressing PL intensity. At the higher-potential contact the interface behaves as in forward bias: the depletion region becomes smaller and PL intensity is enhanced. Further studies are necessary to quantify the relative importance of each mechanism. Self-trapped carriers in the crystal lattice (strong-coupled polarons) have been suggested to play a role in charge carrier dynamics of hybrid perovskites and affect the radiative recombination rate \cite{252}. In the case of polaron formation, a red-shift in the energy of the PL peak is expected, but no red-shift was resolved within the detection limit of the PL setup in this study (see Figure 3.12, SI). Continued detailed study of ionic migration is critical because vacancies, as inherent material defects, may act as mediator or direct participants in non-radiative recombination centers in CH$_3$NH$_3$PbBr$_3$.

### 3.4 DFT calculations of ionic migration energy

The experimentally observed changes in Br concentration in the CH$_3$NH$_3$PbBr$_3$ single crystal are substantiated by the low energetic barrier to migration of Br$^-$ found by DFT climbing-image nudged elastic band (CI-NEB) calculations. To elucidate the ionic migration mechanism under applied bias, CI-NEB calculations were performed using $2 \times 2 \times 2$ supercells (computational details in SI). CI-NEB is a common method for finding minimum energy paths for ion migration \cite{253–255}. A single positively-charged Br$^-$ vacancy ($V_{Br}^+$) was introduced, and overall charge neutrality was achieved via a compensating background charge. We find that the lowest energy configuration for pristine CH$_3$NH$_3$PbBr$_3$ is in which the polar methylammonium cations are aligned, which is the expected orientation under an applied bias \cite{228, 234}. This alignment of the MA cations breaks the cubic symmetry, resulting in three distinct migration paths for Br$^-$, which are shown in Figure 3.7.
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The energy-migration coordinate diagram and the corresponding pathways viewed in a supercell are presented in the SI (see Figure 3.14). The paths where the Br$^-$ moves with a component in the direction of the C-N bond alignment, denoted as B-C-B and B-A-B, show the lowest migration energy barriers of 227 meV and 306 meV, respectively. The other hop, C-A-C, shows a migration energy of 425 meV. The alignment of the CH$_3$NH$_3^+$ cations under bias appears to create a channel with a lower energy of Br$^-$ vacancy migration along the field direction. In the absence of an electric field, this lowered barrier will be averaged out as methylammonium ions are randomly oriented at room temperature per CH$_3$NH$_3$PbBr$_3$ single crystal shown by neutron diffractometry [256]. Halide migration appears to benefit from CH$_3$NH$_3^+$ alignment that results in a lower migration energy barrier under an applied bias. The migration, in turn, is correlated with the density of recombination active defects as evidenced by the changes seen in the photoluminescence response under bias.

![Diagram of Br$^-$ diffusion pathways in CH$_3$NH$_3$PbBr$_3$](image_url)

**Figure 3.7: Schematic of Br$^-$ diffusion pathways in CH$_3$NH$_3$PbBr$_3$ by nudged elastic band (NEB)** The PbBr$_6$ octahedron becomes distorted after NEB relaxation. Primitive cell has lattice constants of 6.017, 6.041, and 6.115 Å, along the $a$-, $b$-, and $c$-axis, respectively. The geometrically distinct Br atoms are labeled as A, B and C and the corresponding migration energy barriers between Br atoms are shown in the table. White spheres represent the interpolated Br trajectories along pathway B-A-B and C-A-C, while yellow spheres indicating the smallest barrier migration for pathway B-C-B.
3.5 Conclusion

