Wafer Quality Target for Current-Collapse-Free GaN-HEMTs in High Voltage Applications

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Abstract

We investigated the relation between photoluminescence and current collapse of AlGaN/GaN HEMT wafers grown on silicon substrates. A very good correlation between yellow luminescence intensity and current collapse was found. By optimizing the growth condition to diminish the intensity of yellow luminescence, we obtained AlGaN/GaN HEMT wafers with very small current collapse. It is concluded that the yellow luminescence should be utilized as a very useful index for improving the wafer quality.

INTRODUCTION

Owing to the features of high breakdown voltage and high channel conductance, AlGaN/GaN high electron mobility transistors (HEMTs) have been receiving considerable attention as prospective candidate for future high power devices. Although a number of feasible results have been reported with AlGaN/GaN HEMTs, many issues still remain before introducing them into practical use [1-5]. Among these issues, poor crystal quality is the most critical drawback in this material system. AlGaN/GaN layers grown on heterogeneous substrates contain very high density defects due to large mismatch of lattice constants. It is strongly presumed that some of fatal phenomena such as large leakage current, deterioration in breakdown voltage and current collapse should be related to those defects [1-2]. When a high electric field is applied, capturing and/or emitting electrons at the defects result in those fatal phenomena in the worst situation. In order to solve these problems, therefore, two approaches have been taken; one is designing the device structure to relax the electric field, and the other is reducing the density of defects. For example, a properly designed field plate structure exhibited a remarkable effect to suppress the current collapse [3-5]. In this former approach, CAD tools have afforded precise calculation of the field and accelerated the design optimization. By contrast, improvement of the crystal quality according to the latter approach has not been prompted yet. It should be attributed to the fact that no proper index of crystal quality has been found for the guide to the degree of current collapse. Contrary to the case of electron devices, photoluminescence has been intensively used in the development of light emitting devices [6-7].

Figure 1 shows a typical photoluminescence spectrum of AlGaN/GaN HEMT wafer. An intense emission around 365nm is related to the band-to-band and/or band-to-shallow transition in GaN [8-10]. This band-edge luminescence (BE) reflects the intrinsic optical nature of the material. Apart from that, a broad band emission around 550nm is usually observed. This yellow-band luminescence (YL) is believed to be related to a radiative recombination via defects and/or impurities [11-18]. Although the origin of YL has been still argued, it is widely recognized that diminishing YL intensity is indispensable to obtain superior optical devices [6-7]. On the analogy of the experiences in optical devices, it can be expected to find some relation between photoluminescence quality and AlGaN/GaN HEMT performance.

With this assumption, we investigated the relation between YL and current collapse, and found a good correlation between them. We also confirmed a significant reduction of current collapse could be achieved by using yellow-to-band-edge intensity ratio as an index for optimization of the growth condition of AlGaN/GaN HEMT wafers.

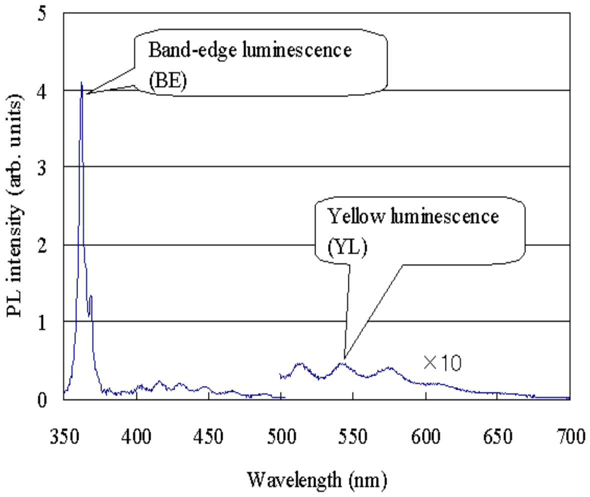

Fig.1 Typical PL spectrum from GaN-HEMT wafer

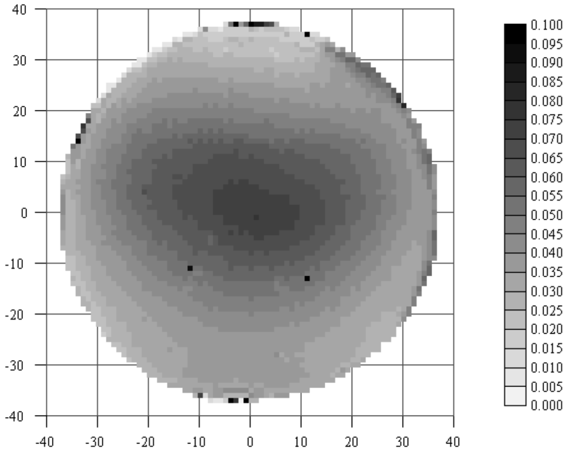

Fig.2 YL-to-BE peak intensity ratio (YL/BE) map (step size=1 x 1mm)

