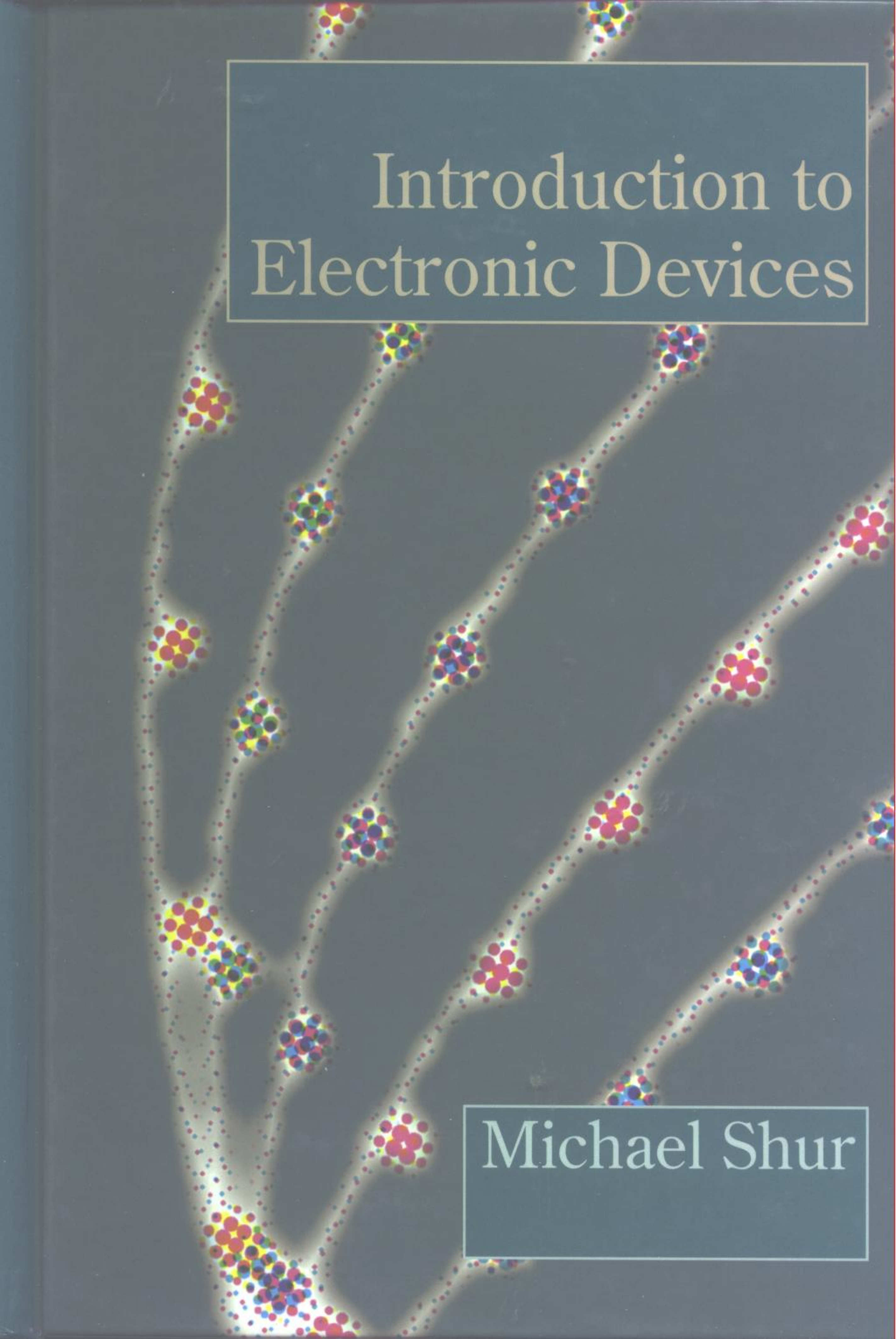
Introduction to Electronic Devices



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Preface

This is a textbook for electrical engineering students taking their first course in electronic devices during their junior or senior year. For many students, such a course may be the only one they will take on electronic devices; for others, it may become a gateway to an exciting career in this important engineering field. In either case, this course must form a solid foundation for understanding the basics of electronic device technology. This technology has penetrated every aspect of our lives. Electronic devices are found in home electronics, computers, cars, appliances, bank machines, copiers, phones, toys, and medical equipment. More and more, these devices determine the competitiveness of our economy and the strength of our defense. Just recall the role of smart munitions and night vision devices in the Gulf war. Both sides used the same explosives and their shells were made from the same metal. However, the Allied forces had superior semiconductor electronics. Or think about the large trade imbalance between the United States and Japan – a relatively small island country with few natural resources – in favor of the Japanese. We come to the conclusion that small semiconductor chips have become mightier than gold, or oil, or troops, or a large territory, or a large work force.

