

Charge Selective Contacts to Metal Halide Perovskites Studied with Photoelectron Spectroscopy: X-Ray, Ultraviolet, and Visible Light Induced Energy Level Realignment

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The electronic properties of metal halide perovskites (MHPs) are crucial for achieving the full potential of MHPs-based optoelectronic devices, and they are extensively studied by photoelectron spectroscopy (PES). However, there are numerous complexities during PES measurements, which can result in inconsistent experimental data or even misinterpretation of results. Here, it is demonstrated that in the presence of charge selective junctions with MHPs, significant electronic energy level realignment can occur during PES measurements due to the sample excitation with high-energy photons used in PES, amounting up to over 0.8 eV in the present case. This is caused by unbalanced charge carrier accumulation within the perovskite due to the charge-selective interface. X-ray photoelectron spectroscopy further reveals that photoexcitation due to bremsstrahlung, as produced in commonly employed twin-anode lab-sources, can readily produce sizable photoinduced shifts of core levels of MHPs films, whereas monochromatized X-ray lab-sources (irradiation flux reduced by >50 times by eliminating the bremsstrahlung) induce negligible shifts within the range of presently applied anode powers. The data and measurement conditions presented here are intended to enable others to obtain reliable MHP electronic property information from PES measurements.

1. Introduction

With significant progress achieved in the field of photovoltaics,^[1,2] metal halide perovskites (MHPs) have attracted enormous attention across various scientific disciplines.^[3–5] To reach the ultimate performance of MHPs-based devices, a thorough understanding of the electronic properties of MHPs and their interfaces in devices is crucial. To that end, these properties have been investigated in numerous theoretical^[6–10] and experimental studies.^[11–15] Photoelectron spectroscopy (PES) has been widely employed to investigate the electronic band structure of functional materials. Based on the photoelectric effect, a monochromatic light source ejects electrons from the occupied states, whose kinetic energy and emission angle distribution are directly recorded. The key electronic parameters relevant for perovskite-based devices, i.e., the work function (Φ) and the energy positions of the valence band edges with respect to the Fermi level (E_F), are commonly determined by ultraviolet

photoelectron spectroscopy (UPS),^[11–17] from which the energy level alignment at interface and/or across layer stack can then be established. In addition, the chemical state information, i.e., the (environment-dependent) binding energy of a chemical element at the surface or an interface, can be assessed by X-ray photoelectron spectroscopy (XPS).^[13,18–23] This makes both variants of PES technique the most widely applied analysis methods for MHPs and their interfaces, furthered by the increasing number of commercial turn-key PES instruments that require little method-specific knowledge for operation. However, when employing these fundamentally relevant methods, one may face numerous challenges for obtaining reliable electronic properties of MHPs. For instance, the determination of the valence band edge position from UPS spectra using the conventional linear intensity scale extrapolation method has been shown to largely overestimate the valence band (VB) onset due to the very low effective density of states (DOS) from the highly dispersive top-most valence band, as demonstrated by previous studies.^[12,15] An accurate VB onset can only be obtained by plotting the UPS

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spectrum on a logarithmic intensity scale. Another example of methodological challenge is the dependence of the MHP Fermi level position on the substrate's Φ ,^[24] i.e., the *n*- or *p*-type character of MHP films cannot be readily concluded on when using only one type of substrate. This evaluation can be further complicated by the presence of the gap- and/or surface-states of the MHP.^[24,25] Beyond that, it was demonstrated that heterojunctions between organic charge transport layers and MHPs can exhibit huge energy level realignments during photoexcitation with visible and UV light, caused by unbalanced charge carrier accumulation at the junction with charge selective character.^[26,27] Consequently, an illumination-intensity-dependent energy level alignment at perovskite-based interfaces is observed in UPS measurements. Thus, these critically important phenomena, if not properly checked and accounted for, can result in severe discrepancies between measurements performed in different laboratories or even overall misinterpretation of the experimental data.

