Mater. Res. Soc. Symp. Proc. Vol. 1108 © 2009 Materials Research Society 1108-A02-04

Correlation among Material Quality, Performance and Reliability of High Power and High Frequency AlGaN/GaN HFET

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ABSTRACT

Performances of AlGaN/GaN HFETs have much improved recently and very high potential of this hetero- structure for high power and high frequency electronic devices has been verified. Application of new device technologies such as field plate, recessed gate, digital pre-distortion circuit and dual field plate was essential to realize such high device performances both at 2 GHz, 5GHz and 26 GHz. However, practical requirements on the quality and structure of these material systems for production of these devices are still not clear. Extensive studies on correlation among material quality, device performance and reliability were investigated under Japanese NEDO project. Firstly, this paper reviews recent progress of the performances of high power and high frequency AlGaN/GaN HFETs. Then, several interesting results which suggest practical requirements on material quality and structure will be discussed based on our extensive characterization studies in terms of device performances and reliabilities.

INTRODUCTION

With its high mobility, high saturation velocity, high breakdown electric field and good thermal conductivity, AlGaN/GaN heterostructure system attracted much attention as a promising material system for high power and high frequency transistors. In contrast with these high potential, actual performances of these devices five years ago were far below the level of those we expected. It was widely understood that the performances of these devices were limited by an undesirable effect of current collapse induced by electron trapping at the surface states of AlGaN. SiN passivation film on AlGaN top layer decreases this current collapse. However, breakdown voltage decreased and trade off relation between current collapse and breakdown voltage has become apparent. In this paper, several new device technologies applied in this study to solve this problem will be shown, together with recent progress in device and amplifier performances. Then, practical requirements on material quality and structure for production of high performance and good reliable devices will be discussed.

RECENT PROGRESS IN DEVICE PERFORMANCES

To improve trade off relation between current collapse and breakdown voltage, a recessed gate FET with a field modulating plate (FP) [1, 2] has been developed. Using this device structure, suppression of current collapse, high voltage operation and improved gain performance have been successfully achieved simultaneously. FP electrode is found to be very effective in suppressing current collapse [3, 4], whereas additional gate recess is effective to further minimize the residual current collapse as well as to increase breakdown voltage with reduced gate leakage current [1, 2, 5]. The gate-drain breakdown voltage defined at 1 mA/mm was improved from 160 V to 200 V after applying recessed structure to planar FP structure [4].

Corresponding to the adoption of FP gate structure [3, 4] and additional recessed gate FP structure [1, 2, 5], rapid progress has been made in total output power from a single chip HFET within a relatively short period of time.

Thus, serious problem related to a trade off relation between current collapse and breakdown characteristics has been much improved by applying FP structure. In this structure, however, gain is slightly reduced by the increase in gate-drain capacitance. Dual field-modulation plate structure with additional source-terminated FP has been developed to reduce gate-drain capacitance [6]. Owing to reduction in feedback capacitance, this device successfully provided simultaneous improvements in linear gain and output power.

RECENT PROGRESS IN POWER AMPLIFIERS

230 W output power from 48 mm-wide FP-FET was achieved at a drain-bias voltage of 53 V. Based on this recessed-gate FP structure FET, a high power GaN amplifier for CDMA base station was developed. This amplifier successfully delivered record high CW output power of 416 W [7]. Good linearity with IM3 less than 50 dBc at 63 W output power, which is good enough for practical use in CDMA base station, was also realized by using digital pre-distortion circuit [6].

Under pulsed operation, a single packaged amplifier delivered a saturated output power as high as 758 W at 2.14 GHz [8].

A C-band high-power amplifier with two GaN-based FET chips exhibited a CW output power of 208 W with 11.9 dB linear gain and 35 % power-added efficiency at 5.0 GHz [9].

