Extreme-Temperature and Harsh-Environment Electronics (Second Edition)

Physics, technology and applications

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To my late father Shri Amarnath Khanna

For his earnest endeavors to shape my educational career.

To my late mother Smt. Pushpa Khanna

For her love and blessings to guide me on the path of life.

To my grandson Hansh and daughter Aloka

For bringing joy and happiness in the family.

To my wife Amita

For her unflinching and unfailing support.

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Preface to the revised edition

The first edition of this popular reference book presented a new perspective on electronic applications catering to hostile environments, and filled a long-felt need for an advanced reference book on the subject. This second edition provides fully updated content, including new references and developments during the years since the first edition was published. New material in this edition includes overall updating of chapter contents, an extensively upgraded bibliography, addition of sections on GaAs, SiC, GaN and diamond sensors (sections 7.15, 8.12, 9.10, and 10.11) together with incorporation of five new chapters added as sub-part IIB providing expanded discussion of electromagnetic interference and compatibility issues anticipated with the colossal spread of communication links and power infrastructure, sensors for hostile environments, medical electronic devices implanted in the human body for corrective therapy, electronic equipment operation in the vacuum and radiation environments experienced during space odysseys, and last but not the least, protection from dangers faced from malicious jamming and hacking attacks. The second edition of the book is organized in two parts I (chapters 1–14) and II (chapters 15–25), with parts I and II further subdivided into sections A and B. Their content coverage is concisely spelt out as follows:

Part I: Environmental hazards and extreme-temperature electronics (chapters 1–14)

'*Sub-part IA: Environmental hazards (chapters 1 and 2)*' gives an overview of the hazardous environments of operation of electronics.

'*Sub-part IB: Extreme-temperature electronics (chapters 3–14)*' covers the effects of temperature on semiconductors, silicon bipolar devices and circuits, silicon MOS devices and circuits, and SiGe heterojunction bipolar transistors. This part presents gallium arsenide electronics, silicon carbide electronics, gallium nitride electronics, diamond electronics, passive components, interconnections and packaging, superconductive electronics, superconductor-based microwave circuits, and high temperature superconductor-based delivery of power.

Part II: Harsh-environment electronics (chapters 15–25)

'*Sub-part IIA: Harsh-environment electronics (chapters 15–20): General considerations*' describes humidity and contamination effects on electronics, moisture and waterproof electronics, chemical corrosion and radiation effects on electronics, radiation-hardened electronics, and vibration-tolerant electronics.

'*Sub-part IIB: Harsh-environment electronics: Application-specific robust electronics techniques (chapters 21–25)*' explains electromagnetic interference and methods to achieve electromagnetic compatibility, sensors for aggressive environments, implantable medical electronics, space electronics, electronic jamming mitigation and assurance of cyber security.

The electronics engineer faces numerous challenges to develop electronic components and devices that can operate in difficult environmental conditions or situations where long-term reliability is critical and where mission failure will lead to human safety risks besides incurring substantial financial losses. The precautionary measures begin right at the outset during the conception phase of an electronic circuit in reference to conditions under which it is planned to function. They must be addressed at all stages commencing from device or circuit design to its fabrication and packaging, including proper choice of constructional materials.

It is hoped that the revised edition encapsulating latest information on the subject will serve as a treasure-trove of knowledge immensely useful to researchers, postgraduate students, practising engineers and other concerned stakeholders working with electronic devices and circuits under extreme temperatures and harsh environments, including the automotive, avionics, oil and nuclear power industries. Like its predecessor, the new edition will motivate and inspire all readers tackling environmental perils confronting electronics to strive with greater zeal and enthusiasm towards the goal of rugged, durable and reliable electronics.

