Atomic Layer Etching
Room Baekeland - Session ALE2-TuM

ALE for GaN Devices

Moderators: Steven M. George, University of Colorado at Boulder, Nicolas Possémé, CEA-Leti

10:00am **ALE2-TuM-7 GaN Damage Evaluation After Conventional Plasma Etching and Anisotropic Atomic Layer Etching**, ***Simon Ruel**, P Pimenta-Barros,* CEA-Leti, France*; N Chauvet,* Lam Research, France*; F Le Roux,* CEA-Leti, France*; S Tan,* Lam Research*; F Gaucher,* Lam Research, France*; N Posseme,* CEA-Leti, France **INVITED**

GaN-based high electron-mobility transistors (HEMTs) are promising for high power device applications because of their high electric field strength, high mobility, and good thermal stability. The traditional GaN-based HEMTs is inherently normally-on because a two-dimensional electron gas (2DEG) channel is created at the AlGaN/GaN interface. As normally-off operation is desirable for commercial power applications, several structural approaches have been proposed such as recessed gate and pGaN gate. The different processing steps of GaN-based HEMTs can induce trapping effects, leading to the reduction of the 2DEG density and thus to the electrical degradation of GaN devices. In this context, plasma etching is one of the most critical step in the manufacturing of GaN devices.

In this paper, we propose to evaluate a promising Atomic Layer Etching (ALE) approach allowing to reduce or eliminate the damage compared to the conventional plasma etching.

The process investigated in this study for GaN etching consists in two steps of cyclic plasma chlorination followed by Argon or Helium bombardment. Fig 1a shows that the GaN etching is negligible after pure chlorination and pure sputtering (Ar or He plasma). GaN etching only occurs by cycling chlorination and sputtering steps, meaning that the basic concept of ALE is demonstrated for both ALE Ar and He. The etch per cycle (EPC) of ALE Ar and He is 0.5nm/cy and 1.1nm/cy respectively. Therefore, ALE He is faster than ALE Ar whereas a same bias voltage of 50V has been applied. After plasma parameters optimization, Fig 1b shows that the ideal ALE Ar and ALE He process window in term of ion energy is between [70-100V] and [50-80V] respectively. XPS analyses and roughness studies by AFM (Fig 2a and b, respectively) reveal a very similar surface state after etching with ALE or Steady only.

The plasma induced damage has also been evaluating for both ALE processes on blanket wafers and compared to the steady process. Fig 3 shows that, for a similar over etch, ALE He induces higher R_{sheet} degradation than ALE Ar. This result can be explained by deeper He ion penetration within the substrate compared to Ar ion as the He ions are lighter. While ALE Ar presents a lower R_{sheet} than the steady process, confirming a lower film damage induced by ALE process compared to the steady process.

10:30am **ALE2-TuM-9 Analysis of Ion Energy Dependence of Depth Profile of GaN by In-situ Surface Analysis***, M Hasagawa,* ***Takayoshi Tsutsumi,*** Nagoya University, Japan*; A Tanide, S Nakamura,* SCREEN Holdings Co., Ltd., Japan*; H Kondo, K Ishikawa, M Hori,* Nagoya University, Japan

In fabrication of the next-generation power electronic devices of gallium nitride (GaN), an atomic layer etching (ALE) technique with cyclic processes of ion irradiation and Cl adsorption steps has been attracted for reduction of plasma induced damage. To control surface stoichiometry of GaN in the ALE, we focus on the ion energy dependence of the depth profile of GaN at each Ar and Cl reaction step using the beam experiments with *in situ* X-ray photoelectron spectroscopy (XPS).[1,2]

The plasma beam system was used for Cl adsorption and Ar ion irradiation process. The as-cleaned surface was exposed by Cl radicals with a dosage of 10^{19} cm^{-2} generated in Cl_2 gas (flow rate 0.5 sccm) plasma by application of RF power of 400 W, while the shutter was placed in front of the sample to block the Cl ion to the surface. The Ar ion energy, that has a narrow ion energy distribution, was specified by applying a direct current (dc) voltage bias to the acceleration electrode. The one cycle consisted of these Ar ion irradiation and Cl radical exposure. To stabilize the GaN surface, five cyclic processes were carried out. Then, the GaN surface at each step was analyzed by angle-resolved *in-situ* XPS. Depth profiles of atomic concentration were estimated by the maximum entropy method.