EXPERIMENTAL

MOCVD-grown AlGaN/GaN HEMT structures on (111)-plane silicon substrates with 3-inch diameter were employed through this work. Typical structure consists of a nominally 200nm-thick buffer, a 1.5μm-thick undoped GaN layer, and a 30nm-thick undoped $Al_{0.25}Ga_{0.75}N$ layer. The sheet resistance was about 500Ω.

Before the device fabrication, photoluminescence measurements were carried out with 325nm He-Cd laser as an excitation beam. As shown in Fig.1, all wafers exhibited BE and YL peaks in their PL spectra. The excitation probe was scanned over the whole wafer with 1mm-step pitch to produce maps of photoluminescence data. Figure 2 shows the map of the ratio of YL to BE peak intensities (noted as YL/BE hereafter) for the initial wafer. It should be noted that higher YL/BE values are observed at the center portion of the wafer.

Figure 3 depicts the schematic cross section of the fabricated device. The gate is Schottky structure. To achieve a high breakdown voltage, the source electrode is extended to cover the drift region between gate and drain. Devices with 2μm gate length, 8μm gate-drain spacing, and 20μm gate width were tested. The typical breakdown voltage, maximum drain current, and threshold voltage were about 370V, 550mA/mm and -6.3V, respectively.

In this study, the magnitude of current collapse was characterized with the change in on-resistance defined by following steps; (1) initial turn-on resistance is extracted from Ids-Vds curve under the condition of Vgs=0-V. Ron(ini) is defined by Vds/Ids at Vds=5V (see point-A in Fig.4); (2) applying an electric field stress with the conditions of Vgs=-8V and Vds=100V for 30sec (see point-B in Fig.4); (3)again low field on-resistance is measured under the same conditions as those of step-1. The change in charge state of traps during electric field stress results in increased on-resistance noted by Ron(col) (see point-C in Fig.4); (4)finally the ratio of Ron(col) to Ron(ini) is defined for the magnitude of current collapse.

Figure 5 shows the map of current collapse magnitude for the same wafer as used in Fig.2. Devices were measured with 4x4mm pitch. The magnitude of current collapse was larger in the center portion than that in outer portion for this wafer, which was very similar to the distribution of YL/BE shown in Fig.2. It should be noted that Ron(ini) was almost uniform over the entire wafer. Then the features of distribution shown in Fig.5 almost corresponded to the distributions of Ron(col) magnitude.

