High selectivity GaN to AlGaN etching for HEMT devices

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Abstract

Realization of modern HEMT devices requires etching structural layers with both high precision, and high selectivity between layers. One of the critical etches in certain device types is etching a p-type (usually magnesium) doped GaN layer known as p-GaN to a AlGaN layer containing up to 25% Aluminium, the loss value of this layer having a critical impact on device electrical performance. Various other studies have highlighted the high selectivity required for this process but concentrate either on a selectivity metric, or occasionally on AlGaN loss but not both together. This work investigates the relationship between loss and selectivity and demonstrate that some loss is inevitable in current production designs. Although very low loss targets are theoretically achievable through ALE etching if the p-GaN layer thickness was constant, in reality, manufacturing a uniform p-GaN layer is known to be extremely challenging in volume production and ALE does therefore not offer a practical way forward for this particular step at this time, but this work shows that traditional constant-mode etches can be demonstrated to manufacture devices with acceptable performance.

INTRODUCTION

Modern HEMT structures (Fig 1.) include a requirement to etch a relatively thick doped GaN layer to a thin underlying AlGaN layer with a high selectivity. This selectivity requirement comes from two aspects. The first is that doped GaN deposition in older generation reactors is commonly non uniform leading to a requirement for substantial over-etching [1]. The second driving force is that the remaining AlGaN thickness affects both the sheet resistance of this layer itself and will affect the 2DEG layer parameters formed by the heterojunction. At this scale even a single nanometer variation is a large percentage difference which will be easily detectable in device electrical performance characteristics [2]. A typical request made to KLA by device manufacturers is < 2 nm of AlGaN loss.
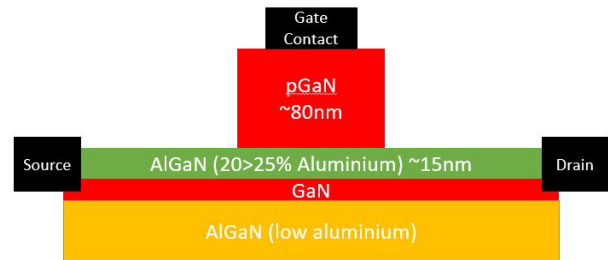

Fig 1 – Illustrative cross section of GaN HEMT device

Many studies concentrate on layer selectivity of the process and maximising this value, mainly because selectivity is an easy figure to measure and calculate, it is often measured by performing large over etches sometimes >1000% in order to generate losses easier to measure with high accuracy on the slowly etching AlGaN. However, we propose that this figure is often misleading, and we will show that selectivity is also a non-linear characteristic. These studies measure the ultimate, or maximum, selectivity of a process regime once it has reached steady state. Instead, it is the loss of AlGaN that is the only important metric needed for a real device. Therefore, the process variable of most importance is not the ultimate selectivity, but how rapidly that selectivity is formed and can only be investigated by short etches investigating the 1-2nm loss region.

INVESTIGATION

A standard SPTS ICP module was used for this investigation; this system is capable of various chemistries and can be run in ICP conditions, RIE mode or in 'looped' process modes allowing ALE regimes to be investigated.

GaN and related material etching is chlorine based, as Gallium is non-volatile in other common etching chemistries and is typically relatively high bias due to the relatively high strength of the Ga-N bond. Since Aluminium is also easily etched by chlorine there is no intrinsic selectivity present with a normal GaN etch recipe and relative layer selectivity is ~1:1 or lower.

The basic principle of generating selectivity is to focus on the Aluminium, the one element that is different between the two layer types and convert this to a form that is not readily volatile. Oxygen or fluorine to generate AlO_3 or AlF_3 are the most commonly found examples in the literature [3,4] and we have explored both in this study. Since GaO and GaF are not readily volatile either, once this process is established it is important to position the ion energy of the process between the GaF_x/GaO_x and AlF_x/AlO_x sputter levels to preferentially remove the gallium component. It is important to note though that at the time of reaching the interface the surface is only 20% to 25% aluminium and therefore a large proportion of 'layer 1' will be removed. This now masks parts of 'layer 2' which has most of its exposed surface removed, and so on, leading to a gradual enrichment of Aluminium compounds on the surface slowing the etch, requiring some loss which is unavoidable (See Fig 2).
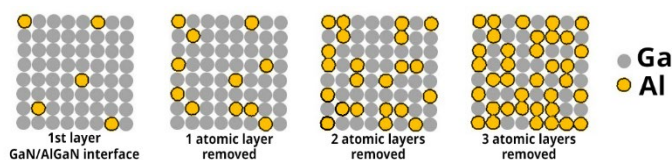

