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Catalyst Design Strategies for Enhanced Hydrogen Evolution Reaction Performance

Kenji Nakamura*

Institute of Materials Research, Tohoku University, Japan

***Corresponding author:** Kenji Nakamura, Tohoku University, Japan, Email: knakamura@tohoku.ac.jp

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Abstract

The hydrogen evolution reaction (HER) is a critical half-reaction in electrochemical hydrogen production and energy conversion technologies. While platinum-based catalysts exhibit exceptional HER activity, their scarcity and high cost limit widespread deployment. This article examines recent strategies for designing cost-effective HER catalysts, including transition-metal compounds, heterostructures, and defect-engineered nanomaterials. The relationship between electronic structure, hydrogen adsorption energy, and catalytic performance is analyzed. Advances in alkaline and acidic HER systems are compared, highlighting key challenges in catalyst durability and reaction kinetics.

Keywords:* *Hydrogen evolution reaction, electrocatalysis, transition metals, nanocatalysts, hydrogen energy

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Introduction

The hydrogen evolution reaction is central to electrochemical technologies aimed at producing clean hydrogen fuel. HER kinetics strongly influence the overall efficiency of water electrolysis and other hydrogen-based energy systems. Although noble metals such as platinum provide benchmark activity, their limited availability necessitates alternative catalyst development. Recent research has focused on tailoring catalyst surfaces at the atomic level to optimize hydrogen adsorption and desorption steps. Understanding the mechanistic pathways of HER under different pH environments has become increasingly important, enabling rational catalyst design and improved performance. Electrochemical water splitting represents a promising solution to the global demand for clean energy carriers, particularly hydrogen. As concerns over fossil fuel depletion and greenhouse gas emissions intensify, hydrogen produced via water electrolysis offers an environmentally benign alternative. The process involves splitting water molecules into hydrogen and oxygen using electrical energy, ideally sourced from renewables such as solar or wind. Despite its conceptual simplicity, the practical realization of efficient water splitting is hindered by sluggish reaction kinetics and high overpotentials. Significant research efforts have therefore focused on developing efficient electrocatalysts and optimizing electrode–electrolyte interfaces to minimize energy losses. Understanding the interplay between materials chemistry, electrochemical kinetics, and system design is critical for advancing this technology toward large-scale implementation.

Conclusion

Significant progress has been made in developing non-noble metal HER catalysts with competitive activity and stability. Continued exploration of electronic structure modulation and nanoscale engineering is expected to further enhance catalytic efficiency. Future work should prioritize scalable synthesis methods and long-term durability studies to facilitate industrial adoption.

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