Light response in buffer leakages and its application for epi quality development in AlGaN/GaN HEMT structures

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Abstract

Unique light responses in GaN based buffer structures were observed and mechanism of low photon energy light induced collapse will be proposed. Both doped carbon and iron worked as compensation in the layers to realize high resistance buffer; however, only carbon doped layer showed existence of long time constant trap from the light response experiments. Understanding and controlling of intrinsic behavior of these dopants seemed to be the key elements in epi structure design.

INTRODUCTION

Because of its excellent high power handling capability and power consumption efficiency at high frequency, GaN HEMT based RF devices have successfully been utilized in wireless communication infrastructure market in recent years. Deployment of GaN devices in homeland security segments has also been realized and its presence in the fields is becoming important than ever. Establishing stable material preparation is one of the crucial elements in industrializing this technology, and thus making continuous effort and development is indispensable for commercial GaN epitaxial wafer suppliers. Hitachi Cable, Ltd. has focused on achieving high level of quality control and market oriented reproducibility, in which both performance and uniformity were improved for high production yields. Figure 1 shows an example of sheet resistance map of Hitachi Cable AlGaN/AlN/GaN HEMT epitaxial wafer on 3inch SiC substrate. By optimizing process condition and equipment maintenance sequence, sheet resistance uniformity of less than 0.20% has been achieved. In figure 2, the trend of average sheet resistance in one of our GaN HEMTs on SI-SiC legacy epiwafer products was plotted. Over 1000 data points have been taken and it turned out that 97% of sheet resistance was within +/-5%. These uniformity and repeatability are beneficial not only for device production control but also for series of accurate research and development.

Another Hitachi Cable's great asset in GaN activity is its focus on the development in characterization method and its

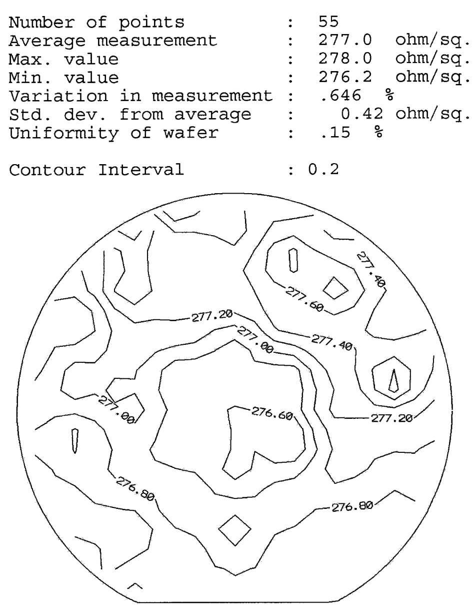

FIGURE 1. Sheet resistance map of AlGaN/AlN/GaN HEMT epitaxial wafer on 3inch semi-insulating SiC.

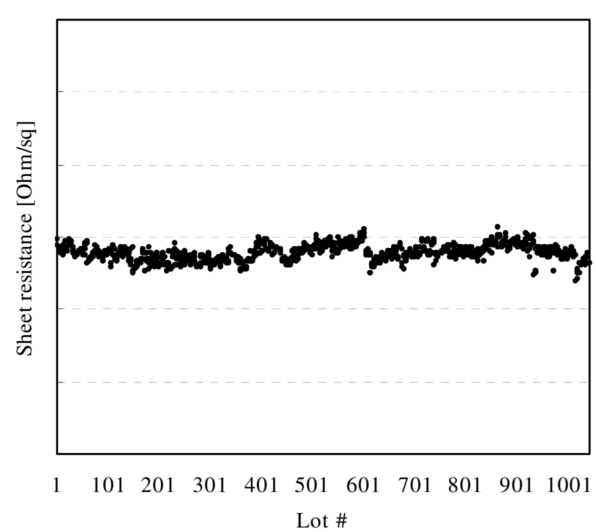

FIGURE 2. Plot of typical average sheet resistance trend in Hitachi Cable's AlGaN/ GaN HEMT epitaxial wafers on 3inch semi-insulating SiCs.

application for material improvement. As tradeoffs between current collapse and buffer leakage are severe challenge in designing AlGaN/GaN HEMT epitaxy, characterization and swift device performance feedback are essential for buffer structure optimization. This buffer performance improvement had to be planned from the view point of device operation for multiple applications. For this purpose, establishing effective characterization method was prioritized. We successfully found a unique light response of buffer leakage in GaN in which irradiation of low energy light to the samples switched the devices into collapsed states [1]. Analysis of this light response gave us a thorough insight into the buffer quality for HEMT devices without expending cost and time for device fabrications or introducing expensive special equipments. In this work, we will provide background model of this light response and then present how our epi material was developed using this characterization method.

