

Rapid flash Joule heating synthesis of Pt-doped carbon fibers for efficient hydrogen evolution in acidic and alkaline media

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ABSTRACT

Developing highly active, pH-universal electrocatalysts for the hydrogen evolution reaction (HER) is challenging because water dissociation kinetics are slow in alkaline environments. This work introduces a scalable Flash Joule Heating (FJH) method to synthesize efficient Pt-doped carbon nanofiber (Pt-CF) catalysts for HER in both acidic and alkaline electrolytes. Characterization results show that adjusting the FJH voltage allows precise control of the Pt electronic structure and the metal-carbon interface. The 150 V/Pt-CF sample exhibited a higher platinum loading (5.41 wt%) and primarily consisted of metallic Pt⁰. In comparison, 200 V/Pt-CF catalyst showed a lower Pt loading (3.61 wt%) and contained both Pt⁰ and Pt²⁺. The results indicate that applied voltage influences the Pt oxidation state and surface chemistry. Electrochemical measurements reveal clear pH-dependent behavior. In acidic media (0.5 M H₂SO₄), 200 V/Pt-CF catalyst shows faster HER kinetics, indicated by a lower Tafel slope (23.43 mV dec⁻¹) and a slightly reduced overpotential (56 mV at 10 mA cm⁻²). Under alkaline conditions (1.0 M KOH), 150 V/Pt-CF catalyst performs better, requiring only 25 mV to reach 10 mA cm⁻², with improved kinetics and higher intrinsic activity. This work provides a scalable strategy for designing high-performance metal-carbon electrocatalysts that are effective over a wide pH range via flash Joule heating.

1. Introduction

The pressing need to decarbonize the energy sector has positioned green hydrogen as a key pillar of future sustainable energy systems. Produced through water electrolysis powered by renewable electricity, green hydrogen provides a carbon-free alternative that separates industrial hydrogen demand from fossil fuels [1,2]. By 2050, hydrogen could supply up to 18% of global final energy demand, highlighting the need for efficient and scalable production methods [3,4]. A major challenge is the hydrogen evolution reaction, the cathodic half-reaction in water electrolysis, which faces slow charge-transfer kinetics and high activation barriers. These factors increase overpotentials, reduce energy efficiency, and raise hydrogen production costs [4–6]. The performance of electrocatalysts is key to the efficiency, stability, and cost of the hydrogen evolution reaction. Platinum remains the standard HER electrocatalyst due to its hydrogen adsorption free energy ($\Delta G_{H^*} \approx 0$ eV), which allows Pt to readily absorb and desorb protons in both acidic and alkaline environments [6–8]. However, using Pt on an industrial scale is limited by its low abundance and high cost. During electrochemical operation, Pt nanoparticles can undergo Ostwald ripening,

agglomeration, and surface reconstruction. These changes reduce the number of active sites and lower catalytic performance over time [9]. Immobilizing Pt on conductive carbon-based support is the most effective way to improve atomic utilization, electronic tunability, and long-term durability. Among these supports, carbon nanomaterials, such as carbon nanofibers, carbon nanotubes, and graphene derivatives, offer a unique combination of properties for HER electrocatalysis [10–12]. Their high electrical conductivity results in rapid electron transport to Pt sites, while their large surface area supports uniform Pt dispersion and increases active-site density. The tunable defect chemistry of carbon supports can prevent Pt nanoparticle migration and coalescence during operation. These metal-support interactions also adjust the d-band electronic structure of Pt, bringing hydrogen adsorption energetics closer to the thermoneutral ideal and enhancing HER activity [13,14]. Carbon nanofibers are particularly advantageous due to their three-dimensional interconnected structure, which supports efficient electrolyte infiltration and mechanical stability during extended electrochemical cycling [15,16]. Despite recent advances, synthesizing Pt/CF electrocatalysts with precise nanoscale structures and optimal interfacial electronic properties remains challenging. Common methods such

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as wet-chemical reduction, hydrothermal synthesis, and thermal annealing operate near thermodynamic equilibrium and exhibit slow nucleation rates. This makes it hard to control the size and dispersion of Pt particles, as well as their interactions with the support. Long-duration high-temperature treatment can also induce nanoparticle agglomeration and alter active sites, thereby reducing the catalyst's uniformity and long-term stability [17].

Flash Joule heating is an advanced synthesis method that can overcome key limitations of traditional techniques. It operates by applying a high-density electrical current pulse to a carbon-based material, rapidly increasing the temperature above 3000 K within milliseconds, followed by rapid cooling [18–21]. This process pushes the system far from equilibrium, allowing the creation of metastable phases, defect-rich interfaces, and unusual electronic structures that standard thermal methods cannot achieve [19,21].

When applied to Pt-loaded CF precursors, rapid temperature changes decompose the Pt precursor, forming small, uniformly distributed Pt particles on the CF surface. Fast cooling limits nanoparticle growth, prevents agglomeration, and promotes strong Pt–carbon bonding. These effects improve the accessibility of active sites, speed up electron transfer, and improve structural stability during electrocatalysis. FJH is also energy-efficient and scalable, taking only seconds to process materials, while traditional methods can take hours.

This study introduces a fast, scalable flash Joule heating method for producing Pt-doped carbon nanofibers with tunable structural and electronic properties. We synthesized Pt–CF electrocatalysts using FJH at 150 and 200 V to investigate the impact of rapid heating on Pt distribution, defect formation, and metal–support interactions. The properties of the catalysts were characterized using scanning electron microscopy (SEM), transmission electron microscopy (TEM), energy-

dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD), Raman spectroscopy, inductively coupled plasma optical emission spectroscopy (ICP-OES), and X-ray photoelectron spectroscopy (XPS). Electrocatalytic HER performance was evaluated in both acidic and alkaline conditions, including assessments of reaction kinetics and long-term stability. The results demonstrate that FJH is an effective approach for producing highly active and durable Pt–carbon electrocatalysts for sustainable hydrogen production.

2. Experimental section

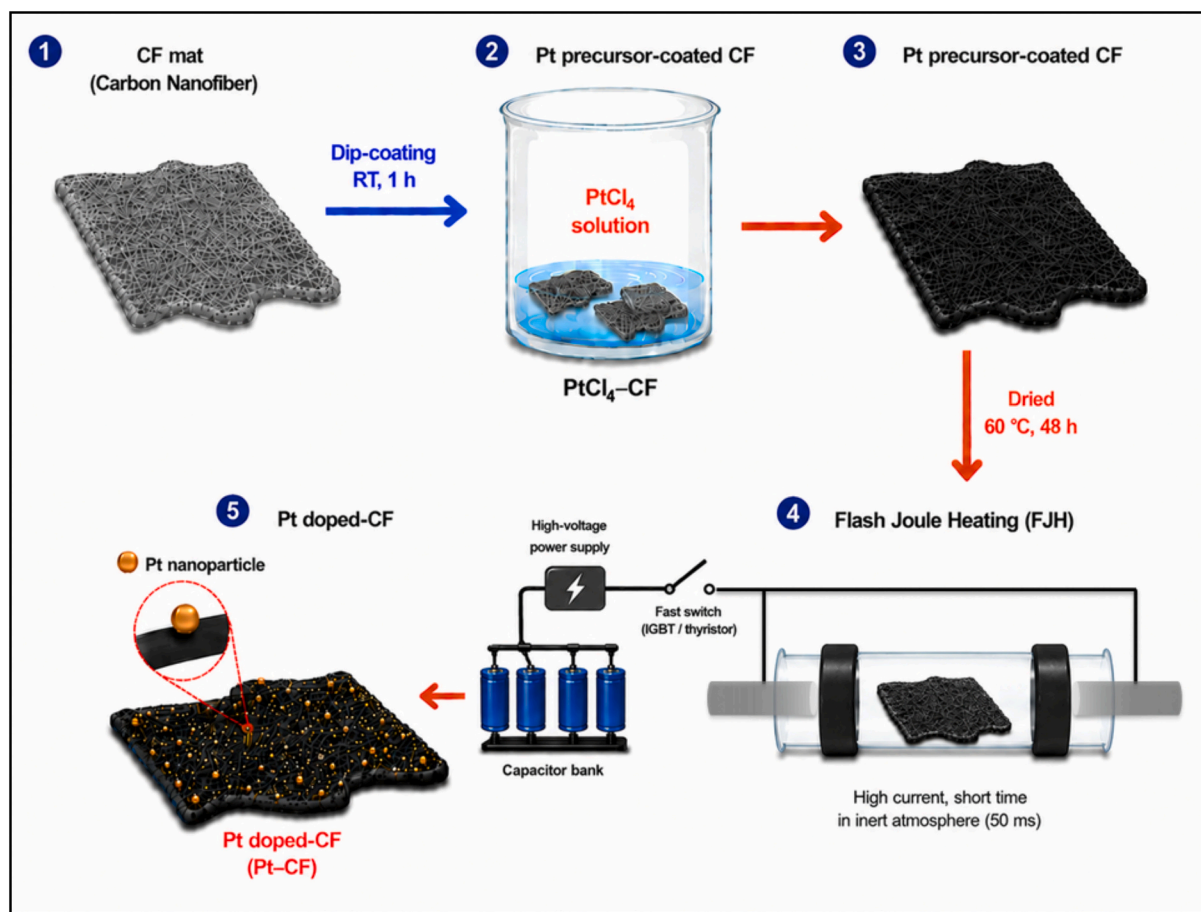
2.1. Materials

2.1.1. Chemicals

Platinum(IV) chloride (PtCl_4 , 96%, Sigma-Aldrich), sulfuric Acid (H_2SO_4 , 98%, J.T Baker), potassium hydroxide (KOH, Pellets, 85%, Alfa Aesar). Commercial platinum on carbon black (nominally 20 wt% Pt/C, Alfa Aesar) was used as the reference catalyst. All chemicals were used as received without further purification.

2.1.2. Preparation of Pt–CF catalysts

Carbon nanofibers were purchased from Sigma-Aldrich and cut into small pieces before use. Pt-doped carbon fiber was synthesized using the flash Joule heating process (Scheme 1), as described in previous studies [18,22]. For preparation, CF substrates were immersed in 10 mL of 0.1 M PtCl_4 solution for 60 min to allow precursor adsorption, then dried at 60 °C for 48 h. The dried, Pt-loaded CF was placed in a quartz tube (1.8 cm inner diameter) and connected to carbon electrodes at both ends for the FJH treatment. The distance between the electrodes was adjusted to maintain a resistance of 10 Ω . A short electrical pulse lasting 50 ms was



Scheme 1. Schematic illustration of FJH-assisted synthesis of Pt-doped CF.

applied to rapidly heat the sample. The influence of FJH voltage on the structural and electrocatalytic properties of Pt-CF was examined by applying voltages of 150 V and 200 V during the FJH process. The resulting samples were denoted as 150 V/Pt-CF and 200 V/Pt-CF, corresponding to the applied voltages of 150 and 200 V, respectively.

2.2. Characterization of catalysts

Surface structure and morphology were characterized by scanning electron microscopy (SEM, S-4300, Hitachi) operated at 15 kV. Elemental composition of the samples was determined by energy-dispersive X-ray spectroscopy (EDS; X-Max-65 T, Oxford). The crystal-line structures of CF and Pt-doped CF samples were examined by X-ray diffraction (XRD, D8 Discover+, Bruker AXS GmbH) with Cu K α radiation (1.54 Å). Surface chemical composition and oxidation states were assessed using X-ray photoelectron spectroscopy (XPS, K Alpha+, Thermo VG). Transmission Electron Microscope (TEM) and High-Resolution Transmission Electron Microscope (HRTEM) images were obtained using JSM-7900F (JEOL, Japan). Raman spectra were recorded using a Raman spectrometer (XperRam Compact, Nanobase, South Korea) equipped with a 532 nm laser. Inductively coupled plasma optical emission spectroscopy (ICP-OES; Agilent 5110) was used to determine the Pt content of the 150 V/Pt-CF and 200 V/Pt-CF catalysts.

2.3. Electrochemical measurements

To prepare the working electrode, 2 mg of catalyst was mixed with 1 mL of ethanol and 40 μ L of 5 wt% Nafion solution. This mixture was sonicated for 30 min to form a uniform ink. Next, 7.5 μ L of the catalyst ink was placed on a glassy carbon electrode (3 mm diameter) and left to dry at room temperature, resulting in a catalyst loading of 0.215 mg cm⁻². Electrochemical measurements were carried out using a Metrohm Autolab electrochemical workstation with a standard three-electrode setup. A saturated Ag/AgCl electrode served as the reference electrode, and a platinum wire was used as the counter electrode. The potential of the saturated Ag/AgCl electrode versus the reversible hydrogen electrode (RHE) was calculated using Eq. (1):

$$E(\text{vs. RHE}) = E(\text{vs. Ag/AgCl}) + E^\circ(\text{Ag/AgCl}) + 0.0591 \times \text{pH} \quad (1)$$

where $E(\text{vs. RHE})$ is the potential vs. RHE, $E(\text{vs. Ag/AgCl})$ is the potential vs. Ag/AgCl, and $E^\circ(\text{Ag/AgCl})$ is the potential of Ag/AgCl with respect to the standard hydrogen electrode.

