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Atomic Layer Etching - Breaking Through the Limitation of Etch

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Abstract

This paper presents an overview of our recent studies on plasma-enhanced ALE for various materials. The concept, mechanism and advantages of ALE are described. ALE has already moved from lab to fab. Self-aligned contact (SAC) application has been adopted into production at 10 nm node Logic devices.

1. Introduction

At the sub-10 nm technology node, atomic-scale processing precision is required because the pattern size is equivalent to 10s of atomic layers, and variability should be less than a few atoms. Plasma etching is widely used for patterning in semiconductor manufacturing. However, in conventional plasma etching, ions and neutrals interact with the surface simultaneously and continuously [1], limiting the precise process control and inducing the lattice disorder [2]. Atomic layer etching (ALE) is recently highlighted as a method that can break through the limitations of conventional plasma etching [3]-[5]. In the ALE process, ultra-thin layers of the material are removed by a multi-step cycling process, which consists of surface modification and removal. Surface modification and removal are functionally separated, which enables more precise process control and less ion-induced damage. In this paper, we present an overview of our recent studies on plasma-enhanced ALE for various materials.

2. Experimental

In this study, Lam's Kiyo® F Series conductor etch system was used for Si, Ge, C, W, Ta, Ru and GaN ALE. Flex® F Series dielectric etch system was used for SiO_2 and SiN ALE. Both systems are equipped with fast, repeatable, and reliable power/gas switching function which ensures the process robustness for production. We used a plasma for surface modification to enhance the reaction. For removal step we used Ar ion bombardment to achieve the directionality.

3. Results and Discussion

3.1 Self-limiting reactions

When the chemisorption is used for surface modification, reaction is self-limiting. Figure 1(a) shows the example of W ALE [4]. Here plasma chlorination is used and the reaction saturates after 2s. The removal step is also self-limiting because the reaction stops when the adsorbed chlorines are consumed. In Fig. 1(b), the etch amount saturates at etch per cycle (EPC) = 0.21 nm/cycle.

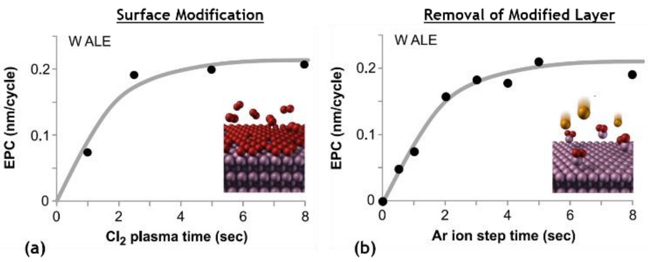

Fig. 1. Self-limiting behabior in W ALE. (a) Surface modification step. (b) Removal step. [4]

3.2 Ion energy scan at removal step

Figure 2 shows the EPC of GaN as a function of RF bias voltage at removal step [5]. Cl_2 plasma was used for surface modification. Three different process regimes are visible. In regime I (< 50 V), the EPC increases with bias voltage. In this regime, the ion energy is insufficient to remove the modified layer. In regime II (50 to 100 V), a self-limited EPC was observed. EPC was almost constant. This regime can be considered as the ALE window. EPC at 80 V was 0.37 nm. This indicates only a few layers of GaN were chemisorbed by the preceding chlorination step. Over 100 V (regime III), EPC increased with bias voltage because the ion energy exceeded physical sputtering threshold.

3.3 Correlation with surface binding energy

We found both sputtering threshold and net EPC [4] have a strong correlation with surface binding energy as shown in Fig. 3 [4]. Sputtering threshold increases with the surface

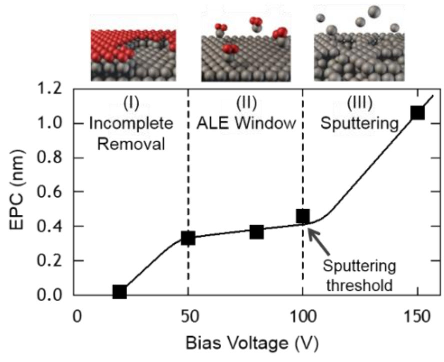

Fig. 2. EPC of GaN as a function of bias voltage at removal step [5].

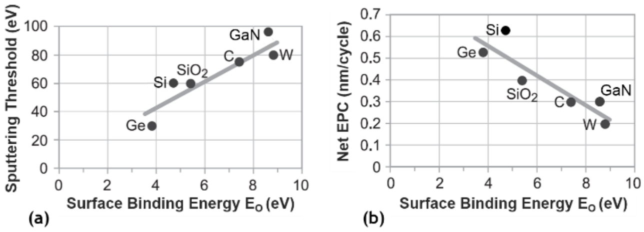

Fig.3. ALE behavior as a function of surface binding energy E_0. (a) Sputtering threshold vs. E_0. (b) Net EPC vs. E_0. [4]

binding energy (Fig. 3(a)). This result is consistent with previous sputtering report, in which the sputtering yield is inversely proportional to the surface binding energy [6]. Net EPC decreases with the surface binding energy (Fig. 3(b)). This indicates materials with stronger binding energy have thinner modification layers.