Figure 1 show the depth profile of Ga-Ga and Ga-Cl bond distribution GaN after 5th Ar irradiation and 6th Cl adsorption process at accelerated voltages of 100 and 200 V. After Ar ion irradiation, Ar ion irradiated depth where concentration of Ga-Ga decreased by 1/e of maximum concentration is increased by Ar ion energy. After Cl radical exposure, Cl penetration depth where concentration of Ga-Cl and Ga-Cl_2 decreased by 1/e of maximum concentration is similar to Ar ion irradiated depth. This suggests that chlorinated layer thickness relates to damaged layer thickness. As a result, the etched depth would be predominantly determined by the damaged layer thickness. Namely, the etch depth is enabled to control by the ion energy in the Ar ion irradiation cycle.

[1] T. Takeuchi et al., J. Phys. D: Appl. Phys. 46, 102001 (2013).

[2] Y. Zhang et al., J. Vac. Sci. Technol. A 35, 060606 (2017).

10:45am **ALE2-TuM-10 Atomic Layer GaN Etching by HBr Neutral Beam***, S Samukawa,* ***Takahiro Sawada,*** *D Ohori,* Tohoku University, Japan*; K Sugawara, M Okada, K Nakata, K Inoue,* Sumitomo Electric Industries, Ltd., Japan*; D Sato, H Kurihara,* Showa Denko K.K., Japan

Refining AI/IoT techniques is absolutely essential for developing smart and sustainable societies. The amount of information in networks is becoming larger and larger as time goes on, and wireless high-speed and large-capacity data communication technologies such as 5G and beyond are key for processing big data. AlGaN/GaN high electron mobility transistors (HEMTs) are promising for both high-power and high-frequency applications because their two-dimensional electron gas (2DEG) has high saturation velocity, high mobility, and high carrier concentration with a high breakdown field. Although AlGaN/GaN HEMTs have many advantages, normally-off operation for GaN HEMTs is still a big challenge. In the gate-recess, normally-off operation is achieved by removing the barrier layer by dry etching to reduce the 2DEG concentration under the gate electrode. Thus, an atomic layer and defect-free etchings for GaN are indispensable to achieve high-frequency, high-power, and normally-off operation. In this work, we investigated atomic layer defect-free GaN etching by using Cl_2 and HBr neutral beams.

GaN etching rates and etching products on the substrate surface were investigated by using Cl_2 or HBr neutral beams with the beam acceleration bias power from 0 to 20 W. The gas flow rate and substrate temperature were fixed to 40 sccm and –20 ºC, respectively. To analyze the surface atomic layer etching reactions, we measured the Ga3d signal by X-ray photoelectron spectroscopy (XPS) and found that the surface composition ratio consisted of four kinds of peaks (Ga-Cl_3 or Ga-Br_3, Ga-O, Ga-N, and Ga metal) using Gaussian peak fitting. With the Cl_2 neutral beam, the Ga-O ratio (Ga dangling bond) increased, and the Ga-N ratio (GaN) decreased with bias power increases. The Ga-Cl3 ratio (etching product) did not significantly change, regardless of the bias power. In contrast, with the HBr neutral beam, higher Ga-N and lower Ga-O ratios could be achieved in spite of the high bias power, and the Ga-Br_3 ratio (etching product) was increased with increasing the bias power. The HBr neutral beam could make a thinner surface product layer than the Cl_2 neutral beam because the atomic size of Br is larger than that of Cl. The Cl_2 neutral beam had a five times higher etching rate than that of the HBr neutral beam at 20 W of beam acceleration bias power. These results suggest that $GaBr_3$ is a more involatile product and that the GaN surface is protected by the $GaBr_3$ layer. We found that HBr neutral beam etching could obtain more precise atomic layer level neutral beam assisted etching with the thinner and more involatile etching product layer.

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