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## Enhanced CO<sub>2</sub> conversion in dielectric barrier discharge plasma coupled with a heterojunction photocatalyst†

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**CsPbBr<sub>3</sub> quantum dots were grown on ReS<sub>2</sub> nanosheets to form CsPbBr<sub>3</sub>@ReS<sub>2</sub> heterojunctions using an anti-solvent method. The composition, morphology, spatial distribution, and optical absorption of samples were characterized. CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 exhibits not only a higher photocatalytic performance than CsPbBr<sub>3</sub> due to the improved optical absorption and Z-scheme charge migration, but also a higher CO<sub>2</sub> conversion ratio (35.60%) and energy efficiency (13.10%) in the dielectric barrier discharge (DBD) plasma due to superior photocatalytic activity, increased micro-discharge time, and improved discharge uniformity. This work provides a strategy for plasma photocatalytic CO<sub>2</sub> conversion.**

Conversion of CO<sub>2</sub> into high value-added chemicals and fuels *via* renewable green electricity is becoming increasingly pressing because promising potential exists to resolve the greenhouse effect and energy crisis problems.<sup>1,2</sup> CO<sub>2</sub> molecules are inert and possess ultra-high thermal stability, requiring the energy of 750 kJ mol<sup>-1</sup> to disintegrate the carbon–oxygen double bond, which leads to significant challenges for the traditional thermal approach to CO<sub>2</sub> decomposition.<sup>3</sup> Non-thermal plasma (NTP) is considered a promising alternative for reducing CO<sub>2</sub> gases into syngas or other valuable chemicals at mild temperatures.<sup>4</sup> At present, various NTP methods have been proven to convert CO<sub>2</sub> into CO, including dielectric barrier discharge (DBD),<sup>5</sup> corona discharge,<sup>6</sup> glow discharge,<sup>7</sup> microwave discharge,<sup>8</sup> gliding arc,<sup>9</sup> and radio-frequency plasma.<sup>10</sup> It is advantageous to use DBD plasma because it is affordable, and it can produce a high electron density. Thus far, DBD plasma has been widely used for CO<sub>2</sub> conversion, and previous reports indicate that packing materials in the DBD plasma reactor can increase the CO<sub>2</sub> conversion efficiency.<sup>6</sup> In fact, during CO<sub>2</sub> conversion *via* the DBD

plasma approach, there are many high-energy electrons and ultraviolet-visible photons that can stimulate the photocatalysis process. Therefore, it is significant to exploit suitable photocatalysts as packing materials to enhance the CO<sub>2</sub> conversion efficiency for DBD plasma.

There has recently been great interest in halide perovskites, such as CsPbBr<sub>3</sub>, in photocatalytic fields due to their wide range of visible light absorption and high absorption coefficient.<sup>11</sup> However, the low separation and high recombination rate of photoexcited carriers leads to low CO<sub>2</sub> conversion efficiency for CsPbBr<sub>3</sub>.<sup>12</sup> Fortunately, the construction of a heterojunction is proposed to break through these issues. The combination of CsPbBr<sub>3</sub> with two-dimensional (2D) semiconductors to form a heterojunction is a potential strategy to increase the CO<sub>2</sub> photoreduction efficiency, because 2D semiconductors usually have a large specific area, abundant active sites, and short distance of charge transportation.

