

## RESEARCH ARTICLE

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# Adhesion, stability, structural and electronic properties of perovskite/BaWO<sub>4</sub> heterostructures: first-principles and experimental characterizations†

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The poor stability of lead halide perovskites poses a critical challenge for realizing potential applications. Constructing latticed-matched perovskite/BaWO<sub>4</sub> heterostructures is highly advantageous for achieving enhanced stability. However, there is limited knowledge about the interfacial properties. Herein, we conducted combined first-principles and experimental investigations of the perovskite/BaWO<sub>4</sub> heterostructures in this work. First, eight different interfacial configurations were constructed and investigated systematically. The influence of surface terminations on interfacial properties was examined through the adhesive strength and electronic structures. The results of adhesion work suggest that the MAPbBr<sub>3</sub>/BaWO<sub>4</sub> configurations possess stronger interfacial interaction than the CsPbBr<sub>3</sub>/BaWO<sub>4</sub> configurations. The formation of BaW/PbBr and BaW/MAPb configurations was more facile compared to their counterparts. The interfacial charge transfer direction, potential difference, and valence band edges of the perovskite/BaWO<sub>4</sub> heterostructures were found to be significantly influenced by the surface termination of BaWO<sub>4</sub>. The absorption intensity of the perovskite/BaWO<sub>4</sub> heterostructures is significantly affected by the surface termination of the perovskite. Finally, the CsPbBr<sub>3</sub>/BaWO<sub>4</sub> heterostructure was fabricated and characterized, thereby validating the first-principles predictions. This study provides a fundamental contribution to establishing perovskite/BaWO<sub>4</sub> heterostructures for the advancement of perovskite-based optoelectronic devices.

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## 1. Introduction

During the past decade, lead bromide perovskites in the guise of colloidal nanocrystals (NCs), such as cesium lead bromide (CsPbBr<sub>3</sub>) and methylammonium lead bromide (MAPbBr<sub>3</sub>), have been extensively explored for diverse applications, such as light-emitting diodes (LEDs) and photodetectors, owing to their distinctive photophysical characteristics including tunable band gap, high absorption coefficient, strong defect tolerance, high quantum yield, low fabrication cost, and so on.<sup>1–5</sup> Unfortunately, the excellent properties and exciting pro-

gress of lead bromide perovskite NCs are overshadowed by their limited operational lifetime under ambient conditions, which is severely hindering their real-world implementation and widespread adoption. The instability of perovskite NCs renders them vulnerable to environmental factors, which results in a series of detrimental effects, including structural alterations and phase transitions, reduced luminescence efficiency, and limited electron mobility.<sup>6–10</sup> An efficient way to enhance the stability of perovskite NCs and preserve their colloidal stability and photoluminescence is to couple them with another material to form a heterostructure.<sup>11–16</sup> Although perovskite NC heterostructures have been successfully designed to enhance their optical stability and emission intensity, their applications are still limited to a few combinations.<sup>17–22</sup> The design of perovskite NC heterostructures in combination with lattice-matched materials is still a topic that requires further investigation.

Barium tungstate (BaWO<sub>4</sub>) with a scheelite structure is known for its high ionic/electronic conductivity and high thermal/chemical stability, and has potential applications in catalysis.<sup>23–26</sup> Recently, the heterostructural growth of CsPbBr<sub>3</sub>

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and MAPbBr<sub>3</sub> NCs on a BaWO<sub>4</sub> crystal was successfully demonstrated based on lattice matching.<sup>27,28</sup> Compared to the pure perovskite, the perovskite/BaWO<sub>4</sub> heterostructures exhibited enhanced luminescence intensity and sustained stability against UV-light radiation, heat, and diverse solvents. The BaWO<sub>4</sub> crystal can effectively inhibit halogen migration in the perovskite, leading to tunable emissions with different compositions. This implies the great potential of combining barium tungstate with lead bromide perovskite in advanced anticounterfeiting and encryption applications. To date, the CsPbBr<sub>3</sub>/BaWO<sub>4</sub> and MAPbBr<sub>3</sub>/BaWO<sub>4</sub> heterostructures have been examined by experimental investigations.<sup>27,28</sup> The interfacial characteristics of these heterostructures, which are directly determined by the arrangement of atoms and their interactions, are still not fully understood. Systematic and comparative investigations of the interfacial systems are therefore of great interest.<sup>29–33</sup> In this study, we utilize the first-principles approach to explore the heterostructures of CsPbBr<sub>3</sub>/BaWO<sub>4</sub> and MAPbBr<sub>3</sub>/BaWO<sub>4</sub>. Moreover, the composition and morphological characteristics were further verified by microscopic and spectroscopic tools. The interfacial behavior and mechanism of the heterostructure were investigated by combining theoretical and experimental approaches to assess the photocatalytic potential of these newly developed heterostructures.

## 2. Computational and experimental details

The first-principles density functional theory (DFT) calculations were carried out based on projector augmented wave (PAW) formalism<sup>34</sup> within the Vienna *ab initio* simulation package (VASP, version 5.4.4).<sup>35–37</sup> The exchange correlation effect was evaluated by means of the generalized gradient approximation (GGA) of the Perdew–Burke–Ernzerhof (PBE) functional.<sup>38</sup> The kinetic plane wave energy cutoff was set to 450 eV with Gaussian smearing ( $\sigma = 0.1$  eV).<sup>39</sup> Brillouin-zone integration was done using the Monkhorst–Pack<sup>40</sup> *k*-point mesh with 0.02 Å<sup>−1</sup> separation. The vacuum layer thickness was set to 15 Å to neglect the coupling between the images. The spurious interactions between periodic images were significantly reduced by using the dipole correction in the VASP (IDIPOL = 3). The DFT-D3 with the BJ-damping method<sup>41</sup> was included to consider the van der Waals (vdW) interactions. The convergence criteria for energy and force were 10<sup>−6</sup> eV and 0.005 eV Å<sup>−1</sup>, respectively. During the geometric optimizations, the bottom layers were constrained to the bulk geometry, while the remaining layers were fully relaxed. The VESTA (Visualization for Electronic and Structural Analysis) program<sup>42</sup> was utilized to visualize the crystallographic, volumetric, and morphological data.

