Indirect-to-direct band gap transition and optical properties of metal alloys of Cs$_2$Te$_{1-x}$Ti$_x$I$_6$: a theoretical study

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In recent years, double perovskites have attracted considerable attention as potential candidates for photovoltaic applications. However, most double perovskites are not suitable for single-junction solar cells due to their large band gaps (over 2.0 eV). In the present study, we have investigated the structural, mechanical, electronic and optical properties of the Cs$_2$Te$_{1-x}$Ti$_x$I$_6$ solid solutions using first-principles calculations based on density functional theory. These compounds exhibit good structural stability compared to CH$_3$NH$_3$PbI$_3$. The results suggest that Cs$_2$TeI$_6$ is an indirect band gap semiconductor, and it can become a direct band gap semiconductor with the value of 1.09 eV when the doping concentration of Ti$^{4+}$ is 0.50. Moreover, an ideal direct band gap of 1.31 eV is obtained for Cs$_2$Te$_{0.75}$Ti$_{0.25}$I$_6$. The calculated results indicate that all the structures are ductile materials except for Cs$_2$Te$_{0.50}$Ti$_{0.50}$I$_6$. Our results also show that these materials possess large absorption coefficients in the visible light region. Our work can provide a route to explore stable, environmentally friendly and high-efficiency light absorbers for use in optoelectronic applications.

1. Introduction

Lead-based halide perovskites have attracted great attention for optoelectronic applications in the past ten years.$^{1-5}$ The power conversion efficiency (PCE) of lead-based halide perovskite solar cells increased to a high value of 25.2% in 2019.$^4$ However, the toxicity of lead and poor stability still remain significant challenges for commercial applications. Extensive efforts have been paid to exploring lead-free or lead-less and stable halide perovskite materials for solar cells. Sn$^{2+}$ and Ge$^{2+}$ metal ions have been expected to replace Pb$^{2+}$ ions in perovskites.$^9$-$^{10}$ Sn$^{2+}$ ion is highly unstable and can be easily oxidized to Sn$^{4+}$, in which results in decreased photovoltaic performance. To date, the highest PCE of Ge-based halide perovskites is only 4.94%.$^{11}$ Two dimensional (2D) layered perovskites have been also explored such as A$_2$B$_2$X$_6$ (A = Cs, Rb; B = Bi, Sb; X = I, Br, Cl).$^{12-17}$ However, these materials have large band gaps over 2.0 eV, which are not suitable for perovskite solar cells.

In recent years, halide double perovskites A$_2$B$^+$B$^{3+}$X$_6$ have been developed as stable and non-toxic alternatives to lead-based perovskite materials, where two toxic lead ions are substituted by using monovalent B$^+$ and trivalent B$^{3+}$, such as Ag$^+$, Bi$^{3+}$, and Sb$^{3+}$. Although most of the reported double perovskites show excellent stability, their band gaps are too large for application in single-junction solar cells.$^{18-21}$ A low band gap (1.66 eV) of double perovskites Cs$_3$NaBiI$_6$ has been synthesized, which possesses excellent stability and strong light absorption performance.$^{22}$ However, its PCE is only 0.42%, which is much lower than those of lead-based hybrid perovskites.