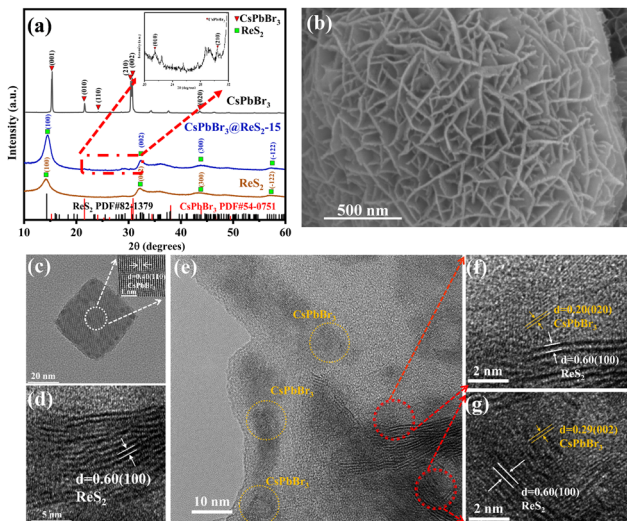
ReS<sub>2</sub>, one member of 2D semiconductors, presents the outstanding optoelectronic properties of direct bandgap, strong optical absorption, and ultra-high optical responsivity. Therefore, it is meaningful to build a heterojunction of CsPbBr<sub>3</sub> and ReS<sub>2</sub> to increase the CO<sub>2</sub> photoreduction efficiency. Additionally, it is also beneficial to prepare a porous heterostructure of CsPbBr<sub>3</sub> and ReS<sub>2</sub>. The porous structure has the advantages of a large specific surface area and abundant surface topographies to increase the CO<sub>2</sub> photoreduction.<sup>13</sup> The porous photocatalysts in DBD plasma can create micro-discharges in the pores, which in turn change the local electric field strength and discharge type of the plasma, affecting CO<sub>2</sub> conversion reactions. Porous surfaces can adsorb active excited species generated during the plasma discharge, thus increasing the residence time of active species and facilitating surface catalytic reactions.<sup>14</sup> To the best of our knowledge, the construction of a CsPbBr<sub>3</sub>@ReS<sub>2</sub> heterojunction with a porous surface structure has not been previously reported.

In this work, CsPbBr<sub>3</sub> quantum dots (QDs) were grown *in situ* on porous ReS<sub>2</sub> microspheres to form a CsPbBr<sub>3</sub>@ReS<sub>2</sub> heterojunction. Due to the increased optical absorption and enhanced separation of photogenerated carriers, the CO<sub>2</sub>

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**Fig. 1** (a) XRD patterns of CsPbBr<sub>3</sub>, ReS<sub>2</sub>, and CsPbBr<sub>3</sub>@ReS<sub>2</sub>. (b) SEM image of ReS<sub>2</sub>. HRTEM images of (c) CsPbBr<sub>3</sub>, (d) ReS<sub>2</sub>, and (e)–(g) CsPbBr<sub>3</sub>@ReS<sub>2</sub>. The inset in (c) shows an enlarged HRTEM image of CsPbBr<sub>3</sub>.

photoreduction efficiency of CsPbBr<sub>3</sub>@ReS<sub>2</sub> is higher than that of pristine CsPbBr<sub>3</sub>. CsPbBr<sub>3</sub>@ReS<sub>2</sub> heterojunction photocatalysts were used to increase the CO<sub>2</sub> conversion ratio and energy efficiency in DBD plasma, which benefitted from the synergistic conversion of CO<sub>2</sub> by the DBD plasma and heterojunction photocatalyst. This work provides guidance for future designs of plasma photocatalytic systems for efficient CO<sub>2</sub> conversion.

