Characterization of GaAs/AlGaAs non-selective ICP etch process for VCSELs applications

M W DeVre,[a] Y S Lee,[a] B H Reelfs,[a] R J Westerman,[a] and S D Roh[b]
[a]Unaxis USA, Inc., St. Petersburg, FL 33716
[b]Agilent Technologies, San Jose, CA 95131

A systematic investigation of a baseline GaAs/$Al_xGa_{1-x}As$ non-selective etch using BCl_3/Cl_2 chemistry was conducted in an Inductively Coupled Plasma (ICP) through designed experiments (DOE) to establish a working process window and obtain optimum process conditions for VSCEL etch applications. The DOE was comprised of four factors: Cl_2/BCl_3 ratio, RF bias power, ICP power and pressure. Factor responses, including GaAs/AlGaAs etch rate, selectivity, etched profile, and uniformity, are discussed in this paper. In addition, the comparison of GaAs and AlGaAs etch rates are examined. Controllable etch rates, anisotropic feature profiles, smooth etched surfaces and excellent uniformity were obtained over a wide range of process parameters. Two endpoint detection techniques: laser CCD and optical emission spectroscopy (OES), were incorporated in this study.

1. Introduction

Vertical Cavity Surface Emitting Laser devices (VCSELs), representing some of the latest technology in laser design, have gained much attention in the photonic devices field due to their high power conversion efficiency at low operating currents [1]. While similar in operating principle to conventional diode lasers, where the light emerges from the edges of the device through mechanically cleaved surfaces, VCSELs are unique in that the reflecting mirror surfaces are stacked vertically, with the light emerging normal to the substrate surface. Typically, these mirrors consist of alternating layers of doped III-V compound semiconductor materials such as GaAs and $Al_xGa_{1-x}As$. VCSEL devices require a process that nonselectively etches through these epitaxial layers with smooth feature walls stopping on the specific layer in the active region. Controllable etch rates near 1 μm/min and vertical feature profiles are necessary to meet these requirements.

GaAs/$Al_xGa_{1-x}As$ non-selective etching using RIE, ICP and ECR reactors has been studied in the past; $SiCl_4$, BCl_3, $SiCl_4/Cl_2$ and $BCl_3/Cl_2/Ar$ plasmas have historically been the choices for achieving equal-rate or near equal-rate etch for GaAs/$Al_xGa_{1-x}As$ layers [2]. However, very few papers have reported the utilization of high density plasma for VCSELs applications. In addition, a implementation of an etch process monitoring technique is becoming increasingly important in the manufacturing environment [3]. In this study, we describe an ICP based non-selective GaAs/$Al_xGa_{1-x}As$ etch processes for the fabrication of VCSEL micro-laser devices. The process space is characterized using designed experiments. Endpoint detection techniques including laser reflectance and Optical Emission Spectroscopy (OES) were also evaluated in this work.

2. Experimental

All experimental work was performed in a commercially available Unaxis SLR ICP system equipped with electrostatic clamping and He backside cooling. In this system, a high-density plasma is generated by a 2 MHz coil; while the ion energy is controlled by a 13.56 MHz RF biased cathode. Gas flow rates are controlled by mass flow controllers. The substrate was set at room temperature and controlled by backside He cooling. The Unaxis SLR ICP etcher was also equipped with two endpoint systems including laser reflectance and Unaxis Spectraworks optical emission spectrometer. The (SOFIE Instruments S.A. Inc.) laser reflectance system consists of the polarized 670.4 nm He-Ne laser head, CCD detector and video camera for laser spot positioning. The Unaxis Spectraworks OES system has a spectral range was 200 – 800 nm with a resolution of 1 nm. The plasma emission was coupled to the spectrometer through a sapphire reactor viewport and a silica optical fiber.

3. Results and Discussion

Prior to the DOE, a number of preliminary experiments were conducted to independently examine the etch rate GaAs and AlGaAs. Figure 1 shows similar etch rates for GaAs and AlGaAs over a 0% - 50% Cl_2%. Later experiments confirmed that the etch rates of the alternating layers in the VCSEL devices were in good agreement with the etch rates of the individual films.. Based on these results a series of designed experiments were performed on VCSEL device structures.

