Inductively Coupled Plasma Reactive Ion Etching of GaN

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We investigate in deep etching recipes for GaN based compound semiconductors. For nitride semiconductors wet chemistry does not work, therefore plasma etching is required. For deep structures of wavelength scale in GaN, a good etchant to mask selectivity and vertical etch profiles is needed. We present an inductively coupled plasma recipe that can etch 6 µm deep with smooth sidewalls with a SiNx hard mask.

Introduction

Since etching of GaN [1] cannot be accomplished by wet chemistry to a satisfactory degree, reactive ion etching (RIE) becomes very important, as it is the only means of obtaining vertical structuring. The only practical wet etch [2] is KOH at 50 …100 °C. The inability to find a mask that will hold up to such aggressive chemistry makes it more or less useless for accurate transfer of patterns. Unlike for other III-V semiconductors this is also valid for shallow structures for electronics. Demands on etch quality become even more stringent for deeper optically waveguided structures; especially where lithographic resolution needs to be on the micrometer scale. In that mask thickness will be limited by some lithographic technique; here selectivity plays a significant role.

With respect to the demands in optically integrated circuits a RIE recipe is needed to produce vertical or at least overcut sidewalls. Undercut would not be compatible with subsequent metallization steps. Preferably this sample preparation technique should be fast and reliable, which is not a matter of course for the nitrides, since etch rates are generally slow [1]. Smoothness of sidewalls becomes a crucial issue for optoelectronic devices operating at 1.55 µm or less. In rough sidewalls scattering will take place and hence will boost the waveguide losses. Additionally cleavage of waveguide facets is difficult or even impossible in the GaN/InGaAlN system if grown on commonly used sapphire substrate; therefore cleaved facets for in-plane fiber coupling are no option. Etched facets [3] are an excellent solution but this again demands vertical and smooth etches, in this case even in excess of 5 µm in order to make space for fiber tapers.

So far most groups used chlorine based RIE techniques, mainly because these provide the highest etch rates for GaN in the order of 50 nm/min for capacitively coupled plasma (CCP) RIE [4]. Going to higher plasma densities with inductively coupled plasma (ICP) RIE [5] enhances rates to the order of 600 nm/min. In this work we are mainly concerned with developing such an ICP process for very large etch depths.

Sample preparation

For advanced structures like tightly guiding rib waveguides a better mask to etchant selectivity is needed than the one obtained for GaN versus photo resist, which was smaller then 1:1 in favor of the photo resist. The use of an intermediate mask does not only enhance selectivity but also improves the sidewall smoothness which will be important for etched mirrors. Since SiN_X is available in almost any processing lab and has very good adhesive properties to GaN/AlN it is a good choice. Remaining SiN_X can easily be removed by HF after etching. We used a two step fabrication scheme as outlined in Fig. 1. The photo resist to SiN_X selectivity is only slightly better than 1:1, but the expected selectivity of GaN to SiN_X in an ICP RIE process step is well above 1:1 as will be shown later. Also, the process utilizing SiNx masks has the advantage of being totally free of organic substances during the deep etch process. Remaining photo resist is stripped by plasma oxidizing and KOH. By this additional cleaning procedure we avoid any micro masking [6] effects and wall roughening by contaminants.

Experiment

In ICP-RIE a $N_2/SiCl_4$ based chemistry, as compared to commonly used Ar/Cl_2, has proved itself due to two reasons: Nitrogen has less than half the atomic weight than Argon and therefore does much less damage the masking material. Concerning the acceleration voltage acting on the inert gas atoms normally there is an onset voltage where sputter removal of the mask just starts to be efficient. If one manages to stay below that only very slightly, etch selectivity is very much improved. This fine tuning works especially nice with nitrogen. Second, the $SiCl_4$ [7] is split in the plasma and provides silicon compounds that are again not reluctant to react with chlorine; these compounds can serve as passivation layers that stick on sidewalls were sputtering does not take place. So at the end it can act as a chemical underetch inhibitor. This inhibitor is still efficient at very high chlorine flow. Furthermore, $SiCl_4$ is much more compatible with residual water in the etch chamber. In contrary, the use of Cl_2 gas causes major troubles with residual water vapors and needs additional cleaning steps to prevent hydrogen-chlorine based erosion.