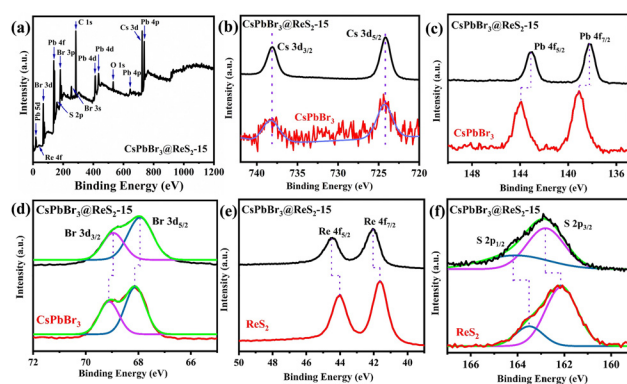
The sample preparation details are shown in the Experimental section (ESI<sup>†</sup>). Fig. 1a shows the X-ray diffraction (XRD) patterns of CsPbBr<sub>3</sub>, ReS<sub>2</sub>, and CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15. The XRD peaks of CsPbBr<sub>3</sub> QDs at 15.3°, 21.6°, 24.1°, 30.4°, 30.7°, and 43.6° were attributed to the (001), (010), (110), (210), (002), and (020) planes, respectively, and were consistent with the standard card PDF #54-0751. XRD peaks corresponding to the (100), (002), (300), and (−122) planes were detected for ReS<sub>2</sub> microspheres. Obvious XRD peaks for ReS<sub>2</sub> were observed for CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15, while weak XRD peak signals at 21.6° and 30.4° belonging to the (010) and (210) planes of CsPbBr<sub>3</sub> were also detected, which were due to the low content and small size of CsPbBr<sub>3</sub>. A scanning electron microscopy (SEM) image of prepared ReS<sub>2</sub> revealed a microsphere structure (Fig. 1b). Additionally, there were many flakes and holes on the microsphere surface, which are favorable for anchoring CsPbBr<sub>3</sub> QDs and absorbing CO<sub>2</sub> molecules.

In the high-resolution transmission electron microscopy (HRTEM) image in Fig. 1c, the CsPbBr<sub>3</sub> QDs exhibited a cubic shape and lattice spacing of 0.40 nm. The ReS<sub>2</sub> flake in Fig. 1d presents a few layers with a lattice distance of 0.60 nm corresponding to the (100) plane. Fig. 1e shows that CsPbBr<sub>3</sub> QDs are anchored on the ReS<sub>2</sub> surface for CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15. Compared with the pristine CsPbBr<sub>3</sub> QDs, the size of CsPbBr<sub>3</sub> QDs on ReS<sub>2</sub> decreases, and the corresponding shape changes into an irregular structure, which may induce more catalytic active sites because of a higher surface volume ratio. Fig. 1f and g shows the HRTEM images corresponding to the red circle regions in Fig. 1e. It is observed that the (020) plane with a lattice spacing of 0.2 nm and the (002) plane with a lattice spacing of 0.29 nm for CsPbBr<sub>3</sub> adjoin the (100) plane

with a lattice spacing of 0.60 nm for ReS<sub>2</sub>, verifying the formation of a CsPbBr<sub>3</sub>@ReS<sub>2</sub> heterojunction. In addition, the energy dispersive spectroscopy (EDS) elemental mapping (Fig. S1, ESI<sup>†</sup>) shows that there is adequate overlap of Cs, Pb, Br, Re, and S elements.

The surface chemical states and interfacial interactions were investigated by X-ray photoelectron spectroscopy (XPS) analysis. The XPS full spectrum (Fig. 2a) verified the presence of Cs, Pb, Br, Re, and S elements in CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15. Compared to the pristine CsPbBr<sub>3</sub>, the Cs 3d spectrum of CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 (Fig. 2b) exhibited two XPS peaks at 737.79 and 723.82 eV corresponding to Cs 3d<sub>3/2</sub> and Cs 3d<sub>5/2</sub>, respectively, which were not significantly shifted. However, the Pb 4f (Fig. 2c) and Br 3d (Fig. 2d) binding energies were redshifted by 1.20 and 0.23 eV, respectively. In contrast, the Re 4f (Fig. 2e) and S 2p (Fig. 2f) binding energies of CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 showed the opposite trend, whereby the Re 4f and S 2p peaks were blueshifted by 1.00 and 0.68 eV, respectively. A higher electron binding energy indicates a decrease in electron density, while a lower electron binding energy indicates an increase in electron density. Consequently, the XPS results denote electron transfer from ReS<sub>2</sub> to CsPbBr<sub>3</sub> within the CsPbBr<sub>3</sub>@ReS<sub>2</sub> heterojunction, indicating the intimate interfacial contact and robust chemical interaction between CsPbBr<sub>3</sub> and ReS<sub>2</sub>. Fig. S2 (ESI<sup>†</sup>) shows that CsPbBr<sub>3</sub>@ReS<sub>2</sub> has a lower photoluminescence (PL) intensity than that of CsPbBr<sub>3</sub>, demonstrating the increased separation of photogenerated carriers due to the heterojunction.