The importance of the course on the fundamentals of solid state devices for all electrical engineering students, irrespective of their future area of interest, cannot be overstated. A technician may treat an electronic device simply as a black box with characteristics described in manufacturer's data sheets but an electrical engineer cannot. She or he must understand how these devices work because the present dominance of solid-state devices will surely pale compared with what is expected to come in the near future. Three-dimensional flat panel room-size TVs integrated with private video phones with teleconference capabilities, cellular phones for everybody, paperless offices, notebook supercomputers, personal digital assistants, interactive university courses widely available on television, smart robots, intelligent electric cars, widespread use of photovoltaic technology, smart energy-efficient controls of heating and air conditioning in offices and homes, new sensors to control and protect environment are but a few technologies that will very soon become a reality. All these technologies will utilize new generations of electronic devices with vastly improved capabilities and at greatly reduced cost.

According to a great economist, Adam Smith, (who published "An Enquiry into Nature and causes of the Wealth of Nations" in 1776) wealth is created by a laissez-faire economy and free trade. According to John Maynard Keynes (who published "The General Theory of Employment Interest, and Money" in 1936), wealth is created by careful government planning and government stimulation of the economy. However new ideas in economics in 1990s (often linked to Paul Romer of Berkeley) emphasize the role of innovation (such as an invention of a computer chip) in creating wealth.

In the 1960s, a single semiconductor device, which was slow and inefficient by modern standards, may have cost a few dollars. Today, high-speed, low-power transistors used in computers or other electronic equipment cost as little as 10^{-3} cents.

Modern semiconductor electronics needs faster and faster devices which operate at less and less power. This requires the scaling down of typical device sizes. Advances in fabrication technology have reduced the minimum device feature size from about 20 microns in the early 1960s to submicron dimensions in the 1990s. In shorter devices, electrons take less time to travel across the device, leading to higher speeds and operating frequencies. A smaller device volume also translates into lower operating power and denser circuits. For example, the new Intel® microprocessor – Pentium™ – uses dimensions as short as 0.8 μm. It contains 3.1 million transistors on a one square inch semiconductor chip and runs approximately 15 times faster than microprocessors ran just a decade ago. Another new microprocessor – PowerPC 620 – (developed jointly by Apple, IBM, and Motorola) utilizes 7 million transistors with 0.5 μm feature sizes and operates at 133 MHz clock rate. Still, its power requirements are quite high (up to 30 W power dissipation at 3.3 V power supply). Texas Instruments is using even smaller, 0.35 μm devices in its new T5 microprocessor operating at up to 200 MHz clock rate. In research laboratories, engineers and scientists are experimenting with devices with dimensions less than one tenth of a micron.

Today, most semiconductor devices are made of silicon. However, submicron devices made of compound semiconductors, such as gallium arsenide or indium phosphide, successfully compete for applications in microwave and ultra-fast digital circuits. Other semiconductors, such as mercury cadmium telluride, are utilized in infrared detectors. Silicon carbide, aluminum nitride, and gallium nitride promise to be suitable for power devices operating at elevated temperatures and in harsh environments. As device dimensions shrink and more exotic compound semiconductor materials are used in electronic circuits, the physics involved in understanding the device behavior becomes more complicated and more fascinating. In novel device structures, the dimensions are so small that quantum effects become important or even dominant. Modeling, or even qualitative understanding, of these structures presents a formidable challenge. In this respect, the physics of semiconductor devices differs from more established "classic" engineering courses, such as courses on electromagnetic fields or circuit theory. The material here is not as firmly established and is somewhat in a state of flux. Kirchoff's current law will never change. However, even basic semiconductor equations, used for decades to analyze semiconductor devices, have to be questioned and revised when applied to very small devices.

