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BREAKDOWN PHENOMENA IN SEMICONDUCTORS AND SEMICONDUCTOR DEVICES

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Published by

World Scientific Publishing Co. Pte. Ltd.

5 Toh Tuck Link, Singapore 596224

USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601

UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data

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

BREAKDOWN PHENOMENA IN SEMICONDUCTORS AND SEMICONDUCTOR DEVICES

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ISBN 981-256-395-4

Editor: Tjan Kwang Wei

Printed in Singapore by Mainland Press

To the memory of Julia Titova	<i>M. L.</i>
To my family	<i>J. K.</i>
To my parents Serafima and Naum Vainshtein	<i>S. V.</i>

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Preface

One form of avalanche breakdown has been known to mankind from ancient times: lightning, the terrifying gas discharge, the fear of which is inscribed in the tales and myths of all primitive tribes.

The first known practical application of the avalanche breakdown principle goes back to the first century of our era. There is a fish in the Mediterranean, the electric ray, or skate, which was called "*narcae*" by the ancient Greeks, a word which means "paralyzing". It is known nowadays that the voltage generated by this fish can reach 200 Volts. The Roman physician Scribonius, in his famous writing "De Compositiones Medicamentorum", published in AD 40, described the using of this *narcae* for the treatment of headaches, gout and some other diseases. The treatment was rather painful. This may be the reason why the term "breakdown" is associated very often with such unpleasant concepts as "failure" and "destruction".

Electrical breakdown itself is not connected with any form of destruction, however. One widely used microwave device, the IMPATT diode, for example, has a characteristic operation frequency of about 100 GHz (10^{11} Hz), which means that it goes into a mature avalanche breakdown regime 10^{11} times a second. Since the guaranteed lifetime of a commercial IMPATT diode is at least 5000 hours, each diode will go into this regime safely no less than $\sim 3 \times 10^{18}$ times. Moreover, impact ionization, avalanche and breakdown phenomena form the basis of many very interesting and very important semiconductor devices, such as avalanche photodiodes, avalanche transistors, suppressors, sharpening diodes (diodes with delayed breakdown), and IMPATT and TRAPATT diodes.

We should note at the same time that avalanche phenomena are always associated with high electric fields F , and that the optimal regimes of many devices can be realised only at high current densities j . Thus the power density $P_0 = j \times F$ can be extremely large. The value of the characteristic breakdown field F_i for a silicon IMPATT diode with an operation frequency of about 100 GHz, for example, is about 5×10^5 V/cm, its characteristic current density j is approximately 10^5 A/cm², and P_0 is about 5×10^{10} W/cm³. As a result, the breakdown phenomena are often accompanied by a high temperature. It is probable, of course, that if the temperature is too high, the device may be destroyed due to melting or decomposition of

the material of which it is constructed. This is *not an electric breakdown as such, but only "overheating", ("heat breakdown") causes the device destruction.*

It is worth noting that operation in high electric fields is the backbone of modern semiconductor electronics. Indeed, the mainstream of the modern electronics lies in increasing the operation frequency and velocity of semiconductor device "switching". Both the operation frequency and the velocity of switching are inversely proportional to the length of the "active region" of the device, L . For the most important devices used in semiconductor electronics, Field Effect Transistors (FETs) and Bipolar Transistors (BJTs), the characteristic length of the active region (gate or base) is about $0.1\ \mu\text{m}$. With a standard operation bias V_0 of about 1 V, the average value of the electric field F_0 across the active region of the device is approximately $10^5\ \text{V/cm}$, which means that the maximal value of the electric field in the active region can be as large as $(2-3)\times 10^5\ \text{V/cm}$, i.e. practically equal to the characteristic breakdown field F_i . Generally speaking, in order to provide maximal speed and maximal power, many semiconductor devices must operate either under breakdown conditions or very close to these. Consequently, an acquaintance with breakdown phenomena is very important and useful for any scientist or engineer dealing with semiconductor devices.

Many books contain chapters or sections devoted to the principal features of the avalanche and breakdown phenomena, and there are many good books and outstanding reviews concerning certain special aspects of these phenomena. The aim of this book is to summarize the main experimental results on avalanche and breakdown phenomena in semiconductors and semiconductor devices and to analyse them from a unified point of view. This book has been written by experimentalists for experimentalists. We will scarcely deal at all with fundamental theoretical aspects such as the distribution function of hot electrons, nuances of the band structure at high energy, etc., but instead we will focus our attention on the phenomenology of avalanche multiplication and the various kinds of breakdown phenomena and their qualitative analysis.

The book is organised as follows. In the introductory chapter (Chapter 1) we will briefly discuss the main definitions and establish the main approaches to describing breakdown phenomena.

Chapter 2 will be devoted to avalanche multiplication phenomena, and the main parameters of avalanche photodiodes will be discussed and analysed on this basis.

In Chapter 3 we will consider the reverse current-voltage characteristic of semiconductor diodes over an extremely wide range of current densities, including pre-breakdown leakage current, microplasma breakdown, mature (homogeneous) breakdown, the part of the current-voltage characteristic with negative differential resistance at very high current densities, and the second part with positive differential resistance. The operation regimes and main characteristics of two important devices: suppressor diodes and IMPATT diodes, will be also observed in this chapter.

