

# Ultralow Loading Platinum Films by Direct Atomic Layer Processing for Efficient Hydrogen Evolution

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Platinum provides benchmark hydrogen evolution reaction (HER) kinetics in acid, but reducing noble-metal inventory requires deposition routes that form active, electrically continuous films at ultralow loading. Here, Direct Atomic Layer Processing (DALP), a maskless microreactor implementation of spatial atomic layer deposition, was used to deposit Pt films with nominal thicknesses of 2, 10, 20, 30, and 50 nm directly onto 1 cm<sup>2</sup> glassy-carbon electrodes [1]. The corresponding nominal Pt loadings were 4.29, 21.45, 42.9, 64.35, and 107.25 µg cm<sup>-2</sup>. Electrochemical performance was evaluated in 0.5 M H<sub>2</sub>SO<sub>4</sub> by cyclic voltammetry and linear-sweep voltammetry, with potentials referenced to the reversible hydrogen electrode. Characteristic hydrogen-underpotential-deposition and Pt oxide-reduction features confirmed electrochemically accessible Pt surfaces. The 2 nm film exhibited a roughness factor of 0.43 and required about 100 mV overpotential to reach 10 mA cm<sup>-2</sup>. Increasing the film thickness to 10 nm sharply reduced this overpotential to approximately 45 mV and produced the lowest fitted Tafel slope, 21.7 mV dec<sup>-1</sup>. Films from 20 to 50 nm retained near-zero HER onset, approximately 50-60 mV overpotential at 10 mA cm<sup>-2</sup>, and Tafel slopes of 26.8-33.7 mV dec<sup>-1</sup>, while additional Pt did not improve benchmark performance proportionally. Thus, the 10 nm film delivered activity comparable to films containing up to five times more Pt, consistent with prior low-loading Pt studies [2]. These results identify film continuity as the key transition from sparse ultralow-loading Pt to an efficient electrode and establish DALP as a digital route for screening and patterning binder-free catalysts with high precious-metal utilization.

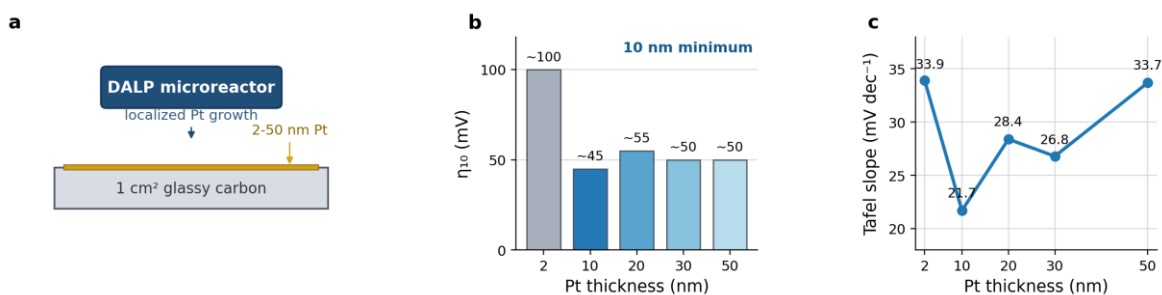


**Figure 1.** DALP Pt deposition and thickness-dependent HER metrics. Overpotentials are approximate values read from the polarization results.

[1] I. Kundrata et al., *Small Methods* 6, 2101546 (2022).

[2] A. Villamayor et al., *Coatings* 14, 868 (2024).

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