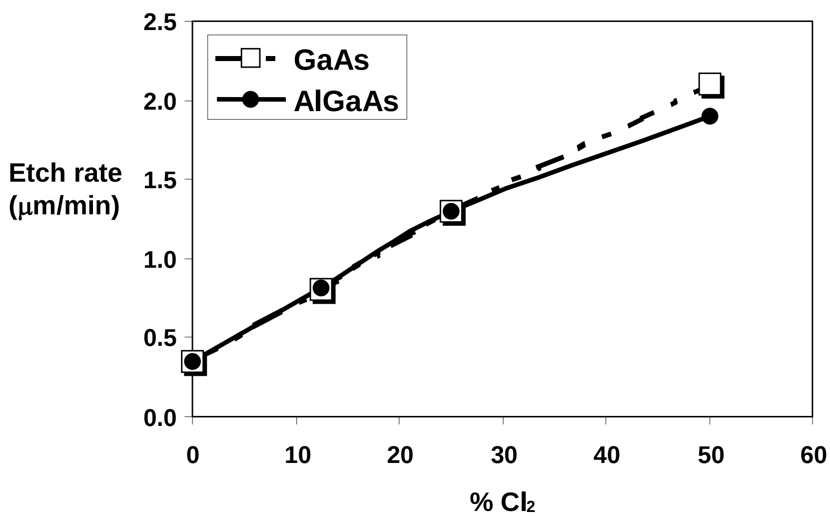

Figure 1. The etch rates of GaAs and AlGaAs as the function of the $\%Cl_2$

3.1. DOE results

The analyzed DOE response for the composite GaAs/AlGaAs stack etch rate is illustrated in Figure 2. Consistent with a chemically driven etch mechanism, the GaAs/AlGaAs composite etch rate increases with increased chamber pressure and Cl_2 percentage. This suggests that the generation of Cl radicals is the key factor determining the etch rate of GaAs/AlGaAs. Furthermore, since the GaAs/AlGaAs etch rate is independent of both the RF bias and ICP powers over the range of parameters tested suggests that process is reactant-limited.

Based on the DOE analysis, the mask (silicon nitride) etch rates were mainly controlled by Cl_2% and weakly affected by RF bias power . High Cl_2% and RF bias powers tended to increase SiN_x etch rates. The GaAs/AlGaAs:SiN_x etch selectivity was found to be a function of both Cl_2% and pressure with high Cl_2 percentages significantly improving the etch selectivity due to a strongly enhanced GaAs/AlGaAs etch rate. The DOE analysis also showed that Cl_2% is the only parameter having the significant effect on the profile. High Cl_2% tends to result in re-entrant (undercut) feature profiles; while high BCl_3% lead to positively tapered (sloped) profiles.. The DOE results did not show a significant parameter dependence on the non-uniformity in over the range of parameters tested. All cells within the designed experiment showed etch rate uniformities well below ± 3% (Range / (2 Mean method))

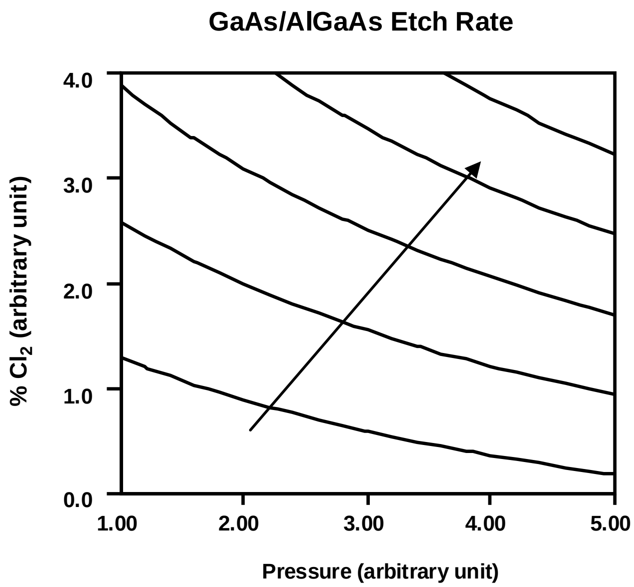

Figure 2. Contour plot of the GaAs/AlGaAs etch rate response surface as a function of pressure and Cl_2%.

3.2. Mask effect

The initial mask properties such as mask profile and edge roughness had a profound effect on the etched feature profiles and sidewall morphology. The magnitude of the effect depends primarily on the etch selectivity which in turn is a function of the process conditions. A positively sloped etched profile can be achieved through the use of a sloped mask profile and lowering selectivity of the stack material to the mask (driving the mask profile into the etched feature through mask erosion). For applications requiring vertical feature profiles, it is preferable to utilize a hard mask such as silicon nitride or silicon dioxide. Selectivities to these materials can be up to 4 times higher compared to photoresist mask materials. Figure 3 demonstrated the etched results of applying the optimized process on a nitride masked AlGaAs based VCSEL stack structure. As is apparent from Figure 3, a highly anisotropic profile was obtained through the use of nearly vertical mask combined with highly selective process conditions.

