Enhanced control of Plasma surface interaction to etch alloys using Transient Assisted Plasma Etching (TAPE)

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The evolution of devices towards 3D architectures and the introduction of new ultra-thin materials bring along many patterning challenges. In terms of plasma etching, extreme pattern fidelity, control over compositional changes, and limiting damages caused to sensitive materials are becoming critical requirements. Atomic Layer Etching in principle proposes solutions to these challenges, by splitting the etch mechanism into sequential self-limiting reactions[1]. However, the main drawbacks of such an approach are its poor throughput[2] and sensitivity to ion angular distribution and in particular differential charging effects[3].Therefore, there is a clear need for an etching process that can offer comparable performance with Atomic Layer Etching at an etch rate closer to conventional plasma etching, while minimizing the consumption of environment-unfriendly gases.

A novel plasma process design called transient-assisted plasma process (TAPP) has been recently introduced[4]. In the realm of dry-etching, it has exhibited promising patterning capabilities at etch rates compatible with high-volume manufacturing. In deposition applications, It also has demonstrated superior control over precursor dosage and fragmentation for in-situ hard-mask deposition compared to conventional methods [5]. Moreover, from a sustainability perspective, Transient-assisted processing (TAP) presents considerable advantages by notably reducing the consumption of problematic gases. TAPE operates in cycles, involving at least two phases: Time-limited injection of the reactant (with or without plasma), and when the injection is stopped, a gas transient happens in the plasma, where the reactant concentration diminishes over time, as shown in Figure 1. The fluence of reactive species is regulated by the gas pulse characteristics (partial pressure, etc.) and its associated plasma transient, while ion fluence is governed by the duration of the plasma phase. This segregation yields significantly enhanced control over plasma-surface interactions compared to conventional plasma etching techniques. This design is compatible with any gas mixture and energy sources(ions, photons, electrons, fast neutral species/clusters, etc.)

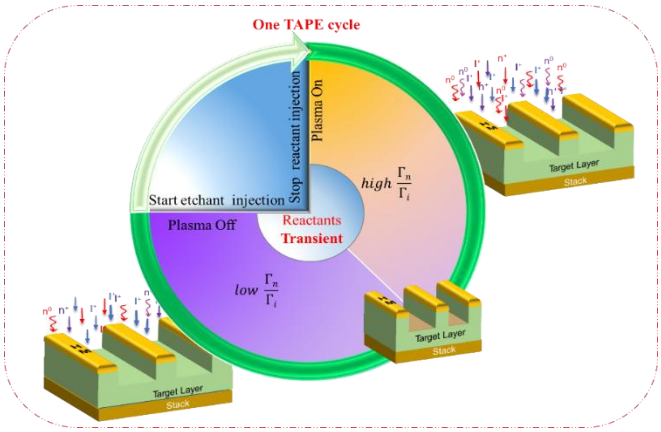

Figure 1. Schematic diagram of the general TAPE process (showing the example of the gas phase injection case).

Enhancing control over plasma-surface interactions holds promise in rectifying the uneven etching observed in multicomponent materials like alloys [6,7]. This imbalance in etching can trigger various complications, including a compositional drift, thereby impeding the process and deteriorating material characteristics as shown in Figure 2a. Typically, one component undergoes predominantly chemical etching, while the other experiences primarily physical etching, influenced by factors such as etchant composition, ion energy, or ion mass. In TAPE, most chemically-driven etching occurs early during the plasma step when a substantial amount of etchant is present. The modified surface/profile will then be

exposed to a reduced etchant quantity and a continued ion bombardment. Each cycle is thus capable of providing the necessary species for a balanced etching of the compound's elements. Figure 2b compares the chemical composition of InGaZnO after conventional etching and TAPE, while Figure 2c compares the etch rate, and profile relative to a previously published ALE process [8]. Meanwhile, TAPE consumes 25 times less CH_4 than the ALE process.

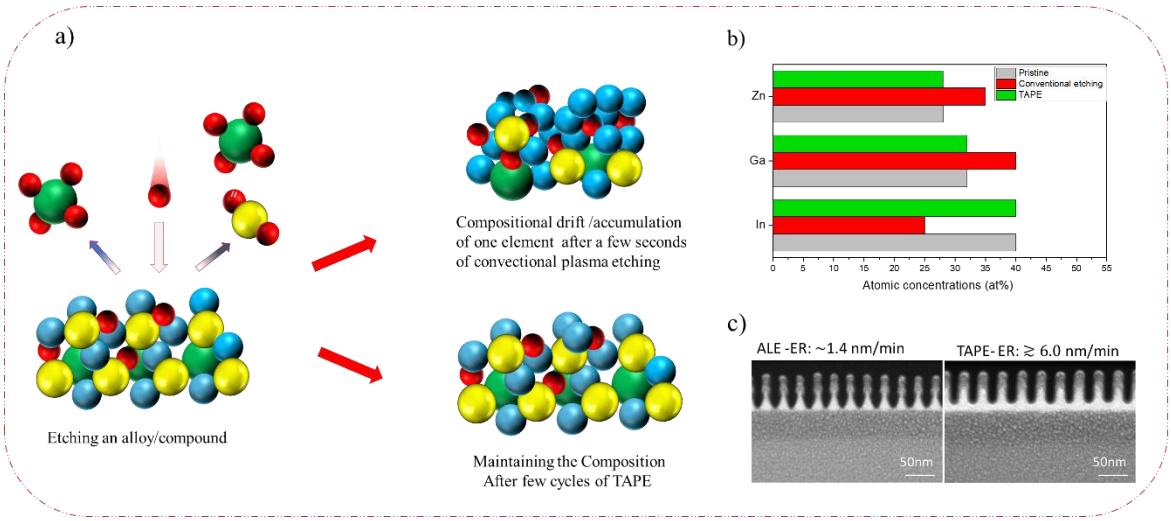

Figure 2. a) Schematic diagram of elemental accumulation due to unbalanced etching, **b)** Atomic concentration of IGZO surface before and after etching using different processes with the same etch depth, and **c)** Cross-SEM Images of patterned IGZO (Pitch 28 nm) etched using TAPE vs. ALE.

In this study, we aim to demonstrate the flexibility and capabilities of Transient Assisted Plasma Etching (TAPE) through the etching of InGaZnO and NbTiN.

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