

論文 / 著書情報
Article / Book Information

題目(和文)	SiCパワーデバイスの特性に結晶欠陥や界面準位が与える影響に関する研究
Title(English)	Study of the influence of crystal defects and interface traps on SiC power device characteristics
著者(和文)	長谷川 淳一
Author(English)	Junichi Hasegawa
出典(和文)	学位:博士(工学), 学位授与機関:東京工業大学, 報告番号:甲第10478号, 授与年月日:2017年3月26日, 学位の種別:課程博士, 審査員:波多野 睦子,小田 俊理,宮本 恭幸,河野 行雄,小寺 哲夫,中田 修平
Citation(English)	Degree:Doctor (Engineering), Conferring organization: Tokyo Institute of Technology, Report number:甲第10478号, Conferred date:2017/3/26, Degree Type:Course doctor, Examiner:,,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	要約
Type(English)	Outline

Doctor of Engineering Thesis

Study of the influence of crystal defects and interface traps on SiC power device characteristics

Junichi HASEGAWA

February 2017

Department of Physical Electronics
Graduate School of Science and Engineering
Tokyo Institute of Technology

Contents

1. Introduction	1
1.1. Research background of SiC power devices	1
1.1.1. Placement of power devices in power electronics	1
1.1.2. Present status of SiC power devices	1
1.2. Challenges of SiC power devices	3
1.2.1. Diodes	3
1.2.2. MOSFETs	3
1.2.3. Optically triggered thyristors	4
1.3. Objectives of this research and structure of the thesis	4
2. Theoretical background and previous research	7
2.1. The benefits of physical properties of SiC	7
2.1.1. Crystal structure and physical property	7
2.1.2. Advantages of SiC unipolar devices	8
2.1.3. Advantages of SiC bipolar devices (breakdown voltage)	9
2.1.4. Advantages of SiC bipolar devices (lifetime)	10
2.2. Manufacturing process and operating principles of SiC devices	11
2.2.1. Crystal growth	11
2.2.2. Doping and oxide film formation process	11
2.2.3. SiC rectifier device and its operating principles	12
2.2.4. SiC unipolar switching device and its operating principles	15
2.2.5. SiC bipolar switching device and its operating principles	18
2.3. Crystal defects in SiC power devices	19
2.3.1. Crystal defects and density	19
2.3.2. Stacking fault	21
2.3.3. Interface states	21
2.3.4. Bulk traps	22
2.4. Device simulation for SiC power devices	24
3. Static characteristic simulation of SiC-junction barrier Schottky diode including stacking faults	29
3.1. Research background	29
3.2. Device structure	29
3.3. Evaluation method and simulation model	29
3.3.1. Electrical and optical measurement techniques	29
3.3.2. TCAD simulation model of JBS without stacking faults	30
3.4. Results	31
3.4.1. Reverse I–V characteristics and the image of thermal emission	31
3.4.2. Structure identification of stacking faults	31
3.4.3. Simulation results	38
3.5. Discussions	40
3.5.1. A mechanism of reverse leakage	40
3.5.2. Strategy for reducing reverse current	40

3.6. Conclusions	40
4. Clarification and simulation modeling of the influence of interface states in SiC MOSFETs on static characteristics	43
4.1. Research background	43
4.2. Device structure	43
4.3. Experimental method and simulation model	44
4.3.1. Conventional interface state density measurement method	44
4.3.2. Measurement of interface states density in a wide energy region using a long-time capacity transient	49
4.3.3. TCAD simulation models	52
4.4. Results	54
4.4.1. Evaluation of interface state density before and after nitriding by Hi-Lo CV method and DLTS	54
4.4.2. Measurement of interface states density after post-nitridation wet oxidation by DLTS	56
4.4.3. Evaluation of interface state density after post-nitridation wet oxidation in the wide-energy region	59
4.4.4. Transfer characteristic simulation based on the experimental results of interface states density	60
4.5. Conclusions	62
5. Dynamic characteristics simulation focusing on lifetime of optically triggered SiC thyristors	65
5.1. Research background	65
5.2. Device structure	65
5.3. Modeling method	66
5.3.1. TCAD simulation model of optical triggered thyristor	66
5.3.2. Models and parameters related to photo response	67
5.4. Results and Discussions	69
5.4.1. The lifetime dependence of the characteristics	69
5.4.2. Light irradiation response	70
5.4.3. Lifetime variation of light irradiation response	74
5.5. Conclusions	75
6. Conclusions	77
A. Appendix	79
A.1. Time dependence of MOS capacitor capacitance and interface state density . .	79