To obtain the band structure, UV-vis spectra and valence band (VB) XPS spectra were obtained. The optical absorption edges of pristine CsPbBr<sub>3</sub> and ReS<sub>2</sub> are about 544 and 805 nm in Fig. S3a (ESI<sup>†</sup>), respectively, suggesting their wide light absorption range. According to the inset in Fig. S3a (ESI<sup>†</sup>), the optical absorption ability of CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 is stronger compared to CsPbBr<sub>3</sub> and ReS<sub>2</sub>, which may be due to the strong electron coupling between CsPbBr<sub>3</sub> and ReS<sub>2</sub>, indicating the promising capacity of solar light utilization. In addition, Fig. S3b (ESI<sup>†</sup>) presents the Tauc plots of CsPbBr<sub>3</sub> and ReS<sub>2</sub>, from which the bandgap energy ( $E_g$ ) of 2.30 and 1.57 eV was determined for CsPbBr<sub>3</sub> and ReS<sub>2</sub>, respectively. Meanwhile, the VB positions of CsPbBr<sub>3</sub> and ReS<sub>2</sub> are respectively confirmed to be 1.03 and 1.25 eV, as shown in Fig. S4 (ESI<sup>†</sup>). Then, the conduction band (CB) positions ( $E_g = CB - VB$ ) of CsPbBr<sub>3</sub> and ReS<sub>2</sub> are calculated to be −1.27 eV and −0.32 eV, respectively.



**Fig. 2** (a) XPS full spectrum of CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15. High-resolution XPS spectra of (b) Cs 3d, (c) Pb 4f, and (d) Br 3d of (e) Re 4f and (f) S 2p.

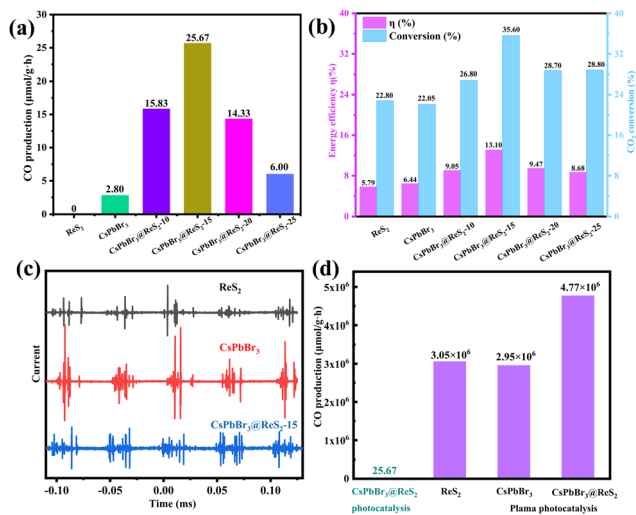


Fig. 3 (a) Photocatalysis, (b) plasma photocatalysis performances, and (c) discharge current of ReS<sub>2</sub>, CsPbBr<sub>3</sub>, and CsPbBr<sub>3</sub>@ReS<sub>2</sub>; (d) CO yield of CsPbBr<sub>3</sub>@ReS<sub>2</sub> photocatalysis, ReS<sub>2</sub> plasma catalysis, and plasma photocatalysis of CsPbBr<sub>3</sub> and CsPbBr<sub>3</sub>@ReS<sub>2</sub>.

