LARGE SCALE INTEGRATED CIRCUITS TECHNOLOGY: STATE OF THE ART AND PROSPECTS

edited by

LEO ESAKI

and

GIOVANNI SONCINI

LARGE SCALE INTEGRATED CIRCUITS TECHNOLOGY: STATE OF THE ART AND PROSPECTS

Proceedings of the NATO Advanced Study Institute on "Large Scale Integrated Circuits Technology: State of the Art and Prospects",
Erice, Italy, July 15–27, 1981

edited by

Leo Esaki
IBM T.J. Watson Research Center
Yorktown Heights, N.Y. 10598
U.S.A.

and

Giovanni Soncini
CNR-Lamel
40126 Bologna
Italy

1982

Martinus Nijhoff Publishers
The Hague / Boston / London

Distributors:

for the United States and Canada
Kluwer Boston, Inc.
190 Old Derby Street
Hingham, MA 02043
USA

for all other countries
Kluwer Academic Publishers Group
Distribution Center
P.O.Box 322
3300 AH Dordrecht
The Netherlands

Library of Congress Cataloging in Publication Data

NATO Advanced Study Institute on "Large Scale Integrated Circuits Technology: State of the Art and Prospects" (1981 : Erice, Italy)
Large scale integrated circuits technology.

(NATO advanced study institutes series. Series E, Applied sciences ; no. 55)
1. Integrated circuits--Large scale integration--Congresses. I. Esaki, Leo 1925- . II. Soncini, Giovanni. III. North Atlantic Treaty Organization. IV. NATO Advanced Study Institute. V. Title. VI. Series.
TK7874.N337 1981 621.381'73 82-14229
ISBN 90-247-2725-1

ISBN 90-247-2725-1 (this volume)
ISBN 90-247-2689-1 (series)

Printed in The Netherlands.

LARGE SCALE INTEGRATED TECHNOLOGY:
STATE OF THE ART AND PROSPECTS

NATO ADVANCED STUDY INSTITUTES SERIES

Proceedings of the Advanced Study Institute Programme, which aims at the dissemination of advanced knowledge and the formation of contacts among scientists from different countries.

The series is published by an international board of publishers in conjunction with NATO Scientific Affairs Division

A	Life Sciences	Plenum Publishing Corporation
B	Physics	London and New York
C	Mathematical and Physical Sciences	D. Reidel Publishing Company Dordrecht and Boston
D	Behavioural and Social Sciences	Martinus Nijhoff Publishers The Hague, Boston and London
E	Applied Sciences	

Series E: Applied Sciences – No. 55

PREFACE

A NATO Advanced Study Institute on "Large Scale Integrated Circuits Technology: State of the Art and Prospects" was held at Ettore Majorana Centre for Scientific Culture, Erice (Italy) on July 15-27, 1981, the first course of the International School of Solid-State Device Research.

This volume contains the School Proceedings: fundamentals as well as up-to-date information on each subject presented by qualified authors. The material covered in this volume has been arranged in self-consistent chapters. Therefore, the Proceedings may be used as a suitable textbook or authoritative review for research workers and advanced students in the relevant field.

The nascent information society is based on advanced technologies which will revolutionize human abilities to manipulate and communicate information. One of the most important underpinnings for developing such an information society lies in innovations in semiconductor microelectronics. Such innovations, indeed, are dramatically reducing the cost of transmitting, storing, and processing information with improved performance, ushering in an era characterized by large scale integration - the subject of this book.

L. Esaki

G. Soncini

March 1982

Contributors

D. A. Antoniądis

G. Baccarani

C. M. Bailey

F. Bertotti

A. N. Broers

G. J. Declerck

R. H. Dennard

C. Donolato

R. C. Eden

L. Esaki

B. Hoefflinger

W. Holt

R. W. Keyes

K. Kimura

B. O. Kolbesen

M. Montier

B. Murari

F. H. Reynolds

H. Ryssel

G. Soncini

T. Takahashi

E. J. VanDerveer

B. M. Welch

CONTENTS

CHAPTER V. MOS DEVICES

CHAPTER VI. RELIABILITY

CHAPTER VII. FUTURE TRENDS

These Proceedings were prepared by Peggy Powers and Maryann Pulice.

CHAPTER I

OVERVIEW

SEMICONDUCTOR DEVICES AND THE ROLE OF PHYSICS IN THEIR DEVELOPMENT

L. Esaki

IBM Thomas J. Watson Research Center
Yorktown Heights, New York 10598

ABSTRACT: Following a brief description of early semiconductor history, important events in device development are presented in perspective, with emphasis on the role of semiconductor physics.