Thesis Summary

Silicon carbide (SiC) is an attractive material for manufacturing low on-resistance, high-voltage power devices with less energy conversion loss. A full SiC inverter composed of a SiC metal oxide semiconductor field effect transistor (MOSFET) and SiC diode has already been put into practical use, and the performance of the SiC insulated-gate bipolar transistor (IGBT) and SiC thyristor has also been reported. However, because SiC is a compound and multiple polytypes exist, SiC power devices contain more high-density crystal defects and interface states/bulk traps than Si power devices. As an example, stacking faults (SFs) in the SiC epilayer exists on the order of $0.1\text{--}1\text{ cm}^{-2}$, the density of SiO_2/SiC interface states is $10^{11}\text{--}10^{13}\text{ cm}^{-2}$, and the density of bulk traps in SiC is $10^{11}\text{--}10^{14}\text{ cm}^{-3}$. It is known that the performance of SiC power devices is determined by defects and states. To improve the characteristics of SiC power devices, it is necessary to evaluate the influence of crystal defects and interface states.

In this research, we aimed at quantitatively clarifying the influence of SiC crystal defects and interface states/bulk traps on device characteristics, including its mechanism, for the purpose of improving the performance of SiC power devices. We focused on SiC-junction barrier Schottky diode (JBS, a kind of Schottky diode in which the p-wells are fabricated at constant intervals in the Schottky barrier diode), MOSFETs, and optically triggered thyristors. The following common approach is used to clarify the degree and mechanisms of influence of defects/states on the device characteristics.

1. Evaluate defects/states in the device by optical or electrical measurement, and reflect the result in technology computer aided design (TCAD) simulation model.
2. Measure the device characteristics and compare them with the simulation results; then, make the simulation model more accurate.
3. Simulate the physical phenomena inside the device structure including defect/states behavior.

In Chapter 1, the backgrounds and objectives of this research are described.

In Chapter 2, we describe the basic theoretical background and review the previous literature. We also describe the basic approach of TCAD simulation here.

In Chapter 3, we clarified the relationship between the enhanced leakage current of SiC JBS and 3C-SiC inclusions that were a type of SF. The SF structure was identified by photoluminescence (PL) mapping and cross-sectional transmission electron microscopy (TEM). Numerical simulations of the I - V characteristics considering local lowering of Schottky barrier height at the Ti/3C-SiC contact area, which was 0.8 eV lower than that of Ti/4H-SiC Schottky barrier, explained the 4–6 orders of magnitude increase in reverse leakage current caused by SFs.

In Chapter 4, we investigated the mechanism of positive threshold voltage V_{th} shift by wet oxidation without a significant decrease in field effect mobility μ_{fe} , focusing on the variations in interface state density D_{it} . The μ_{fe} increased from 3.27 to 26.4 $\text{cm}^2/(\text{V}\cdot\text{s})$ by nitridation. Then, V_{th} was shifted +0.52 and +0.71 V by wet oxidation at 700 and

800 °C, respectively, without significantly decreasing mobility. After wet oxidation at 900 °C, mobility became 60 % of the nitridation sample. By combining DLTS and ICTS, we obtained D_{it} measurements for a wide energy range without exceeding the upper temperature limit of the device (450 K). Compared to the nitridation-only sample, the relatively deep states at $E_c - E_t = 1.2$ eV were increased by an order of magnitude of 10^{11} eV⁻¹cm⁻² due to wet oxidation at 700 and 800 °C without a significant increase in relatively shallow states. On the other hand, the relatively shallow states at $E_c - E_t = 0.2$ eV increased by an order of magnitude of 10^{12} eV⁻¹cm⁻² after wet oxidation at 900 °C. The simulations of transfer characteristics using D_{it} measurement results were also conducted to quantitatively investigate the relationship between V_{th} and D_{it} . Considering the measured D_{it} , the simulated V_{th} accurately reproduced the actual value well. In this simulation, interface states deeper than $E_c - E_t = 0.2$ eV are affected V_{th} .

In chapter 5, we developed the simulation model for an optically triggered thyristor, focusing on the lifetime, which depends on the bulk traps, and response to incident light. The model accuracy, especially the minimum incident light intensity to turn-on I_{0min} , was compared to experimental results. We estimated the lifetime from the holding current, and we considered the literature values of the refractive index, penetration depth, and quantum efficiency. The simulation results of I_{0min} accurately reproduced the actual values at $V_{ak} = 300$ V. We also evaluated the influence of the drift-layer lifetime τ_{drift} and wavelength λ on the I_{0min} . When the carrier lifetime of the drift layer τ_{drift} improved from 0.4 μ s to 10 μ s, I_{0min} was reduced by 1/30 times.

In Chapter 6, we summarize the outcomes, discuss the challenges for the future, and conclude this thesis.

With regards to the SiC JBS, SiC MOSFET, and SiC optical triggered thyristor, TCAD simulation models for predicting characteristics based on the information of crystal defects/interface states were constructed. Then, we quantitatively analyzed the influence of crystal defects/interface states on SiC power device characteristics to improve performance and reliability of SiC power devices.