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Chandigarh, India

Preface to first edition

Customarily, electronic devices and circuits are required to operate at room temperature. This is more a matter of convenience and convention than optimization. On lowering the temperature, the performance of electronic devices is improved two-fold or by several orders of magnitude. This upgradation is observed in various forms, e.g. increased speed of digital systems, a better signal-to-noise ratio and greater bandwidth for analog systems, improved sensitivity for sensors, greater precision and range for measuring instruments, and overall deceleration of the ageing process of materials. However, low temperature is not always beneficial, e.g. the current gain and breakdown voltage of bipolar transistors are degraded with decreasing temperature. Broadly speaking, low-temperature electronics (LTE) has two offshoots: semiconductor-based electronics and superconductor-based electronics. Semiconductor-based electronics pertains to electronics that can be made to operate at any temperature from room temperature, or even much higher, down to the lowest cryogenic temperatures, 1 K or below. On the other hand, present-day systems based on superconductivity are confined to operation at low cryogenic temperatures, below about 10 K, which has been a serious impediment to their widespread use. The advent of high-temperature superconductors and associated systems appears to hold some promise.

The other side of the story is high-temperature electronics (HTE). ‘High temperature’ is any temperature above 125 °C. This cut-off point is frequently specified as the upper limit at which standard commercial silicon devices are supposed to function properly. However, tests on standard commercial components indicate that even temperatures up to 150 °C may be applied to selected silicon components. Certain niche applications have to operate beyond the melting point of many materials used in present-day industrial electronics. Examples are monitors and down-hole well-drilling tools for energy exploration. Aircraft and turbine engine controls also have to withstand high temperatures.

The scope of extreme-temperature electronics (ETE) encompasses operation in temperature ranges outside the traditional commercial, industrial or military ranges, i.e. −55 °C/−65 °C to +125 °C. There are three categories of ETE, known as HTE referring to temperatures over +125 °C, LTE for temperatures below −55 °C/−65 °C, and cryogenic temperature electronics, below −150 °C.

Apart from the extreme-temperature applications discussed above, mention may be made of chemically corrosive conditions. Excessively high humidity causes corrosion in electronic devices. Low humidity favors the building up of static electricity. Atmospheric corrosion, an electrochemical process that occurs on metals covered by a thin film of water and ions, is often responsible for damage to electrical and electronic components leading to premature failures even in indoor ambient conditions.

Ionizing radiation consisting of electromagnetic waves such as x-rays and γ-rays, and particulate radiation, i.e. protons, electrons, neutrons, etc, causes malfunctions and failures in electronic components and circuits. The extent of damage depends on the type of radiation, its intensity or energy, the time of exposure and hence the dose, in addition to the distance between the radiation source and the electronic equipment.

Unconventional electronics is subdivided into different areas, e.g. electronics capable of operating at high temperatures for deep well and geothermal logging, lightweight ground and air vehicles, and space exploration; electronics benefitting from low-temperature operation as well as electronics able to withstand low temperatures for infrared systems, satellite communications and medical equipment, and newer opportunities in wireless and mobile communications, computers, and measurement and scientific equipment; electronics capable of countering the detrimental effects of humid and chemically corrosive environments for use in tropical climates and industries such as pulp and paper processing, oil and petroleum refining, mining, foundry, chemicals, etc; and radiation environment electronics for the space, medical and nuclear power industries.

This book has three objectives:

(i) to explore the beneficial/harmful impacts of extreme temperatures on electronic devices and circuits, as well as to enquire into the complexities introduced by harsh conditions such as damp, dirty and radiation-filled environments;
(ii) to describe the techniques adopted to utilize the advantages of these unconventional situations; and
(iii) to present the remedial measures taken to counteract and deal with these unfavorable circumstances.

This book is written for graduate and research students in electrical and electronic engineering. It will serve as a useful supplement to microelectronics course material, treating this specialized discipline with breadth and depth. The book answers several questions that come to mind when one starts thinking and imagining beyond a normal electronics course. The book is also written to fulfill the needs of electronic device and process design engineers, as well as circuit and system developers engaged in this fast-moving field, covering both fundamentals and applications. Scientists and professors engaged in this field will also find it useful as a comprehensive guide to the state-of-the-art electronic technologies for hostile environments.

