

Silicon Carbide

Volume 2: Power Devices and Sensors

Edited by
Peter Friedrichs, Tsunenobu Kimoto,
Lothar Ley, and Gerhard Pensl



**WILEY-
VCH**

WILEY-VCH Verlag GmbH & Co. KGaA

Contents

Preface *XI*

List of Contributors *XV*

Volume 2 Silicon Carbide: Power Devices and Sensors

Part A View from Industry

- 1 **Present Status and future prospects for electronics
in electric vehicles/hybrid electric vehicles and expectations
for wide-bandgap semiconductor devices** *1*
Kimimori Hamada
 - 1.1 Issues surrounding automobiles *1*
 - 1.2 Past, present, and future of Toyota hybrid vehicles *4*
 - 1.3 Newest hybrid vehicle *10*
 - 1.4 Expectations for wide-bandgap semiconductors in HV inverter
applications *12*
 - 1.5 Toyota Group research and development an wide-bandgap
semiconductor devices *14*
 - 1.6 Conclusions *18*
References *19*

- 2 **Silicon carbide power-device products —
Status and upcoming challenges with a special attention
to traditional, nonmilitary industrial applications** *21*
Peter Friedrichs
 - 2.1 Introduction *21*
 - 2.2 SiC in power electronics *22*
 - 2.3 Summary *31*
References *32*

Part B I Unipolar Devices Schottky Diodes

- 3 Effect of an intermediate graphite layer on the electronic properties of metal/SiC contacts 35**
Sergey A. Reshanov, Konstantin V. Emtsev, Florian Speck, Kun-Yuan Gao, Thomas K. Seyller, Gerhard Pensl, and Lothar Ley
- 3.1 Introduction 35
3.2 Experimental 36
3.3 Results 40
3.4 Discussion 46
3.5 Conclusions 48
References 49
- 4 Reliability aspects of SiC Schottky diodes 51**
Mathias Holz, Jochen Hilsenbeck, and Roland Rupp
- 4.1 Introduction 51
4.2 Micropipes 52
4.3 Avalanche ruggedness by design improvement 57
4.4 Product improvement by high performance die attach 63
4.5 Reliability test results 67
4.6 Summary 74
References 74

Part B II JFET

- 5 Design, process, and performance of all-epitaxial normally-off SiC JFETs 77**
Rajesh K. Malhan, Mietek Bakowski, Yuuichi Takeuchi, Naohiro Sugiyama, and Adolf Schöner
- 5.1 Introduction 77
5.2 Advantages of the SiC JFET technology 78
5.3 All-epitaxial normally-off SiC DGTJFET design 97
5.4 Innovative device process technologies 103
5.5 All-epitaxial 1200 V trench 4H-SiC DGTJFET 111
5.6 Conclusion 117
References 118

- 6 Extreme temperature 6H-SiC JFET integrated circuit technology 121**
Philip G. Neudeck, Steven L. Garverick, David J. Spry, Liang-Yu Chen, Glenn M Beheim, Michael I. Krasowski, and Mehran Mehregany
- 6.1 Introduction 121
 6.2 Transistors 124
 6.3 Circuits 134
 6.4 Summary & future work 149
 References 152
- 7 1200 V SiC vertical-channel-JFETs and cascode switches 157**
Victor Veliadis
- 7.1 Introduction 157
 7.2 Large-area 1200 V 4H-SiC vertical JFET structures 158
 7.3 Investigation of the suitability of 1200 V normally-off vertical-channel SiC JFETs for power switching applications 160
 7.4 1200 V normally-off all-SiC VJFET based cascode switch 169
 7.5 Reliability of the 1200 V normally-off all-SiC VJFET cascode switch 172
 7.6 Thermal properties of VJFET/cascode 174
 7.7 0.143 cm active-area 1200 V class vertical-channel JFETs 181
 7.8 Edge termination of large-area vertical-channel JFETs 184
 7.9 Summary 187
 References 189

Part B III MOS Interfaces

- 8 Alternative techniques to reduce interface traps in n-type 4H-SiC MOS capacitors 193**
Gerhard Pensl, Svetlana Beljakowa, Thomas Frank, Kunyuan Gao, Florian Speck, Thomas Seyller, Lothar Ley, Florin Ciobanu, Valery Afanas'ev, Andre Stesmans, Tsunenobu Kimoto, and Adolf Schöner
- 8.1 Introduction 193
 8.2 Material, processing parameters, and analysis techniques 196
 8.3 Thermal oxidation in a tungsten camp furnace combined with a microwave plasma 197
 8.4 Over-oxidation of N-implanted 4H-SiC 200
 8.5 Over-oxidation of N-/Al-implanted 4H-SiC 208
 8.5.1 Material and Implantation parameters 208
 8.5.2 Results and discussion 210
 8.6 Summary 212
 References 213

