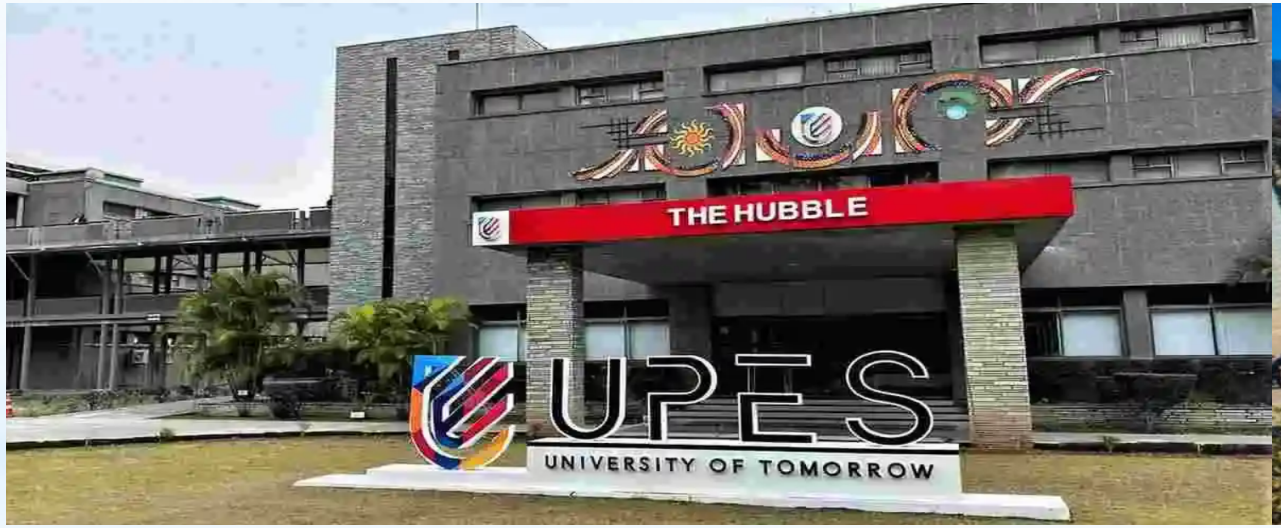
Department of Physics, SNS
Shiv Nadar Institution of Eminence Delhi NCR, India
SWPNIOE 2026
Symposium on Women in Physics
Networking, Innovation, Opportunity, and Equity
11 - 12 SEPTEMBER, 2026

Advanced Nanostructured Electrode Materials for Sustainable Energy Conversion and Storage

Dr. Debosmita Banerjee

Assistant Professor
Department of Physics, Applied Science Cluster,
School of Advanced Engineering, UPES (Bidholi), Dehradun.





ELECTROCHEMICAL ENERGY STORAGE & CONVERSION: ENABLING THE CLEAN ENERGY TRANSITION

Mapping the Sustainable Energy Cycle

RENEWABLE SOURCES

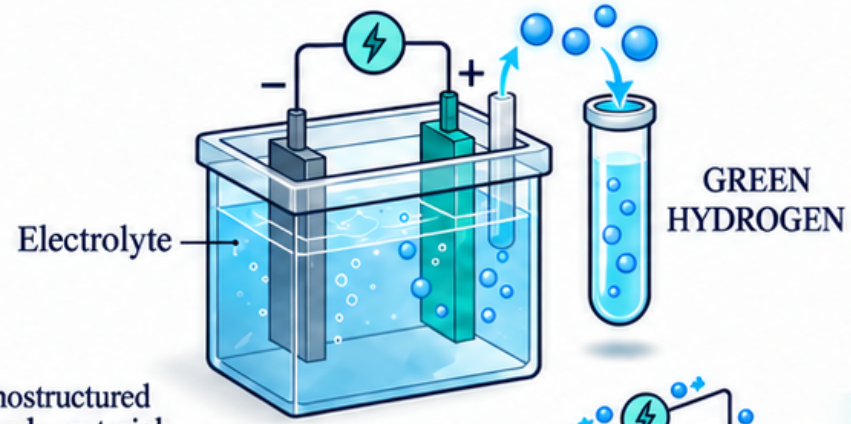


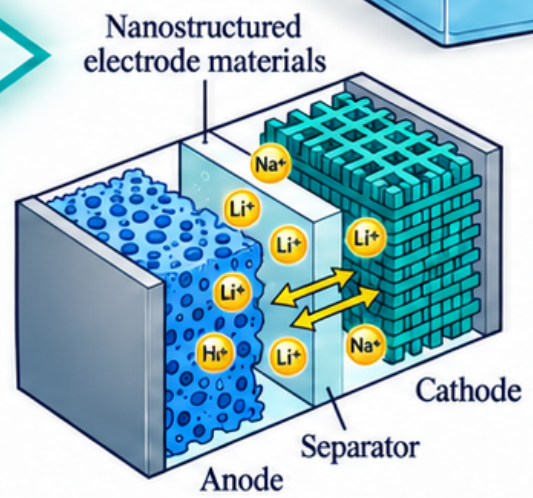
Wind Energy



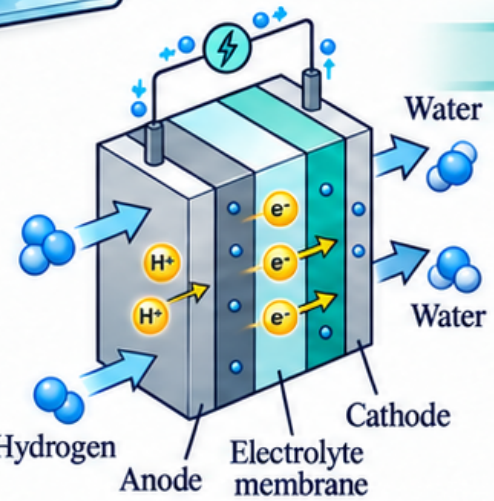
Solar PV Arrays

ELECTROCHEMICAL SYSTEMS (CORE)





Ion Migration



Electricity Generation

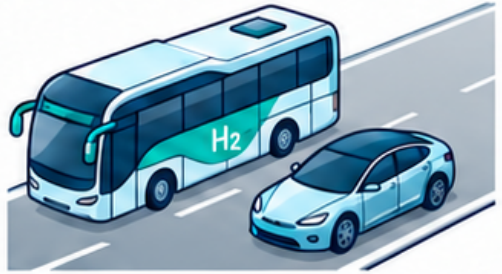
APPLICATION SECTORS



Clean Electricity Grid

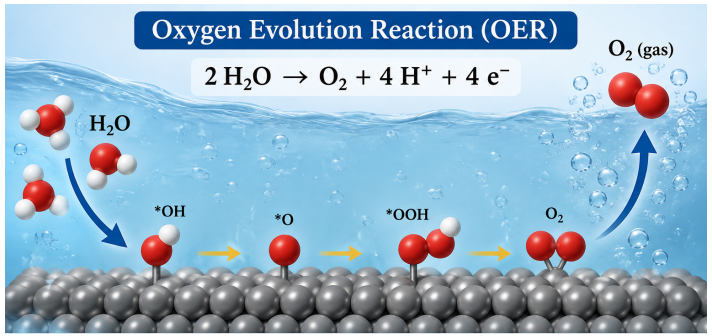


Residential & Smart Homes

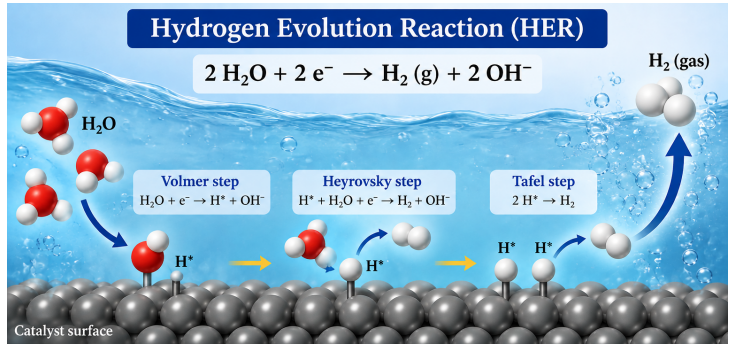


H2 Fuel-Cell Transportation

Driving Global Decarbonization Through Rational Design of Advanced Electrodes



Overall water splitting



High Performance Electrode Materials

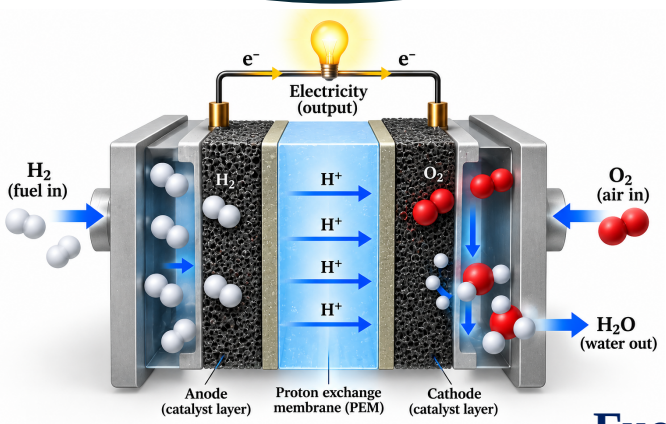
- Superior catalytic activity
- Rapid charge transfer
- Abundant active sites
- Long-term stability

Supercapacitor



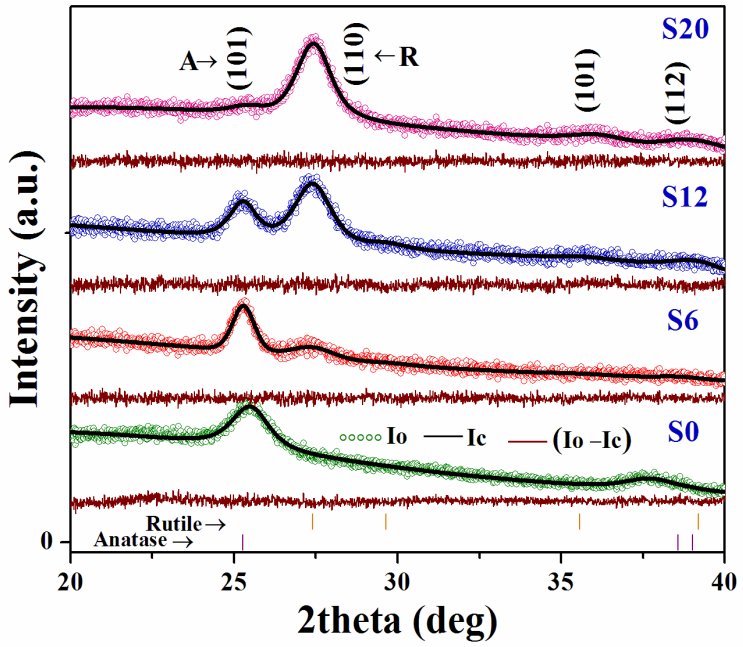


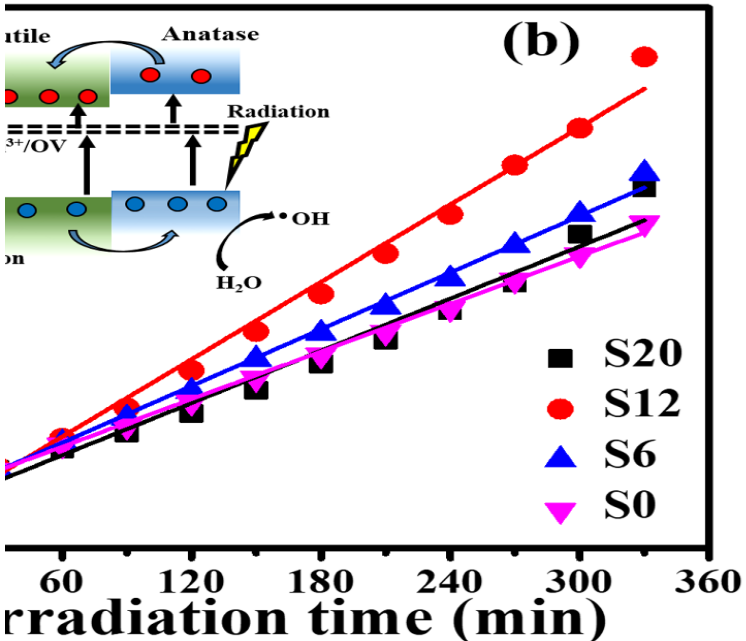
Sustainable Batteries (Zn, Na, K-ion, Metal Air, etc.)