Substantial work has been devoted to obtain high-quality MHPs films utilizing various functional molecules,^[20,22,23,28,29] and XPS has been applied as method of choice to investigate chemical interactions by probing changes of the perovskites' characteristic core levels (e.g., Pb 4f or I 3d).^[20,22,23,28,29] Observations of core level shifts of perovskites are often erroneously taken as an indication of bond formation,^[23] chemical reactions,^[20] or the establishment of a space-charge region,^[29] which, however, can stem from different physical origins. It should be considered that with the presence of a charge selective interface, a non-equilibrium electronic state resulting from charge accumulation could also occur upon X-ray excitation, which would re-position the perovskite core levels with respect to the (dark) equilibrium state. This, however, has not been the subject of study yet.

In the present contribution, taking into account possible photoinduced (including X-rays) energy level realignment, we present a detailed study on the electronic properties of the prototypical triple cation perovskite with a focus on the interplay between the excitation fluxes used for PES and the measured energy levels. To warrant high relevance of the samples studied herein for perovskite-based photovoltaics, we employed the commonly used Cs_{0.05}(FA_{0.83}MA_{0.17})_{0.95}Pb(I_{0.83}Br_{0.17})₃ (hereafter abbreviated as CsFAMA), which produced energy conversion efficiencies of over 20%.^[16] We demonstrate that the valence bands of CsFAMA films shift significantly by up to 0.85 eV toward the highest occupied molecular orbital (HOMO) levels of a hole transport layer (HTL) under white light illumination, accompanied by equivalent shifts of the sample surface electrostatic potential (SEP, corresponding to the work function when measured in dark conditions). These shifts are clear signs of interfacial energy level realignment caused by selective charge accumulation, in line with recent studies.^[26,27] More importantly, the perovskites' core levels not only show equivalent displacements under white light illumination in XPS, but they also display a noticeable shift under standard X-ray excitation from widely available dual-anode X-ray sources. In contrast, high-resolution XPS measurements using monochromatized (mono-) X-ray excitation do not show notable core level shifts upon varying the X-ray flux, owing to the fact that the photon flux is significantly attenuated (>50 times) by eliminating the bremsstrahlung via the monochromator. Our findings demonstrate that great care must be taken when characterizing MHP films using UPS and XPS, and in the presence of charge

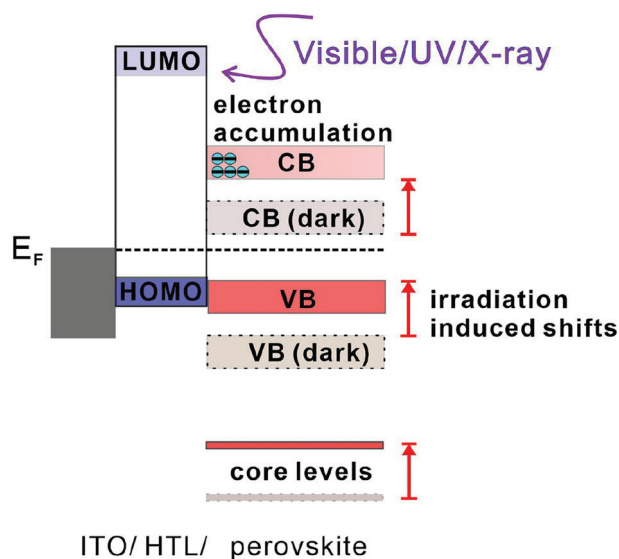


Figure 1. Schematic presentation of the photoinduced charge accumulation effect on the energy level diagram for the case of a charge selective HTL/perovskite interface. The gray and red lines depict the energy levels in dark and under illumination (with X-rays, UV, or visible light), respectively. E_F refers to the Fermi level of the conductive substrate.

selective interfaces it is necessary to minimize any excitation flux (visible light, UV, and X-ray) in order to approach the electronic ground state situation.

2. Results and Discussion

To support easier grasping the effect of photoinduced energy level realignment, a HTL/perovskite interface is schematically illustrated in **Figure 1**.