In this study, we adopted the cubic structure (space group *Pm*3̄*m*) for CsPbBr<sub>3</sub>, the monoclinic (space group *P*2<sub>1</sub>/*m*) structure for MAPbBr<sub>3</sub>, and the tetragonal (space group *I*4<sub>1</sub>/*a*) structure for BaWO<sub>4</sub>. The atomic structures and lattice parameters derived from first-principles simulations are provided in

Fig. S1 and Table S1,<sup>†</sup> exhibiting excellent agreement with the corresponding experimental results.<sup>43–45</sup> Following the rigorous lattice matching principle, the (200) in-plane lattice spacing in BaWO<sub>4</sub> closely matched those of CsPbBr<sub>3</sub> and MAPbBr<sub>3</sub>, serving as the foundation for constructing the perovskite/BaWO<sub>4</sub> heterostructures. The perovskite (200) slabs were constructed employing a stoichiometric six-layer slab, while the BaWO<sub>4</sub> (200) slab was generated using an eleven-layer symmetric slab. CsPbBr<sub>3</sub> (or MAPbBr<sub>3</sub>) exhibits two potential surface terminations: the termination by Cs (or MA) cations, and the termination by Pb cations. In contrast, the BaWO<sub>4</sub> slab features two distinct surface types: BaW- and O-terminated surfaces. By combining the perovskite and BaWO<sub>4</sub> slabs, we generated a total of eight lattice-matched interfacial configurations, as depicted in Fig. 1. The lattice parameters and mean absolute strain values for the eight models are presented in Table S2.<sup>†</sup>

The CsPbBr<sub>3</sub>/BaWO<sub>4</sub> heterostructure was prepared through an *in situ* synthesis thermal-assisted method. The stoichiometric proportions of Na<sub>2</sub>WO<sub>4</sub>·2H<sub>2</sub>O (1 mmol) and Ba(NO<sub>3</sub>)<sub>2</sub> (1 mmol) were dissolved in a 20 ml aqueous solution and stirred in a 50 ml beaker, immediately resulting in a white BaWO<sub>4</sub> precipitate. After centrifugation and drying, 145 mg of the precipitate was weighed and put together with PbBr<sub>2</sub> (0.8 mmol) into a three-neck flask with 20 ml of octadecene as the solvent, then heated to 120 °C with nitrogen protection; the air and water impurities in the three-neck flask were extracted. The reaction mixture was kept for 30 min, heated up to 180 °C, and immediately infused with 3 ml of Cs-OA to obtain a yellow solution, which was reacted for 10 seconds. The solution was cooled to room temperature with a cold-water bath, and the precipitates were centrifuged and washed with *n*-hexane three times, toluene twice, anhydrous ethanol once, and finally vacuum dried at 60 °C for 8 hours, to obtain the CsPbBr<sub>3</sub>/BaWO<sub>4</sub> heterostructure.

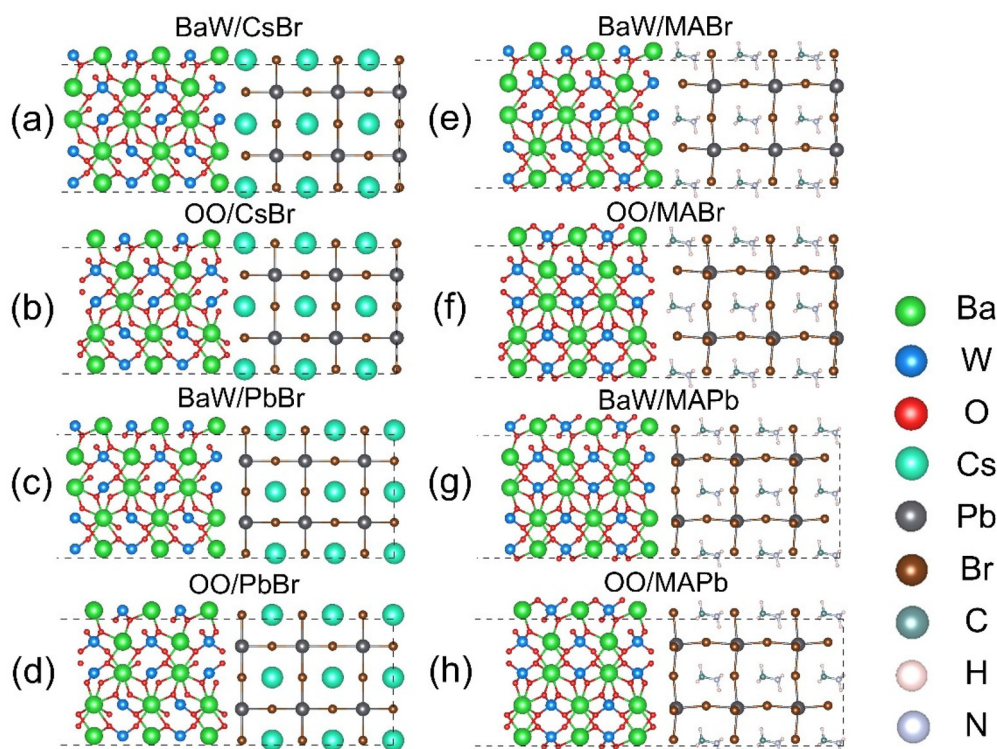
## 3. Results and discussion

### 3.1. Interfacial adhesion

The work of adhesion ( $W_{\text{ad}}$ )<sup>46–48</sup> is commonly employed to characterize the interfacial stability and bonding strength. The work of interfacial adhesion can be described as the reversible energy necessary to divide the heterostructure into two free surfaces, quantified by the following equation:

$$W_{\text{ad}} = [E_{\text{PVK}} + E_{\text{BWO}} - E_{\text{total}}]/A \quad (1)$$

where  $E_{\text{PVK}}$  and  $E_{\text{BWO}}$  correspond to the total energy of the fully relaxed perovskite and BaWO<sub>4</sub> slabs, respectively.  $E_{\text{total}}$  represents the total energy of the perovskite/BaWO<sub>4</sub> interface, while  $A$  specifies the interface area. It is widely accepted that a higher  $W_{\text{ad}}$  value corresponds to enhanced bonding strength. The calculated  $W_{\text{ad}}$  values of the CsPbBr<sub>3</sub>/BaWO<sub>4</sub> and MAPbBr<sub>3</sub>/BaWO<sub>4</sub> heterostructures are compared in Table 1. The formation of all eight observed interfacial configurations is facilitated by the positive adhesion work. The perovskite/



**Fig. 1** Schematic illustration of the perovskite/BaWO<sub>4</sub> interfaces: (a) BaW/CsBr, (b) OO/CsBr, (c) BaW/PbBr, (d) OO/PbBr, (e) BaW/MABr, (f) OO/MABr, (g) BaW/MAPb, and (h) OO/MAPb.

