

## Atomic Layer Etching

### Room Tampa Bay Salons 3-4 - Session ALE1-TuA

#### Plasma and Energy-enhanced ALE II

**Moderators:** Harm C.M. Knoops, Oxford Instruments Plasma Technology, Netherlands, Nicolas Poss  m  , CEA-Leti

#### 1:30pm ALE1-TuA-1 Etch Characteristics of Iridium with Atomic Layer Etching Technique, Wendy Yan, IBM Research INVITED

Iridium (Ir) is a promising replacement for copper (Cu) in next-generation interconnects, yet its plasma etching is limited by low-volatility reaction products. This work investigates Ir plasma atomic layer etching (ALE) using Cl/O<sub>2</sub> and CF<sub>4</sub>/O<sub>2</sub> chemistries. The ALE sequence employs oxygen-assisted halogenation for surface modification, followed by low-energy ion activation to enable directional desorption of Ir-containing byproducts.

Etching mechanisms are examined using X-ray photoelectron spectroscopy (XPS), time-of-flight secondary ion mass spectrometry (TOF-SIMS), and transmission electron microscopy (TEM). XPS identifies Ir-Cl, Ir-F, and Ir-O bonding states, TOF-SIMS quantifies modified layer thickness and molecular distribution, and TEM probes small critical-dimension feature profiles and sidewall chemical composition. Correlating these surface and structural analyses with etch-per-cycle, profile anisotropy, line-edge roughness, and hardmask selectivity enables a better understanding of Ir ALE characteristics and guides the optimization of Ir interconnect pattern fidelity and dimensional control.

#### 2:00pm ALE1-TuA-3 Selectivity, Surface Roughness and Residue of Plasma-Based Atomic Layer Etching of Metals and Dielectric Materials for Semiconductor Devices, Heeyeop CHAE, Sungkyunkwan University (SKKU), Republic of Korea

The critical dimensions of semiconductor devices continue to shrink, reaching nanometer and even angstrom scales in both 2D and 3D structures. Consequently, the demand for atomic-scale precision in etching processes is rapidly increasing. This talk will present various examples of plasma-based atomic layer etching (ALE) with emphasis on etch selectivity, surface roughness, and residue control for both metal and dielectric materials. Materials discussed include silicon nitride, titanium nitride, zirconium oxide, silicon oxide, aluminum oxide, hafnium oxide, molybdenum, ruthenium, and tantalum nitride. Typical ALE processes consist of two sequential steps: surface modification and material removal. Surface modification is achieved through various reaction pathways, including fluorocarbon film deposition, surface fluorination, chlorination, and oxidation using plasma-generated radicals. In the subsequent removal step, the modified layers are eliminated through mechanisms such as ion bombardment, thermal desorption, ligand exchange, ligand volatilization, or halogenation. This talk will also address key characteristics of plasma-based ALE processes, including etching selectivity, surface roughness, and residual surface contamination.

#### 2:15pm ALE1-TuA-4 Directional Atomic Layer Etching of MgO-Doped Lithium Niobate Using Br-Based Plasma, Ivy Chen, California Institute of Technology; Frank Greer, Jet Propulsion Laboratory (NASA/JPL); Austin Minnich, California Institute of Technology

Lithium niobate (LiNbO<sub>3</sub>, LN) is a nonlinear optical material of high interest for integrated photonics with applications ranging from optical communications to quantum information processing. The performance of on-chip devices based on thin-film lithium niobate (TFLN) is presently limited by fabrication imperfections such as sidewall surface roughness and geometry inhomogeneities over the chip. Atomic layer etching (ALE) could potentially be used to overcome these difficulties. Although an isotropic ALE process for LN has been reported, performing LN fabrication completely with ALE faces several challenges, including the lack of a directional ALE process for pattern transfer and the redeposition of involatile compounds. We report a directional ALE process for LN consisting of sequential exposures of HBr/BCl<sub>3</sub>/Ar plasma for surface modification and Ar plasma for removal. The HBr chemistry is found to decrease redeposition compared to F- and Cl-based plasmas, which we attribute to the higher vapor pressures of Br-based products. A grating pattern etched entirely by the process (total etch depth of 220 nm) exhibits no aspect ratio dependent etching (ARDE) down to the smallest tested gap of 150 nm, in contrast to ion milling in which ARDE manifests even at 300 nm gaps for the same etch depth. The HBr plasma chemistry is also found to support an isotropic process consisting of sequential exposures of H<sub>2</sub> plasma and HBr/BCl<sub>3</sub>/Ar plasma. These processes could be used together to perform the complete

fabrication process for TFLN devices, eliminating imperfections arising from ion milling.