All this makes teaching the first course on electronic devices a real challenge. Rational choices and compromises have to be made so that the students do not feel completely overwhelmed and can find links between this course and other core electrical engineering courses.

I wrote this book keeping all that in mind. Above all, I wanted to help the students gain a firm grasp of fundamentals. Ten years from now, solid-state device technology will surely change a great deal, but the fundamentals of semiconductor materials and device physics will probably remain the same. These fundamentals will still provide the firm foundation for mastering whatever new technologies will have been developed. Therefore, a considerable fraction of the material included into this book is devoted to physics and basic principles of device operation.

My other goal was to make the acquired knowledge very practical and to teach students how to use it for solving real problems. I tried to link the semiconductor device models described in the book to the models implemented in the popular integrated circuit simulator SPICE, which is used by a vast majority of electrical engineers. At least two free versions of SPICE are readily available for students - the student version of PSpice^{tm} by Microsim, Inc., and the student version of AIM-Spice. The student version of PSpice^{tm} can be ordered from Prentice Hall; the latest student version of AIM-Spice can be downloaded using an electronic mail (see the Instructions given in Appendix A8). I also included an example of a computer simulation of a semiconductor device using one of the most popular device simulators called PISCES (developed at Stanford). At many universities nowadays, PISCES is available even to undergraduate students.

Finally, my objective was to bring the reader to the forefront of modern electronic device technology. This is the reason why I included such topics as heterojunction devices, liquid crystal displays, and single electron electronics. The last chapter, "Novel Devices," gives the student an opportunity to use his or her basic knowledge of semiconductor device physics gained from the first eight chapters for the understanding of emerging device technologies.

After taking this course, students should be able to design a solar panel power supply for a portable computer. They should be able to use the circuit simulator, SPICE, to predict how the speed of an amplifier or a digital electronic circuit increases when the device dimensions are scaled down, and they should gain enough understanding of electronic devices to make an intelligent choice of device technology for a particular application. This is an example of how students can use the knowledge acquired in this course in combination with a very powerful Computer Aided Design (CAD) tool such as SPICE. For those students who will decide to delve into the subject matter more deeply, this course will give a firm foundation for further studies.

I am hoping that this book will appeal to a wide audience and that most readers will be find this book useful, perhaps, for different reasons. Quoting Alexander Pope (from an *Essay on Man*):

> The learned is happy nature to explore,
> The fool is happy that he knows no more;
> The rich is happy in the plenty given,
> The poor contents him with the care of Heaven.

The vast majority of electrical engineering students definitely fall into the first category.

Almost every section of the book ends with a summary of basic equations in a tabular form. This material can be useful for review purposes and exam preparation. Students taking advanced courses on semiconductor and solid state devices can use these tables to make sure that they know the material required as the prerequisite for these courses. These tables may also be useful for students and engineers preparing for qualifying or professional engineer examinations.

Not all of the material included into the book needs to be covered in a one semester lecture course. The section on tunneling in Chapter 1, the section dealing with one-dimensional and two-dimensional electron gas in Chapter 2, the section on the Hall effect in Chapter 3, the sections in Chapter 4 on the tunnel, Gunn, and IMPATT diodes and on computer simulations, Chapters 7 and 9 may be used for reading assignments or even skipped altogether. However, these sections and chapters (marked with asterisks in the table of contents) will be very useful for the students who intend to specialize in the area of the solid-state devices. Some other sections, such as the section on MOSFET modeling, can be better mastered by solving practical problems using SPICE.

For a typical 40-lecture course, two lectures may be devoted to the material in the Introduction, three lectures to quantum mechanical concepts (Sections 1.2 and 1.4), four lectures may cover basic solid-state physics (Chapter 2), and four more lectures may cover electrons and holes in semiconductors (Chapter 4). Approximately six lectures may be devoted to diodes and contacts (Sections 4.1 through 4.9), six lectures to BJTs (Sections 5.1 through 5.5), ten lectures to MOSFETs (Chapter 6), four lectures to photonic devices (Chapter 8), and two lectures to the final review. Chapter 9 could be also used as a starting point for undergraduate research projects.