Upon sample illumination with photons of energy higher than the perovskite bandgap, photogenerated electron-hole pairs within the perovskite are separated at the interface with the HTL, leading to accumulation of electrons within the perovskite film, where holes are free to move into the HTL and electrode. As a result, a rigid upward shift of all perovskite energy levels with respect to those of the HTL are observed in UPS and XPS, because of the electrostatic nature of this effect. In analogy, the energy level shifts in the opposite direction when an electron transport layer is employed instead of the HTL. This was explained in detail previously,^[27] and the realignment of the perovskite levels occurs at the direct contact with the HTL due to the weak electronic coupling between the two materials.

The UPS spectra of a CsFAMA films (ca. 400 nm^[16]) deposited on ITO/poly-[bis-(4-phenyl)-(2,4,6-trimethylphenyl)-amin] (PTAA) substrate (Φ_{PTAA} of 4.65 eV) measured under varying illumination conditions are presented in **Figure 2**. UPS results of PTAA film (ca. 8 nm) are presented in Figure S1 (Supporting Information). The morphological and crystallographic characterizations of the perovskite films are shown in Figures S2 and S3 (Supporting Information), respectively. As seen from the secondary electron cutoff (SECO) in Figure 2a and VB regions in Figure 2b,c, the sample exhibits initially (without additional visible or X-ray illumination) a Φ (or SEP) of 4.01 eV

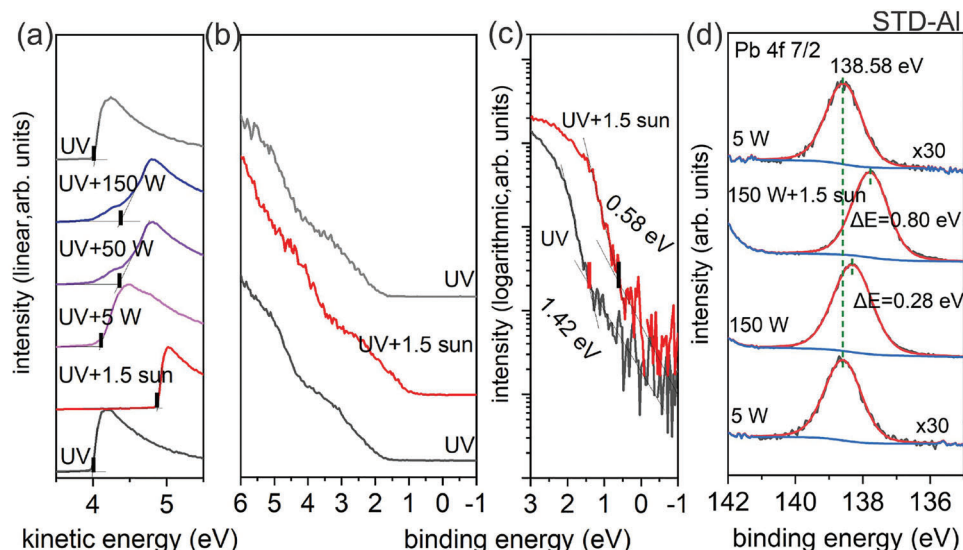


Figure 2. UPS and XPS spectra of a CsFAMA film deposited on ITO/PTAA. a) SECO spectra measured with UV, additional white light (ca. 150 mW cm⁻²) and standard Al X-ray under various anode power as indicated. Valence bands measured in dark (UV only) and with additional white light, plotted in b) linear and c) logarithmic intensity scale. d) Pb 4f_{7/2} core levels using a standard Al X-ray source at various anode power and additional white light illumination (150 mW cm⁻²); black, blue, and red lines denote the raw, background, and fitted spectra, respectively.