Before starting the electrochemical measurements, dissolved oxygen was removed from 0.5 M H₂SO₄ and 1 M KOH electrolytes by bubbling high-purity nitrogen for 30 min. Catalysts were activated using 10 cyclic voltammetry (CV) scans from 0 to 0.5 V versus RHE at a scan rate of 100 mV s⁻¹. Afterward, linear-sweep voltammetry (LSV) polarization curves were recorded at a scan rate of 20 mV s⁻¹ with 90% iR compensation applied to correct for an uncompensated solution resistance (R_s) of 6–8 Ω .

Electrochemical impedance spectroscopy (EIS) measurements were performed from 100 kHz to 1 Hz using a sinusoidal potential signal with 5 mV amplitude. The Tafel slopes for the catalysts were determined from Tafel plots using Eq. (2):

$$\eta = a + b \log j \quad (2)$$

where η is the overpotential, j is the current density and b is the Tafel slope.

The double-layer capacitance (C_{dl}) and turnover frequency (TOF) were further analyzed to determine the electrochemically accessible surface area and the intrinsic HER activity of the Pt-CF catalysts. The Cdl values were obtained from cyclic voltammetry (CV) measurements at scan rates between 20 and 120 mV s⁻¹ in the non-faradaic potential region.

The slope of the plot of $(j_a - j_c)/2$ versus scan rate was used to

estimate the Cdl. Further, the TOF was calculated to assess the intrinsic catalytic activity of the Pt-CF catalysts as described by Eq. (3).

$$\text{TOF} = \frac{j(E) \cdot A}{2F \cdot N_{\text{active}}} \quad (3)$$

Here, $j(E)$ is the measured current density at the selected potential, A is the geometric electrode area (0.0706 cm²), F is the Faraday constant (96,485 C mol⁻¹), and N_{active} is the number of electrochemically active sites. The active site density was estimated from the electrochemically active surface area (ECSA) obtained from CV/Cdl measurements using Eq. (4):

$$N_{\text{active}} = \text{ECSA} \times \Gamma / N_A \quad (4)$$

where $\Gamma = 1.3 \times 10^{15}$ sites cm⁻² (Pt surface atoms); N_A = Avogadro number 6.022×10^{23} .

2.3.1. Stability tests

The stability of the 150 V/Pt-CF catalyst was evaluated by chronopotentiometry in 0.5 M H₂SO₄ and 1 M KOH at a constant current density of 10 mA cm⁻². LSV, Tafel, EIS, and Cdl measurements were performed using catalyst ink drop-cast on GCE, whereas chronopotentiometry stability was evaluated using catalyst-loaded carbon paper.

3. Results and discussion

3.1. Characterization of catalysts

3.1.1. Surface morphology and microstructure

Scanning electron microscopy analysis demonstrates that the 150 V Flash Joule Heating treatment produces an enhanced electrocatalytic architecture. As shown in Fig. 1a, carbon nanofibers exhibited an interconnected network of uniformly distributed fibers with consistent diameter and smooth surface morphology [15,16,23]. However, the doped samples 150 V/Pt-CF and 200 V/Pt-CF consist of a carbon fiber network with platinum nanoparticles uniformly distributed on the surface (Fig. 1b and c). The result confirms the successful loading of Pt onto CF through the FJH method [23]. Moreover, the 150 V/Pt-CF catalyst exhibits a more uniform distribution of platinum nanoparticles on the carbon fiber than the 200 V/Pt-CF sample. This higher Pt nanoparticle density in 150 V/Pt-CF is expected to improve hydrogen evolution reaction performance by increasing the electrochemically active surface area. The results also suggest that higher voltages decrease the loading of Pt nanoparticles onto CF. This behavior is likely due to elevated temperatures, which induce accelerated metal sintering and result in the coalescence of Pt species into larger aggregated clusters [19–21].

Transmission electron microscopy (TEM) was conducted to examine the morphology and distribution of Pt species on 150 V/Pt-CF and 200 V/Pt-CF catalysts. As shown in Fig. 2a, the undoped CF has a smooth surface without visible Pt particles [13,23,25]. After the FJH treatment, Pt particles are observed on the CF surface in both the 150 V/Pt-CF and 200 V/Pt-CF samples, confirming the successful formation of Pt species on the carbon nanofibers [25,26]. Compared with 200 V/Pt-CF, 150 V/Pt-CF catalyst shows smaller and more uniformly distributed Pt particles. The larger Pt particles observed in the 200 V/Pt-CF sample may result from the higher thermal energy generated during the FJH treatment, which promotes Pt particle growth and aggregation. In contrast, the smaller particle size and more uniform Pt dispersion in the 150 V/Pt-CF sample may increase the number of accessible active sites, thus contributing to its improved HER performance.

High-resolution TEM (HRTEM) further reveals the crystalline structure of the Pt particles [23,26]. The HRTEM image of 150 V/Pt-CF (Fig. 2f) shows clear lattice fringes with a spacing of 0.226 nm, corresponding to the Pt (111) plane. Similarly, the 200 V/Pt-CF sample (Fig. 2g) exhibits a lattice spacing of 0.225 nm, which is also assigned to

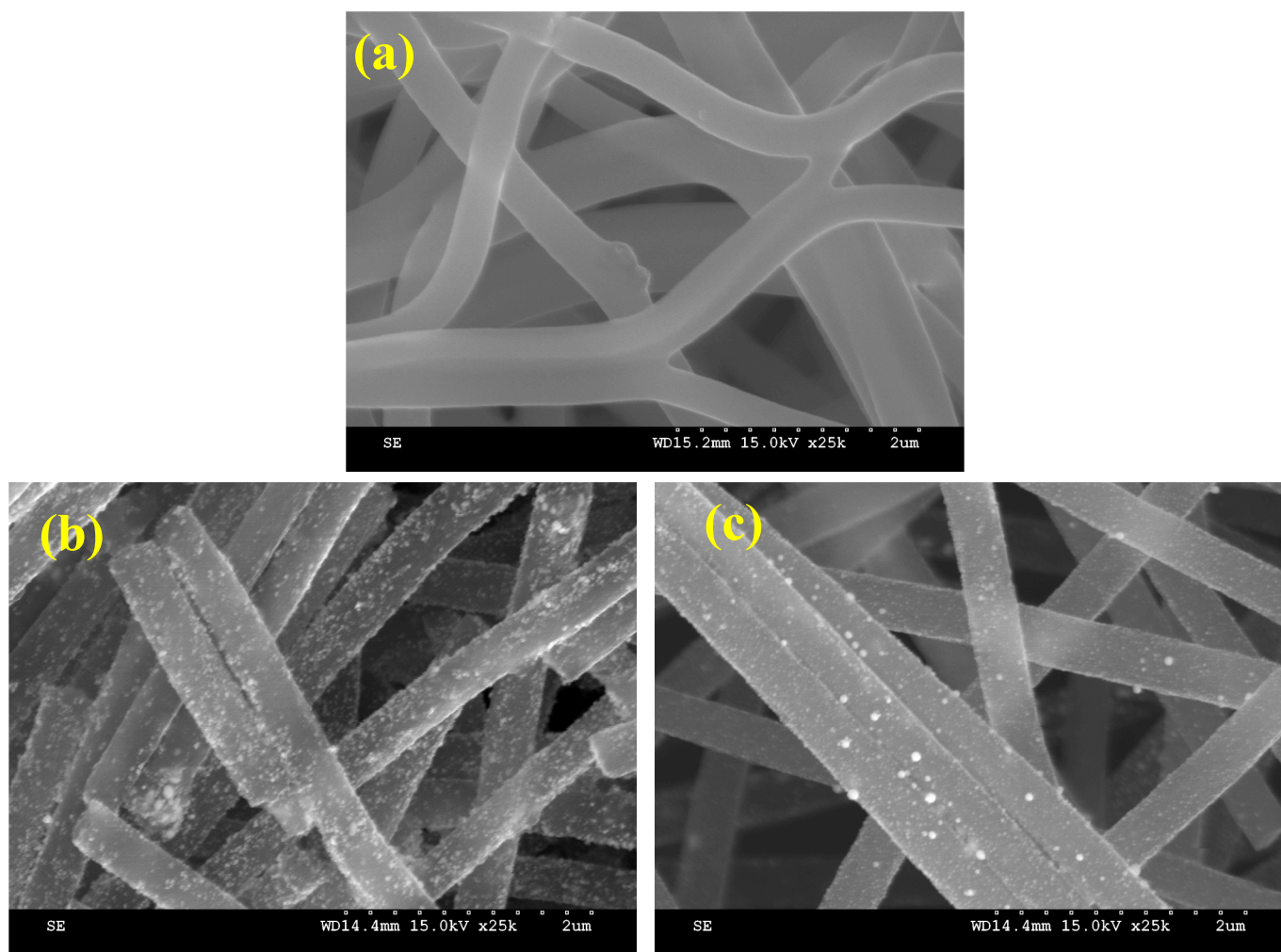


Fig. 1. Surface morphologies of (a) CF, (b) 150 V/Pt-CF, and (c) 200 V/Pt-CF.

the Pt (111) plane. In addition, a larger lattice spacing around 0.245 nm is observed in the 200 V/Pt-CF sample [26,27]. This may be related to the presence of surface oxide species or partial oxidation at the Pt surface.

3.1.2. Elemental composition and distribution

Energy-dispersive X-ray spectroscopy (EDS) and elemental mapping were used to analyze the elemental composition and distribution of the synthesized catalysts (Fig. S1). The pristine CF sample (Fig. S1a–b) shows only a carbon signal, confirming the absence of Pt species in the unmodified carbon fibers [16,23,25]. After the FJH treatment, the 150 V/Pt-CF and 200 V/Pt-CF catalysts exhibit clear Pt signals (Fig. S1c–f), confirming the successful incorporation of Pt onto the carbon fibers [23,25]. Moreover, the elemental mapping images (Fig. S1e and S1h) reveal that Pt is more uniformly distributed in the 150 V/Pt-CF sample than in the 200 V/Pt-CF sample, indicating enhanced Pt dispersion at the lower FJH voltage.

The Pt loading of the catalysts was quantified by ICP-OES (Table 1). The 150 V/Pt-CF sample exhibited a higher Pt loading (5.41 wt%) than the 200 V/Pt-CF sample (3.61 wt%). Both catalysts were prepared using the same amount of Pt precursor, but the final Pt loading differed after FJH treatment, suggesting that the applied voltage affects Pt deposition and retention on the carbon fiber surface. The higher Pt loading in 150 V/Pt-CF may contribute to its improved HER performance. However, the improved catalytic activity likely results from a combination of factors, including higher Pt loading, reduced Pt particle size, more uniform Pt dispersion, a favorable Pt electronic structure, and enhanced

conductivity of the carbon support.

3.1.3. Raman analysis

The Raman spectrum of CF (Fig. 3) exhibits broad peaks at around 1366 cm^{-1} (D band) and 1672 cm^{-1} (G band), which are attributed to defect-induced disordered carbon and graphitic sp^2 carbon, respectively [25,26,28,29]. Moreover, the I_D/I_G ratio of CF was calculated to be 1.04, indicating a highly defective carbon structure with a low degree of graphitization [23,25,30,31]. After FJH treatment, the 150 V/Pt-CF and 200 V/Pt-CF samples show significant changes compared with CF. In detail, the D and G bands become sharper, and a clear 2D band appears at around 2710 cm^{-1} . At the same time, the I_D/I_G ratio decreases significantly to 0.138 for 150 V/Pt-CF and 0.160 for 200 V/Pt-CF, indicating greater graphitization and reduced structural disorder [23,26,31].

The 200 V/Pt-CF sample shows a slightly higher I_D/I_G ratio than the 150 V/Pt-CF sample, which might be due to the higher FJH voltage introducing a limited number of additional structural defects. In addition, more intense thermal treatment can produce local lattice distortion while maintaining a highly graphitized carbon framework. Nevertheless, the sharp G band and well-defined 2D band confirm that a highly ordered graphitic framework is maintained in both FJH-treated samples [26,27,32]. The improved graphitic ordering of the carbon support expected to enhance electrical conductivity, electron transport and provide a stable environment for Pt species during electrocatalytic reactions [27,33].

