Introduction to VLSI Silicon Devices

Physics, Technology and Characterization

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TABLE OF SYMBOLS

Symbol	Description	Units
a	Grade constant, pn junction	cm^{-4}
a	Voltage ramp rate, quasistatic measurement	V/s
A	Area	cm^2
A_s	Silicon surface area	cm^2
BV	Breakdown voltage	V
BV_{CBO}	Collector-base breakdown voltage, emitter open	V
BV_{CEO}	Collector-emitter breakdown voltage, base open	V
C	Capacitance	F
C_A	Capacitance area component	F
C_D	Diffusion capacitance	F
C_C	Collector capacitance	F
C_E	Emitter capacitance	F
C_{FB}	Flatband capacitance	F
C_{it}	Interface trap capacitance	F
C_{HF}	High frequency capacitance	F
C_{LF}	Low frequency capacitance	F
C_{max}	Maximum MIS capacitance	F
C_{min}	Minimum MIS capacitance, thermal equilibrium	F
C_{ox}	Equivalent oxide capacitance	F
C_P	Capacitance perimeter component	F
C_{si}	Silicon capacitance	F
C_{siFB}	Silicon capacitance at flatband	F
D_n	Diffusion constant of electrons	cm^2/s
D_p	Diffusion constant of holes	cm^2/s
E	Electric field	V/cm
E_c	Critical field	V/cm
E_p	Peak electric field	V/cm
E_g	Energy gap	eV
h_{FE}	Large signal transistor gain	---
f_T	Frequency at which $\beta = 1$	Hz
I	Current	A
i_A	Leakage current per unit area	A/cm^2
I_C	Collector current	A
I_{CBO}	Collector-base leakage current, emitter open	A

TABLE OF SYMBOLS
(Continued)

Symbol	Description	Units
I_D	Drain current	A
I_E	Emitter current	A
I_F	Forward current	A
I_{FIJ}	Leakage current in field-induced junction	A
I_G	Gate current	A
I_{gen}	Generation current	A
I_L	Leakage current	A
I_m	Current due to mobile ions	A
I_{MJ}	Leakage current in metallurgical junction	A
I_n	Electron current	A
I_o	Saturation current	A
i_p	Leakage current per unit perimeter	A/cm
I_p	Hole current	A
I_{PT}	Punch-through current	A
I_R	Reverse current	A
I_s	Transistor saturation current	A
I_s	Substrate current	A
I_w	Well current	A
j	Current density	A/cm^2
j_G	Gate current density	A/cm^2
j_n	Electron current density	A/cm^2
j_{ni}	Electron current density in intrinsic base	A/cm^2
j_{nc}	Electron current density into base contact	A/cm^2
j_p	Hole current density	A/cm^2
j_{pc}	Hole current density into emitter contact	A/cm^2
j_{pl}	Lateral hole current density	A/cm
j_{pv}	Hole current density into substrate	A/cm^2
j'_{pv}	Hole current density into buried n^+ layer	A/cm^2
k	Boltzmann constant	$eV/°K$
k	Scaling factor	---
L	Channel length	cm
L_{eff}	Effective channel length	cm
L_D	Extrinsic Debye length	cm

TABLE OF SYMBOLS
(Continued)

Symbol	Description	Units
L_i	Intrinsic Debye length	cm
L_n	Diffusion length of electrons	cm
L_p	Diffusion length of holes	cm
m	Mass of electron	g
M	Multiplication factor	---
n	Electron density	cm^{-3}
n	Ideality factor	---
n_i	Intrinsic carrier concentration	cm^{-3}
n_n	Electron concentration in n-type silicon	cm^{-3}
$\bar{n}_n$	Equilibrium majority electron concentration	cm^{-3}
n_{no}	Boundary majority electron concentration	cm^{-3}
$\bar{n}_{no}$	Boundary equilibrium majority electron conc.	cm^{-3}
n_p	Minority Electron concentration	cm^{-3}
$\bar{n}_p$	Equilibrium minority electron concentration	cm^{-3}
n_{po}	Boundary minority electron concentration	cm^{-3}
$\bar{n}_{po}$	Boundary equilibrium minority electron conc.	cm^{-3}
n_s	Surface electron concentration	cm^{-3}
N_a	Acceptor concentration	cm^{-3}
N_a^-	Ionized acceptor concentration	cm^{-3}
N_d	Donor concentration	cm^{-3}
N_d^+	Ionized donor concentration	cm^{-3}
N_{si}	Density of atoms in silicon	cm^{-3}
N_t	Density of traps in silicon	cm^{-3}
N_{ox}	Density of atoms in silicon-dioxide	cm^{-3}
p	Hole concentration	cm^{-3}
P	Power	W
P	Perimeter	cm
p_n	Minority Hole concentration	cm^{-3}
$\bar{p}_n$	Equilibrium minority hole concentraton	cm^{-3}
p_{no}	Boundary minority hole concentration	cm^{-3}
$\bar{p}_{no}$	Boundary equilibium minority hole concentration	cm^{-3}
p_p	Majority hole concentration	cm^{-3}
$\bar{p}_p$	Equilibrium majority hole concentration	cm^{-3}
p_{po}	Boundary majority hole concentration	cm^{-3}