9	High electron mobility achieved in n-channel 4H-SiC MOSFETs oxidized in the presence of nitrogen 215 <i>B. Zippelius, S. Beljakowa, M Krieger, G. Pensl, S. A. Reshanov, M Noborio, T. Kimoto, and V. V. Afanas 'ev</i>
9.1	Introduction 215
9.2	Experimental 216
9.3	Results 217
9.4	Discussion 229
9.5	Summary 231
	References 232
10	4H-SiC MISFETs with nitrogen-containing insulators 235 <i>Masato Noborio, Jun Suda, Svetlana Beljakawa, Michael Krieger, and Tsunenobu Kimoto</i>
10.1	Introduction 235
10.2	Survey of "nitridation" 237
10.3	Device fabrication 238
10.4	Characteristics of MIS capacitors and FETs on 4H-SiC(0001) 240
10.5	Characteristics of MIS capacitors and FETs on 4H-Si (0001) 250
10.6	Influence of effective fixed charge density on channel mobility 253
10.7	Application of N-containing insulators to p-channel MIS capacitors and FETs 256
10.8	Summary of effects of N-Containing insulators on n- and p-type SiC MIS capacitors and FETs 260
10.9	Conclusion 261
	References 262
11	Inversion layer electron transport in 4H-SiC metal—oxide—semiconductor Field-effect transistors 267 <i>Vinayak Tilak</i>
11.1	Introduction 267
11.2	Silicon MOS history 268
11.3	4H-silicon carbide MOS mobility characterization 270
11.4	Physical characterization of the interface 282
11.5	Differences between inversion layer electron transport in Si MOS and 4H-SiC MOS 285
11.6	Future work 286
11.7	Summary 287
	References 288

Part C MOSFET and JFET Power Devices

- 12 Development of SiC diodes, power MOSFETs and intelligent power modales 291**
Takashi Nakamura, Mineo Miura, Noriaki Kawamoto, Yuki Nakano, Takukazu Otsuka, Keiji Okumura, and Akira Kamisawa
- 12.1 Introduction 291
- 12.2 SiC diodes 294
- 12.3 SiC MOSFETs 298
- 12.4 SiC trench MOSFETs 304
- 12.5 SiC IPMs 310
- 12.6 Summary 316
 References 317

- 13 Reliability issues of SiC power MOSFETs toward high junction temperature Operation 321**
Satoshi Tanimoto and Iiromichi Ohashi
- 13.1 Introduction 321
- 13.2 issues and measures for high T Operation 323
- 13.3 Device structure and process integration 340
- 13.4 Discussion 343
- 13.5 Conclusion 345
 References 345

- 14 Application of silicon carbide transistors in photovoltaic — inverters 347**
Dirk Kranzer and Bruno Burger
- 14.1 Introduction 347
- 14.2 Photovoltaic trend 348
- 14.3 Photovoltaic systems 349
- 14.4 Normally-off SiC-JFETs 353
- 14.5 SiC-MOSFETs 361
- 14.6 SiC-FETs as synchronous rectifiers 367
- 14.7 Single phase inverter with normally-off SiC-JFETs 372
- 14.8 Three phase full bridge inverter with SiC-MOSFETs 377
- 14.9 Production costs of PV-inverters 379
- 14.10 Financial benefits with SiC-transistors 381
- 14.11 Conclusions and outlook 383
 Appendix: measurement setup 385
 References 386

Part D Bipolar Devices

- 15 Design and technology considerations for SiC bipolar devices: BJT, IGBT, and GTOs 389**
Qingchun (Jon) Zhang and Anant K. Agarwal
- 15.1 SiC bipolar junction transistors 389
15.2 SiC insulated gate bipolar transistors 412
15.3 SiC Gate turn-off thyristors 428
15.4 Technical challenges in SiC bipolar devices 440
15.5 Summary 441
References 441
- 16 Suppressed surface-recombination structure and surface passivation for improving current gain of 4H-SiC BJTs 445**
Kenichi Nonaka, Akihiko Horiuchi, Yuki Negoro, Kensuke Iwanaga, Seiichi Yokoyama, Hideki Hashimoto, Masashi Sato, Yusuke Maeyama, Masaaki Shimizu, and Hiroaki Iwakuro
- 16.1 Introduction 445
16.2 Survey of the conventional BJTs with high common emitter current gain 447
16.3 Basic structure and operating principle of the proposed BJTs 448
16.4 Evaluation of surface passivation for improving current gain 450
16.5 Design and fabrication of the SSR-BJT 454
16.6 Characteristics of the SSR-BJT 456
16.7 Conclusion 464
References 465
- 17 SiC avalanche photodiodes and photomultipliers for ultraviolet and solar-blind light detection 467**
Alexey Fiert, Stanislav Soloviev, and Peter Sandvik
- 17.1 Introduction 467
17.2 Silicon carbide avalanche photodiodes 468
17.3 Influence of defects in SiC substrate on device performance 475
17.4 Silicon carbide photomultiplier 480
17.5 Summary 484
References 485

Index 487