and a VB onset at 1.42 eV binding energy (with respect to the E_F at 0 eV), as determined by extrapolation of the leading edge on the logarithmic intensity scale. This reveals a pronounced *n*-type character at the surface, given the fundamental bandgap of ca. 1.63 eV of this MHP.^[30] It is noted that we do not observe any structured gap state density on the perovskite surface from the valence band spectra, thus the probed E_F position on the surface most likely reflects its bulk electronic properties. Although the level alignment at PTAA/CsFAMA buried interface is not directly probed by UPS, given the Φ difference between PTAA (shown in Figure S1, Supporting Information) and CsFAMA, the change of vacuum level at the PTAA/CsFAMA interface is likely due to the formation of interface dipole and/or band bending, where the latter was recently observed at PTAA/FA_{0.85}Cs_{0.15}PbI₃ interfaces.^[27] For simplicity of the energy level diagrams, an interface dipole is assumed to account for the change of vacuum level at PTAA/CsFAMA interface. Upon white light illumination (ca. 1.5 sun), we observe a huge increase of sample SEP by 0.85 eV, accompanied with a decrease of the VB onset from 1.42 eV down to 0.58 eV, i.e., the ionization energy of 5.43 eV is the same under both conditions. This is a clear signature of the energy level realignment being driven by the large energy offset for hole extraction at the buried interface, as illustrated in Figure 1. The measured energy levels (VB and vacuum level) whether in dark (i.e., only the UV light used to excite the photoelectrons in UPS) or under light are all referred to the E_F of the conductive ITO substrate. We emphasize that the UV flux from the helium discharge lamp was intentionally attenuated by a monochromator, and potential other light sources in the vacuum chamber, such as visible light from viewports and that produced by the ion gauge, were turned off in order to minimize the overall sample photoexcitation. Higher intensity UV light from conventional discharge lamps has been found to induce noticeable shifts of perovskite energy levels during UPS measurements.^[27] To investi-

gate whether X-rays can also induce energy level shifts in addition to UV and/or visible light, a standard dual-anode X-ray source was operated at varied anode power while the SECO spectra were acquired, as displayed in Figure 2a. Clearly, upon increasing the X-ray power, we observe a progressive increase of sample SEP by 0.09 eV at 5 W and up to 0.36 eV at 150 W (the latter being a typically employed anode power in most experiments). This evidences noticeable shifts of perovskite energy levels induced by a standard, non-monochromatized X-ray gun, even when operated at extraordinarily low anode power of 5 W. As a side note, the appearance of the small tailing toward the low kinetic energy side upon X-ray exposure can be ascribed to the fact that SECO measurement provides an area-averaged sample SEP^[31] where the X-ray beam spot does not overlap fully with the UV light, giving rise to an inhomogeneous spatial distribution of the surface electrostatic potential under photoexcitation.

To illustrate also core level shifts during XPS measurements, the Pb 4f levels under varied anode power were measured, as shown in Figure 2d. It can be clearly seen that the Pb 4f_{7/2} peak initially positioned at 138.58 eV under 5 W, exhibits a rigid shift toward lower binding energy by 0.28 eV under 150 W, consistent with the shift of the sample SEP by 0.27 eV due to X-ray irradiation. Furthermore, additional white light exposure of 1.5 sun leads to a drastic decrease of Pb 4f peak binding energy by 0.80 eV, which is in line with the observation of the valence level and SEP shifts. The key electronic parameters of these PES data are summarized in Table 1. At this point, it is worth mentioning that the observed shifts in the perovskite valence and core level regions are fully reversible when reducing the excitation flux again, as demonstrated in Figure 2b,d, respectively. To further demonstrate the reproducibility and universality of such phenomena, analogous UPS measurement were conducted on several PTAA/CsFAMA samples, as shown in Figure S4 (Supporting Information), with the key parameters summarized in

Table 1. Key electronic parameters determined from PES data as a function of excitation sources and fluxes. Pb 4f core levels were excited using a standard Al anode source. SEP in dark corresponds to the sample work function. All values refer to the E_F at 0 eV binding energy. W denotes the employed X-ray anode power.