Especially, it is noted that the band structure of ReS<sub>2</sub> does not match with the reduction potential (−0.52 V) of CO<sub>2</sub> conversion to CO, which agrees with the result of the CO<sub>2</sub> photoreduction for ReS<sub>2</sub> in Fig. 3a. However, the band alignment of the CsPbBr<sub>3</sub>@ReS<sub>2</sub> heterojunction meets the requirements for CO<sub>2</sub> conversion to CO, as shown in Fig. S3c (ESI<sup>†</sup>). CsPbBr<sub>3</sub>@ReS<sub>2</sub> presents increased photocatalytic efficiency of CO<sub>2</sub> reduction as compared to that of CsPbBr<sub>3</sub> and ReS<sub>2</sub> in Fig. 3a. The traditional type II heterojunction mechanism cannot reasonably explain the principle of charge carrier transfer and photocatalytic CO<sub>2</sub> reduction for CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15. Therefore, a Z-type charge flow path is proposed for CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15. As a result, the photogenerated carrier separation efficiency of ReS<sub>2</sub> and CsPbBr<sub>3</sub> in the heterostructure is enhanced, improving the CO<sub>2</sub> photoreduction performance.<sup>15,16</sup> Additionally, the main CO<sub>2</sub> photoreduction processes for CsPbBr<sub>3</sub>@ReS<sub>2</sub> are summarized as reaction Formulas S1–S4 (ESI<sup>†</sup>).

To examine the photocatalytic performance of samples, the products of CO<sub>2</sub> photoreduction were tested. In Fig. 3a, after 3 h of continuous light irradiation, all samples showed 100% selectivity for CO, while CsPbBr<sub>3</sub> possessed low activity (CO yield = 2.80 μmol g<sup>−1</sup> h<sup>−1</sup>). Additionally, ReS<sub>2</sub> does not show CO<sub>2</sub> photoreduction ability, which is consistent with the band arrangement structure of ReS<sub>2</sub>. However, when CsPbBr<sub>3</sub> is anchored on ReS<sub>2</sub>, the CO<sub>2</sub> photoreduction performance is greatly enhanced. Particularly, the largest CO yield (25.67 μmol g<sup>−1</sup> h<sup>−1</sup>) was for CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15, and was 9.17-fold higher than that of CsPbBr<sub>3</sub> (2.80 μmol g<sup>−1</sup> h<sup>−1</sup>). Because coupling with ReS<sub>2</sub> had a significant role in the photocatalytic performance of CsPbBr<sub>3</sub>, the effects of the molar ratio of CsPbBr<sub>3</sub> to ReS<sub>2</sub> in the heterojunction on the photocatalytic activity were further investigated. Compared to CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 (25.67 μmol g<sup>−1</sup> h<sup>−1</sup>), the CO production of CsPbBr<sub>3</sub>@ReS<sub>2</sub>-20 (14.33 μmol g<sup>−1</sup> h<sup>−1</sup>) and CsPbBr<sub>3</sub>@ReS<sub>2</sub>-25 (6.00 μmol g<sup>−1</sup> h<sup>−1</sup>) clearly decreased, which occurred because the excess ReS<sub>2</sub> impeded effective utilization of the photon energy due to a lack of photocatalytic activity for CO<sub>2</sub> reduction by pristine ReS<sub>2</sub>.

In DBD plasma, electrons are subjected to an applied electric field and gain sufficient energy to obtain high velocity. Afterwards, the high-energy electrons collide with the gas molecules in the discharge gap, resulting in gas ionization, which triggers an electron avalanche.<sup>17</sup> In addition to elastic collisions, inelastic collisions also occur in the plasma to produce many active species, which can be involved in a range of chemical reactions. More importantly, CO<sub>2</sub> molecules can be activated and enter into vibrationally excited states CO<sub>2</sub><sup>V\*</sup> in plasma to decrease the reaction barrier to CO<sub>2</sub> reduction.<sup>18</sup> Therefore, it is significant to employ the active state CO<sub>2</sub><sup>V\*</sup> in DBD plasma to induce photocatalytic CO<sub>2</sub> conversion.