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Acknowledgements

Above all, I must thank Almighty God for giving me the vigor and wisdom to complete this work. I am grateful to all my colleagues and Director, CSIR-CEERI, Pilani for constant encouragement in my efforts. I wish to thank my editor and editorial assistant for rejuvenating my interest and boosting my confidence from time to time. Their kind co-operation and support led to timely completion of the work. I owe a profound debt of gratitude to all authors/editors of research papers, magazine articles and web pages, on whose work this book is based. Most of these excellent works are cited in the bibliographies at the end of each chapter. However, if anyone has inadvertently escaped mention, I hope it may be forgiven. Last but not least, I am grateful to my family for providing the serene atmosphere and relieving me of many domestic responsibilities so that I could devote more time to book writing. To all the above, I express my sincere thanks.

Vinod Kumar Khanna
CSIR-CEERI, Pilani, India

About this book

Extreme-Temperature and Harsh-Environment Electronics (Second Edition): Physics, technology and applications presents a unified perspective combining the impact of extremely high and exceedingly low temperatures on the operation of semiconductor electronics, in addition to the influence of hostile environments such as high-humidity conditions, as well as surroundings contaminated by chemical vapors, nuclear radiation or those disturbed by mechanical shocks and vibrations. Incorporating the preliminary background material and thus laying down foundations for easy understanding, the progress in mainstream silicon, silicon-on-insulator and gallium arsenide electronics is sketched. Contemporary wide bandgap semiconductor technologies such as silicon carbide, gallium nitride and diamond electronics are explored. After a brief treatment of superconductivity, concepts of superconductive electronics are introduced. Progress in Josephson junctions, SQUIDs and RSFQ logic circuits is highlighted. The state of the art in high-temperature superconductor-based power delivery is surveyed. Succeeding chapters look at various protection schemes that have been devised to shield electronic circuits and equipment from adverse ambient conditions. These conditions range from the presence of high moisture concentrations in the atmosphere, to showers of high-energy particles such as the alpha particles, protons and nuclei of heavy elements that flood the atmosphere from outer space. A particularly attractive area is the dampening of vibration effects to protect electronics from the quivering disturbances or jerks that are always present near large machines or during accidental falls of electronic equipment. Specialized topics explored include electromagnetic interference and compatibility, use of sensors in aggressive environments, implantable medical electronics, space electronics, and protection of electronics from jamming and hacking.

In this book, a lucid description of this vast panorama of topics is reinforced by an elegant mathematical treatment. Broad in scope, this comprehensive treatise provides a coherent, well-organized and amply illustrated exposition of the subject which will be immensely useful for graduate and research students, professional engineers and researchers engaged in this frontier of technology. Its three-pronged approach encompassing physical aspects, technological breakthroughs and application examples will make reading interesting and enjoyable.

Author biography

Vinod Kumar Khanna

Introduction

Vinod Kumar Khanna is an independent researcher at Chandigarh, India. He is a retired Chief Scientist from Council of Scientific and Industrial Research (CSIR)-Central Electronics Engineering Research Institute (CEERI), Pilani, India, and a retired Professor from Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, India. He is a former Emeritus Scientist, CSIR and Professor Emeritus, AcSIR, India. His broad areas of research were the design, fabrication and characterization of power semiconductor devices, micro- and nanosensors.

Academic qualifications

He received the MSc Degree in Physics with specialization in Electronics from University of Lucknow in 1975 and PhD degree in Physics from Kurukshetra University in 1988 for the thesis entitled, 'Development, characterization and modeling of the porous alumina humidity sensor'.

Work experience and accomplishments

His research experience spans over a period of 40 years from 1977 to 2017. He started his career as a Research Assistant in the Department of Physics, University of Lucknow from 1977 to 1980. He joined CSIR-Central Electronics Engineering Research Institute, Pilani (Rajasthan) in April 1980. At CSIR-CEERI he worked on several CSIR-funded as well as sponsored research and development projects. His major fields of research included power semiconductor devices and microelectronics/MEMS and nanotechnology-based sensors and dosimeters.

