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Performance Improvement of GaN-based MSM Photodiodes Grown on Si(111) Substrate by Thermal Cycle Annealing Process

Jyun-Hao Lin[a], Shyh-Jer Huang[a], Yan-Kuin Su[a,b]* and Chao-Hsin Lai[a]

a Institute of Microelectronics, Department of Electrical Engineering, and Advanced Optoelectronic Technology Center, National Cheng Kung University, Tainan 701, Taiwan.
b Department of Electrical Engineering, Kun Shan University of Technology, Yung-Kang, Tainan 710, Taiwan.
* Corresponding author E-mail address: yksu@mail.ncku.edu.tw
Phone: +886-6-2757575-62382

Abstract

A simple thermal cycle annealing (TCA) process was used to improve the quality of GaN grown on Si substrate. The XRD results revealed that using more process cycles, the defect density can be further reduced. And the performance of GaN-based MSM photodiodes prepared on Si substrate also have the same tendency. With two cycles TCA process, it is found that the dark current of the device was only 1.46×10^{-11} A, and the photo to dark current contrast ratios were about 1.33×10^{5} at 5V.

1. Introduction

Nowadays, III-Nitride devices market is focusing on the technique of growing GaN on Si substrate because employing Si substrates can give a short-cut to combine GaN based optoelectronics and Si integrated circuit. Besides, compared with the commercial substrates (sapphire or silicon carbide) for Nitride-based devices grown by metal organic chemical vapor deposition (MOCVD), Si substrate is not only conductive but also mature for large size mass production. However, the poor crystal quality is the handicap for its applications in GaN-based optoelectronic devices.

We attained a hint from Yamaguchi's works. His group had revealed the method of using thermal cycle annealing (TCA) process can manage the strain and improve the crystal quality in the system of GaAs grown on Si substrate[1]. In the growth of GaN on Si substrate, there were rarely reports. In this work, we employed TCA process and studied its influence on device performance.

2. Experimental procedure

The samples in this work were all grown by MOCVD on Si (111) substrate. The conventional structure was using high temperature AlN as a buffer layer. Then a 1.5 μm initial GaN layer was grown at high temperature as a reference sample. In the case with one cycle and two cycles TCA process, the growth of GaN is paused at 0.75 μm and paused twice at 0.5 μm and 1 μm, respectively. Followed by the TCA process (ones or twice) and kept growing until the total thickness reached 1.5 μm to meet a comparable condition with the reference one (As shows in Fig. 1 (a)). The description of TCA process was as follows. The Ga source was turned off during the decrease of temperature to 400 °C, stay low, and rise back to growth temperature. After stabilization time at growth temperature, the Ga source was then turned on. The temperature decreased and rose back is called a cycle (As shows in Fig. 1 (b)). Finally, we fabricated the MSM photodiodes. The Ni (3 nm)/ Au (7 nm) metal contact layer was deposited onto the samples by E-beam evaporate. Standard lithography and lift off techniques are used to define interdigitated contact electrodes. The fingers of the contact electrodes are 10μm wide and 170 μm long with a spacing of 10 μm.

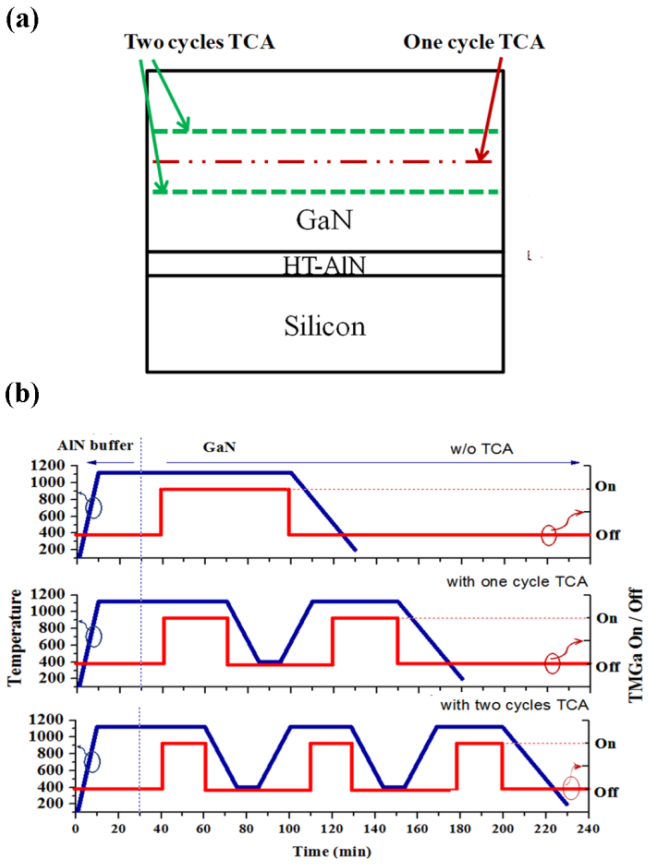

Fig. 1 (a) Schematic diagrams of the conventional structure and the position we insert thermal cycle annealing process, and (b) the profile of thermal cycle annealing process.