The plasma photocatalytic CO<sub>2</sub> reduction performances for ReS<sub>2</sub>, CsPbBr<sub>3</sub>, and CsPbBr<sub>3</sub>@ReS<sub>2</sub> with different molar ratios are shown in Fig. 3b, and the test details are described in the ESI.<sup>†</sup> It is found that the plasma photocatalytic performance of CsPbBr<sub>3</sub>@ReS<sub>2</sub> is higher than that of ReS<sub>2</sub> and CsPbBr<sub>3</sub>. CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 exhibits the highest CO<sub>2</sub> conversion (35.60%) and energy efficiency (13.10%), which is attributed to the optimal photocatalytic activity, as shown in Fig. 3a. Moreover, the porous surface structure of ReS<sub>2</sub> results in increased residence time of CO<sub>2</sub> molecules in the reaction region<sup>19</sup> and increases the chance of collisions between electrons and CO<sub>2</sub>. This explains the higher CO<sub>2</sub> conversion in DBD plasma filled with ReS<sub>2</sub> (22.80%) compared to CsPbBr<sub>3</sub> (22.05%). In contrast, the energy efficiency of the plasma filled with ReS<sub>2</sub> was slightly lower than that of the plasma filled with CsPbBr<sub>3</sub>, which may be due to the higher energy input per CO<sub>2</sub> molecule, resulting in a decreasing trend in energy utilization efficiency.<sup>20</sup>

The reasons for performance differences were further explored by measuring the discharge characteristics and charge properties of DBD plasma. The total current consists of both conduction current and displacement current. Conduction current is formed by the directional movement of charged particles in the plasma under the influence of an electric field. The charge characteristics such as lifetime and discharge intensity can be determined by conduction current. In fact, filling the DBD plasma with catalyst is expected to reduce the amplitude of the current peak and cause a change in the discharge modes. Usually, filamentary discharge mainly occurs between particles or between particles and wall surfaces, while surface discharge mainly exists on the surface of the catalyst. Compared with regularly shaped catalysts, filling materials with a porous structure are more likely to cause surface discharge.<sup>13</sup>

It is observed that the discharge current amplitude of DBD plasma filled with ReS<sub>2</sub> and CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 is lower than that of CsPbBr<sub>3</sub>, as shown in Fig. 3a. This is consistent with previous works demonstrating that DBD plasma packed with BaTiO<sub>3</sub>,<sup>5</sup> glass beads,<sup>5</sup> or Ni/Al<sub>2</sub>O<sub>3</sub><sup>21</sup> significantly reduced the current amplitude. Furthermore, CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 increases the micro-discharge time, which is the time of the continuous plasma discharge during a discharge period, compared with ReS<sub>2</sub> and CsPbBr<sub>3</sub> (Fig. 3a), implying that a heterogenous photocatalyst improves the plasma discharge characteristics. The uniformity of the plasma discharge for CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 is optimal, which is beneficial for plasma-driven CO<sub>2</sub> conversion. In addition, the amounts of the peak-to-peak charge (Q<sub>pk-pk</sub>) and discharge charge (Q<sub>d</sub>) are also one of the indicators of the actual reaction (Fig. S5, ESI<sup>†</sup>). DBD plasma with

CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 holds the largest  $Q_{\text{pk-pk}}$  (545 nC) and  $Q_{\text{d}}$  (290 nC) compared with CsPbBr<sub>3</sub> ( $Q_{\text{pk-pk}} = 500$  nC,  $Q_{\text{d}} = 250$  nC) and ReS<sub>2</sub> ( $Q_{\text{pk-pk}} = 530$  nC,  $Q_{\text{d}} = 280$  nC) (Fig. S6, ESI<sup>†</sup>), which indicates that the physical and chemical reactions in the DBD plasma filled with CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 are the most violent for CO<sub>2</sub> conversion.

