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## Strategic Ni-doping improved electrocatalytic H<sub>2</sub> production by Bi<sub>3</sub>O<sub>4</sub>Br in alkaline water†

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Establishing a cost-effective and efficient electrocatalytic pathway for the hydrogen evolution reaction (HER) is the key to our quest for a carbon-neutral energy landscape. We report a simple and straightforward approach to synthesize an efficient, stable, and low-cost noble metal-free Bi<sub>3</sub>O<sub>4</sub>Br electrocatalyst. Tactical doping of Ni ions into Bi<sub>3</sub>O<sub>4</sub>Br effectively enhanced the conductivity, accelerated the charge transfer process, and provided more catalytic active sites to significantly boost the alkaline electrochemical HER performance of Bi<sub>3</sub>O<sub>4</sub>Br. This Ni-doped Bi<sub>3</sub>O<sub>4</sub>Br exhibited a lower overpotential of 662 mV compared to that of Bi<sub>3</sub>O<sub>4</sub>Br (736 mV) at a higher current density (50 mA cm<sup>-2</sup>). Additionally, the HER kinetics were also enhanced in terms of Tafel slope for this doped material (159 mV dec<sup>-1</sup>) compared to the pristine Bi<sub>3</sub>O<sub>4</sub>Br (245 mV dec<sup>-1</sup>), which coincides with a significant improvement in the mass activity (52 A g<sup>-1</sup> to 98 A g<sup>-1</sup>). Notably, the overpotential of Ni-doped Bi<sub>3</sub>O<sub>4</sub>Br was further reduced to 614 mV at the same current density of 50 mA cm<sup>-2</sup> during photoelectrochemical HER performance testing, and the faradaic efficiency was improved from 79% to 87%. Finally, an enhanced durability of the material was observed for Bi<sub>3</sub>O<sub>4</sub>Br following the Ni-doping. Hence, this strategy highlights the importance of unravelling upgraded catalytic behaviour for abundant materials with rational doping.

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### Introduction

Hydrogen is a popular choice of future energy material for transducing renewable energy to practically usable electricity with minimal greenhouse gas emissions.<sup>1–4</sup> In this flow of events, the hydrogen evolution reaction (HER) from abundant water is reckoned as a key step. Water electrolysis is looked upon as the primary pathway for industrial-scale HER, which is required to be executed at a rapid rate with low overpotential requirements. Over the last few decades, extensive research efforts have been made to develop an electrocatalyst that can produce hydrogen *via* the electrocatalytic splitting of water at a lower overpotential with appreciable rates.<sup>5–9</sup> Electrocatalytic water splitting can be carried out in both acidic and alkaline media, and the lack of acid-tolerant counter electrode materials is a bottleneck for the production of multimillion tons of H<sub>2</sub> *via* acidic electrolyzers.<sup>10–12</sup> Therefore, major emphasis has been

given to the quest for a stable and highly active catalyst for alkaline HER in the past few decades.<sup>7,13</sup> Moreover, similar efforts are being made to develop compatible, stable, and efficient electrocatalysts for the other half-cell reaction of water electrolysis: the complementary oxygen evolution reaction (OER) under similar conditions. The appropriate assembly of HER and OER electrocatalysts is vital for a fully functional alkaline water electrolyzer.<sup>14–19</sup> Here, the challenge is to generate an electrocatalyst composed of earth-abundant elements that can display good stability and high efficiency while executing the HER in an alkaline medium.<sup>20–22</sup> There has been a plethora of electrocatalysts containing earth-abundant transition metals developed recently for electrocatalytic water splitting.<sup>23–25</sup>

Bismuth oxyhalides (BiOX, where X = Cl, Br or I), classified as a ternary compound, have a layered structure consisting of repetitive units of [Bi<sub>2</sub>O<sub>2</sub>]<sup>2+</sup> and X<sup>–</sup>, which are typically held together by van der Waals forces of attraction. These materials have emerged as a serious contender for practical electrocatalytic applications owing to their ease of preparation, excellent photocatalytic properties, relative nontoxicity, and low cost. These materials are promising photocatalysts due to their inherent wide bandgap that broadens their absorption profile through the ultra-violet and visible region. Nevertheless, these materials exhibit facile charge recombination, leading to low catalytic responses in the absence of any charge-trapping centers.<sup>26,27</sup> Tactical incorporation of surface defects in these nanomaterials is reckoned as a key approach for stabilizing the charge-separated holes and electrons, which in turn proceeds

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to effective catalysis. Enriching the bismuth oxyhalide framework with additional bismuth ions is found to produce promising results.<sup>28</sup> These bismuth-rich bismuth oxyhalides are formulated as  $\text{Bi}_m\text{O}_n\text{X}_p$ , where X = Cl, Br or I, and m, n, and p are various stoichiometric proportions.

Among these bismuth-rich bismuth oxyhalides,  $\text{Bi}_3\text{O}_4\text{Br}$  is one of the popular choices due to the ease of synthesis, tuneable morphology with controllable stoichiometry, and enhanced visible light absorption properties.<sup>29–31</sup> It is reported that  $\text{Bi}_3\text{O}_4\text{Br}$  has a layer structure composed of  $[\text{Bi}_3\text{O}_4]^{1+}$  units attached to the  $\text{Br}^-$  by van der Waals force of attraction. Two bismuth coordination environments were reported for this material. In the first coordination geometry, the bismuth ion is ligated to three oxygen atoms and one bromine atom. In the second environment, one bismuth atom is attached to four oxygen atoms in the unit cell of  $\text{Bi}_3\text{O}_4\text{Br}$ . To further tailor the catalytic properties of  $\text{Bi}_3\text{O}_4\text{Br}$ , the bismuth is substituted with a transition metal, such as Co, which was reported to be an effective strategy. Recently, single atom (Co)-doped  $\text{Bi}_3\text{O}_4\text{Br}$  was also reported that illustrated remarkable photo-electrocatalytic activity for carbon dioxide conversion.<sup>29</sup> Jiang *et al.* developed Ag-doped  $\text{Bi}_3\text{O}_4\text{Br}$  for the efficient photodegradation of bisphenol-A.<sup>32</sup> Wang *et al.* fabricated an Ni-doped  $\text{CsPbBr}_3/\text{Bi}_3\text{O}_4\text{Br}$  heterostructured material for efficient photocatalytic  $\text{CO}_2$  conversion following a Z-scheme of electron transfer.<sup>33</sup> Hence,  $\text{Bi}_3\text{O}_4\text{Br}$ -based materials have been widely used in the field of photochemical applications.