In power semiconductor devices area, he worked on the high-voltage and high-current rectifier (600 A, 4300 V) for railway traction, high voltage TV deflection transistor (5 A, 1600 V), power Darlington transistor for AC motor drives (5 A, 1600 V), fast-switching thyristor (1300 A, 1700 V), power DMOSFET and IGBT. He contributed towards the development of sealed tube Ga/Al diffusion for deep junctions, surface electric field control techniques using edge beveling and contouring of large-area devices, and floating field limiting ring design; and characterization of minority-carrier lifetime as a function of process steps. He also contributed towards the development of P–I–N diode neutron dosimeter and PMOSFET-based gamma ray dosimeter.

In the area of sensor technology, he worked on the nanoporous aluminum oxide humidity sensor, ion-sensitive field-effect transistor-based microsensors for biomedical, food and environmental applications; microheater embedded gas sensor for automotive electronics, MEMS acoustic sensor for launch vehicles and capacitive MEMS ultrasonic transducer for medical applications.

Semiconductor facility creation and maintenance

He was responsible for setting up and looking after diffusion/oxidation facilities, edge beveling and contouring, reactive sputtering and carrier lifetime measurement facilities. As the Head of MEMS and microsensors group, he looked after the maintenance of six-inch MEMS fabrication facility for R&D projects as well as augmentation of processing equipment under this facility at CSIR-CEERI.

Scientific positions held

During his tenure of service at CSIR-CEERI from April 1980 till superannuation in November 2014, he was promoted to various positions including one merit promotion. He retired as Chief Scientist and Professor (AcSIR: Academy of Scientific and Innovative Research), and Head of MEMS and Microsensors Group. Subsequently, he worked for three years as Emeritus Scientist, CSIR and Emeritus Professor, AcSIR from November 2014 to November 2017. After completion of the emeritus scientist scheme, he now lives at Chandigarh. He is a passionate author, and enjoys reading and writing.

Membership of professional societies

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

Foreign travel

He is widely travelled. He participated in and presented research papers at IEEE Industry Application Society (IEEE-IAS) Annual Meeting at Denver Colorado, USA, in September–October, 1986. His short-term research assignments include deputations to Technische Universität Darmstadt, Germany in 1999, at Kurt-Schwabe-Institut fur Mess- und Sensortechnik e.V., Meinsberg, Germany in 2008 and at Fondazione Bruno Kessler, Trento, Italy in 2011 under collaborative program. He was a member of the Indian Delegation to Institute of Chemical Physics, Novosibirsk, Russia in 2009.

Scholarships and awards

He was awarded National Scholarship by the Ministry of Education and Social Welfare, Government of India, on the basis of Higher Secondary result, 1970; CEERI Foundation Day Merit Team Award for projects on fast-switching thyristor (1986); power Darlington transistor for transportation (1988), P–I–N diode neutron dosimeter (1992); and high-voltage TV deflection transistor (1994); Dr N G Patel Prize for best poster presentation in 12th National Seminar on Physics and Technology of Sensors 2007, BARC, Mumbai; CSIR-DAAD Fellowship in 2008 under Indo-German Bilateral Exchange Programme of Senior scientists, 2008. He is featured in the Stanford–Elsevier prestigious list of world top 2% scientists (2022, Elsevier Data Repository, V4, doi: 10.17632/btchxktzyw.4).

Research publications and books

He has published 194 research papers in leading peer-reviewed national/international journals and conference proceedings. He has authored 19 books, and has also contributed six chapters in edited books. He has five patents to his credit, including two US patents.