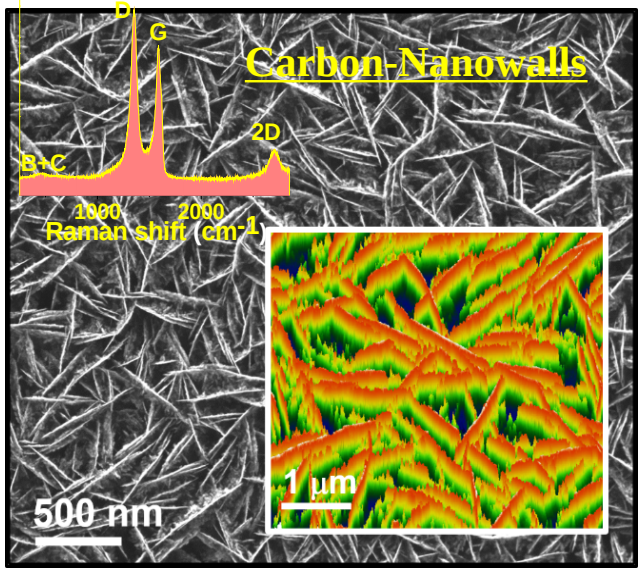


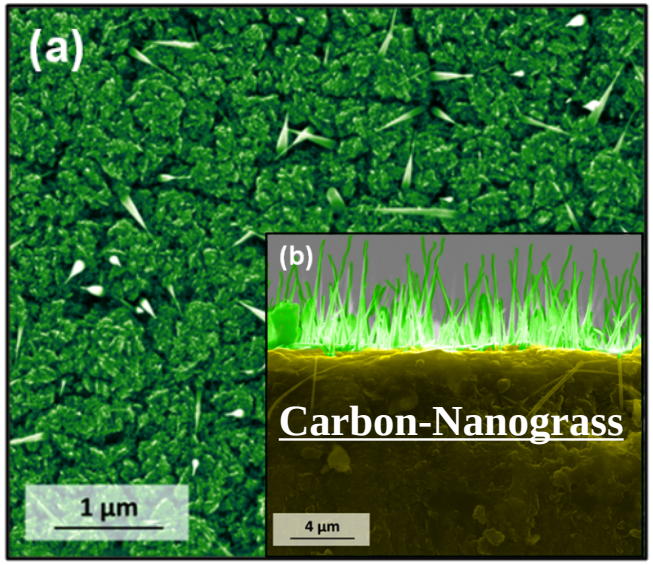
Fuel Cell

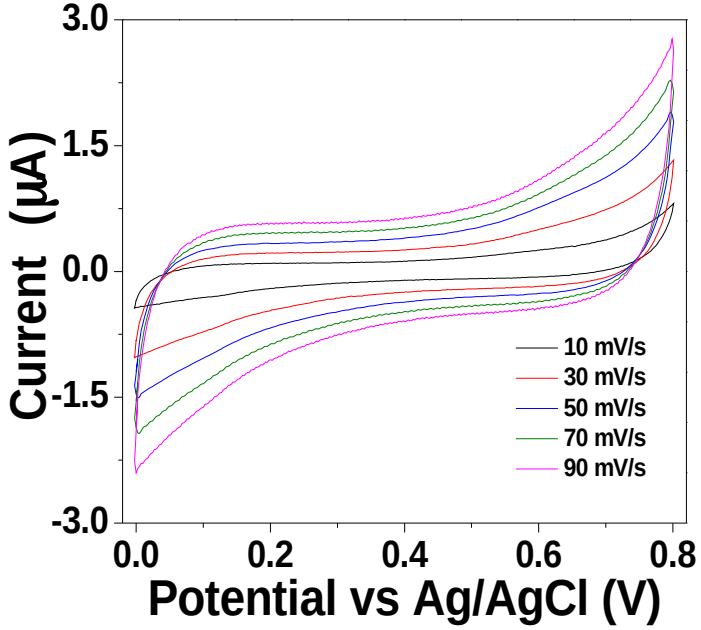
Energy storage and conversion projects

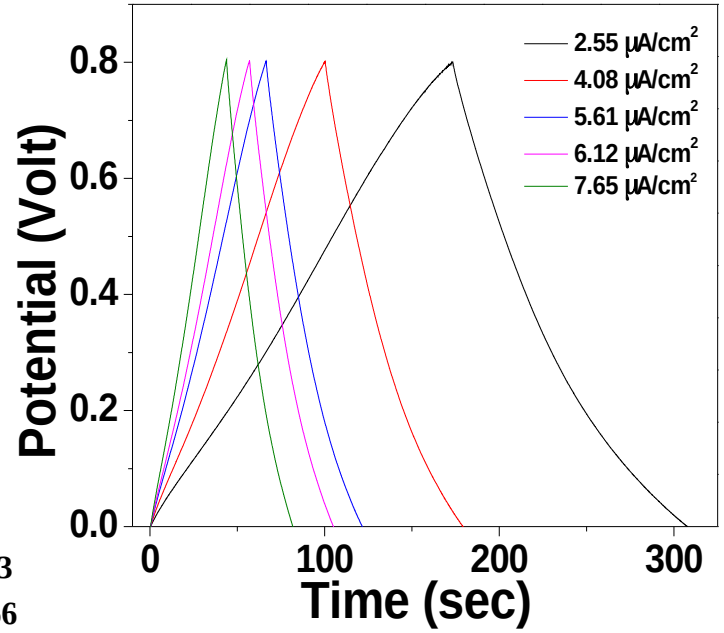












Collaboration with Hasselt University Belgium and Gdansk University of Technology Poland

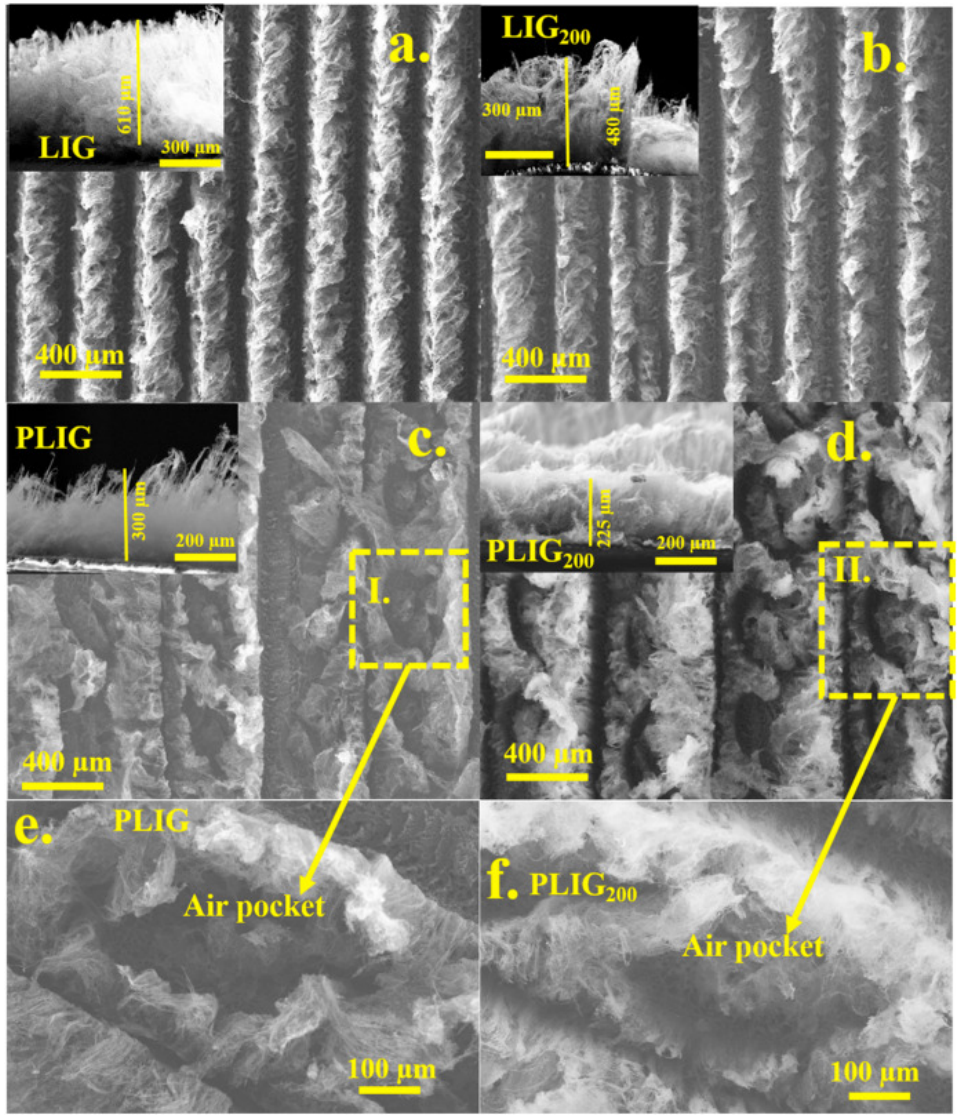
D. Banerjee et al. *Applied Physics Letters*, 2018, 113, 084103

D. Banerjee et al. *J. Phys. Chem. C*, 2019, 123, 15458−15466

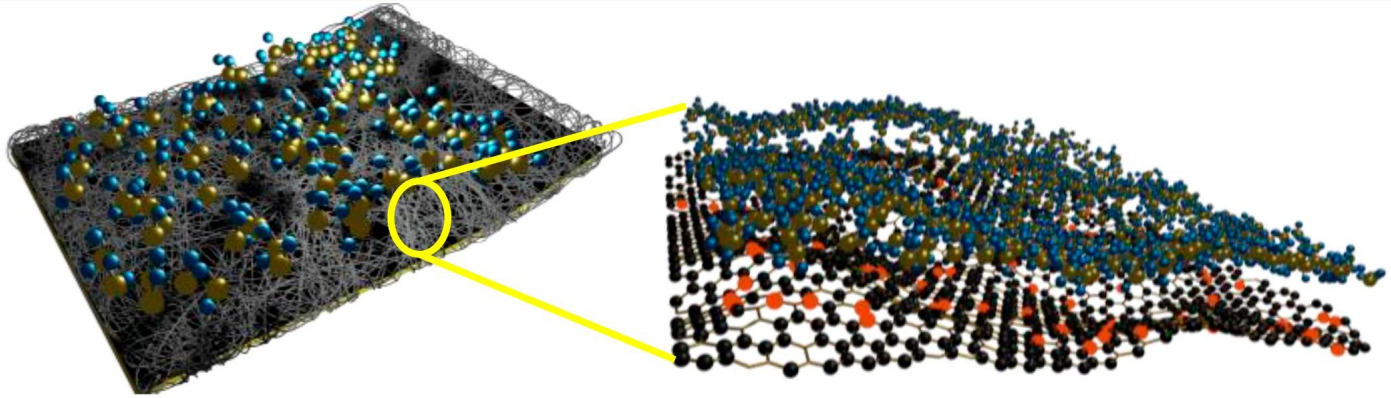
D. Banerjee et al. *Nanoscale*, 2020, 12(18), 10117−10126

Energy storage and conversion projects

Laser-induced graphene (LIG) fibers
collaboration with University of Alberta, Canada