**Table 1** Calculated adhesion work (eV Å<sup>-2</sup>), charge transfer (e), plane-averaged electrostatic potential difference (eV) and work function (eV) of the relaxed perovskite/BaWO<sub>4</sub> interfaces

| Interface | Adhesion work | Charge transfer <sup>a</sup> | Potential difference | Work function |
|-----------|---------------|------------------------------|----------------------|---------------|
| BaW/CsBr  | 0.018         | -0.2                         | 2.0                  | 2.8           |
| OO/CsBr   | 0.024         | 2.0                          | 1.0                  | 6.7           |
| BaW/PbBr  | 0.035         | -1.5                         | 2.0                  | 2.6           |
| OO/PbBr   | 0.008         | 1.8                          | 1.0                  | 6.5           |
| BaW/MABr  | 0.036         | -0.6                         | 1.0                  | 2.8           |
| OO/MABr   | 0.014         | 0.7                          | -0.5                 | 6.7           |
| BaW/MAPb  | 0.052         | -1.4                         | 1.0                  | 2.5           |
| OO/MAPb   | 0.026         | 1.9                          | -0.5                 | 6.7           |

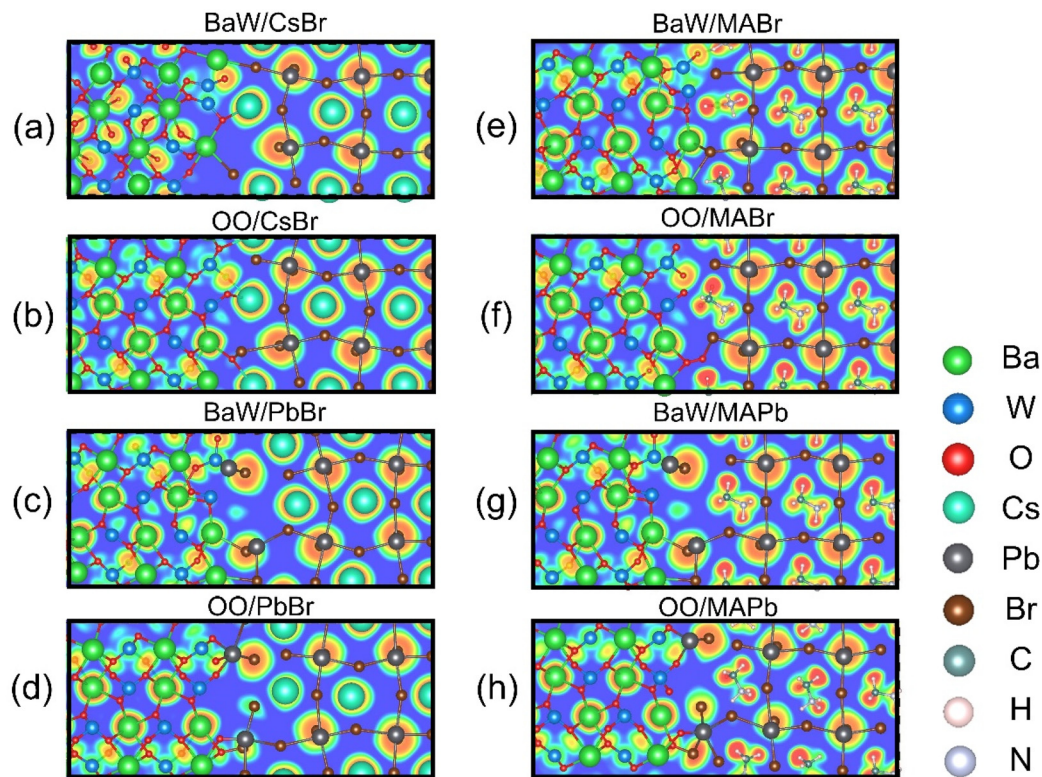
<sup>a</sup> The positive values indicate charge transfer from perovskite to BaWO<sub>4</sub>, whereas the negative values exhibit charge transfer from BaWO<sub>4</sub> to perovskite.

BaWO<sub>4</sub> interface exhibits larger  $W_{ad}$  values when compared to the weak perovskite/MXene system,<sup>30</sup> while exhibiting equivalent  $W_{ad}$  values to the strong perovskite/Ga<sub>2</sub>O<sub>3</sub> system,<sup>31</sup> thereby suggesting a high degree of interface stability. Among them, the MAPbBr<sub>3</sub>/BaWO<sub>4</sub> interface exhibits larger  $W_{ad}$  values, ranging from 0.014 to 0.052 eV Å<sup>-2</sup>, when compared to those of the CsPbBr<sub>3</sub>/BaWO<sub>4</sub> interface, which span from 0.008 to 0.035 eV Å<sup>-2</sup>. This comparison further suggests that the MAPbBr<sub>3</sub>/BaWO<sub>4</sub> structure possesses a relatively higher degree of stability. The comprehensive investigations indicate that the  $W_{ad}$  values at the interfaces between BaW- and Pb-termin-

ations are higher compared to the other three interfaces, regardless of CsPbBr<sub>3</sub>/BaWO<sub>4</sub> and MAPbBr<sub>3</sub>/BaWO<sub>4</sub>. Therefore, the formation of BaW/PbBr and BaW/MAPb interfaces was more facile compared to their counterparts in experiments. The stability of the interface correlates with the extent of atomic rearrangement.