TABLE OF SYMBOLS
(Continued)

Symbol	Description	Units
$\bar{p}_{po}$	Boundary equilibrium majority hole conc.	cm^{-3}
p_s	Surface hole concentration	cm^{-3}
q	Elementary charge	C
Q	Charge per unit area	C/cm^2
Q_b	Bulk charge density of ionized impurities	C/cm^2
Q_{eff}	Effective insulator charge density	C/cm^2
Q_f	Fixed oxide charge density	C/cm^2
Q_G	Charge density induced on the gate	C/cm^2
Q_{it}	Interface trap charge density	C/cm^2
Q_m	Mobile ion charge density	C/cm^2
Q_n	Free electron charge density	C/cm^2
Q_{ot}	Oxide trap charge density	C/cm^2
R	Resistance	Ohm
R_c	Contact resistance	Ohm
R_C	Collector resistance	Ohm
R_{ch}	Channel resistance	Ohm
r_E	Emitter dynamic resistance	Ohm
r_j	Junction curvature	cm
R_E	Emitter resistance	Ohm
R_P	Projected range of ions	cm
R_s	Sheet resistance	Ohm/square
R_s	Substrate resistance	Ohm
R_w	Well resistance	Ohm
s_o	Surface recombination velocity	cm/s
t	Time	s
t	Thickness	cm
t	Temperature	°C
T	Temperature	°K
t_f	Fall-time	s
t_d	Delay time	s
t_{eq}	Equivalent oxide thickness	cm
t_i	Insulator thickness	cm
t_n	Thickness of silicon-nitride	cm
t_r	Rise-time	s

TABLE OF SYMBOLS
(Continued)

Symbol	Description	Units
t_s	Storage time	s
t_{si}	Thickness of silicon	cm
t_{ox}	Oxide thickness	cm
v	Velocity	cm/s
v_d	Drift velocity	cm/s
v_s	Scattering limited velocity	cm/s
v_{th}	Thermal velocity	cm/s
V	Voltage	V
V_b	Built-in voltage	V
V_{BE}	Base-emitter voltage	V
V_{CB}	Collector-base voltage	V
V_D	Drain voltage	V
V_G	Gate voltage	V
V_H	Most positive voltage	V
V_{ox}	Voltage across oxide	V
V_{PT}	Punch-through voltage	V
V_s	Source to substrate bias	V
V_t	Thermal voltage	V
V_T	Threshold voltage	V
x	Depth	cm
x_d	Depletion width	cm
x_{dmax}	Maximum field-induced depletion width	cm
x_{dn}	Depletion width in n-side	cm
x_{dp}	Depletion width in p-side	cm
x_{ds}	Depletion width at surface	cm
x_j	Junction depth	cm
W	Channel width	cm
W_b	Base width	cm
W_{eff}	Effective channel width	cm
W_n	Width of n-type material	cm
W_p	Width of p-type material	cm
α	Current gain, I_C/I_B	---
α_n	Current gain of npn transistor	---
α_p	Current gain of pnp transistor	---

TABLE OF SYMBOLS
(Continued)

Symbol	Description	Units
β	Current gain, I_C/I_B	---
β	IGFET beta, = $\gamma W/L$	$\Omega^{-1}V^{-1}$
γ	Injection ratio	---
γ	Normalized transconductance	$\Omega^{-1}V^{-1}$
Δ	Small variation	---
ΔR_p	Range straggling	cm
ε_i	Insulator dielectric constant	---
ε_n	Dielectric constant of nitride	---
ε_o	Permittivity of free space	F/cm
ε_{ox}	Dielectric constant of oxide	---
ε_{si}	Dielectric constant of silicon	---
μ	Mobility	cm^2/Vs
μ_n	Electron mobility	cm^2/Vs
$\bar{\mu}_n$	Effective electron mobility	cm^2/Vs
μ_p	Hole mobility	cm^2/Vs
ρ	Resistivity	$\Omega - cm$
ρ	Charge density	C/cm^3
σ	Conductivity	$\Omega^{-1}cm^{-1}$
τ	Time constant	s
τ_B	Base transit time	s
τ_C	Collector time constant	s
τ_{FIJ}	Minority lifetime, field-induced junction	s
τ_{MJ}	Minority lifetime, metallurgical junction	s
τ_n	Electron lifetime	s
τ_p	Hole lifetime	s
ϕ	Barrier	V
ϕ_b	Schottky Barrier height	V
ϕ_m	Metal work function	V
ϕ_{ms}	Work function difference	V
ϕ_{si}	Silicon work function	V
χ	Electron affinity	eV
ψ_s	Surface potential	V
ω	Angular frequency	s^{-1}