EXPERIMENTAL

High resistive nitride buffer structures were grown on substrates by MOVPE. An un-doped layer, Fe-doped layers, and Carbon-doped layers were prepared with deferent doping concentrations. In order to eliminate isolation process, AlGaN/AlN barrier layers were not formed and buffer quality was purely compared. Ti/Al metallization was formed directory on the buffer surfaces as source/drain contacts, and surface passivation and contact annealing were also skipped to simplify the process. This device fabrication process took less than 3 hours. The device was tested for I-V characteristics under a dark environment and then commercially available LEDs were used for light source to observe the change in response. The LEDs had 1.95[eV] (red) to 3.24[eV] (ultra violet) photon energy. They were illuminated onto the device surfaces and I-V measurements were repeated. The device was exposed to fluorescent light after each I-V measurement, hence the effect of current collapse by the measurement was eliminated.

In this experiment, current degradation was observed when the device was exposed under LED light with lower photon energy (1.95-2.37[eV]). It is counterintuitive that the current decreases under light irradiation, but this could be explained by assuming a mechanism in which electrons excited by low energy light occupy the traps. In this phenomenon, the low energy light excites valence band electrons and the excited electrons coactively occupy the electron traps in the buffer layers, and then the traps are negatively charged to prevent current flow. One of the features of the phenomenon is that traps with relatively long time constant shall be occupied forcibly and instantly, assisted by the low photon energy light. Based on these understandings, the magnitude of the light response to the buffer leakage was connected with the buffer quality. The effect of compensation doping in high resistive layers was also evaluated.

RESULTS AND DISCUSSION

Leak current in un-doped buffer layer is shown in figure 3(a). Dark leakage at over VDS=20[V] became larger than 1E-6[A/mm], indicating inferior pinch-off and isolation performances in the device. The existence of free carriers generated from background impurities and nitrogen vacancies are said to be the possible cause of deterioration in resistance of un-doped GaN layers. In order to compensate for these native free carriers, carbon or iron is normally used as dopant to form deep level sites and achieve high resistance in the buffer structures. Figures 3(b) and 3(c) show I-V characteristics of carbon doped structure with different carbon density, in which dark currents in both are controlled to less than 1E-6[A/mm]. In these layers, degradation of current under low photon energy light illumination was significant. Compared with dark current, approximately two orders of reduction in current were observed in devices under green light exposure. The magnitude of the light response was comprehended as the existence of high density electron traps with long time constant that could cause current collapse in device structures. Figures 3(d) and 3(e) show I-V curves of iron doped structures, in which completely different light responses were observed. In iron doped structures, dark currents were controlled to less than 1E-6[A/mm] as well, thought current reduction under low photon energy light illumination was much smaller than those observed in the carbon structures. The small light responses indicated smaller density of defects with long time constant, which could prevent signal transient in device operations.

Figure 4 shows the buffer current as a function of the photon energy of the LED light exposed on the device surfaces. It was understood that un-doped and iron doped samples showed similar behaviors against the photon energy whereas current in carbon doped samples had steep light response. Especially, the currents in carbon doped samples exhibited energy discontinuity between 2.67[eV] and 2.88[eV], indicating existence of high density trapping levels in this range. On the other hand, iron doping had effectively compensated for the free carriers in the buffer without creating extra traps of long time constant. These light response trends suggested that both carbon doped and iron doped structures showed sufficiently high resistance, thought its mechanism on free carrier compensation is completely deferent. Iron doped structure exhibited small density of long time constant traps, thus iron doping shall be useful for pinch-off improvement in signal modulation devices in which time divided signal switching is crucial. Carbon doped structure has advantages in achieving higher level of isolation performances in operation thus it should be

