Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp729-730

Fabrication of 4H-SiC PiN Diodes on Substrate Grown by HTCVD Method

Yuichiro Tokuda[1], Hideyuki Uehigashi[1], Koichi Murata[2] and Hidekazu Tsuchida[2]

[1] DENSO CORPORATION
Minamiyama, Komenoki-cho, Nisshin-shi, Aichi 470-0111, Japan
Phone: +81-561-75-1003 E-mail:yuichiro.tokuda.j2h@jp.denso.com
[2] Central Research Institute of Electric Power Industry (CRIEPI)
Nagasaka, Yokosuka-shi, Kanagawa, Japan
Phone: +81-561-75-1003

Abstract

We fabricated 4H-SiC PiN diodes on the high-quality substrate grown by the HTCVD method and confirmed that the fabricated diodes showed correct operation for current-voltage characteristic. In addition, it was found that forward voltage V_f increase were not observed even after forward pulse current stress test under the current densities of 2500 A/cm^2.

1. Introduction

As a wide band-gap semiconductor suitable for high-voltage switching devices, 4H-polytype silicon carbide (4H-SiC) has received great attention since they have excellent electronic properties [1]. In recent decades, 4H-SiC unipolar devices such as metal-oxide-semiconductor field effect transistors (MOSFETs) and Schottky barrier diodes (SBDs) with much higher performance compared to those of silicon have been demonstrated.

Producing high-quality 4H-SiC substrates more economically is crucial to allow the penetration of 4H-SiC power devices into wider-ranging power electronics applications. While commercially available substrates are mostly manufactured by physical vapor transport (PVT) method, high-temperature chemical vapor deposition (HTCVD) method [2] is expected as an alternative approach contributing to reducing the production cost of the 4H-SiC substrates.

We have been developing the HTCVD method, and our studies showed a great potential of this metod for realizing a high-productivity in high quality 4H-SiC bulk crystal growth [3,4]. For instance, crystal growth with no increase in threading screw dislocation (TSD) density or void formation was demonstrated at a high growth rate of 3.1 mm. Although high-quality growth at very high speed has already been achieved, little research has been conducted to show the impacts of the high-quality substrates obtained by this method on the device performance.

In this study, 4H-SiC PiN diodes were fabricated on the substrates grown by the HTCVD method, and the device performance, in particular, relation of forward and reverse current-voltage was studied. By appliying pulse forward current to the diodes, the change in forward voltage V_f of the diodes was also studied.

2. Experimental

A 4H–SiC single crystal was grown on an off-oriented 4H–SiC $(000\bar{1})$C seed crystal by HTCVD method. After the grown crystal was sliced into $\{0001\}$ substrates 4° off-oriented toward $[11\bar{2}0]$, some n-type substrates with 3 inch diameter were obtained. The surfaces of the substrates were mechano-chemically polished and the thickness was controlled to be 350 μm. The resistivity was evaluated to be 23 mΩcm by eddy current measurements, and the nitrogen concentration was estimated to be 5×10^{18} cm^{-3} by secondary ion mass spectrometry (SIMS). Melton KOH etching was performed for other substrates obtained from the same crystal to estimate the crystal quality.

The PiN diodes fabricated on the substrate are seen in Fig. 1. The n^- drift layer with a nitrogen concentration of 9.0×10^{15} cm^{-3} was grown on the (0001)Si-face substrate by chemical CVD method [5]. The thickness of the epitaxial layer was 10.7 μm. The p^+ anodes with the Al concentration of $\sim1\times10^{20}$ cm^{-3} were fabricated using Al ion implantation.

Forward and reverse current-voltage characteristics were investigated for the fabricated diodes in initial state. In addition, forward pulse current stress tests, where 1.2 million pulses at one pulse duration of 50 μs were applied, were successively performed under the current densities of 1500, 2000 and 2500 A/cm^2. After each stress test, the forward current-voltage characteristic, in particular the V_f change was estimated.

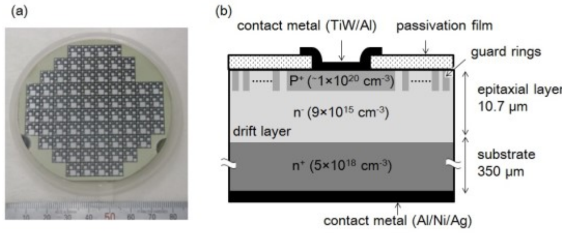

Fig. 1 (a) A photograph of fabricated PiN diodes on the substrate and (b) a cross sectional illustration of the fabricated PiN diode.

3. Results and Discussion

The characteristics of forward current-voltage for typical fabricated 5 PiN diodes with the size of 1 mm×1 mm are shown in Fig. 2 (a). Considering the threshold current density was above 100 A/cm^2 at the forward voltage V_f of 3.5 V, most of the fabricated diodes correctly operated in a forward bias. The characteristics of the reverse current-voltage for the 5 diodes are seen in Fig. 2 (b). As well as the forward-current operation, we confirmed that the fabricated PiN diodes showed a good performance given the threshold leak current was below 10^{-8} A at the reverse voltage of 1000 V. The yield of good

PiN diodes fabricated on the substrate was over 90 %, which was assumed to be equal to or better than the yields for the diodes fabricated on commercial substrates.