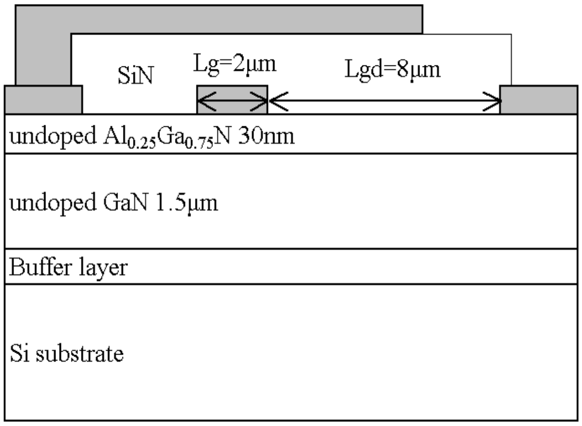

Fig.3 Cross-sectional structure of fabricated high voltage HEMT

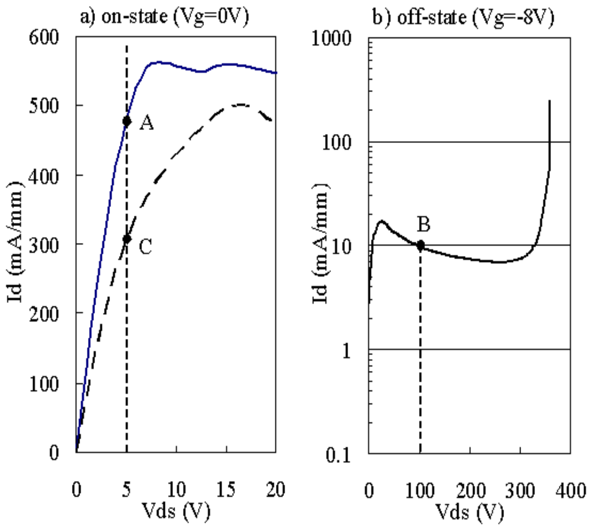

Fig.4 Procedure for derivation of on-resistance ratio:
(1) Ron(ini) measurement (point-A),
(2) applying Vd to 100-V under Vg=-8V for 30 seconds(point-B),
(3) Ron(col) measurement (point-C),
(4) calculating the ratio Ron(col)/Ron(ini).

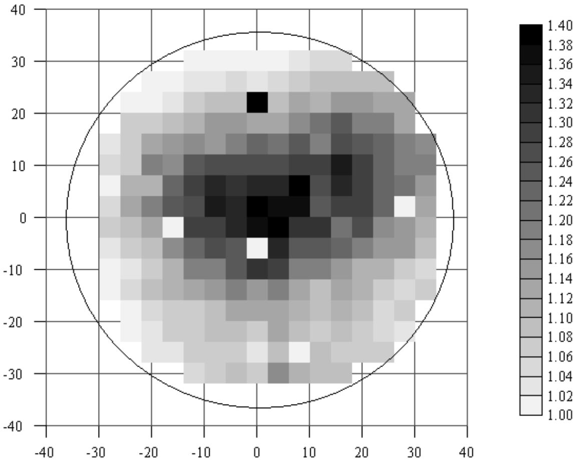

Fig.5 Map of current collapse magnitude in terms of on-resistance ratio (pitch size = 4 x 4mm)

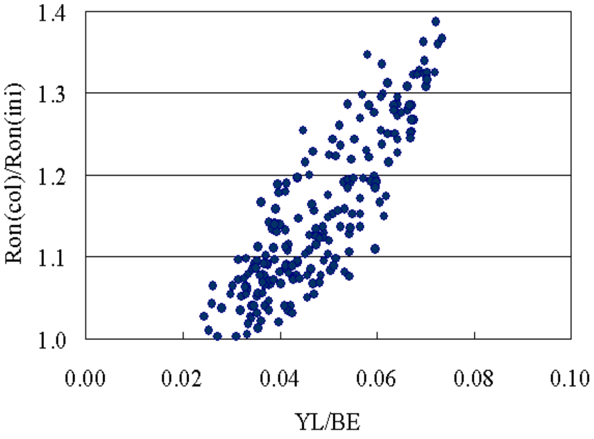

Fig.6 Correlation between YL-to-BE intensity ratio (YL/BE) and on-resistance ratio Ron(col)/Ron(ini)

RESULTS AND DISCUSSION

Figure 6 shows the magnitude of current collapse as a function of YL/BE. A strong correlation is confirmed. The magnitude of current collapse varies in proportion to YL/BE. This result means that diminishing YL intensity is indispensable to achieve collapse-free AlGaN/GaN HEMTs. As a guide line for the wafer quality, YL/BE could be used. For example, according to Fig.6, YL/BE should be controlled under 0.04 when the magnitude of current collapse is set to be less than 1.1, although it depends on other factors such as device structures, bias conditions and fabrication process.

At this stage, we have no knowledge whether the defects for YL and ones for current collapse correspond to each other. However, both are cross correlated to each other at least. Then YL/BE can be used a guide index to improve the crystal quality for lowering current collapse. Because diminishing YL intensity has been one of most important issues for optical devices, there has been accumulated a lot of relating knowledge. By using these guides, we prepared other wafers.

Figure 7 (a) and (b) show YL/BE maps of a conventional and an improved wafer, respectively. With optimization in growth conditions, the magnitude of YL/BE was reduced and the uniformity was also improved significantly. With these wafers, we fabricated AlGaN/GaN HEMTs similar to that in Fig.3 except for the gate structure; MIS structure replaced Schottky gate at this time. The magnitude of current collapse of these wafers was measured with the same condition as described in Fig.4, although the stress voltage was increased to 200V for this time.

