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Low Hydrogen Isotope Retention and High Irradiation Resistance in Columnar-Grained Tungsten Prepared via Chemical Vapor Deposition

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With its advantages of high density, ultra-high purity (>99.99997%), and ease of preparing into complex geometries, chemical vapor deposited tungsten (CVD-W) stands out as a promising candidate for plasma-facing materials (PFMs) in future fusion devices. Atmospheric pressure CVD was employed to fabricate millimeter-thick columnar-grained W materials. The exposed surface, oriented perpendicular to the growth direction (GD), exhibits radial grain sizes ranging from 15 to 50 μm and a strong [001] preferential grain orientation ([001] GD). The columnar grains feature an aspect ratio as high as 20. This study systematically reports the exceptional low hydrogen isotope retention and high irradiation resistance of CVD-W under various irradiation and thermal loading conditions.

Low-energy deuterium (D) plasma exposures were performed at ˜500 K over a wide fluence range (1024 - 1027 D m-2, up to 30 h). The results demonstrate that surface blistering in CVD-W is significantly suppressed by its [001] preferential grain orientation, with the blister area ratio being only 10% of that observed in ITER-like W. The total D retention in CVD-W was only 12 - 30% of that in ITER-like W. Simulations using the rate equation code indicate that D retention in tungsten is primarily governed by dislocation defects induced by D-induced surface blistering. Additionally, plasma-driven permeation (PDP) experiments revealed that vertical grain boundaries in CVD-W enhance the outward transport of D, further reducing D retention.

Sequential irradiation experiments, involving pre-damage by 7 MeV tungsten ions (up to 2 dpa) followed by exposure to pure D or D+5% He mixed plasma, demonstrated that D retention in CVD-W was significantly lower than that in ITER-like W, amounting to 38% and 82% of the total, respectively. This highlights the superior low hydrogen retention of CVD-W even under synergistic high-energy heavy ion and low-energy plasma irradiation conditions. Additionally, a combination of extensive Transmission Electron Microscopy (TEM) defect analysis and nanoindentation tests confirmed that after 6 MeV copper ion irradiation at various temperatures up to 973 K, the irradiation defect populations and hardness of as-irradiated CVD-W were comparable to those of ITER-like W, indicating that CVD-W exhibits competitive resistance to displacement damage.

Moreover, the remarkable structural thermal stability of CVD-W was demonstrated in annealing experiments, where no obvious grain growth or loss of the columnar grain structure was observed after annealing at 2173 K for 3 h. Furthermore, under simulated ELM-like thermal shock conditions (duration: 1 ms, 100 pulses), CVD-W demonstrated a significantly higher cracking threshold (0.33 - 0.44 GW m-2) compared to ITER-like W (0.19 - 0.33 GW m-2), confirming its superior resistance to thermal shock cracking.

In conclusion, the results from this comprehensive study highlight the excellent performance of CVD-W, relative to ITER-like W, in terms of low hydrogen isotope retention, high resistance to hydrogen-induced blistering, high-temperature microstructural stability, resistance to displacement damage and thermal shock.