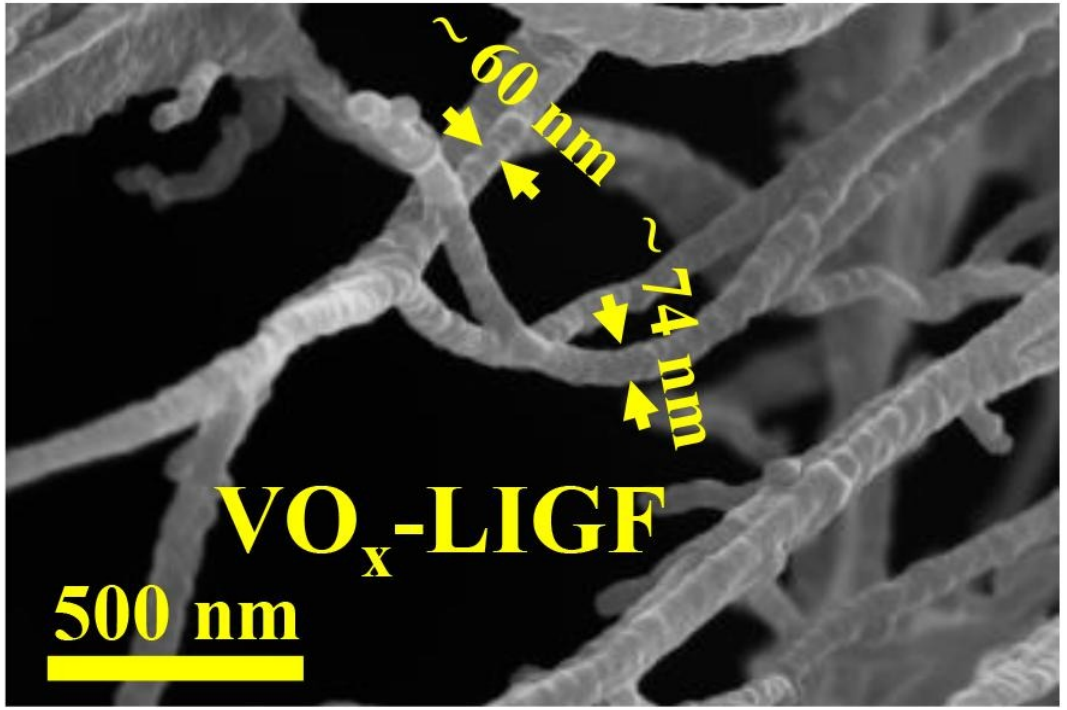


S. Deshmukh, D. Banerjee et al. Carbon 182 (2021): 605-614



ALD deposition of
VO_x on LIGF

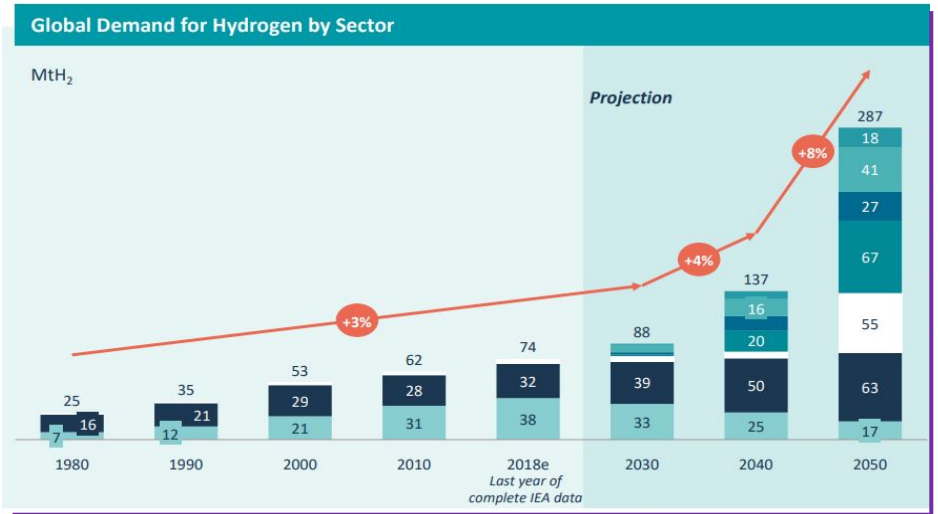
N C

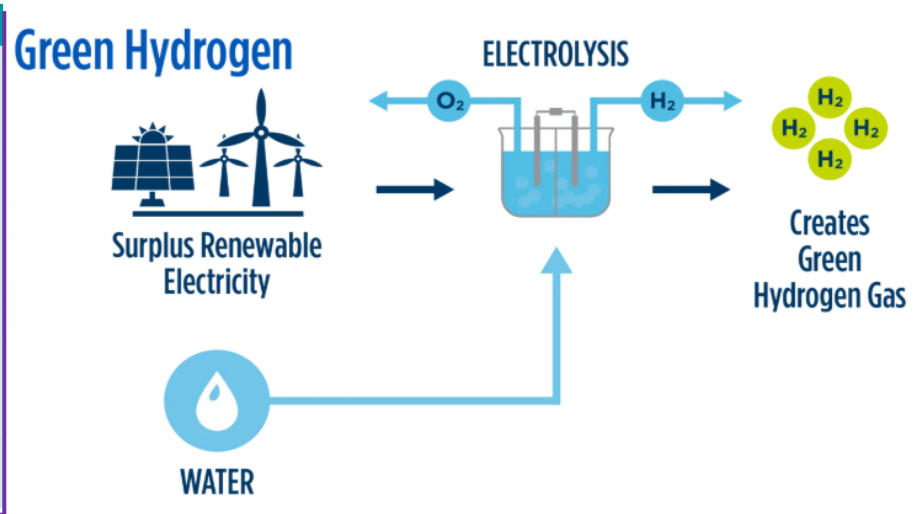


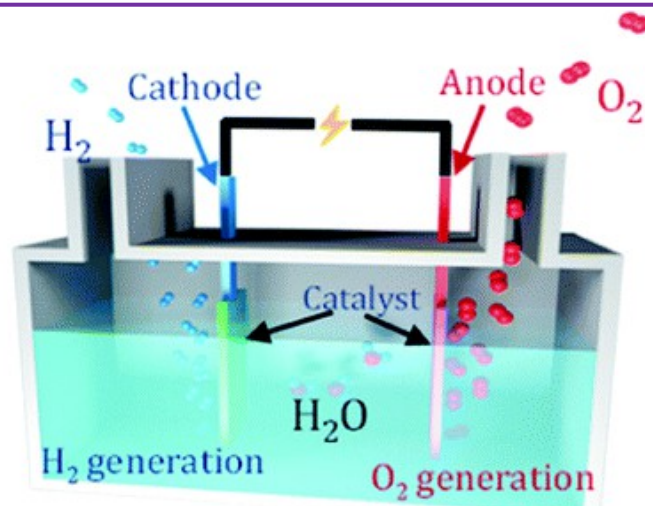
Chemical Engineering Journal 480 (2024): 147895.

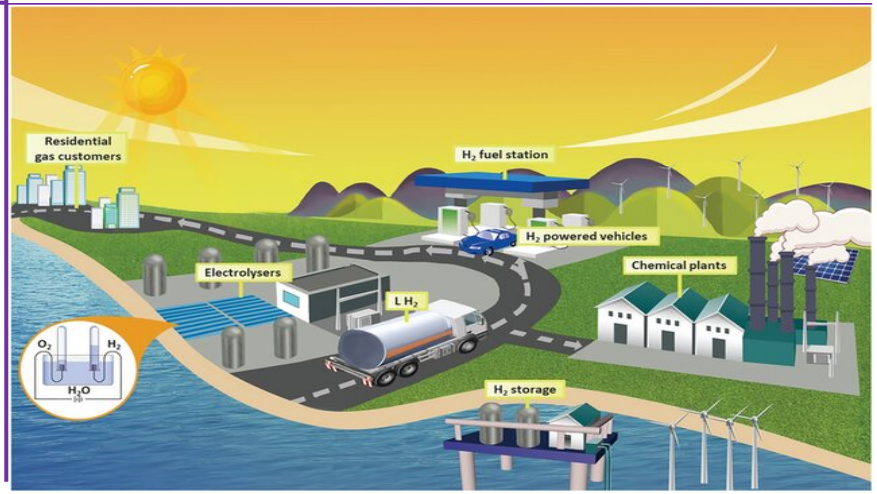
Nanoengineered NiO/ZnO heterostructures integrated WS_2 nanostructures as a bifunctional catalyst for water splitting applications

A collaborative UPES- SNIoE Innovation



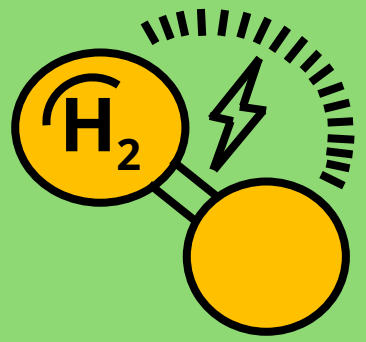






Chem. Sci., 2020, 11, 10614-10625
Alexandria Engineering Journal 100 (2024) 182–207

The bottlenecks of scalable green hydrogen production



The Promise: Green Hydrogen

Offers unmatched gravimetric energy density as a fossil fuel substitute

1. The OER Kinetic Bottleneck

Sluggish, multiproton coupled electron transfers limit overall electrolysis efficiency

2. Noble Metal Dependency

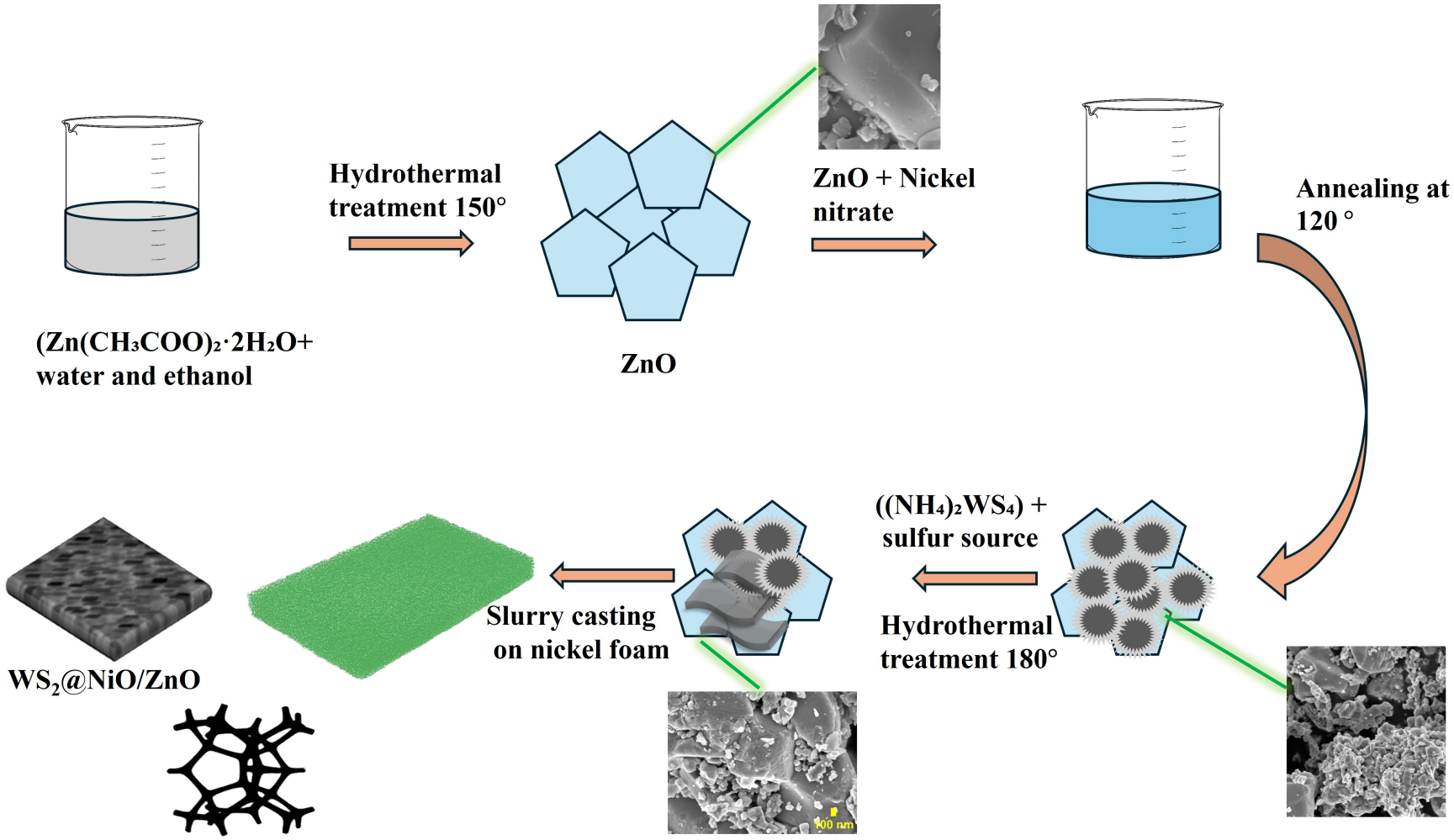
Industrial reliance on expensive, scarce IrO_2 and RuO_2 prevents cost effective scaling

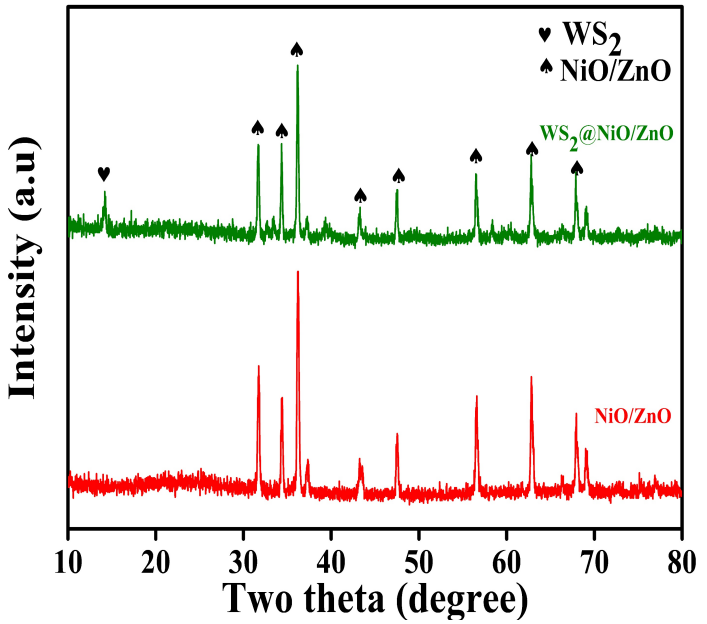
3. The seawater challenge

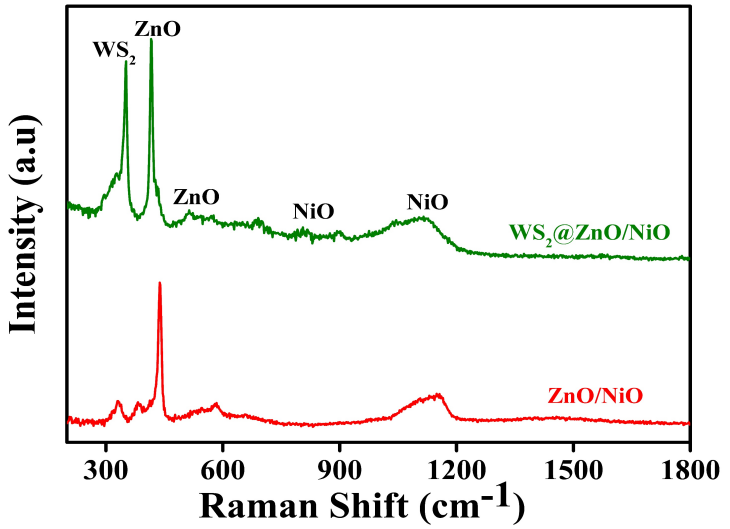
Severe corrosive environments and the highly competitive Chlorine Evolution Reaction (CER) degrades conventional catalysts.