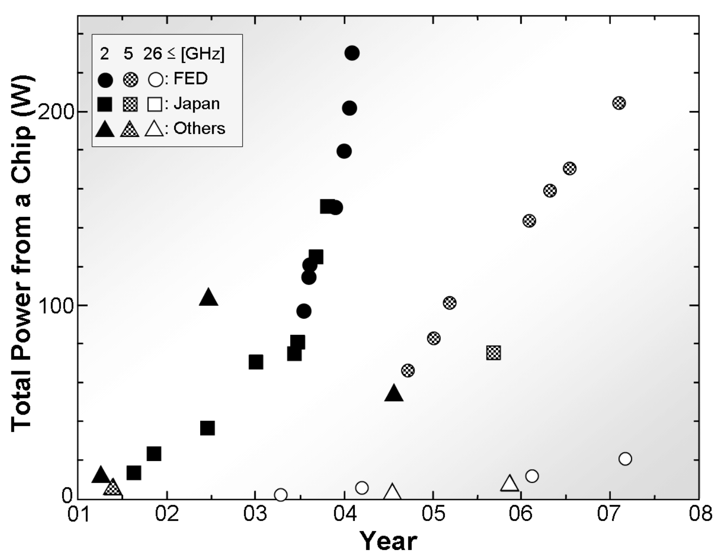

Figure 1. Recent annual progress of AlGaN/GaN HFETs.

A Ka-band high-power amplifier with a 0.2 μm-long, 6.3 mm-wide recessed gate FET exhibited a CW output power of 20.7 W, a linear gain of 5.4 dB and a power-added efficiency of 21.3 % at 26 GHz [10].

Recent rapid annual progresses of AlGaN/GaN HFETs in terms of total output power at 2 GHz, 5GHz and 26 GHz operations are shown in Fig. 1. Here, FED stands for R&D Association for Future Electron Devices, where NEDO's national project was carried out.

EXTENSIVE STUDIES ON CORRELATION AMONG MATERIAL QUALITY, DEVICE PERFORMANCE AND RELIABILITY

Various studies carried out on correlation among material quality, device performance and reliability of AlGaN/GaN HFETs were schematically shown in Fig. 2, which includes (1) effect of crystal defects in the substrates, (2) correlation between crystal defects and buffer leakage currents, (3) origin of gate leakage currents, (4) actual electric field in an operating device, (5) effects of AlGaN surface traps, (6) effects of AlN mole fraction and thickness of AlGaN and residual stress and (7) actual temperature distribution in an operating device. Here, actual electric fields in operating devices were measured by newly developed Kelvin force microscope in this NEDO's project. On the other hand, actual temperature distribution in operating devices was measured by micro-Raman observation system, again newly developed in this project.

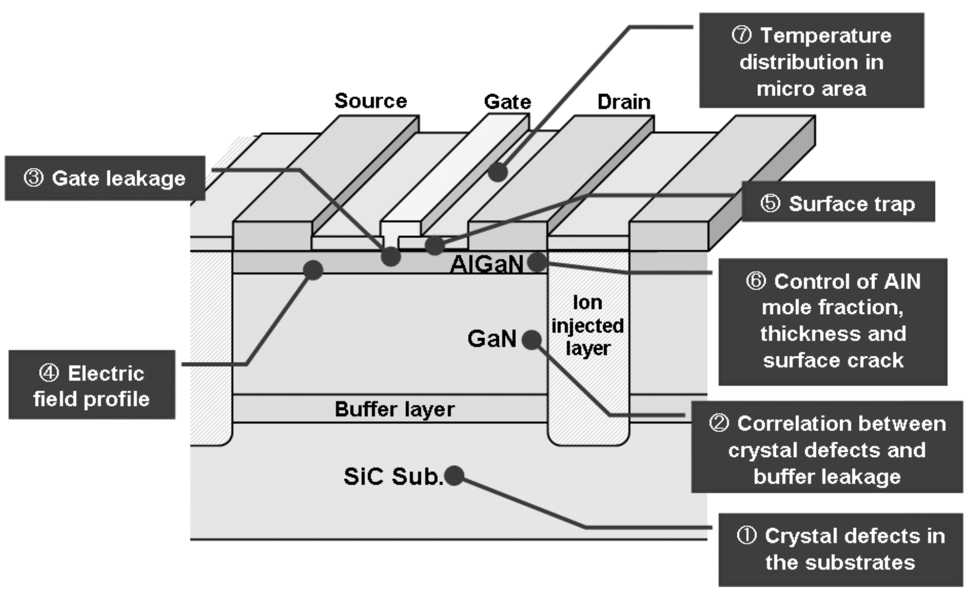

Figure 2. Various studies carried out on correlation among material quality, device performance and reliability.