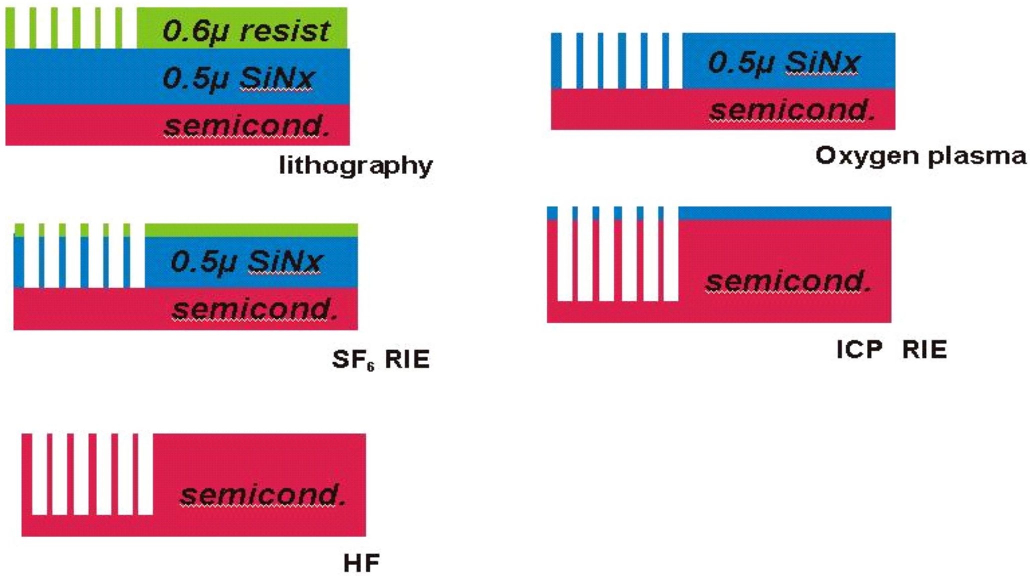

Fig. 1: Fabrication scheme for deep GaN/AlN structures

Initially processes with high flow of chemically reactive gas species have been tried assuming that this will enhance selectivity in any case. Unlike in, e.g., GaAs etching, where it represents an annoying problem, apparently chemical underetching of sidewalls is unlikely in GaN at least in the parameter range investigated within this study. Therefore it was thought that more $SiCl_4$ than N_2 flow would be advantageous. This resulted in an ultimate etch depth of about 2 µm (Fig. 2). But surprisingly the opposite ratio, namely 20:10 $N_2:SiCl_4$ had almost double the selectivity, which we believe to be due to better etch product sputter removal, since the etch process is not flow limited at all, if in excess of 10 sccm $SiCl_4$. There is an additional argument supporting this gas mixture that was mentioned already: the $SiCl_4$ sputter rate of the SiN_x mask is about 50% higher than the mask sputter rate achieved by using N2 only.

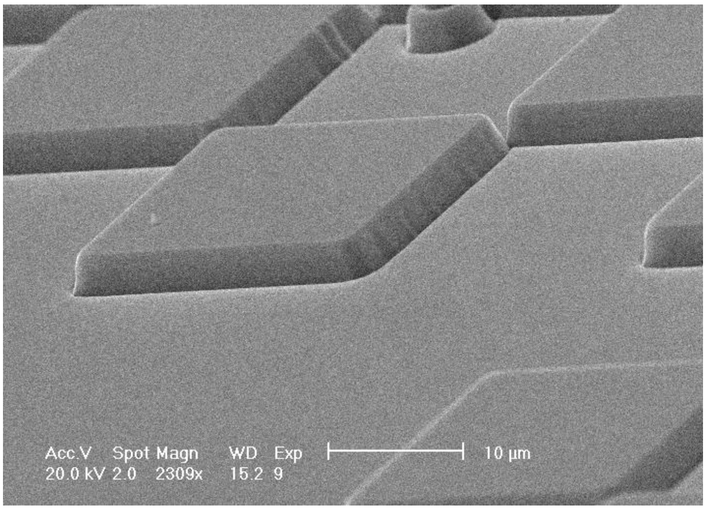

Fig. 2: Typical result of the first set of process testing obtained by etching thick intentionally undoped C-GaN layers on sapphire susbstrates. DC bias set to 200 V, $SiCl_4$:N_2 ratio was 20:10.

