Implantable Medical Electronics

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Prosthetics, Drug Delivery, and Health Monitoring

Springer

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This book is dedicated to:
My late father Shri Amarnath Khanna
for giving me education and wisdom
My mother Shrimati Pushpa Khanna
for her tender care and affection
My daughter Aloka for bringing joy
and happiness in the family
and
My wife Amita for her unstinted support
and cooperation

Preface

About this Book

Implantable medical electronics brings together the essentials of electronics and medical devices implanted in the human body for overcoming various disease conditions such as for pacing the activities of the heart, the brain, and the network of nerves interconnecting the brain or the spinal cord with vital organs of the body; for performing measurements of vital biological parameters to keep surveillance over the health status of a person; and for delivering precise doses of drugs at targeted sites at predetermined dose rates and times. Notable among these diseases are the abnormal rhythms of the heart, the movement disorders, chronic back pain, epileptic seizures, respiratory deficiencies, urine and fecal incontinence problems, deafness due to sensorineural hearing loss, blindness caused by photoreceptor degeneration in the retina, and so forth. In many of these diseases, conventional pharmacological therapies have failed either totally or have been unsuccessful in eliciting a satisfactory response. Thus apart from taking drugs with associated side effects and correction by surgical interventions with attendant risks, there is a definite possibility of getting relief from serious diseases by means of implanted electronic pulse generators as pacing devices, along with implanted/wearable sensors and wireless body sensor networks, telecommunication, and advanced electronic gadgetry as health watchdogs.

This book is written at an introductory level to meet the requirements of students of both electronic and biomedical engineering and electronic instrumentation as well as professionals and researchers engaged in this fast-advancing multidisciplinary field. Providing definitions of important terms wherever necessary, it will be of great interest to the general reader interested in this emerging area of immense value to humankind at large.

Why This Book Was Written?

Implantable medical electronics is a fast-growing area, which has not only brought succor to a vast chunk of population but has also helped in pulling out many from the claws of death. Every day new technologies and new devices are reported, bringing immense relief to the suffering people. However, the information on implantable electronics lies scattered at different places. A cohesive compendium of knowledge on this field, synthesizing the information dispersed among different databases, is therefore called for. So, the foremost reason that this book was needed was that the latest information on implantable medical electronics is presently found only in research journals and on web pages. Therefore, a broad-spectrum compilation making this information available as an all-in-one resource between the covers of a single book was urgently required.

Another major reason for the need of this book was that the information given in electronics journals and magazines is provided at a level which is not comprehensible to medical students. The same is true about the information in medical journals and magazines, which is not easily grasped by students of electronics engineering. Therefore, a book steering the midway course and providing the information at a level understandable to both categories of students was the need of the hour.

Perhaps the paramount motivation was that the book was mandated by the need of an interdisciplinary book striking a balance between electronics and biomedical engineering. Keeping this in view, definitions of both the electronics and medical terms are provided, as and when it is felt that the subject will be elusive to any of the above categories of audience.

For Whom This Book Was Written?

The book is written to cater to the needs of the graduate students of electronics engineering, electronic instrumentation, and biomedical engineering. Apart from these students, another class of targeted audience is that of academic researchers in this field. They will benefit from the up-to-date bibliographies that will refer them to the excellent original literature and thus help them in pursuing their exploratory ventures. Additionally, professional engineers, practicing doctors and paramedical staff, and interested lay readers too are likely to acquire useful knowledge about this interesting field.

Layout of the Book

The book is divided into two parts: basic concepts and principles (Chaps. 2–11) and applications (Chaps. 12–23). In this book, an all-embracing perspective of the necessary electronics background is provided in the preliminary chapters (2–11).

Chapter 12 deals with implantable neural amplifiers and Chap. 13 with implantable sensors. Chapters 14–22, describe pacing techniques used for the heart, the brain, the spinal cord, and the network of nerves running through the body and interlinking the brain/spinal cord with its main organs. In the final chapter, Chap. 23, glimpses of controlled drug delivery systems are presented. Chapter-wise organizational arrangement of the book will be elaborated in the introductory chapter.

Pilani, Rajasthan, India Vinod Kumar Khanna

Acknowledgments

This book would never have come to reality without the blessings from a lot of people. To name all these people without forgetting anybody is a difficult task.

To be able to write a book is to have traversed a long and twisting road, full of bumps and depressions. To write the acknowledgments section is to try to tell which stepping stones en route were the most important ones.

I will begin with thanking the "reader" of this book. Perhaps the astute reader is the one that always gave me inspiration for writing the book on this burning topic-topic, which signifies a paradigm shift from the traditional approaches of drug therapy and corrective surgery. This paradigm shift is leading a transformative wave, redefining medical benchmarkings and outcomes.

