Quantum Waveguide in Microcircuits

Jian-Bai Xia | Duan-Yang Liu | Wei-Dong Sheng

Integrated circuits were developed following Moore's law, which predicted that the degree of microprocessor integration would double every 18 months in dynamic random-access memory (DRAM). However, as the size of circuit elements approaches its physical limit, the optical method used in manufacturing 16 nm-node chips is also approaching a limit. Although the scaling of microelectronic circuit elements still follows Moore's law, the unit density of power consumption will become unacceptable. Therefore, on the one hand, while the microelectronic technology is being developed continuously, on the other, the feasibility of overcoming Moore's law is also being considered—that is, the More than Moore strategy.

Physically, when the scale of the circuit elements decreases to 10 nm or even less, the quantum effect appears and plays a more and more important role. The electron transport becomes non-classical and non-linear. Even electron motion is like waveguide motion. This book introduces some interesting theories and experiments related to quantum transport. It consists of two parts: (i) Non-classical, Non-linear Transport, and (ii) Quantum Waveguide Theory in Mesoscopic Systems. It provides solid foundations for semiconductor micro- and nanoelectronics for the after-Moore age, develops the transfer matrix method and uses it to study the Rashba electron transport in the Aharonov–Bohm circular ring and square ring, and discusses theories in view of their applications in next-generation semiconductor electronics and industry.

Jian-Bai Xia is a professor at the Institute of Semiconductors, Chinese Academy of Sciences, Beijing. He has many firsts to his credit. Prof. Xia was the first to propose the plane wave expansion method, the tensor model of quantum spheres, the effective-mass theory of (11N)-oriented superlattices, and hole tunneling theory. He developed a systematic method in the framework of the effective-mass theory to study the electronic structures of quantum dots and wires in a magnetic or electric field, especially spin-related properties, besides predicting a series of new phenomena relating to quantum dots, quantum wires, and nanofilms. A recipient of many awards and honors, Prof. Xia has published more than 105 articles, authored or coauthored two monographs, and served in important capacities in several universities.

Duan-Yang Liu was born in Hunan, China, in 1985. He received his BS in applied physics from the College of Science, Tsinghua University, Beijing in 2006 and a PhD in condensed matter physics from the Institute of Semiconductors, Chinese Academy of Sciences, Beijing in 2011. Since 2011, he has been a lecturer in the Physics Department, College of Science, Beijing University of Chemical Technology, Beijing. He is currently engaged in research on semiconductor physics, especially carrier transport in low-dimensional semiconductor devices.

Wei-Dong Sheng is a professor in the Department of Physics, Fudan University, Shanghai. From 1996 to 1999, he developed systematic transfer-matrix and scattering-matrix approaches to ballistic transport in quantum waveguides and investigated electron waveguide couplers, magneto-transport through edge states, and quantum coherent networks. From 2000 to 2008, he developed a comprehensive framework of numerical approaches to strain distribution, electronic structure, and optical properties of self-assembled quantum dots and is currently engaged in developing an efficient configuration-interaction method for strongly correlated electron systems. Prof. Sheng has held significant positions in many universities.

V516
ISBN 978-981-4669-85-6
9 789814 669856

PAN STANFORD PUBLISHING
www.panstanford.com

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Pan Stanford Publishing

Published by

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

Email: editorial@panstanford.com
Web: www.panstanford.com

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Quantum Waveguide in Microcircuits

ISBN 978-981-4669-85-6 (Hardback)
ISBN 978-1-315-36477-3 (eBook)

Printed in the USA

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Introduction

Last century, the development of semiconductor microelectronic technology changed the whole world. The world entered the information society from the industrial society. The productive forces rose greatly, which promoted the development of human material and the spirit of civilization. Just because of the importance of semiconductor microelectronic technology, many governments and international companies invested heavily in developing the technology, hoping to make a break through and occupy an advanced position in the development of the whole information technology.

Integrated circuits were invented in 1958, and in subsequent years, development and progress in the degree of integration have largely followed Moore's law. Moore's law is a rule that combines technology development and economics to predict the degree of advancement in microelectronic circuit integration within a specified period. It predicts that the degree of microprocessor integration would double every 18 months in DRAM. Moore's law is still proving accurate today. However, as the sizes of circuit elements approach their physical limits, the optical method used in manufacturing 16-nm-node chips is also approaching a limit. Although the scaling of microelectronic circuit elements still follows Moore's law, the unit density of power consumption will become unacceptable. Therefore, on the one hand, people continuously develop microelectronic technology, while on the other hand, they consider the developing road after Moore's law is broken, that is, more Moore's law or more than Moore's law.

Physically, when the scale of the circuit element decreases to 10 nm or even less, the quantum effect will appear and play an increasingly important role. The electron transport becomes non-classical and non-linear, and even the electron motion likes the waveguide motion. This book consists of two parts: (i) non-classical, non-linear transport, and (ii) quantum waveguide theory.