In this work, we have synthesized a Ni-doped (0.4 atomic %)  $\text{Bi}_3\text{O}_4\text{Br}$  material and probed its reactivity as an electrocatalyst in an alkaline aqueous medium (pH ~14.0). The inclusion of Ni 3d-bands into the Bi 4f orbitals reduced the original band-gap of the  $\text{Bi}_3\text{O}_4\text{Br}$ , which was supported by the X-ray photo-electron spectroscopy (XPS) data. During the assembly of the electrocatalytic material, polyvinylpyrrolidone (PVP) was added to prevent any lateral growth of  $\text{Bi}_3\text{O}_4\text{Br}$  nanocrystals. The PVP directly interacts with  $\text{Bi}_3\text{O}_4\text{Br}$ , as a passivation layer is created around the crystal core through the strong interaction between the  $\text{Bi}^{3+}$  and the oxygen and nitrogen atoms present on the pyrrolidone ring, resulting in the formation of 2D-plate-shaped nanocrystals. The catalyst is fully characterized by an array of analytical techniques, such as XRD, XPS, UV-vis, FTIR, and Raman spectroscopy. For comparison, we have also synthesized pristine  $\text{Bi}_3\text{O}_4\text{Br}$  by following the same protocol and compared its electrocatalytic HER properties with those of the Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  in an aqueous alkaline (1.0 M KOH, pH 14.0) medium.

## Experimental procedures

### Reagents and materials

All the chemicals mentioned are of analytical grade unless otherwise mentioned, which were used as procured without further purification.  $\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$  (98%), KCl, KBr,  $\text{HNO}_3$  (70%),  $\text{Ni}(\text{II})(\text{CH}_3\text{COO})_2 \cdot 4\text{H}_2\text{O}$  (98%), polyvinyl pyrrolidone (PVP), mannitol, ethanol (absolute), and NaOH (> 97%) were purchased from Sigma Aldrich, India. Milli Q water (resistivity 18.2  $\text{M}\Omega \text{ cm}$ ) was used throughout for all the experiments. The

pH value was maintained by using buffer capsules (Merck, India).

### Synthesis of $\text{Bi}_3\text{O}_4\text{Br}$ and Ni-doped $\text{Bi}_3\text{O}_4\text{Br}$

$\text{Bi}_3\text{O}_4\text{Br}$  and Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  nanoparticles were prepared by the hydrothermal method under similar experimental conditions as reported in the literature.<sup>29</sup> In summary, 0.5 mmol of  $\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$  was added to 0.2 g polyvinyl pyrrolidone (PVP) and 0.1 M mannitol solution in 15.0 mL of Millipore water. 0.005 mmol of  $\text{Ni}(\text{II})(\text{CH}_3\text{COO})_2 \cdot 4\text{H}_2\text{O}$  was added to the above mixture with vigorous stirring. In another beaker, 0.5 mmol of KBr was dissolved in 0.1 M mannitol solution (5 mL) in water. The KBr solution was added dropwise to the  $\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$  solution with vigorous stirring (1000 rpm). The reaction mixture was stirred for 30 minutes, and thereafter, the pH was adjusted to 11.5 with the addition of 1.0 M NaOH. The solution was heated at 160 °C for 20 hours in an autoclave and thereafter cooled down to room temperature gradually. The reaction mixture was washed repeatedly with distilled water and ethanol. The off-white color with greenish taint powder compound was isolated by centrifugation and dried at 50 °C overnight.  $\text{Bi}_3\text{O}_4\text{Br}$  was prepared following the same protocol without added nickel salt during the preparation.

### Characterization techniques

Crystal structure and phase identification studies were carried out through X-ray diffractometer (XRD, Pananalytical) using a Cu K $\alpha$  source with wavelength,  $\lambda = 1.54 \text{ \AA}$ . The Raman scattering measurements were conducted using an electrically cooled CCD camera coupled with an Olympus BX41 Raman spectrometer by WITEC with laser lines at 532 nm. The absorption of light in the wavelength range 300–800 nm was studied by UV-vis diffuse reflectance spectroscopy (DRS) (UV-vis Cary series, Agilent Technologies). A Metrohm Auto lab PGSTAT 204 potentiostat galvanostat was used for all electrochemical measurements with a conventional three-electrode system at room temperature (298 K) using Nova 2.1.6 software. Transmission electron microscopy (TEM) analysis was performed by a Thermo Scientific, Themis 300 G3 instrument. The sample was drop cast on a carbon coated 300 mesh Cu grid (Ted Pella, Inc.) for TEM analysis. Fourier transform infrared spectroscopy (FTIR) (Vertex 70v, Bruker) was performed to understand the bonding structure. XPS was performed with a PHI-5702 X-ray photoelectron spectrometer.