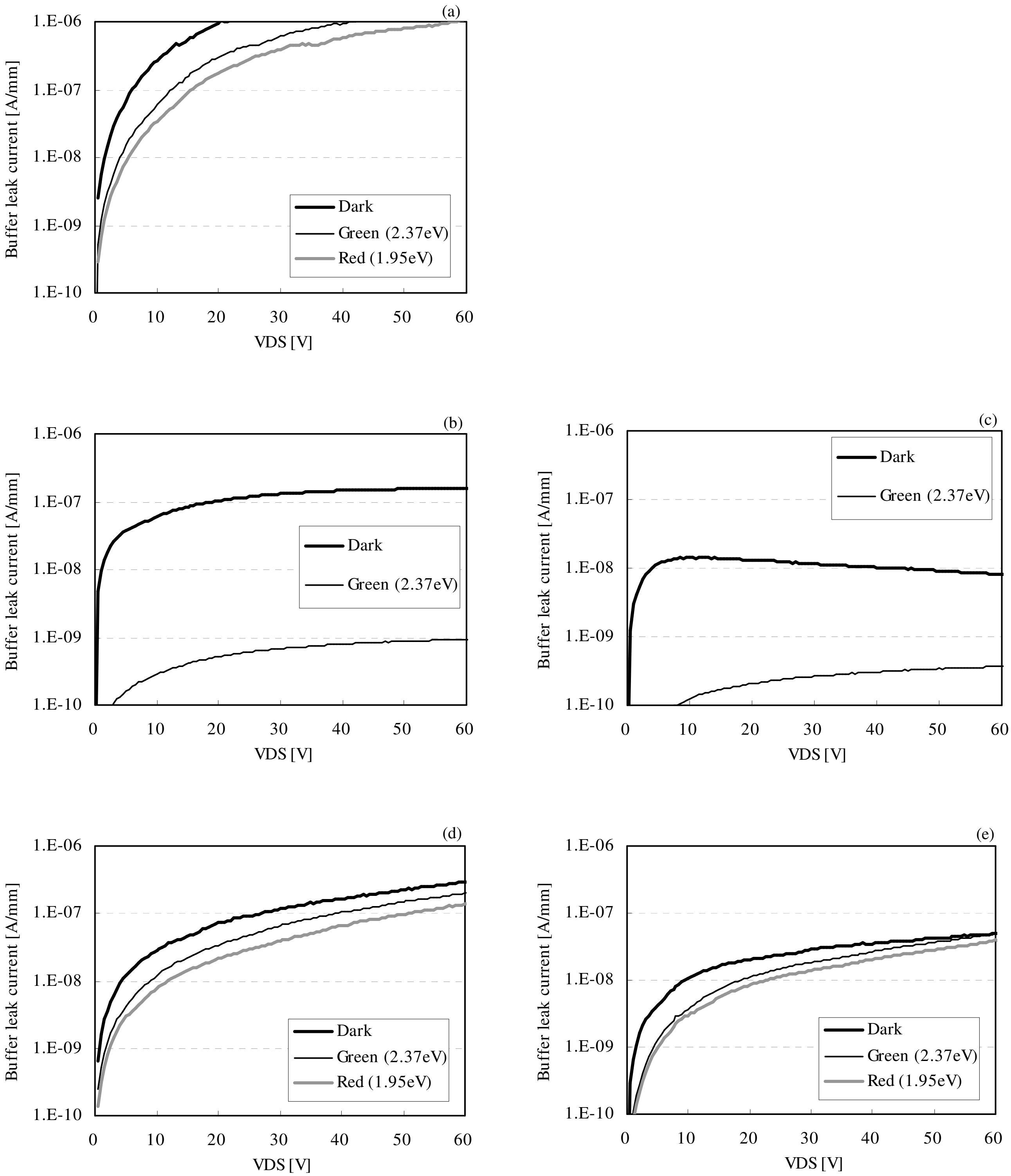

FIGURE 3. Leak current in GaN based buffer layers in dark environment and under low photon energy LED light exposure; (a)un-doped structure, (b) lightly carbon doped structure, (c) heavily carbon doped structure, (d) lightly iron doped structure, and (e) heavily iron doped structure.

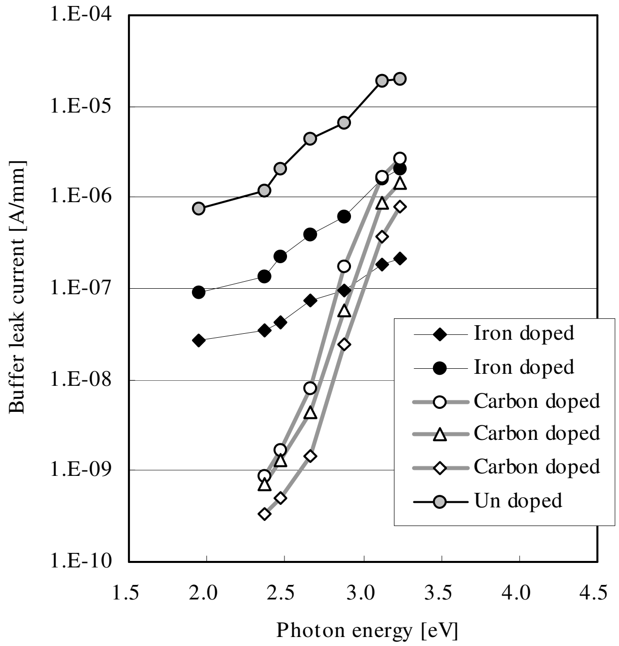

FIGURE 4. Leak current at VDS=48 [V] in GaN based buffer layers as a function of photon energy of the LED light illuminated on the surfaces of the devices during I-V measurements.

applicable in high power and high efficiency pulse amplifiers. Understanding these differences in high resistance characteristics and appropriate buffer epi structure design for individual applications are obviously important in achieving the right performance balance of the GaN based electron devices. And optimization using feedback from simple and agile characterization method is crucial in the development.

CONCLUSIONS

In summery, high uniformity and mass production capability of Hitachi Cable's GaN materials were demonstrated. Unique light responses in high resistance buffer structures were observed and mechanism of low photon energy light induced collapse was explained. Carbon and iron were employed to compensate for free carriers in the layers. The formation of different trapping levels was predicted from its correlation between current degradation and photon energy exposed for I-V measurement. Understanding and controlling of intrinsic behavior of these dopants were key elements in epi structure design.

REFERENCES

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ACRONYMS

GaN: Gallium Nitride
HEMT: High Electron Mobility Transistor
MOVPE: Metal Organic Vapor Phase Epitaxy