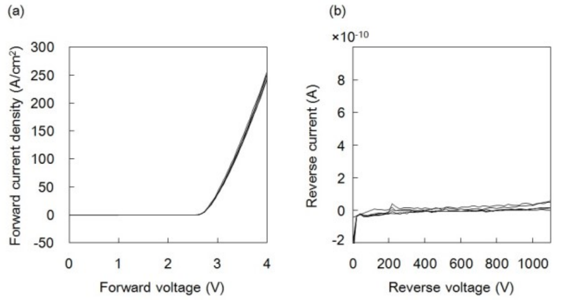

Fig. 2 (a) Forward and (b) reverse current-voltage characteristics for fabricated 5 PiN diodes with the size of 1 mm×1 mm.

It is known that single-Shockley stacking faults (SSFs) expand in 4H-SiC PiN diodes under a forward bias and the forward voltage V_f increases with the SSF expansion [6]. Thus, we investigated the V_f change in 5 PiN diodes with the size of 3 mm×3 mm through the pulse current stress tests. The results of the V_f change are shown in Fig. 3 (a), which indicates the forward voltage V_f was not increased in the 5 diodes even after the stress tests under the current densities of 1500, 2000 and 2500 A/cm^2. We note that the V_f was increased for the PiN diodes fabricated on the commercially available substrates at the similar stress tests.

Photoluminescence (PL) images of the No.1 and No.2 diodes after the stress test at the forward current density of 2500 A/cm^2 are shown in Fig. 3 (b). The images, taken with a band pass filter of 420±20 nm, indicate that no SSFs expanded in the diodes. Similarly, we confirmed that no SSFs were formed in the other 3 diodes. Hence, little changes in V_f were attributed to the suppression of the SSF expansion in the diodes under forward bias.

Since the dislocation densities of the grown crystal were estimated to be approximately 800-1000 cm^{-2} for threading dislocations (TDs) and 100-150 cm^{-2} for basal plane dislocations (BPDs), the substrate prepared for the fabrication of the PiN diodes would be also low BPD density. Furthermore, almost all of the BPDs would be converted into threading edge dislocations (TEDs) during the CVD growth, implying the few BPDs penetrate in the drift layers of the diodes. In fact, no BPDs were observed in PL images of the epitaxial layer after the CVD growth. Since the BPDs act as the nuclei of SSFs and no BPDs lied in the drift layers, such low BPD density in the substrates would have contributed to the suppression of SSF expansion.

However, it has also been reported that the SSF expansion can originate from the BPD segments in the substrates, even if the BPDs are converted to TEDs during the CVD growth [7,8]. The SSF expansion from the substrate is considered to occur when a certain number of holes reach to the BPD-TED conversion points inside of the substrate. Taking account of the previous studies, the suppression of the SSF expansion may be attributed to few holes reaching the BPDs in the HTCVD substrate. The crystals are grown at very high temperature exceeding 2500 °C at the HTCVD method [4], which may result in that many point defects were generated in the crystals and shorten the carrier lifetime for the holes in the substrates.

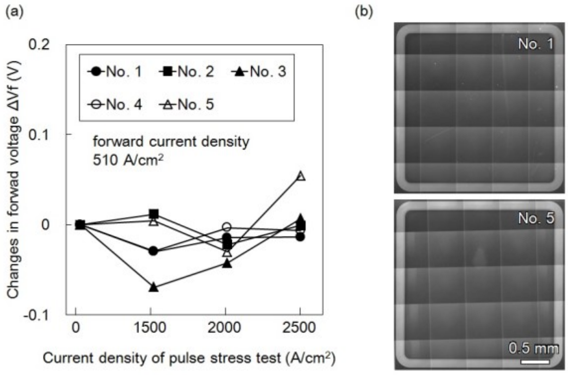

Fig. 3 (a) Change in forward voltage V_f measured at 510 A/cm^2 for fabricated PiN diodes with the size of 3 mm×3 mm before and after pulse current stress tests, and (b) PL images of the 2 PiN diodes after current stress test at 2500 A/cm^2

3. Conclusions

We fabricated 4H-SiC PiN diodes on the high-quality SiC substrate with 3 inch diameter grown by HTCVD method. The densities of the BPDs were presumed to be 100-150 cm^{-2}. Through the investigations of forward and reverse current-voltage characteristics, it was found that most of fabricated PiN diodes operated correctly. The yield was over 90 %, which is assumed to be equal to or greater than that fabricated on the commercial substrates. In addition, we studied the degradation in forward-current operation. Then, we found that forward voltage V_f increase and SSF expansion were not observed even after forward pulse current stress test under current densities of 1500, 2000 and 2500 A/cm^2.

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