### Electrochemical measurements

All the electrochemical studies were performed by using the Metrohm Auto lab potentiostat with a conventional three-electrode system at room temperature (298 K). The pH of the solutions was adjusted using an ORION STAR A111 (Thermo Scientific) or LMPH-9 (Labman Scientific) pH Meter. A spiral platinum electrode (Pt) and an Ag/AgCl electrode submerged in 3.0 M KCl were taken as the counter and reference electrodes, respectively. The catalyst ink was then prepared by taking 3.0 mg of catalyst in the solution of 120  $\mu\text{L}$  of HPLC grade IPA, 80  $\mu\text{L}$  of millipore water (18.2  $\text{M}\Omega \text{ cm}$  at 298 K), and 30  $\mu\text{L}$



of 5 wt% Nafion. The prepared catalyst was deposited on carbon fiber paper (with approximate mass loading of  $1.04 \text{ mg cm}^{-2}$ ) and directly used as the working electrode. 1.0 M KOH solution (pH 14.0) was utilized as the electrolyte solution. Before performing the linear sweep voltammetry (LSV) and electrochemical impedance spectroscopy (EIS), 100 cycles of cyclic voltammetry (CV) were performed with a  $50 \text{ mV s}^{-1}$  scan rate to obtain a steady state of the electrocatalysts. The Nyquist plots were measured by the application of a sinusoidal wave with an AC amplitude of 10 mV from the  $10^5 \text{ Hz}$  to 0.1 Hz operating frequency range. The potential values were measured against the Ag/AgCl reference electrode, which was then converted to a reversible hydrogen electrode (RHE) by using this equation.

$$E_{\text{RHE}} \text{ (V)} = E_{\text{Ag}/\text{AgCl}} \text{ (V)} + 0.059 \text{pH} + E_{\text{applied}}$$

where  $E_{\text{applied}}$  is the applied potential. Hydroxymethyl ferrocene ( $E = +0.385$  V at SHE) was added as an internal standard to measure the exact potential of the reference electrode. All the mentioned potentials, in this work are the values concerning RHE.

## Results and discussion

The pristine  $\text{Bi}_3\text{O}_4\text{Br}$  and Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  were synthesized via the hydrothermal process. The crystalline structures and associated crystal phases of  $\text{Bi}_3\text{O}_4\text{Br}$  and Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  were identified by deploying powder X-ray diffraction (XRD). All the peaks for the  $\text{Bi}_3\text{O}_4\text{Br}$  were indexed with the already existing literature that implied the presence of an orthorhombic unit cell (Fig. 1).<sup>29,34</sup> The XRD signals broadened following the Ni-doping, suggesting that the inclusion of Ni in the structure reduces the crystallinity of  $\text{Bi}_3\text{O}_4\text{Br}$ . Ni-doping possibly creates bismuth and oxygen vacancies in the matrix due to the size mismatch to induce a change in the crystallinity of  $\text{Bi}_3\text{O}_4\text{Br}$ . The influence of the Ni-doping was specifically vivid with a shift

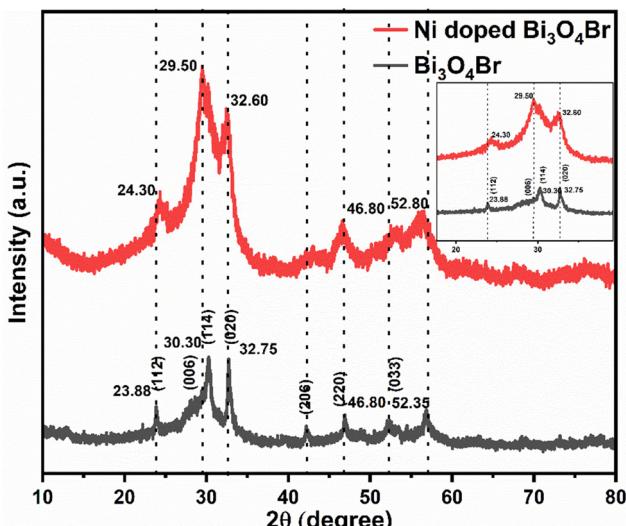


Fig. 1 Powder XRD patterns for the  $\text{Bi}_2\text{O}_4\text{Br}$  and Ni-doped  $\text{Bi}_2\text{O}_4\text{Br}$

observed for the peaks associated with the (112) and (114) planes, while the rest of the peaks remained constant.

The X-ray photoelectron spectroscopic (XPS) study was performed next to further confirm the chemical composition, electronic structure, and valence state of each element present in  $\text{Bi}_3\text{O}_4\text{Br}$  and Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  (Fig. 2). All the XPS spectra were corrected for specimen charging by referencing the C1s peak to 284.60 eV. Two high-intensity peaks in the high-resolution XPS spectra of Bi are observed at 158.48 eV and 163.81 eV that are assigned as  $\text{Bi } 4f_{7/2}$  and  $\text{Bi } 4f_{5/2}$ , respectively, with a splitting energy  $\Delta = 5.33$  eV (Fig. 2a).<sup>35</sup> On the contrary, the  $\text{Bi } 4f_{7/2}$  and  $\text{Bi } 4f_{5/2}$  peaks for the Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  were red-shifted by 0.2 eV compared to the pristine  $\text{Bi}_3\text{O}_4\text{Br}$ . This low-energy shift indicates that the electronic environment around the bismuth atom has changed slightly after nickel doping. The two high-intensity peaks denote the +3 oxidation state of Bi in the Bi–O bonding inside the crystal lattice, and the slight shift towards lower binding energy (by 0.2 eV) following the Ni-addition possibly suggests an elongated Bi–O bonding in the Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$ . It is important to mention that the very low-intensity shoulders around 156.2 eV and 161.4 eV are due to the  $\text{Bi } 4f_{7/2}$  and  $\text{Bi } 4f_{5/2}$ , respectively, arising from the  $\text{Bi}^{3+}$  sites of the Bi–Br bonding. O 1s showed two peaks with the binding energy values of 529.02 eV and 530.22 eV in  $\text{Bi}_3\text{O}_4\text{Br}$  with a splitting energy  $\Delta = 1.2$  eV. These two peaks are assigned to oxygen present in the vicinity of oxygen defects and the lattice oxygen (bound to metal, Bi), respectively (Fig. 2b).<sup>35</sup> Similar peaks were observed at slightly higher energies of 529.92 eV and 531.80 eV with a splitting energy  $\Delta = 1.88$  eV. Such a shift in binding energy presumably appeared due to the redistribution of the electronic charge around the O atoms subsequent to the Ni-addition. The oxygen defect peak is relatively higher in intensity in the case of Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  compared to pristine  $\text{Bi}_3\text{O}_4\text{Br}$ . Hence, the XPS data insinuates that the Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  is more defect-rich in terms of oxygen vacancies than the pristine  $\text{Bi}_3\text{O}_4\text{Br}$ . Similarly, two Br peaks were observed at 67.6 eV and 68.70 eV and were allocated to  $\text{Br } 3d_{5/2}$  and  $\text{Br } 3d_{3/2}$ , respectively (Fig. 2c).<sup>30</sup> A Ni  $2p_{3/2}$  peak is observed at 854.88 eV for the Ni-doped sample, which can be assigned to the +2 oxidation state of Ni (Fig. 2d).<sup>36,37</sup> Lastly, the valence band XPS spectra show that the Ni doping shifts the valence band (VB) towards a more (0.05 eV) positive side in the energy scale with higher oxidizing ability than the pristine  $\text{Bi}_3\text{O}_4\text{Br}$ . From the XPS peak area analysis, the presence of Ni was observed as  $ca \sim 0.4$  atomic %.