PRACTICAL REQUIREMENTS ON THE QUALITY AND THE STRUCTURE OF HETEROSTRUCTURES

Buffer Leakage

Reduction of buffer leakage current and enabling high voltage supply between source and drain are essential part to realize high output power from the device. Ideally, better quality buffer layer with reduced amount of impurities, dislocations and point defects should be prepared for this purpose. For reproducible and cost effective production of these high power and high frequency devices, however, this approach is not always the most practical way.

Firstly, correlation between buffer leakage current and yellow luminescence intensity was investigated by using UV lamp as an excitation source. Results shown in Fig. 3 demonstrated good correlation with higher leakage current observed when point-defect-related yellow luminescence is stronger. This result suggests that high quality material with less yellow luminescence are required for FET application.

Then, buffer leakage characteristics have been carefully studied using hetero-structures with various thickness of buffer layers to find out how thick buffer layer should be to be improved to device quality material. On the contrary to our preoccupation, epi-structure with thinner i-GaN layer and poorer crystal quality with higher dislocations sometimes helps to suppress buffer leakage current and eventually helps to obtain higher source-drain breakdown voltage. Typical relation between buffer leakage current and applied voltage for various thickness of buffer layers are shown in Fig. 4. These measurements were carried out between the two ohmic contacts formed on single buffer layer structure. Actual FETs with 1.0 μm-gate length were fabricated using AlGaN/GaN hetero-structures with various GaN buffer layer thickness. Exactly the same relation between leakage current and buffer layer thickness as shown in Fig. 4 was obtained, confirming that epi-structure with thinner i-GaN layer with higher dislocations helps to suppress buffer leakage currents. Buffer leakage mechanisms in the i-GaN are carefully analyzed. It was found that these buffer-leakage current can be explained by space-charge limited currents with high density of electron traps [11].

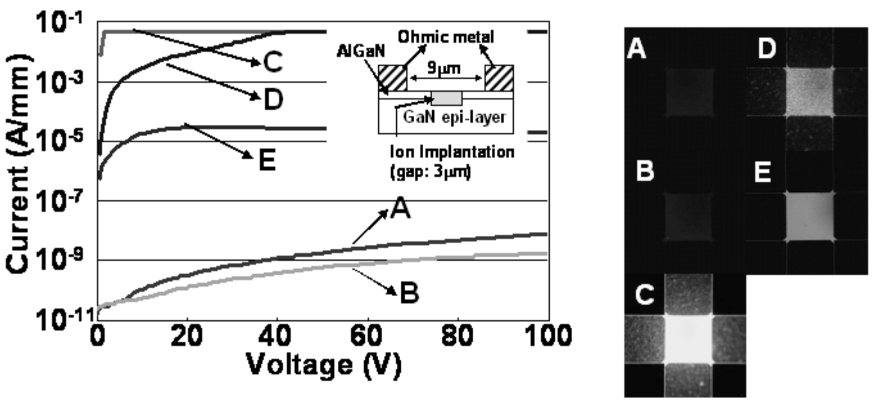

Figure 3. Correlation between buffer leakage current and yellow luminescence intensity of i-GaN in AlGaN/GaN HFET structure.

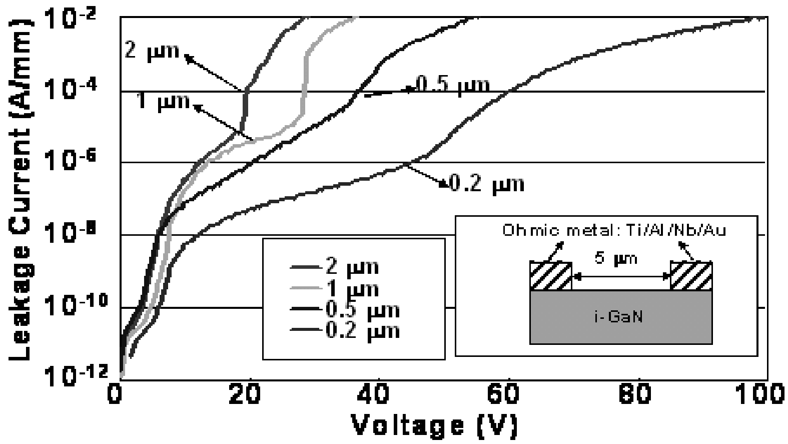

Figure 4. Correlation between buffer leakage current and applied voltage for various thickness of buffer layers.

