

Table of Contents

| | |
|--|-----------|
| Preface | xi |
| Chapter 1. Power MOSFET Transistors | 1 |
| Pierre ALOÏSI | |
| 1.1. Introduction | 1 |
| 1.2. Power MOSFET technologies | 5 |
| 1.2.1. Diffusion process | 5 |
| 1.2.2. Physical and structural MOS parameters | 7 |
| 1.2.3. Permanent sustaining current | 20 |
| 1.3. Mechanism of power MOSFET operation | 23 |
| 1.3.1. Basic principle | 23 |
| 1.3.2. Electron injection | 23 |
| 1.3.3. Static operation | 25 |
| 1.3.4. Dynamic operation | 30 |
| 1.4. Power MOSFET main characteristics | 34 |
| 1.5. Switching cycle with an inductive load | 36 |
| 1.5.1. Switch-on study | 36 |
| 1.5.2. Switch-off study | 38 |
| 1.6. Characteristic variations due to MOSFET temperature changes | 44 |
| 1.7. Over-constrained operations | 46 |
| 1.7.1. Overvoltage on the gate | 46 |
| 1.7.2. Over-current | 47 |
| 1.7.3. Avalanche sustaining | 49 |
| 1.7.4. Use of the body diode | 50 |
| 1.7.5. Safe operating areas | 51 |
| 1.8. Future developments of the power MOSFET | 53 |
| 1.9. References | 55 |

| | |
|--|------------|
| Chapter 2. Insulated Gate Bipolar Transistors | 57 |
| Pierre ALOÏSI | |
| 2.1. Introduction | 57 |
| 2.2. IGBT technology | 58 |
| 2.2.1. IGBT structure | 58 |
| 2.2.2. Voltage and current characteristics | 60 |
| 2.3. Operation technique | 63 |
| 2.3.1. Basic principle | 63 |
| 2.3.2. Continuous operation | 64 |
| 2.3.3. Dynamic operation | 71 |
| 2.4. Main IGBT characteristics | 74 |
| 2.5 One cycle of hard switching on the inductive load | 75 |
| 2.5.1. Switch-on study | 76 |
| 2.5.2. Switch-off study | 78 |
| 2.6 Soft switching study | 86 |
| 2.6.1. Soft switching switch-on: ZVS (Zero Voltage Switching) | 86 |
| 2.6.2. Soft switching switch-off: ZCS (Zero Current Switching) | 88 |
| 2.7. Temperature operation | 94 |
| 2.8. Over-constraint operations | 98 |
| 2.8.1. Overvoltage | 98 |
| 2.8.2. Over-current | 99 |
| 2.8.3. Manufacturer's specified safe operating areas | 113 |
| 2.9. Future of IGBT | 116 |
| 2.9.1. Silicon evolution | 116 |
| 2.9.2. Saturation voltage improvements | 117 |
| 2.10. IGBT and MOSFET drives and protections | 119 |
| 2.10.1. Gate drive design | 119 |
| 2.10.2. Gate drive circuits | 122 |
| 2.10.3. MOSFET and IGBT protections | 128 |
| 2.11. References | 130 |
| Chapter 3. Series and Parallel Connections of MOS and IGBT | 133 |
| Daniel CHATROUX , Dominique LAFORE and Jean-Luc SCHANEN | |
| 3.1. Introduction | 133 |
| 3.2. Kinds of associations | 134 |
| 3.2.1. Increase of power | 134 |
| 3.2.2. Increasing performance | 135 |
| 3.3. The study of associations: operation and parameter influence on imbalances in series and parallel | 135 |
| 3.3.1. Analysis and characteristics for the study of associations | 135 |
| 3.3.2. Static operation | 137 |

