Evaluation of dislocations under the electrodes of GaN pn diodes by X-ray topography

Masakazu Kanechika, Satoshi Yamaguchi, Masayuki Imanishi, and Yusuke Morii

1Toyota Central R&D Labs., Inc., Aichi 480-1192 Japan
2Osaka University, Suita, Osaka 565-0871, Japan

E-mail: e1005@mosk.tytlabs.co.jp

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We have successfully obtained the clear images of the dislocation mapping even under the electrodes of the GaN vertical pn diodes by reflection X-ray topography using monochromatic synchrotron radiation (SPring-8, BL16B2 & BL20B2). This is a powerful analysis because of the non-destructive and rapid tool unlike the etch-pit method and TEM (transmission electron microscopy). This allows us to directly study the relationship between the dislocation and the leakage current. Applying this method to vertical pn diodes on Na-flux GaN substrates, we found that leakage current per dislocation is of the order of 10 pA. This analysis has a potential to reveal the killer dislocation structure.

1. Introduction

Gallium nitride (GaN) is a promising candidate for semiconductors for power devices, due to its excellent material properties, such as high critical electric field strength, high electron mobility, compared to Si and silicon carbide (SiC). Lateral AlGaN/GaN devices using on-Si technology were mainly developed. Recently, vertical devices using GaN freestanding substrates have been extensively developed.1–11 They will be applicable to high-power switching devices for automobiles and so on. However, there remain lots of threading dislocations and other crystal defects in most commercial GaN substrates. They have a density of dislocations as high as 10^6 cm^-2. Some dislocations are supposed to generate leakage current, since they are almost parallel to the strong electrical field in the vertical devices, unlike lateral ones. This has been controversial, and there are lots of works on the relationship of the dislocation and the leakage current.12–16

There are several analyses to evaluate the dislocations, as shown in Table I. The etch-pit method by KOH etc is a simple way, and has been employed extensively. This allows us to find the dislocation mapping and to speculate the dislocation structure by the pit shape,16–18 but it is a destructive method. It is well known that some stacking faults are generated during operation in the SiC power devices.19 In the GaN devices, an inverse–piezoelectric effect20,21 was reported, and leads to the generation of some pits during high electric field condition.21 Thus, it is significant to monitor the dislocations and some crystal defects non-destructively. Although cathode luminescence (CL) is a non-destructive tool,22 it is not easy to obtain the information on the dislocation structure and the dislocation mapping of a whole sample. Recently, multi-photon spectroscopy23 has been developed. Although it is a promising method to reveal a three-dimensional image non-destructively, its turn around time (TAT) is very long. A TEM (transmission electron microscopy) has been employed traditionally.24 It makes the structure of the dislocation clear, however the sample preparation is very complicated and it is tough to obtain the dislocation information on a whole sample or large area.

In this work, we propose a novel method using X-ray topography. This analysis using monochromatic synchrotron radiation X-ray allows us to achieve the detail and clear dislocation mapping even under the electrodes rapidly and non-destructively. In addition, we can obtain the dislocation mapping of the whole wafer, and directly study the relationship between the dislocation and the leakage current. Since this is a non-destructive analysis, it has a potential that we could study the dynamics of the dislocations during the operation.

2. Experiments

Figure 1 shows the schematic cross-section of the vertical GaN pn diode. These were fabricated on three kinds of GaN substrates: an Na-flux substrate,25,26 an ammonothermal substrate,27,28 and a conventional HVPE (hydride vapor phase epitaxy) substrate. The epitaxial layers on these substrates were grown by MOCVD (metal organic chemical vapor deposition). The layer consists of p⁺(0.1 μm, Mg: 8 × 10¹⁹ cm⁻³)/p(0.5 μm, Mg: 5 × 10¹⁷ cm⁻³)/n (10 μm, Si: 2 × 10¹⁶ cm⁻³)/p⁺(0.2 μm, Mg: 2 × 10¹⁵ cm⁻³). After Mg activation annealing at 800 °C, for 5 min in N₂, the mesa isolation was formed by inductively coupled plasma (ICP) using the main gas of Cl₂. Next, p-type ohmic anode electrodes Ni(10 nm)/Au(200 nm) were formed. For the pn diodes on the ammonothermal substrate, the anode electrodes Ni(10 nm)/Au(50 nm) were formed to examine the effect of the electrode thickness on clearness of the topography images. The sinter at 530 °C for 5 min in O₂ was performed. Finally, the backside surface cathode electrodes Ti(20 nm)/Al(200 nm)/Ni(40 nm) were formed.