To clarify the bonding mechanism in the perovskite/BaWO<sub>4</sub> heterostructures, the electron localization function (ELF),<sup>49</sup> as well as the atomic structures of CsPbBr<sub>3</sub>/BaWO<sub>4</sub> and MAPbBr<sub>3</sub>/BaWO<sub>4</sub> systems, was analyzed, as shown in Fig. 2. In the colorimetric representation of electron localization, red is used to represent electrons with a high degree of localization, while blue is used to represent electrons with a high degree of delocalization. Localization and delocalization represent the spatial distribution patterns of electrons within the system. Localization signifies the concentration of electron density in specific regions, whereas delocalization denotes the free movement of electrons throughout the system, indicating enhanced electron mobility. The nearly spherical electron distribution indicates the strong ionic bonding character between Pb and Br atoms. In contrast, the BaWO<sub>4</sub> side exhibits the covalent bonding for the WO<sub>4</sub> anions and the ionic bonding character for the Ba cations. The MAPbBr<sub>3</sub>/BaWO<sub>4</sub> configurations with less blue area in the interface region indicate stronger interfacial interaction than the CsPbBr<sub>3</sub>/BaWO<sub>4</sub> configurations. Upon closer inspection of the interface region, noticeable distortions of the Pb-Br<sub>6</sub> octahedra in the cubic structure can be observed.<sup>50</sup> These distortions are attributed to the strong inter-





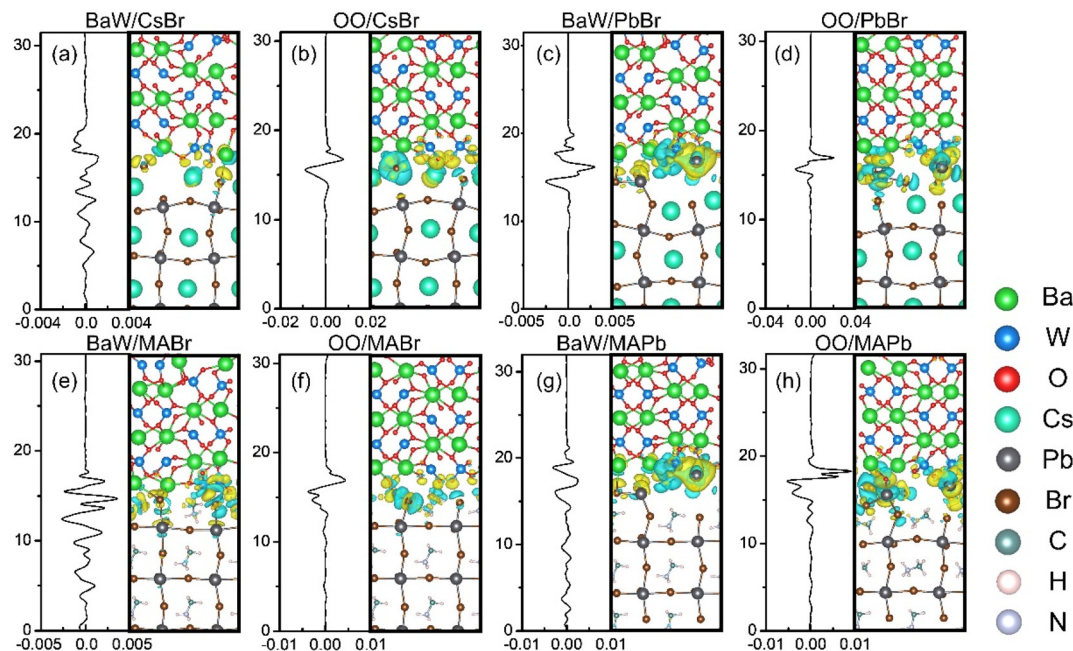
**Fig. 2** ELF of the relaxed perovskite/BaWO<sub>4</sub> interfaces: (a) BaW/CsBr, (b) OO/CsBr, (c) BaW/PbBr, (d) OO/PbBr, (e) BaW/MABr, (f) OO/MABr, (g) BaW/MAPb, and (h) OO/MAPb.

actions between BaWO<sub>4</sub> and perovskite. Moreover, the CsPbBr<sub>3</sub>/BaWO<sub>4</sub> configurations undergo more significant distortions compared to the MAPbBr<sub>3</sub>/BaWO<sub>4</sub> configurations. Among the various terminations, the BaW/PbBr and BaW/MAPb configurations with the highest  $W_{ad}$  values demonstrate more significant distortions compared to their counterparts, which is coincident with the results in Table 1. To provide a quantitative measure of charge transfer between perovskite and BaWO<sub>4</sub>, we conducted Bader charge analysis<sup>51</sup> on representative atoms. The values of calculated charge transfer are presented in Table 1. The charge transfer direction is significantly influenced by the surface termination, irrespective of the CsPbBr<sub>3</sub>/BaWO<sub>4</sub> or MAPbBr<sub>3</sub>/BaWO<sub>4</sub> systems. Specifically, the BaW/perovskite (BaW/CsBr, BaW/PbBr, BaW/MABr, and BaW/MAPb) configurations exhibit electron transfer from BaWO<sub>4</sub> to the perovskite layer, whereas the OO/perovskite (OO/CsBr, OO/PbBr, OO/MABr, and OO/MAPb) configurations indicate charge transfer from the perovskite to the BaWO<sub>4</sub> layer. The above results can be attributed to the interfacial bonding between perovskite and BaWO<sub>4</sub>.