Excitation	SEP [eV]	VB onset [eV]	Pb 4f _{7/2} [eV]
UV	4.01	1.42	/
UV + 1.5 sun	4.86	0.58	/
UV + 5 W	4.10	/	/
5 W	/	/	138.58
UV + 50 W	4.35	/	/
UV + 150 W	4.37	/	/
150 W	/	/	138.30
150 W + 1.5 sun	/	/	137.78
UV	4.01	0.58	/

Table S1 (Supporting Information). Although sample-to-sample variations of their initial energy levels are noted, all samples exhibit strong illumination-dependent SEP of perovskites, with the shifts ranging from 0.61 to 0.78 eV. Again, the shifts are fully reversible once returned to dark, indicating electrostatic origin of the phenomenon. In addition, the line shape of the valence band and core level spectra remain essentially the same before and after X-ray and white light illumination.

Given the unknown level alignment with the buried PTAA upon illumination, we thus propose two scenarios of the interfacial energy level diagram: 1) fixed HOMO level position of PTAA with respect to the substrate E_F and 2) realignment of PTAA HOMO level likely caused by redistribution of photogenerated charges at the interface, as shown in **Figure 3b,c**, respectively. The former scenario is based on the observation of photoinduced level realignment of organic transport layers deposited on perovskite film, where the perovskite film in direct contact with conductive

substrate remains unchanged under illumination.^[26] Although at this point we cannot rule out one of the two scenarios, in both cases, perovskite energy levels exhibit significant shifts with regard to the conductive substrate E_F , which always remains constant at 0 eV binding energy.

To further investigate whether such level realignment during XPS measurements can be reduced by eliminating the bremsstrahlung from the characteristic Al $K\alpha$ X-ray line by a monochromator, the CsFAMA sample was also measured employing a mono-X-ray source. The core level characterization using a mono-X-ray source not only features a better energy resolution, but it also benefits from a significantly reduced X-ray flux (>50 times, estimated from the sample current) mainly owing to the removal of the bremsstrahlung contribution. The SECO and the Pb 4f core level spectra probed by the mono-X-ray source are presented in **Figure 4**. Upon increasing the X-ray anode power from 5 to 150 W, the sample Φ exhibits a slight increase from 3.95 to 4.05 eV, meanwhile, the Pb 4f_{7/2} peak remains nearly constant at 138.70 eV, demonstrating a very small shift of perovskite core levels upon mono-X-ray exposure. The slight variation in photoinduced shifts between sample Φ and core levels can be ascribed to the difference in the probing depth as the SECO carries only the information from the very top surface. In addition, it is further noted that the measured Pb 4f_{7/2} peak position varies by 0.12 eV between standard and mono-X-ray at same anode power of 5 W, i.e., a higher binding energy being acquired by the mono-X-ray source. The above observation conclusively reveals a non-negligible photoinduced level realignment by bremsstrahlung using standard X-ray sources even at low operation power, and the photoinduced shifts appear to be almost negligible under mono-X-ray excitation within the range of anode powers examined here. Therefore, the utilization of mono-X-ray sources is highly recommended for XPS characterization of MHPs in order to minimize photoinduced shifts when a charge selective contact is investigated. Furthermore, by eliminating the bremsstrahlung,