I thank my editors for providing me an opportunity to work on this project and providing me the requisite guidance and help, as and when necessary.

I am thankful to Director, CSIR-CEERI, Pilani for constant encouragement in my work.

I thank all colleagues at CSIR-CEERI for their moral support, companionship in despair, and motivation to move on.

I wish to thank my family, my daughter, and my wife without whose support I would never have been able to complete this task and, more importantly, not even begun it.

Thank you all!

Acronyms, Abbreviations, and Symbols

AC	Alternating current
AC-LSK	Auxiliary carrier load shift keying
A/D	Analog-to-digital (converter)
ADC	Analog-to-digital converter
AED	Antiepileptic drug
AFE	Analog front end
Ah	Ampere hour
Al_2O_3	Aluminum oxide
ALIC	Anterior limb of the internal capsule
ALU	Arithmetic and logic unit
AM	Amplitude modulation
A_M	Midband gain
ARM	Advanced RISC machines
ARMD	Age-related macular degeneration
ASK	Amplitude shift keying
ATP	Adenosine triphosphate, antitachycardia pacing
ATPase	Adenosine triphosphatase
AV	Atrioventricular (node)
AZA	Autozeroing amplifier
BAP	Bio-artificial pancreas
BASK	Binary amplitude shift keying
BFSK	Binary frequency shift keying
BGA	Ball-grid array
BJT	Bipolar junction transistor
BPEG	British Pacing and Electrophysiology Group
bps	Bits per second
BPSK	Binary phase shift keying
C	Capacitance
CAN	Controller area network
CAP	Carbonated apatite
CCCS	Current-controlled current source

CCS	Current-controlled stimulation
CDIP	Ceramic dual in-line package
CF_x	Carbon monofluoride
CG	Control gate
ChCS	Charge-controlled stimulation
CHS	Chopper stabilized
CI	Cochlear implant
CISC	Clean intermittent self-catheterization
cm	Centimeter
CMOS	Complementary metal–oxide–semiconductor
CMRR	Common mode rejection ratio
CPU	Central processing unit
CRC	Cyclic redundancy check
CRPS	Complex regional pain syndrome
CSF	Cerebrospinal fluid
CT	Computerized tomography
C_T	Timing capacitor
CTAT	Complementary to absolute temperature
D	Duty cycle
DAC	Digital-to-analog converter
dB	Decibel = 10 $\log_{10}$(power P_2/power P_1)
DBS	Deep brain stimulation
DC	Direct current
DCS	Dorsal column stimulation
DIBL	Drain-induced barrier lowering
DIP	Dual-in-line package
DMA	Direct memory access
DNA	Deoxyribonucleic acid
DOD	Depth of discharge
D/P	Diaphragmatic/phrenic (nerve)
DRAM	Dynamic random access memory
DREZ	Dorsal root entry zone
DSP	Digital signal processing
DVS	Dynamic voltage scaling
E_C	Critical electric field
ECC	Error-correcting code
ECT	Electroconvulsive therapy
EEG	Electroencephalography
EEPROM	Electrically erasable programmable read-only memory
EIA	Electronic Industries Association
EIRP	Effective isotropic radiated power
EMF	Electromotive force
EMG	Electromyography
EMI	Electromagnetic interference
EPS	Extrapyramidal symptoms

ESD	Electrostatic discharge
ET	Essential tremor
f	Frequency
FASTROM	Factory advanced service technique read-only memory
FBSS	Failed back surgery syndrome
FCBGA	Flip chip ball-grid array
FCC	Federal Communications Commission
FDA	Food and Drug Administration, USA
FDTD	Finite-difference time domain
FET	Field-effect transistor
FG	Floating gate
FGMOSFET	Floating gate metal–oxide–semiconductor field-effect transistor
FM	Frequency modulation
FPU	Floating-point unit
FSK	Frequency shift keying
FXTAS	Fragile X-associated tremor ataxia syndrome
G	Gate, Giga
g	Gram
GABA	Gamma-amino butyric acid
GCT	Gate control theory
GHz	Gigahertz
GIDL	Gate-induced drain leakage
g_m	Transconductance
GPi	Globus pallidus internus
GUI	Graphic user interface
HAP	Hydroxyapatite
H_2O_2	Hydrogen peroxide
Hz	Hertz
I	Current
IC	Integrated circuit
ICD	Implantable cardioverter defibrillator
IDDS	Implantable drug delivery system
I_{DQQ}	Quiescent power supply current
I_{DS}	Drain-source current
IEEE	Institute of Electrical and Electronics Engineers
I_{in}	Input current
IM	Intermodulation
IMD	Implanted medical device, intermodulation distortion
I/O	Input/output
I_{out}	Output current
IPG	Implanted pulse generator
IV	Intravenous
I/V	Current-to-voltage (converter)
J	Joule
K	Kelvin