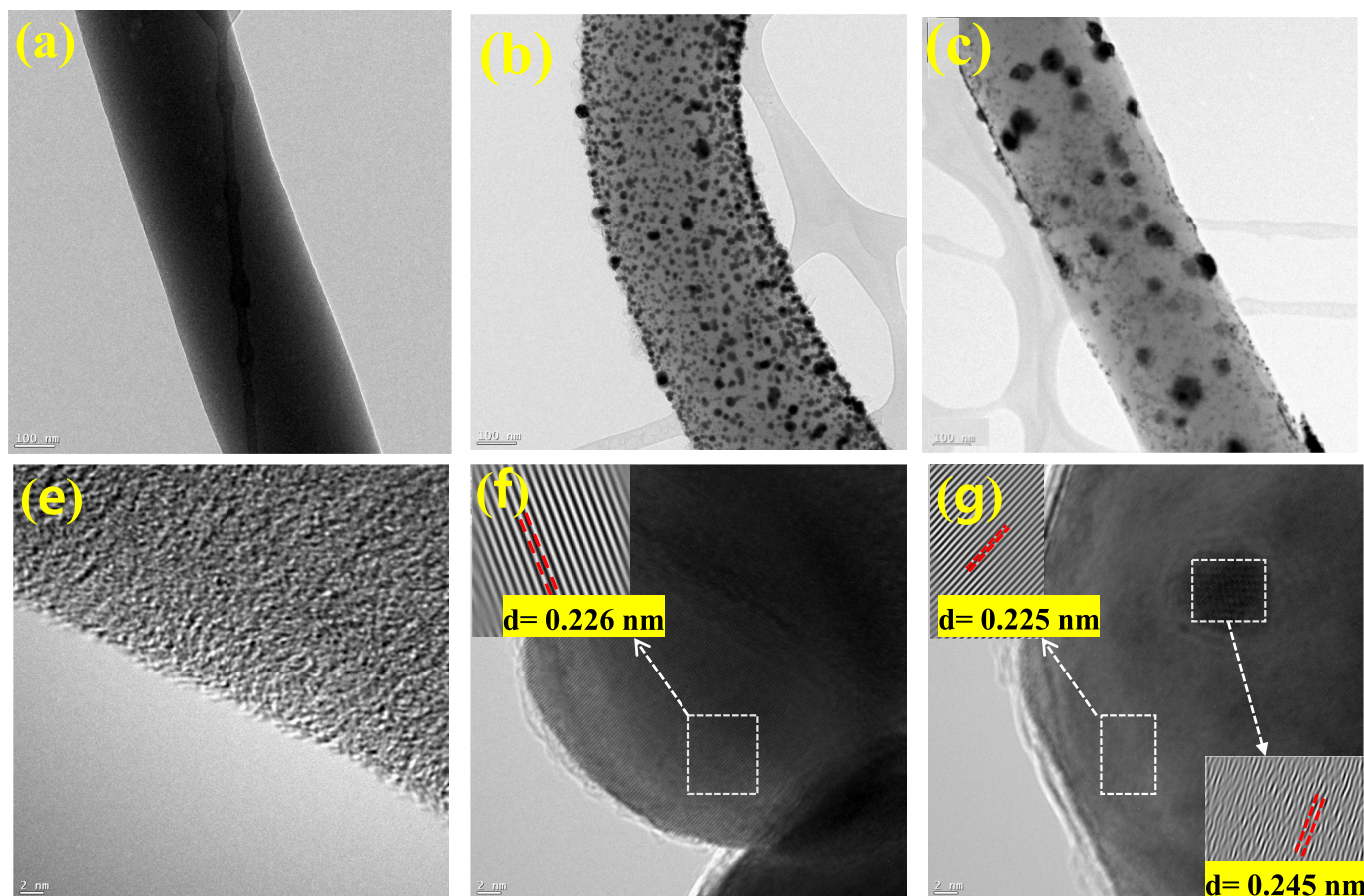


Fig. 2. TEM and HRTEM images of (a,e) CF, (b,f) 150 V/Pt-CF, and (c,g) 200 V/Pt-CF.

Table 1

Pt loading of catalysts determined by ICP-OES.

Material	Pt loading (wt%)
CF	0
150 V/Pt-CF	5.41
200 V/Pt-CF	3.61

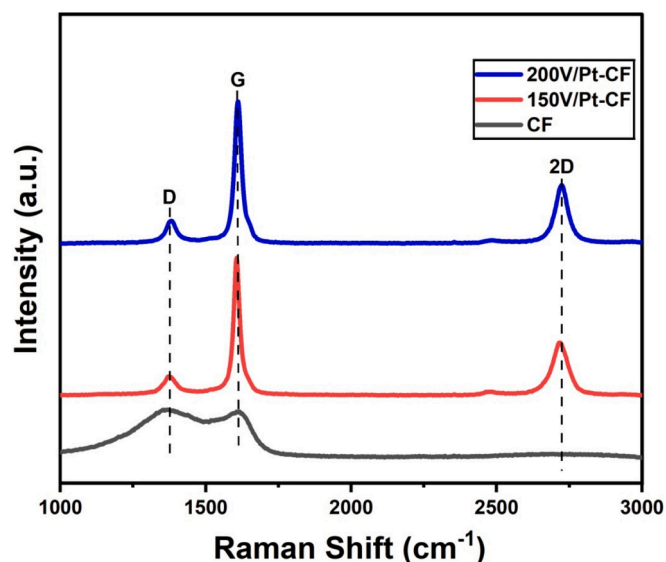


Fig. 3. Raman spectra of CF, 150 V/Pt-CF and 200 V/Pt-CF.

3.1.4. X-ray diffraction

The XRD patterns of CF, 150 V/Pt-CF, and 200 V/Pt-CF are shown in Fig. 4. The undoped CF sample exhibits a strong diffraction peak at around $2\theta = 26^\circ$ and a weak peak at around $2\theta = 43^\circ$, which correspond to the (002) and (101) planes of graphitic carbon, respectively (Fig. 4a) [29,32]. The peaks match well with the standard pattern of graphitic carbon (JCPDS Card No. 75-1621) [16,23]. However, the doped samples (150 V/Pt-CF and 200 V/Pt-CF) prepared through the FJH treatment display additional peaks at around $2\theta = 39.7^\circ$, 46.2° , 67.4° , and 81.2° (Fig. 4b and c). These peaks are assigned to the (111), (200), (220), and (311) planes of Pt, respectively, and agree well with the standard Pt pattern (JCPDS Card No. 04-0802) [23,25,26]. The results confirm the successful incorporation of crystalline Pt species onto the carbon nanofibers through the FJH process. Compared with 200 V/Pt-CF, the 150 V/Pt-CF sample shows stronger Pt diffraction peaks, suggesting higher Pt crystallinity or a larger amount of detectable crystalline Pt. This result suggests that the lower treatment voltage provides suitable thermal energy for Pt precursor reduction and crystallization while maintaining the carbon nanofiber support. The weaker Pt peaks observed for 200 V/Pt-CF may be associated with changes in Pt crystallinity or reduced retention of crystalline Pt during the higher-voltage treatment.

The results from XRD analysis also demonstrate that control of thermal energy during FJH is important for tuning platinum crystallization and retaining the stability of the CF-supported catalyst [19,21].

3.1.5. X-ray photoelectron spectroscopy

X-ray photoelectron spectroscopy (XPS) was utilized to analyze the surface chemical composition and electronic states of both doped and undoped samples. The XPS survey spectra of CF, 150 V/Pt-CF, and 200

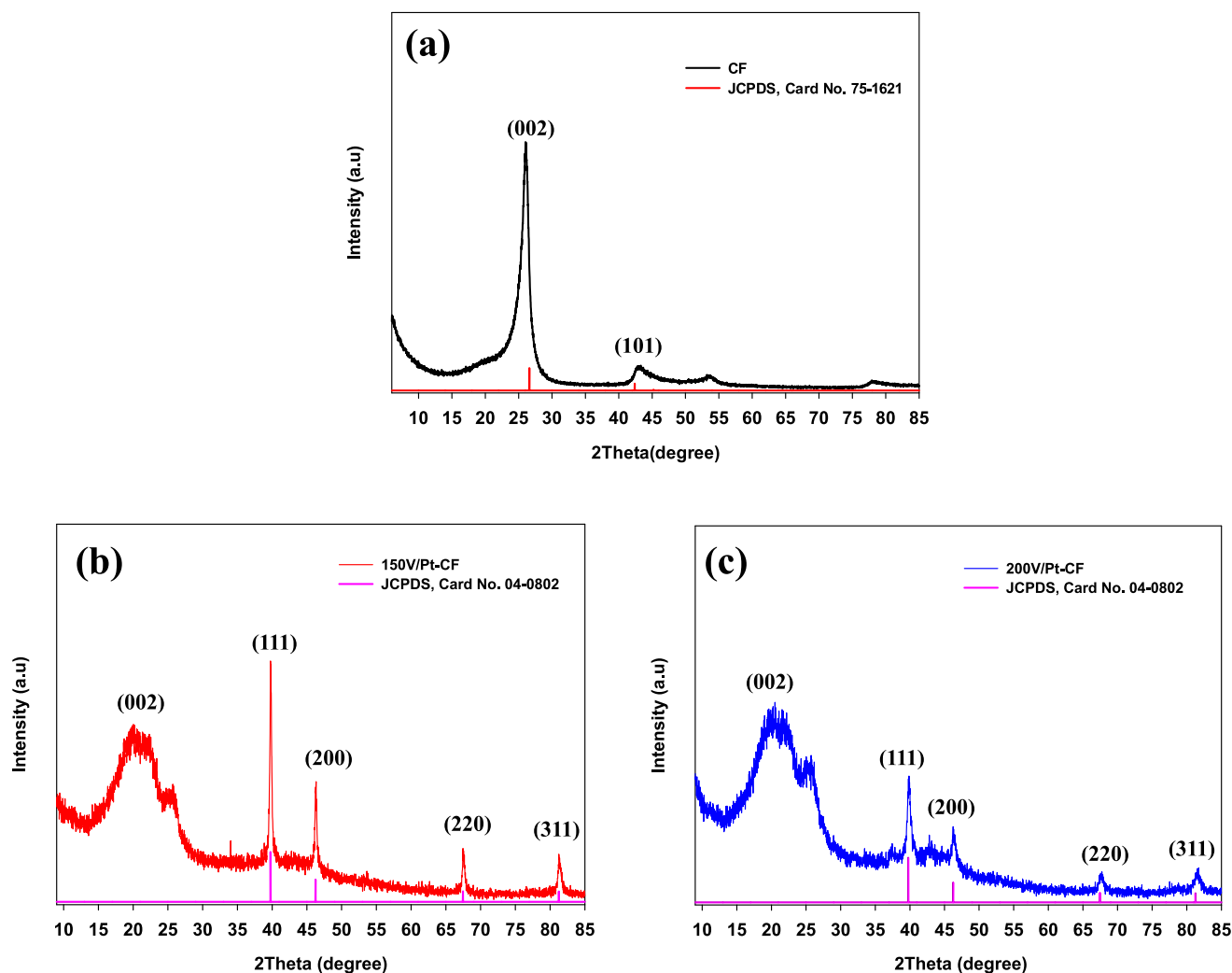


Fig. 4. XRD pattern of CF (a), 150 V/Pt-CF (b) and 200 V/Pt-CF (c).

V/Pt-CF are consistent with the structural information obtained from XRD analysis, further confirming the successful combination of Pt species into the carbon nanofiber framework through the FJH method [13,14,23,27]. The CF sample (Fig. 5a) exhibits only C and O signals, while the 150 V/Pt-CF and 200 V/Pt-CF samples (Fig. 5b and c) display distinct Pt 4f peaks, confirming the presence of Pt species on the modified catalyst surfaces.

High-resolution Pt 4f spectra reveals the influence of FJH voltage on the chemical state and electronic environment of Pt species in the doped samples. As presented in Fig. 5(d-e), 150 V/Pt-CF catalyst mainly contains metallic Pt⁰, as evidenced by the binding energy of Pt 4f_{7/2} and Pt 4f_{5/2} assigned at around 71.2 and 74.5 eV, respectively [10,23,33,34]. The absence of oxidized Pt components indicates that the 150 V FJH treatment efficiently reduces the Pt precursor and stabilizes metallic Pt within the conductive carbon framework. These metallic Pt⁰ sites are advantageous for the hydrogen evolution reaction because they facilitate rapid electron transfer and efficient hydrogen adsorption and desorption.

However, 200 V/Pt-CF sample exhibits a more complex Pt 4f spectrum, containing both metallic Pt⁰ and Pt²⁺ species [23,25,26,34]. The result suggests incomplete reduction of the Pt⁴⁺ precursor during the FJH process at higher voltage. The coexistence of Pt⁰ and Pt²⁺ may result from the destabilization of the Pt coordination environment and the high voltages used in the FJH process, which promote the partial oxidation of surface Pt. This may also reduce Pt retention and result in less uniform dispersion of Pt within the CF framework.

As a result, the mixed oxidation states in 200 V/Pt-CF likely produce an unfavorable electronic structure and reduce interfacial electron-transfer properties for HER electrocatalysis. Moreover, 150 V/Pt-CF catalyst is mainly composed of metallic Pt⁰, which enhances its electronic structure and strengthens the interaction with the carbon matrix. This improved interface promotes charge redistribution and accelerates electron transfer during the HER [26,27].