The vacancy-ordered double perovskites with formula of A$_2$BX$_6$ can be regarded as a derivative structure of the traditional ABX$_3$, where two toxic lead ions are substituted by one tetravalent ion to keep charge conservation as the conventional perovskites. Cs$_3$SnI$_6$ is one of the most representative perovskite materials, which belongs to a cubic structure with space group Fm3m.$^{23}$ The previous study classified Cs$_3$SnI$_6$ as zero dimensional (0D) structure.$^{24}$ However, this compound still maintains three dimensional (3D) structure and presents 3D materials' properties, so it is still considered as 3D material.$^{25}$ Cs$_3$SnI$_6$ exhibits air and moisture stability, and strong visible light absorption, which are advantageous properties for photovoltaic applications.$^{26,27}$ The first tested solar cell using Cs$_3$SnI$_6$ as absorber material in air showed a small PCE of 0.96%.$^{28}$ Meanwhile, MA$_3$SnI$_6$ was found to have a direct band gap of 1.81 eV with a strong absorption coefficient of $\sim 7 \times 10^4$ cm$^{-1}$.$^{28}$
The material properties of Cs$_2$Sn$_{1-x}$Te$_x$I$_6$ were investigated to explore structure–property relationships with potential applications in photovoltaics. In 2017, a promising family of all-inorganic based-Ti double perovskites were predicted to possess suitable band gaps, excellent optical absorption, and high stability. In particular, the band gap of Cs$_2$TiI$_6$ is $1.8$ eV can be tuned from $1.38$ to $1.78$ eV for single-junction and tandem solar cells. A comprehensive and systematic study of halide perovskites has been performed by using density functional theory (DFT) calculations. The theoretical study on the material properties of Cs$_2$TiX$_6$ ($X = I, Br$) has been investigated. The PCE of $3.28\%$ can be obtained for Cs$_2$TiBr$_6$ when it is incorporated into planar-heterojunction PSCs. In 2018, Zhou et al. synthesized lead-free all-inorganic Cs$_2$PdBr$_6$ perovskite nanocrystals with a narrow band gap ($1.69$ eV) for the first time. A series of lead-free Te-based double perovskites A$_2$TeX$_6$ ($A = MA, FA, or BA; X = Br$ or I; $MA = CH$_3$NH$_3; FA = CH(NH$_2$)$_2; BA = benzylamine$) were reported to be potential materials for optoelectronic devices. These Te-based double perovskites exhibited a tunable band gap, a low trap density, and a high mobility. Recently, the structural stability and electronic and optical properties of Te-based double perovskite materials were investigated by using first-principles calculations. Therefore, the design of new non-/low-toxic stable halide perovskites for solar cells is inevitable.

In this work, the structural stability, mechanical properties, electronic and optical properties of double perovskites Cs$_2$Te$_{1-x}$Ti$_x$I$_6$ were investigated for the first time. The results show that Cs$_2$Te$_{0.50}$Ti$_{0.50}$I$_6$ has excellent stability, suitable direct band gap, and strong optical absorption, which is a promising candidate material for optoelectronic device. The mechanical properties of these materials are discussed in detail, and the results indicate that they are ductile materials except for Cs$_2$Te$_{0.50}$Ti$_{0.50}$I$_6$.

2. Computational details

First-principles calculations were performed by using Vienna ab initio simulation package (VASP). The interaction between the core and valence electrons was described by the projector-augmented wave (PAW) method. The generalized gradient approximation (GGA) of Perdew–Burke–Ernzerhof (PBE) was employed to describe the exchange–correlation functional. A plane-wave energy cutoff of $500$ eV was used. A $4 \times 4 \times 4$ $k$-point grid was adopted for geometric optimization until the convergence criteria of energy and forces were set to be $10^{-5}$ eV and $0.01$ eV Å$^{-1}$, respectively. The structures were fully relaxed without any constraints. A denser $8 \times 8 \times 8$ $k$-point grid was employed for electronic and optical properties calculations. Four $k$-points $X (0.5, 0, 0)$, $R (0.5, 0.5, 0.5)$, $M (0.5, 0.5, 0)$, and $G (0, 0, 0)$ were selected for the bandgap calculations. In order to gain accurate lattice parameters of the studied systems, the van der Waals (vdW) interactions were adopted within vdw-DFT in all calculations. For Cs$_2$TiI$_6$, considering the underestimation of the band gap in the standard DFT calculation, we used the DFT+$U$ method to obtain accurate electronic structure. Various values of $U$ have been tested for Ti 3d orbitals of Cs$_2$TiI$_6$. $U = 2$ eV was finally chosen for the electronic and optical calculations for the Cs$_2$Te$_{1-x}$Ti$_x$I$_6$ solid solutions.