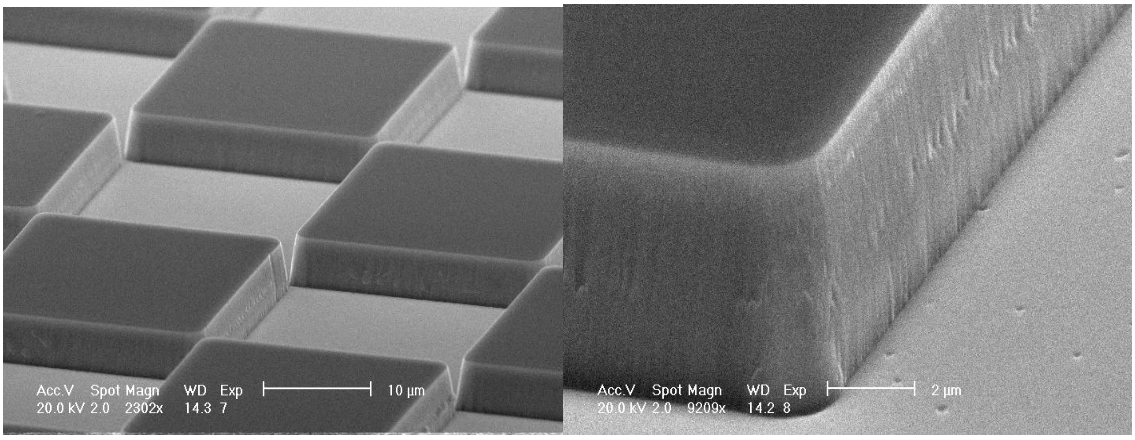

Fig. 3: SEM picture of the 20:10 N_2:$SiCl_4$ process with magnified sidewalls in the picture on the right. The surface roughness is well below a critical roughness for 1.55 µm light. Note that deviations from the verticality are well below 5°.

During optimization it also turned out that very low DC bias does give much better selectivity as well. This might seem somewhat contradictory to the above assumption about sputter removal, but even at room temperature the energy typical $GaCl_X$ compounds need for removal are very low. Thus, there is no additional enhancement in the sputter rate by increasing the ion energy via the applied DC bias. Higher ion energy on the other hand sputters the mask faster and, therefore, reduces the total achievable thickness for a given mask thickness. More reactive species are much more effectively supplied by high powers to the ICP coil, which should break up the $SiCl_4$ in larger amounts. The resulting etch rates we found in our optimized process are about 106 nm/min for GaN and 13 nm/min for the SiN_X mask. This should be sufficient selectivity to prepare waveguides as well as deep etched mirrors. As can be seen in Fig. 3 the sidewall roughness is low and verticality <5° sufficient not to refract light off plane. This small angle deviation from rectangular sidewalls originates from mask erosion, which is always a little bit faster at the edges than in the center of large areas. The etch rate of both, the SiN_X mask and the GaN epilayers did not scale with temperature notably in the investigated temperature range spanning from 150 °C to 300 °C. This is exactly the temperature window in which $InCl_3$ evaporates at pressures around 10 mtorr. The consequence of this particular finding is that it will be easy to obtain smooth but still not underetched profiles of InGaN of any Indium content.

Conclusions

We developed and optimized an etch recipe to perform deep etching of GaN-based materials with a low surface roughness. The process employing inductively coupled plasma reactive ion etching (ICP-RIE) with N_2 and $SiCl_4$ allows an etch depth exceeding 5 µm, sidewalls deviate <5° from verticality. A SiN_X mask gives a selectivity of about 7:1. No trenching occurs at the bottom or into Al containing layers. This process can be readily used for processing of rib waveguides for 1.55 µm wavelength as well as etched reflecting facets.

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