The presence of Pt²⁺ in 200 V/Pt-CF reduces electrical conductivity and decreases the number of active interface sites, thereby limiting HER activity. This effect is more significant under alkaline conditions, where efficient charge transfer and rapid water dissociation are important for improving HER performance.

These results show that the applied FJH voltage is key to controlling the Pt electronic state and the metal-carbon interface. 150 V/Pt-CF displays a higher amount of metallic Pt, which improves access to active sites and boosts electrocatalytic HER performance.

3.2. Hydrogen evolution reaction performance

The hydrogen evolution reaction performance of materials was evaluated in 0.5 M H₂SO₄ using a standard three-electrode setup. Undoped CF and Pt-doped samples were deposited on a glassy carbon electrode (GCE) as the working electrode. A platinum wire served as the counter electrode, and an Ag/AgCl (3 M KCl) electrode was used as the reference. All potentials were referenced to the reversible hydrogen electrode (RHE) scale [35].

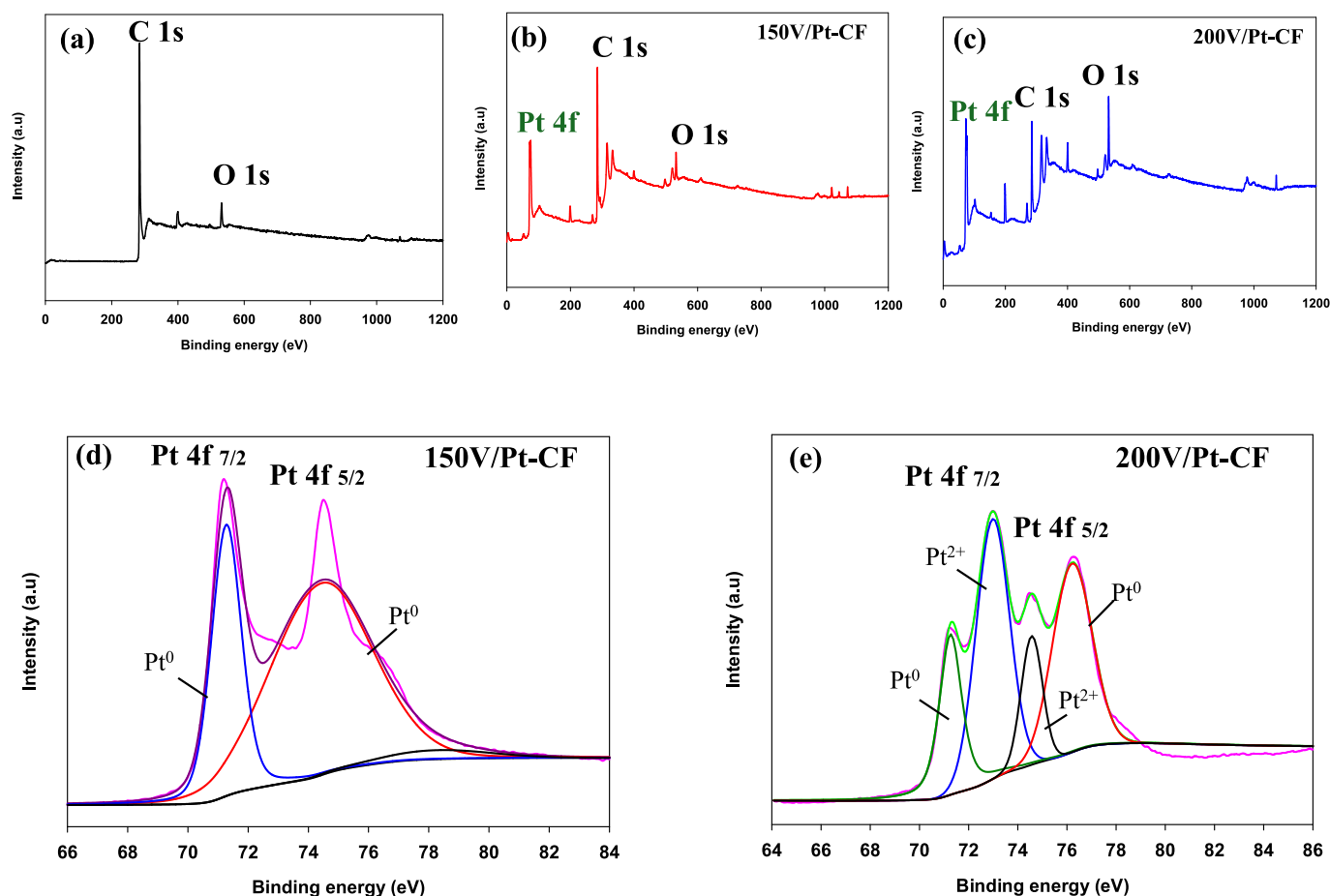


Fig. 5. XPS survey spectra for (a) CF, (b) 150 V/Pt-CF, and (c) 200 V/Pt-CF; High-resolution Pt 4f spectra for (d) 150 V/Pt-CF and (e) 200 V/Pt-CF.

Fig. 6(a) shows the linear sweep voltammetry (LSV) curves of the synthesized catalysts in an acidic electrolyte. Both Pt-modified samples exhibit significantly higher HER activity than the undoped sample, demonstrating the positive effect of Pt incorporation via the FJH process. Among all the catalysts, 200 V/Pt-CF exhibits the highest current density at a given overpotential, indicating superior HER electrocatalytic performance.

At low current density of 10 mA cm^{-2} , the overpotentials are 51 mV for commercial 20 wt% Pt/C, 56 mV for 200 V/Pt-CF, and 66 mV for 150 V/Pt-CF. At a higher current density of 100 mA cm^{-2} , commercial 20 wt% Pt/C requires an overpotential of 74 mV, which is very close to that of 200 V/Pt-CF (75 mV) and much lower than that of 150 V/Pt-CF (143 mV). These results demonstrate that 200 V/Pt-CF exhibits HER performance comparable to commercial Pt/C and significantly better than 150 V/Pt-CF, particularly at high current densities [11,25,36,37].

Fig. 6(b) presents the Tafel plots derived from the LSV curves. The 200 V/Pt-CF catalyst exhibits the lowest Tafel slope ($23.43 \text{ mV dec}^{-1}$), compared with $30.35 \text{ mV dec}^{-1}$ for commercial 20 wt% Pt/C and $46.90 \text{ mV dec}^{-1}$ for 150 V/Pt-CF. The lower Tafel slope of 200 V/Pt-CF indicates faster HER kinetics, reflecting more efficient charge transfer and favorable hydrogen adsorption during the reaction [38,39]. The low Tafel slope of 200 V/Pt-CF ($23.43 \text{ mV dec}^{-1}$) indicates fast HER kinetics and efficient charge transfer, which are consistent with its excellent electrocatalytic performance, particularly at high current densities. This value is slightly lower than that of commercial 20 wt% Pt/C ($30.35 \text{ mV dec}^{-1}$) and may be attributed to non-ideal factors, such as mass-transport effects, variations in surface hydrogen coverage, or differences in the selected fitting region. On the other hand, 150 V/Pt-CF catalyst exhibits a higher Tafel slope ($46.90 \text{ mV dec}^{-1}$), indicating slower HER kinetics than both 200 V/Pt-CF and commercial 20 wt% Pt/C. This result

suggests less efficient charge-transfer kinetics during the hydrogen evolution reaction [38–40]. The double-layer capacitance (Cdl) values of commercial 20 wt% Pt/C, 150 V/Pt-CF, and 200 V/Pt-CF catalysts were measured by cyclic voltammetry (CV) at different scan rates (Fig. 6c). The calculated Cdl values were 5.63, 2.06, and 0.41 mF cm^{-2} , respectively. Among the catalysts, the Cdl value of 150 V/Pt-CF is about five times higher than that of 200 V/Pt-CF, indicating a larger electrochemically active interface [10,11,13,14].

The finding is consistent with the Hupd-derived ECSA results (Fig. S2), which also suggest that 150 V/Pt-CF has more electrochemically accessible Pt active sites than 200 V/Pt-CF. Therefore, the higher Cdl and ECSA values may contribute to the better HER activity of 150 V/Pt-CF at low overpotentials [13,14,40].

In addition, 200 V/Pt-CF exhibits lower Cdl and ECSA values but still shows good HER performance and a lower Tafel slope, particularly at high current densities. This suggests that its enhanced HER activity is associated with faster reaction kinetics and higher intrinsic activity of the accessible Pt sites, rather than only the number of electrochemically accessible active sites.

Table S1 summarizes the electrochemically accessible Pt surface area calculated from the baseline-corrected hydrogen underpotential deposition (HUPD) desorption region. The obtained QH charges were 0.83, 0.21, and 0.11 mC cm^{-2} for commercial 20 wt% Pt/C, 150 V/Pt-CF, and 200 V/Pt-CF, respectively. Using a conversion factor of 0.21 mC cm^{-2} and the Pt contents, the apparent HUPD-ECSA values were calculated to be 130.13, 121.87, and $84.04 \text{ m}^2 \text{ gPt}^{-1}$ for commercial 20 wt% Pt/C, 150 V/Pt-CF, and 200 V/Pt-CF, respectively.

The QH value of 150 V/Pt-CF is comparable to those reported for monometallic Pt catalysts in previous studies [41–43]. These values should be interpreted with caution because the baseline correction

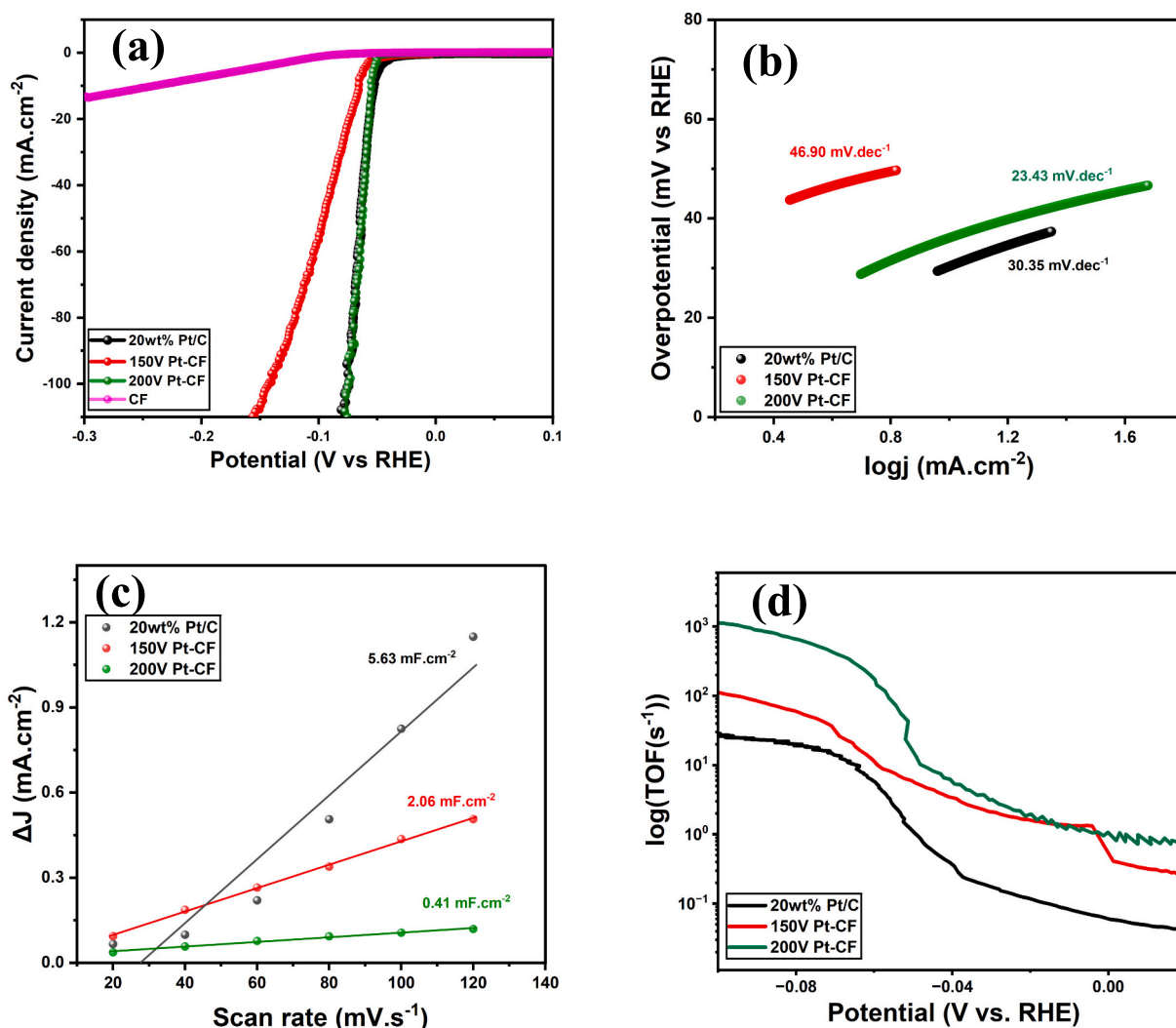


Fig. 6. LSV diagrams (a), Tafel plot (b), computed C_{dl} (c) and TOF (d) in H₂SO₄ 0.5 M.

method assumes a constant background current. However, the background current may vary with potential and overlap with the HUPD desorption region, which can affect the calculated ECSA values [41]. Nevertheless, both HUPD-ECSA and C_{dl}-derived ECSA results indicate that 150 V/Pt-CF provides more electrochemically accessible Pt sites than 200 V/Pt-CF [43].