I. INTRODUCTION

New scientific knowledge, arising from great inventions or discoveries, often leads to a large-scale engineering effort which eventually has far-reaching consequences in our society. The invention of the transistor by three solid state physicists, Shockley, Bardeen, and Brattain, is one such example. The development of the transistor began in 1947 through interdisciplinary cooperation with physicists, chemists, metallurgists and electronic engineers at Bell Laboratories. A large-scale developmental effort for a variety of semiconductor devices followed in a number of institutes throughout the world. Particularly, integrated circuits (ICs) have made an impressive evolution toward higher levels of integration during the past twenty years. Semiconductor know-how, thus established, has revolutionized the whole world of electronics --- data processing, telecommunications, industrial process control, military gears, scientific instruments and consumer products.

Solid-state or semiconductor physics undoubtedly has given an impetus in creating semiconductor technology. Semiconductor physics involves experimental investigation as well as theoretical understanding of the physical properties, including electrical, optical, and thermal properties and interactions with all forms of radiation in semiconductors. Many of these have been of interest since the 19th century, partly because of their practical applications and partly because of the richness of intriguing phenomena that semiconductor materials present.

Point-contact rectifiers made of a variety of natural crystals found practical applications as detectors of high-frequency signals in radio telegraphy in the early part of this century.[1] The natural crystals employed were lead sulphide (galena), ferrous sulphide, silicon carbide, etc. . Plate rectifiers made of cuprous oxide or selenium were developed for handling large power output. The selenium photocell was also found useful in the measuring of light intensity because of its photo-sensitivity.

In the late 1920's and during the 1930's, the new technique of quantum mechanics was applied to develop electronic energy band structure,[2] whereby a modern picture of the elementary excitations in semiconductors was obtained. Of course, this modern study has its roots in the discovery of x-ray diffraction by von Laue in 1912, which provided quantitative information on the arrangements of atoms in semiconductor crystals. Within this framework, attempts were made to obtain a better understanding of semiconductor materials and quantitative or semiquantitative interpretation of their transport and optical properties, such as rectification, photoconductivity, electrical breakdown, etc.

During this course of investigation on semiconductors, it was recognized in the 1930's that the phenomena of semiconductors should be analyzed in terms of two separate parts: surface phenomena and bulk effects. Rectification and photovoltaic effects appeared to be surface or interface phenomena, while ohmic electrical resistance with a negative temperature coefficient and ohmic photocurrent appeared to belong to bulk effects in homogeneous semiconductor materials. Relatively thick depletion layers near the surface are formed because of the existence of surface states which trap electrons and, also because of long screening lengths in semiconductors arising from much lower carrier concentrations than in metals. Thus the depletion of carriers creates potential barriers on the semiconductor surface or at the interface between a semiconductor and a metal contact, or between two semiconductors. The early recognition of the importance of surface physics was one of the significant aspects in semiconductor physics.

II. TRANSISTORS

Since the rectification in semiconductor diodes is analogous to that obtained in a vacuum diode tube, a number of attempts had been made to build a solid-state triode by inserting a "grid" into semiconductors or ionic crystals - a solid-state analog of the triode tube amplifier.[3] Because of relatively low densities of carriers in semiconductors, Shockley thought, control of the density of carriers near the semiconductor surface should be possible by means of an externally applied electric field between the surface and a metal electrode insulated from the surface -- the field effect device. The observed effect, however, was much less than predicted.[4] In 1947, in the course of trying to make a good "field effect" device with two gold contacts less than fifty microns apart on the germanium surface, Bardeen and Brattain made the first point-contact transistor where they discovered a phenomenon -- minority carrier injection into a semiconductor.[5] The importance of this phenomenon was soon recognized and led to the invention of the junction transistor by Shockley. The realization of this junction device, which did not occur until 1950,[6] was far more significant than its precursor.

The development of such junction transistors, as well as the progress in semiconductor physics on Ge and Si, would not have been accomplished without the key contribution of materials preparation techniques. Soon after Teal and Little prepared large Ge single crystals, Sparks successfully made a grown junction transistor.[7] The subsequent development was Pfann's zone refining and then Theuerer's floating zone method for silicon processing. These developments made it possible to make Ge and Si crystals of controlled purities and unprecedented perfection.

The early Ge junction transistors had poor frequency response and relatively low reliability. In fabricating these transistors, the grown-junction technique, or the alloying technique, was used to form p-n junctions. Then a procedure for forming p-n junctions by thermal diffusion of impurities was explored in order to obtain better reproducibility and tighter dimensional tolerances. This technique, indeed, enabled bringing forth the double diffused transistor with desirable impurity distribution, which was the prototype of the contemporary transistor.[8] Attention was also turned toward Si because of its expected high reliability and improved temperature capability.

In the 1940's, a team at Bell Laboratories selected elemental semiconductors, Ge and Si, for their solid-state amplifier project, primarily because of the possible simplicity in understanding and material preparation, in comparison with oxide or compound semiconductors. This not only was a foresighted selection but also had important implications: Ge and Si single crystals exhibited long diffusion lengths of hundreds of microns at room temperature, arising from both high carrier mobilities and long trapless lifetimes of minority carriers, which were a prerequisite to the desirable operation of the transistor. The long lifetimes may arise from the indirect energy-gap in these elemental semiconductors in contrast with the direct energy-gap in some III-V compound semiconductors which exhibit high rates of radiative recombination of electrons and holes.