This book contains many examples, problems, and review questions. The relative difficulty of review questions is rated by points based on my experience of using these questions for quizzes and exams. Most of the problems are fairly traditional and self-contained "engineering science" problems. Some of the problems will require a student to make reasonable guesses. Many problems and review questions (with numbers underlined) are "engineering design" problems that do not have unique solutions. I also included a fair number of problems that require a student to do calculations using a personal computer. I believe that students should be strongly encouraged to use MathCad^{tm} (a student version is really quite sufficient) or Mathematica^{tm} (at the universities where this software is available for undergraduate students), or even spreadsheets such as Lotus^{tm} or Excel^{tm}. This will give students an opportunity to gain some rudimentary number crunching experience and, perhaps more importantly, to build a sense of confidence in their ability to perform relatively long calculations and computations correctly, the ability that is crucial for all electrical engineers. In making up the problems, I tried to ensure that after taking the course the students will be comfortable with units and numbers, since I strongly believe that students must be able not just to understand how to solve a problem in principle but also be able to obtain accurate answers.

A few problems (marked with asterisks) are more advanced. They may be suitable for problem-solving sessions or may be worked in class.

For courses based on this book, I recommend that 75% of the credit hours should be allocated to engineering science and 25% to engineering design.

The book includes references to key monographs and textbooks in the field of semiconductor devices. In a way, I tried to make this book "a reference of references".

The Instructor's Manual (available free of charge to instructors) includes the answers to the review questions and problem solutions, basic semiconductor modeling software for the Macintosh computer, proposed lecture outlines, reading assignments, viewgraphs, and two types of handouts (2 slides per page and 6 slides per page) for each lecture for a 40 lecture course. The Instructor's Manual is also available in electronic form in order to simplify the preparation of homework assignments and exams.

We live in an unsentimental age, but I cannot help but admire the ideas and hard work of thousands and thousands of bright people who have contributed and are contributing to the area of electronic devices. The power of human mind, which transcends national boundaries and differences between generations, is behind every single electronic device. A great deal of thought and innovation went into every step along the way – from material growth and device fabrication to simulation and modeling. I feel truly privileged to be able to work in this field and admire these achievements. As the Japanese would say, I bow twice to device scientists and engineers, past, present, and future.

During the writing of this book, my wife, Paulina, provided me with invaluable support and encouragement. My colleagues at the Applied Electrophysics Laboratory here at the University of Virginia, especially Professors Bob Mattauch, Bill Peatman, Tom Crowe, Steve Jones, Elias Towe, and Kiang Lee, Drs. Boris Gelmont, Bjornar Lund, Hyunchang Park, and Alexei Bykhovski shared with me their insights into device physics and created an excellent environment for both research and teaching. I greatly benefited from working with Professors Tor Fjeldly, Kwyro Lee, Drs. Trond Ytterdal and

Michael Hack on the development of device models. I would like to thank Professor Konstantin Likharev for his suggestions regarding the superconductivity and single electronics sections. Dr. Peter Rabkin of Silvaco International helped me with the ATLAS-II simulation discussed in Section 4.13. Professors Tor Fjeldly, Mikhail Dyakonov, Gennadi Gildenblat, Ms. Holly Slade, Ms. Jodi Bowers, Mr. Mark Jacunski, and Mr. Jason Robertson made many useful comments. I am also most appreciative of the useful comments and suggestions of Professors Pritpal Singh, Reginald Perry, and Jasprit Singh who reviewed this manuscript. I am very grateful to my former and present graduate and undergraduate students for their hard work, enthusiasm, friendship, and support.

I will appreciate any comments, corrections, or suggestions which can be sent via electronic mail to *shur@virginia.edu.*

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List of Symbols

α	absorption coefficient
α	base transport factor
α	short-circuit common-base current gain
a, b, c	primitive basis vectors
a_B	Bohr radius
A_i	current gain
α_{ni}	electron impact ionization coefficient
A_p	power gain
α_{pi}	hole impact ionization coefficient
A_v	voltage gain
B	magnetic field
β	short-circuit common-emitter current gain
B_c	critical magnetic field
C	capacitance
c	velocity of light
C_d	differential capacitance
C_{dep}	depletion capacitance
D	detectivity
D	transmission coefficient
D	two dimensional density of states
D_n	electron diffusion coefficient
D_p	hole diffusion coefficient
E	energy
ε	dielectric permittivity
E_B	Bohr energy
E_c	conduction band edge
E_F	Fermi level