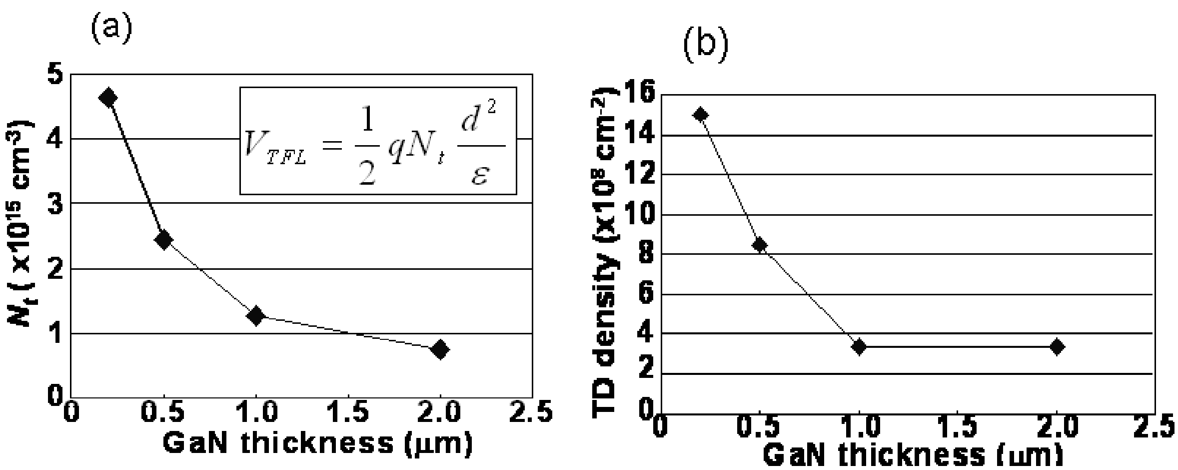

Figure 5. GaN thickness dependence on (a) trap density and (b) threading dislocation density.

Traps-filled-limit voltage, where leakage current sharply increases, can be presented by the equation

$$V_{TFL} = \frac{1}{2} q N_t \frac{d^2}{\varepsilon} \quad . [11] \qquad (1)$$

Here, Nt is the density of traps in i-GaN.

Trap densities estimated from this equation using observed breakdown voltage in Fig. 4 is found to agree reasonably with threading dislocation density in i-GaN, determined by TEM measurements as shown in Fig. 5. [12] Accordingly, unexpected result with higher breakdown voltage with thinner buffer layers can be well explained reasonably by assuming threading dislocations in the buffer layers as dominant electron traps to achieve high resistivity of buffer layers.

Impurity doping with such impurities as C, Fe and Mg, to buffer layer is another approach to obtain reproducible high breakdown buffer layers. Correlation between defects in buffer layer and reliability and/or stability of device performances should be further studied before drawing conclusions on real applicability of thin undoped buffer layer for real production of the devices.

Gate Leakage

AlGaN/GaN hetero-structure on thinner buffer layer contains higher density of dislocations and the adverse effect of these defects on gate leakage currents should become a big concern. Dislocation density in these AlGaN layers are generally higher than 10^8 /cm^2. Schottky contacts with less than 1 μm diameter should be used to study the effect of these dislocations on gate leakage. Here, Ni/Au Schottky contacts with 0.6-1.0 μm diameter were fabricated and gate leakage current was measured using conductive AFM. Typical results of I-V characteristics are shown in Fig. 6. After removal of Schottky electrodes, screw-type and edge-type dislocations were identified by appearance of dislocation pits, as shown in Fig. 7. It was found that edge-type dislocations increase gate leakage current by 5-6 times, whereas screw-type dislocations increase gate leakage current by over 500 times, as compared with Schottky contacts without dislocations.

Thus, it may be concluded that gate leakage current is dominated by screw-type dislocations. It is well known that screw-type dislocation density dose not decrease rapidly as the increase in thickness of epi-layers. This experimental result offers another reason on the availability of hetero-structure with thinner buffer layers for device production.