Kbps	Kilobits per second
kDa	Kilo Dalton
kHz	Kilohertz
L	Inductance, liter
LBT	Listen before talk
LC	Inductance–capacitance
LCD	Liquid crystal display
LCP	Liquid crystal polymer
LCR	Inductance–capacitance–resistance
LDD	Lightly doped drain
Li	Lithium
$Li_xAg_2V_4O_{11}$	Lithiated silver vanadium oxide
$LiBF_4$	Lithium tetrafluoroborate
$LiCoO_2$	Lithium cobalt oxide
$LiFePO_4$	Lithium iron phosphate
LIGA	Lithographie, galvanoformung, abformung (German words for lithography, electroplating, and molding)
LPF	Low-pass filter
LPS	Li_3PS_4 (lithium thiophosphate)
LSB	Least significant bit
LSK	Load shift keying
m	Meter
mA	Milliampere
Mbps	Megabits per second
MDD	Major depressive disorder
MEDS	Medical data services
MEMS	Microelectromechanical systems
MHz	Mega hertz
MICS	Medical implant communication service
MITS	Medical implant telemetry system
MnO_2	Manganese dioxide
MOD	Modulo
MOSFET	Metal–oxide–semiconductor field-effect transistor
MPE	Maximum permissible exposure
MRI	Magnetic resonance imaging
ms	Millisecond
MSB	Most significant bit
mV	Millivolt
mW	Milliwatt
nA	Nanoampere
NASPE	North American Society of Pacing and Electrophysiology
NBG	North British Generic (code)
NBTI	Negative-bias temperature instability
nm	Nanometer
NMOS	N-Channel MOSFET

NOS	Nitric oxide synthase
NVM	Nonvolatile memory
OCD	Obsessive–compulsive disorder
OCT	Optical coherence tomography
OFC	Orbitofrontal cortex
OOK	On–off keying
OP-AMP	Operational amplifier
OTA	Operational transconductance amplifier
OTP	One-time programmed memory
pA	Pico ampere
PAA	Peroxyacetic acid
PAM	Pulse amplitude modulation
PBN	Parabrachial nucleus
PC	Personal computer
pCO_2	Partial pressure of carbon dioxide (in blood)
PD	Parkinson's disease
PDIP	Plastic dual in-line package
PDM	Pulse duration modulation
PDMS	Polydimethylsiloxane
PDN	Pull-down network
PEEK	Polyetheretherketone
PEG	Polyethylene glycol
pH	Potential of hydrogen = $-\log_{10}[H^+]$
PHM	Pulse harmonic modulation
PI	Polyimide
PLCC	Plastic leaded chip carrier
PMMA	Poly(methyl methacrylate)
PMOS	P-Channel MOSFET
pO_2	Partial pressure of oxygen (in blood)
PPGA	Plastic pin-grid array
PPN	Pedunculopontine nucleus
PPSK	Passive phase shift keying
PROM	Programmable ROM
PSK	Phase shift keying
PSRR	Power-supply rejection ratio
PTAT	Proportional to absolute temperature
PTFE	Polytetrafluoroethylene
PUN	Pull-up network
PVDF	Polyvinylidenedifluoride
PVP	Polyvinylpyridine
PWM	Pulse width modulation
Q	Charge, quality factor
QRS complex	A grouping of three deflections in ECG recording
Quad	Four
R, r	Resistance

RAM	Random access memory
RC	Resistance–capacitance
RCs	Respiratory control centers
R-D	Reaction–diffusion (model)
RDAC	Resistive digital-to-analog converter or digipot
RF	Radio frequency
RISC	Reduced instruction set computer
R_L	Load resistor
RMS	Root mean square
ROI	Return on investment
ROM	Read-only memory
RP	Retinitis pigmentosa
RSD	Reflex sympathetic dystrophy
RSNOs	S-Nitrosothiols
R_T	Timing resistor
RV	Right ventricle
RWTT	Reflected wave transit time
SA	Sinoatrial (node)
SAB	Surface-activated bonding
SAR	Successive-approximation-register, specific absorption rate
SAW	Surface acoustic wave
SCCwm	Subcallosal cingulate white matter
SCD	Sudden cardiac death
SCI	Serial communications interface
SCS	Spinal cord stimulation
SDSR	Self-driven synchronous rectifier
SHDN	Shut down
Si	Silicon
SILC	Stress-induced leakage current
SiO_2	Silicon dioxide
SMPS	Switch-mode power supply
SNHL	Sensorineural hearing loss
SNM	Sacral neuromodulation
SNS	Sacral nerve stimulation
SOC	State of charge
SoC	System on chip
SPI	Serial peripheral interface
SRAM	Static random access memory
Steel: 316	Steel containing 16 % chromium, 10 % nickel, and 2 % molybdenum
Steel: 316L	Low-carbon version of 316 stainless steel resistant to highly corrosive environments
STN	Subthalamic nucleus
SVO	Silver vanadium oxide $Ag_2V_4O_{11}$
SWCNT	Single-walled carbon nanotube

