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Problems with cracking of $Al_xGa_{1-x}N$ layers

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$Al_xGa_{1-x}N$ is a wide band-gap material, which can be used for manufacture of UV detectors. Unfortunately, there are problems with the cracking of those layers occurring above some critical thickness, which is a bit smaller from the one used for detectors (about 1 μm). Our investigation concentrated on the causes of crack formation. To avoid it we used so-called special AlN nucleation layer, which was to stop the relaxation. We obtained a strained layer free of cracking, but with a very big number of dislocations. We compared dislocation densities of strained and relaxed $Al_{0.4}Ga_{0.6}N$ layers. The first one was characterized by a higher dislocation density than the second one. We also investigated the problem with cracking occurring in $Al_{0.4}Ga_{0.6}N$ epitaxial layers during the doping, and how to control this process. The relaxation of the layers started for very low impurity densities and went on when we increased the amount of the dopant.

Keywords: $Al_{0.4}Ga_{0.6}N$, GaN, Si doping.

1. Introduction

$Al_xGa_{1-x}N$ is a very interesting wide band-gap material because it can be used for fabrication of many optoelectronic devices such as blue-green light emitting diodes, laser diodes, and visible-blind photodetectors [1]. $Al_xGa_{1-x}N$ grown on GaN layer is the most often used component in all of these devices in order to ensure a very good performance. Unfortunately, a big lattice mismatch (2.16%) between GaN and AlN layers results in generation of a big number of dislocations. This causes the cracking of $Al_xGa_{1-x}N$ layers with either big thickness or high Al content, which material is used for preparation of UV detectors. This cracking seems to deteriorate performance of the device [2].

According to Qu *et al.* [3], increasing $Al_xGa_{1-x}N$ thickness makes more and more dislocations generate for relaxation. The propagation of cracks will not occur dislocations are generated easily enough. If some processes which impede the generation of misfit dislocations exist, cracks will generate to relax the strain at some thickness. After that, the cracks will propagate with increasing the thickness and when the latter reaches the critical value, the will propagate to the surface of the film. The insertion of LT-interlayer between high temperature grown layers is very promising for the improvement of the $Al_xGa_{1-x}N$/GaN heterostructure. The LT-interlayer is thought to have similar effect as that of the LT buffer layer, acting as a kind of nucleation layer. This method succeeded with thick $Al_xGa_{1-x}N$ layer (about 3 μm) free of cracks [3].

The problem with cracking occurs also during the growth of intentionally doped *n*-type $Al_xGa_{1-x}N$ layers. Si doping changes the growth mode of $Al_xGa_{1-x}N$ layer. CANTU *et al.* [4] showed that it is either the composition or the strain that changes during the layer growth. These effects cause relaxation of the strain and finally cracking.

In this work we investigated the effect of the behavior of cracks and then its suppression by applying so-called special AlN nucleation layer as proposed by QU *et al.* [3]. In the second part we studied the behavior of $Al_xGa_{1-x}N$ layers during the *n*-type doping.

2. Experiment

Both experiments were carried out in metal organic vapor phase epitaxy low-pressure reactor. The heterostructures were grown on *c*-plane (0001) sapphire substrates. Trimethylgallium (TMGa), trimethylaluminium (TMAl), ammonia (NH_3) and silane (SiH_4) were used as precursors of Ga, Al, N and Si, respectively. High purity H_2 was used as a carrier gas.

First, $Al_{0.4}Ga_{0.6}N$ layer of about 1 μm in thickness was grown directly on GaN high temperature layer (1.5 μm thick), on GaN nucleation layer (20 nm thick) at a temperature of 1100°C and pressure of and 75 mBar. The flows of TMGa, TMAl and NH_3 were kept at 4.4×10^{-5}, 1.2×10^{-4} and 6.7×10^{-2} mol/min, respectively. Then, for comparison, special AlN nucleation layer (about 20 nm thick) was deposited at a temperature of 550°C between GaN and $Al_{0.4}Ga_{0.6}N$ high temperature layers. Both layers were etched in melted eutectic of KOH, NaOH in order to check the dislocation density.