In summary, we systematically manipulate the halide concentration laterally within a thin CH$_3$NH$_3$PbBr$_3$ single crystal by applying a voltage bias. We observe the changes of Br distribution at the nanoscale by means of Nano-XRF. The halide migration is directly correlated to variations in PL response. As Br$^-$ migrates away from the negatively biased electrode and the perovskite becomes locally sub-stochiometric, the PL intensity decreases. NEB calculations indicate that the alignment of the methylammonium cation under bias forms channels that facilitate halide migration along the field direction. Combining the quantitative analysis of ion migration with local optoelectronic characterization provides insight into the fundamental operation of halide perovskite devices. The link between intrinsic point defect migration and photoluminescence intensity makes it clear that controlling the crystal chemistry is paramount. Possible strategies to mitigate the effects of Br migration and improve optoelectronic performance in the perovskite include growing perovskites in halide-rich conditions [257] or applying post-growth treatments to lower the concentration of halide vacancies. Future work is needed to understand the defect kinetics of ion migration as a function of the absorber chemistry and to reveal the nature of the optoelectronic defects that arise under bias to achieve the full potential of the hybrid perovskite materials for optoelectronic devices.

3.6 Supplementary Information

3.6.1 Experimental details

In this study, we used the same method for the fabrication of perovskite precursors, solution and PDMS-stamped CH$_3$NH$_3$PbBr$_3$ single crystal devices as explained in Chapter 2 (See Section 2.6.1 for more details)

Synchrotron-Based XRF Characterization

In order to determine the elemental distribution in the absorber, the perovskite crystals were investigated by synchrotron-based nano-XRF with a 250 nm full-width half-maximum focused beam at 13.6 keV with a 50% aluminum absorption filter in place at beamline 2-IDD in a helium environment of the Advanced Photon Source at Argonne National Laboratory. Fly-scanning was used with a dwell time per point of 100 ms. Using the beamline's nanopositioning stage, we scanned the sample in front of the focused X-ray beam and precisely mapped the local Pb and Br chemistry with a step size as small as 200
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Figure 3.8: XRF maps of a CH$_3$NH$_3$PbBr$_3$ crystal with full beam illumination without electric bias. The Br XRF maps with the corresponding histograms are shown. The length of the scale bar is 5 μm. The mean and standard deviation for Map a, b and c are 1.82±0.12, 1.83±0.12, and 1.84±0.11 μmol/cm$^2$, respectively.

nm. An SRS 570 current pre-amplifier at the beamline was used to bias the sample in-situ +/- 2V.

CH$_3$NH$_3$PbBr$_3$ stability was examined under focused X-ray beam at 13.6 keV with no filter in place (Figure 3.8). Br:Pb elemental ratio XRF maps indicate good stability of the material with no systematic change in its elements spatial distribution upon repetitive scanning with 100 ms dwell time per point. In our analysis, we focus on the quantitative Br:Pb ratio. NIST standard reference material 1832 and 1833 standards were used to quantify the XRF data, correcting for the uncertainty in the extrapolation of the fluorescence yield to the Br line using the initial perovskite stoichiometry. Additional XRF maps of quantitative Pb:Pt and Br:Pt mass ratio are presented in Figure 3.9. Linear color scale is applied to each elemental ratio, where yellow indicates high mass ratio and red indicates low mass ratio.

Analysis of spatially resolved PL maps of different CH$_3$NH$_3$PbBr$_3$ crystals

A WITec alpha300 SR confocal imaging microscope was used to collect photoluminescence spectra of CH$_3$NH$_3$PbBr$_3$ crystals while the crystal was being moved using a piezostage. Sample was excited with a 405 nm diode laser (Thorlabs S1FC405) through a NA 0.9 objective and the luminescence was collected in reflection using a spectrometer. The calibration of the spectral response of the collection optics, fiber, and spectrometer was done with a standard mercury light source, and the
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Figure 3.9: PtPb and PtBr mass ratio XRF maps within the CH$_3$NH$_3$PbBr$_3$ crystal. The elemental ratio in each row has the same linear color scale. The scale bar is 33 μm.