Preface

There was a long felt need for this book in industrial and academic institutions. It provides new engineers, as well as practicing engineers and advanced laboratory personnel in the field of semiconductors a clear and thorough discussion of state-of-the-art silicon devices, without resorting to the complexity of higher mathematics and physics. This difficult task was made possible by detailing the explanation of equations that describe the device operation and characteristics without endeavoring their full derivation. This is reinforced by several problems which reflect practical cases observed in the laboratory. The problems are given after introducing a major equation or concept. They are arranged in the order of the text rather than in the order of difficulty. The answers to most of the problems are given in order to enable the student to "self-check" the method used for the solutions. The illustrations may prove to be of great help to "newcomers" when dealing with the characterization of real devices and relating the measured data to device physics and process parameters. The new engineer will find the book equivalent to "on the job training" and acquire a working knowledge of the fundamental principles underlying silicon devices. For the engineer with theoretical background, it offers a means for direct application of solid state theory to device analysis and synthesis.

The book originated from a set of notes developed for an in-house one-year course in Device Physics, Technology and Characterization at IBM. It is specifically written for the college graduate new in the field of semiconductors. It is also potentially useful to the practicing engineer and scientist who seek to "update" their knowledge on VLSI devices and methods for parameter extractions. It can be used for an introductory course in semiconductors in universities, colleges and technical institutes and may be introduced early in the curriculum because the only prerequisite in mathematics is algebra and elementary calculus. The book consists of six chapters, organized in a logical sequence and covering the range from basic silicon properties to advanced FET and bipolar concepts, including short-channel and narrow-channel effects, and device limitations. There is frequent cross-reference between the chapters. However, occasional overlapping in material was necessary in order to discuss major sections independently. The units used throughout are not consistent mks units. There is frequent use of the angstrom, micrometer and centimeter as the unit of length and electron-volt as the unit of energy. Furthermore, units have been associated with several equations. It is believed that this approach will help better visualizing the quantities in semiconductors. A table of conversion factors is provided on the inside covers of the book. It was attempted to gradually raise the level from chapter 1 to the more difficult sections in chapter 3 after which the level of difficulty remains fairly constant. In each chapter a qualitative description of the device is first given and then followed by a gradual progression into a deeper understanding of the formulas that describe the relations between device and process parameters.

The book begins with the properties of the silicon crystal. The two-carrier concept is introduced on the basis of localized covalent bond-breaking rather than the band-diagram. The effects of temperature and impurities on the carrier concentrations and transport are discussed in detail. Finally, techniques are described to measure bulk and contact resistances and to relate the data to the impurity profile and temperature.

The second chapter details the description of real pn junctions. The formation of the junction is described, using first a thought experiment and then a simple process sequence. The concepts of built-in voltage, depletion regions and junction capacitance are introduced. Methods are described to characterize the junction at thermal equilibrium and under forward and reverse bias.

The third chapter begins with a qualitative discussion of bipolar action and methods to fabricate typical bipolar devices in the planar technology. The process and design parameters that determine the current-voltage characteristics of the device are then discussed quantitatively. This includes devices operated in forward and reverse, vertical and lateral transistors, low-level and high-level injection, second-order effects and voltage and current limitations. In addition, there is useful information on the characteristics of Schottky-barrier diodes, and their applications.

The analysis of the Metal-Insulator-Silicon (MIS) structure in chapter 4 lays the groundwork for a thorough understanding of Insulated Gate Field Effect transistors (IGFET). The structure is introduced not only as a device that is later extended to an IGFET but also as a powerful tool for process control and diagnostics. The concepts of accumulation, flatband, weak and strong inversion, and threshold voltage are introduced, and the effects of work function difference and oxide charge on the flatband voltage are discussed in detail. Finally, the pulsed CV and quasistatic techniques are described and used to further characterize the silicon surface, sub-surface and insulator quality.

