Since their development in the 1980s, IGBTs have become established as the standard component in many different power electronics applications. They cover a performance range from a few hundred watts to several megawatts. In the course of their development, different IGBTs have separated out into different packages so that, for example, there are now IGBTs as discrete components in, for example, TO-247 packages, IGBT in high-power modules, and complex designs that include both IGBTs and other electronic components and functions.

The aim of this book is to make the basics specific to IGBTs as they interact with the application accessible to readers. In many published works, practical details and expert knowledge are often left out or are not presented in a way that clearly shows how they relate to the application. This book brings together detailed information about power electronics in relation to IGBTs, supplemented and complemented by our own experience in the field.

After explaining the internal structure and the IGBT variants derived from the prototype or basic model, we then examine how the package technology is constructed. Then, the book discusses electrical and thermal matters, getting to grips with gate drives for IGBTs, including their specific application and parallel connection. This broad coverage of the applications also includes the practicalities of the switching behaviour of IGBTs, basic circuit arrangements, application examples, and rules of design. To complement that, we also look at measurement engineering and signal electronics. The conclusion deals with the requirements of IGBTs and IGBT modules in terms of quality and reliability.

In presenting each chapter, we have tried as far as possible to present information visually and avoid using more equations than necessary. There are more than 500 figures and tables. However, equations are used if they are the best way to explain basic principles or are relevant to the everyday use of IGBTs. We hope thereby to have achieved a good balance between pure theory and practice-oriented application.

We owe a particular debt of thanks to our families and friends, as work on this book – during our already limited leisure time – took several years.

We would also like to thank Professor Leo Lorenz, Jost Wendt, Hubert Ludwig and Martin Hierholzer, as well as Infineon Technologies, for their support in making this book a reality.

Warstein, summer 2010

Andreas Volke

Michael Hornkamp

Although utmost care has been taken to ensure accuracy in presentation and content, no work can claim to be error-free and complete. Therefore, suggestions for improvement are cordially welcomed.

The arrival and consistent development of MOS-controlled power semiconductor components has helped the entire field of power electronics towards a breakthrough regarding high power density and system efficiency. It has also improved reliability and made economical technical solutions possible. The key technology, facilitating the wide power range of a few tens of watts up to the region of many megawatts, has been the IGBT (insulated gate bipolar transistor), the exceptional technical properties of which mean that it has replaced all previous fully controllable power semiconductor components in existing systems and opened up completely new fields of application. However, a fundamental understanding of component technology, the requirements of the fields of application and operation, and tried and tested designs for the drive and protection functions, are essential for fail-safe and reliable operation across the entire power range, and in order to take the optimisation of system costs into account.

An analysis of the literature currently available reveals a large number of highly qualified papers and books on the topic of power electronics converters, switching topologies and systems, and several comprehensive works that present the semiconductor physics and cellular structures of the major new power semiconductor components both in theory and from the technological and realisation point of view.

What makes this book unique is that it is tailor-made to fill the gap that still existed between semiconductor physics and power electronics systems technology, and provides valuable support to users of these components.

Given the work done in this area over the last twenty years, the two authors, who were involved in applying and spreading this new technology, deserve special commendation: They did not balk at the effort of putting all the knowledge gathered so far in readable form. By fortunate coincidence, both authors have been involved in developing innovative application guidelines for the whole spectrum of power IGBTs and are familiar with – indeed helped to shape – major drive and protection designs, measurement methods for high performance IGBTs and many applications.

This book will provide students of power electronics with valuable information about the main contemporary power semiconductor components and their application while development engineers targeting power electronic converters will find all the essentials of selecting, dimensioning and applying IGBT modules laid out clearly and comprehensively.

I would like to thank the authors for their hard work and express my hope that this book will become a new milestone and a standard work in the development of energy electronics.