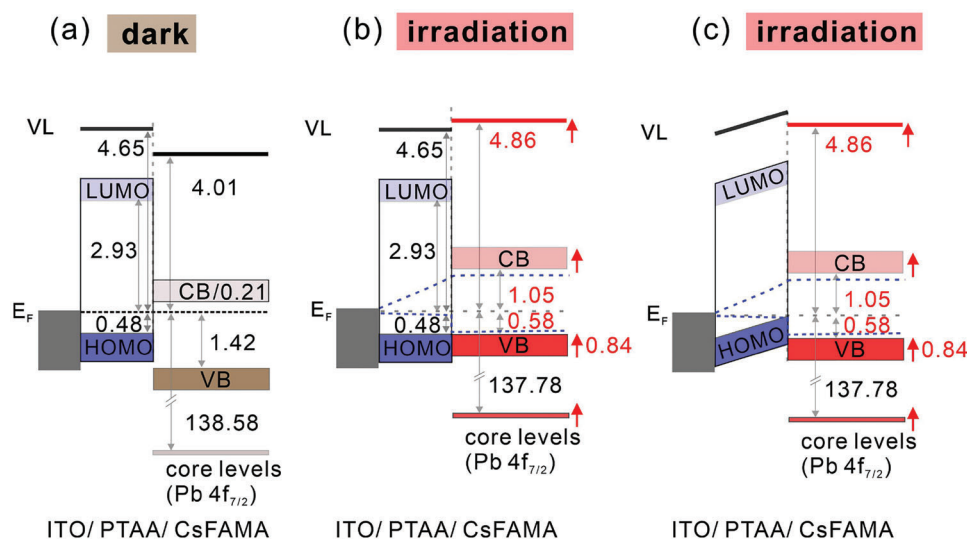


Figure 3. Schematic energy level diagrams of ITO/PTAA/CsFAMA stack a) in dark and under 1.5 sun illumination assuming PTAA HOMO level b) fixed and c) realigned with respect to the E_F of the conductive substrate. VL is the vacuum level and E_F the Fermi level of the conductive substrate set at 0 eV binding energy. All values are referred to the E_F and in unit of eV. LUMO of PTAA and CB of CsFAMA are extracted given their bandgaps.

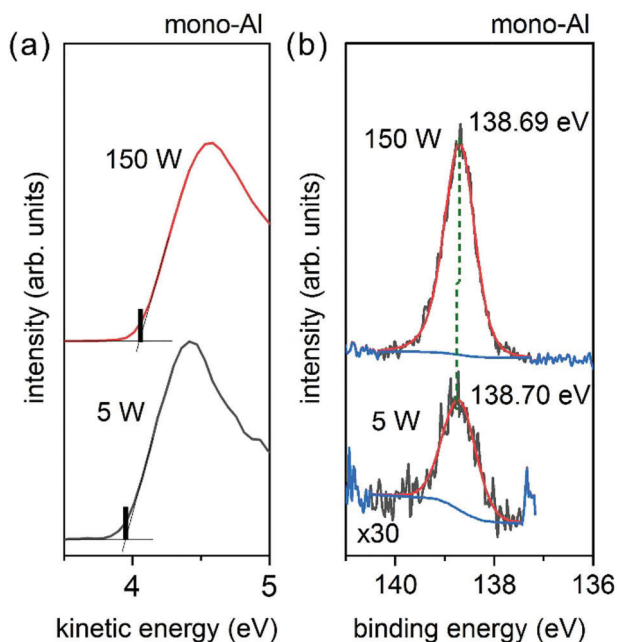


Figure 4. a) SECO and b) high-resolution Pb 4f_{7/2} core levels spectra measured with mono-X-ray (Al source) under various anode powers. Black, blue, and red lines denote the raw, background, and fitted spectra, respectively.

photoinduced degradation processes are expected to be significantly slowed down in ultrahigh vacuum (UHV),^[32] which permits a more detailed and reliable chemical state characterization using XPS.

As mentioned above, the shifts of the MHPs valence bands and core levels are fully reversible upon removing additional photoexcitation, and solely depend on the applied excitation intensity, underpinning the electrostatic nature of the observed phenomenon. Therefore, photoinduced degradation processes are not expected to occur throughout PES characterization described above, as otherwise photoinduced decomposition in UHV will lead to creation of PbI₂ species and Pb⁰-related density of surface states, the latter with high density being able to cause strong Fermi level pinning.^[19] This is supported by the lack in the present set of experiments of Pb⁰-related peaks in the Pb 4f spectra, usually reported at ca. 1.7 eV toward the lower binding energy from the pristine Pb²⁺ peak. In addition, as displayed in Figure S5 (Supporting Information), additional optical absorption spectra measured on the CsFAMA film before and after PES experiments present almost identical absorption features in the visible range with a sharp absorption onset at ca. 1.63 eV and no sign for the formation of PbI₂ species with an expected absorption feature at ca. 2.5 eV.

