Reactive ion beam etching of piezoelectric ScAlN for bulk acoustic wave device applications

R James*, Y Pilloux and H Hegde
Ion Beam Business Unit, Plasma Therm, USA

*Corresponding author: robinson.james@plasmatherm.com

Abstract. Etching piezoelectric Scandium Aluminum Nitride (ScAlN) films containing a high concentration of Scandium with controllable feature profile angle and smooth surface is needed for next-generation Bulk Acoustic Wave (BAW) RF filter applications. This paper reports the facile etching of ScAlN with Scandium concentration of up to 15% using Reactive Ion Beam Etching (RIBE) with a very smooth surface of less than 5 nm average roughness and profile angle between 60 to 80 degrees. Recent studies show that doping AlN with a high concentration of Sc increases the piezoelectric response by five times and the bandwidth of RF filters also improved. However, etching ScAlN with a high concentration of Sc using traditional RIE and ICP based methods are extremely difficult and often results in low etch rate and rough surface. We have developed RIBE processes using a mixture of Reactive Gas and Ar with highly controllable profile angle from 60 to 80 degrees, improved etch rate (~ 36nm/min) and selectivity to photoresist mask (0.7:1), in comparison to conventional IBE. This work has positive implications in fabricating ScAlN based BAW RF filters for next-generation mobile and wireless applications.

1. Introduction

Demand for bulk acoustic wave RF filters has been growing continuously over the past few years. The reason for this growth includes the introduction of new bands above 2 GHz, the demand for the close proximity of bands and the less sensitivity of BAW filters towards temperature variation [1]. The demand for a large number of high-performance filters in the next generation of wireless and smartphone devices is the driving force in exploring RF filters based on new materials. AlN has shown to exhibit comparable power generation figure of merit (FOM) to traditional Lead Zirconate Titanate (PZT) materials (~ 14 GPa) while having desired low dielectric constant and the advantages of facile microelectronic fabrication. Recent studies show that doping AlN with a high concentration of Sc (up to 41%) increases the power generation FOM (~67 GPa) by five times and the bandwidth of RF filters also improved [2-7] as shown in figure 1.

Etching of materials like ScAlN, LiTaO₃ or LiNbO₃ using traditional ICP/RIE based methods is extremely difficult, resulting in low etch rates and rough etched surfaces due to the non-volatility of the etch by-products. On the other hand, ion beam etching offers a reasonably high etch rate, and provides process flexibility to form smooth etched surfaces due to its ability to etch at different tilt angles. Etch rate and selectivity can be further improved by using RIBE process by utilizing reactive gases along
with Ar. Here we report the facile etching of ScAlN with reactive ion beam etching with a smooth etched surface and improved selectivity towards photoresist mask.

2. Experimental details

2.1. Device structure
The cross-section SEM image of the pre-etch device structure is shown in figure 2. The device is on the silicon substrate with 150 nm SiO$_2$ film. The device consists of ~200 nm Pt top and bottom electrodes with ~10nm Ti adhesion layers. Etching of top Pt electrode and 2 um ScAlN and precisely stop at the bottom electrode is needed. Approximately 1.3 um photoresist is used as an etch mask.

2.2. Ion Beam System used for reactive ion beam etching

![Figure 3. Schematic diagram of IBE Process Module with labelled components.](image)

Details of the Ion Beam Etch system used in the ScAlN processing is shown schematically in figure 3. The reactive gas mixed with Ar is introduced into the source through the gas inlet. Plasma is generated...
using 2 MHz RF generator and the generated ions are extracted and focused through the grids by applying the desired beam conditions. Electrostatic damage to the wafer is addressed by having an external electrons source outside of the ion source. The wafer is mounted on a wafer stage that can rotate and tilt the wafer with respect to the ion beam. Thermal damage to the wafer is avoided by Helium backside cooling of the wafer during the processing. A secondary ion mass spectrometry based endpoint detector can be used to precisely endpoint the etch process on the bottom electrode as the etching of the ScAlN is completed. SEM is used to characterize the etching and the white light interferometer (WLI) is used to measure the surface roughness.

3. Results and discussion

Due to the non-volatility of etch by-products generated in the etching of ScAlN, IBE method is preferred to traditional ICP/RIE based methods. The advantage of IBE is mainly due to its ability to control etch/clean angle to avoid sidewall redeposition and sloped sidewall. However, ScAlN etch using IBE has lower selectivity to mask and etch rate is low. RIBE has the advantages of IBE along with improved etch rate and selectivity to mask as shown in Table 1.

| No. | Process Type                     | Beam Voltage (V) | Beam Current (mA) | ScAlN Etch rate (nm/min) | Selectivity (ScAlN:PR) | Sidewall angle (˚) |
|-----|---------------------------------|-----------------|------------------|-------------------------|------------------------|-------------------|
| 1   | IBE (100% Ar)                  | 715             | 485              | 17                      | 0.5                    | 79                |
| 2   | RIBE (60% Ar & 40% reactive Gas) | 715             | 485              | 19                      | 0.6                    | 76                |
| 3   | RIBE (40% Ar & 60% reactive Gas) | 715             | 485              | 12                      | 0.4                    | 76                |
| 4   | IBE (100% Ar)                  | 900             | 600              | 24                      | 0.4                    | 71                |
| 5   | RIBE (75% Ar & 25% reactive Gas) | 900             | 600              | 36                      | 0.7                    | 73                |
| 6   | RIBE (75% Ar & 25% N2)         | 900             | 600              | 27                      | 0.5                    | 76                |

In the IBE process, the etch rate is improved slightly by increasing the beam voltage and beam current as shown in entries 1 and 4 in table 1. However, the selectivity is decreased slightly. Using RIBE with moderate beam conditions ScAlN etch rate and the selectivity to photoresist were increased slightly compared to IBE process. When the reactive gas is 60%, the etch rate decreased indicating that the sputtering of the surface is the rate-limiting step. The ratio of reactive gas to Ar needs to optimized to obtain high etch rate and selectivity to photoresist.

Etching of ScAlN and Pt top electrode using RIBE with optimized reactive gas to Ar ratio of 1:3 is shown in figure 4 and in table 1 entry 5. ScAlN etch rate of 36nm/min with the selectivity to photoresist of 0.7:1 and the sidewall angle of ~73˚ was achieved. WLI measurements show that the etched surface was very smooth with the average roughness of less than 5 nm. Replacing reactive gas with N2 resulted in lower etch rate and selectivity. These results suggest that the reactive gas interacts with ScAlN to form by-products which are subsequently removed by sputtering. When the percent of Ar in the reactive
gas/Ar mixture is very low, the etch rate of ScAlN decreases. This is due to the fact that there is not enough Ar ion bombardment to remove the non-volatile reaction by-products from the surface.

Figure 4. Cross section SEM images after RIBE using Reactive Gas/Ar depicting a) ScAlN etch depth of 438 nm, etch rate 36 nm/min and selectivity to PR was ~ 0.7  b) Smoothness of the etched bottom surface

4. Conclusions
Reactive ion beam etching of ScAlN was demonstrated with reasonably high etch rate, good selectivity to photosist, good sidewall angle, and smooth etched surface. A combination of wafer tilt, Reactive Gas/Ar ratio, beam voltage, and beam current was used to achieve these results. Further improvements in etch rate and selectivity to mask will enable the fabrication of highly Scandium doped ScAlN based BAW devices. This, in turn, will result in the high-performance BAW filters for mobile and wireless applications.

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