### 3.2. Electronic structures

To thoroughly elucidate the intricate characteristics of interface coupling and charge redistribution within the perovskite/BaWO<sub>4</sub> heterostructures, we explored the z-axis dependence of the three-dimensional and plane-averaged charge density difference ( $\Delta\rho$ ).<sup>52</sup> The yellow-colored segment signifies charge

accumulation, whereas the cyan-colored segment denotes charge depletion. Fig. 3 suggests that the interface region is the primary site for charge transfer and redistribution. The magnitude of the charge distribution at the interface is significantly influenced by the strength of the interfacial interaction. The BaW/PbBr and BaW/MAPb configurations exhibit denser electron isosurfaces compared to the other configurations, consistent with their highest  $W_{ad}$  values listed in Table 1. The plane-averaged charge density difference curves obtained from isosurfaces exhibit distinct trends depending on various surface terminations. The curves of the OO/perovskite (OO/CsBr, OO/PbBr, OO/MABr, and OO/MAPb) configurations exhibit a similar pattern, with electron accumulation on the BaWO<sub>4</sub> side and depletion on the perovskite side, indicating a distinct contrast at the interface. In contrast, the curves of BaW/perovskite (BaW/CsBr, BaW/PbBr, BaW/MABr, and BaW/MAPb) configurations display an irregular distribution, signifying complex charge redistribution at the interface regions. The above results are entirely consistent with the direction of charge transfer presented in Table 1. The OO/perovskite configurations are bonded with the Cs–O and Pb–O bonds. Such configurations under O-rich conditions contain more interfacial bonds and exhibit distinct charge redistributions at the interface. The accumulation of various carriers at the interfaces on both ends of the heterointerface leads to the formation of a built-in electric field, which is directed from the hole accumulation region to the electron accumulation area.<sup>53</sup>

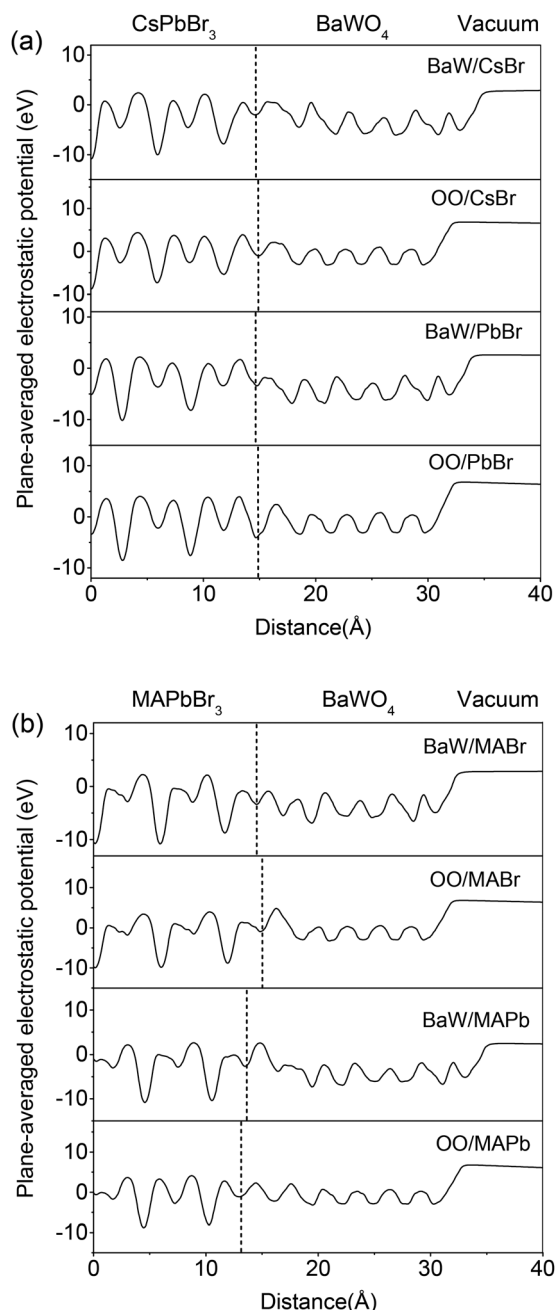


**Fig. 3** Plane-averaged electron density difference  $\Delta\rho(z)$  and 3D charge density difference ( $0.002 \text{ e } \text{\AA}^{-3}$ ) of the relaxed perovskite/ $\text{BaWO}_4$  interfaces: (a) BaW/CsBr, (b) OO/CsBr, (c) BaW/PbBr, (d) OO/PbBr, (e) BaW/MABr, (f) OO/CsBr, (g) BaW/MAPb, and (h) OO/MAPb.

To offer a comprehensive assessment of electronic transport behavior at the perovskite/ $\text{BaWO}_4$  heterostructures, the plane-averaged electrostatic potentials in the vertical direction were analyzed and are plotted in Fig. 4. The band alignment and the work function of the perovskite/ $\text{BaWO}_4$  heterostructures can be estimated *via* the electrostatic potentials.<sup>54</sup> Evaluation of the potential offset and work function of the heterostructures is based on the theoretical framework of the plane-averaged electrostatic potentials. When two distinct surfaces come into contact and create heterostructures, the disparity in Fermi energy leads to electron transport at the heterointerface, resulting in band offsets. As shown in Fig. 4, a notable contrast exists in the atomic arrangements of perovskite and  $\text{BaWO}_4$ , with atoms near the interface undergoing substantial migration toward their final stable state, ultimately leading to a macroscopic discrepancy in the plane-averaged electrostatic potentials. The plane-averaged electrostatic potential difference ( $\Delta V$ ) between the perovskite and  $\text{BaWO}_4$  was estimated and is summarized in Table 1. The positive value indicates that the plane-averaged potentials of the  $\text{BaWO}_4$  side are higher than those at the perovskite side. The potential offset, influenced by the atomic configurations near the interface, plays a crucial role in shaping the electronic barrier and ultimately affects the device performance.<sup>55</sup> The BaW/perovskite configurations display greater  $\Delta V$  compared to the OO/perovskite configurations, irrespective of whether  $\text{CsPbBr}_3$  or  $\text{MAPbBr}_3$  is involved. Simultaneously, the  $\text{CsPbBr}_3/\text{BaWO}_4$  configurations show a larger  $\Delta V$  compared to the  $\text{MAPbBr}_3/\text{BaWO}_4$  configurations. In particular, for the OO/MABr and OO/MAPb configurations, negative  $\Delta V$  values are observed, indicating a reversal in the potential offset. The work function signifies the