Abbreviations, acronyms, chemical symbols and mathematical notation

A	ampere
AC	alternating current
ACE	arbitrary code execution
ACK	acknowledge
Ag	silver (argentum)
AgCl	silver chloride
Ag_2O	silver oxide
Ag_2S	silver sulfide
AH	absolute humidity
AI	artificial intelligence
Al	aluminum
ALD	atomic layer deposition
AlGaAs	aluminum gallium arsenide
AlGaN	aluminum gallium nitride
AlN	aluminum nitride
Al_2O_3	aluminum oxide, alumina
AO	atomic oxygen
APT	advanced persistent threat
Ar	argon
As_2O_3	arsenic trioxide
As_2O_5	arsenic pentoxide
ASTM	American society for testing and materials
Au	gold (aurum)
$BaCO_3$	barium carbonate
BCS	Bardeen–Cooper–Schrieffer (theory of superconductivity)
Be	beryllium
BFSK	binary frequency-shift keying
BGJFET	buried-grid JFET
B_2H_6	diborane
Bi_2Te_3	bismuth telluride
BiCMOS	bipolar CMOS
BJT	bipolar junction transistor
BLS	board level shielding
BN	boron nitride
B_2O_3	boron trioxide
BOX	buried oxide
BPF	bandpass filter
BPSK	binary phase-shift keying
BSCCO	bismuth–strontium–calcium–copper oxide
BSG	borosilicate glass
C	carbon

°C	degrees centigrade
Ca^{2+}	calcium cation
cal g^{-1}	calorie $gram^{-1}$
CaO	calcium oxide
$Ca_3(PO_4)_2$	calcium phosphate
$Ca_{10}(PO_4)_6(OH)_2$	calcium hydroxyapatite
CBMA	carboxybetaine methacrylate
CCD	charge-coupled device
CEN	Comité Européen de Normalisation
CeO_2	cerium (IV) oxide
CF-PEEK	carbon fiber reinforced PEEK (polyetheretherketone)
CH_4	methane
$(CH_3)_3B$	trimethylborane
$C_{16}H_{14}Cl_2$	parylene C
$-(C_2H_2F_2)_n-$	PVDF
CHFET	complementary heterojunction FET
$C_7H_7N_3$	tolytriazole
$C_{17}H_{16}N_2O_4$	polyurethane
$C_{12}H_{24}N_2O_2$	dicyclohexylammonium nitrite
$C_{35}H_{28}N_2O_7$	polyimide resin
$C_6H_8O_7$	citric acid
$C_6H_{10}O_4$	adipic acid
$C_6H_{10}O_6$	glucono-delta-lactone or gluconolactone
$C_6H_{12}O_6$	glucose
$(C_2H_6OSi)_n$	polydimethylsiloxane (PDMS)
CISPR	Comité International Spécial des Perturbations Radioélectriques
Cl^-	chloride anion
CMOS	complementary metal–oxide–semiconductor (FET)
CO	carbon monoxide
Co	cobalt
CO_2	carbon dioxide
COB	chip-on-board (assembly)
CO-OP	controlled over pressure (process)
$CoSi_2$	cobalt silicide
CP-Ti	commercially pure titanium
CPU	central processing unit
CQT	cascaded quadruplet trisection coupling structure (filter geometry)
Cr	chromium
Cr_2O_3	chromium (III) oxide
CRT	cathode ray tube
CSFs	colony-stimulating factors
3C-SiC	cubic silicon carbide
CSMA	carrier sense multiple access (protocol)
CT	computed tomography
CTE	coefficient of thermal expansion
Cu	copper
CuO	copper oxide
Cu_2S	copper sulfide
CVD	chemical vapor deposition
CZ	Czochralski (single-crystal silicon)