Synthesis and Characterization of Catalyst

Synthesis of WS_2@NiO/ZNO

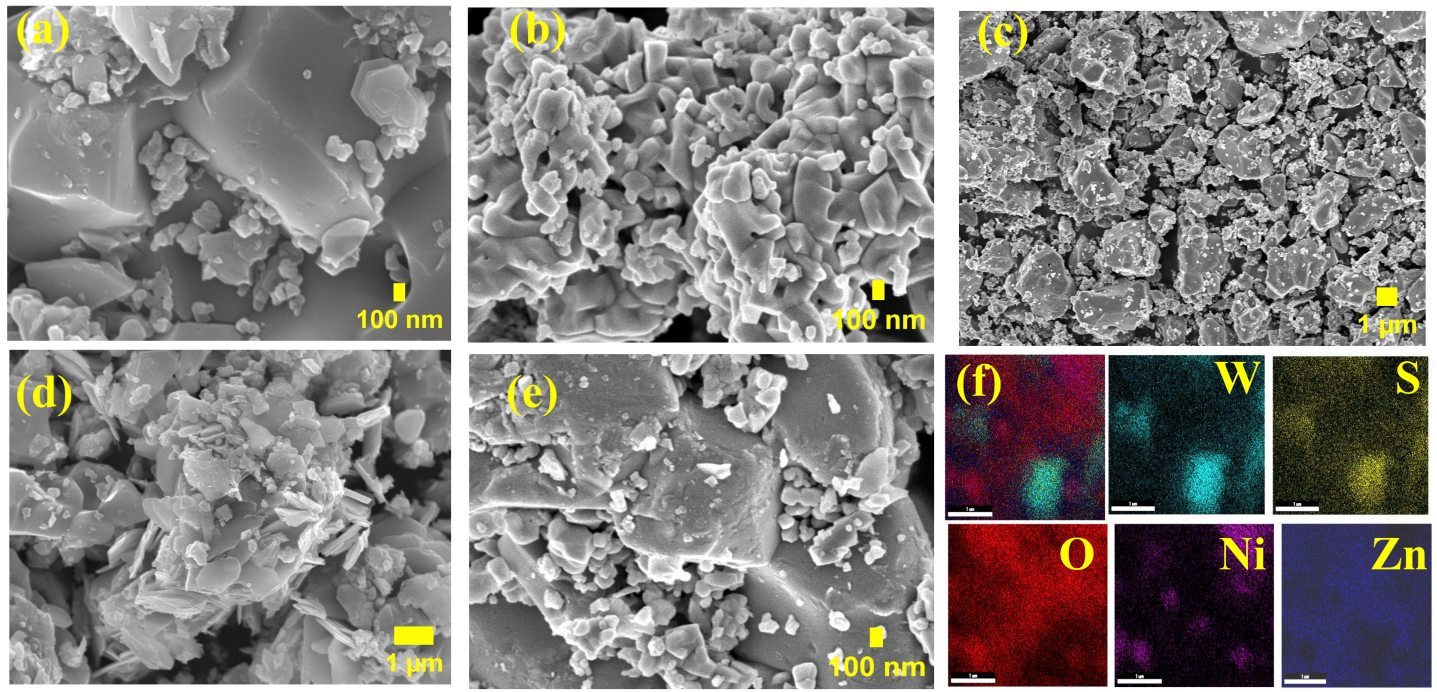


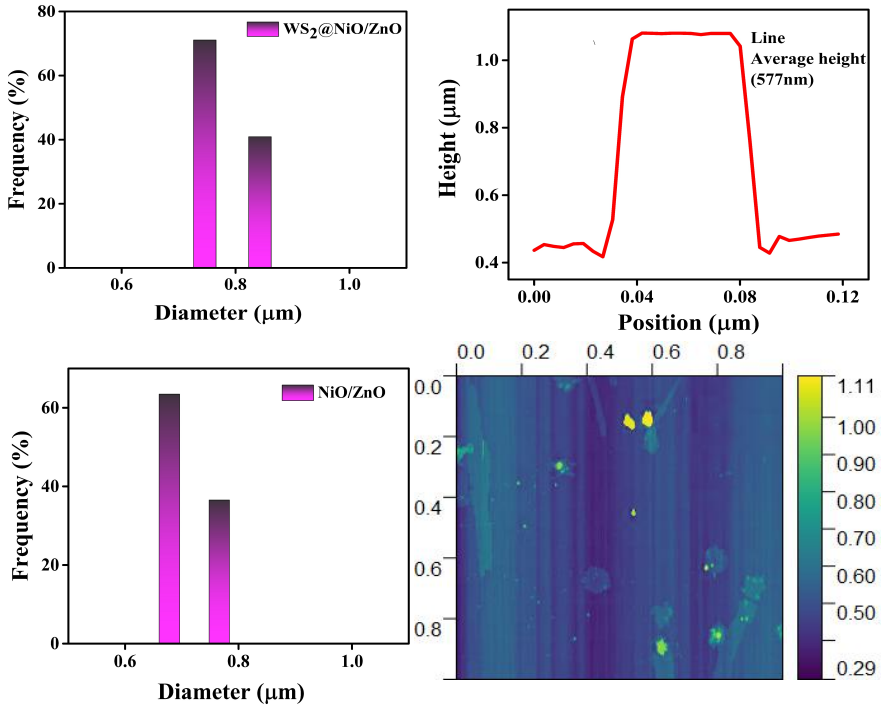


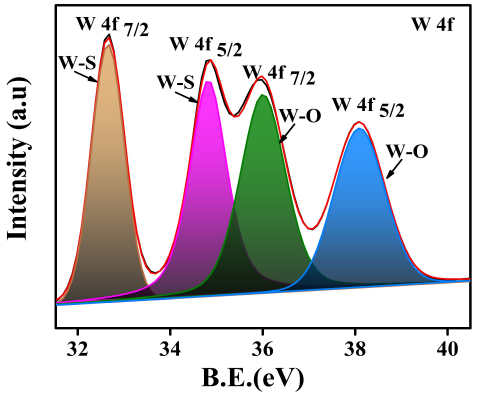


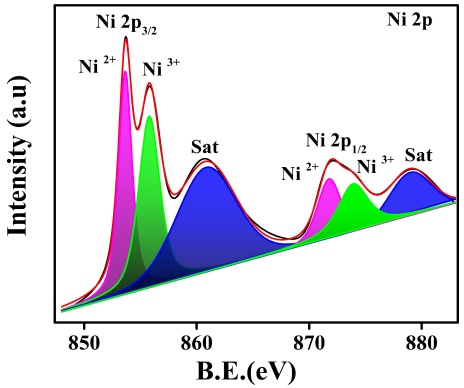
ACS Appl. Energy Mater. (2026) 9 (13): 8251–8267