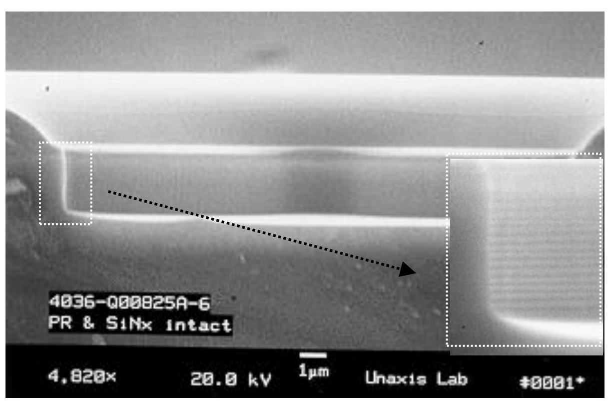

Figure 3. SEM photograph of VCSELs structure after etching with the optimized process; a vertical profile is observed.

3.3. Endpoint Detection

In this work, two primary types of endpoint systems were employed to examine the feasibility of monitoring the process: laser reflectance and optical emission spectroscopy. Figure 4 shows an example of a laser reflectance trace of a VCSEL etch process. The etch depth is monitored by counting the reflectance peaks. Each peak represents etching through a GaAs/AlGaAs mirror pair. OES was also utilized to monitor the etch depth in the stack. An OES endpoint signature for the VCSEL etch process is shown in Figure 5. As can be seen from Figure 5, the amplitude of the peak initially varies along with the processing, which may be due to a compositional difference between subsequent layers in the stack. After experiencing the significant change in the amplitude, the trace returns a constant pattern, which was found to correlate with the etch reaching the active region.

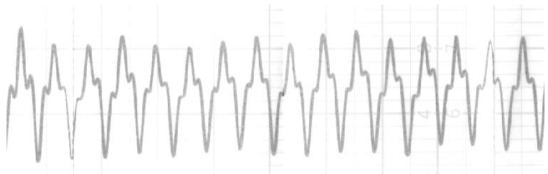

Figure 4. Laser reflectivity as a function of etch time.

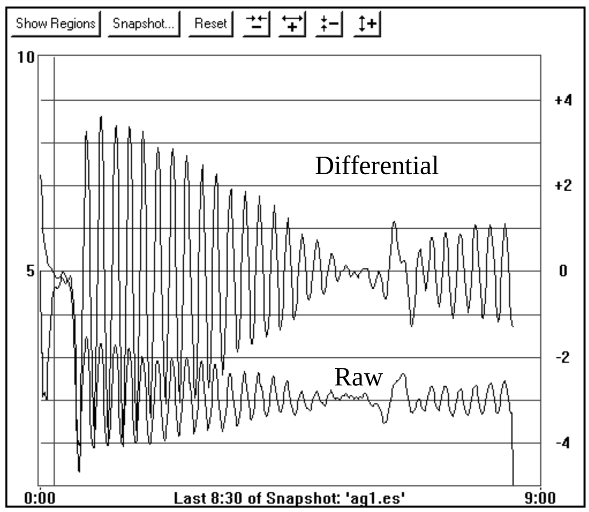

Figure 5. OES intensity as a function of etch time.

4. Conclusions

A systematic investigation of a dry etch process for GaAs/$Al_xGa_{1-x}As$ using a BCl_3/Cl_2 chemistry in a high density plasma has been performed. GaAs/AlGaAs etch rates ranged from approximately 0.25 to 2.5 μm/min. The DOE results show that the composite GaAs/AlGaAs etch rate is a strong function of Cl_2/BCl_3 ratio and pressure. The etch rates of GaAs and AlGaAs obtained with Cl_2% varying from 20% to 50% were nearly identical. The mask (SiN_x) etch rate was mainly controlled by Cl_2% and weakly affected by RF bias power. Cl_2/BCl_3 percentage and pressure were the factors that influenced the stack:mask etch selectivity. Etch rate uniformity well under ± 3% (Range / (2 Mean)) was obtained over all etch conditions. High Cl_2% tended to result in re-entrant etched profiles; while high BCl_3% lead to positively tapered profiles. We are able to etch the stack GaAs/AlGaAs with equal etch rate and excellent non-uniformity. Laser reflectance has been demonstrated as a powerful tool to determine the etch depth during processing; while a success of utilizing OES as an endpoint technique was found to be a function of exposed area and will strongly depend on the individual application.

5. References

[1] Choquette K D and Hou H Q 1997 *Proc. IEEE* **85** 1056-1058.
[2] Agarwala S, King O, Horst S, Wilson R Stone D and Dagenais M 1999 *J. Vac. Sci. Technol. A* **17(1)** 52-55.
[3] Johnson D, Westerman R., DeVre M, Lee Y and Sasserath J. 2000/2001 *Compound Semiconductor* **6(9)** 62-64.