| | |
|--|------------|
| 3.3.3. Dynamic operation: commutation | 140 |
| 3.3.4. Transient operation | 149 |
| 3.3.5. Technological parameters that influence imbalances | 151 |
| 3.4. Solutions for design | 152 |
| 3.4.1. Parallel association | 152 |
| 3.4.2. Series associations | 161 |
| 3.4.3. Matrix connection of components | 179 |
| 3.5. References | 182 |
| Chapter 4. Silicon Carbide Applications in Power Electronics | 185 |
| Marie-Laure LOCATELLI and Dominique PLANSON | |
| 4.1. Introduction | 185 |
| 4.2. Physical properties of silicon carbide | 186 |
| 4.2.1. Structural features | 186 |
| 4.2.2. Chemical, mechanical and thermal features | 189 |
| 4.2.3. Electronic and thermal features | 188 |
| 4.2.4. Other “candidates” as semiconductors of power. | 195 |
| 4.3. State of the art technology for silicon carbide power components. | 296 |
| 4.3.1. Substrates and thin layers of SiC. | 296 |
| 4.3.2. Technological steps for achieving power components | 203 |
| 4.4. Applications of silicon carbide in power electronics. | 216 |
| 4.4.1. SiC components for high frequency power supplies | 216 |
| 4.4.2. SiC components for switching systems under high voltage and high power | 233 |
| 4.4.3. High energy SiC components for series protection systems | 249 |
| 4.5. Conclusion | 252 |
| 4.6. Acknowledgments | 255 |
| 4.7. References | 255 |
| Chapter 5. Capacitors for Power Electronics | 267 |
| Abderrahmane BÉROUAL, Sophie GUILLEMET-FRITSCH and Thierry LEBEY | |
| 5.1. Introduction | 267 |
| 5.2. The various components of the capacitor – description | 268 |
| 5.2.1. The dielectric material | 269 |
| 5.2.2. The armatures | 269 |
| 5.2.3. Technology of capacitors | 270 |
| 5.2.4. Connections | 271 |
| 5.3. Stresses in a capacitor | 272 |
| 5.3.1. Stresses related to the voltage magnitude | 272 |
| 5.3.2. Losses and drift of capacity | 273 |
| 5.3.3. Thermal stresses | 274 |

| | |
|---|------------|
| 5.3.4. Electromechanical stresses | 275 |
| 5.3.5. Electromagnetic constraints | 276 |
| 5.4. Film capacitors | 276 |
| 5.4.1. Armatures | 276 |
| 5.4.2. Dielectric materials | 279 |
| 5.5. Impregnated capacitors | 279 |
| 5.6. Electrolytic capacitors | 280 |
| 5.7. Modeling and use of capacitors | 282 |
| 5.7.1. Limitations of capacitors | 283 |
| 5.7.2. Application of capacitors | 290 |
| 5.8. Ceramic capacitors | 293 |
| 5.8.1. Definitions | 294 |
| 5.8.2. Methods of producing ceramics | 296 |
| 5.8.3. Technologies of ceramic capacitors | 299 |
| 5.8.4. The different types of components | 302 |
| 5.8.5. Summary – conclusion | 310 |
| 5.9. Specific applications of ceramic capacitors in power electronics | 311 |
| 5.9.1. Snubber circuits | 311 |
| 5.9.2. In ZVS | 312 |
| 5.9.3. Series resonant converters | 313 |
| 5.10. R&D perspectives on capacitors for power electronics | 313 |
| 5.10.1. Film capacitors | 313 |
| 5.10.2. Electrolytic capacitors | 314 |
| 5.10.3. Ceramic capacitors | 314 |
| 5.11. References | 315 |
| Chapter 6. Modeling Connections | 317 |
| Edith CLAVEL, François COSTA, Arnaud GUENA, Cyrille GAUTIER, James ROUDET and Jean-Luc SCHANEN | |
| 6.1. Introduction | 317 |
| 6.1.1. Importance of interconnections in power electronics | 317 |
| 6.1.2. The constraints imposed on the interconnections | 318 |
| 6.1.3. The various interconnections used in power electronics | 319 |
| 6.1.4. The need to model the interconnections | 320 |
| 6.2. The method of modeling | 321 |
| 6.2.1. The required qualities | 321 |
| 6.2.2. Which method of modeling? | 322 |
| 6.2.3. Brief description of the PEEC method | 324 |
| 6.3. The printed circuit board | 329 |
| 6.3.1. Introduction | 330 |
| 6.3.2. Thin wire method | 330 |