The exploration of the III-V compound semiconductors was initiated through Welker's ingenuity and imagination, in the early 1950's, to produce semiconductor materials even more desirable for transistors than Ge or Si.[9] Although this initial expectation was not easily met, III-V compound semiconductors found their most important applications in LED, injection lasers, Gunn microwave devices, etc.; this could not have been achieved through elemental semiconductors. One might add that some III-V compound semiconductors demonstrate very intriguing characteristics: small effective masses for electrons (GaAs:0.067m_0 and InAs:0.023m_0), hence high electron mobilities (more than 100,000 cm^2/volt•sec at low temperatures) desirable for high-speed FETs; semi-insulating materials suitable for IC substrates; nearly perfect heteroepitaxy between two compounds enabling us to fabricate novel structures, etc. Such characteristics obviously will be exploited further in device development of the future.

III. IMPORTANT DEVICES

Now, in order to reach a perspective in semiconductor device development, it may be worthwhile to comment on some selected semiconductor devices:

1) Solar Cells - In 1940, Ohl observed a photovoltage as high as 0.5V by flashlight illumination in "naturally" grown Si p-n junctions.[10] The modern Si solar cell, however, was created by bringing together the seemingly unrelated activites, namely, large area p-n junctions by Fuller's diffusion method, Pearson's effort for power rectifiers, and Chapin's search for power sources of communication systems in remote locations.[11] This cell showed a conversion efficiency from solar energy to electrical energy of 4%. Low as this efficiency may seem today, in 1953 it was very exciting, improving on selenium by a factor of five. Development and production of solar cells were stimulated by the needs of the space program.

In 1972, heterojunction solar cells consisting of $pGa_{1-x}Al_xAs$-pGaAs-nGaAs, exhibiting power conversion efficiency of 16-20%, were reported by Woodall and Hovel.[12] The improved efficiencies were attributed to the reduction of both series resistance and surface recombination losses resulting from the presence of the heavily-doped $Ga_{1-x}Al_xAs$ layer. The recent advent of the energy crisis, however, generated a renewed interest in research and development for such solar cells as are economically viable for terrestrial applications. The development of amorphous Si solar cells is one such example.[13]

2) Tunneling Devices - Interest in the tunnel effect goes back to the early years of quantum mechanics. In the early 1930's, attempts were made to explain phenomena in solids such as rectification, contact resistance, etc., in terms of electron tunneling across the insulating barriers. However, since theories and experiments often gave conflicting results, not much progress was made at that time. Around 1950, semiconductor p-n junctions generated a renewed interest in the tunneling process. Experiments to observe such a process in the reverse breakdown of the junctions, however, were again inconclusive.

In 1957, Esaki demonstrated convincing experimental evidence for tunneling in his heavily-doped (narrow) p-n junction -- the tunnel diode.[14] This diode found usefulness in microwave applications because of its differential negative resistance being responsive to high frequencies. The discovery of the tunnel diode not only generated an interest in heavily-doped semiconductors but also helped to open a new research field on tunneling in semiconductors as well as in superconductors. The 1973 Nobel prize citation states, "....the pioneering work by Esaki provided the foundation and direct impetus for Giaever's discovery and Giaever's work in turn provides the stimulus which led to Josephson's theoretical predictions." The Josephson tunnel-junction devices, operated at superconducting temperatures, now find usefulness in rather unique applications The attempt has been made to use such quantum-mechanical devices as the basic switching elements for ultra high-speed computers, although their development is still at the early stage.

3) Integrated Circuits and MOS Devices - In 1958, Kilby initiated the fabrication of a circuit which included a number of transistors, diodes, resistors, and capacitors, all residing on one semiconductor chip.[15] This structure is called the (monolithic) integrated circuit. Around the same time, Noyce and Moore introduced improved fabrication techniques called the "planar" process which enabled the birth of the first modern transistor - a landmark in semiconductor history. It was soon realized that this transistor with dished junctions (extending to the surface) and oxide passivation (protecting the junctions), was most suited for assembling integrated circuits, because metal stripes evaporated over the surface oxide layer could be readily used for interconnections.[16]

As mentioned earlier, the transistor was invented while searching for a field-effect device. The field-effect concept originated as early as the 1920's, and yet no successful device was made in spite of a number of attempts because of lack of adequate technology. However, thermally-grown SiO_2 on Si single crystal surfaces, which was originally developed for the above-mentioned oxide passivation of junctions in the later 1950's, was found to be a most ideal insulator for such a field effect device by Kahng and Atalla.[17] This insulator, indeed, had relatively low loss and high dielectric strength, enabling the application of high gate fields. More importantly, the density of surface states at the Si-SiO_2 interface was kept so low that