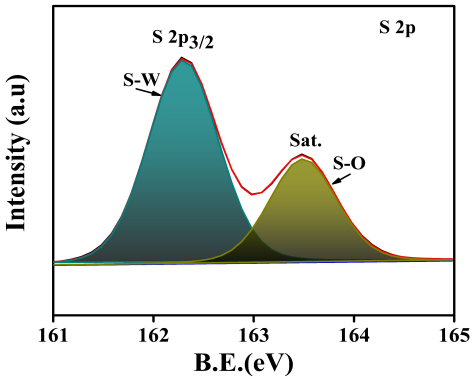
Structural and Morphological Analysis

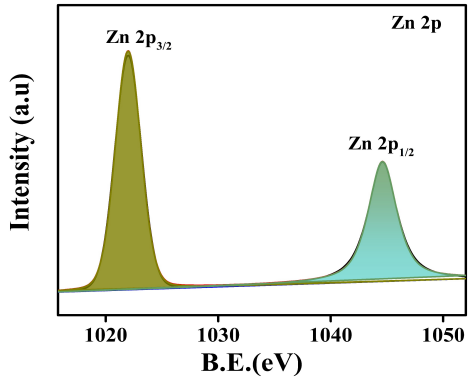






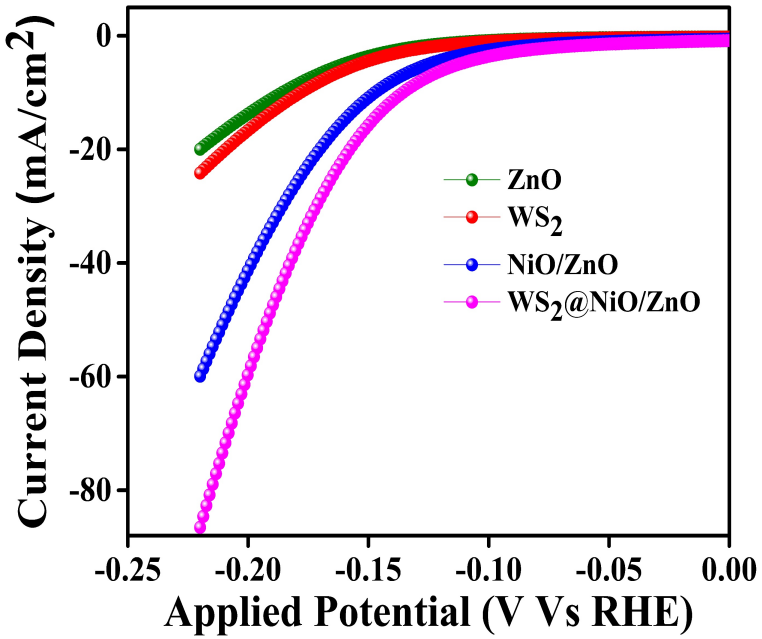


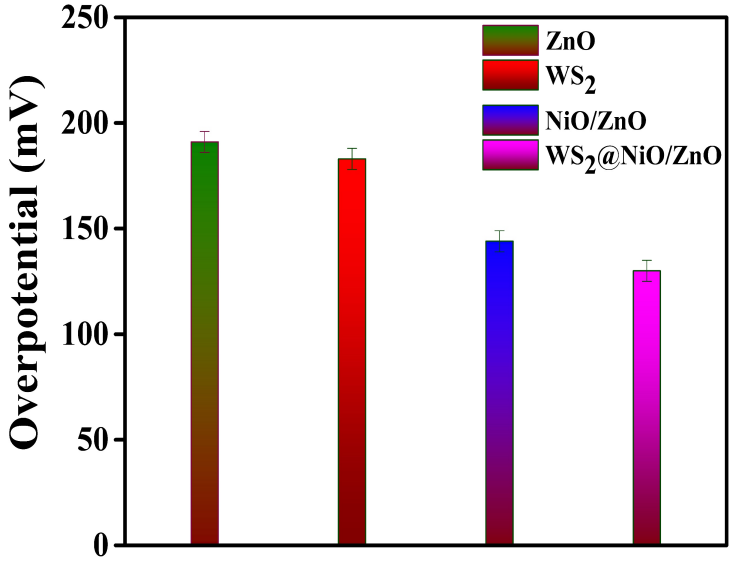


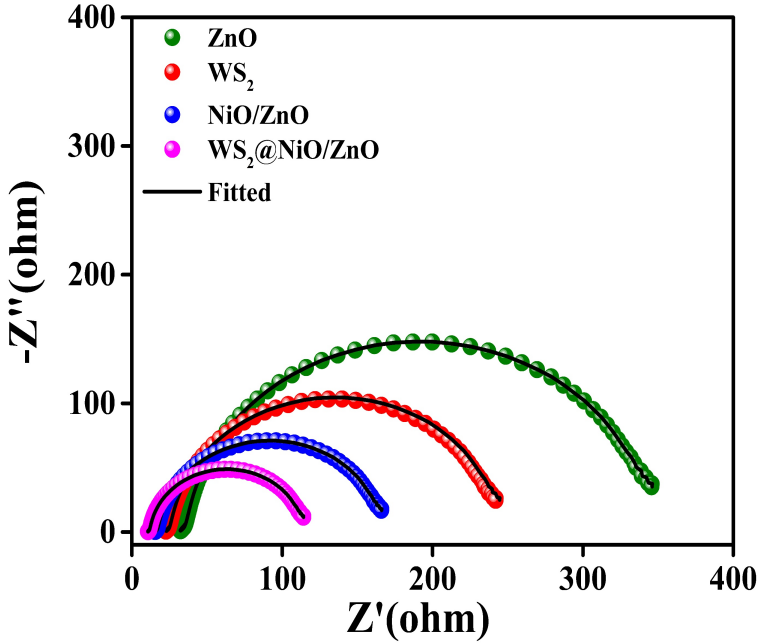


ACS Appl. Energy Mater. (2026) 9 (13): 8251–8267

Electrochemical Analysis: HER activity in 0.5 M H_2SO_4

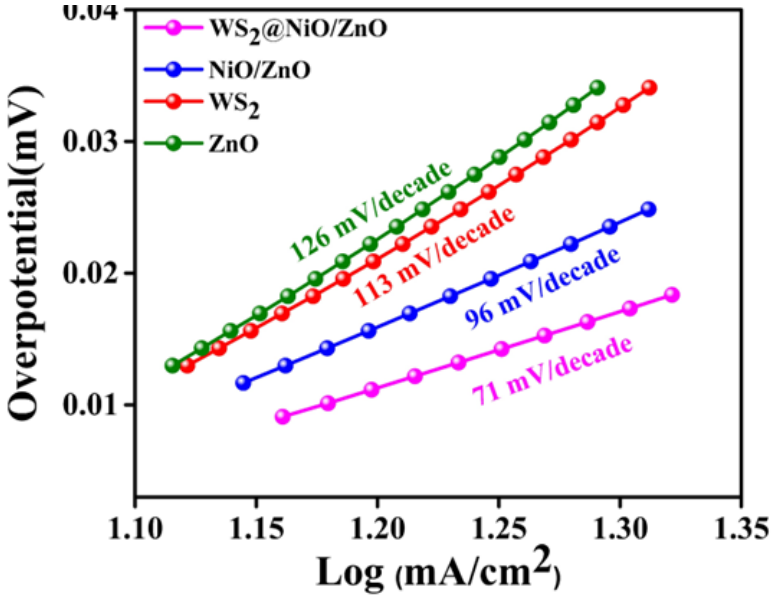






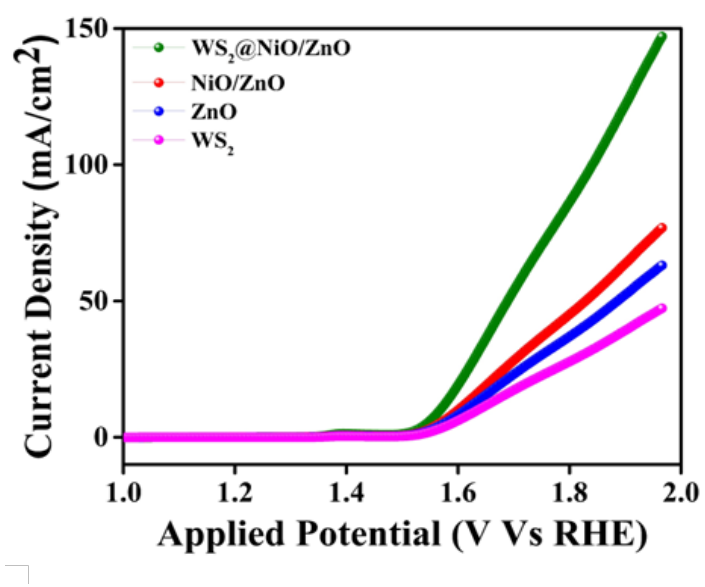
- **Overpotential: 131 mV at 10 mA/cm2**
- **Tafel Slope: 71 mV/dec**
- **Excellent chronopotentiometry over 30+ hours with negligible voltage decay**

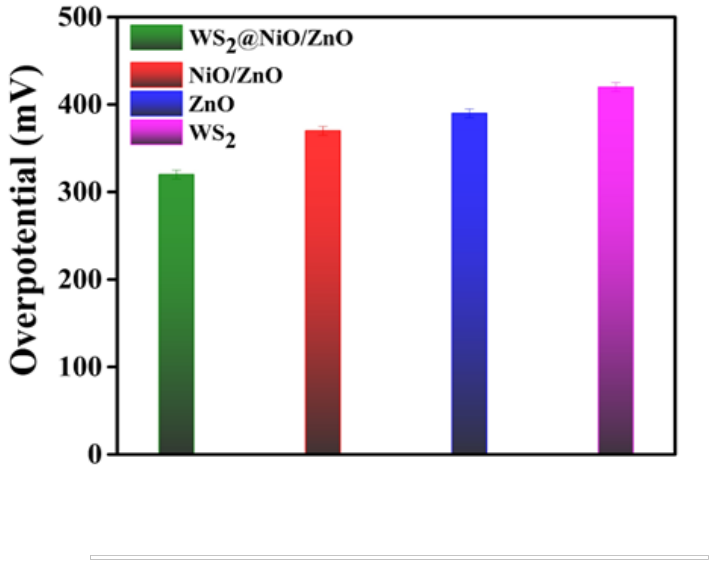
Sample	Tafel slope (mV/dec)
WS_2	126
ZnO	113
NiO	96
WS_2@NiO/ZnO	**71**

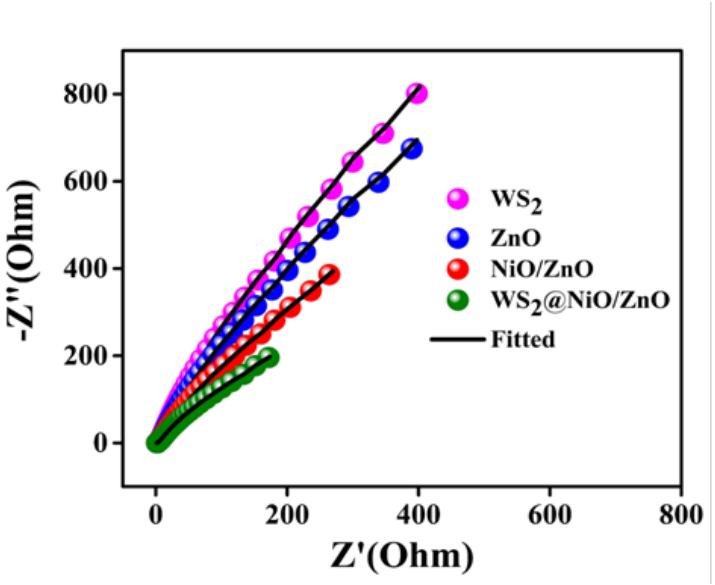


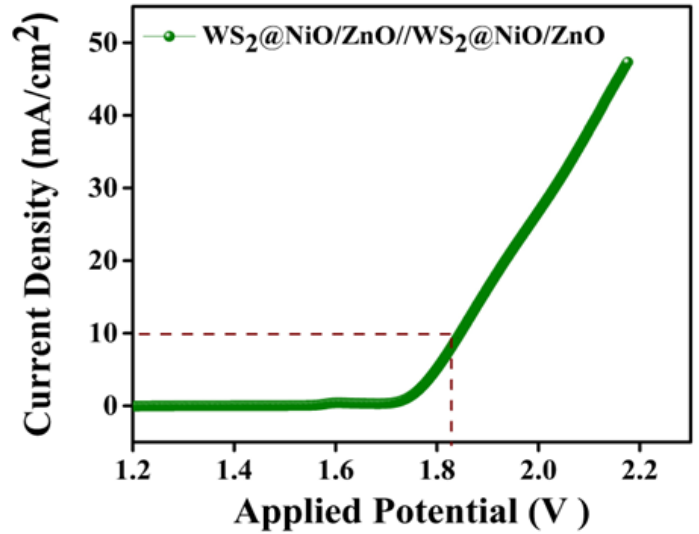
ACS Appl. Energy Mater. (2026) 9 (13): 8251–8267

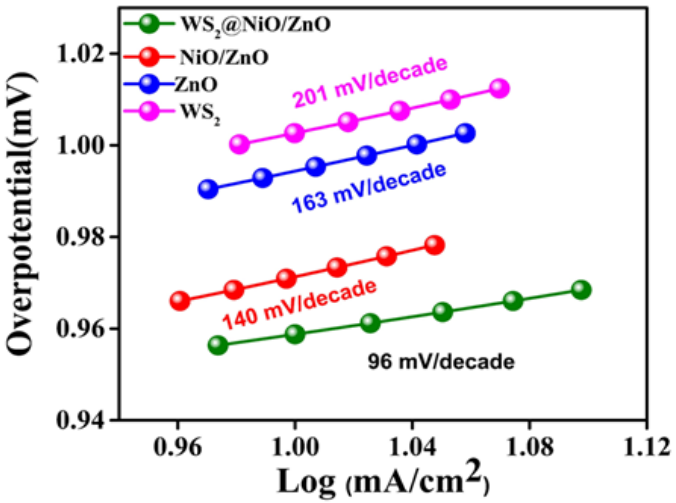
Electrochemical Analysis: OER activity in 1 M KOH







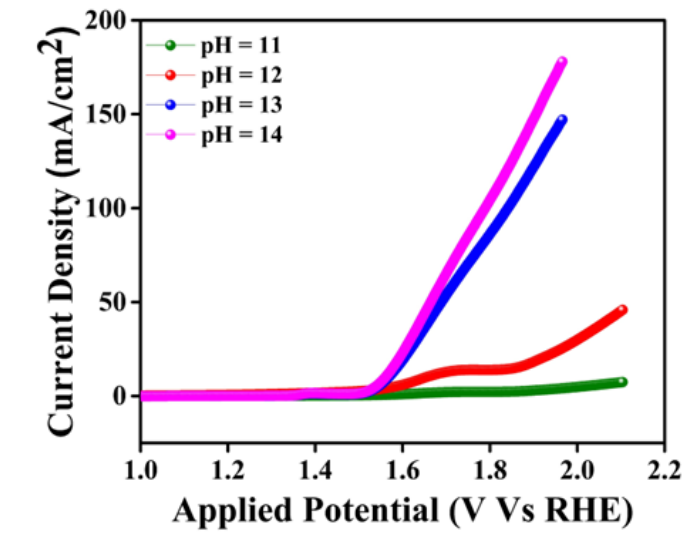


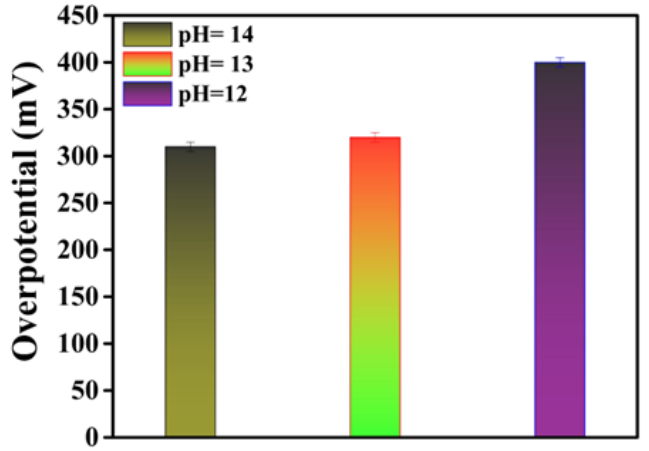


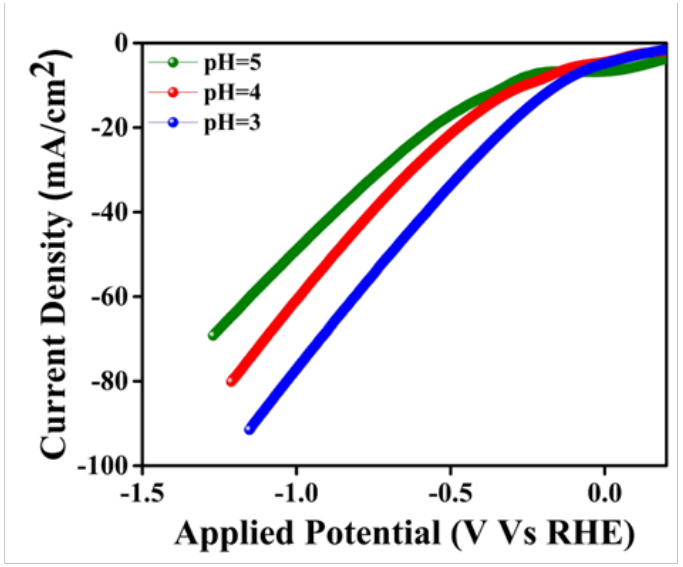
- **OER Overpotential: 320 mV at 10 mA/cm²**
- **OER Tafel Slope: 96 mV/dec**
- **Overall cell voltage 1.82 V at 10 mA/cm²**
- **Excellent chronopotentiometry over 30+ hours with negligible voltage decay**