A transmission electron microscopy (TEM) study was performed for the morphological investigation of the materials. The TEM images of pure  $\text{Bi}_3\text{O}_4\text{Br}$  and Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  represent the 2D-plate-like morphology (Fig. 3, and Fig. S1, ESI<sup>†</sup>). The fast Fourier transform (FFT) is used to convert the raw image data obtained from the transmission electron microscope into a frequency domain representation. This permits the analysis of the spatial frequency content of the image, which can provide information about the crystal structure, defects, and other features of the sample being studied. The FFT is particularly useful for analysing diffraction patterns, which can

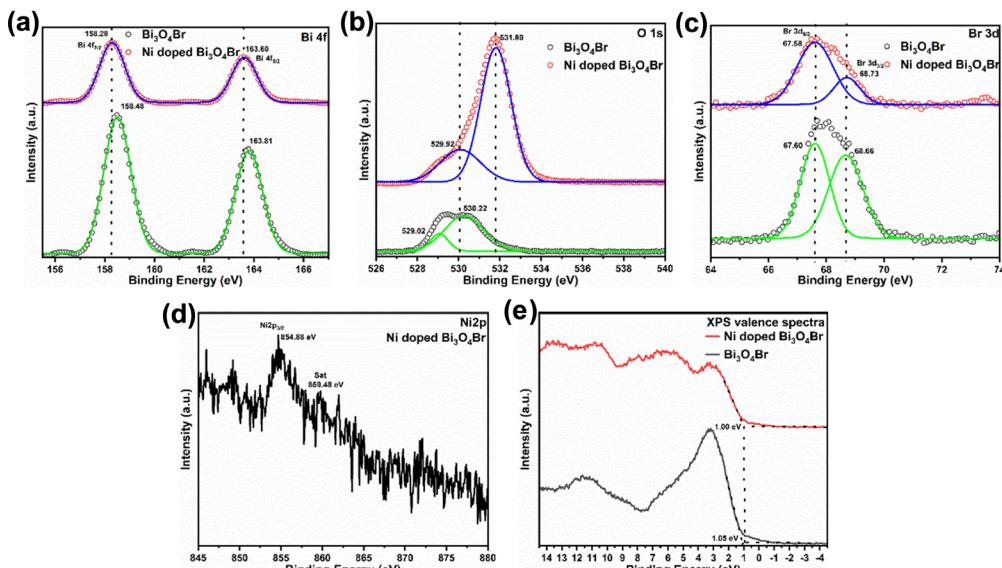


Fig. 2 High resolution XPS spectra of (a) Bi 4f, (b) O 1s, (c) Br 3d, (d) Ni 2p, and (e) valence spectra for  $\text{Bi}_3\text{O}_4\text{Br}$  and Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$ .

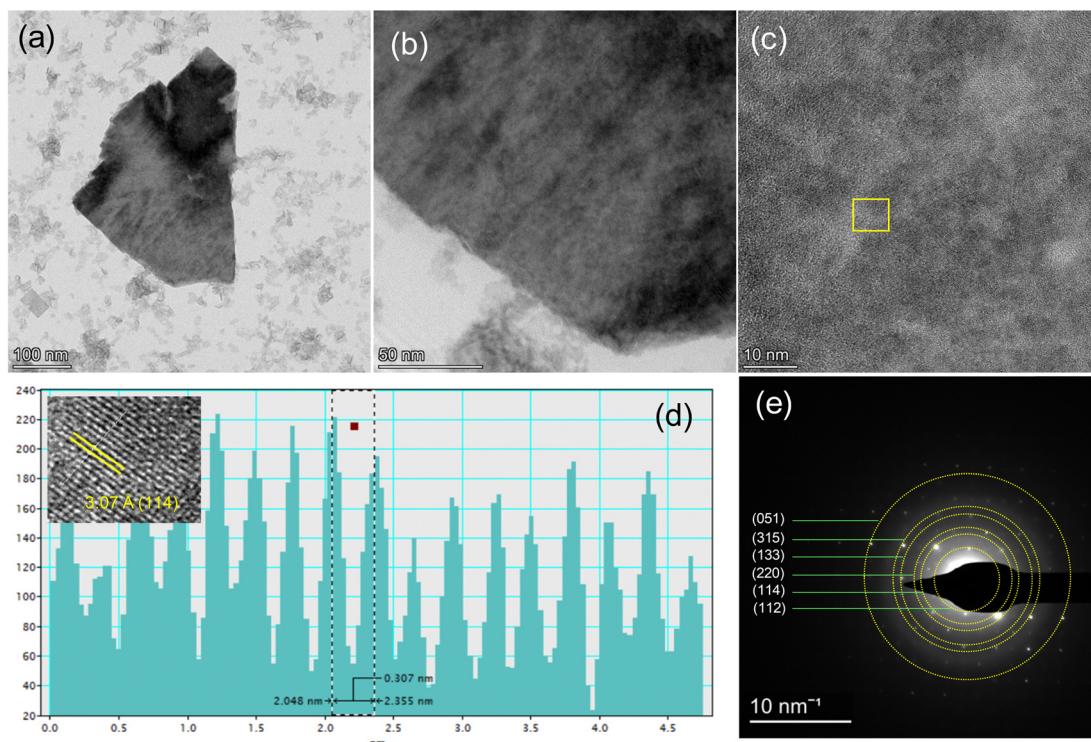


Fig. 3 (a) and (b) TEM images of Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$ , (c) HR-TEM image, and (d) line-scanning intensity profile of the inserted inverse FFT and live FFT of the selected area in (c). (e) SAED pattern of Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$ , (FFT = fast Fourier transform).