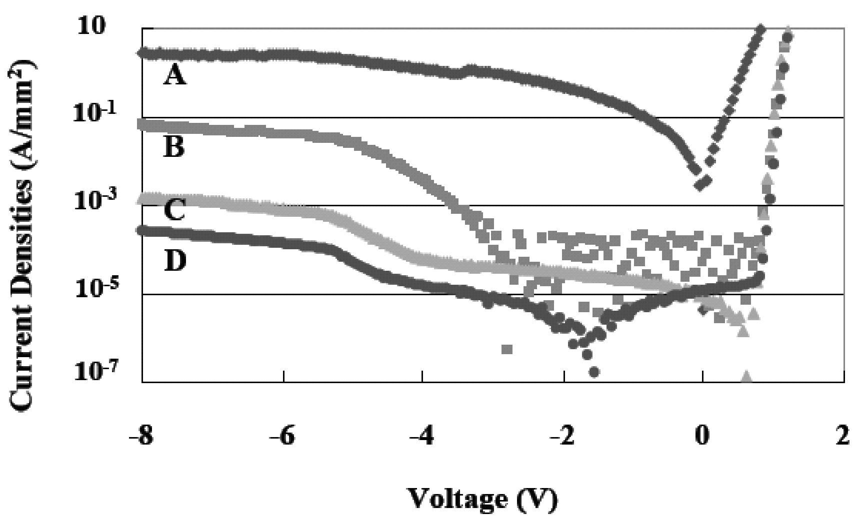

Figure 6. Gate leakage current at micro-scale.

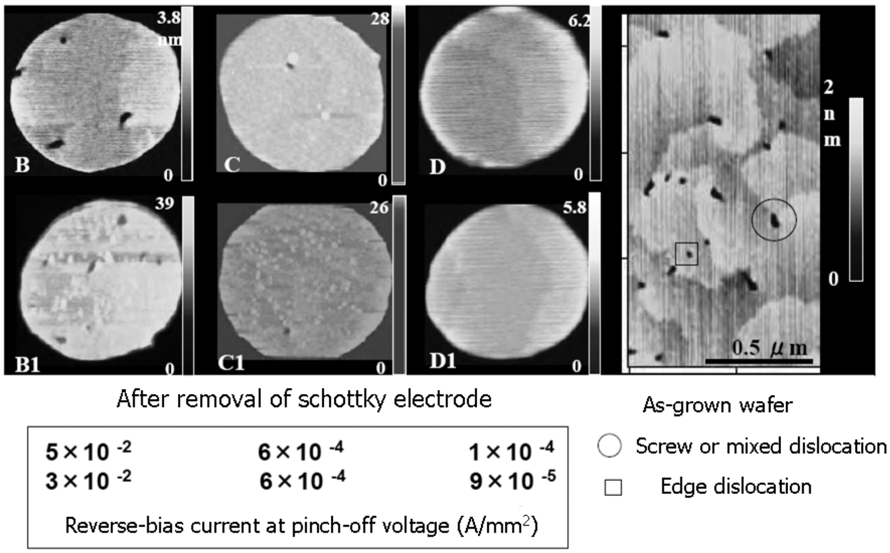

Figure 7. Correlation between gate leakage currents and dislocations.

Alloy Composition in AlGaN

For better performances and reliability of devices, AlN molar fraction, thickness and residual strain of AlGaN are other big concerns. It was found that sheet resistance of 2D electron gas increases sharply as AlN molar fraction in AlGaN increases over the critical value of around 0.3, as shown in Fig. 8, even though the thickness is well below the critical thickness to generate dislocations. It was further found that resistivity of 2D electron gas gradually increases with time as shown in Fig. 9a, when AlN molar fraction in AlGaN comes closer to this critical value of 0.3. This resistivity increase is mainly caused by reduction of mobility rather than sheet carrier concentration, as shown in Fig. 9b and 9c. It was further found that micro-surface-cracks snowballs or develops in the accelerated manor as time passes.