Fig 2 Simplified diagram showing Al concentration increasing as a proportion of etch depth, assuming perfect Al passivation process – illustrating how passivating the surface requires some material loss and that the effect is non-linear in the early stages

ALE has often been proposed as the way forward to improve GaN to AlGaN selective etches, however it will still be subject to the same rules of loss described above. ALE was investigated as part of this study, removing ~0.5nm per loop average (similar to the lattice constant, or ~2 atoms thickness per loop), however, the base process of chlorine doping is intrinsically not selective for the same chemical reasons already stated and it progresses as per a steady state etch at a slower rate. Adding the passivation oxygen or fluorine, either mixed into dosing or as a separate step, would cause the etch to stall completely. That is, unless the bias was increased above the sputter threshold of the material, at which point it returned to non-selective. We therefore conclude that although ALE is a practical etch and may be essential for other parts of the production process, it is not the optimum solution for this step.

Adding passivation gases into continuous mode operation was more successful and a reasonable maximum selectivity can be achieved in a variety of process regimes using both fluorine and oxygen methods, *Figure 3*. Overetch times were varied and resultant AlGaN loss figures measured by TEM, from which it becomes apparent that even with a limited data set as overetch time is reduced the process within many
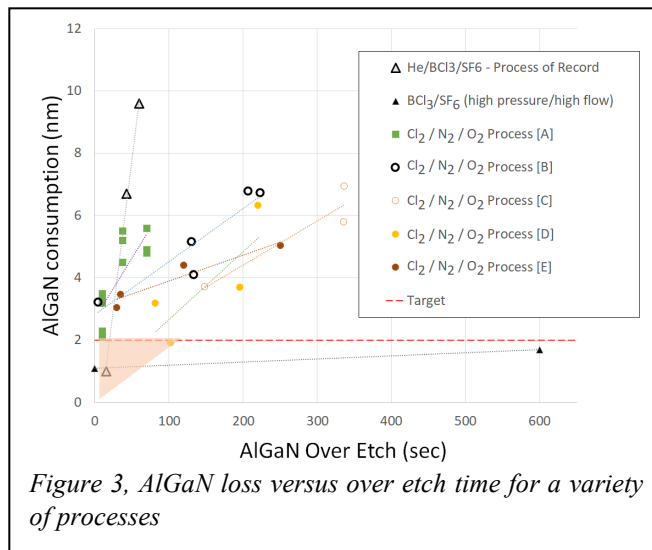

Figure 3, AlGaN loss versus over etch time for a variety of processes

regimes does not tend towards zero. This is illustrated by adding best fit straight lines to the graph that in most cases will not pass through the origin and always indicate a positive loss, which supports a real effect rather than measurement noise. We therefore conclude that the data supports the theory that formation of selectivity is non instantaneous and the etch rate of AlGaN is high at the moment of reaching the GaN/AlGaN interface. Generating data at large overetch times provides information on the ultimate steady state selectivity but is of limited value in determining practical AlGaN loss achievable unless a loss figure can be achieved in combination with extended overetch times such as the best process shown here.