Furthermore, the turnover frequency (TOF) values of 150 V/Pt-CF, 200 V/Pt-CF, and commercial 20 wt% Pt/C were calculated to evaluate the intrinsic catalytic activity of the Pt sites (Fig. 6d). The results show that 200 V/Pt-CF catalyst exhibits higher TOF values over the entire tested potential range than both 150 V/Pt-CF and commercial 20 wt% Pt/C. It suggests that 150 V/Pt-CF provides a larger electrochemically ECSA, while the individual Pt sites in 200 V/Pt-CF possess higher intrinsic catalytic activity [44,45].

The higher TOF of 200 V/Pt-CF compared with commercial 20 wt% Pt/C indicates more efficient utilization of Pt active sites. The commercial Pt/C provides a larger electrochemically accessible surface area, while the Pt sites in 200 V/Pt-CF exhibit higher catalytic efficiency, resulting in enhanced intrinsic HER activity. The improved intrinsic activity of 200 V/Pt-CF may be related to the benefit of Flash Joule Heating method, which could enhance the interaction between Pt and the carbon support and improve the catalytic behavior of Pt sites

[13,34].

The HER activity of the 150 V/Pt-CF, 200 V/Pt-CF, and commercial 20 wt% Pt/C were evaluated in 1 M KOH electrolyte. As shown in Fig. 7a, 150 V/Pt-CF exhibits the best HER performance among the tested catalysts, requiring only 25 mV overpotential to reach a current density of 10 mA cm⁻². In comparison, commercial 20 wt% Pt/C and 200 V/Pt-CF require overpotentials of 38 and 164 mV, respectively, under the same conditions. A similar trend is observed at a higher current density of 50 mA cm⁻², where the overpotentials increase to 103, 110, and 383 mV for 150 V/Pt-CF, commercial 20 wt% Pt/C, and 200 V/Pt-CF, respectively.

To further understand the improved HER performance, the electrochemically accessible surface area was evaluated using double-layer capacitance (C_{dl}) measurements (Fig. 7c). The 150 V/Pt-CF catalyst exhibits a C_{dl} value of 0.92 mF cm⁻², which is higher than that of 200 V/Pt-CF (0.267 mF cm⁻²) and lower than 20 wt% Pt/C (2.68 mF cm⁻²).

The finding indicates that 150 V/Pt-CF provides more electrochemically accessible active sites, which is consistent with the results obtained in acidic electrolyte. The enhanced HER activity of 150 V/Pt-CF may be attributed to the improved accessibility of Pt active sites after the 150 V Flash Joule Heating treatment [45–48].

Tafel plot analysis (Fig. 7b) shows that the 150 V/Pt-CF catalyst has

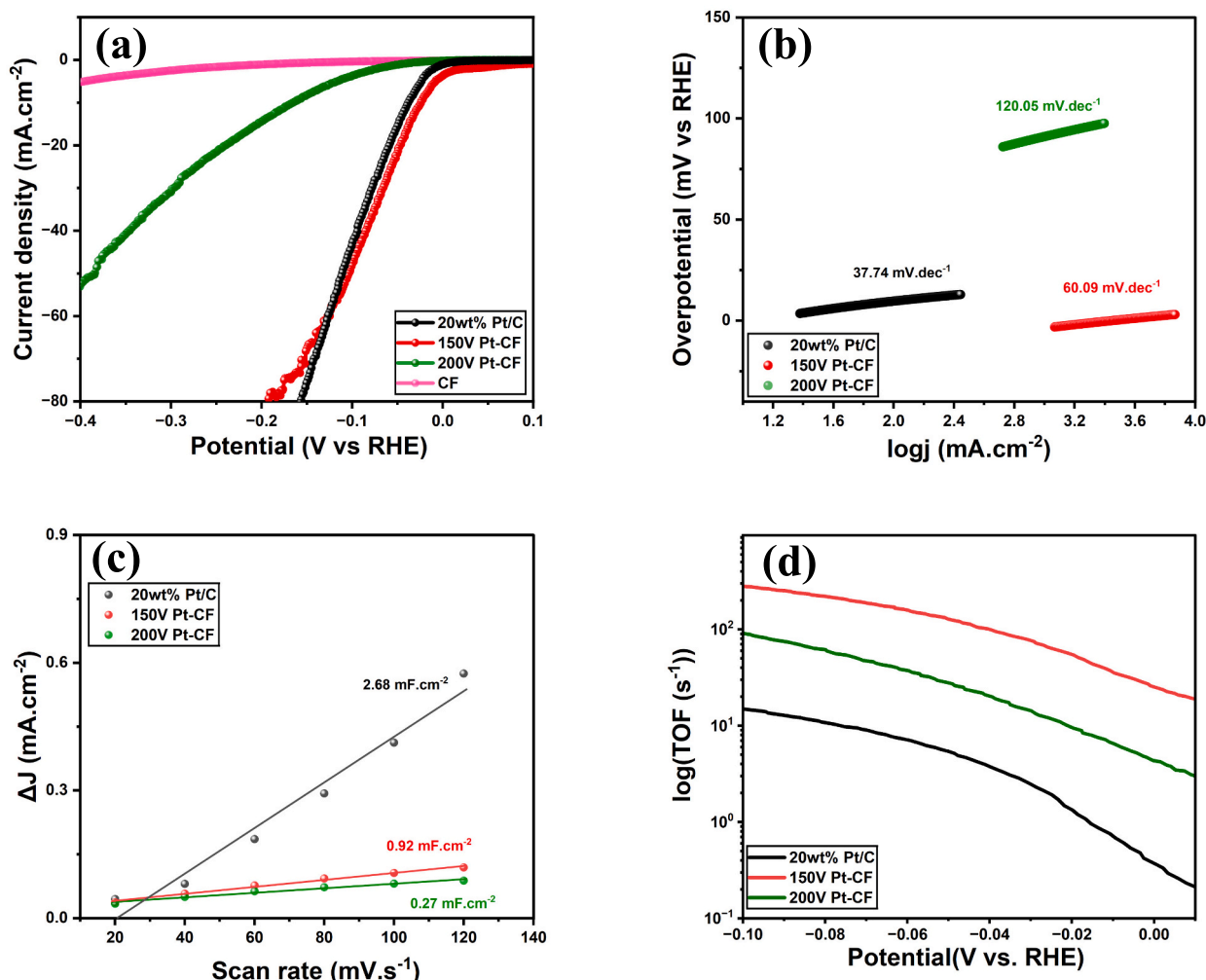


Fig. 7. LSV diagrams(a), Tafel plot (b), computed C_{dl} (c) and TOF (d) in KOH 1 M.

a lower Tafel slope of 61 mV dec⁻¹ than 200 V/Pt-CF (121 mV dec⁻¹), indicating improved HER kinetics under alkaline conditions. In comparison, commercial 20 wt% Pt/C exhibits a Tafel slope of 37.74 mV dec⁻¹, confirming its excellent HER kinetics as a benchmark catalyst. While 150 V/Pt-CF has a slightly higher Tafel slope, it maintains competitive HER performance with significantly lower Pt content, indicating more efficient utilization of Pt sites on the carbon support. These results highlight the effectiveness of the Flash Joule Heating method in producing Pt-CF catalysts with high HER activity.

In alkaline electrolyte, HER generally proceeds through the Volmer–Heyrovsky mechanism, in which water dissociation during the Volmer step can become the rate-limiting process [39,46,49]. The lower Tafel slope of 150 V/Pt-CF indicates faster HER kinetics, which may be related to improved interfacial charge transfer and more favorable reaction processes under alkaline conditions. Compared with acidic electrolyte, both Pt-doped catalysts show lower HER activity in alkaline media, mainly due to the lower availability of protons and the additional energy required for water dissociation, which increases the kinetic barrier for hydrogen evolution [49,50]. However, a different activity trend is observed for the Pt-doped catalysts under alkaline conditions. As shown in Fig. 7d, 150 V/Pt-CF exhibits higher TOF values than 200 V/Pt-CF across the entire tested potential range in 1 M KOH. Unlike in acidic electrolyte (0.5 M H₂SO₄), where 200 V/Pt-CF exhibited higher activity despite lower ECSA, the 150 V/Pt-CF catalyst in alkaline

solution demonstrates both more active sites and greater intrinsic activity. This combination likely contributes to its improved HER performance in alkaline conditions.

3.2.1. Electrochemical impedance spectroscopy

The interfacial charge-transfer properties of the catalysts were investigated using electrochemical impedance spectroscopy (EIS). The Nyquist plots were fitted using an equivalent circuit model (Fig.S3) to obtain the charge-transfer resistance (R_{ct}) at the electrode/electrolyte interface. As shown in Fig. 8, undoped CF exhibits larger impedance response, indicating slower charge transfers due to the absence of Pt catalytic sites [51]. The result highlights the important role of Pt in improving interfacial electron transfer and enhancing HER performance. Under acidic condition, 200 V/Pt-CF exhibits the smallest semicircle diameter, corresponding to the lowest R_{ct} value (19.04 Ω), indicating the most favorable charge-transfer kinetics (Fig. 8a). In comparison, 150 V/Pt-CF shows slightly larger semicircle diameter with R_{ct} value of 21.63 Ω , suggesting relatively slower interfacial charge transfer [46,47,49].

Under alkaline conditions (Fig. 8b), 150 V/Pt-CF exhibits a smaller semicircle diameter than 200 V/Pt-CF, indicating faster charge-transfer kinetics. The R_{ct} value was 71 Ω for 150 V/Pt-CF and 975 Ω for 200 V/Pt-CF, confirming significantly faster interfacial electron transfer in 150 V/Pt-CF [42,48,50,52].

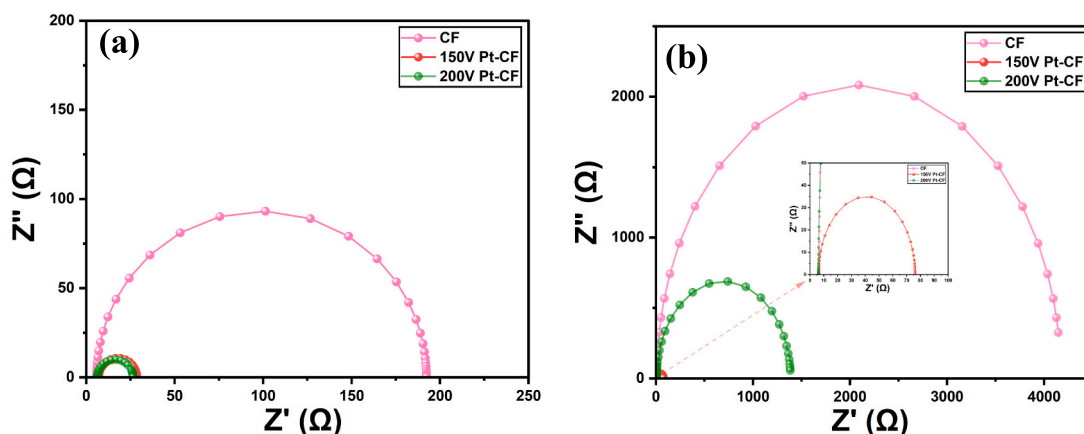


Fig. 8. Electrochemical impedance spectroscopy spectra of materials under acidic (a) and alkaline (b) conditions.

The EIS results are consistent with the LSV and Tafel analyses, demonstrating that 150 V/Pt-CF exhibits a lower overpotential and a smaller Tafel slope in alkaline electrolyte. Efficient charge transfer is particularly important for the Volmer step in alkaline HER, where water dissociation is required before hydrogen formation. The lower R_{ct} of 150 V/Pt-CF indicates faster interfacial electron transfer, which promotes the Volmer reaction. This result is consistent with its higher Cdl, larger ECSA, and higher TOF, which together contribute to its improved alkaline HER performance.

3.2.2. Stability tests

The long-term electrochemical stability of the 150 V/Pt-CF catalyst was evaluated using chronopotentiometry at a constant cathodic current density of 10 mA cm^{-2} in both $0.5 \text{ M H}_2\text{SO}_4$ and 1.0 M KOH electrolytes (Fig. 9). In both electrolytes, an initial equilibration phase occurred during the first 0.5 to 1 h. During this period, the working potential shifted toward the cathode as the electrode surface became fully wet and the active sites were activated. Such short-term behavior is commonly observed with carbon-supported Pt catalysts [25,41–43].