The next step was *n*-type doping of $Al_{0.4}Ga_{0.6}N$ layers (about 1.5 μm thick) on AlN nucleation layer grown for 6 min (20 nm thick) at a temperature of 550°C and pressure of 70 mBar. The amount of dopant was varied from 0.1 to 6 nmol/min in order to get the carrier concentration as high as possible.

3. Results and discussion

Figure 1 shows the surface morphologies of about 1 μm thick $Al_{0.4}Ga_{0.6}N$ layers grown without (Fig. 1**a**) and with special AlN nucleation layer (Fig. 1**b**) obtained by means of SEM.

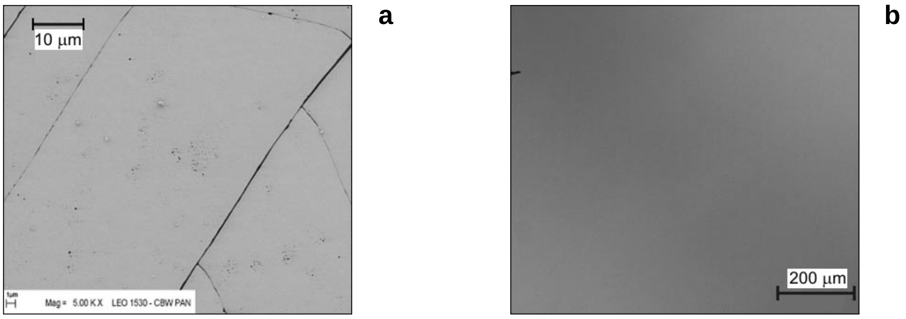

Fig. 1. $Al_xGa_{1-x}N$ layer surface morphology made without (**a**) and with (**b**) special nucleation layerobserved with scanning microscope.

The first layer is characterized by hexagonal cracks typical of the layer grown just on GaN buffer layer. The $Al_{0.4}Ga_{0.6}N$ layer grown on special LT AlN layer has the mirror-like surface without any defects such as cracks and hillocks. We obtained the same results as Qu *et al*. [3]. LT AlN interlayer prevented the layer from cracking. It reduced the strain caused by growing $Al_{0.4}Ga_{0.6}N$ directly on GaN layer and acted as a filter against threading dislocations, which have screw components and make the grown layer crack. On the other hand, additional pure edge dislocations were generated instead [5].

Figure 2 shows the etched surfaces of both $Al_{0.4}Ga_{0.6}N$ layers without (Fig. 2**a**) and with (Fig. 2**b**) LT AlN layer. Each pit, which is present on the surfaces occurred on one dislocation [6].

The pit densities are 4×10^7 and 5×10^9 counted for $Al_{0.4}Ga_{0.6}N$ layer grown without and on special nucleation layer, respectively. Similar results are given by other authors for layers grown with special AlN or $Al_{0.4}Ga_{0.6}N$ low temperature nucleation layers. The relaxation of strain of the first layer made it crack and lowered the dislocation density (EPD) about two orders of magnitude. The special AlN nucleation layer

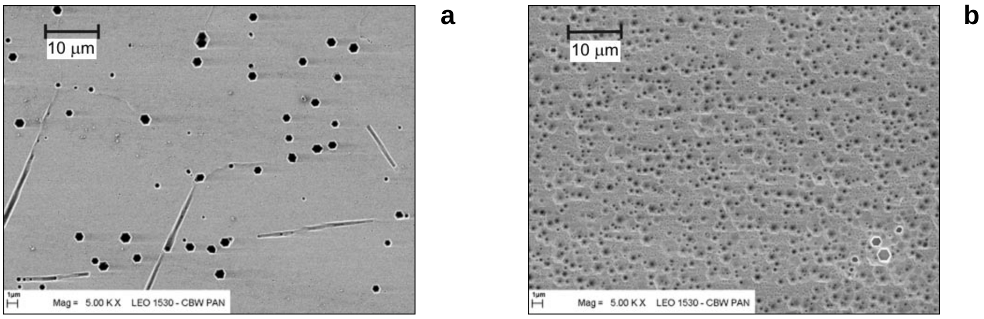

Fig. 2. Etched surface of $Al_xGa_{1-x}N$ layer grown without (**a**) and with (**b**) LT AlN layer observed with SEM.