provide valuable information about the atomic arrangement within a material. The obtained FFT contains diffraction spots (reciprocal space pattern), which can be further used to create images of the region of interest using the inverse FFT method. HR-TEM image and inverse fast Fourier transition (FFT) analysis confirmed the presence of the (114) plane on the surface of the Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  nanostructure (Fig. 3c and d). It is worth

mentioning that this (114) plane displayed a distinct shift following the Ni-doping to  $\text{Bi}_3\text{O}_4\text{Br}$ . Selected area electron diffraction (SAED) is a crystallographic experimental technique performed using a transmission electron microscope. In the SAED pattern, each obtained spot corresponds to a satisfied diffraction condition. For any crystalline nanomaterial, SAED patterns typically provide an image composed of single spots

(dots) only if it is a single crystal, and a ring pattern for a polycrystalline material. This feature of SAED is useful for distinguishing crystalline nanomaterials from their amorphous counterparts. Herein, the selected area electron diffraction (SAED) pattern of Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  reveals the formation of a polycrystalline nanostructured material (Fig. 3e). The high-angle annular dark-field scanning transmission electron microscopy image and corresponding elemental mapping confirm the uniform distribution of Bi, O, Br, and Ni elements in the Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  nanostructures (Fig. 4 and Fig. S2, ESI<sup>†</sup>). Analogous data was also recorded for pristine  $\text{Bi}_3\text{O}_4\text{Br}$  (Fig. S3, ESI<sup>†</sup>).

The optical absorption properties of  $\text{Bi}_3\text{O}_4\text{Br}$  and Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  were investigated by UV-vis absorption and diffuse reflectance spectra (DRS). A significant optical absorption band for the Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  was extended beyond 500 nm. However, the analogous band terminates around 450 nm for the  $\text{Bi}_3\text{O}_4\text{Br}$  (Fig. S4, ESI<sup>†</sup>).<sup>31,38,39</sup> This shows that Ni doping shifts the bandgap of  $\text{Bi}_3\text{O}_4\text{Br}$  towards the visible region. For crystalline semiconductor materials, the optical absorption near the band edge follows the equation:  $\alpha h\nu = A(h\nu - E_g)^{n/2}$ , where  $\alpha$ ,  $\nu$ ,  $A$ , and  $E_g$  are the absorption coefficient, frequency of light, proportionality constant, and energy bandgap, respectively. The quantity of “ $n$ ” depends on the characteristics of transition. For a direct bandgap semiconductor,  $n$  is taken as 1, and for an indirect bandgap semiconductor,  $n$  is taken as 4. Since  $\text{Bi}_3\text{O}_4\text{Br}$  is known as an indirect bandgap semiconductor,  $n$  is taken as 4. By plotting  $(\alpha h\nu)^{1/2}$  vs. energy (eV), we have obtained the bandgaps of the  $\text{Bi}_3\text{O}_4\text{Br}$  and Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  as 2.49 eV and 2.36 eV, respectively. From the XPS valence spectra and the diffuse reflectance spectra (DRS), we have obtained the positions of the valence band (VB) and conduction band (CB) in  $\text{Bi}_3\text{O}_4\text{Br}$  and Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  (Fig. 2e and Fig. S4, ESI<sup>†</sup>). The VB after Ni doping becomes less positive. Hence, the Ni-doped

$\text{Bi}_3\text{O}_4\text{Br}$  is a better oxidizing catalyst than the pristine  $\text{Bi}_3\text{O}_4\text{Br}$ . On the other hand, the pristine  $\text{Bi}_3\text{O}_4\text{Br}$  is a better reducing catalyst than the Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  as the position of the CB is more negative for the  $\text{Bi}_3\text{O}_4\text{Br}$  than the Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$ .

To further characterize  $\text{Bi}_3\text{O}_4\text{Br}$  and Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$ , we also studied Raman and FTIR analysis, as depicted in Fig. S5 (ESI<sup>†</sup>). The Raman bands centered at 108.9 and 151.34  $\text{cm}^{-1}$  belong to the  $A_{1g}$  internal and  $E_g$  internal Bi-Br stretching modes, respectively (Fig. S5a, ESI<sup>†</sup>).<sup>39,40</sup> An increased peak intensity and broadening of the signals was observed for Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  compared to pristine  $\text{Bi}_3\text{O}_4\text{Br}$ . This can be attributed to the difference in electron-phonon coupling in the single-unit cell regime for the two compounds. The distinct signatures that appeared in the FTIR spectrum of  $\text{Bi}_3\text{O}_4\text{Br}$  at 1450–1190  $\text{cm}^{-1}$  can be ascribed to the asymmetric and symmetric stretching vibrations of Bi-Br bonds, while the peak at 524  $\text{cm}^{-1}$  is assigned to the Bi-O vibration modes (Fig. S5b, ESI<sup>†</sup>).<sup>39</sup> A broad band at 3442  $\text{cm}^{-1}$  and a peak at 1638  $\text{cm}^{-1}$  are associated with the stretching and bending vibration modes of  $\text{H}_2\text{O}$  molecules adsorbed on the surface of  $\text{Bi}_3\text{O}_4\text{Br}$  during FTIR analysis.<sup>41</sup> Similar characteristic peaks were also observed in the FTIR spectrum of the Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  material.