Munich, summer 2010

Professor Leo Lorenz
IEEE Fellow
Member of the Academy of Science

**1 Power semiconductors ........ 1**

1.1 Introduction ........ 1
1.1.1 Intrinsic charge carrier concentration ........ 2
1.1.2 Doping ........ 6
1.1.3 Charge carrier movement in the semiconductor ........ 8
1.1.4 Charge carrier generation and recombination ........ 11
1.1.5 pn-junction ........ 13
1.1.6 Breakdown ........ 17
1.1.7 Manufacturing process ........ 18
1.2 Diodes ........ 23
1.2.1 Fast recovery diodes ........ 24
1.2.2 Mains (rectifier) diodes ........ 26
1.2.3 Schottky diodes ........ 26
1.2.4 Z-diodes and avalanche diodes ........ 28
1.3 Thyristors ........ 30
1.4 Bipolar junction and field effect transistors ........ 31
1.4.1 Bipolar junction transistors (BJTs) ........ 31
1.4.2 Field effect transistors (FETs) ........ 34
1.4.2.1 Junction field effect transistors (JFETs) ........ 34
1.4.2.2 Metal oxide semiconductor field effect transistors (MOSFETs) ........ 35
1.4.2.3 Superjunction MOSFETs ........ 38
1.5 Insulated gate bipolar transistors (IGBTs) ........ 39
1.5.1 Punch through (PT) IGBTs ........ 46
1.5.2 Non-punch through (NPT) IGBTs ........ 48
1.5.3 Fieldstop (FS) IGBTs ........ 49
1.5.4 Trench IGBTs ........ 50
1.5.5 CSTBT™ ........ 52
1.5.6 IEGTs ........ 53
1.5.7 Trench-FS IGBTs ........ 54
1.5.8 RC IGBTs ........ 55
1.5.9 Integrated additional functions ........ 55
1.6 Outlook ........ 58
1.7 Manufacturers ........ 62
1.8 References ........ 63

**2 Construction of IGBT components ........ 66**

2.1 Introduction ........ 66
2.2 Materials for the construction of IGBT modules ........ 67
2.2.1 Plastic frame ........ 68
2.2.2 Substrates ........ 69
2.2.3 Baseplate ........ 71
2.2.4 Moulding compound, epoxy resin and silicone gels ........ 72
2.3 Electrical bonding technology ........ 74
2.3.1 Internal connection technology ........ 74
2.3.1.1 Chip soldering ........ 75
2.3.1.2 System soldering ........ 75
2.3.1.3 Ultrasonic bonding ........ 75
2.3.1.4 Soldering ........ 78
2.3.1.5 Ultrasonic welding ........ 79
2.3.1.6 Low temperature joining ........ 82
2.3.1.7 Diffusion soldering ........ 82

2.3.2 External bonding technology ... 83
2.3.2.1 The fritting effect ... 83
2.3.2.2 Screw connection ... 84
2.3.2.3 Solder connection ... 86
2.3.2.4 Plug connections ... 87
2.3.2.5 Press-in technology ... 88
2.3.2.6 Spring contact ... 92
2.4 Design concepts ... 94
2.4.1 Standard IGBT modules ... 94
2.4.2 Press pack IGBTs ... 94
2.4.3 Intelligent power modules (IPMs) ... 95
2.4.4 IGBT moulded modules ... 97
2.4.5 Discrete IGBTs ... 99
2.4.6 Stacks ... 99
2.5 Internal parallel connection of semiconductors ... 100
2.6 Low inductance design ... 103
2.7 Circuit topologies in IGBT modules ... 104
2.8 Insulation coordination ... 107
2.8.1 Clearance and creepage distances ... 108
2.8.2 Insulation voltage ... 111
2.8.3 Partial discharge ... 112
2.9 Overview of manufactures ... 113
2.10 References ... 115