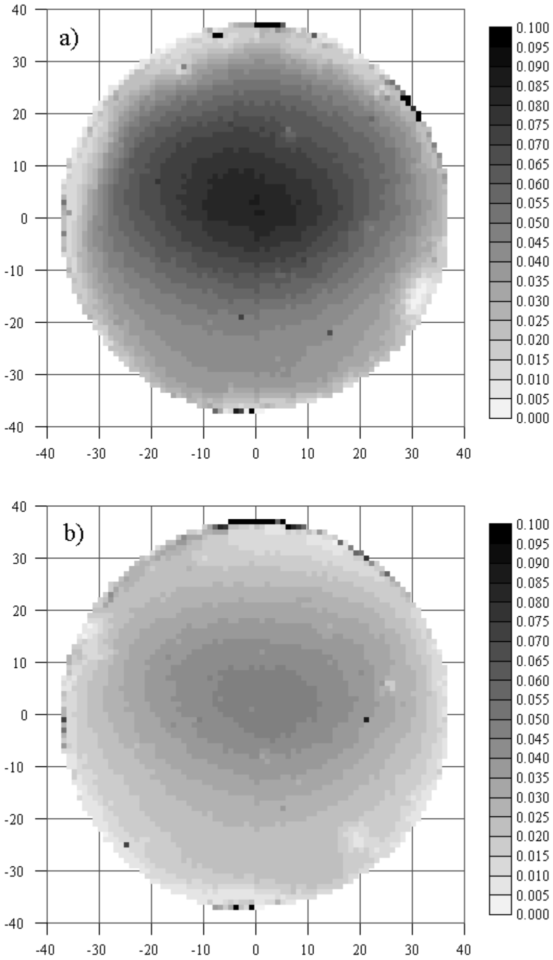

Fig.7 YL-to-BE intensity ratio (YL/BE) map for (a) conventional and (b) improved wafers

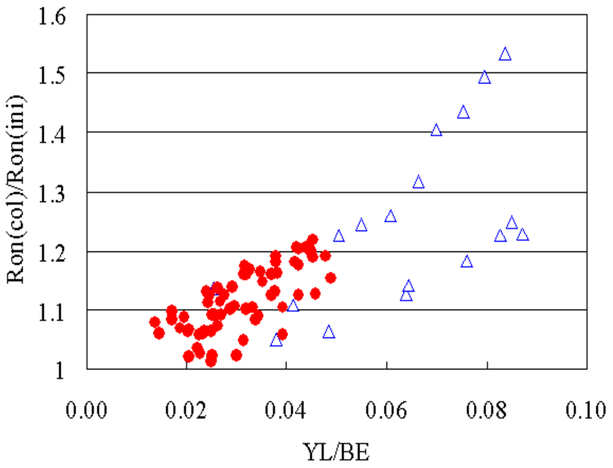

Fig.8 Correlation between YL-to-BE intensity ratio (YL/BE) and on-resistance ratio Ron(col)/Ron(ini) for conventional (triangles) and improved (circles) wafers

Figure 8 shows the results as a function of YL/BE, where open triangles and solid circles represent the results from the conventional wafer and the improved wafer, respectively. We can clearly recognize good correlations between current collapse magnitude and YL/BE for each wafer, and confirm that a significant improvement could be achieved by the optimization in growth conditions. While the magnitude of current collapse was scattered in the range form 1 to 1.6 before optimization, it was controlled less than 1.2 for the entire wafer after optimization. It should be noted that by introducing YL/BE as an index for crystal quality, the growth optimization could be carried out independently of device fabrication. This fact means the index accelerates the improvement process.

CONCLUSIONS

We found a very good correlation between yellow luminescence and current collapse in AlGaN/GaN HEMT wafers grown on silicon substrates by investigating their distributions over entire wafer in detail. It was revealed that the magnitude of current collapse is proportional to the intensity of yellow luminescence. This suggests that the defects causing yellow luminescence might be related to the current collapse.

We confirmed that the optimization of growth condition for diminished yellow luminescence also leads to superior wafer quality with small current collapse. As discussed above, yellow luminescence is a very useful index for improving wafer quality of AlGaN/GaN HEMTs.

It is expected that the target wafer quality for current-collapse-free GaN-HEMTs will be achieved in near future.

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ACRONYMS

HEMT: High Electron Mobility Transistors
CCD: Charge Coupled Device
MIS: Metal-Insulator-Semiconductor