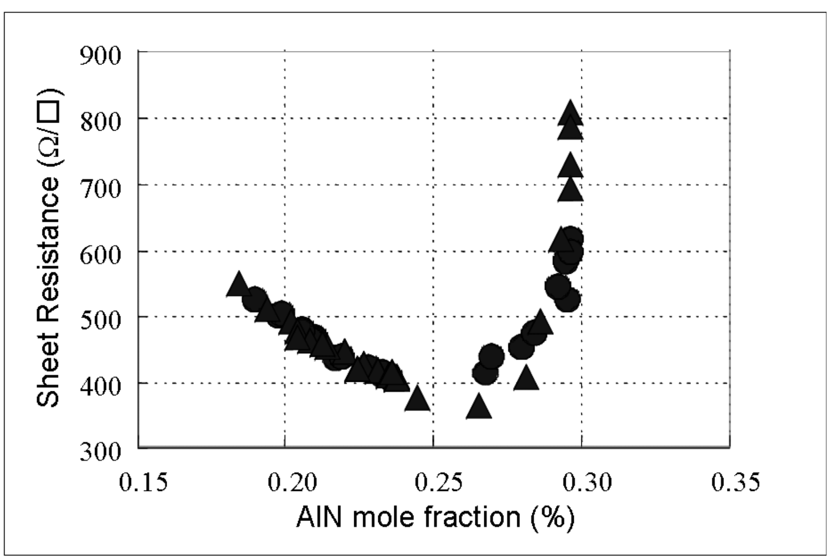

Figure 8. Correlation between AlN mole fraction and AlGaN/GaN hetero-structure sheet resistance.

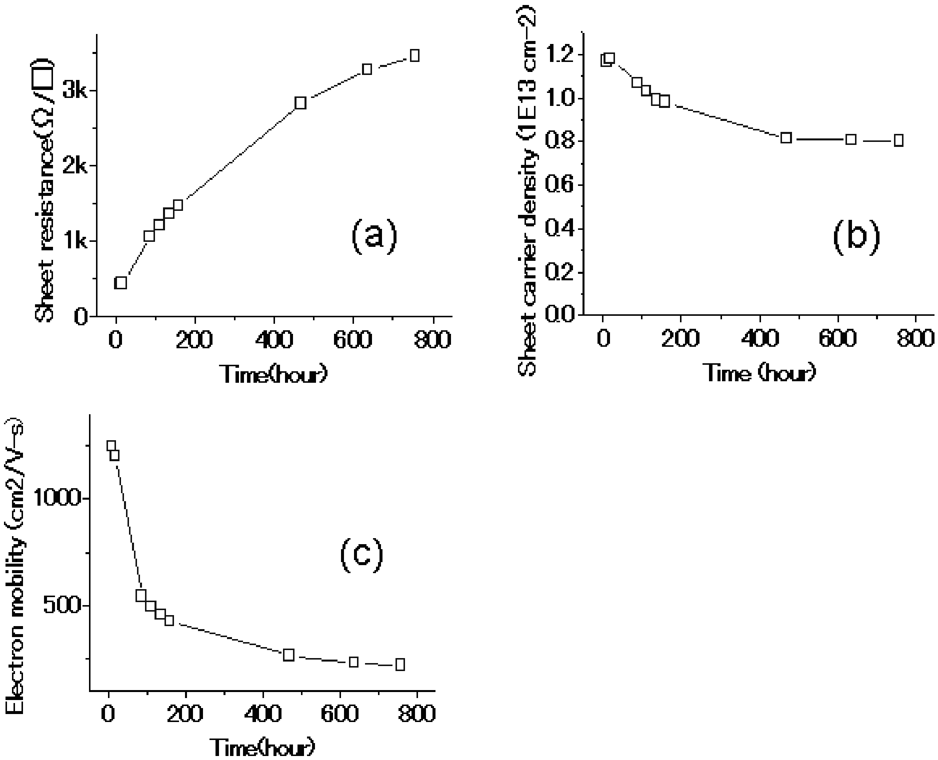

Figure 9. Long-term Stabilities of (a) sheet resistance, (b) sheet carrier density and (c) electron mobility on AlGaN/GaN HFET Structure.