### Electrochemical and photoelectrochemical HER performance

The electrocatalytic HER performances of  $\text{Bi}_3\text{O}_4\text{Br}$  and Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  were studied by a series of electrochemical experiments in 1.0 M KOH (pH ~14.0) with a standard three-electrode system. Linear sweep voltammetry (LSV) measurements showed that Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  exhibited an overpotential of 545 and 662 mV to achieve a conventional current density of 10 and 50  $\text{mA cm}^{-2}$ , respectively. On the other hand, pristine  $\text{Bi}_3\text{O}_4\text{Br}$  showed an overpotential of 547 and 736 mV to attain the same current density (Fig. 5a). Hence, there is a significant

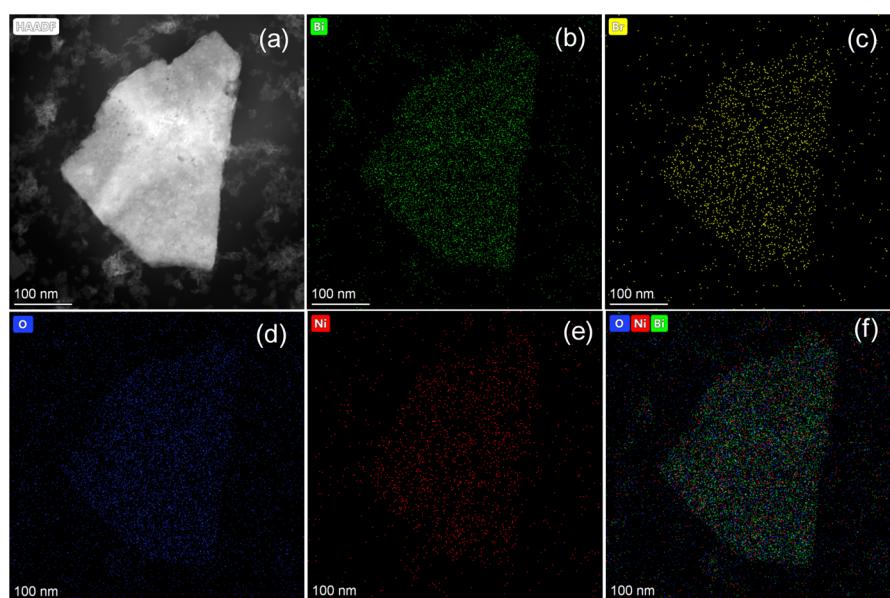


Fig. 4 (a) HAADF image of Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  for the elemental mapping of (b) Bi, (c) Br, (d) O, (e) Ni, and (f) mixed elements of Bi, O, and Ni.



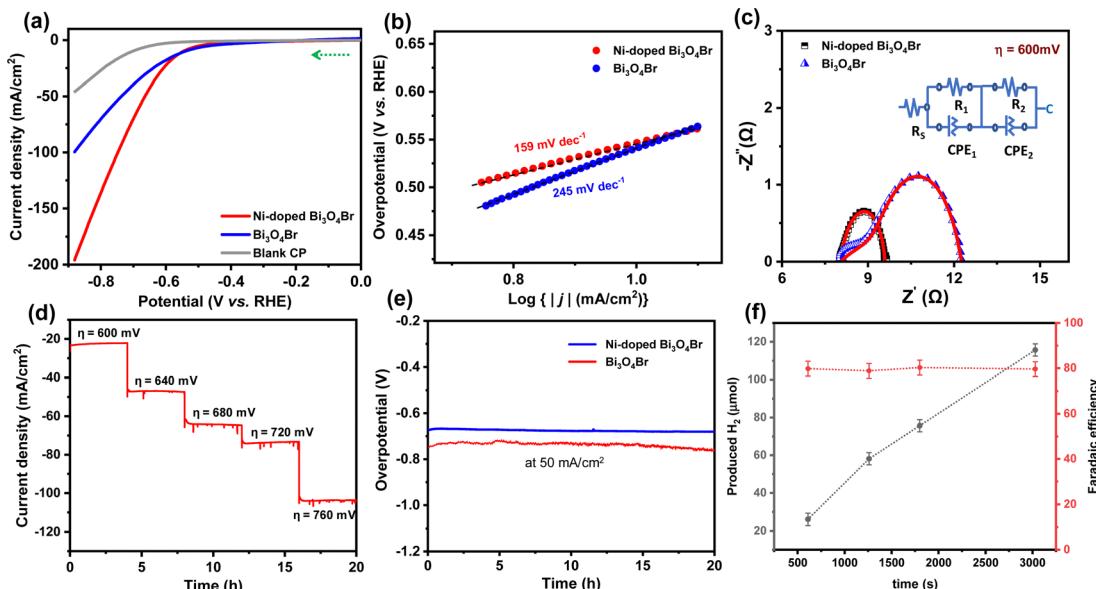


Fig. 5 (a) LSV polarization curves, (b) corresponding Tafel plots, (c) electrochemical impedance spectra obtained at an overpotential of 600 mV of the Ni-doped Bi<sub>3</sub>O<sub>4</sub>Br and Bi<sub>3</sub>O<sub>4</sub>Br catalysts. (d) Potential dependent chronoamperometry stability test of Ni-doped Bi<sub>3</sub>O<sub>4</sub>Br, (e) chronopotentiometry stability of Ni-doped Bi<sub>3</sub>O<sub>4</sub>Br and Bi<sub>3</sub>O<sub>4</sub>Br. (f) Time dependent hydrogen gas production ( $\mu\text{mol}$ ) and faradaic efficiency of the Ni-doped Bi<sub>3</sub>O<sub>4</sub>Br catalyst during chronoamperometry study at  $-0.6$  V vs. RHE.

deterioration in overpotential at higher current density after the Ni-doping into Bi<sub>3</sub>O<sub>4</sub>Br. The reaction kinetics of the catalysts were examined by Tafel slope analysis of the catalysts (Fig. 5b). A relatively low Tafel slope of  $159$  mV dec<sup>-1</sup> was exhibited by Ni-doped Bi<sub>3</sub>O<sub>4</sub>Br compared to the pristine Bi<sub>3</sub>O<sub>4</sub>Br ( $245$  mV dec<sup>-1</sup>), which indicated a better HER kinetics for the Ni-doped sample in an alkaline medium. Electrochemical impedance spectroscopy (EIS) was carried out at an applied overpotential of  $600$  mV to have a better insight into the charge transfer resistance ( $R_{\text{ct}}$ ) at the electrode and electrolyte interface. The obtained EIS spectra and corresponding circuit diagrams are represented in Fig. 5c, where  $R_{\text{s}}$  is the resistance of the electrolyte, and CPE is a constant phase element. The lower  $R_{\text{ct}}$  value of Ni-doped Bi<sub>3</sub>O<sub>4</sub>Br ( $1.55$   $\Omega$ ) further confirms higher electron transfer ability across the electrode and electrolyte interface than that of Bi<sub>3</sub>O<sub>4</sub>Br ( $5.12$   $\Omega$ ) during the HER process. Therefore, it can be concluded that Ni-doping substantially improves the background HER activity of Bi<sub>3</sub>O<sub>4</sub>Br.