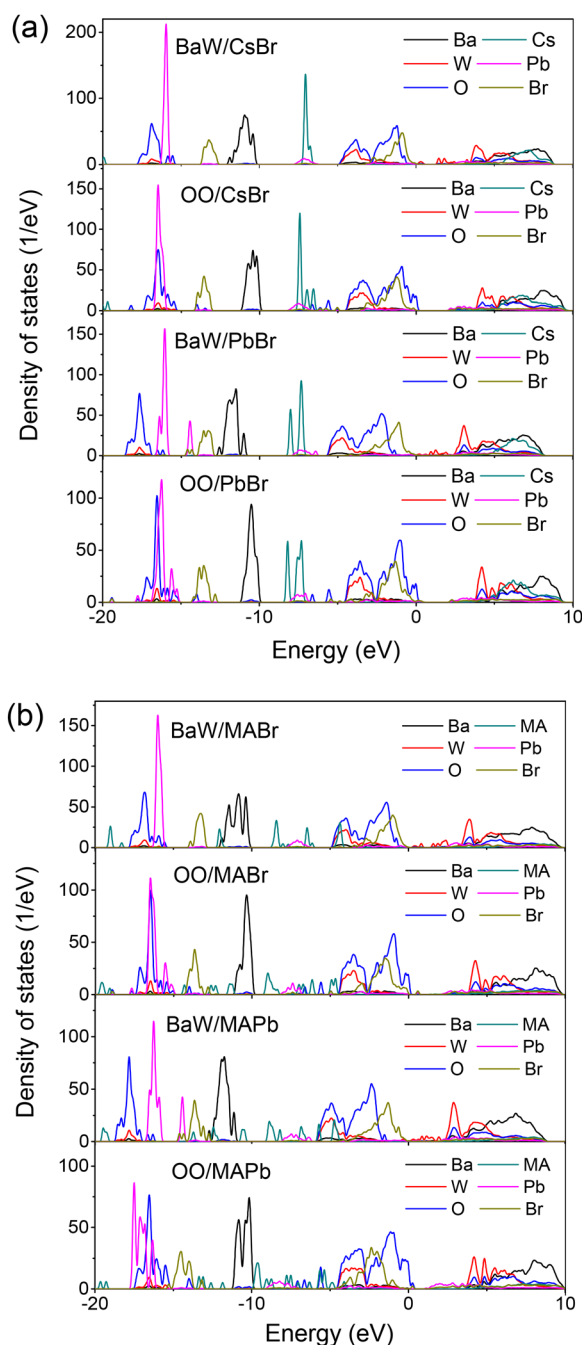
minimum energy needed to extract electrons from the Fermi level to reach the vacuum level. Table 1 details the work functions of the corresponding perovskite/ $\text{BaWO}_4$  heterostructures. Importantly, the work functions of the OO/perovskite configurations undergo substantial modulation towards higher values, presenting a stark contrast to the work function observed in the BaW/perovskite configurations. The results of potential differences and work function measurements exhibit a high degree of consistency with the charge transfer data outlined in Table 1. The considerably altered work function indicates that surface engineering holds promise as an effective approach for achieving ohmic contact of n- and p-type.

The density of states (DOS) provides a quantitative description of the electronic states in different orbitals, which is essential for a comprehensive understanding of the interfacial bonding mechanism. For a more in-depth exploration of the perovskite/ $\text{BaWO}_4$  heterostructures, we calculated and depicted the atom-projected DOS in Fig. 5. More details of the calculated DOS for  $\text{CsPbBr}_3$ ,  $\text{MAPbBr}_3$ , and  $\text{BaWO}_4$  in the bulk phase are plotted in Fig. S2.† As a member of the scheelite family,  $\text{BaWO}_4$  has a larger band gap compared to  $\text{CsPbBr}_3$  (or  $\text{MAPbBr}_3$ ).<sup>56</sup> The calculated DOS of the perovskite/ $\text{BaWO}_4$  heterostructures shows that the top of the valence band is entirely composed of O 2p and Br 4p orbitals while the bottom of the conduction band is dominated by the W 5d orbitals. The formation of the perovskite/ $\text{BaWO}_4$  heterointerface is a consequence of the hybridization of Br 4p and W 5d states. The eight different interfacial configurations exhibit similar DOS features. The OO/perovskite configurations are identified as belonging to a type-II heterostructure, with the conduction band minimum (CBM) contributed by the perovskite and the



**Fig. 4** Plane-averaged electrostatic potential of the relaxed perovskite/ $\text{BaWO}_4$  interfaces: (a)  $\text{CsPbBr}_3/\text{BaWO}_4$  and (b)  $\text{MAPbBr}_3/\text{BaWO}_4$ .

valence band maximum (VBM) contributed by  $\text{BaWO}_4$ . A close examination of the top of the valence band reveals that the O 2p and peaks move toward the lower energy region for the BaW/perovskite configurations. In particular, the BaW/PbBr and BaW/MAPb configurations exhibit the largest peak shift,<sup>57</sup> suggesting enhanced binding energy between the two materials at the interface. The observation of interfacial defect states across the band gap of the BaW/perovskite configurations also suggests that hybridization is enhanced at the interface. Hence, the typical type-II band alignment observed in the OO/perovskite config-



**Fig. 5** DOS of the relaxed perovskite/ $\text{BaWO}_4$  interfaces: (a)  $\text{CsPbBr}_3/\text{BaWO}_4$  and (b)  $\text{MAPbBr}_3/\text{BaWO}_4$ .

urations was transformed into the typical type-I band alignment in the BaW/perovskite configurations. This is consistent with the results of charge transfer, potential difference and work function as outlined in Table 1. The findings imply that the electronic structures of the perovskite/ $\text{BaWO}_4$  heterostructures are dependent on the surface termination of  $\text{BaWO}_4$ , not that of perovskite. The surface termination of  $\text{BaWO}_4$  has crucial potential significance in the transformation of a type-I heterostructure to a type-II heterostructure.