The first part discusses the quantum correction effect in ultrasmall devices, including strong field transport and transport related to space (Chapter 2). The quantum mechanics effect is most obvious in the longitudinal transport of superlattices because the longitudinal length of the superlattice is about 10 nm, smaller than the electron mean free path. Quantum transport includes resonant tunneling (Chapter 3) and longitudinal transport of a superlattice (Chapter 4), which were observed early in the last century eighties. Due to the development of electron beam lithography in the last century nineties, people can fabricate an ultrathin metallic wire on a two-dimensional electron gas (2DEG). Applying a bias voltage on a metallic contact can form a small quantum dot in the 2DEG underneath the contact. In studying the transport of quantum dots and thin circuits, Landauer and Büttiker proposed their famous formulas named after them. This kind of transport is named mesoscopic transport (Chapter 5). People fabricated 3D quantum dots in the longitudinal direction of a quantum well by using lithography. The quantum dot is confined in the upper and lower directions by the barriers in the original quantum well, and its lateral direction is confined by vacuum due to the lithography. These kinds of quantum dots are similar to an artificial atom, in which the electrons are filled according to the shell. This characteristic is reflected in the quantum transport, for example, the Coulomb blockade (Chapter 6). Last, we introduce the applications of single-electron transport: single-electron transistor (Chapter 7) and single-electron memory (Chapter 8).

The second part studies quantum waveguide theory, mainly our own works. Since the Aharonov–Bohm effect (AB effect) was experimentally discovered by Webb et al., there have been many advances in the transport of mesoscopic systems. Electron transport in mesoscopic systems is not of the diffusing type but of the waveguide type because there are no electron collisions in such small systems. Transport of the waveguide type has many characteristics different from those of the diffusing type, and the theoretical research methods of these two types are also different. The former is based on quantum mechanics, while the latter is based on the classical statistical physics: Boltzmann equation. In application, mesoscopic systems, especially semiconductor mesoscopic systems, will be the basis of next-generation microelectronics.

This part summarizes the research results of our group in this field in the past 20 years. Chapter 9 covers the general concept of quantum transport. Chapter 10 discusses 1D quantum waveguide theory, which proposes two basic equations similar to Kirchhoff equations in electric circuits. Then the two basic equations are applied to many cases: AB rings, quantum interference devices, etc. Last, the theory is extended to the hole case, whose wave function has two components. Chapter 11 describes 2D quantum waveguide theory. When the width of the circuit is so large that the energy level spacing between the transverse modes in the circuit is comparable to the electron kinetic energy, we should consider the transport of multiple transverse modes, that is, 2D waveguide theory. In this chapter, the transfer matrix method, the scattering matrix method, and the theory of a waveguide with multiple terminals are developed. Chapter 12 discusses the 1D quantum waveguide theory of Rashba electrons. In recent years, much attention has been paid to the field of Rashba spin–orbit interaction (RSOI) in low-dimensional semiconductor structures because of its potential application in spintronic devices, which is based on the idea of the possible manipulation of electron spin by a magnetic or an electric field. Chapter 12 extends the 1D quantum waveguide theory of electrons without considering spin to the case of electrons with spin and RSOI, deriving the boundary conditions of the Rashba current. The theory is applied to study the transport of Rashba electrons in turning structures, spin-polarized devices, etc. Chapters 13 and 14 extend the 1D quantum waveguide theory of a Rashba electron in straight-line structures to curved-line structures. For this objective, the transfer matrix method is developed. With this method, the Rashba electron transport in the AB circular ring and square ring and related spin polarization modulation are studied. In Chapter 15, the 1D quantum waveguide theory of a Rashba electron is extended to the 2D case and some basic results are obtained.

In summary, the transport theories and experiments beyond classical transport quantum waveguide are introduced, which are prepared for future semiconductor micro- and nanoelectronics. They will be the basis of next-generation semiconductor electronics and industry. We believe that these theories will have more and more applications, popularization, and developments.

In January 3–8, 2011, I (J.-B. Xia) gave a talk in the IEEE INEC 2010 (HK) titled "Rashba Electron Transport in Quantum Waveguide." Afterward, the director and publisher of Pan Stanford Publishing, Dr. Stanford Chong, wrote to me on February 7, 2011: "You have given an interesting talk on the above topic at the recent IEEE INEC 2010 (HK, 3–8 Jan 2011) and I am wondering if you would be keen to develop this idea into a book.... The scope could be further expanded and the primary aim would be to inspire students and new scientists into the field." Under his kind urge and help, I and my undergraduate colleagues Dr. Duan-Yang Liu and Dr. Wei-Dong Sheng finished this book. Here we would express our sincere thanks to Dr. Chong and the editor Sarabjeet Garcha. We also thank Dr. Hai-Bin Wu and Dr. Yi-Xin Zong for helping to prepare the manuscript.

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