Furthermore, according to the optical absorption spectrum of CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 (inset of Fig. S3a, ESI<sup>†</sup>) and optical emission spectrum of DBD plasma filled with CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 (Fig. S7, ESI<sup>†</sup>), the photons generated in the plasma can be absorbed by the photocatalyst for CO<sub>2</sub> conversion.<sup>22</sup> In fact, the vibrationally excited CO<sub>2</sub> molecules in the plasma can be absorbed on the photocatalyst surface to reduce the potential barrier for the subsequent reduction process, which facilitates the “state-to-state catalytic chemistry” so that high-efficiency photocatalysis is obtained.<sup>23</sup> The spectral bands of various active groups, including CO ( $b^3\Sigma_{2u}^- - a^3\Pi_{1g}$ ), CO<sub>2</sub><sup>+</sup> ( $B^2\Sigma_u^+ - X^2\Pi_g$ ), and CO<sub>2</sub><sup>+</sup> ( $A^2\Pi_u - X^2\Pi_g$ ), were detected, as demonstrated in Table S2 and Fig. S7 (ESI<sup>†</sup>).

The vertical ionization energy of CO<sub>2</sub> stands at 13.77 eV,<sup>24</sup> while exciting CO<sub>2</sub><sup>+</sup> from its X<sup>2</sup>Π<sub>g</sub> state to the A<sup>2</sup>Π<sub>u</sub> and B<sup>2</sup>Σ<sub>u</sub><sup>+</sup> states necessitates energies of 3.54 eV and 4.31 eV, respectively.<sup>25</sup> This indicates that the formation of CO<sub>2</sub><sup>+</sup> in the X<sup>2</sup>Π<sub>g</sub>, A<sup>2</sup>Π<sub>u</sub>, and B<sup>2</sup>Σ<sub>u</sub><sup>+</sup> states within the plasma relies on the presence of high-energy electrons, as outlined in eqn S5–S7 (ESI<sup>†</sup>), while the de-excitation of these active species leads to the emission of photons possessing specific energies, as shown in eqn S8 and S9 (ESI<sup>†</sup>).

The CO yield of the CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 photocatalysis, ReS<sub>2</sub> plasma catalysis, and plasma photocatalysis of CsPbBr<sub>3</sub> and CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 under the same mass condition was compared. It is observed that the CO yield in the DBD plasma filled with CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 ( $4.77 \times 10^6 \mu\text{mol g}^{-1} \text{h}^{-1}$ ) is 56.4% higher than that of ReS<sub>2</sub> ( $3.05 \times 10^6 \mu\text{mol g}^{-1} \text{h}^{-1}$ ), and is much larger than the sole photocatalytic process ( $25.67 \mu\text{mol g}^{-1} \text{h}^{-1}$ ) (Fig. 3d). This highlights the superiority of plasma photocatalysis in the CO<sub>2</sub> conversion. Compared with CsPbBr<sub>3</sub>, the ability of the CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 heterojunction photocatalyst to absorb light and effectively utilize the photons generated in the DBD plasma is greater, while the presence of a Z-type charge transfer path between ReS<sub>2</sub> and CsPbBr<sub>3</sub> suppresses the recombination of charge carriers, thereby improving the overall CO<sub>2</sub> conversion performance.

In summary, CsPbBr<sub>3</sub> QDs were grown on ReS<sub>2</sub> to construct the CsPbBr<sub>3</sub>@ReS<sub>2</sub> heterojunction. The CsPbBr<sub>3</sub>@ReS<sub>2</sub> photocatalysts show stronger optical absorption and a type-Z heterojunction, and the photocatalytic CO production is  $25.67 \mu\text{mol g}^{-1} \text{h}^{-1}$  for CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15. The increase in photocatalytic activity is attributed to the improved light absorption and the formation of a Z-scheme heterojunction, facilitating the spatial separation of photogenerated charge carriers. Moreover, DBD plasma filled with CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15 delivers the optimum CO<sub>2</sub> conversion ratio of 35.60% and energy efficiency of 13.10%. This exceptional performance was obtained due to not only the excellent photocatalytic activity of CsPbBr<sub>3</sub>@ReS<sub>2</sub>-15, but also the increased micro-discharge time and

satisfactory discharge uniformity of the DBD plasma. This work will promote the development of plasma photocatalytic CO<sub>2</sub> conversion.

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## Data availability

The data supporting this article have been included as part of the ESI<sup>†</sup>.

## Conflicts of interest

There are no conflicts to declare.

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