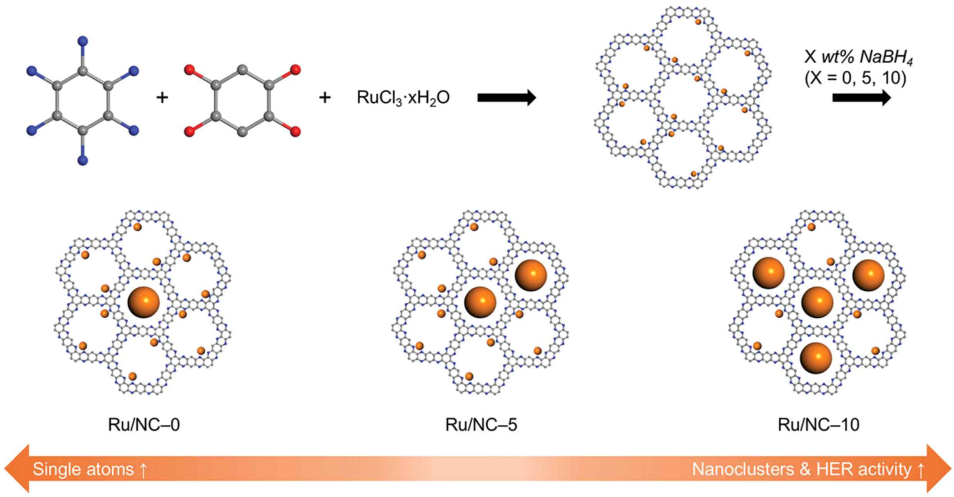
붙임2 **Research Outcomes Report**

Research Outcomes	Dominant Role of Coexisting Ruthenium Nanoclusters Over Single Atoms to Enhance Alkaline Hydrogen Evolution Reaction
Performance Objectives	Published in a Top 10% JCR Journal
Type of Performance	☑ Research Article(Paper) ☐ Patents ☐ Researcher Exchange ☐ Researcher Engagement ☐ Information Exchange ☐ Others
Description of Performance Type	Published in ***Advanced Science*** (JCR Top 2.07%)
Research Institutes	UNIST / Jong-Beom Baek / Jae-Hoon Baek et al. (8 others)
Attachments (Image, Photograph, Ect.)	 <Catalytic synthesis scheme and corresponding HER activity>
Achievement Date	2025.02.05
Summary of Performance	- Synthesized by controlling the ratio of ruthenium single atoms (Ru_1) and nanoclusters (Ru_{NC}) on a nitrogen-doped covalent organic framework template using a reducing agent. - Requires a low overpotential of 1.72 V to achieve a current density of 500 mA cm^{-2} under alkaline conditions, outperforming commercial platinum catalysts (Pt/C) at 1.95 V. - The coexistence of Ru_1 and Ru_{NC} enables the division of roles in water dissociation and hydrogen recombination steps, maximizing catalyst efficiency. - Published in ***Advanced Science*** in the top 2.07% by JCR.
Description of Performance	■ **Key Features** - Development of an HER catalyst featuring the coexistence of Ru singel atom and nanoclusters. ■ **Performance** - Requires a lower overpotential than commercial Pt/C (Ru/CN-10: 1.72 V vs. Pt/C: 1.95 V). - Exhibits a Tafel slope of 34.6 mV dec^{-1}, lower than Pt/C catalyst (43.6 mV dec^{-1}). - Maintains stable activity without degradation during 180 hours.. ■ **Excellence of the Results** - Optimizes the two key steps of alkaline HER through coexistence of SaC and nanoclusters, maximizing overall reaction efficiency. Elucidates the synergistic effect between single atoms and nanoclusters, providing design principles for mixed catalyst systems. ■ **Uniqueness of the Results** - Proposes an HER catalyst with low precious metal content as a cost-effective alternative to expensive platinum-based catalysts. - Offers a technique to freely adjust the ratio of single atoms to nanoclusters by controlling the reducing agent concentration, enhancing industrial applicability.