Single-Electron Devices and Circuits in Silicon

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Imperial College Press

Published by

Imperial College Press
57 Shelton Street
Covent Garden
London WC2H 9HE

Distributed 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.

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ISBN-13 978-1-84816-413-0
ISBN-10 1-84816-413-0

Printed in Singapore.

To my wife, Olivia, and to my parents,
Khalid and Rahila

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Preface

Single-electron devices provide a means to control electronic charge at the level of one electron, by means of the single-electron charging or ‘Coulomb blockade’ effect. These devices operate by controlling the transfer of charge across tunnel barriers onto nanometre-scale conducting regions or ‘islands’. In such a process, the energy needed to charge an island with even one electron can be large enough to influence the tunnelling process. This energy, the ‘single-electron charging energy’, must be overcome to allow current to flow across the island, preventing current flow at low applied voltage and temperature.

The possibility that the single-electron charging energy of a nanostructure could influence the tunnelling of even one electron onto the nanostructure was identified as early as the 1950s. In 1951, C.J. Gorter proposed that the observed increase in resistance in thin, granular metal films at low electric fields and temperatures was associated with the need to overcome the single-electron charging energy of the nanometre-scale grains in the film. In the mid-1980s, K.K. Likharev and co-workers predicted, in great detail, effects relating to single-electron charging in nanometre-scale tunnel junctions. By this stage, advances in nanofabrication techniques had led to the ability to fabricate well-defined, nanometre-scale, islands and tunnel junctions. In 1987, this led to the first demonstration, at low temperature, of a *designed* single-electron device, the single-electron transistor (SET) of Fulton and Dolan.

Over the following two decades, a wide variety of single-electron devices, in many material systems, were demonstrated. These included numerous different types of SETs, single-electron memory devices, single-electron logic circuits, and devices for the controlled transfer of

charge packets formed by single or small numbers of electrons. Furthermore, there were many demonstrations of the room-temperature operation of single-electron devices, particularly in silicon semiconductor material.

The great interest in single-electron devices has been driven in part by the potential of these devices for applications in large-scale integrated (LSI) circuits. In comparison with conventional semiconductor devices, devices such as the SET and the single-electron memory cell are inherently nanometre-scale, and tend to improve in performance when scaled down in size. Furthermore, these devices possess the advantages of very low power consumption, associated with the small amounts of charge they use, and control over any statistical fluctuations in this charge.

This book discusses the design, fabrication and electrical characterization of single-electron devices and circuits in silicon. We concentrate on single-electron devices in silicon, as these are of particular interest for LSI circuit applications. Single-electron devices in metals, and in other semiconductor systems such as GaAs/AlGaAs heterostructures, are discussed only when necessary to understand the operation of particular device types, or when device implementations in silicon are limited. This book considers the physics of single-electron charging effects. This is followed by a review of the fabrication and operation of SETs in crystalline and nanocrystalline silicon materials. Single-electron memory devices are then discussed, where the stored 'bits' are defined by single, or at most a few, electrons. We then consider few-electron charge transfer devices, such as single-electron pumps and turnstiles, where small numbers of electrons can be transferred through the device using radio frequency signals. Finally, we discuss single-electron logic circuits. Throughout this book, we follow an approach where the various types of single-electron devices are reviewed first, and then explained in more detail using examples from the author's research.

The author's research work would not have been possible without the collaboration and support of many colleagues. Firstly, the author would like to acknowledge the help and support of Prof. Haroon Ahmed at the Microelectronics Research Centre, University of Cambridge, UK. The major part of the author's research was conducted in collaboration with

Prof. Ahmed, and would not have been possible otherwise. The author would also like to acknowledge the great support of, and collaborations with, many others at the Microelectronics Research Centre, especially Dr John Cleaver, Dr Andrew Irvine, Dr David Hasko, Dr Yong Tsong Tan, Dr Toshio Kamiya, Dr Mohammed Khalafalla, Dr Jin He and Dr Aftab Rafiq (now at Tokyo Institute of Technology, Japan). This research was also conducted in collaboration with Hitachi Cambridge Laboratory, and in this regard, the author would like to acknowledge extremely valuable collaborations with, and the help and support of, Prof. Hiroshi Mizuta (now Professor of Nanoelectronics at the University of Southampton, UK), Prof. Kazuo Nakazato (now at the University of Nagoya, Japan) and Dr David Williams. Furthermore, a large part of the author's research has been possible only through longstanding and very productive collaborations with Prof. Shunri Oda at Tokyo Institute of Technology, Japan, and with Prof. William Milne at the Department of Engineering, University of Cambridge, UK. The author would also like to acknowledge the help and support of Prof. Richard Syms, Prof. Mino Green and Dr Kristel Fobelets, at the Department of Electrical and Electronic Engineering, Imperial College, London, UK, and the support of many other colleagues and friends at the Microelectronics Research Centre, Cambridge, Hitachi Cambridge Laboratory and the Department of Engineering, University of Cambridge. The author would like to acknowledge the financial support of various research programmes. These include the FASEM project (part of the ESPRIT programme of the European Union), the 'Single-electron logic' project, funded by EPSRC, UK, and the CREST and SORST programmes of Japan Science and Technology Corp., Japan.

Finally, the author would like to acknowledge the invaluable support and encouragement of his wife, Olivia Kesselring-Durrani, his parents, Khalid and Rahila Durrani, and his mother-in-law, Ursula Kesselring. Their support has made the writing of this book a far less arduous task.

Zahid A.K. Durrani

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