**3 Electrical properties ... 117**

3.1 Introduction ... 117
3.1.1 Definition of terms ... 118
3.1.1.1 Voltages ... 118
3.1.1.2 Currents ... 119
3.1.1.3 Times ... 119
3.1.1.4 Temperatures ... 121
3.1.1.5 Energies ... 122
3.1.1.6 Modulation factor ... 125
3.2 Forward characteristics of the diode ... 127
3.3 Diode switching characteristics ... 130
3.3.1 Diode turn-on ... 130
3.3.2 Diode turn-off ... 132
3.4 IGBT forward characteristics ... 137
3.4.1 Forward characteristics at low temperatures ... 139
3.5 IGBT switching characteristics ... 140
3.5.1 IGBT turn-on ... 140
3.5.2 IGBT turn-off ... 143
3.5.3 Gate charge and Miller effect ... 145
3.5.4 Turn-off behaviour NPT versus Trench IGBT switching characteristics ... 147
3.6 Short circuit behaviour ... 148
3.7 Blocking behaviour ... 151
3.8 Static and dynamic avalanche breakdown ... 152
3.9 Stray inductance ... 155
3.10 Different manufacturing sources ... 158
3.11 References ... 159

**4 Thermal principles ... 161**

4.1 Introduction ........ 161
4.1.1 Definitions ........ 161
4.1.1.1 Temperatures ........ 161
4.1.1.2 Power ........ 161
4.1.1.3 Thermal resistances and impedances ........ 162
4.1.2 Thermal conduction ........ 163
4.1.2.1 Thermal resistance ........ 163
4.1.2.2 Thermal capacity ........ 164
4.1.2.3 Thermal impedance ........ 166
4.1.2.4 Thermal lateral spread ........ 167
4.1.3 Thermal radiation ........ 169
4.1.4 Convection ........ 172
4.2 Materials and their thermal properties ........ 173
4.2.1 Thermal Interface Material (TIM) ........ 176
4.3 Thermal model ........ 178
4.4 Heatsink ........ 185
4.4.1 Air coolers ........ 186
4.4.2 Liquid cooling system ........ 187
4.5 References ........ 190

**5 Module datasheet ........ 191**

5.1 Introduction ........ 191
5.2 IGBT ........ 192
5.3 Freewheeling diodes ........ 195
5.4 Rectifier diodes (PIM/CIB modules) ........ 196
5.5 Brake chopper (PIM/CIB modules) ........ 197
5.6 NTC resistor (optional) ........ 197
5.7 Module ........ 198
5.8 Diagrams ........ 199
5.9 Circuit topologies ........ 200
5.10 Package (case) drawing ........ 200
5.11 References ........ 201

**6 IGBT Driver ........ 202**

6.1 Introduction ........ 202
6.2 Signal transmission ........ 203
6.2.1 Level shifter ........ 204
6.2.2 Optocouplers ........ 208
6.2.3 Pulse transformers ........ 210
6.2.4 Capacitive couplers ........ 213
6.2.5 Fibre optics ........ 214
6.2.6 Summary ........ 216
6.3 IGBT gate drives ........ 217
6.3.1 Voltage source drivers ........ 218
6.3.1.1 H-bridge circuit ........ 218
6.3.1.2 Emitter follower in the gate path ........ 219
6.3.1.3 Emitter follower in the emitter path ........ 221
6.3.1.4 MOSFET push-pull gate drives ........ 222
6.3.1.5 MOSFET source followers ........ 224
6.3.1.6 n-channel push-pull drives ........ 225
6.3.1.7 IGBT gate boosting ........ 226

