

# Power Devices for Efficient Energy Conversion

**Gourab Majumdar  
Ikunori Takata**





# Power Devices for Efficient Energy Conversion



# Power Devices for Efficient Energy Conversion

**Gourab Majumdar**  
**Ikunori Takata**



*Published by*

Pan Stanford Publishing Pte. Ltd.  
Penthouse Level, Suntec Tower 3  
8 Temasek Boulevard  
Singapore 038988

Email: [editorial@panstanford.com](mailto:editorial@panstanford.com)

Web: [www.panstanford.com](http://www.panstanford.com)

**British Library Cataloguing-in-Publication Data**

A catalogue record for this book is available from the British Library.

**Power Devices for Efficient Energy Conversion**

Copyright © 2018 Pan Stanford Publishing Pte. Ltd.

*All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the publisher.*

For photocopying of material in this volume, please pay a copying fee through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In this case permission to photocopy is not required from the publisher.

ISBN 978-981-4774-18-5 (Hardback)

ISBN 978-1-351-26232-3 (eBook)

# Contents

<i>Preface</i>	ix
<b>1 Introduction</b>	<b>1</b>
1.1 Era Predating the Birth of Power Semiconductor Devices	2
1.2 Dawn of Power Electronics	5
1.3 Japan's Leading Effort in Power Electronics	7
1.4 Chronology of Power Devices in the 1980s	10
1.5 Chronology of Power Modules in the 1980s	11
1.6 History of Recent Power Switching Semiconductors	12
1.7 Key Role of Power Devices for Efficient Power Conversion	15
1.7.1 Role of Devices in Power Amplification	15
1.7.2 Role of Devices in Power Switching Applications	21
1.7.2.1 Power losses by power switches in power conversion electronics	23
<b>2 Basic Technologies of Major Power Devices</b>	<b>27</b>
2.1 Power Device Categories	27
2.2 Key Semiconductor Operation Principles	28
2.2.1 Essence of the Power Device	28
2.2.2 Characteristics of the Semiconductor	32
2.2.3 p-Type and n-Type Semiconductors	36
2.2.4 Potential Barrier between Regions Having Different Impurity Concentrations	39
2.3 Basic Operation of Power Devices	43
2.3.1 Reverse Voltage Blocking	43
2.3.2 Forward Conducting	51

2.3.3	Voltage-Holding Ability with Large Current: SOA	54
2.4	Diode Rectifiers	60
2.4.1	Diode Structures	60
2.4.2	Transient Operation of a pin Diode	65
2.4.3	Basic Operation of a pin Diode	72
2.4.4	High-Voltage Large-Current Operation of a pin Diode	81
2.5	Fast-Recovery Diode for a Typical Freewheeling Function	83
2.5.1	Need for First-Recovery Diodes	83
2.5.2	Effect of Lifetime Control	87
2.5.3	Control Methods of the Lifetime	90
2.5.4	Various Recombination Models	93
2.5.5	Leakage Current Caused by Lifetime Killers	99
2.5.5.1	Pair generation leakage current	99
2.5.5.2	Diffusion leakage current	101
2.5.6	Interpretation of Observed $J_F-V_F$ Characteristics	103
2.6	Devices of the Thyristor Family	105
2.6.1	Thyristor	105
2.6.2	GTO/GCT	107
2.7	Bipolar Junction Transistors	112
2.7.1	BJT Structures	112
2.7.2	Basic Operation of the BJT	124
2.7.3	High-Voltage Large-Current Operation of the BJT	129
2.7.4	Safe Operating Area of the BJT	135
2.8	Metal-Oxide-Semiconductor Field-Effect Transistors	136
2.9	Insulated Gate Bipolar Transistors	144
2.9.1	IGBT Structures	144
2.9.2	Basic Operation of the IGBT	158
2.9.3	High-Voltage Large-Current Operation of the IGBT	166
2.9.4	Safe Operating Area of the IGBT	170
2.9.4.1	Observation of IGBT destructions	171
2.9.4.2	Destruction mechanism of real IGBTs	175