#### 2:30pm ALE1-TuA-5 Examining AlGaIn Atomic Layer Etch per Cycle Uniformity and Repeatability by Cross-Referencing In-Situ Etch Depth Monitoring with Electrical Characterisation, Ben Jones, Matthew Loveday, Sung-Jin Cho, Andrew Newton, Oxford Instruments Plasma Technology, UK

Atomic layer etching (ALE) of AlGaIn is well suited to the critical gate recess step of AlGaIn/GaN normally-off metal insulator semiconductor-high electron mobility transistors (MIS-HEMT) [1]. A two-dimensional electron gas (2DEG) forms at the AlGaIn-GaN interface (Fig. 1) enabling the mobility and carrier density required for high-performance power devices. As shown in Fig. 2, 2DEG mobility directly governs device efficiency [2]. Its formation depends strongly on AlGaIn film properties and thickness. Precise control of the AlGaIn gate-recess thickness is essential for engineering threshold voltage (V<sub>TH</sub>) and blocking capability, ideally ~5 nm thickness [3]. Low-damage processing is necessary to minimise interface traps, leakage, and electric-field crowding [4].

Using a reflectance-based endpoint technique, sub-5 nm AlGaIn films have been etched with Cl<sub>2</sub>/BCl<sub>3</sub> ALE. Fig. 3 plots dose time vs etch-per-cycle (EPC) for 30 - 120 ms doses, with a clear EPC jump at 40 ms and plateauing thereafter, indicating saturation. Process repeatability is demonstrated in Fig. 4: across 11 runs, EPC ranged from 0.79-0.88 nm/cycle. The normal distribution of this data set is plotted in Fig. 5, indicating run-to-run EPC uniformity of 5.4 %. However, reflectance end pointing only measures the targeted point and gives no cross-wafer EPC uniformity. Such uniformity is difficult to measure on <10 nm AlGaIn due to surface roughness, ellipsometry limits, and FIB/SEM damage. We aim to infer etched film uniformity by correlating reflectance-measured AlGaIn thickness with sheet resistance obtained via Hg-probe analysis. Fig. 6 shows in-situ thickness measurements for targeted 5 nm and 0 nm endpoints, illustrating the strength of the technique: the ALE sequence stops automatically when the desired thickness is reached [5]. Fig. 7 displays raw reflectance data; the initial smooth region occurs before the "turning point," after which true thickness is extracted, shown by the stepped profile. Accurate end thickness does not require knowledge of the initial AlGaIn thickness.

In this submission we will quantify EPC uniformity across Ø150 mm AlGaIn-GaN substrates by combining in-situ reflectance thickness measurement with local Hg-probe C-V/I-V sheet-resistance mapping. We will also electrically characterise surface roughness of sub-5 nm AlGaIn films produced by ALE and ICP etching. Finally, we will expand the current dataset to show how etch-process parameters influence run-to-run uniformity across multiple AlGaIn-GaN wafers.

#### 2:45pm ALE1-TuA-6 Atomic Layer Etching Techniques for Sidewall Surface Damage Removal in GaN-Based LEDs, Chan Ho Kim, Sung Hyun Kim, Young Woo Jeon, Jong Woo Hong, Jong Soon Park, Geun Young Yeom, Sungkyunkwan University, Republic of Korea INVITED

As the GaN light emitting diode (LED) device technology is developed from conventional LED to micro LED, the lateral dimension of LED devices is decreased, and the ratio of sidewall area relative to overall device area is increased. Especially, as the GaN LED device size decreases below 5 microns, the performance and reliability of GaN devices are significantly degraded. One of the reasons for the degradation of the micro LED device is the damage from the sidewall due to the ion bombardment during the reactive ion etching (RIE). Ion bombardment during the RIE can lead to various issues such as surface composition changes, surface defects, surface contamination, and increased leakage current.

In this study, we focused on the etching of GaN LED devices with a multi quantum well (MQW) layer, which is composed of multiple InGaIn and GaN layers. A mesa structure of GaN LED device consisted of p-GaN/MQW/n-GaN/undoped-GaN layer on sapphire wafers (or silicon wafers) was etched using BCl<sub>3</sub>/Cl<sub>2</sub>/Ar RIE, and the sidewall damage remaining after the RIE was removed using wet etching and/or ALE methods using conventional ICP etch system and an ion beam-based etch system. The effect of wet etching of damaged GaN LED sidewall using a KOH-based solution was compared with the sidewall damage removal using ALE methods. The effect of ion beam-based ALE on the removal of sidewall damage for vertical GaN LED devices will be also discussed. The results showed that, the wet etching improved the sidewall stress or defects due to the damage by RIE, however, the optimized ALE processes removed the sidewall stress and defects on MQW layers of patterned GaN structure almost completely. This indicates that, as GaN-based devices decrease in size, the effectiveness of ALE increases, making ALE more effective than wet etching for removing sidewall etch damage for next-generation device fabrication.

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