To explore the enhanced activity, double layer capacitance ( $C_{\text{dl}}$ ) values of the catalysts were measured, followed by the electrochemically active surface area (ECSA) from CV measurements in a non-faradaic potential region (Fig. S6, ESI<sup>†</sup>). A higher ECSA value ( $40.5$   $\text{cm}^2$ ) was observed for the Ni-doped Bi<sub>3</sub>O<sub>4</sub>Br catalyst in comparison to the precursor Bi<sub>3</sub>O<sub>4</sub>Br ( $31.5$   $\text{cm}^2$ ). This data implies that Ni-doped Bi<sub>3</sub>O<sub>4</sub>Br possesses more active sites, which is beneficial for the adsorption of water molecules and close contact with the electrolyte during HER catalysis. The LSV results of the materials are normalized with these obtained electrochemically active surface area values to provide the intrinsic effect of Ni-doping in the Bi<sub>3</sub>O<sub>4</sub>Br template (Fig. S7, ESI<sup>†</sup>). The ECSA normalized LSV plots represent that the HER activity trend is maintained, as it is in the geometric area normalized polarization curve for Ni-doped Bi<sub>3</sub>O<sub>4</sub>Br and

Bi<sub>3</sub>O<sub>4</sub>Br catalysts. Moreover, the mass activity of Bi<sub>3</sub>O<sub>4</sub>Br was improved drastically from  $52$  to  $98$   $\text{A g}^{-1}$  after incorporation of Ni in the pristine nanostructure (Fig. S8, ESI<sup>†</sup>).

In addition to showcasing the HER performance, long-term stability is another crucial factor for a promising electrocatalyst that can be translated to industrial applications. A potential-dependent chronoamperometry stability test was performed with  $4.0$  hour intervals (Fig. 5d). The chronoamperometry stability test demonstrated consistent current densities at different applied overpotential values. In addition, we have studied the chronopotentiometry stability of the Ni-doped Bi<sub>3</sub>O<sub>4</sub>Br and Bi<sub>3</sub>O<sub>4</sub>Br catalysts at the current density of  $50$   $\text{mA cm}^{-2}$  which exhibited an enhancement in the overpotential of  $13$  and  $17$  mV after  $20$  hours, respectively (Fig. 5e). Therefore, Ni-doped Bi<sub>3</sub>O<sub>4</sub>Br demonstrates superior durability in a strongly alkaline medium while displaying HER activity. Interestingly, the pristine Bi<sub>3</sub>O<sub>4</sub>Br catalyst exhibited a significant loss of  $19\%$  current density after an analogous  $20$  hours chronoamperometry stability test (Fig. S9, ESI<sup>†</sup>). Notably, the incorporation of Ni ions into Bi<sub>3</sub>O<sub>4</sub>Br not only enhanced the HER activity but also improved the durability of the catalyst. Faradaic efficiency is an important parameter to measure the efficiency of charge transfer in an electrochemical reaction. It was measured by comparing the theoretically and experimentally obtained amount of H<sub>2</sub>, which was evaluated using a gas chromatography (GC) instrument equipped with a TCD detector and  $5$   $\text{\AA}$  molecular sieve column for separation of the gases with argon as the carrier gas (CIC Dhruva). The GC instrument was calibrated using three standard gas samples containing  $1\%$ ,  $2\%$ , and  $5\%$  H<sub>2</sub>, respectively. The Bi<sub>3</sub>O<sub>4</sub>Br and Ni-doped Bi<sub>3</sub>O<sub>4</sub>Br catalyst exhibited a faradaic efficiency of  $\sim 65$  and  $79\%$  for the HER in an alkaline medium (pH  $\sim 14.0$ ) with constant



growth in accumulated  $\text{H}_2$  during the chronoamperometric experiment (Fig. 5f and Fig. S10 and S11, ESI<sup>†</sup>).

Moreover, we have also studied the photoelectrochemical HER performance under UV-vis light irradiation. LSV measurements displayed that  $\text{Bi}_3\text{O}_4\text{Br}$  exhibited an overpotential of 614 and 668 mV to achieve a conventional current density of 10 and 50  $\text{mA cm}^{-2}$ , whereas the same current density was exhibited by Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  at the overpotential of 418 and 614 mV, respectively (Fig. 6a). Therefore, a significant improvement in overpotential was observed in the HER performance under UV-vis light irradiation. Furthermore, a substantial increase in photocurrent response by 60% was observed for the Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  compared to that of  $\text{Bi}_3\text{O}_4\text{Br}$  in the PEC measurements, indicating that enhanced charge separation occurred due to the incorporation of Ni in the  $\text{Bi}_3\text{O}_4\text{Br}$  catalyst (Fig. 6c and d). The faradaic efficiency of Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  was calculated to be 87% during the photoelectrocatalytic HER, which was ~33% and 10% superior to that of  $\text{Bi}_3\text{O}_4\text{Br}$ , and Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  during the electrocatalytic HER process, respectively (Fig. 6b and Fig. S11, ESI<sup>†</sup>).