T	Temperature, time, time period
T1D	Type 1 diabetes
TDDS	Transdermal drug delivery system
TiN	Titanium nitride
TNF	Tumor necrosis factor
TRD	Treatment-resistant depression
TRM	Tissue response modifier
UART	Universal asynchronous receiver/transmitter
U/F	Urgency–frequency
UI	Urge incontinence
UR	Urinary retention
USB	Universal Serial Bus
USRP	Universal Software Radio Peripheral
V	Volt
V_{BE}	Base-emitter voltage
V_{cc}	Positive supply voltage (BJT)
VCCS	Voltage-controlled current source
VCS	Voltage-controlled stimulation
VCVS	Voltage-controlled voltage source
VDA	Voltage-differencing amplifier
V_{dd}	Drain voltage, positive supply voltage (FET)
V_{DG}	Drain-gate voltage
VF	Ventricular fibrillation
V_f	Feedback voltage
V_G	Gate voltage
V_{GS}	Gate-source voltage
VIC	Voltage-to-current converter
Vim	Ventralis intermedius, ventral intermediate nucleus
V_{IN}	Input voltage
VLSI	Very large-scale integration
VNS	Vagus nerve stimulation
V_{out}	Output voltage
V_p	Peak value of the input voltage
V_{ref}	Reference voltage
Vss	Source voltage, negative supply voltage/ground (FET)
VT	Ventricular tachycardia
W	Watt
WBAN	Wireless body area network
Z	Impedance
ZrO_2	Zirconium oxide
α	Temperature coefficient
η	Size ratio
μA	Microampere
μm	Micrometer

μS	Micro Siemen
μs	Microsecond
μV	Microvolt
μW	Microwatt
τ	Time constant
Ω	Ohm

Contents

About the Author

Vinod Kumar Khanna was born on 25 November 1952 at Lucknow, Uttar Pradesh, India. He received his M.Sc. degree in physics with specialization in electronics from the University of Lucknow in 1975. From 1977 to 1979, he was a Research Assistant in the Physics Department, Lucknow University. He joined the solid-state devices division of CSIR-Central Electronics Engineering Research Institute, Pilani, in April 1980. He received his Ph.D. degree in physics from Kurukshetra University, Kurukshetra, Haryana, in 1988 for his work on thin-film aluminum oxide humidity sensor.

During his tenure of more than 34 years of service at CSIR-CEERI, Pilani, he worked on various research and development projects on power semiconductor devices (high-current and high-voltage rectifier, high-voltage TV deflection transistor, power Darlington transistor, fast switching thyristor, power DMOSFET, and IGBT), PIN diode neutron dosimeter and PMOSFET gamma ray dosimeter, ion-sensitive field-effect transistor (ISFET), microheater-embedded gas sensor, capacitive MEMS ultrasonic transducer, and other MEMS devices. He superannuated in November 2014 as Chief Scientist and Head, MEMS and Microsensors Group, and Professor, AcSIR (Academy of Scientific and Innovative Research). Presently, he is working as an Emeritus Scientist, CSIR, and Emeritus Professor, AcSIR. His research interests are micro- and nanosensors and power semiconductor devices.

Dr. Khanna's deputations abroad include Technische Universität Darmstadt, Germany, 1999; Kurt-Schwabe-Institut für Mess- und Sensortechnik e.V., Meinsberg, Germany, 2008; and Institute of Chemical Physics, Novosibirsk, Russia, 2009. He also participated and presented research papers in IEEE-IAS Annual Meeting, Denver, Colorado, USA, 1986.

He is a Fellow of the Institution of Electronics and Telecommunication Engineers (IETE), India. He is a Life Member of Indian Physics Association (IPA), Semiconductor Society (SSI), India, and Indo-French Technical Association.

He has published 8 previous books, 6 chapters in edited books, and 180 research papers in national/international journals and conference proceedings; he holds two US and two Indian patents.