6.3.1.8 Design of the gate drives ... 227
6.4 Driver voltage supply ... 229
6.4.1 Bootstrap circuit ... 230
6.4.2 DC/DC converters ... 233
6.4.2.1 Flyback converters ... 234
6.4.2.2 Push-pull converters ... 236
6.4.2.3 Push-pull converters in half-bridge configuration ... 236
6.4.3 Under-voltage lock-out (UVLO) ... 237
6.5 Coupling capacitances ... 238
6.6 Influencing the switching behaviour ... 240
6.6.1 Gate resistor ... 240
6.6.2 External gate-emitter capacitor $C_G$ ... 243
6.6.3 Gate lead inductance ... 246
6.7 Protective measures ... 247
6.7.1 $U_{CEsat}$ monitoring ... 247
6.7.1.1 Inadvertent tripping of the $U_{CEsat}$ monitoring ... 254
6.7.1.2 $U_{CEsat}$ monitoring with capacitive loads ... 255
6.7.2 Collector-emitter clamping (Active Clamping) ... 256
6.7.2.1 Conditional Active Clamping ... 260
6.7.2.2 Dynamic voltage rise control (DVRC) ... 263
6.7.2.3 Dynamic Active Clamping ... 267
6.7.3 Gate clamping ... 269
6.7.4 Miller clamping ... 273
6.7.5 Utilising the parasitic emitter inductance ... 275
6.7.6 Two-level turn-off (TLTO) ... 276
6.7.7 Soft shutdown ... 278
6.8 Logic functions ... 279
6.8.1 Minimum pulse suppression ... 280
6.8.2 Dead-time generation and half-bridge interlocking ... 280
6.8.3 Error messages, blocking times and fault memory ... 281
6.9 Safe Stop ... 282
6.10 Parallel and series connection ... 284
6.10.1 Connection in parallel ... 284
6.10.2 Connection in series ... 285
6.11 Three-level NPC circuits ... 286
6.12 Selecting a driver by performance and cost ... 287
6.13 Overview of manufacturers ... 287
6.14 References ... 288

**7 Switching behaviour in the application ... 290**

7.1 Introduction ... 290
7.2 IGBT control voltage ... 290
7.2.1 Positive control voltage ... 290
7.2.2 Negative control voltage and switching with 0V ... 291
7.2.2.1 Parasitic turn-on caused by the Miller capacitance ... 293
7.2.2.2 Parasitic turn-on caused by the emitter stray inductance ... 294
7.3 Minimal on-times ... 295
7.4 Dead-time (interlock delay time) ... 297
7.5 Switching speeds ... 299
7.6 Turning off short circuits ... 301
7.7 Influence of the stray inductance ... 306

7.7.1 Stray inductance in the commutation path ..... 306
7.7.2 Stray inductance in the gate path ..... 308
7.8 Safe operating area (SOA) ..... 310
7.8.1 IGBT RBSOA and SCSOA ..... 310
7.8.2 Diode SOA ..... 311
7.9 IGBT reverse blocking voltage ..... 312
7.10 Si IGBT with SiC freewheeling diode ..... 312
7.11 Load reduced switching and (quasi-) resonant switching ..... 315
7.11.1 Operation with a snubber ..... 316
7.11.2 Resonant switching ..... 321
7.12 References ..... 323

**8 Connecting IGBT modules in parallel and in series ..... 324**

8.1 Introduction ..... 324
8.2 Parallel connection ..... 325
8.2.1 Notes on static operation ..... 326
8.2.2 Notes on dynamic operation ..... 329
8.2.3 Gate drive in parallel connection ..... 334
8.2.3.1 Direct gate drive in parallel connection ..... 334
8.2.3.2 Indirect gate drive in parallel connection ..... 337
8.2.3.3 Galvanically isolated gate drive in parallel connection ..... 339
8.2.4 Balancing in parallel connection through external components ..... 341
8.3 Series connection ..... 344
8.4 References ..... 348

**9 RF oscillations ..... 349**

9.1 Introduction ..... 349
9.2 Short circuit oscillations ..... 350
9.3 Oscillations during IGBT turn-off ..... 351
9.4 Tail current oscillations ..... 352
9.5 References ..... 355

**10 Mechanical handling and mounting ..... 356**

10.1 Introduction ..... 356
10.2 Connection techniques ..... 356
10.2.1 Electrical connections ..... 356
10.2.2 Heatsink assembly and thermal grease ..... 357
10.2.3 Mounting directly cooled modules ..... 363
10.3 Environmental influences ..... 365
10.3.1 Mechanical loads ..... 365
10.3.2 Gases and fluids ..... 366
10.4 Transport and storage ..... 367
10.5 References ..... 368