3. Results and discussion

3.1 Structure properties

The crystal structures of both Cs$_2$TeI$_6$ and Cs$_2$TiI$_6$ belong to the cubic phase with space group $Fm3m$. The calculated lattice constant of Cs$_2$TeI$_6$ is $11.66$ Å, which is in good agreement with experimental value (11.71 Å). The corresponding lattice constant of Cs$_2$TiI$_6$ is predicted to be $11.38$ Å, which is much lower than its experimental value (11.67 Å). The ion radii of Te$^{4+}$ and Ti$^{4+}$ are $0.97$ Å and $0.61$ Å, respectively. Interestingly, the experimental lattice constants of Cs$_2$TeI$_6$ and Cs$_2$TiI$_6$ are almost the same. It should be noted that the lattice parameter of Cs$_2$TiI$_6$ is estimated to be $11.67$ Å according to the experimental XRD results. The optimized structures of the Cs$_2$Te$_{1-x}$Ti$_x$I$_6$ solid solutions are depicted in Fig. 1. $x$ is the concentration of Ti$^{4+}$. The $x$ values of $0.00, 0.25, 0.50, 0.75, and 1.00$ are adopted in this study. For the species with $x = 0.25, 0.50,$ and $0.75$, all the possible arrangements are considered in this work. The results show that different structures with the same doping percentage
have the same stability, with calculated energy differences within less than 2 meV. The lattice constant of Cs$_2$Te$_{1-x}$Ti$_x$I$_6$ decreases gradually when the concentration of Ti$^{4+}$, as shown in Fig. 2. Moreover, the bond length Te–I (2.96 Å) of Cs$_2$TeI$_6$ is larger than the bond length Ti–I (2.76 Å) of Cs$_2$TiI$_6$.

The tolerance factor ($t$) has been widely used to predict the structural stability of perovskite material. The formula is defined as follows:

$$t = \frac{R_A + R_X}{\sqrt{2(R_B + R_X)}}$$  \hspace{1cm} (1)

where $R_A$, $R_B$, and $R_X$ are the effective ionic radii for A, B, and X, respectively. In general, the perovskite structure is stable when the $t$ value is in the range of 0.81–1.11.\textsuperscript{44} Our calculated values of $t$ are 0.86 and 0.97 for Cs$_2$TeI$_6$ and Cs$_2$TiI$_6$, respectively. These results confirm that the substitution of Ti$^{4+}$ for Te$^{4+}$ in Cs$_2$TeI$_6$ is feasible. To further assess the thermodynamic stability of the Cs$_2$Te$_{1-x}$Ti$_x$I$_6$ solid solutions, we have calculated their formation energies. The formation energy can be obtained according to the following equation:

$$\Delta H = \Delta E(Cs_2Te_{1-x}Ti_xI_6) - 2\Delta E(CsI) - (1-x)\Delta E(TeI_4) - x\Delta E(TiI_4)$$  \hspace{1cm} (2)

where $\Delta E(Cs_2Te_{1-x}Ti_xI_6)$, $\Delta E(CsI)$, $\Delta E(TeI_4)$, and $\Delta E(TiI_4)$ are the total energy of Cs$_2$Te$_{1-x}$Ti$_x$I$_6$, CsI, TeI$_4$, and TiI$_4$, respectively. The calculated formation energies of the Cs$_2$Te$_{1-x}$Ti$_x$I$_6$ solid solutions are demonstrated in Fig. 3. Our calculated result shows that the $\Delta H$ value of MAPbI$_3$ is 0.01 eV per f.u., which is in good agreement with the previous reported data.\textsuperscript{46} These results indicate that MAPbI$_3$ is marginally stable. It can be seen that all the compounds exhibit good stability with larger negative $\Delta H$ values compared to MAPbI$_3$. Moreover, it is observed that the structural stability of Cs$_2$Te$_{1-x}$Ti$_x$I$_6$ decreases gradually with the increasing concentration of Ti$^{4+}$. In addition, the phonon spectrum of the mixed-metal double perovskites are also studied. As shown in Fig. 4, it can be seen that none of the imaginary phonon mode exists for Cs$_2$Te$_{0.75}$Ti$_{0.25}$I$_6$ and Cs$_2$Te$_{0.25}$Ti$_{0.75}$I$_6$, which indicate that they are kinetically stable. Interestingly, Cs$_2$Te$_{0.50}$Ti$_{0.50}$I$_6$ has very small imaginary frequencies. According to the previous study,\textsuperscript{47} all small imaginary frequencies will disappear when it is at room temperature. Therefore, Cs$_2$Te$_{0.50}$Ti$_{0.50}$I$_6$ is considered to be a stable structure at room temperature.