3. Results and discussions

There are three samples labeled as A, B and C in this

work. Sample A is the reference while Sample B and C are those with TCA process once and twice. We use XRD to measure the crystal quality and then use the results to estimate the defect density. The full width at half maximum (FWHM) at the (002) plane of samples A, B and C were 983.2, 657.2 and 566.8 arcsec, respectively. And the (102) plane FWHM values of samples A, B and C were 1356, 951.5 and 896.6 arcsec, respectively. The screw and edge type dislocation density can be calculated with the aid of equations [2,3]

$$D_{screw} = \frac{\beta^2_{(002)}}{9b^2_{screw}}, \quad D_{edge} = \frac{\beta^2_{(102)}}{9b^2_{edge}}$$
$$D_{dis} = D_{screw} + D_{edge} \quad (1)$$

Where D_{screw} is the screw type dislocation density and D_{edge} is the edge type dislocation density, $\beta_{(002)}$ and $\beta_{(102)}$ are the FWHM values measured by XRD (002) and (102) plane rocking curves, b represents the Burger vector length (b_{screw} = 0.5185 nm, b_{edge} = 0.3189 nm). The values of FWHM and its correspondence to threading dislocations are also listed in Table I. As predicted, the defect density shows the dependence on the numbers of TCA cycles. With two cycles TCA process, one can reduce the defect density from 1.70×10^{10} to 7.83×10^{9} cm^{-2}.

Fig. 2 shows I-V characteristics of the fabricated GaN MSM photodiodes measured in dark and photo current. With 5V applied bias, it was found that dark current of samples A, B and C were 8.17×10^{-10}, 2.73×10^{-11} and 1.46×10^{-11} A, respectively. It can be seem that dark currents became significantly smaller by TCA process. The reason is that the leakage path will be reduced if the GaN film quality is better. Therefore, the sample C with two cycles TCA process has the lowest dark current. The photo to dark current contrast ratios could also be calculated from this figure. It was found that photo to dark current contrast ratios of sample A, B and C were about 1.10×10^{3}, 6.48×10^{3} and 1.33×10^{5}, respectively. These values indicate that we can indeed enhance the performance of the GaN MSM photodiode by using a simple TCA process. And the more cycles it processed, the better performance we get.

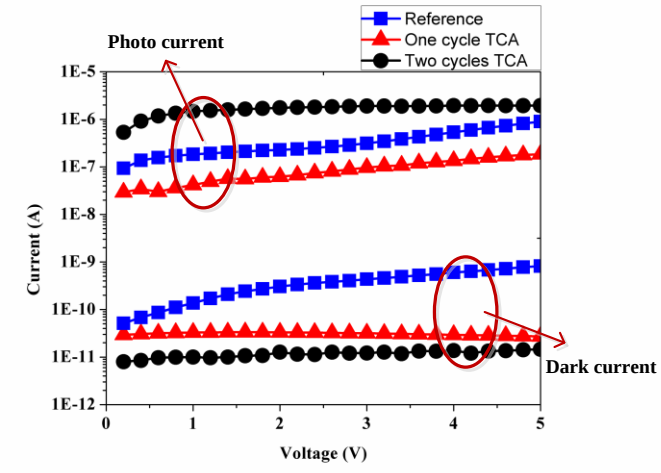

Fig. 2 Dark and Photo currents of the GaN photodiodes

Table I The FWHM values of XRD (002) and (102) plane rocking curve and the correspondence to dislocation densities

	Reference	One cycle TCA	Two cycles TCA
$\beta_{(002)}$ (arcsec)	983.2	657.2	566.8
$\beta_{(102)}$ (arcsec)	1356	951.5	896.6
D_{dis} (cm^{-2})	1.70×10^{10}	8.53×10^{9}	7.83×10^{9}

4. Conclusions

We have studied the influence of thermal cycle annealing method on the subsequent GaN layer. It is found that, by a simple TCA process, one can reduce the defect density on initial layer. Furthermore, the performance of GaN MSM photodiodes with two cycles TCA process was also better than the reference sample. It is found that the dark current of the device was only 1.46×10^{-11} A, and the photo to dark current contrast ratios were about 1.33×10^{5} at 5V.

Acknowledgements

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