E_{Fn}	electron quasi-Fermi level
E_{Fp}	hole quasi-Fermi level
E_g	energy gap
E_i	intrinsic Fermi level
E_t	trap level
E_v	valence band edge
Φ	wave function (time dependent)
ϕ	electric potential
f	frequency
$f(\nu)$	radiation density for black-body radiation
$\mathbf{F}$, F	electric field
$F_{1/2}$	Fermi integral
F_{br}	breakdown field
FF	fill factor
Φ_m	metal work function
f_{max}	maximum frequency of oscillations
f_n	electron distribution function
f_p	hole distribution function
Φ_s	semiconductor work function
f_T	cutoff frequency
G	generation rate
γ	injection efficiency
g_d	drain conductance
g_m	transconductance
g_n	electron density of states
g_p	hole density of states
η	efficiency
η	ideality factor
h	Planck constant
$\hbar$	reduced Planck constant
I	current
i	$\sqrt{-1}$
I_L	light-generated current
I_s	saturation current
j	current density
j	quantum number
j_s	saturation current density
$\mathbf{K}$	reciprocal lattice vector
$\mathbf{k}$, k	wave vector
k_B	Boltzmann constant
l	orbital quantum number

λ	wavelength
L_{Dn}	electron Debye radius (electron Debye length)
L_{Dp}	hole Debye radius (hole Debye length)
L_n	electron diffusion length
L_p	hole diffusion length
m	grading coefficient
m	magnetic quantum number
m	mass
m_e	free electron mass
m_n	electron effective mass
m_p	hole effective mass
m_{ph}	heavy hole effective mass
m_{pl}	light hole effective mass
n	electron concentration
n	principal quantum number
N_a	acceptor concentration
N_c	electron effective density of states
N_d	donor concentration
n_G	Gummel number
n_i	intrinsic carrier concentration
n_{po}	equilibrium electron concentration in p-type semiconductor
n_r	refraction index
n_s	surface electron concentration
N_v	hole effective density of states
p	hole concentration
$\mathbf{p}$, p	momentum
p_{no}	equilibrium hole concentration in n-type semiconductor
q	electronic charge
Q_c	collection efficiency
Q_d	depletion charge per unit area
Q_e	quantum efficiency
$q\phi_b$	Schottky barrier height
Q_s	surface charge per unit area
R	recombination rate
R	reflection coefficient
R	resistance
R	responsivity
ρ	space charge density
$\mathbf{r}$	space vector
R_c	contact resistance

ρ_c	specific Ohmic contact resistance
R_d	differential resistance
r_H	Hall factor
R_s	series resistance
S	cross section
S	spin
σ	conductivity
S_n	electron surface recombination rate
S_p	hole surface recombination rate
T	temperature
t	film thickness
t	time
T_c	critical temperature
τ_{gen}	generation time
τ_{md}	Maxwell dielectric relaxation time
τ_{nE}	electron energy relaxation time
τ_{nl}	electron lifetime
τ_{np}	electron momentum relaxation time
τ_{pl}	hole lifetime
U	potential difference
U	potential energy
V	voltage
V_{abr}	critical voltage of avalanche breakdown
V_{bi}	built-in voltage
V_{brt}	critical voltage of tunneling breakdown
V_{BS}	substrate bias
V_{FB}	flat-band voltage
V_H	Hall voltage
$\mathbf{v_n}$, v_n	electron drift velocity
V_{oc}	open circuit voltage
$\mathbf{v_p}$, v_p	hole drift velocity
V_s	surface potential
v_s	saturation velocity
v_{sn}	electron saturation velocity
V_T	threshold voltage
V_{th}	thermal voltage
v_{th}	thermal velocity
W	device width
Ω	Ohm
Ω	two-dimensional density of states
ω	radian frequency

x	mole fraction
x, y, z	space coordinates
x_d	depletion region width
X_s	electron affinity
ψ	wave function (time independent)
μ_{FET}	field effect mobility
μ_H	Hall mobility
μ_n	electron mobility
μ_p	hole mobility
Δ	energy gap in superconductor energy spectrum
ΔE_c	conduction band discontinuity
ΔE_g	energy band discontinuity
ΔE_v	valence band discontinuity

Contents