The phenomenon of avalanche injection will be discussed in Chapter 4 for sam-

ples of the $n^+ - n - n^+$ and $p^+ - p - p^+$ types and for bipolar transistors. The operation of Si avalanche transistors will be analysed for both a conventional regime and a very effective, fast operation regime realised at extremely high current densities (Section 4.4). In Section 4.5 we will discuss the recently discovered effect of extremely fast switching of GaAs avalanche transistors at high current densities.

The phenomena of so called “dynamic breakdown” will be analysed in Chapter 5. This regime is realized under conditions in which the avalanche ionization front moves along the samples with a velocity which is higher than the saturated velocity of free carriers (the TRAPATT zone or streamer). The operation regimes of Silicon Avalanche Sharpers (SAS) and Diodes with Delayed Breakdown (DDB) will be considered in this chapter.

The main ideas of the book will be summarised in the Conclusion.

We are deeply indebted to Dr. Pavel Rodin (The Ioffe Institute) for valuable discussions. We would like to thank our wives and children for their understanding and patience.

We will greatly appreciate any comments and suggestions which can be e-mailed to

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Contents

<i>Preface</i>	vii
1. Introductory Chapter	1
1.1 Elementary act of impact ionization	1
1.2 Auger recombination	5
1.3 Energy of electrons and holes as a function of electric field	8
1.4 Main approaches for describing ionization phenomena	10
1.4.1 Approximation of the characteristic breakdown field F_i . . .	10
1.4.2 Monte-Carlo simulation	13
1.4.3 Approximation of ionization rates	14
2. Avalanche Multiplication	21
2.1 Fundamentals of avalanche multiplication	21
2.2 Avalanche photodiodes	26
2.2.1 Spectral sensitivity	26
2.2.2 Dark current	27
2.2.3 Quantum efficiency	29
2.2.4 Time response	29
2.2.5 Multiplication factor	32
2.2.6 Avalanche excess noise	36
3. Static Avalanche Breakdown	39
3.1 Introduction	39
3.2 General form of the static “breakdown” current-voltage characteristic	39
3.2.1 Microplasma breakdown	41
3.2.2 Homogeneous (“mature”) breakdown	44
3.2.2.1 Contact resistivity	44
3.2.2.2 Thermal resistance	45
3.2.2.3 Space-charge resistance	47

3.2.3	Negative differential resistance	50
3.2.3.1	Qualitative consideration	50
3.2.3.2	The zero doping ($p - i - n$) structure	50
3.2.3.3	Computer simulation	55
3.2.4	Second part of the current-voltage characteristic, with positive differential resistance at very high current densities	58
3.3	Avalanche suppressor diodes	60
3.3.1	Principle of operation	60
3.3.2	Main parameters	62
3.4	IMPATT diodes	65
3.4.1	Principle of operation	66
3.4.2	Some physical problems that arise at very high frequencies	75
4.	Avalanche Injection	81
4.1	Introduction	81
4.2	Avalanche injection in $n^+ - n - n^+$ ($p^+ - p - p^+$) structures	81
4.3	Avalanche injection in bipolar transistors	91
4.3.1	Introduction	91
4.3.2	Avalanche transistor: conventional regime of operation	92
4.3.2.1	Difference in breakdown voltages of a BJT between the common-base and common-emitter configurations	92
4.3.2.2	Dependence of the bipolar transistor gain coefficient α_0 on current density	98
4.3.2.3	Main features of ABT operation in a conventional regime	103
4.4	Operation regime of a Si avalanche transistor at very high current densities	105
4.4.1	Introduction	105
4.4.2	Steady-state collector field distribution. Residual collector voltage	109
4.4.3	Transient properties of Si avalanche transistor at extreme current densities	115
4.5	Operation regime of GaAs avalanche transistor at very high current densities	122
4.5.1	Experimental results	122
4.5.2	Breakdown in moving Gunn domain in GaAs: qualitative analysis	124
4.5.3	Computer simulations of superfast switching in GaAs avalanche transistor	133
5.	Dynamic Breakdown	137
5.1	Introduction	137

5.2	Impact ionization front (TRAPATT zone)	140
5.3	Silicon Avalanche Sharpers (SAS)	142
5.3.1	Computer simulations and comparison with experimental results	144
5.3.2	Stability of the plane ionization front	148
5.3.2.1	Short-wavelength instability of the plane ionization front	150
5.3.2.2	Long-wave length instability of the plane ionization front	152
5.3.3	The problem of the initial carriers	154
5.4	GaAs diodes with delayed breakdown	157
5.5	Superfast switching of GaAs thyristors	162
5.6	Main features of streamer breakdown	168
5.6.1	Introduction	168
5.6.2	Analytical theory of a streamer discharge	169
5.6.3	Computer simulation	176

<i>Conclusion</i>	179
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<i>List of Symbols</i>	181
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<i>Bibliography</i>	185
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<i>Index</i>	195
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