To further demonstrate the selective charge accumulation as the origin of the above observed energy level shifts, analogous experiments were performed with CsFAMA films deposited on a conductive substrate. In this case, the conductive polymer poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) was employed. The UPS and XPS spectra of the PEDOT:PSS/CsFAMA sample and the corresponding energy level diagram are presented in Figures S6 and S7 (Supporting Infor-

mation). The perovskite exhibits a slightly different level alignment as compared to that of PTAA/CsFAMA sample, with a Φ of 4.44 eV and VB onset at 0.97 eV, due to the higher work function substrate ($\Phi_{\text{PEDOT:PSS}}$ of 5.00 eV). This further implies build-up of a space-charge region where the depletion width is expected to exceed the film thickness, as otherwise, a constant E_F position in the energy gap on surface comes into play. The exact band alignment requires thickness-dependent UPS measurements, which faces a great challenge to obtain nanometer scale perovskite films from solution-process. Nevertheless, illumination is not found to change the perovskite energy levels on PEDOT:PSS, as shown in Figure S6a,b (Supporting Information). In addition, as shown in Figure S6d (Supporting Information), perovskite core levels also remain unaffected regardless of the applied X-ray power and additional illumination. This can be understood from the fact that the photogenerated electrons and holes are free to move across the interface with PEDOT:PSS (being not charge selective), giving rise to balanced charge distribution in perovskite film. This further rules out the impact of mobile ions and/or vacancies, which come into play when strong electric fields (or under open-circuit conditions due to the work function difference of the electrodes) are applied across the perovskite film with a magnitude of ca. 1 V μm^{-1} .^[33,34] Such electric field can induce redistribution of mobile ions and/or vacancies in the device which leads to changes of energy level alignment. This is in strong contrast to our study where no top electrode, i.e., no electric field, is employed upon sample illumination.

To facilitate a better overall understanding, the impact of photoexcitation on determining the energy levels of perovskites using photoelectron spectroscopy is summarized in Table 2. It can be clearly seen that precise determinations of perovskite energy levels and associated energy level alignment require careful consideration of the charge selectivity of the substrate when photoexcitation is inevitably employed. Upon contacting with charge selective substrate, minimal photoexcitation, e.g., by using mono-X-ray source, is vital to access the perovskite energy levels in the ground state.

3. Conclusion

In conclusion, we demonstrated that for charge selective interfaces the work function/surface electrostatic potential and the electronic energy levels (valence band and core levels) of CsFAMA films exhibit significant shifts by up to 0.85 eV upon white light illumination, demonstrating a strong photoexcitation intensity-dependent energy level realignment. This is ascribed to unbalanced charge accumulation at the interface driven by the

Table 2. Summary of impact of excitation sources on determining the energy levels of perovskites.

Charge selective contacts	Excitation sources		Energy level shifts of perovskites
Yes	X-ray	mono	Marginal
		standard	up to hundreds of meV
		visible light	up to hundreds of meV
No		irrelevant	None

large energy offset between the frontier energy levels, in line with recent studies.^[26,27] More importantly, by comparing XPS measurements using standard and monochromatized X-ray sources under varied anode power, we find that the bremsstrahlung can readily cause considerable shifts of the perovskite energy levels, while the monochromatized X-ray induced band realignment is negligible within the range of typically applied anode powers. These findings highlight the importance of being aware of the presence of charge selective junctions and the accompanying energy level realignment in MHPs materials when photoexcitation is inevitably employed. With this in mind, the characterization of the MHPs electronic properties can be conducted with high accuracy.