<b>3 Applied Power Device Family: Power Modules and Intelligent Power Modules</b>	<b>181</b>
3.1 Review of the Power Module Concept and Evolution History	181
3.2 Power Module Constructional Features and Design Aspects	185
3.2.1 Basic Aspects of Power Module Construction and Design	189
3.2.1.1 What are the characteristics required from a power module package?	189
3.2.1.2 What are the features and issues related to typical power module package designs?	192
3.2.2 Fundamentals of Power Module Structural Reliability and Life Endurance	197
3.3 State-of-the-Art Key Power Module Components	207
3.3.1 Dual-in-Line Intelligent Power Module	208
3.3.2 Intelligent Power Module	211
3.3.2.1 A review of the IPM's fundamental concept	213
3.3.2.2 Chip technologies driven by the IPM evolution	217
3.4 Tips on and Guidelines for Applying Power Modules	236
3.4.1 Formulas Common for Power Device Driver Circuit Designs	236
3.4.2 Structure and Operation of the IGBT Device Used in a Power Module	237
3.4.2.1 Review of power MOSFET and IGBT basic operation principle	240
3.4.2.2 Review of a parasitic thyristor's destructive latch-up in an IGBT cell	248
3.4.3 Power Circuit Design	248
3.4.3.1 Turn-off surge voltage	249
3.4.3.2 Freewheeling diode recovery surge	250
3.4.3.3 Design issues related to ground loops	253
3.4.3.4 Reducing gate circuit inductance and avoiding mal-triggering	256

3.4.3.5	Power circuit impedance and overvoltage protection	260
3.4.4	Power Circuit Thermal Design Aspects	265
3.4.4.1	Estimating power losses	266
3.4.4.2	Estimating the junction temperature	271
<b>4</b>	<b>Future Prospects</b>	<b>273</b>
4.1	Summarizing Device Achievements	274
4.2	Future Prospects of Silicon-Based Power Device Technologies	278
4.2.1	Overview of the Power MOSFET and the Superjunction MOSFET	278
4.2.1.1	Power MOSFET	278
4.2.1.2	Superjunction MOSFET	281
4.2.2	Review of IGBT Chip Technology and Its Future Prospects	283
4.2.3	Review of Diode Chip Technology and Its Future Prospects	286
4.2.4	Integrated Power Chips Combining IGBT and Diode Functions	291
4.2.4.1	Reverse-conducting IGBT	292
4.2.4.2	Reverse-blocking IGBT	293
4.3	Prospect of Using Wide-Bandgap Materials	295
4.3.1	WBG Material-Based Advanced Power Chip Technologies	296
4.3.2	Benefits from SiC Application	299
4.3.3	Status of SiC Devices	301
4.3.4	Looking at Application Ranges for WBG Devices	313
	<i>Bibliography</i>	317
	<i>Index</i>	323

# Preface

Recently the role of power electronics and power devices in addressing the challenges in power and energy conversion and storage has been given wide attention as climate change has become a crucial global issue. In power electronics applications, the power density factor related to system design has improved remarkably in the past two decades. The main contributions in this growth have come from timely development of newer power modules, achieved through multidimensional major breakthroughs in insulated gate bipolar transistor (IGBT) and other power chip technologies; packaging structures; and functionality integration concepts. Driven by various application needs in the past decades, various generations of the IGBT and intelligent power modules (IPMs) have evolved so far and have been widely applied in different power electronics devices, covering industrial motor controls, household appliances, railway traction, automotive power-train electronics, windmill and solar power generation systems, etc. Additionally, aggressive R&D achievements have been made in wide-bandgap (WBG) power devices, especially by employing SiC as the base semiconductor material.

In this book, state-of-the-art power device technologies, their physics and operating principles, features related to design, and tips for applications that have driven the various device evolutions will be discussed. Also, the major development trends in the areas of power chip and module technologies will be introduced, including perspectives of WBG devices.

**G. Majumdar**  
**I. Takata**