### 3.3. Optical properties

The light absorption coefficient of the perovskite/BaWO<sub>4</sub> heterostructures is a key parameter for evaluating their optical response to sunlight. The absorption spectra of the CsPbBr<sub>3</sub>/BaWO<sub>4</sub> and MAPbBr<sub>3</sub>/BaWO<sub>4</sub> heterostructures are calculated and displayed as in Fig. 6. For comparison, the light absorption spectra of CsPbBr<sub>3</sub>, MAPbBr<sub>3</sub>, and BaWO<sub>4</sub> in the bulk phase were calculated, which are shown in Fig. S3.† The shapes of the absorption curves of CsPbBr<sub>3</sub>/BaWO<sub>4</sub> and MAPbBr<sub>3</sub>/BaWO<sub>4</sub> heterostructures are quite similar. The optical absorption spectrum of the heterostructures shows three distinct peaks at 3.5, 5.5, and 9.5 eV. The first peak at 3.5 eV is primarily due to the transition from Br 4p to Pb 6p states between the conduction and valence bands.<sup>58</sup> The second peak around 5.5 eV is attributed to the optical transition from O 2p orbitals to W 5d orbitals. The third peak around 9.5 eV originates from the transition from hybridized W 5d and O 2p states to W 5d states.<sup>59</sup> A close inspection of the absorption spectra reveals that the absorption intensity of the perovskite exhibits a similar trend for both CsPbBr<sub>3</sub>/BaWO<sub>4</sub> (BaW/CsBr > OO/CsBr > BaW/PbBr > OO/PbBr) and MAPbBr<sub>3</sub>/BaWO<sub>4</sub> (BaW/MABr > OO/MABr > BaW/PbBr > OO/PbBr). The BaW/CsBr heterostructure (or BaW/MABr) exhibits the lowest interfacial distortion and remarkably well-preserved perovskite-type struc-

tures, leading to a significantly higher absorption coefficient. These results suggest that the optical properties of the perovskite/BaWO<sub>4</sub> heterostructures are significantly affected by the surface termination of the perovskite layers, but not the BaWO<sub>4</sub> layers. To improve the device performance through interface modification, focusing on the perovskite layer should be a promising strategy.

### 3.4. Experimental verification

The CsPbBr<sub>3</sub>/BaWO<sub>4</sub> heterostructure was successfully fabricated to further verify the first-principles predictions. The X-ray diffraction (XRD) patterns of CsPbBr<sub>3</sub>, BaWO<sub>4</sub>, and CsPbBr<sub>3</sub>/BaWO<sub>4</sub> are displayed in Fig. 7. The XRD pattern showed diffraction peaks at 2θ values of 15.1°, 21.3°, 30.6°, 37.7°, and 43.6° corresponding to the (100), (110), (200), (211), and (220) phases of the typical cubic CsPbBr<sub>3</sub>, respectively.<sup>60,61</sup> In addition, the diffraction peaks at 17.3°, 27.9°, 31.7°, 42.8°, 45.6°, and 53.5° are attributed to the (101), (112), (200), (204), (220), and (312) phases of the tetragonal BaWO<sub>4</sub>, respectively.<sup>62</sup> All diffraction peaks are consistent with the crystalline phase of CsPbBr<sub>3</sub> (JCPDS No. 18-0364) and BaWO<sub>4</sub> (JCPDS No. 43-0646). The results showed that CsPbBr<sub>3</sub> and BaWO<sub>4</sub> exhibited high crystallinity with well-maintained cubic perovskite and

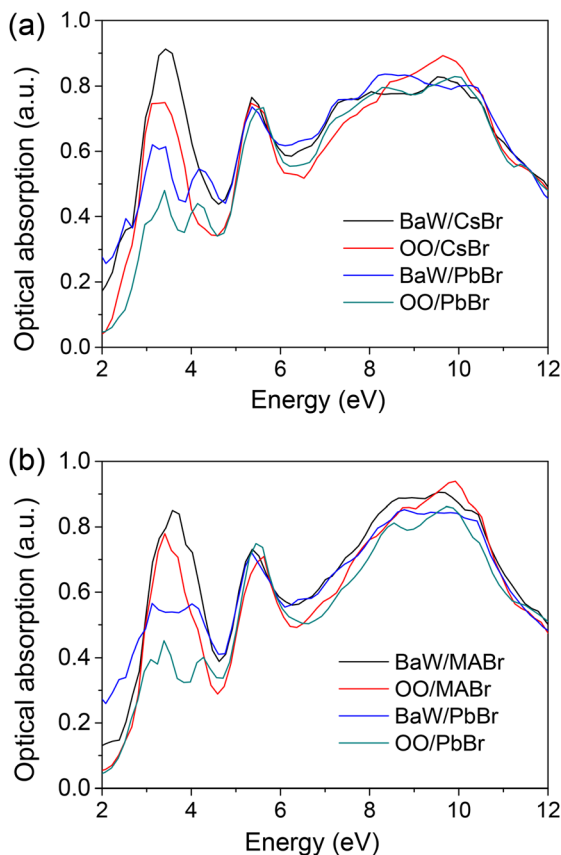


Fig. 6 Absorption coefficients of the relaxed perovskite/BaWO<sub>4</sub> interfaces: (a) CsPbBr<sub>3</sub>/BaWO<sub>4</sub> and (b) MAPbBr<sub>3</sub>/BaWO<sub>4</sub>.

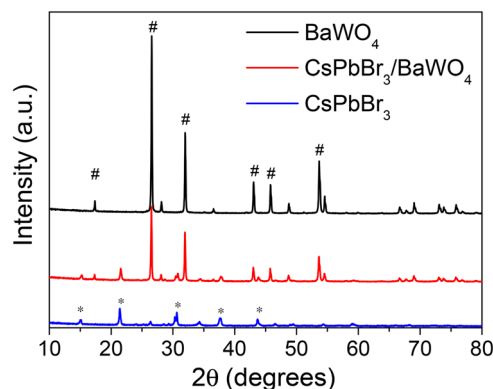


Fig. 7 Experimental XRD patterns of CsPbBr<sub>3</sub>, BaWO<sub>4</sub>, and CsPbBr<sub>3</sub>/BaWO<sub>4</sub>.

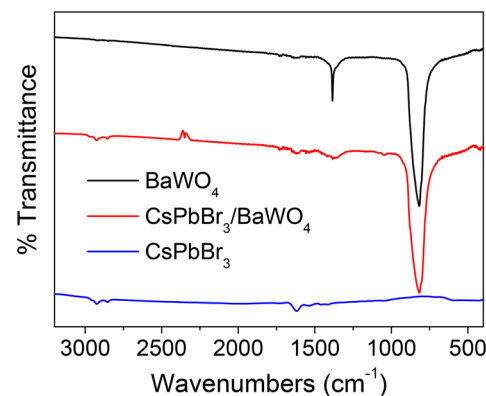


Fig. 8 FT-IR patterns of CsPbBr<sub>3</sub>, BaWO<sub>4</sub>, and CsPbBr<sub>3</sub>/BaWO<sub>4</sub>.

