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Pulsed laser deposition with in situ diagnostics: Roadmap to 2D materials processing and synthesis

2D monolayers and heterostructures have become central to nanoscience in recent years, offering promising applications in electronics, sensing, and future computing. Significant progress has been made in 2D materials bottom-up synthesis and subsequent processing, driven by the need for harnessing and exploring exciting functional properties. Techniques such as encapsulation, doping, and implantation in atomically thin 2D materials are crucial to transitioning them from fundamental research to scalable, real-world applications, while also enabling the emergence of novel properties. However, the ultrathin nature that makes 2D materials attractive also poses substantial challenges for traditional plasma-based processing methods. To fully harness the potential, it is essential to develop reliable processing techniques that offer precise control and reproducibility. Pulsed laser deposition (PLD) emerges as a promising non-equilibrium method that allows precise control over the kinetic energy (KE) of ablated species. In our work, we investigate plasma plume interactions with 2D materials using in situ plasma diagnostics and optical characterization tools. Our approach enables low temperature substitution and implantation of foreign atoms, such as chalcogens and metals, facilitating the selective synthesis of Janus monolayers and alloys. We demonstrate that a deep understanding and control of plasma plume dynamics enables new approaches for 2D material engineering, including the formation of Janus monolayers, metal atom implantation, and encapsulation with minimal damage. These findings highlight the potential of PLD to drive the practical advancements in 2D materials for microelectronics and quantum information science.

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