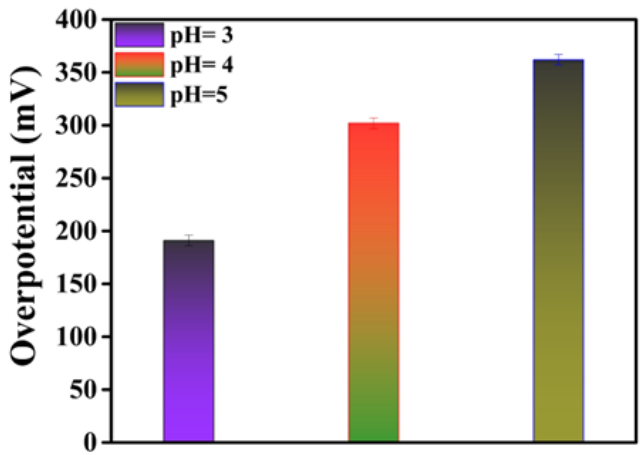
ACS Appl. Energy Mater. (2026) 9 (13): 8251–8267

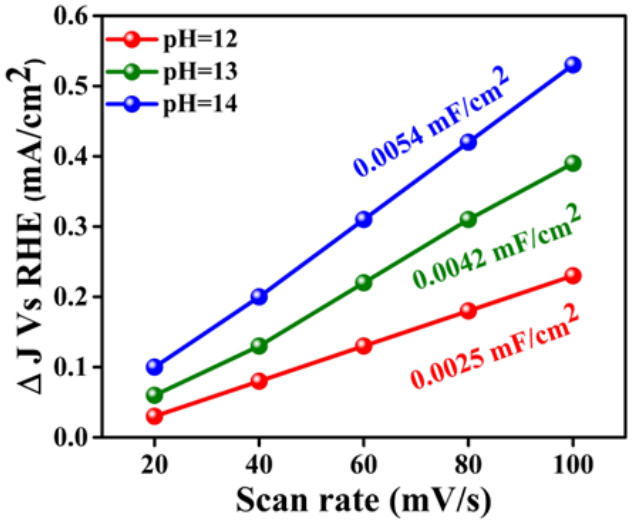
Electrocatalysis in Different pH Media

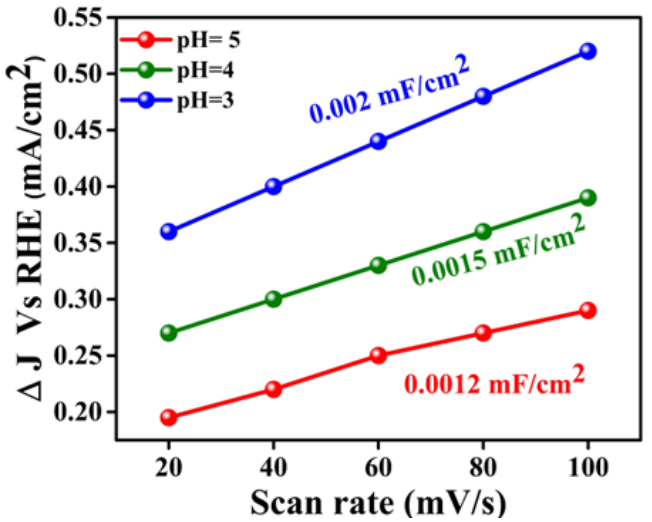












ACS Appl. Energy Mater. (2026) 9 (13): 8251–8267

Conclusion

Sustainable Energy Conversion & Storage

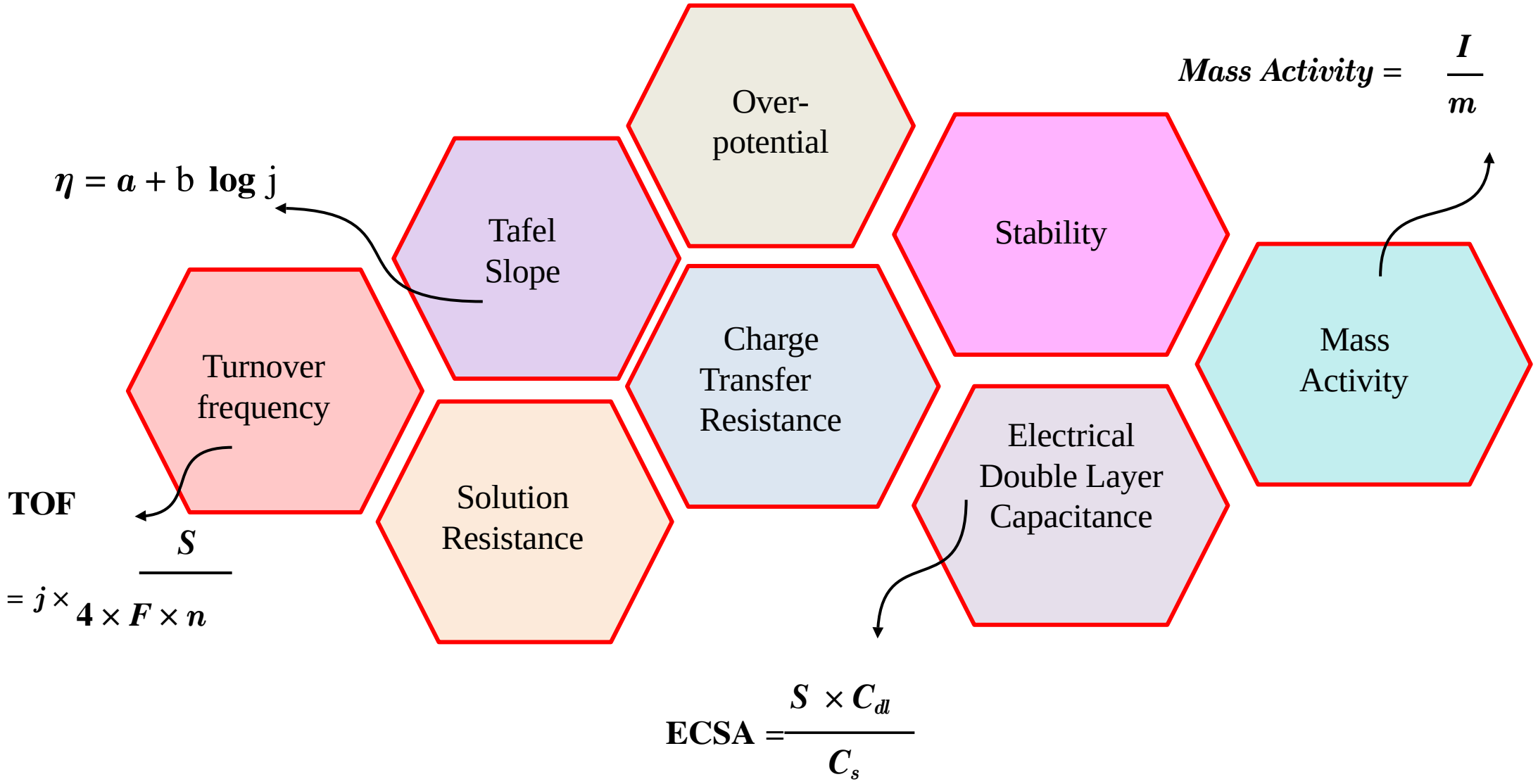
- **Rational molecular design:** Precise tuning of electronic structure, coordination environment
- **Bifunctional catalysts** can simultaneously promote complementary reactions such as **HER/OER** enabling efficient overall water splitting.
- **Strong structure-property relationships** between active sites, reaction intermediates, charge transfer, and catalyst-electrolyte interactions provide pathways to minimize **overpotential, energy loss, and degradation**.
- **Advanced materials platforms:** HEAs, Group 13, 14, 15 2D analogues**,** heterostructures, defect-engineered nanocarbons.
- **Coupling energy conversion with storage** will enable sustainable energy cycle:
  H_2 production → Fuel cells / energy storage → Electricity

Thank You!

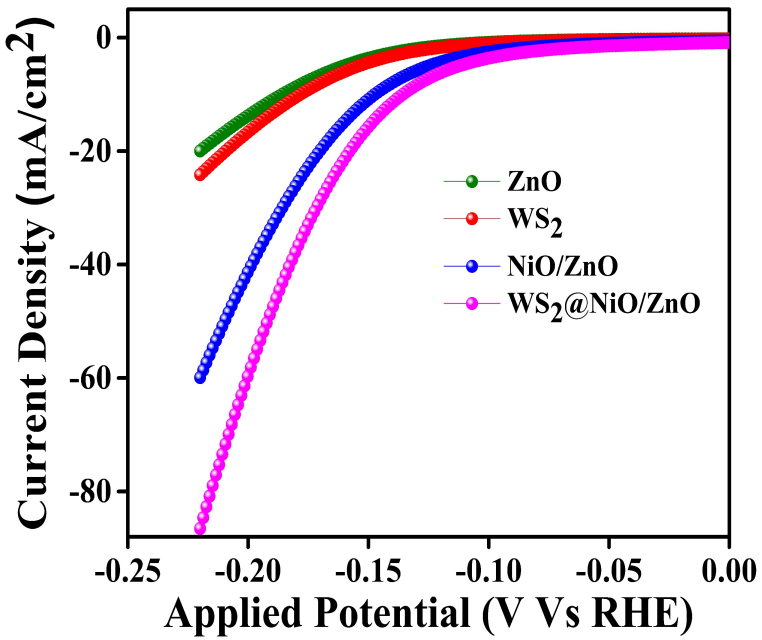


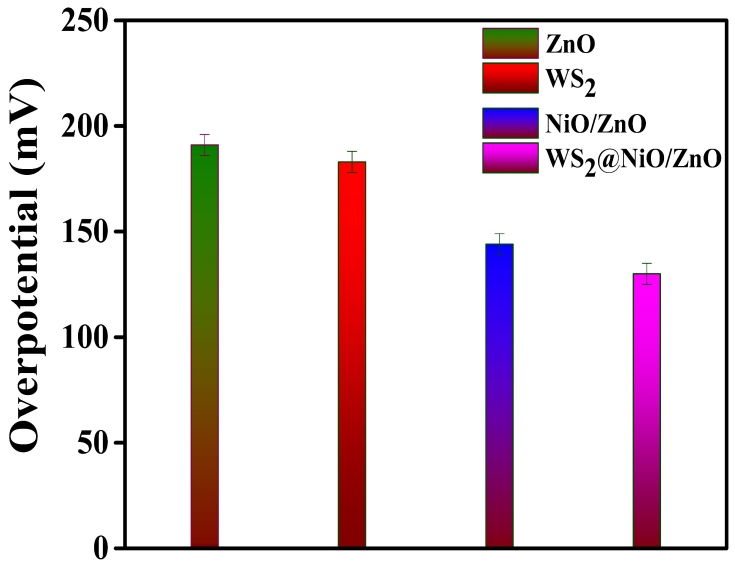
Email: debosmita.banerjee@ddn.upes.ac.in
debosmitabn@gmail.com
Google Scholar: https://scholar.google.com/citations?user=5_Lap9QAAAAJ&hl=en&oi=ao
LinkedIn: www.linkedin.com/in/debosmita-banerjee-321667122