4. Experimental Section

Sample Preparation: Substrates: Indium-tin-oxide substrates (ITO, Automatic Research, Germany) were cleaned with acetone, 3% Hellmanex solution, DI-water and iso-propanol, by sonication for 10 min in each solution. After a microwave plasma treatment (3 min, 200 W), the samples were transferred to a N₂-filled glovebox. The first layer of a Poly[bis-(4-phenyl)-(2,4,6-trimethylphenyl)-amin] (PTAA, Sigma-Aldrich) layer with thickness of 8 nm was spin-coated from a 2 mg mL⁻¹ in toluene solution at 6000 rpm for 30 s. After 10 min annealing on a hotplate at 100 °C, the films were cooled down to room temperature and a solution of N,N-Dimethylformamide (DMF, anhydrous, SigmaAldrich) was spin-coated onto PTAA substrate while the substrate was spinning at 4000 rpm for 30 s. No further annealing occurred. This aims to increase the wettability upon spin-coating of perovskite solution. Poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS, AI 4083) was spin-coated onto ITO at a speed of 3000 rpm for 60 s, followed by annealing at 150 °C for 15 min in the N₂-filled glove box.

Perovskite Solution: The triple cation perovskite solution was prepared by mixing two 1.2 M formamidinium lead iodide (FAPbI₃) and methylammonium lead bromide (MAPbBr₃) perovskite solutions in DMF/Dimethyl sulfoxide (DMSO, anhydrous, SigmaAldrich) (4:1 volume ratio) in a particular volume ratio of 83:17. The 1.2 M FAPbI₃ solution was prepared by dissolving FAI (GreatCellSolar, 722 mg) and PbI₂ (TCI, 2130 mg) in 2.8 mL DMF and 0.7 mL DMSO. The 1.2 M MAPbBr₃ solution was made by dissolving MABr (Dysol, 470 mg) and PbBr₂ (TCI, 1696 mg) in 2.8 mL DMF and 0.7 mL DMSO. Lastly, 40 µL of a 1.5 CsI (Sigma-Aldrich) solution in DMSO (389 mg CsI in 1 mL DMSO) was mixed with 960 µL of the above-described mixture of FAPbI₃ and MAPbBr₃ resulting in a nominal perovskite stoichiometry of Cs_{0.05}(FA_{0.83}MA_{0.17})_{0.95}Pb(I_{0.83}Br_{0.17})₃.

Perovskite Samples: All triple cation perovskite films were prepared in the N₂-filled glove box by spin-coating the precursor onto ITO/PTAA and ITO/PEDOT:PSS substrates at 4000 rpm for 40 s, and 10 s after the start of the spinning process, the spinning substrate was washed with 300 µL ethylacetate for ≈ 1 s (the anti-solvent was placed in the center of the film). The perovskite films were then annealed at 100 °C for 1 h on a preheated hotplate. All samples were transferred to ultrahigh vacuum (UHV) system directly from the glove box without air exposure.

Photoelectron Spectroscopy Measurements: UPS and standard XPS spectra were recorded using a hemispherical analyzer (Phoibos 100, SPECS) in a UHV system (base pressure of 1 × 10⁻⁹ mbar). A monochromatized helium discharge lamp (mono HIS 13, FOCUS GmbH, photon energy of 21.22 eV) and a standard Al Kα radiation (1486.6 eV) generated from a twin-anode X-ray source (XR50, SPECS) were employed as excitation sources. XPS measurements equipped with a monochromatized Al Kα radiation source were conducted at a JEOL JPS-9030 UHV system (base pressure of 2 × 10⁻⁹ mbar). For UPS measurements, it was noted that the visible light was eliminated and UV flux was significantly reduced by the monochromator (attenuation by a factor of ca. 100-fold as compared to that of the standard helium lamp). The photoelectron energy was cali-

brated using a clean gold foil by setting the Fermi edge to 0 eV for UPS and Au 4f_{7/2} peak to 84.0 eV binding energy for XPS. All spectra were recorded at normal emission and room temperature.

Supporting Information

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

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

energy levels, interfaces, metal halide perovskites, photoelectron spectroscopy

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