| | |
|--|------------|
| 6.3.3. Expressions of per unit length parameters | 332 |
| 6.3.4. Representation by multi-poles, “circuit” modeling | 340 |
| 6.3.5. Topological analysis of printed circuit | 346 |
| 6.3.6. Experimental applications | 349 |
| 6.3.7. Conclusion on the simulation of printed circuit | 353 |
| 6.4. Towards a better understanding of massive interconnections | 353 |
| 6.4.1. General considerations | 353 |
| 6.4.2. The printed circuit board or the isolated metal substrate (IMS) | 359 |
| 6.4.3. Massive conductors | 361 |
| 6.4.4. Bus bars | 361 |
| 6.5. Experimental validations | 362 |
| 6.6. Using these models | 366 |
| 6.6.1. Determination of equivalent impedance | 366 |
| 6.6.2. Other applications: towards thermal analysis and electrodynamic efforts computation | 390 |
| 6.7. Conclusion | 399 |
| 6.8. References | 400 |
| Chapter 7. Commutation Cell | 403 |
| James ROUDET and Jean-Luc SCHANEN | |
| 7.1. Introduction: a well-defined commutation cell | 403 |
| 7.2. Some more or less coupled physical phenomena | 404 |
| 7.3. The players in switching (respective roles of the component and its environment) | 410 |
| 7.3.1. Closure of the MOSFET | 411 |
| 7.3.2. Opening of the MOSFET | 424 |
| 7.3.3. Summary | 431 |
| 7.4. References | 432 |
| Chapter 8. Power Electronics and Thermal Management | 433 |
| Corinne PERRET and Robert PERRET | |
| 8.1. Introduction: the need for efficient cooling of electronic modules | 433 |
| 8.2. Current power components | 436 |
| 8.2.1. Silicon chip: the active component | 436 |
| 8.2.2. Distribution of losses in the silicon chip | 442 |
| 8.3. Power electronic modules | 442 |
| 8.3.1. Main features of the power electronic modules | 442 |
| 8.3.2. The main heat equations in the module | 444 |
| 8.3.3. Cooling currently used for components of power electronics | 446 |
| 8.3.4. Towards an “all silicon” approach | 448 |
| 8.3.5. Conclusion | 451 |

| | |
|--|------------|
| 8.4. Laws of thermal and fluid exchange for forced convection with single phase operation | 452 |
| 8.4.1. Notion of thermal resistance | 452 |
| 8.4.2. Laws of convective exchanges from a thermal and hydraulic point of view: the four numbers of fluids physics | 456 |
| 8.5. Modeling heat exchanges. | 461 |
| 8.5.1. Semi-analytical approach | 461 |
| 8.5.2. The numerical models | 472 |
| 8.5.3. Taking into account electro-thermal coupling | 478 |
| 8.6. Experimental validation and results | 486 |
| 8.6.1. Infrared thermography | 486 |
| 8.6.2. Indirect measurement of temperature from a thermo-sensible parameter | 490 |
| 8.7. Conclusion | 493 |
| 8.8. References | 494 |
| Chapter 9. Towards Integrated Power Electronics | 497 |
| Patrick AUSTIN, Marie BREIL and Jean-Louis SANCHEZ | |
| 9.1. The integration | 497 |
| 9.1.1. Introduction | 497 |
| 9.1.2. The different types of monolithic integration | 499 |
| 9.2. Examples and development of functional integration | 507 |
| 9.2.1. The MOS thyristor structures | 507 |
| 9.2.2. Evolution towards the integration of specific functions | 514 |
| 9.3. Integration of functions within the power component | 520 |
| 9.3.1. Monolithic integration of electrical functions | 520 |
| 9.3.2. Extensions of integration | 530 |
| 9.4. Design method and technologies | 535 |
| 9.4.1 Evolution of methods and design tools for functional integration | 535 |
| 9.4.2. The technologies | 537 |
| 9.5. Conclusion | 541 |
| 9.6. References | 542 |
| List of Authors | 547 |
| Index | 551 |