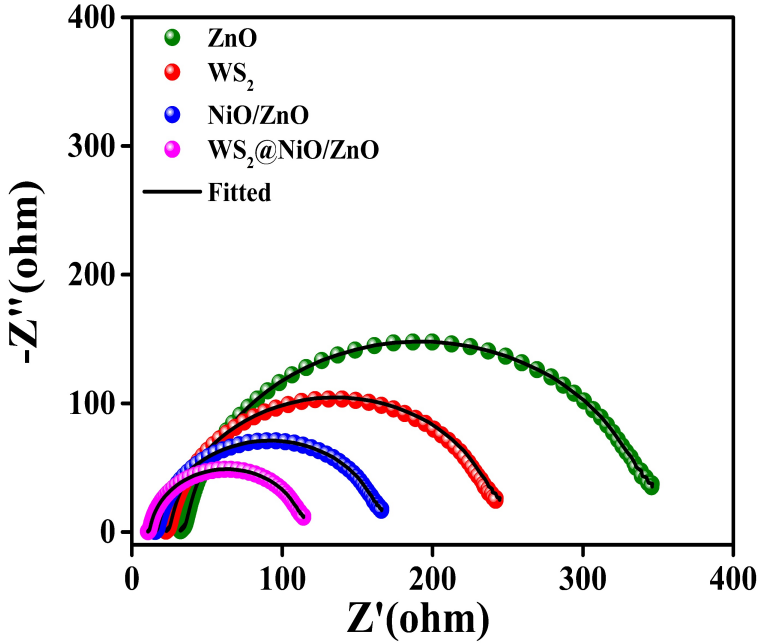
Performance Parameters



Electrochemical Analysis





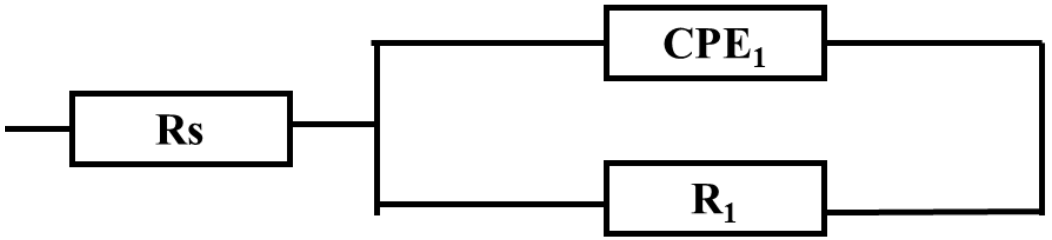


Overpotential η can be obtained by the following equation:

$$E_{RHE} = E_{Ag/AgCl} + 0.059pH + E_{Ag/AgCl}^{0}$$

$$E_{Ag/AgCl}^{0} = 0.199$$

$$\eta = E\ vs\ RHE - 1.23V$$



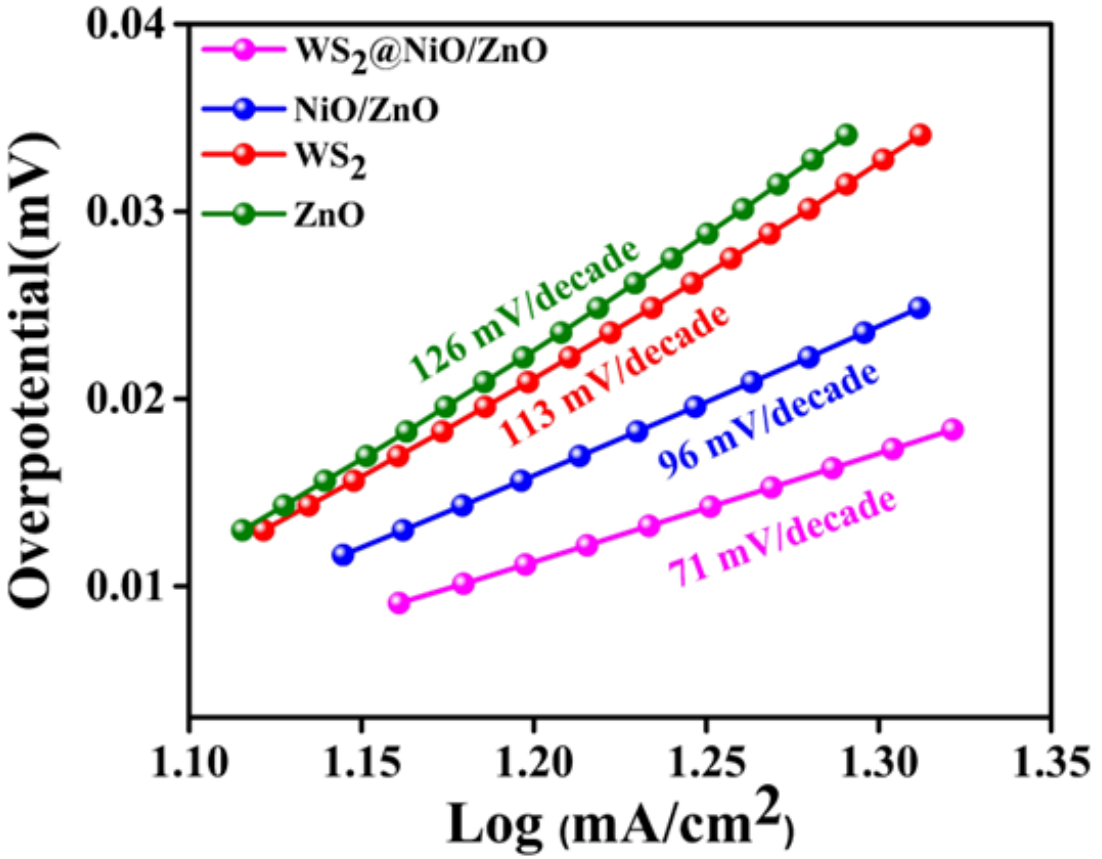
Tafel Slope

Tafel slope can be determined by the following equation

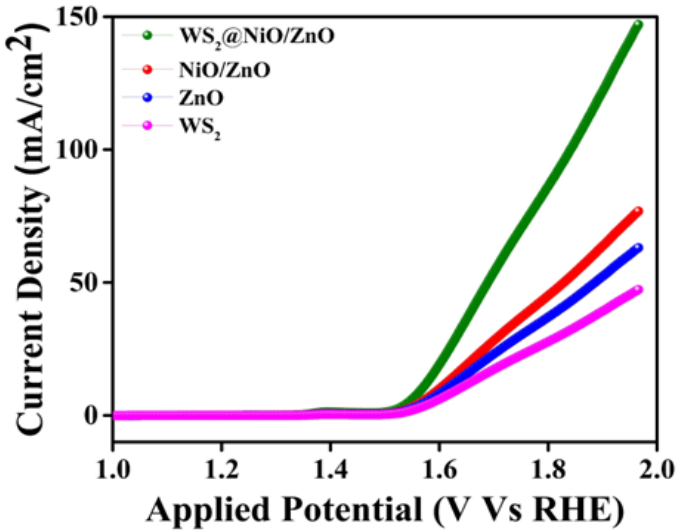
$$\eta = b.\log\left(\frac{j}{j_0}\right)$$

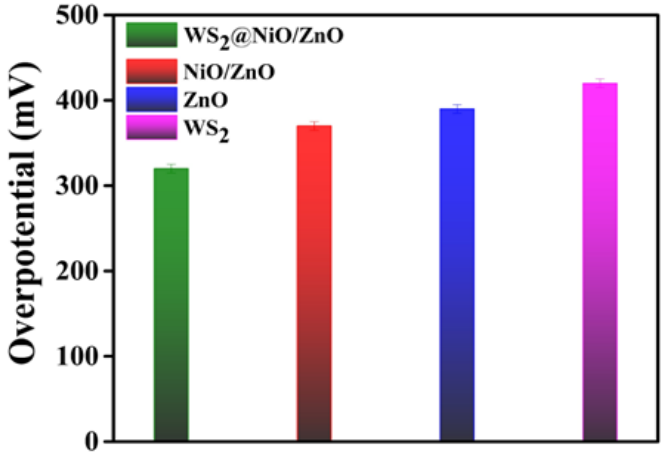
Where, η, j, j_0, b are the overpotential, current density, exchange current density and Tafel slope

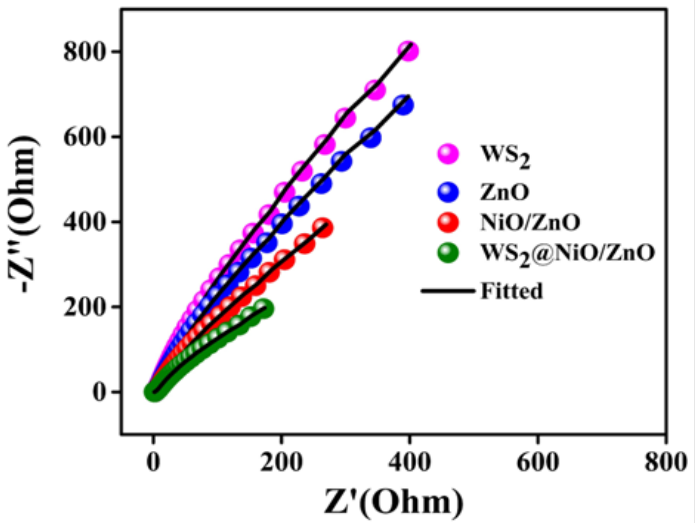
Sample	Tafel slope (mV/dec)
WS_2	126
ZnO	113
NiO	96
WS_2@NiO/ZnO	71