3.2 Mechanical properties

To predict the mechanical stability of double perovskite Cs$_2$Te$_{1-x}$Ti$_x$I$_6$, the corresponding elastic constants were calculated.
using the finite strain theory.\textsuperscript{48} For cubic structure, the Born stability criteria is given as follows:\textsuperscript{49}

\[ C_{11} - C_{12} > 0, \quad C_{11} + 2C_{12} > 120, \quad C_{44} > 0 \]  

(3)

The calculated results of three independent elastic constants are listed in Table 1. All the compounds satisfy the above Born stability criteria, indicating that they are mechanical stable. The bulk modulus \((B)\) and shear modulus \((G)\) can be obtained by using Hill approximations.\textsuperscript{50} The Young’s modulus \((E)\) and Poisson ratio \((\nu)\) can be calculated from the values of bulk modulus and shear modulus by applying the following formula:\textsuperscript{51}

\[ E = \frac{9BG(3B + G)}{3B - 2G}(6B + 2G) \]  

(4)

In order to investigate the ductility and brittleness of the studied double perovskites, we calculated the Pugh’s and Poisson ratios. The Pugh’s ratio is the ratio between bulk modulus and shear modulus \((B/G)\), which is proposed by Pugh.\textsuperscript{52} The material is considered as ductile when the value of Pugh’s ratio is larger than 1.75, otherwise it is brittle. The Poisson’s ratio can also be used to separate the ductile materials from brittle materials. The ductile materials have the Poisson’s ratio greater than 0.26, and it is smaller than 0.26 for brittle materials.\textsuperscript{53} From Table 1, it can be seen that Cs$_2$Te$_{0.50}$Ti$_{0.50}$I$_6$ is a brittle material, while other four compounds are ductile materials. It should be noted that the Poisson’s ratio values of the studied double perovskites are close to the required lowest limit. The smaller the value of Young’s modulus, the better flexibility of a material. The results show that Young’s modulus of Cs$_2$TeI$_6$ is the smallest among the five structures, which indicates that it is

<table>
<thead>
<tr>
<th>Compound</th>
<th>(C_{11}) (GPa)</th>
<th>(C_{12}) (GPa)</th>
<th>(C_{44}) (GPa)</th>
<th>(B) (GPa)</th>
<th>(G) (GPa)</th>
<th>(E) (GPa)</th>
<th>(B/G)</th>
<th>(\nu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs$_2$TeI$_6$</td>
<td>19.14</td>
<td>10.24</td>
<td>8.78</td>
<td>13.21</td>
<td>6.68</td>
<td>17.16</td>
<td>1.98</td>
<td>0.28</td>
</tr>
<tr>
<td>Cs$<em>2$Te$</em>{0.75}$Ti$_{0.25}$I$_6$</td>
<td>20.20</td>
<td>9.80</td>
<td>9.86</td>
<td>13.27</td>
<td>7.63</td>
<td>19.20</td>
<td>1.74</td>
<td>0.26</td>
</tr>
<tr>
<td>Cs$<em>2$Te$</em>{0.50}$Ti$_{0.50}$I$_6$</td>
<td>17.51</td>
<td>8.39</td>
<td>9.98</td>
<td>11.43</td>
<td>7.29</td>
<td>18.03</td>
<td>1.57</td>
<td>0.24</td>
</tr>
<tr>
<td>Cs$<em>2$Te$</em>{0.25}$Ti$_{0.75}$I$_6$</td>
<td>19.14</td>
<td>11.08</td>
<td>10.27</td>
<td>13.77</td>
<td>7.06</td>
<td>18.08</td>
<td>1.95</td>
<td>0.28</td>
</tr>
<tr>
<td>Cs$_2$TiI$_6$</td>
<td>17.85</td>
<td>10.29</td>
<td>10.70</td>
<td>12.81</td>
<td>7.05</td>
<td>17.88</td>
<td>1.82</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Table 1: The calculated elastic constants \(C_{ij}\) (GPa), bulk modulus \(B\) (GPa), shear modulus \(G\) (GPa), Young’s modulus \(E\), Pugh’s ratio \((B/G)\), and Poisson’s ratio \(\nu\) of Cs$_2$Te$_x$Ti$_{1-x}$I$_6$. 