Following the initial equilibration stage in acidic media, the 150 V/Pt-CF catalyst exhibited a stable operating potential of -0.08 to -0.10 V vs. RHE for nearly 7 h. Only a slight negative potential drift of approximately 20 mV was observed during the initial stage, indicating good short-term resistance to electrochemical degradation. Furthermore, Fig. S4 shows that the overpotential at 10 mA cm^{-2} increased by only 13 mV in $0.5 \text{ M H}_2\text{SO}_4$ and 7 mV in 1.0 M KOH after 5000 CV cycles, indicating good electrochemical stability of the 150 V/Pt-CF electrode under both acidic and alkaline conditions.

However, the working potential subsequently shifted sharply and irreversibly to approximately $+0.28$ – 0.30 V vs. RHE within less than 1 h. This substantial increase in potential, accompanied by increased signal fluctuations, persisted throughout the remainder of the 10 h stability test. The results indicate a significant deterioration in HER activity after long exposure to acidic conditions, as evidenced by the substantial positive shift in the operating potential during chronopotentiometric testing. Possible factors contributing to the performance degradation include Pt nanoparticle detachment from the CF support, corrosion of the carbon framework under acidic conditions, and the accumulation of

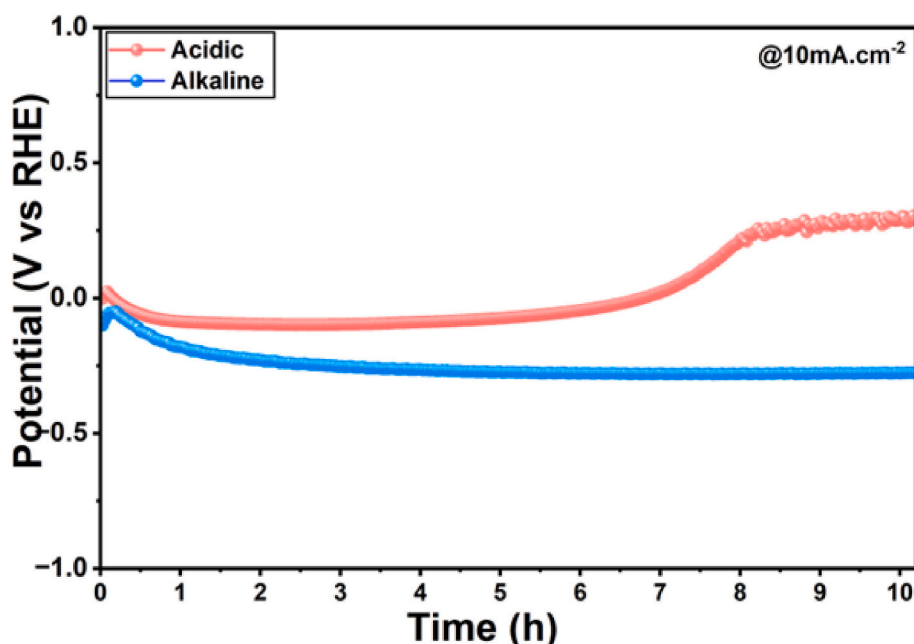


Fig. 9. Chronopotentiometric stability test of 150 V/Pt-CF.

gas bubbles on the catalyst surface, which may block active sites [34].

In addition, the 150 V/Pt-CF catalyst showed much better stability in alkaline conditions during the chronopotentiometric test. The working potential stayed near -0.20 V vs. RHE and slowly moved to about -0.28 to -0.30 V by the end. This change means the overpotential increased by about 80–100 mV during roughly 9 h of continuous use. The potential profile remained stable, indicating strong electrochemical durability during alkaline HER [34]. The higher overpotential in alkaline electrolyte compared to acidic media results from the additional kinetic barrier of the water dissociation (Volmer) step required for proton generation, as well as competing OH^- adsorption on Pt active sites [11,13,33]. Chronopotentiometric tests show that the stability of the 150 V/Pt-CF catalyst depends on the electrolyte used. In acidic electrolyte, the catalyst supports stable HER for several hours before degrading, while in alkaline conditions, it remains stable for the full 10-h test.

To further evaluate catalyst durability, post-reaction analyses were conducted using SEM, EDS, XPS, and ICP-OES.

The SEM images (Fig. S5a and S5c) taken after the stability tests in acidic and alkaline electrolytes show that the interconnected carbon-fiber framework remained intact, with no evidence of structural collapse. This observation indicates good structural stability during HER operation. The corresponding EDS spectra (Fig. S5b and S5d) confirm the presence of Pt after testing, indicating that the Pt nanoparticles remained well anchored to the carbon support.

The 150 V/Pt-CF catalyst showed better structural preservation after operation in alkaline electrolyte than in acidic electrolyte. These observations are consistent with the electrochemical stability results and indicate that the 150 V/Pt-CF catalyst is durable in both electrolytes, with higher stability under alkaline conditions.

The XPS analysis was performed to investigate the surface composition and chemical states of the 150 V/Pt-CF electrode after the stability test. As shown in the survey spectra (Fig. S6a and S6b), the characteristic C 1 s, O 1 s, and Pt signals remain visible after electrolysis in both KOH and H_2SO_4 electrolytes, indicating that the main elemental components are preserved after long-term operation. The F 1 s peak is also detected, which is attributed to the polytetrafluoroethylene (PTFE) binder in the

carbon paper substrate.

The high-resolution Pt 4f spectra (Fig. S6c and S6d) were fitted using metallic Pt^0 and oxidized Pt^{2+} components. After long-term HER operation, the 150 V/Pt-CF catalyst exhibits the coexistence of Pt^0 and Pt^{2+} species (Table S2), indicating the formation of a small amount of surface-oxidized Pt species. The slightly higher fraction of metallic Pt^0 retained after alkaline operation suggests better preservation of the metallic Pt surface under these testing conditions. This difference may result from electrolyte-dependent surface interactions and Pt oxidation behavior during electrochemical operation.

Fig. S7 shows the retained Pt content of the 150 V/Pt-CF catalyst after 5000 CV cycles in acidic and alkaline electrolytes. The Pt loss was about 8.6% in acid and 1.3% in alkaline solution compared with the original catalyst. These results indicate that 150 V/Pt-CF has excellent Pt stability under alkaline conditions, making it suitable for long-term electrocatalytic applications in alkaline media. However, the higher Pt loss in acidic conditions suggests that its stability should be further improved for acid-based applications.

3.2.3. Proposed HER mechanisms

In alkaline electrolytes, HER mainly follows the Volmer–Heyrovsky mechanism, in which the sluggish water dissociation kinetics in the Volmer step often limit the overall reaction rate [13,16,33,42,48]. As a result, HER activity in alkaline media depends not only on hydrogen adsorption but also on the ability of the catalyst surface to adsorb and activate water molecules, as well as efficient charge transfer at the interface. This requirement is different from acidic HER, where protons are directly available for hydrogen formation (Fig. 10). The Pt oxidation state and Pt–carbon interface may play an important role in improving alkaline HER performance. The partially oxidized Pt^{2+} species can provide stronger interaction with water molecules and may facilitate the cleavage of H–OH bonds during the Volmer step. Meanwhile, metallic Pt^0 sites remain favorable for hydrogen adsorption and H_2 formation. Therefore, the coexistence of Pt^{2+} and Pt^0 sites may provide complementary functions, where Pt^{2+} promotes water activation and Pt^0 assists hydrogen evolution. In addition, the interaction between Pt

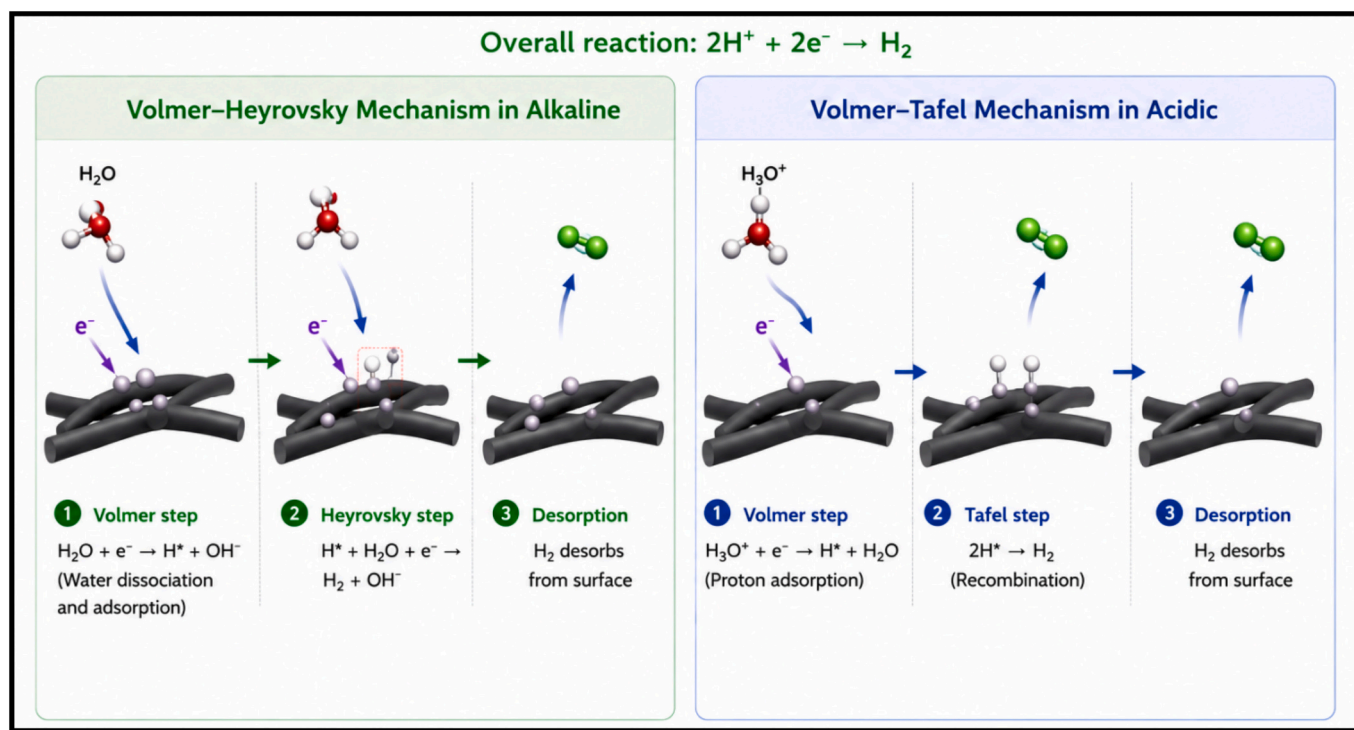


Fig. 10. Proposed HER mechanisms by Pt-CF in alkaline and acidic conditions.

nanoparticles and the conductive CF support can facilitate electron transfer during the reaction. This synergistic effect may contribute to the improved alkaline HER activity of the Pt-CF catalyst [26,34,42].

Under acidic conditions, HER mainly follows the Volmer–Tafel pathway, in which protons are readily adsorbed onto Pt active sites to form H, followed by the recombination of two H species to generate H₂ [34,36,42,54,55]. Proton adsorption on platinum surfaces is thermodynamically favorable and does not require a water dissociation step. As a result, acidic hydrogen evolution reaction (HER) generally exhibits faster kinetics and lower activation barriers than alkaline HER. The activity of acidic HER is mainly influenced by the catalytic properties of platinum sites, hydrogen adsorption and desorption behavior, and the efficiency of electron transfer at the catalyst–electrolyte interface [7,34,56]. The smaller and more uniformly dispersed Pt nanoparticles in 150 V/Pt–CF expose more Pt active sites and improve water dissociation kinetics, resulting in enhanced alkaline HER performance.

3.3. Comparative HER performance and potential of using FJH method

Table 2 and Table 3 compare the HER performance of FJH-derived Pt–CF catalysts with other carbon-supported electrocatalysts in acidic and alkaline electrolytes. In 0.5 M H₂SO₄, the 150 V/Pt–CF and 200 V/Pt–CF catalysts exhibit low overpotentials of 66 and 56 mV at 10 mA cm^{−2}, making their acidic HER activity competitive with recent Pt-based systems. The 200 V/Pt–CF catalyst also shows a low Tafel slope of 23.43 mV dec^{−1}, indicating faster HER kinetics, possibly due to FJH-induced modifications at the Pt–carbon interface and in the electronic structure. In 1 M KOH, the 150 V/Pt–CF catalyst demonstrates high HER performance, requiring only 25 mV overpotential to reach 10 mA cm^{−2} and exhibiting a Tafel slope of 61 mV dec^{−1}. However, the 200 V/Pt–CF catalyst is less effective under alkaline conditions, suggesting that the FJH voltage strongly influences Pt dispersion, interfacial charge transfer, and active-site accessibility.