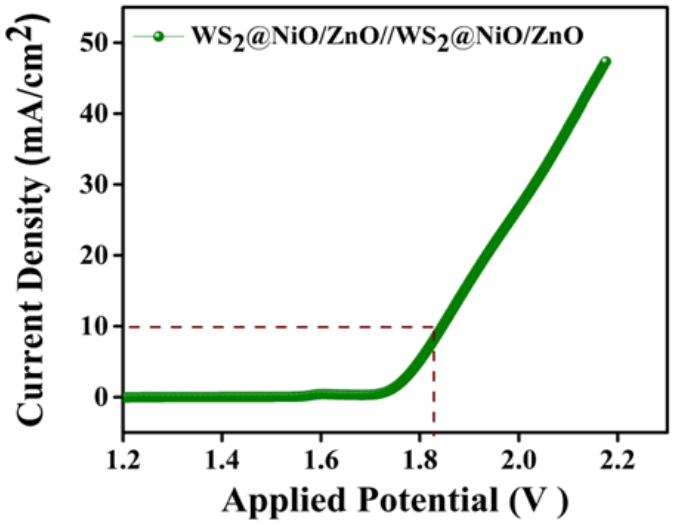


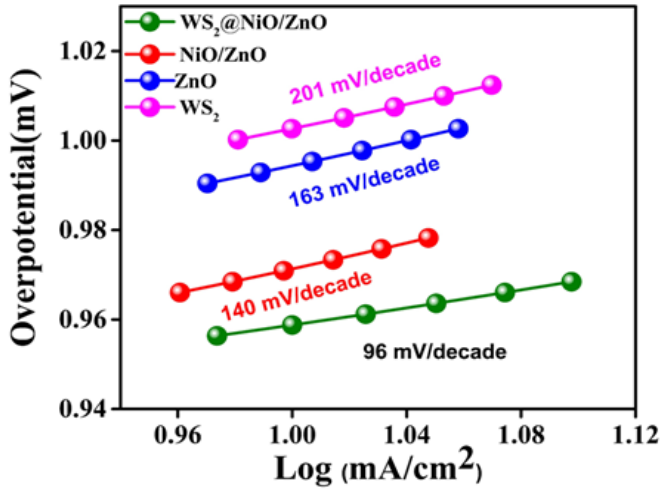
Electrochemical Analysis

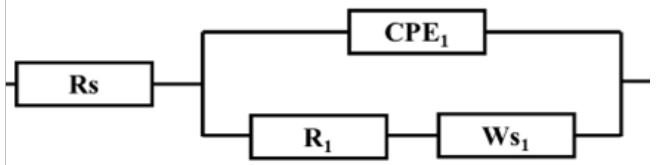




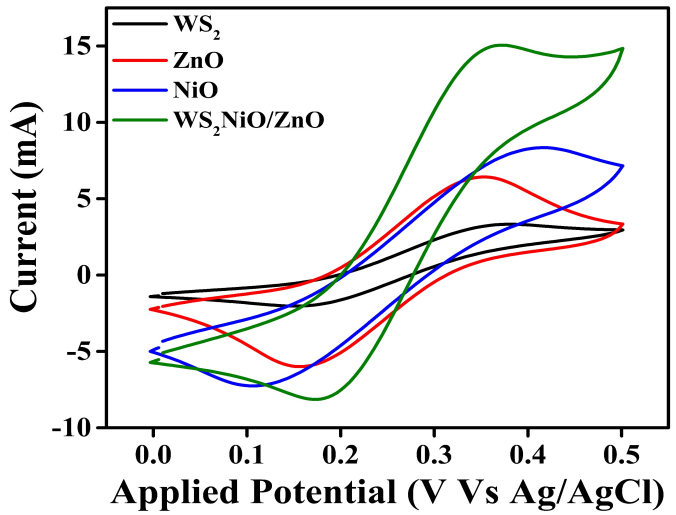


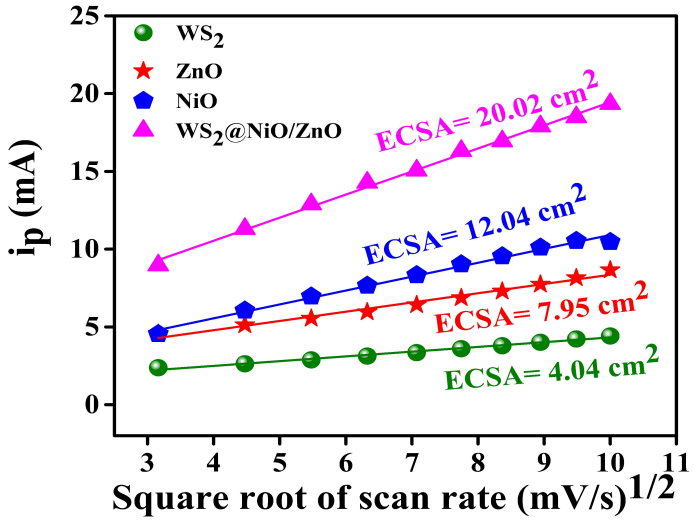


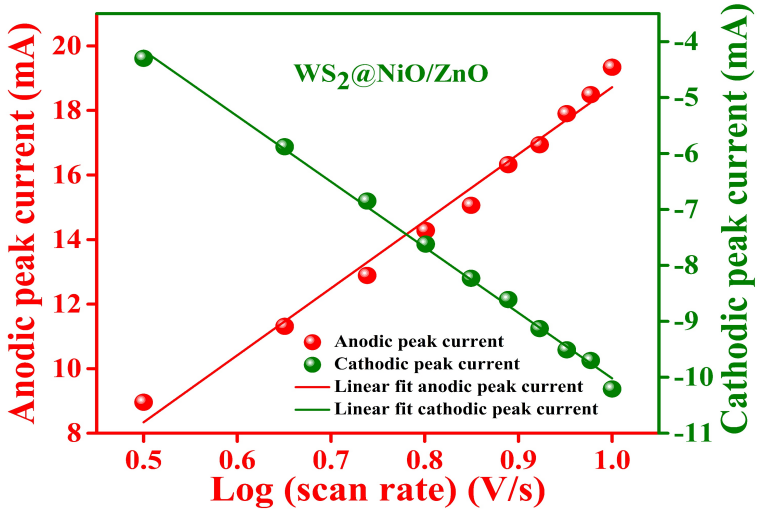


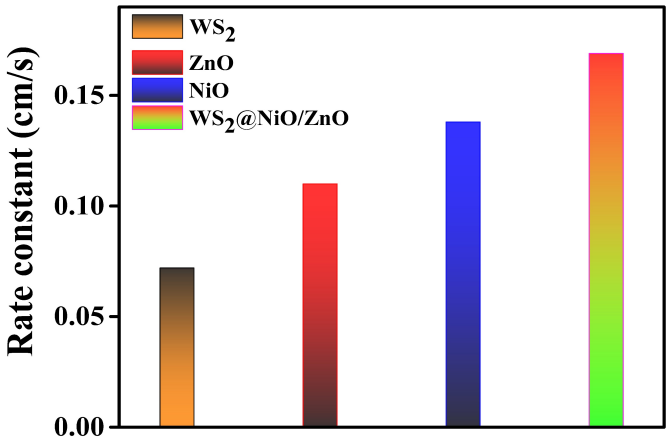


Electrochemical Rate Constant and ECSA









ECSA

$$I_p = 2.69\times10^5\, A\, D^{1/2}\, n^{3/2}\, \upsilon^{1/2}\, C$$

Rate Constant

$$\Psi \cong k_0 \sqrt{\frac{RT}{\pi n F D_0 \vartheta}}$$

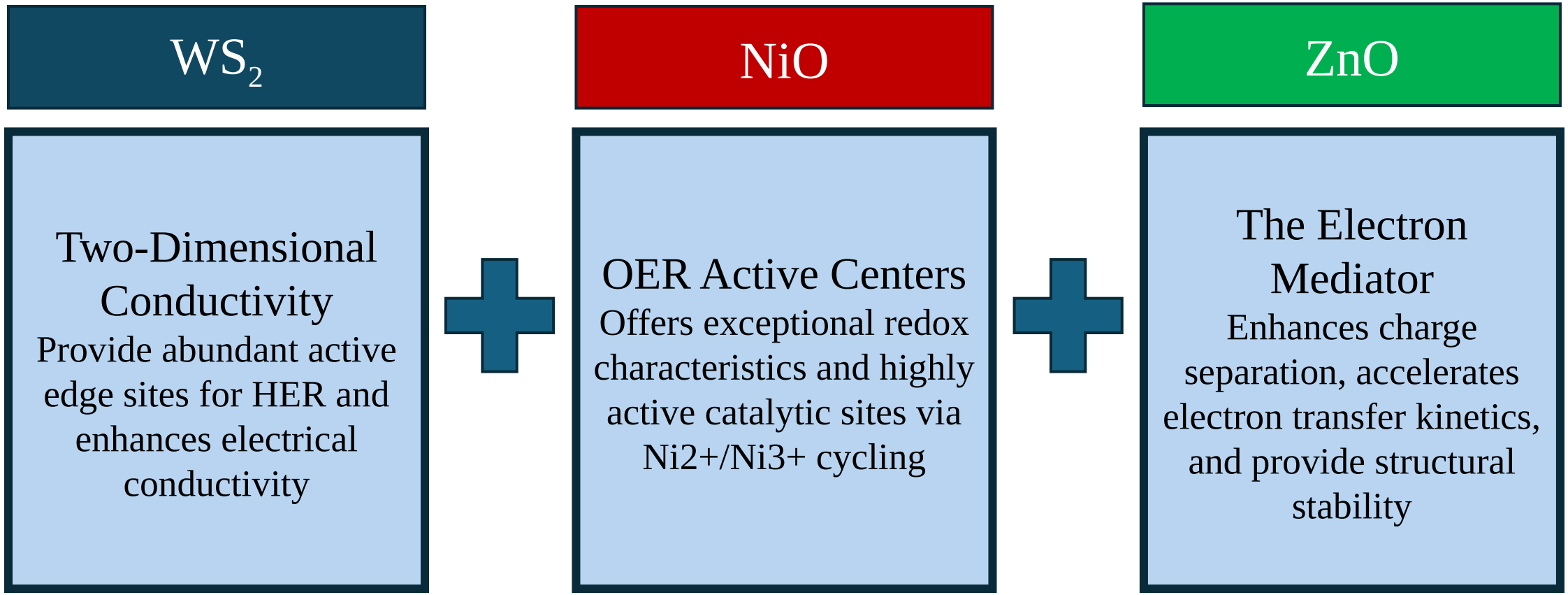
Additionally, Ψ can be calculated as:

$$\Psi = \frac{-0.6288 + 0.0021\Delta E_P}{1 - 0.017\Delta E_P}$$

the value of k_0 can be calculated as the slope of Ψ versus $v^{-1/2}$.

Rational Heterostructure Engineering:

Designing a multi-component bifunctional electrocatalyst to overcome intrinsic material limitations



Mechanism of HER and OER

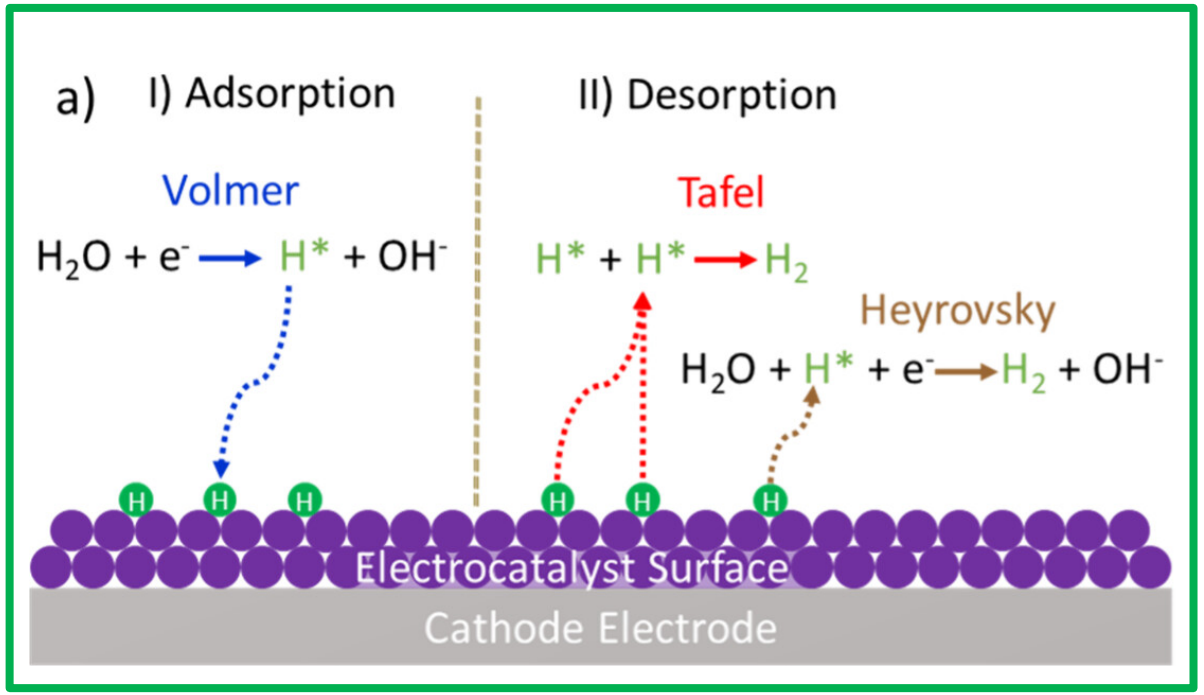
During the water electrolysis process, hydrogen and oxygen are generated simultaneously at the cathode and anode, respectively.

For HER:

$H_2O + e^{-*} \rightarrow$ H* +OH^- Volmer step

H* + e^- + $H_2O \rightarrow H_2 + OH^-$ Heyrovsky step

H* +H* $\rightarrow H_2$ Tafel step



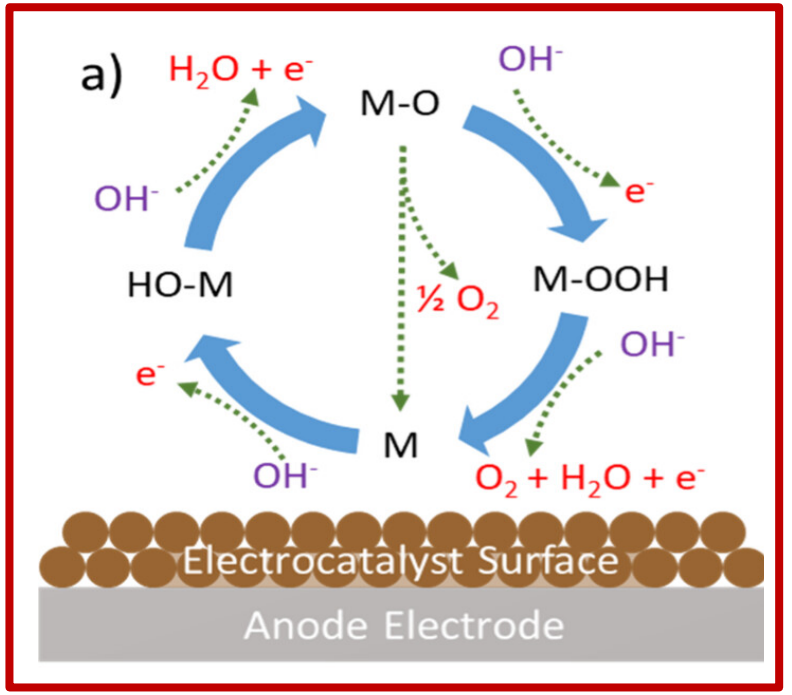
For OER:

$O\ H^- + M^* \rightarrow OH^{M*} + e^-$

$OH^- + OH^{M*} \rightarrow O^{M*} + H_2O + e^-$

$O^{M*} + OH^- \rightarrow OOH^{M*} + e^-$

$OOH^{M*} + OH^- \rightarrow M^* + O_2 + H_2O + e^-$



Transition Metals and Carbonaceous Materials in Electrocatalysis

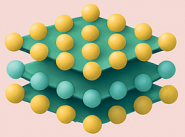
Transition metals

TMDs
- MoS_2, WS_2 etc

TMNs
- VN, Ni_3N

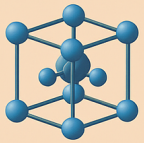
TMOs
- CuO, NiO,
- ZnO

TRANSITION METAL DICHALCOGENIDES



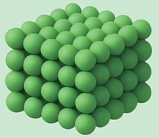
- Layered 2D structure
- Active edge sites
- Stable in acid and alkali

TRANSITION METAL NITRIDES



- Metallic-like conductivity
- Bifunctional catalysts
- High stability in alkaline media

TRANSITION METAL OXIDES



- Multivalent metal centers
- Strongly bind OER intermediates
- Cost-effective

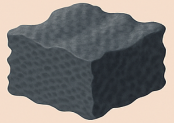
Carbonaceous metals

Laser Induced Graphene

Carbon nanotubes

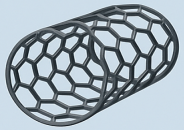
Carbon nanowalls

LASER-INDUCED GRAPHENE



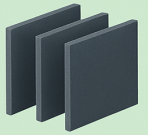
- High surface area
- Good conductivity
- Scalable production

CARBON NANOTUBES



- High aspect ratios
- Large porosity
- Excellent stability

CARBON NANOWALLS



- High edge-site density
- Increased surface area
- Graphitic structure