We have studied the post-electrocatalytic ECSA of the Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  catalyst, which was found to be  $1.51 \text{ cm}^2$  (Fig. S14, ESI<sup>†</sup>). The 6.79% decrease in electrochemically active

surface area may be due to the leaching out of Ni, which is one of the effective active areas. This statement can also be supported by the before and post-catalytic ICP-AES analysis of the Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  catalyst as described in the ESI<sup>†</sup>. Moreover, we have deeply focused on the stability of the catalyst after the long-term electrochemical HER performance test. The structural stability studied was determined using a powder XRD pattern (Fig. S15, ESI<sup>†</sup>); on the other hand the morphological stability of the catalyst was investigated by TEM and bright field elemental mapping (Fig. S16 and S17, ESI<sup>†</sup>). No such morphological and structural deformation was observed after the long-term electrocatalytic HER performance test of the catalyst.

## Conclusions

This specific cation doping approach is certainly one of the best ways to explicitly enhance the electrocatalytic HER performance under alkaline conditions with highly exposed active sites. The doping of Ni ions in  $\text{Bi}_3\text{O}_4\text{Br}$  facilitated the reduction of the overpotential and improved the kinetics during the HER activity. The electrochemically active surface area and mass activity of  $\text{Bi}_3\text{O}_4\text{Br}$  were improved drastically by 29% and 88%,

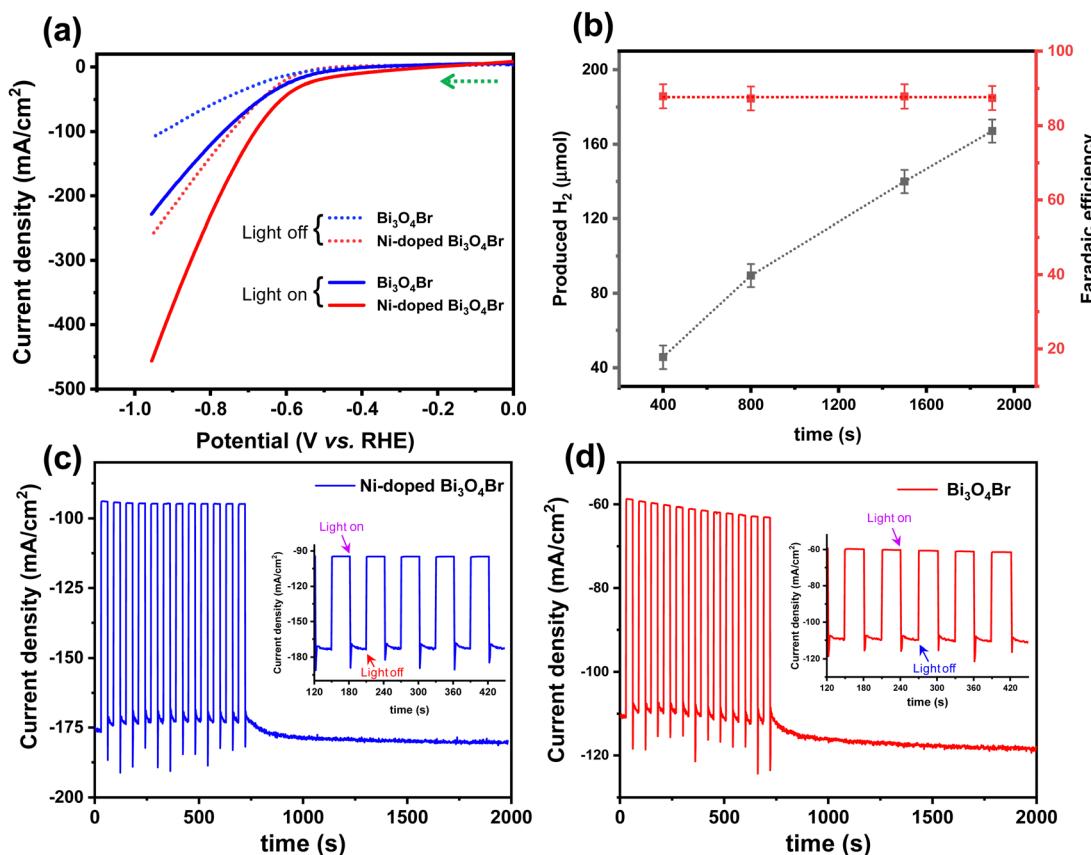


Fig. 6 Photocurrent response and electrocatalytic performance: (a) LSV polarization curves of Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  and  $\text{Bi}_3\text{O}_4\text{Br}$  catalysts in the presence and absence of light, (b) amount of  $\text{H}_2$  produced and faradaic efficiency of Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  during chronoamperometry study at  $-0.62 \text{ V}$  vs. RHE. (c) and (d) Photocurrent response (in chopping mode, light on–off repeatedly) of the Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  and  $\text{Bi}_3\text{O}_4\text{Br}$  catalysts under UV-vis light irradiation (300 W Xe lamp) at an applied potential of  $-0.73 \text{ V}$  (vs. RHE) in  $1 \text{ M KOH}$  solution.



respectively, after the incorporation of Ni ions in the pristine nanostructure. Substantial improvement in the HER performance and faradaic efficiency were also observed under UV-vis light irradiation that contributes to the accelerated evolution of hydrogen in the photocatalysis system. The durability of the  $\text{Bi}_3\text{O}_4\text{Br}$  template was also enhanced following the Ni-doping, which was evident from the stable current density and negligible change in overpotential during a 20-hour stability test at an applied current density of  $50 \text{ mA cm}^{-2}$ . The present work not only demonstrates a facile approach to fabricate cost-effective HER catalysts but also explores a new route to develop a sustainable and highly efficient robust electrocatalyst derived from the family of transition metal-doped semiconductor materials. Ni-doped  $\text{Bi}_3\text{O}_4\text{Br}$  nanostructured materials can further be used in the field of sensors, supercapacitors, and photochemical small molecule activation reactions, aiding the journey towards a carbon-neutral landscape.

## Author contributions

SB and AD conceptualized the project; MP, RB, and SB performed the experiments; MP, RB, SB, and AD analyzed the data; RB, SB and AD wrote the manuscript; SB and AD revised and edited the manuscript; AD supervised the project.

## Conflicts of interest

The authors declare no competing financial interest.

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