Fig. 5 Calculated band structures of double perovskites along the \(X-R-M-G-R\) path for (a) Cs$_2$TeI$_6$, (b) Cs$_2$Te$_{0.75}$Ti$_{0.25}$I$_6$, (c) Cs$_2$Te$_{0.50}$Ti$_{0.50}$I$_6$, (d) Cs$_2$Te$_{0.25}$Ti$_{0.75}$I$_6$, and (e) Cs$_2$TiI$_6$. 

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the most flexible. Moreover, it is beneficial to form high quality film for ductile materials.

### 3.3 Electronic properties

The band structures calculated along high symmetry directions in the Brillouin zone are shown in Fig. 5. Cs₂TeI₆ has an indirect band gap between G and R point, and a direct band gap at R point. The indirect and direct band gaps of Cs₂TeI₆ are 1.12 and 1.48 eV, respectively. The previous reported band gap of Cs₂TeI₆ is about 1.5 eV, and the recent experimentally observed optical gap is 1.59 eV. The band gap of Cs₂TiI₆ with the PBE method is 0.75 eV, which is lower than its experimental value (1.02 eV). Therefore, the DFT+U method is employed to obtain accurate band gap of Cs₂TiI₆. The result shows that Cs₂TiI₆ possesses a direct band gap with 0.98 eV at the G point, which is in good agreement with its experimental value. The Spin–orbit coupling (SOC) effect on the electronic structures of Te- and Ti-based perovskites is small. It is observed that Cs₂Te₀.₅₀⁻Ti₀.₅₀I₆ is a direct band gap semiconductor with the value of 1.09 eV, while Cs₂Te₀.₇₅⁻Ti₀.₂₅I₆ is an indirect band gap semiconductor. The direct band gap of Cs₂Te₀.₂₅⁻Ti₀.₇₅I₆ is 1.05 eV. The trend in band gap is displayed in Fig. 6. The band gap of Cs₂TeI₆ reduces gradually when the ratio of Ti⁴⁺ increases. The band gaps of the two calculations with PBE and PBE+U show the same tendency. The variation in band gap is only 0.11 eV when the concentration of Ti⁴⁺ changes from 0.50 to 1.00. It should be noted that the direct band gap of Cs₂TeI₆ is close to the experimental value. The direct band gap of Cs₂Te₀.₇₅⁻Ti₀.₂₅I₆ is 1.31 eV, which is a potential candidate for single-junction solar cells according to the Shockley–Queisser theory. An indirect-to-direct band gap transition can be observed when the doping content of Ti⁴⁺ increases from 0.25 to 0.50. Moreover, the direct band gap is significantly reduced by 0.22 eV. It can be seen that the band gaps of the Cs₂Te₁₋ₓTiₓI₆ solid solutions are apparently underestimated at the PBE method, as shown in Fig. 6.

Fig. 7 shows the calculated density of states of the Cs₂⁻Te₁₋ₓTiₓI₆ solid solutions. For Cs₂TeI₆, the valence band maximum (VBM) is mainly contributed by the I-p orbitals, while

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**Fig. 6** Experimental and theoretical band gap trends with different methods of Cs₂Te₁₋ₓTiₓI₆.

**Fig. 7** Density of states of (a) Cs₂TeI₆, (b) Cs₂Teₐ.₇₅⁻Ti₀.₂₅I₆, (c) Cs₂Te₀.₅₀⁻Ti₀.₅₀I₆, (d) Cs₂Te₀.₂₅⁻Ti₀.₇₅I₆, and (e) Cs₂TiI₆.
Cs$_2$Te$_{1-x}$Ti$_x$I$_6$ is the most promising candidate due to its strong and wide optical absorption in the visible spectrum. We expect that this study can provide insights into semiconductor with the value of 0.98 eV. These compounds investigated by using first-principles calculations for the mixed Te–Ti double perovskites with respect to Cs$_2$TiI$_6$. Moreover, these materials for optoelectronic devices.

### Conflicts of interest

There are no conflicts to declare.

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### References


Fig. 8 The optical spectra of the Cs$_2$Te$_{1-x}$Ti$_x$I$_6$ solid solutions.