From this work it also became apparent process changes and chemistry choice can alter the relationship between loss and selectivity formation. It is apparent in particular that the intrinsic minimum loss is distinctly higher for Cl_2/O_2 based process regimes. From this, we conclude the rate at which maximum selectivity is formed is slower in this chemistry. Using a DOE on the alternative BCl_3/SF_6 chemistry suggested moving the process to a higher pressure/higher gas flow regime, which not only gave a higher ultimate selectivity but also a much more rapid formation of the selectivity on contact with the interface and demonstrated low loss even with substantially extended overetch times on our test substrates.
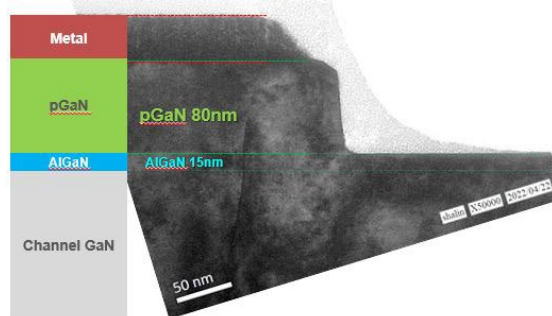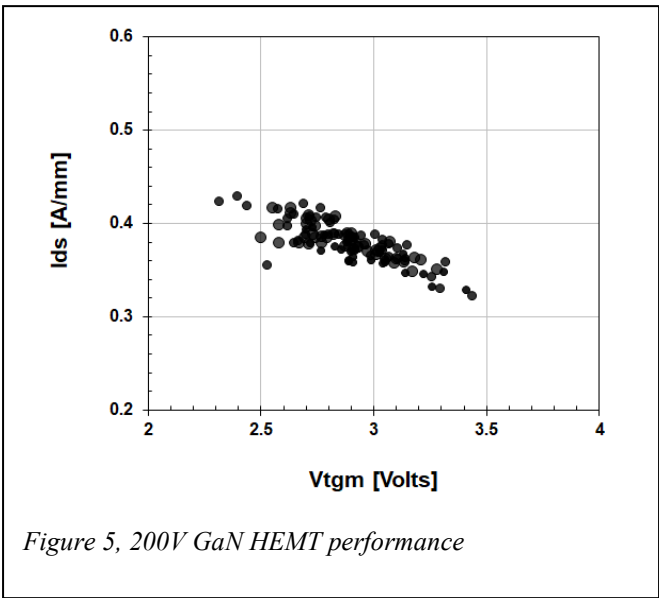

Figure 4, cross section of etched device wafer

The resulting BCl_3/SF_6 process chemistry has been successfully employed in production, and gate etch profile shown in figure 4 and electrical characteristics of 200V GaN HEMTs is shown in Figures 5 and 6. The Ids shown in figure 5 is measured at Vg of 7 volts and Vd of 10 volts, while the Vtgm indicates threshold voltage extrapolated with maximum trans-conductance, Gm.

Figure 5, 200V GaN HEMT performance

CONCLUSIONS

Figure 6, 200V GaN HEMT off state leakage current

It has been previously considered that ALE is the sole solution to providing valid GaN/AlGaN process conditions to enable the production of modern HEMT devices. It has been shown above that continuous etch processes can be used to maintain the integrity 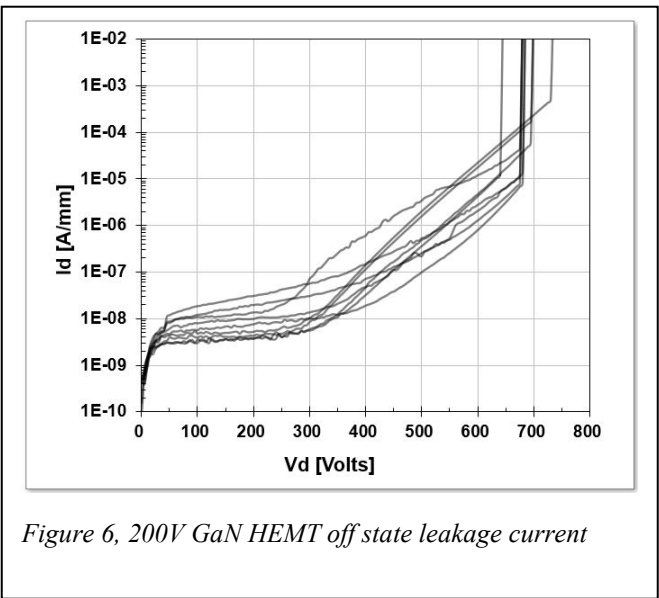of the AlGaN layer such that the device performs as required. A production-qualified, continuous etch process has been demonstrated for GaN to AlGaN layer etching, following isolation of the time that the selectivity takes to maximise from the ultimate selectivity reached which is the standard metric.

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ACRONYMS

ALE – Atomic layer etching
GaN – Gallium Nitride
AlGaN – Aluminium Gallium Nitride
PR – Photoresist
DOE – Design of Experiment