**11 Basic circuits and application examples ..... 369**

11.1 Introduction ..... 369
11.2 AC/DC rectifier and brake chopper ..... 371
11.2.1 Active Front End (AFE) ..... 378
11.2.2 Vienna Rectifier ..... 380
11.3 DC/DC converter ..... 382
11.3.1 Buck converter ..... 382

11.3.2 Boost converter ... 384
11.3.3 Buck-boost converter ... 385
11.3.4 H-bridge ... 387
11.4 DC/AC inverter ... 388
11.4.1 Voltage source inverter (VSI) ... 388
11.4.2 Multi-level inverter ... 391
11.4.3 Current source inverter (CSI) ... 396
11.4.4 Z-inverter ... 397
11.5 AC/AC converter ... 402
11.6 Sample applications ... 404
11.6.1 Servo drives ... 404
11.6.2 Uninterruptible power supply (UPS) ... 405
11.6.3 Solar power inverter ... 407
11.6.4 Wind power inverter ... 408
11.6.5 Traction inverter ... 410
11.6.6 Switched reluctance motor ... 412
11.6.7 Medium-voltage inverter ... 413
11.7 References ... 414

**12 Measurements and signal electronics ... 416**

12.1 Introduction ... 416
12.2 Digital storage oscilloscope (DSO) ... 416
12.3 Measuring current ... 419
12.3.1 Non-magnetic measurement of current ... 420
12.3.1.1 Current measuring resistors (Shunts) ... 420
12.3.1.2 Current Sense IGBTs ... 425
12.3.1.3 Sigma/Delta-ADC ... 426
12.3.2 Magnetic measurement of current ... 431
12.3.2.1 Current transformers (CT) ... 432
12.3.2.2 Rogowski coil ... 433
12.3.2.3 Hall sensors ... 435
12.4 Measuring voltage ... 440
12.5 Measuring temperature ... 443
12.6 Double pulse test ... 450
12.7 References ... 454

**13 Inverter design ... 456**

13.1 Introduction ... 456
13.2 Functional inverter components ... 456
13.3 Voltage ratings ... 458
13.4 Parasitic components ... 459
13.5 DC-bus ... 460
13.6 Snubber capacitors ... 463
13.7 Positioning the driver unit ... 466
13.8 Clearance and creepage distances ... 468
13.9 Influence of long motor cables ... 468
13.10 Filters ... 472
13.10.1 Mains filter ... 473
13.10.2 DC-bus filter ... 473
13.10.3 Output filter ... 474
13.11 Fuses ... 476

13.12 Influence of the modulation algorithm ... 479
13.13 Fundamental equations ... 484
13.13.1 Input rectifier ... 484
13.13.2 Output inverter ... 484
13.13.3 DC-bus ... 485
13.14 References ... 485

**14 Quality and reliability ... 487**

14.1 Introduction ... 487
14.1.1 Failure rate, FIT, MTBF and ppm ... 487
14.2 Failure mechanisms in the application ... 489
14.3 Acceleration models ... 490
14.4 Type tests and routine tests ... 496
14.4.1 HTRB Test ... 497
14.4.2 HTGS Test ... 498
14.4.3 H3TRB Test ... 498
14.4.4 TST ... 499
14.4.5 TC Test ... 499
14.4.6 PC Test ... 501
14.5 Measures to improve the load cycle capability ... 504
14.5.1 Matching the CTE values ... 504
14.5.2 DCB ... 504
14.5.3 Low temperature joining ... 505
14.5.4 Diffusion soldering for the chip solder layer ... 507
14.5.5 Improved system solder layer ... 507
14.5.6 Direct bond ceramics to baseplate ... 508
14.5.7 Copper bond wires ... 509
14.6 Lifetime calculation ... 511
14.7 Failure images ... 515
14.7.1 Failure images of process engineering and mechanics ... 515
14.7.2 Electrically and thermally induced failure images ... 517
14.8 Cosmic particle radiation ... 517
14.9 References ... 520

**Abbreviations ... 522**

**Index ... 525**