The spectrum was corrected accordingly. The spatially-resolved PL maps are obtained by integrating the PL intensity within the optical fluorescence peak width, from 500-580 nm. The relative changes of PL intensity ($\Delta PL$) is computed using Equation (3.2),

$$\Delta X (%) = \frac{PLI_X - PLI_{initial \ 0V}}{PLI_{initial \ 0V}} \times 100$$  \hspace{1cm} (3.2)

where PLI is the photoluminescence intensity and X indicates the number of map according to Figure 3.5. All the relative PL maps of the crystal in the Figure 3.4 are shown in Figure 3.10. Additionally, the PL maps of MAPbBr$_3$ crystals on Au-Ti and Au-Au paired electrodes are shown in Figure 3.11. These maps display similar trends of PL intensity shifts under the influence of bias to the Pt-Pt electrodes shown in Figure 3.4. The PL mapping experiment was also done on the crystal that was exposed to the X-ray beam during XRF mapping, and its the PL spectra were comparable to those of a fresh crystal (Figure 3.12k and l) with the PL peak being blue shifted by 10 nm.

Figure 3.10: Relative PL maps of the crystal in different bias conditions compared to the initial 0V map. $\Delta PL_4$ and $\Delta PL_7$ are the same as maps shown in Figure 3.4d and e, respectively. The dashed arrows show the direction of the electric field that the crystal was under priorly. The total time to collect each map was 30 min. Scale bar is 10 μm.
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Figure 3.11: Series of relative PL maps for CH$_3$NH$_3$PbBr$_3$ crystal on Au-Ti (a-c) or Au-Au electrodes (d-f). The trend of an increase in PL intensity in the opposite direction of electric field is independent of electrode material. 

A similar trend in PL intensity shift with electrical biasing is seen for this crystal, although the change in PL intensity is not as clear as it is for the fresh crystals (Figure 3.13). Synchrotron X-ray irradiation has been shown to degrade carrier collection in hybrid perovskites within seconds of exposure at a single spot [242], and it is thus not surprising that the PL changes are more clear in the fresh crystal.

3.6.2 Climbing-image nudged elastic band (CI-NEB) calculations

All DFT calculations were performed using the Vienna Ab initio Simulation Package (VASP) [258] within the projector augmented-wave approach [259]. Spin-polarized calculations using the Perdew-Burke-Ernzerhof (PBE) generalized-gradient approximation (GGA) [260] functional were used for structure relaxations and all analyses were carried out using the Python Materials Genomics (pymatgen) library [261]. We performed climbing image nudged elastic band (CI-NEB) calculations using $2 \times 2 \times 2$ supercells (8 formula units) of the lowest energy structure obtained for cubic CH$_3$NH$_3$PbBr$_3$ to minimize the interaction between periodic images. To study Br$^-$ vacancy migration, a single positively-charge Br$^-$ vacancy ($V_{Br}^+$) was introduced and overall charge neutrality was achieved by
Figure 3.12: Normalized PL spectra of CH$_3$NH$_3$PbBr$_3$ crystals with different electrodes shows that the energy of PL peak does not vary upon applying electric field. The first column shows the optical image of the tested crystals on different electrode materials. Areas A and B are shown with dashed line on each figure. Second column presents normalized PL spectra after -2V poling for selected regions A and B. Third column shows normalized PL spectra after +2V poling for selected regions A and B. Scale bar is 10μ m.
3 Halide migration and its effect on the PL of single crystal perovskites

Figure 3.13: Percentage changes of PL intensity of the CH$_3$NH$_3$PbBr$_3$ crystal after XRF measurement. (a) optical image of the crystal. (b) and (c) are relative PL maps after -2V and +2V poling respectively. Scale bar is 10μm.

compensating background charge. A $2 \times 2 \times 2$ k-point grid and energy cutoff of 520 eV were adopted for NEB calculations. The forces were converged to 0.05 eV/Å.

Figure 3.14: PBr$^-$ migration barriers from nudged elastic band (NEB) calculations. (i) The migration paths depicted in the $2\times2\times2$ super cell with paths labelled as B-A-B, B-C-B and C-A-C (labelled as in Figure 3.7). The energy vs migration coordinate of each path is shown: ii) B-C-B, iii) B-A-B iv) C-A-C.