This book is the first to give a comprehensive review of the theory, fabrication, characterization, and device applications of abrupt, shallow, and narrow doping profiles in semiconductors. Such doping profiles are a key element in the development of modern semiconductor technology, including silicon very large scale integrated circuits, discrete devices, and optoelectronic devices.

After an introductory chapter setting out the basic theoretical and experimental concepts involved, the fabrication of abrupt and narrow doping profiles by several different techniques, including epitaxial growth, is discussed. The optical, electrical, chemical, and structural techniques for characterizing doping distributions are then presented, followed by several chapters devoted to the inherent physical properties of narrow doping profiles. The latter part of the book deals with particular devices, such as silicon field-effect transistors, and III–V semiconductor devices for electronic and optoelectronic applications.

The book will be of considerable interest to graduate students, researchers, and engineers in the fields of semiconductor physics and microelectronic engineering.

Cambridge University Press
0521017963 - Delta-doping of Semiconductors
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UNIVERSITY PRESS

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CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 2RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521482882

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First published 1996
This digitally printed first paperback version 2005

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data

Delta-doping of semiconductors / edited by E. F. Schubert.
p. cm.
ISBN 0 521 48288 7 (hardback)
1. Semiconductor – Design and construction. 2. Semiconductor
doping. 3. Molecular beam epitaxy. 4. Field effect transistors.
I. Schubert, E. Fred.
TK7871.85.D457 1995
621.3815′2–dc20 94-48903CIP

ISBN-13 978-0-521-48288-2 hardback
ISBN-10 0-521-48288-7 hardback

ISBN-13 978-0-521-01796-1 paperback
ISBN-10 0-521-01796-3 paperback

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0521017963 - Delta-doping of Semiconductors
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Preface

The spatial dimensions of semiconductor device structures have been shrinking since the infancy of semiconductor technology, and will continue to do so in the foreseeable future. The reduction of device dimensions is motivated by higher speeds as well as lower power consumption. Free carriers can traverse smaller dimensions in a shorter time. For example, the base transit time of an electron emitted into the base of a bipolar transistor decreases for thinner base layers. Furthermore, parasitic capacitances are reduced in small device structures. As a consequence, the energy lost in charging and discharging parasitic capacitors is reduced. If, in addition, the operating voltage of such devices is lowered, a further decrease in power consumption results.

Small device structures require that the spatial distribution of dopants is well controlled. Redistribution processes such as diffusion, segregation, drift in an electric field, and other redistribution mechanisms must be understood on a near-atomic length scale. The assessment of such redistribution processes becomes ever more important as the device dimensions shrink.

Delta-doping, spike-doping, and pulse-doping profiles are examples of extremely narrow but well-defined doping profiles. Such profiles are required in semiconductor structures scaled to their practical, economical, and theoretical limits. The fabrication of such profiles, their characterization, and the understanding of their physical properties are necessary steps to taking full advantage of semiconductor doping profiles with atomic level control. In silicon VLSI technology, the depth of the p–n junctions must be controlled within a few tens of angstroms. In optoelectronics, quantum-well lasers require that the location of p–n-junctions be controlled within a few tens of angstroms as well. Any displacement of p–n-junctions over these short distances would have deleterious effects on the device performance.

In the past, native defects, complex defects, and unintentional contaminations in semiconductors have recieved much attention from the research community. *Intentional dopants* and related issues received, surprisingly, much less attention. However, the requirements for the concentration versus depth profiles of intentional impurities are becoming increasingly stringent in modern semiconductor technology. For example, very small semiconductor structures require doping concentrations exceeding 10^{19} cm^{-3}. The limits of the maximum doping concentration in semiconductors have not been well explored, despite a pressing need. I therefore expect that research will be directed towards dopant characteristics, including spatial redistribution effects and high concentration effects.

This book provides the first comprehensive and coherent treatment of extremely narrow doping distributions with very high concentrations. This field is not limited to any

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particular semiconductor material. I have, therefore, invited contributions on the group-IV semiconductor Si as well as on III–V semiconductors. Both material systems receive equal emphasis.

The book is organized as follows. The introduction (E. F. Schubert) is written in a tutorial style and provides many basic experimental as well as theoretical concepts. In Part Two (C. Proetto), the theoretical framework of the spatial and energetic structure of δ-doped semiconductors is presented. Quantum effects which occur in semiconductors with narrow doping profiles are taken into account. The fabrication of δ-doped structures by epitaxial growth is described in Part Three (Ploog, Makimoto, Horikoshi, Ritter, Eisele, and Gossmann). Doping in III–V, as well as in group-IV, semiconductors during epitaxy is discussed in this part. The epitaxial growth techniques described include molecular-beam epitaxy (MBE), gas source MBE, low-temperature MBE, flux-modulated epitaxy, and solid-phase epitaxy. The characterization of δ-doped semiconductors is the subject of Part Four (Luftman, Schubert, Gossmann, Newman, and Koenraad) and includes secondary-ion mass spectrometry (SIMS), the capacitance-voltage (CV) technique, a discussion of redistribution mechanisms, local vibrational mode spectroscopy (LVM), and a section on the DX center in n-type $Al_xGa_{1-x}As$. Part Five (Yao, Schubert, Wagner, Richards, Masselink, Koenraad, Asche, Headrick, Feldman, and Weir) discusses the physical properties of δ-doped semiconductors and includes carrier transport in the bulk and in quantum wells, optical interband and intraband transitions, and a discussion of ordered doping distributions. Device applications and implications are presented in Part Six (Hong, Schubert, Nakagawa, Yamaguchi, Malik, and Eisele) and include field-effect transistors (FETs), heterostructure FETs, detectors, and doping superlattice devices.

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Murray Hill
July 1995

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