While other electrocatalysts offer similar HER activity, they require complex synthesis and compositional engineering. However, our synthesized Pt-doped CF catalyst prepared by the FJH process can avoid multistep fabrication and secondary metal incorporation. These results highlight the potential of voltage-controlled FJH processing to tune Pt–carbon interfacial properties and develop efficient HER electrocatalysts for practical hydrogen production.

FJH also offers several advantages over conventional approaches for synthesizing Pt-doped carbon nanofibers, such as wet-chemical synthesis, precipitation, and sputtering [18–21]. Traditional approaches often require multiple steps, long processing times, and solvents, which increase complexity and limit scalability. FJH delivers ultrafast, millisecond-scale thermal processing under solid-state conditions, simplifying synthesis. This rapid, non-equilibrium heating reduces processing steps and eliminates the need for chemicals or solvents, providing a more direct approach to large-scale catalyst synthesis

Table 2
Comparison of carbon-supported HER electrocatalysts in acidic.

Catalyst	Supporting substrate	η_{10} (mV)	Tafel Slope (mV dec ^{−1})	References
Pt/CNT	CNT	41	17	[34]
RuO ₂ @Co/CNF	CNF	40	71	[50]
Pt ₃ Co@NCNT	CNT	42	27	[57]
10Pt/VS ₂ /CP	Carbon Paper	77	39	[10]
PtCoFe@CN	CN	45	32	[58]
Ni-Pt-Films	Mesoporous carbon	90	49	[55]
Pt ₁ @Fe-N-C	CNF	60	42	[59]
PtCo@C	Nano rods	7.1	15	[56]
Pt-CoO/CNF	CNF	26	32	[23]
200 V Pt-CF	CF	56	23.43	This work
150 V Pt-CF	CF	66	46.90	This work

Table 3

Comparison of carbon-supported HER electrocatalysts in alkaline.

Catalyst	Supporting substrate	η_{10} (mV)	Tafel Slope (mV dec ^{−1})	References
Pt/CNT	CNT	74	70	[34]
RuO ₂ @Co/CNF	CNF	14	44	[50]
Pt ₃ Co@NCNT	CNT	36	54	[57]
Pt@PCM	Mesoporous carbon	139	74	[60]
Pt@NiFe LDHs	LDH sheets	101	127	[37]
Pt ₁ @Co/NC	Carbon sheets	305	151	[59]
Pt ₁ @Fe-N-C	CNF	130	89	[59]
NbS ₂ /MoS ₂ -CNF	CNF	32	33	[11]
Ru/WC _x -CNF	CNF	16	31	[61]
200 V Pt-CF	CF	164	120.05	This work
150 V Pt-CF	CF	25	61.09	This work

[18,21]. Moreover, it can help prevent nanoparticles from growing too large and support the even distribution of metal particles on carbon materials. It also allows control of metal-support interactions through specific thermal conditions, which is important for improving catalytic activity [19,21]. On the other hand, this approach can be extended to other catalytic systems, including non-noble metal catalysts and single-atom catalysts, provided that suitable precursor chemistry and thermal responses are achieved under FJH conditions. Therefore, the synthesis of advanced catalysts using FJH offers a promising direction for the development of high-efficiency, low-cost electrocatalysts for hydrogen production. However, further research on the synthesis of other catalysts and their HER efficiency is required to fully evaluate the potential of the FJH method for industrial applications, particularly in green energy.

4. Conclusions

This study shows that flash Joule heating is an effective and scalable method for modifying the structure and electronic properties of Pt-doped carbon fibers for pH-universal HER electrocatalysis. By precisely controlling FJH voltage, we can adjust platinum incorporation, distribution, valence state, and interfacial charge transfer, all of which influence HER activity in both acidic and alkaline environments. Structural analysis indicates that a 150 V treatment produces more uniform ion distribution and better stabilization of metallic Pt⁰ species than 200 V, resulting in a more favorable catalytic interface. Electrochemical studies reveal a clear dependence of activity on the electrolyte. In acidic conditions, the 200 V/Pt–CF shows faster intrinsic HER kinetics despite a lower electrochemically active surface area, highlighting a trade-off between active-site density and per-site activity. Under alkaline conditions, the 150 V/Pt–CF exhibits a greater electrochemically accessible surface area, higher intrinsic activity, and reduced interfacial charge-transfer resistance, effectively overcoming kinetic barriers to water dissociation. As a result, the 150 V/Pt–CF demonstrates excellent HER performance, with low overpotentials, rapid kinetics, and strong electrochemical stability across a broad pH range. These findings show that HER efficiency depends on the combined regulation of Pt electronic structure, active-site accessibility, and interfacial electron-transfer dynamics, rather than focusing on a single catalytic descriptor.

This study shows that using FJH-enabled interfacial electronic regulation is an effective way to achieve pH-universal HER catalysis. It also points out that rapid Joule-heating strategies could help scale up the production of advanced hydrogen-evolution electrocatalysts.

CRedit authorship contribution statement

Tran Hieu Man: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Pham Tien Song Hiep:** Methodology, Conceptualization. **Pham Thi Huong:** Writing – review &

editing, Resources, Investigation, Conceptualization. **Kim TaeYoung:** Writing – review & editing, Supervision, Methodology, Investigation.

Declaration of competing 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.diamond.2026.114086>.

Data availability

The data that has been used is confidential.

References

- [1] M. Lopez-Juarez, A. Tansini, G. Di Pierro, R. Novella, G. Fontaras, Influence of the driving pattern and hydrogen mix scenario of next-generation FCV on performance and environmental impact in the 2025–2050 timeframe, *Energy Convers. Manage.* X 30 (2026) 101876, <https://doi.org/10.1016/j.ecmx.2026.101876>.
- [2] P.J. Ansell, A blueprint for a zero-emission hydrogen aviation ecosystem for the year 2050, *Prog. Aerosp. Sci.* (2025), <https://doi.org/10.1016/j.paerosci.2025.101169>.
- [3] W. Hilverda, S. Tekeli, E. Ursavas, S.X. Zhu, Hydrogen roadmap 2050: technical and economic perspectives on hydrogen green blending in the heating sector Northern Netherlands, *Int. J. Hydrog. Energy* 212 (2026), <https://doi.org/10.1016/j.ijhydene.2026.153640>.
- [4] R. Erdiwansyah, M.F. Mamat, F. Ghazali, S.M. Basrawi, Rosdi, green hydrogen production and renewable energy storage integration: a review of technologies and system pathways, *Energy Convers. Manage.* X 30 (2026), <https://doi.org/10.1016/j.ecmx.2026.101904>.
- [5] S.A. Mahmood, H.I. Abdu, E.K. Almohannadi, B. Usmonov, A. Khudayberdieva, M. F. Shibl, K.A. Soliman, N.N. Mobarak, K. Eid, Facile one-pot synthesis of hierarchical porous carbon nanofibers encapsulated metal nanocrystals as efficient Pt-free electrocatalysts for green hydrogen production, *Int. J. Hydrog. Energy* 227 (2026), <https://doi.org/10.1016/j.ijhydene.2026.154556>.
- [6] H. Niu, J. Wang, D. Liu, Hydrogen electrolyzer technology mapping and evolutionary trends: a systematic analysis based on global patent data, *Int. J. Hydrog. Energy* 235 (2026), <https://doi.org/10.1016/j.ijhydene.2026.155127>.
- [7] J. Zhang, X. Hu, J. Wang, An efficient and stable low-Pt catalysts for hydrogen evolution reaction in acid, *J. Power Sources* 662 (2026) 238763, <https://doi.org/10.1016/j.jpowsour.2025.238763>.
- [8] Y.H. Li, Y.P. Lin, The behavior of hydrogen bubble flow in the MHD channel composed of platinum electrode, *Int. J. Hydrog. Energy* 99 (2025) 494–503, <https://doi.org/10.1016/j.ijhydene.2024.12.224>.
- [9] X. Deng, M. Tian, J. Cui, H. Liu, W. Zhang, Z. Shang, J. Wen, G. Huang, S. Xu, Efficient recovery of critical metals from spent reforming catalysts and regeneration into highly active Pt-based catalysts for hydrogen evolution reaction, *Sep. Purif. Technol.* 362 (2025), <https://doi.org/10.1016/j.seppur.2025.131826>.
- [10] J. Zhu, L. Cai, X. Yin, Z. Wang, L. Zhang, H. Ma, Y. Ke, Y. Du, S. Xi, A.T.S. Wee, Y. Chai, W. Zhang, Enhanced electrocatalytic hydrogen evolution activity in single-atom Pt-decorated VS₂ nanosheets, *ACS Nano* 14 (2020) 5600–5608, <https://doi.org/10.1021/acsnano.9b10048>.
- [11] P. Gnanasekar, K.S. Ranjith, P. Manivel, Y.K. Han, J. Kulandaivel, Hierarchical NbS₂/MoS₂-carbon nanofiber electrode for highly efficient and stable hydrogen evolution reaction at all ranges of pH, *ACS Appl. Energy Mater.* 3 (2020) 6717–6725, <https://doi.org/10.1021/acsaelm.0c00856>.
- [12] M.R.J. Gujar, S.N. Rindhe, Pt/CNF single-atom catalyst for energy-efficient oxidation: mechanistic and green chemistry insights, *Next Materials* 11 (2026), <https://doi.org/10.1016/j.nxmate.2026.101879>.
- [13] C. Sun, C. Wang, G. Han, Y. Zhang, H. Zhao, Pt atomic clusters/MoS₂ nanosheets/Co-doped hollow carbon nanofibers for high-current-density alkaline hydrogen production, *Chem. Eng. J.* 496 (2024), <https://doi.org/10.1016/j.cej.2024.153665>.
- [14] M. Aftabuzzaman, M.M. Rahman, H. Zhou, J. Masud, K. Lee, H.K. Kim Matyjaszewski, Scrutinizing the electrocatalytic activity of ultra-low Pt- and Se-doped Ni nanoparticles/porous carbon electrocatalysts for tri-iodide reduction and urea oxidation, *Chem. Eng. J.* 539 (2026), <https://doi.org/10.1016/j.cej.2026.176375>.
- [15] W. Huang, Y. He, W. Yan, L. Qiao, Y. Tao, X. Wei, X. Song, L. Yang, L. Tan, X. Wang, Z. Chen, Building 3D conductive networks within sponge-like porous carbon nanofibers: a CNT-based cathode strategy for superior microbial fuel cells, *Chem. Eng. J.* 535 (2026), <https://doi.org/10.1016/j.cej.2026.175312>.
- [16] X. Wei, G. Zhang, S. Sun, C.G. Yuan, Electrospun carbon nanofibers for hydrogen evolution reaction: design, optimization, and mechanisms of electrocatalysts, *Fuel* 407 (2026), <https://doi.org/10.1016/j.fuel.2025.137222>.
- [17] L.-M. Cao, C.-T. He, Molecular enhancement of platinum electrocatalysts for hydrogen evolution, *Chinese J. Struct. Chem.* (2025) 100814, <https://doi.org/10.1016/j.cjsc.2025.100814>.
- [18] J. Yin, K. Yin, S. Zhang, M. Wang, F. Wang, B. Sun, Y. Gong, H. Xie, F. Lian, Millisecond flash joule-heating for rapid synthesis of dual-site graphene catalysts toward enhanced peroxymonosulfate activation in water decontamination, *Sep. Purif. Technol.* 394 (2026), <https://doi.org/10.1016/j.seppur.2026.137579>.
- [19] M. Faizan, M.N. Siddiqui, Advances in scalable 2D material synthesis: flash Joule heating and beyond, *Mater. Res. Bull.* 192 (2025), <https://doi.org/10.1016/j.materresbull.2025.113639>.
- [20] D.R. Lan, P.Y. Ou, S.Q. Pei, K.J. Liu, C.C. Li, M.C. Zhang, Y.X. Liu, S.N. He, L.N. She, Y.X. Yang, W.B. Du, H.G. Pan, Flash joule heating driven in-situ dispersoid synthesis: mechanical-interfacial-conductive coupling mechanisms in silicon-based anodes, *Energy Storage Mater.* 86 (2026), <https://doi.org/10.1016/j.ensm.2026.104956>.
- [21] Q. Zhang, X. Zhao, G. Wei, Flash joule heating drives structural ordering for efficient metal-support interaction in lignin-derived NiRu catalysts toward broad-pH seawater electrolysis, *J. Colloid Interface Sci.* 718 (2026), <https://doi.org/10.1016/j.jcis.2026.140513>.
- [22] M. Ganpat Mapari, S.H. Jung, E. Bi Sohn, J.W. Park, T.Y. Kim, Edge-free graphene-derived mesoporous carbon for high-voltage supercapacitors, *Small Struct.* 6 (2025), <https://doi.org/10.1002/ssr.202500265>.
- [23] J. Gan, Z. Huang, W. Luo, W. Chen, Y. Cao, G. Qian, X. Zhou, X. Duan, Platelet carbon nanofibers as support of Pt-CoO electrocatalyst for superior hydrogen evolution, *Journal of Energy Chemistry* 52 (2021) 33–40, <https://doi.org/10.1016/j.jechem.2020.04.036>.
- [25] Z. Han, W. Deng, Y. Song, H. Cao, Y. Shen, Z. Dang, Z. Zheng, J. Guo, Micropore-confined ultrafine Pt nanoparticles in hierarchical porous carbon nanofibers for pH-universal oxygen reduction with enhanced stability, *Carbon N. Y.* 246 (2026), <https://doi.org/10.1016/j.carbon.2025.120950>.
- [26] Z. Zhang, Y. Chen, Z. Xie, Y. Chen, Y. Xie, Y. Wang, J. Zhang, Incorporating low levels of Pt into carbon materials with different pore structures for hydrogen evolution reaction, *Fuel* 426 (2026), <https://doi.org/10.1016/j.fuel.2026.139524>.
- [27] J. Peng, H. Yang, H. Zheng, Y. Mo, Q. Tang, X. Luo, Y. Chen, Engineering hierarchically porous phenolic resin-derived carbon supports for Pt catalysts toward superior alkaline hydrogen evolution performance, *J. Electroanal. Chem.* 1002 (2026) 119726, <https://doi.org/10.1016/j.jelechem.2025.119726>.
- [28] Y. Chen, C. Zhang, C. Li, T. Gao, Y. Li, Y. Jiang, J. Niu, M. Zhang, S. Yao, Enhanced polysulfide immobilization and conversion enabled by N/O/P Co-doped hollow carbon nanofibers hosts in room-temperature Na-S batteries, *Carbon N. Y.* 251 (2026), <https://doi.org/10.1016/j.carbon.2026.121354>.
- [29] X. Feng, H. Sun, D. Li, J. Li, C. Wu, S. Yao, NiCo₂S₄-incorporated N/P co-doped carbon-CNTs membrane for regulating polysulfide redox kinetics in lithium-sulfur batteries, *Diam. Relat. Mater.* 166 (2026), <https://doi.org/10.1016/j.diamond.2026.113733>.
- [30] Y. Hong, W. Zhang, C. Li, Y. Sun, Y. Zhao, Y. Wu, Y. Jiang, J. Li, C. Wu, S. Guo, S. Yao, Biomass-derived carbon modified with conductive Co₃(HHTP)₂Nanorods as an efficient binder-free cathode for high-performance Li-CO₂batteries, *ACS Sustain. Chem. Eng.* 14 (2026) 3668–3680, <https://doi.org/10.1021/acssuschemeng.5c12789>.
- [31] Y. Deng, W. Zhang, C. Ma, C. Li, Y. Hong, Y. Sun, J. Niu, S. Guo, S. Yao, Self-assembled MoS₂ nanoflowers decorated nitrogen/phosphorous/fluorine heteroatoms co-doped carbon nanotubes as enhanced catalyst for Li-CO₂ batteries, *J. Energy Storage* 113 (2025), <https://doi.org/10.1016/j.est.2025.115640>.
- [32] S. Yao, C. Zhang, Y. He, Y. Li, Y. Wang, Y. Liang, X. Shen, T. Li, S. Qin, J. Xiang, Functionalization of nitrogen-doped carbon nanofibers with polyamidoamine dendrimer as a freestanding electrode with high sulfur loading for lithium-polysulfides batteries, *ACS Sustain. Chem. Eng.* 8 (2020) 7815–7824, <https://doi.org/10.1021/acssuschemeng.0c00300>.
- [33] J. Xu, M. Zhong, N. Song, C. Wang, X. Lu, General synthesis of Pt and Ni co-doped porous carbon nanofibers to boost HER performance in both acidic and alkaline solutions, *Chin. Chem. Lett.* 34 (2023), <https://doi.org/10.1016/j.cclet.2022.03.082>.
- [34] Y. Liu, P. Liu, Y. Cai, M. Zhu, N. Dou, L. Zhang, Y.L. Men, Y.X. Pan, Platinum/(carbon-nanotube) electrocatalyst boosts hydrogen evolution reaction in acidic, neutral and alkaline solutions, *Small* 21 (2025), <https://doi.org/10.1002/smll.202411181>.
- [35] L. Zhang, H. Hu, C. Sun, D. Xiao, H.T. Wang, Y. Xiao, S. Zhao, K.H. Chen, W.X. Lin, Y.C. Shao, X. Wang, C.W. Pao, L. Han, Bimetallic nanoalloys planted on super-hydrophilic carbon nanocages featuring tip-intensified hydrogen evolution electrocatalysis, *Nat. Commun.* 15 (2024), <https://doi.org/10.1038/s41467-024-51370-1>.
- [36] J.F. Callejas, J.M. McEnaney, C.G. Read, J.C. Crompton, A.J. Bacci, E.J. Popczun, T.R. Gordon, N.S. Lewis, R.E. Schaak, Electrocatalytic and photocatalytic hydrogen production from acidic and neutral-pH aqueous solutions using iron phosphide nanoparticles, *ACS Nano* 8 (2014) 11101–11107, <https://doi.org/10.1021/nm5048553>.