In chapter 5 a junction is placed under the MIS structure to form a gate-controlled pn junction. This provides a tool to measure surface effects on the junction reverse and forward characteristics and to analyze the parameters that affect the threshold voltage and substrate bias sensitivity (body-effect). Finally, the mechanism and effect of hot-carrier injection and trapping in the insulator are discussed.

The discussion of the Metal Insulator Silicon and gate controlled structures brings out much of the physics needed to describe the fundamentals of IGFET's. Chapter 6 begins with a description of basic processing technologies of typical IGFET's followed by an analysis of the current-voltage characteristics of devices having large dimensions and uniform and nonuniform substrate profiles. Major IGFET reliability considerations are discussed. This includes the mechanism of substrate and channel hot electron effects and transient upsets due to the incidence of single energetic particles. Second-order effects, such as short and narrow channel effects are introduced together with device limitations as the device dimensions are reduced. The chapter concludes with a detailed discussion of Complementary Metal-Oxide-Silicon (CMOS) structures which has added substantial flexibility to VLSI by combining n-channel and p-channel devices on the same chip. The advantages and limitations of CMOS are detailed using a simple inverter. In particular, the SCR action (latch-up) in CMOS is related to the horizontal and vertical device geometries. The different process considerations and trade-offs are discussed and a typical CMOS technology described for illustration.

The authors hope that the book will be useful to new engineers in the field of semiconductors and that this may justify a second edition at a later time. With this in mind, they would appreciate comments from their readers.

Acknowledgements

Several explanations and illustrations were adapted from available publications which we hope to have given proper credit. In particular, we have used in chapters 1, 2 and 3 descriptions from the SEEC series, as referenced in the text.

We thank all the students and colleagues at IBM for their invaluable discussions and suggestions for improving the manuscript and the course. We also wish to express our thanks to Dr. J. Uyemura, Georgia Institute of Technology, and Dr. W. Bidermann, Digital Equipment Corporation for reading all the book prior to publication and helping improve it. In particular, Dr. Uyemura's critical reading of the text has resulted in several changes and improvements.

One of us (BEK) is grateful to Dr. W.P. Noble Jr. (IBM), for not only allowing him to use some of his notes and figures on the short and narrow channel effects but also for carefully reading and correcting the last two chapters, and to R. C. Flaker (IBM) for reading and correcting the chapter on bipolar transistors.
BEK remains deeply grateful to his dear friend and colleague Dr. A.F. Puttlitz (IBM) for patiently and thoroughly reading the entire book in manuscript and then in proof stage and relentlessly solving several problems, checking the numerical accuracy and correcting the errors. We and not he take the full blame for the remaining errors.

For allowing us the adaptation or reprint of their figures and illustrations acknowledgement is due to J. Wiley Publishing Co. for figures 2.25, 2.26 and 2.27, Pergamon Press Inc. for figure 1.16, MC Morgan-Grampian Publishing Co. (Benwill Publishing Corp.) for figures 1.25, 1.26, 1.27 and 1.29, Bell Telephone Labs. for the nomograph in table 2.1, Tektronix Inc. for figures 3.10, 3.11, 3.13, 3.29 and 3.32, and Academic Press Inc. for figure 6.18.

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BEK, RJB

CONTENTS

CHAPTER 1

RESISTANCES AND THEIR MEASUREMENTS

1.0 Introduction

Electric current is the flow of charged particles. In order to contribute to the current, the charged particles must be free to move. In metals the carriers of electricity are negatively charged free electrons. In semiconductors such as silicon there are two types of carriers, namely free electrons and positive holes. If silicon, a group IV element, is doped with elements of the fifth group, such as arsenic or phosphorus, the concentration of free electrons increases while the concentration of holes decreases. In this case silicon becomes n-type, since it contains electrons as majority carriers and holes as minority carriers. When silicon is doped with elements of the third group, such as boron, it becomes p-type with holes as majority carriers and electrons as minority carriers. At room temperature the carriers have enough thermal energy to keep in constant but random motion as illustrated in figure 1.1.

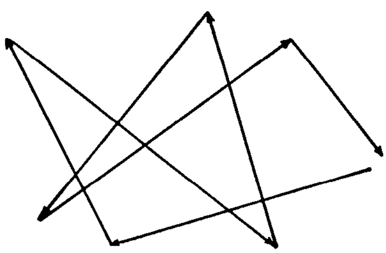

Fig. 1.1 Random motion of a carrier in a crystal. Each arrow represents a random path between collisions. On the average the carrier does not move in a particular direction. At room temperature the carriers fly at a velocity of about 10^7 cm/s between collisions.