3.4 Surface smoothness

Because of the self-limiting layer by layer etching, very smooth surface is obtained in ALE. TEM images in Fig. 4 shows the advantage of ALE over conventional continuous plasma process [5]. Surface roughness R_{RMS} measured by AFM was 0.6 nm which was an order of magnitude less than that of 4.0 nm after the continuous plasma process.

We also found the surface roughness after ALE was improved from an initial R_{RMS} of 0.8 nm. As shown in Table I, this phenomenon was observed in many different materials such as Ta and Ru [7]. ALE can improve the surface smoothness. This is a new benefit of ALE.

3.5 Dielectric ALE for self-aligned contact

In dielectric ALE, fluorocarbon polymer deposition is used for surface modification. Since SiN does not contain oxygen which consumes fluorocarbon, ALE can selectively accumulate polymer on SiN vs SiO_2, achieving very high steady state selectivity as shown in Fig. 5 [8]. Thus, it is suitable for self-aligned contact (SAC) etching, where SiN must be protected during contact hole etching.

Since the modification and removal steps are completely separated in ALE, the process window is wider than that of conventional plasma etching. Figure 6 shows a SiO_2 ALE

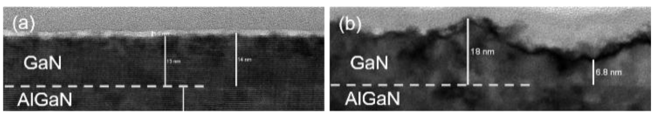

Fig. 4. Cross-sectional TEM images of GaN processed with (a) ALE and (b) continuous plasma [5].

Table I. Smoothing effect by ALE

Material	ALE Cycle	Surface Roughness (R_{RMS}) Pre-etch	Surface Roughness (R_{RMS}) After ALE	R_{RMS} Improvement
GaN	60 cycles	0.8 nm	0.6 nm	25%
Ta	40 cycles	1.0 nm	0.7 nm	30%
Ru	100 cycles	0.8 nm	0.2 nm	75%

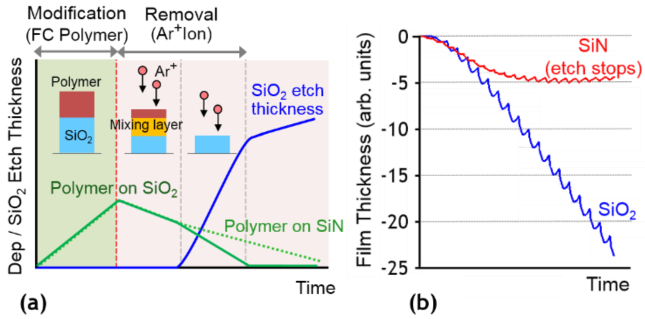

Fig.5. (a) Polymer thickness and etch evolution during modification and removal step. (b) Experimental etch evolution with time. [8]

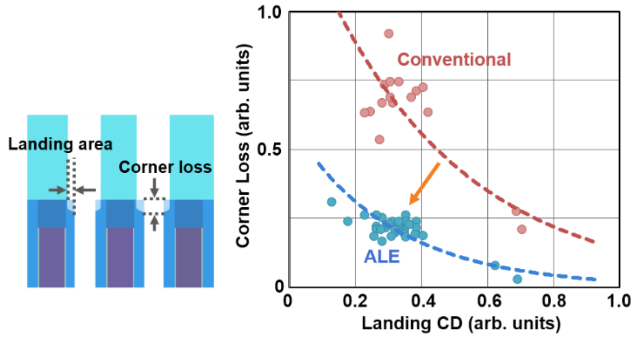

Fig. 6. SiO_2 ALE example for 10 nm Logic self-aligned contact (SAC) etching.

example for 10 nm Logic SAC etching. The spacer corner loss for ALE is dramatically reduced compared with conventional etching. It has been adopted into production at 10 nm node Logic devices [9]. ALE in production was enabled through the hardware specifically designed to reduce the transition time during power/gas switching [8].

4. Conclusions

In this paper, the concept, mechanism and advantages of plasma-enhanced ALE have been described based on our recent studies on various materials. We recently discovered ALE can improve the surface smoothness. ALE has already moved from lab to fab. SAC application has been adopted into production at 10 nm node Logic devices. ALE is the most promising technology for nanoscale device fabrication.

References

[1] R. A. Gottscho *et al*, J. Vac. Sci. Technol. B **10** (1992) 2133.
[2] M. E. Barone *et al*, Plasma Source Sci. Technol. **5** (1996) 187.
[3] K. J. Kanarik *et al*, J. Vac. Sci. Technol. A **33** (2015) 020802.
[4] K. J. Kanarik *et al*, J. Vac. Sci. Technol. A **35** (2017) 05C302.
[5] K. Ohba *et al*, Jpn. J. Appl. Phys. **56** (2017) 06HB06.
[6] P. Sigmund, Phys. Rev. **184**, (1969) 383.
[7] K. J. Kanarik *et al*, J. Phys. Chem. Rev. submitted April, 2018.
[8] G. Delgadino *et al.*, *Abstracts of the Advanced Metallization Conference 2017, Tokyo* (2017) 16.
[9] Lam Research Corporation Press Release (September 6th, 2016).