

Atomic Layer Etching

Room Samda Hall AB - Session ALE2-WeM

ALE Applications III

Moderators: Keun Hee Bai, Samsung Electronics Co., Younghee Lee, Lam Research Corporation

10:45am **ALE2-WeM-12 In-Situ Observation of Surface Reaction and Advanced Process for Damage-Less Atomic Layer Etching, Takayoshi Tsutsumi**, Nagoya University, Japan **INVITED**

11:15am **ALE2-WeM-14 Isotropic ALE of 2D Crystalline MoS₂ using SF₆:H₂ Plasma and O₂ Plasma, Sanne Deijkers, Christian Palmer, Nick Chittock, Guillaume Krieger, Silke Peeters, Marcel Verheijen**, Eindhoven University of Technology, The Netherlands; Harm Knoops, Oxford Instruments Plasma Technology, Netherlands; Erwin Kessels, Adrie Mackus, Eindhoven University of Technology, The Netherlands

Two-dimensional crystalline MoS₂ is an emerging material for nanoelectronics, where it can be applied as a channel material in field effect transistors. MoS₂ exhibits a high carrier mobility, even at the monolayer thickness of 6.5 Å, and therefore it is expected to replace Si in the future [1]. Application of MoS₂ in nanoelectronics requires highly controlled deposition and etching processes. Currently available ALE processes either require an external step like a wet treatment [2], or are optimized for amorphous MoS₂ [3]. Here, we present a plasma-enhanced ALE process, which can etch crystalline MoS₂ in an isotropic manner.

In the ALE cycle, the crystalline ALD-grown MoS₂ film was first fluorinated and subsequently oxygenated to create volatile Mo_xO_yF_z species. The fluorination step employs a plasma mixture containing SF₆ and H₂, which is believed to produce *in situ* HF, as suggested by previous studies on H₂-diluted fluorine plasmas [4,5]. F radicals, which are known to etch MoS₂ continuously [6,7], are scavenged by the hydrogen to form HF as observed in the plasma [8]. The SF₆:H₂ ratio was tuned to ensure modification occurs without continuous etching. For the oxygenation half-cycle an O₂ plasma was used, whereas O₂ gas and H₂O did not result in significant etching.

The resulting etch per cycle combining the SF₆:H₂ plasma and O₂ plasma is 0.92 ± 0.02 Å. Before ALE the crystallinity of the films was confirmed by observation of the characteristic MoS₂ peaks in Raman spectroscopy, and after ALE a decrease in these peaks is seen, verifying etching of the crystalline material. Furthermore, no F contamination was observed after ALE by x-ray photoelectron spectroscopy (XPS). However, XPS showed the presence of some oxidation of Mo and S. The isotropic nature of the ALE process was confirmed using transmission electron microscopy in 3D trenches.

[1] Kim *et al.*, *Nat. Nanotechnol.*, 2024

[2] Lee *et al.*, *Applied Physics Express*, 2017

[3] Soares *et al.*, *Chem. of Mater.*, 2023

[4] Jung *et al.*, *JVST A*, 2020

[5] Kihara *et al.*, *2023 IEEE Symposium on VLSI Technology and Circuits*, 2023

[6] Jeon *et al.*, *Nanotechnology*, 2015

[7] Xiao *et al.*, *Sci Rep*, 2016

[8] Krieger *et al.*, *ALD/ALE 2024*, 2024

11:30am **ALE2-WeM-15 Design of Multi-Coil Single-Switch Induction Heating System with PI-Based Burst Mode Control for ALD/ALE Processes to Achieve High Efficiency and Rapid Transient Response, Sang-Wook Ryu**, Dongguk University, Republic of Korea; Jihyun Kim, Hakmin Kim, Wonik IPS, Republic of Korea; Tae S. Cho, Wonik IPS; KWANGSEON JIN, Wonik IPS, Republic of Korea

Atomic layer deposition (ALD) and atomic layer etching (ALE) processes commonly rely on conventional resistive heating methods, which suffer from significantly low efficiency and slow transient response. To overcome these limitations, this paper proposes an induction heating system and control technique specifically tailored for ALD/ALE applications to achieve higher efficiency and faster transient response. Because ALD/ALE processes require localized temperature control, multiple coils must be employed to provide precise heating across different regions. Therefore, unlike typical multi-switch designs such as full-bridge or half-bridge topologies, which require multiple semiconductor switches per coil, the proposed system

adopts a single-switch topology for each coil, thereby reducing hardware complexity while enabling fine-grained temperature control across the entire region. Because a single semiconductor switch must handle the entire load voltage and current in a single-switch topology, the proposed multi-coil single-switch design is restricted to a narrow switching frequency range to ensure system reliability while controlling the temperature. To enhance stability under this constraint, a burst-mode operation at a fixed switching frequency is introduced to facilitate near-linear temperature control, with its burst interval precisely regulated by a proportional-integral (PI) controller. A prototype of the proposed induction heating system is developed using a TI-TMS320F28335 digital signal processor (DSP). The performance of the proposed multi-coil induction heating system, integrating a PI-based burst mode for ALD/ALE applications, is validated through comparative experiments, demonstrating significantly improved efficiency and faster temperature response than conventional resistive heating.

11:45am **ALE2-WeM-16 Enhanced Plasma Ignition and Sustaining of Transformer-Coupled Plasma Source with a Secondary Coil, Tae S Cho, Jae Haon Choi, Hak Min Kim, Gi Won Shin, Soo Young Hwang, Ji Hyun Kim**, Wonik IPS, Republic of Korea

The need for miniaturization in the semiconductor industry, characterized by sub-10 nm features, 3D stacked architectures, and complex gate-all-around structures, requires increasingly sophisticated plasma processing technologies. These advanced applications require plasma radical sources such as transformer-coupled plasma (TCP) that can operate over a wide pressure range while providing high fluxes of reactive species with minimizing ion-induced damage to delicate device structures. However, ignition with electronegative gases in TCP sources requires high breakdown voltages, often requiring initial plasma generation with an inert gas such as argon, which reduces process throughput. To overcome this limitation, a secondary coil was introduced to generate the high voltage for plasma ignition. The ignition and sustain ranges in argon-nitrogen mixtures were investigated using a TCP source incorporating several ferrite cores. One of the ferrite cores integrated both primary and secondary coils, with the secondary coil terminals connected to reactors on both sides of the core. The current induced in the secondary coil generated an additional electric field between the reactors, enhancing both plasma ignition and sustaining. Experiments were performed at pressures of 0.5–2 Torr and radio frequency (RF) powers up to 3000 W at frequencies of several hundred kHz using various argon-nitrogen gas mixing ratios. The secondary coil enabled stable plasma ignition across a wider range of argon-nitrogen mixtures, eliminating the need for initial plasma generation with inert gas, unlike conventional TCP discharges. This enhanced ignition and sustain ranges provide significant advantages for precise control of process gases and short plasma on/off times in advanced manufacturing processes such as atomic layer deposition (ALD) and atomic layer etching (ALE).

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