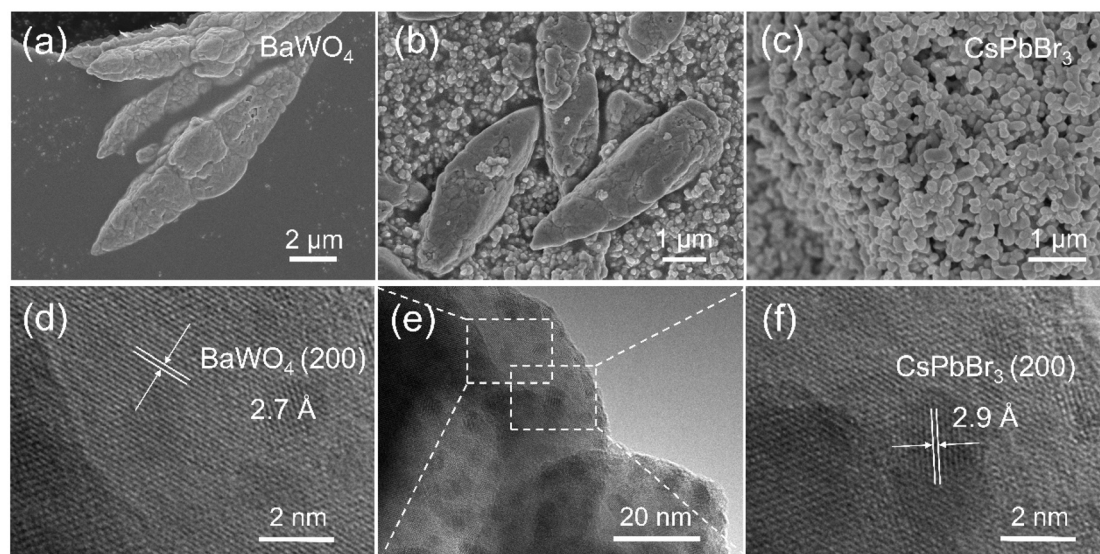


Fig. 9 SEM images of (a) BaWO<sub>4</sub>, (b) CsPbBr<sub>3</sub>/BaWO<sub>4</sub>, and (c) CsPbBr<sub>3</sub>; TEM images of (d) BaWO<sub>4</sub>, (e) CsPbBr<sub>3</sub>/BaWO<sub>4</sub>, and (f) CsPbBr<sub>3</sub>.

tetragonal scheelite crystal phases during the formation of the CsPbBr<sub>3</sub>/BaWO<sub>4</sub> heterostructures.

To evaluate the chemical bond formation and interactions, FT-IR spectral analysis of CsPbBr<sub>3</sub>, BaWO<sub>4</sub>, and CsPbBr<sub>3</sub>/BaWO<sub>4</sub> was performed and the results are displayed in Fig. 8. The spectrum of BaWO<sub>4</sub> reveals a vibrational mode at 820 cm<sup>-1</sup>, associated with asymmetric W–O vibrations, thereby confirming the presence of the typical WO<sub>4</sub> in the prepared BaWO<sub>4</sub> material.<sup>63,64</sup> The additional absorption peak of BaWO<sub>4</sub> around 1400 cm<sup>-1</sup> may be attributed to the stretching vibrations of the organic groups present in the precursor. Two small peaks are recognized around 1600 and 2900 cm<sup>-1</sup> in the spectrum of CsPbBr<sub>3</sub>. The peak at 1600 cm<sup>-1</sup> can be assigned to the N–H bending vibrations of the ligands, whereas the peak at 2900 cm<sup>-1</sup> is associated with the oleyl group.<sup>65</sup> The FT-IR analysis confirms the formation of the CsPbBr<sub>3</sub>/BaWO<sub>4</sub> heterostructures.

The structural features of the prepared CsPbBr<sub>3</sub>/BaWO<sub>4</sub> heterostructures were carefully identified by scanning electron microscopy (SEM) and transmission electron microscopy (TEM), as demonstrated in Fig. 9. The TEM images clearly depict the CsPbBr<sub>3</sub> and BaWO<sub>4</sub> materials. Specifically, the analysis indicates that the interplanar spacings of 2.9 Å correspond to the CsPbBr<sub>3</sub> (200) plane,<sup>66</sup> whereas the interplanar spacings of 2.7 Å correspond to the BaWO<sub>4</sub> (200) plane,<sup>67</sup> respectively. The confirmation of lattice-matched growth between CsPbBr<sub>3</sub> and BaWO<sub>4</sub> is intricately validated through TEM observations, closely aligning with the predictions derived from first-principles calculations.

## 4. Conclusions

To summarize, first-principles and experimental studies were employed to investigate the interfacial properties between per-

ovskite and BaWO<sub>4</sub>. The interfacial properties include atomic arrangement, adhesion work, charge redistribution, potential difference, work function, and their orbital hybridization, as well as their optical absorption. The results indicate that the MAPbBr<sub>3</sub>/BaWO<sub>4</sub> configurations possess stronger interfacial interaction than the CsPbBr<sub>3</sub>/BaWO<sub>4</sub> configurations. The formation of BaW/PbBr and BaW/MAPb configurations was more facile compared to their counterparts. Our study highlights the importance of surface termination for the interfacial properties. The interfacial charge transfer direction, potential difference, and band alignment of the perovskite/BaWO<sub>4</sub> heterostructures were found to be significantly influenced by the surface termination of BaWO<sub>4</sub>. The absorption intensity of the perovskite/BaWO<sub>4</sub> heterostructures is significantly affected by the surface termination of the perovskite. The lattice-matching growth of CsPbBr<sub>3</sub>/BaWO<sub>4</sub> was achieved and the existence of the heterostructure was confirmed by XRD, SEM, and TEM characterization. This study helps us to gain better insight into the nature of the perovskite/BaWO<sub>4</sub> heterostructures, thereby laying the groundwork for the realization of high-performance perovskite-based devices.

## Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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