Pulsed Laser Deposition Ushers in the Hydrogen Energy Era via Atomic-Scale Fabrication

This review systematically explores the breakthrough achievements and provides detailed insights into photo-enhanced water electrolysis and fuel cells.

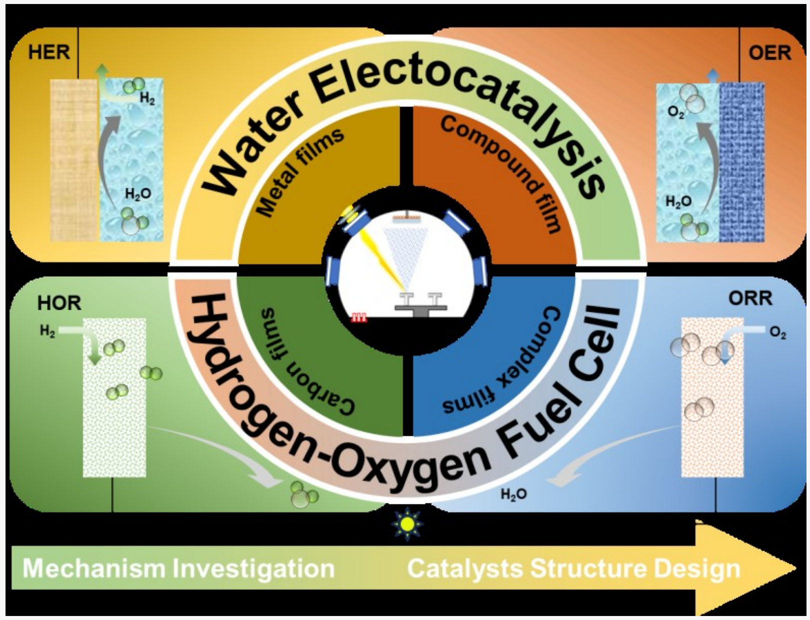

Figure 1. An overview diagram of the content of this review.

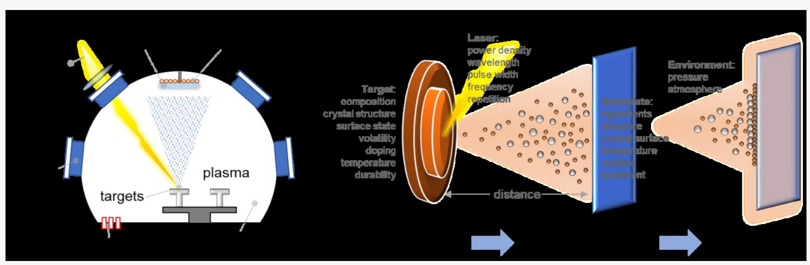

Figure 2. (A) Schematic diagram of the PLD technology; (B) Basic steps and control parameters for the PLD film growth.

CHINA, December 5, 2025 /EINPresswire.com/ -- Pulsed Laser Deposition (PLD), an advanced synthesis technique capable of precise thin-film control, has become a versatile platform for optoelectronic materials engineering. This technology uses high-energy pulsed laser beams to ablate a target material, which then deposits onto a substrate in the form of plasma, allowing atomic-scale control over the film's composition and structure while achieving stoichiometric transfer identical to that of the target.

The development of PLD has been largely driven by the needs of fundamental electrocatalytic research. Scientists require structurally well-defined model catalysts to reveal reaction mechanisms, and PLD enables the preparation of a wide range of precisely controllable materials from single-crystal epitaxial films to nanostructures, providing an ideal platform for establishing reliable structure-property relationships. Originally used for preparing superconducting thin films, PLD has gradually evolved into a critical bridge connecting basic research and practical applications, playing an indispensable role in the study of energy conversion materials.

It is particularly noteworthy that PLD demonstrates significant potential in the field of clean energy, especially in hydrogen-related technologies. Hydrogen energy, valued for its high energy density and green, pollution-free properties, is regarded as a key energy carrier for achieving sustainable development. In an ideal model, electricity generated from renewable sources drives water electrolysis to produce hydrogen, which is then converted back into electricity via fuel cells, forming a material cycle of "water–hydrogen–water" and an energy cycle of "electricity–chemical energy–electricity." However, the overall efficiency of this conversion process is limited by the electrocatalytic reactions occurring at the membrane electrodes in electrolyzers and fuel cells.

Traditional chemical synthesis methods often struggle to produce materials with well-defined structures, making it difficult to identify the true active sites of catalysts. This impedes both the customization of electrocatalysts and the mechanistic understanding of their operation. With its unique capability for atomic-scale precision in fabrication, PLD offers a robust solution to these challenges.

Prof. Liang Qiao's group at the University of Electronic Science and Technology of China reviews the significant value of PLD technology in the field of efficient hydrogen-to-electric energy conversion. By leveraging the capability of PLD for atomically precise thin-film fabrication, researchers can construct well-defined model electrocatalysts with controlled chemical compositions and surface structures, effectively eliminating interference from binders, conductive additives, and complex porous structures commonly associated with traditional powder catalysts.

At the application level, this review demonstrates the broad potential of PLD in key energy conversion systems such as water electrolysis and fuel cells, covering a variety of advanced functional materials including perovskite oxides, high-entropy materials, nitrides, and carbon-based thin films, highlighting its excellent material adaptability and process flexibility. Beyond enhancing the efficiency of hydrogen energy conversion, PLD technology also holds promise for significantly reducing system costs and energy consumption by enabling low-platinum and non-precious metal catalytic materials along with highly stable device architectures, thereby providing critical technical support for building a green energy system.

On the fundamental research front, this review emphasizes that combining PLD with various in situ spectroscopic techniques, including in situ UV-vis spectroscopy, Raman spectroscopy, and X-ray absorption spectroscopy, enables real-time monitoring of dynamic behaviors during electrocatalytic reactions, such as the evolution of catalyst surface structures, the formation of active sites, and reaction intermediates. This offers direct experimental evidence for uncovering the real mechanisms behind key reactions including OER, HER, ORR, and HOR.

This review provides a comprehensive and forward-looking overview of the application and research of PLD technology in hydrogen-electric energy conversion, serving as an important reference for researchers engaged in electrocatalytic mechanism exploration and device development. From a broader perspective spanning materials preparation, characterization science, and energy electrochemistry, this review outlines an interdisciplinary research direction integrating knowledge and techniques from laser physics, surface science, electrochemistry, and beyond. Although challenges remain for the large-scale industrial application of PLD, our study points toward a feasible pathway of using PLD to guide the optimization of catalyst design via traditional chemical synthesis methods, offering a vital scientific foundation for constructing efficient, intelligent, and low-carbon energy conversion systems.

Professor Liang Qiao is a Fellow of the Royal Society of Chemistry (FRSC) and currently serves as a Professor at the School of Physics, University of Electronic Science and Technology of China, Director of the Institute of Condensed Matter Physics, and has been recognized through several prestigious programs including the National Young Talent Program, Sichuan Provincial Talent Program, Sichuan Academic and Technical Leader Program, and Sichuan Outstanding Young Scientist Program. He has published over 240 research papers in leading journals such as Nature, Science, Nature Materials, Nature Reviews Chemistry, Physical Review Letters, and Advanced Materials, with more than 12,000 citations and an H-index of 53. He serves as the Editor-in-Chief of Advanced Superconductivity and is an editorial board member of several international journals including Journal of Physics: Condensed Matter (JPCM), Electron, InfoMat, Superconductivity, Nanomaterials, and Scientific Reports. In addition, he is a member of the National Technical Committee on Nanotechnology Standardization.

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