The reflection X-ray topography measurement system is schematically shown in Fig. 2. This was performed by using monochromatic synchrotron radiation X-ray (SPring-8, BL16B2 (proposal number: 2017B5370, 2018A5370), BL20B2 (proposal number 2018B1023)). The incident X-ray energy was 9.16 keV, the incident angle was as shallow as 3°, 2θB was 84.6° and the diffraction crystal plane was (11–24). Actually, the incident angle was adjusted with a goniometer controlled by a stepping motor where one pulse is 0.00005°. This measurement area is roughly 4 μm deep below the
surface. This was estimated by taking the absorption of X-ray to the GaN crystal into consideration. Since topography generally detects the distortion in the few-hundred-μm zone around a dislocation, the gained image would include the information on the deeper zone. In order to obtain the high-resolution images, we employed films for X-ray for industry use. This topography image would be uniformly black for perfect crystal. However, some lattice distortion induced by the dislocation leads to a white spot in the image. This means that Bragg’s equation is not satisfied for the area around the dislocation. In our measurement system, the smaller and larger ones are supposed to correspond to edge and mixed dislocations (including pure screw dislocations), respectively. In this work, we applied this interpretation of the relation between the spot size and the dislocation structure in the topography image about SiC to GaN, since the GaN crystal is hexagonal like the SiC crystal.

### Results and discussion

#### 3.1. Topography

Figure 3 shows the reflection X-ray topography image of the pn diodes on the Na-flux GaN substrate. It was found that we obtain the detail and clear dislocation mapping even under the electrodes, like outside the electrodes. As shown in Fig. 3, there are at least 8 and 22 white spots under the electrodes of diode:C and diode:D, respectively. The densities of the dislocation of diode:C and diode:D are calculated to be $1.0 \times 10^4$ cm$^{-2}$ and $1.5 \times 10^4$ cm$^{-2}$, respectively. These values are compared to the previous reported ones. In this work, we applied this interpretation of the relation between the spot size and the dislocation structure in the topography image about SiC to GaN, since the GaN crystal is hexagonal like the SiC crystal.
dislocation is calculated to be $1.1 \times 10^5 \text{cm}^{-2}$, which is comparable to the reported value.\textsuperscript{28} From Fig. 3 and Fig. 4, we found that larger spots in the ammonothermal substrate are more than ones in the Na-flux substrate. This implies that the mixed or pure dislocations in this ammonothermal substrate are more than those in the Na-flux substrate. For the Na-flux substrate, the image in the electrode is relative bright, compared to the ammonothermal substrate. This reflects the thickness of the electrode. We will improve the clearness of the topography image by adjusting the thickness of the electrode as well as the X-ray evaporation time.

3.2. PN diodes characteristics

Figure 5 shows the current-voltage characteristics of the diode: C and D on the Na-flux substrate. It is seen that the leakage current is as low as 10 pA at the reverse bias 800 V and that the breakdown voltage was 1180 V, which is about 78\% without the electric field concentration in the mesa termination. Compared with the topography image, it was explicitly shown that even though the diode has some dislocations under the electrode, they never generate the fatal leakage current. The leakage current per dislocation would be of the order of 10 pA on average.

Figure 6 shows the current-voltage characteristics of the diode C on the ammonothermal substrate. The leakage current is about 300 nA at the reverse bias 800 V. Figure 7 shows the current-voltage characteristics of the diode with the same size as diode: C on the HVPE substrate. The leakage current is 1 nA at 800 V. The leakage currents of these two substrates are larger than that in the Na-flux substrate. They include some defects which induce the leakage current, such as surface morphology aberration and the bundle of dislocations which would induce the fatal leakage current.

An emission microscope is extensively used to pinpoint failure locations by detecting the weak light emission or heat emission caused by the leakage current. Using this with the proposed topography method, we could study the relationship between the leakage current and the dislocation structure. It is easy to increase the samples. Since it is non-destructive, we could survey the dislocation dynamism. Hereafter, we could resolve the killer dislocation which causes the sever leakage current.

4. Conclusions

We successfully obtained the detail and clear dislocation mapping even under the electrodes rapidly and non-destructively using reflection X-ray topography with monochromatic synchrotron radiation. We applied this method to the pn diodes on the Na-flux and the ammonothermal GaN substrates. It was explicitly shown that the isolated dislocation never causes a severe leakage current. This would allow us to effectively study the relationship between the leakage current and the dislocation dynamic behavior and to find the killer-defect.

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**Fig. 4.** (Color online) Reflection X-ray topography image of the pn diode on the ammonothermal GaN substrate. A circle shows the dislocation.

**Fig. 5.** (Color online) Current and voltage characteristics of the pn diode on the Na-flux substrate shown in the Fig. 3. Diode:D (a) Reverse region. (b) Forward region. Diode:C (c) Reverse region. (d) Forward region.
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Fig. 6. (Color online) Current and voltage characteristics of the pn diode on the ammonothermal substrate shown in the Fig. 4. (a) Reverse region. (b) Forward region.

Fig. 7. (Color online) Current and voltage characteristics of the pn diode on the HVPE GaN substrate. (a) Reverse region. (b) Forward region.