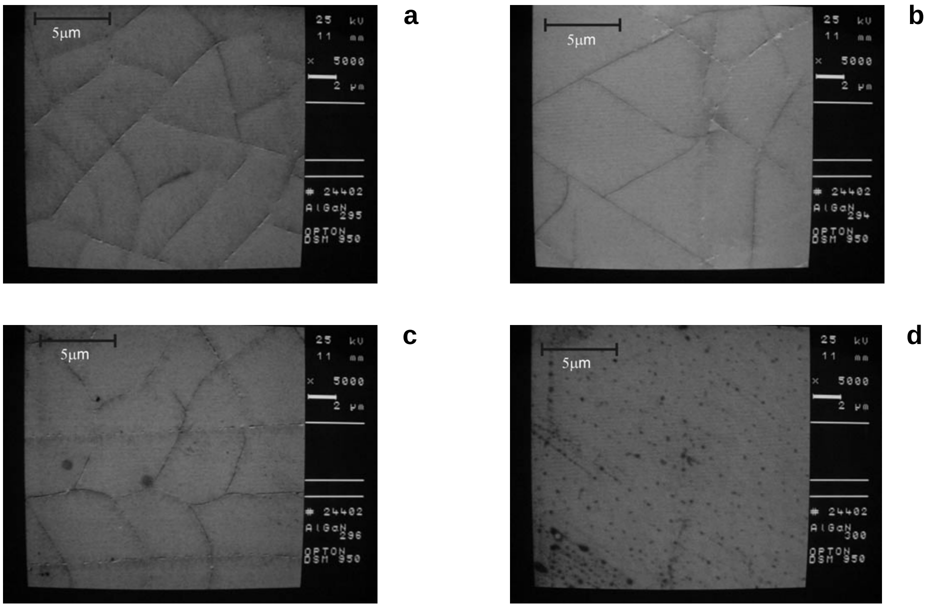

Fig. 3. The *n*-type $Al_xGa_{1-x}N$ layer morphology doped with 6 (**a**), 4 (**b**), 3 (**c**) and 0.1 nmol/min (**d**) of silane observed with SEM.

reduced the strain of $Al_{0.4}Ga_{0.6}N$ layer and prevented it from cracking, but many new edge dislocations appeared instead. We can say that special LT AlN improves the morphology of grown $Al_{0.4}Ga_{0.6}N$ layer but it does not reduce its EPD.

Figure 3 shows the surface morphologies of *n*-type $Al_{0.4}Ga_{0.6}N$ layers (1.5 μm) deposited on sapphire and AlN nucleation layer (20 nm thick) grown for 6 min observed by a scanning microscope. The layers were doped with 6, 4, 3 and 0.1 nmol/min of silicon (Fig. 3**a**–**d**, respectively).

The surfaces of three of these samples were characterized by typical hexagonal cracks made by the intentional doping. The density of cracks depended on the amount of the dopant. Decreasing the amount of silicon made the grown $Al_{0.4}Ga_{0.6}N$ layer less and less cracked. The process of appearing of the cracks was connected with the relaxation of Si doped layer that was grown on sapphire. On the surface of the probe doped with the least amount of silicon only small holes occurred. They seemed to be the intersection of dislocations with the sample surface as shown by CANTU *et al.* [4] for probes of a smaller thickness and bigger amount of dopant. In the case of our layers the relaxation went on with the thickness, and finally caused cracking of layers.

4. Summary

We investigated the behavior of $Al_{0.4}Ga_{0.6}N$ layers during the growth either on GaN buffer layer or the *n*-type doping. Depositing the layer just on GaN layer made the grown layer crack. Inserting special LT AlN layer between both buffer layers stopped the relaxation and prevented grown $Al_{0.4}Ga_{0.6}N$ layer from cracking. We measured the dislocation density for both $Al_{0.4}Ga_{0.6}N$ grown just on GaN layer and on special AlN LT layer. The first probe was characterized by EPD being two orders of magnitude lower than that grown on special AlN LT layer. Doping of $Al_{0.4}Ga_{0.6}N$ layer also caused cracking of the layer. It started from very low amount of dopant causing holes and went on with increasing the dopant causing hexagonal cracks. The main reason of cracking seems to be the process of relaxation of the layer with its thickness. For the smaller amount of the dopant there appeared only intersection of dislocations with the sample surface (small holes), which finally led to cracking with increasing the amount of silicon.

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