- [37] S. Anantharaj, K. Karthick, M. Venkatesh, T.V.S.V. Simha, A.S. Salunke, L. Ma, H. Liang, S. Kundu, Enhancing electrocatalytic total water splitting at few layer Pt-NiFe layered double hydroxide interfaces, *Nano Energy* 39 (2017) 30–43, <https://doi.org/10.1016/j.nanoen.2017.06.027>.
- [38] T. Shinagawa, A.T. Garcia-Esparza, K. Takanabe, Insight on Tafel slopes from a microkinetic analysis of aqueous electrocatalysis for energy conversion, *Sci. Rep.* 5 (2015), <https://doi.org/10.1038/srep13801>.
- [39] O. van der Heijden, S. Park, R.E. Vos, J.J.J. Eggebeen, M.T.M. Koper, Tafel slope plot as a tool to analyze electrocatalytic reactions, *ACS Energy Lett.* 9 (2024) 1871–1879, <https://doi.org/10.1021/acseenergylett.4c00266>.
- [40] X. Zou, Y. Zhang, Noble metal-free hydrogen evolution catalysts for water splitting, *Chem. Soc. Rev.* 44 (2015) 5148–5180, <https://doi.org/10.1039/c4cs00448e>.
- [41] S. Moniri, T. Van Cleve, S. Linic, Pitfalls and best practices in measurements of the electrochemical surface area of platinum-based nanostructured electro-catalysts, *J. Catal.* 345 (2017) 1–10, <https://doi.org/10.1016/j.jcat.2016.11.018>.
- [42] Y. Zhu, M. Klingenhof, C. Gao, T. Koketsu, G. Weiser, Y. Pi, S. Liu, L. Sui, J. Hou, J. Li, H. Jiang, L. Xu, W.H. Huang, C.W. Pao, M. Yang, Z. Hu, P. Strasser, J. Ma, Facilitating alkaline hydrogen evolution reaction on the hetero-interfaced Ru/RuO₂ through Pt single atoms doping, *Nat. Commun.* 15 (2024), <https://doi.org/10.1038/s41467-024-45654-9>.
- [43] W. Ma, J. Wan, W. Fu, Y. Wu, Y. Wang, H. Zhang, Y. Wang, Heterostructures induced between platinum nanoparticles and vanadium carbide boosting hydrogen evolution reaction, *Appl. Catal. A Gen.* 633 (2022), <https://doi.org/10.1016/j.apcata.2022.118512>.
- [44] S. Anantharaj, P.E. Karthik, S. Noda, The significance of properly reporting turnover frequency in electrocatalysis research, *Angew. Chem. Int. Ed.* 60 (2021) 23051–23067, <https://doi.org/10.1002/anie.202110352>.
- [45] M. Smiljanić, S. Panić, M. Bele, F. Ruiz-Zepeda, L. Pavko, L. Gašparić, A. Kokalj, M. Gabersček, N. Hodnik, Improving the HER activity and stability of Pt nanoparticles by titanium oxynitride support, *ACS Catal.* 12 (2022) 13021–13033, <https://doi.org/10.1021/acscatal.2c03214>.
- [46] Z.W. She, J. Kibsgaard, C.F. Dickens, I. Chorkendorff, J.K. Nørskov, T.F. Jaramillo, Combining theory and experiment in electrocatalysis: insights into materials design, *Science* 355 (2017), <https://doi.org/10.1126/science.aad4998> (1979).
- [47] A.J. Bard, L.R. Faulkner, *Electrochemical Methods : Fundamentals and Applications*, John Wiley & Sons, Inc., 2001.
- [48] N. Mahmood, Y. Yao, J.W. Zhang, L. Pan, X. Zhang, J.J. Zou, Electrocatalysts for hydrogen evolution in alkaline electrolytes: mechanisms, challenges, and prospective solutions, *Adv. Sci.* 5 (2018), <https://doi.org/10.1002/advs.201700464>.
- [49] S. Xue, R.W. Haid, R.M. Kluge, X. Ding, B. Garlyyev, J. Fichtner, S. Watzel, S. Hou, A.S. Bandarenka, Enhancing the hydrogen evolution reaction activity of platinum electrodes in alkaline media using nickel-iron clusters, *Angew. Chem. Int. Ed.* 59 (2020) 10934–10938, <https://doi.org/10.1002/anie.202000383>.
- [50] N. Zheng, B. Yang, J. Xie, J. Hu, Z. Lu, Y. Cao, Ru-RuO₂@Co/CNF bifunctional catalysts with enhanced HER and OER activity for efficient acidic and alkaline overall water splitting, *Chem. Eng. J.* 529 (2026), <https://doi.org/10.1016/j.cej.2026.173158>.
- [51] J.R. Macdonald, W.B. Johnson, *Fundamentals of Impedance Spectroscopy, Impedance Spectroscopy*, Wiley, in, 2018, pp. 1–20, <https://doi.org/10.1002/9781119381860.ch1>.
- [52] X. Wang, X. Chen, M. Huang, Z. Liu, Rational fabrication of metal phosphide nanoparticles immobilized in electrospun carbon nanofibers for efficient pH-universal hydrogen evolution and overall water splitting, *Int. J. Hydrog. Energy* 63 (2024) 556–565, <https://doi.org/10.1016/j.ijhydene.2024.03.129>.
- [54] M. Yasin, N. Khan, M. Murad, K. Ali, Z. Zeb, S. Saleem, Z. Ullah, Pt-based electrocatalyst for hydrogen evolution in acidic electrolytes, *Electrochem. Commun.* 180 (2025), <https://doi.org/10.1016/j.elecom.2025.108057>.
- [55] K. Eiler, S. Surinach, J. Sort, E. Pellicer, Mesoporous Ni-rich Ni–Pt thin films: electrodeposition, characterization and performance toward hydrogen evolution reaction in acidic media, *Appl. Catal. B* 265 (2020), <https://doi.org/10.1016/j.apcatb.2020.118597>.
- [56] R. Gao, G. Li, K. Xu, C. Qiu, Y. Cong, Y. Lv, Q. Jiang, J. Qin, Y. Song, Ultrafine PtCoRh nanorods for highly efficient hydrogen evolution reaction in acid, *Chem. Commun.* 58 (2022) 7309–7312, <https://doi.org/10.1039/d2cc02298b>.
- [57] S.L. Zhang, X.F. Lu, Z.P. Wu, D. Luan, X.W. Lou, Engineering platinum–cobalt nano-alloys in porous nitrogen-doped carbon nanotubes for highly efficient electrocatalytic hydrogen evolution, *Angew. Chem. Int. Ed.* 60 (2021) 19068–19073, <https://doi.org/10.1002/anie.202106547>.
- [58] J. Chen, Y. Yang, J. Su, P. Jiang, G. Xia, Q. Chen, Enhanced activity for hydrogen evolution reaction over CoFe catalysts by alloying with small amount of Pt, *ACS Appl. Mater. Interfaces* 9 (2017) 3596–3601, <https://doi.org/10.1021/acsaami.6b12065>.
- [59] X. Zeng, J. Shui, X. Liu, Q. Liu, Y. Li, J. Shang, L. Zheng, R. Yu, Single-atom to single-atom grafting of Pt1 onto Fe-N4 center: Pt1@Fe-N-C multifunctional electrocatalyst with significantly enhanced properties, *Adv. Energy Mater.* 8 (2018), <https://doi.org/10.1002/aenm.201701345>.
- [60] H. Zhang, P. An, W. Zhou, B.Y. Guan, P. Zhang, J. Dong, X. Wen, D. Lou, Dynamic traction of lattice-confined platinum atoms into mesoporous carbon matrix for hydrogen evolution reaction, <https://www.science.org>, 2018.
- [61] P. Sun, R. Jiang, Z. Qiao, S. Huang, S. Wang, D. Cao, Strong metal-support interaction of Ru-NPs/WC_x boosts alkaline hydrogen evolution and oxidation for alkaline fuel cells and electrolyzers, *Nat. Commun.* 16 (2025), <https://doi.org/10.1038/s41467-025-65273-2>.