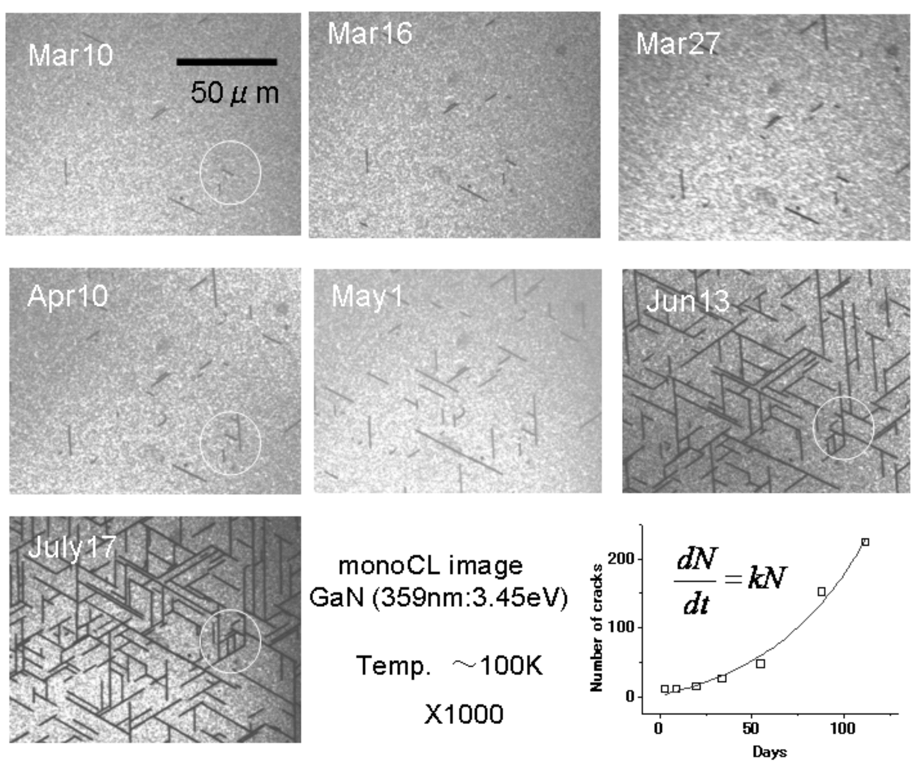

Figure 10. Long-term observation on development of surface cracks.

Figure 10 shows how micro-surface-cracks developed in 4 month interval, which was observed by CL measurements. These remarkable changes in sheet resistance occur only in air and it was not observed in dry nitrogen gas. [13]

SIMS depth analysis shown in Fig. 11, indicated that this degradation involves oxidation process and this phenomenon can not be explained by simple mechanical process to relief built-in strain.

Thus, optimization of AlN molar fraction in AlGaN is another essential condition to produce high performance and good reliability AlGaN/GaN HFETs.

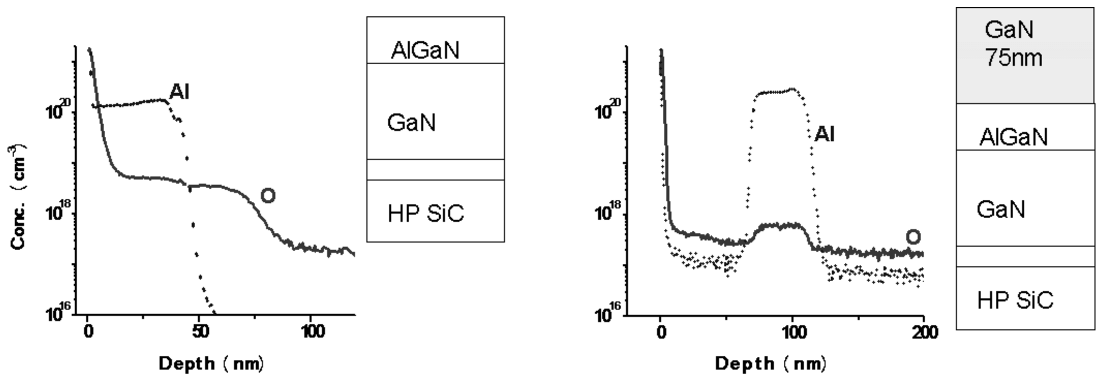

Figure 11. SIMS depth analysis in two different AlGaN/GaN HFET structures after aging.

CONCLUSIONS

Recent remarkable progresses in device performances have verified very high potential of AlGaN/GaN hetero-structure for high power and high frequency electronic devices.
Practical requirements on the quality and structure of these material systems for production of these devices were discussed. The availability of hetero-structure with thin undoped buffer layer was demonstrated. It was also demonstrated that optimization of AlN molar fraction in AlGaN alloy is essential to produce devices with good performances and reliability.

ACKNOWLEDGMENTS

The author would like to acknowledge Dr.s H. Shimawaki, H. Okumura, H. Miyamoto, A. Suzuki and K. Hirata, and all the other colleagues at advanced HF device R&D center at FED for their technical contributions and discussion. This work was carried out under high-power, high-frequency GaN device project of NEDO.

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