DAC	discretionary access control
dB	decibel
DBE	droplet backside exposure
DC	direct current
DCF	Distributed coordination function
DD	displacement damage
DDoS	distributed denial-of-service (attack)
2DEG	two-dimensional electron gas
DGVTJFET	dual-gate vertical channel trench JFET
2DHG	two-dimensional hole gas
DI-BSCCO	dynamically innovative-BSCCO
DICE	dual interlocked storage cell
DICHAN	dicyclohexylammonium nitrite
DIFS	DCF interframe space interval
DMOSFET	double-diffused MOSFET
DMVTJFET	depletion-mode VTJFET
DNS	domain name system
DOM	document object model
DoS	denial-of-service
DRAM	dynamic random-access memory
DSSS	direct sequence spread spectrum
E	east
e^-	electron
e-beam	electron beam
ECF	extracellular fluid compartment
ECOG	electrocorticography
EDR	endpoint detection and response (tool)
EEG	electroencephalogram
EEPROM	electrically-erasable programmable read-only memory
EG	electronic grade (polysilicon)
EHP	electron hole pair
eHTP	extremely high temperature package
EIA	Electronics Industries Association
EL Ni	electroless nickel
EMC	electromagnetic compatibility
EMF	electromotive force
EMI	electromagnetic interference
EMVTJFET	enhancement-mode VTJFET
ESD	electrostatic discharge
ETO	ethylene oxide
eV	electronvolt
2FA	two-factor authentication
FBGCs	foreign body giant cells
FBR	foreign body reaction
FC/APC	fiber connector with angled physical contact
FCC	Federal Communications Commission
fcc	face-centered cubic
FCL	fault current limiter
FET	field-effect transistor
fF Pa^{-1}	femtofard $pascal^{-1}$
FHSS	frequency hopping spread system

FIRST	Far Infra-Red Space Telescope
FR-4	flame retardant-4, a grade designation by National Electrical Manufacturers Association for glass epoxy laminate
FSK	frequency-shift keying
Ga	gallium
GaN	gallium nitride
Ga_2O_3	gallium trioxide
$GaPO_4$	gallium phosphate or gallium orthophosphate
Ge	germanium
GEO	geosynchronous equatorial orbit
GHz	gigahertz
GM	Gifford–McMahon (cryocoolers)
Gox	glucose oxidase
GPS	global positioning system
GSFC	Goddard Space Flight Center
GTO	gate turn-off (thyristor)
Gy	gray
h	hour
H^+	hydrogen cation
HA	hydroxyapatite
HAF	high-attenuation fiber
HASL	hot air solder leveling
HA/Ti-6Al-4V	hydroxyapatite reinforced Ti-6Al-4V
HBT	heterojunction bipolar transistor
HCO_3^-	bicarbonate anion
HCs	hydrocarbons
HEMT	high electron mobility transistor
HFET	heterojunction FET
HfO_2	hafnium oxide
Hg	mercury (hydrargyrum)
H_2O	water, dihydrogen monoxide
H_2O_2	hydrogen peroxide
HPHT	high-pressure and high-temperature
6H-SiC	hexagonal silicon carbide
HT	high-temperature (sensors)
HTCC	high temperature co-fired ceramic
HTE	high-temperature electronics
HTML	hypertext markup language
HTS	high-temperature superconductor
HTTP	hypertext transfer protocol
HVAC	high-voltage alternating current
Hz	hertz
IBAD	ion beam-assisted deposition
IC	integrated circuit
I^2C	inter-integrated circuit
ICF	intracellular fluid (compartment)
ICMP	internet control message protocol
ICQ	short form of the phrase, ‘I seek you’, it is an internet instant cross-platform messenger app supporting audio/video chats, text messaging to cellular network phones, emails and file transfers

iCVD	initiated chemical vapor deposition
IDS/IPS	intrusion detection system/intrusion prevention system
IDT	interdigitated (electrodes)
IEEE	Institute of Electrical and Electronic Engineers
IF	intermediate frequency
i-GaN	intrinsic gallium nitride
IGBT	insulated gate bipolar transistor
IL-3, IL-4, IL-10, etc	interleukin-3, interleukin-4, interleukin-10, etc
IM Au	immersion gold
InAlN	indium aluminum nitride
InAs	indium arsenide
InGaAs	indium gallium arsenide
InP	indium phosphide
InSb	indium antimonide
Intelsat	International Telecommunications Satellite Organization
IP	internet protocol
IPS	intrusion prevention system
Ir	iridium
ISOPHOT	Infrared Space Observatory Photometer
ITO	indium tin oxide
JFET	junction FET
JJ	Josephson junction
JTE	junction termination extension
K	kelvin (scale of temperature), key
K^+	potassium cation
KCl	potassium chloride
keV	kilo-electronvolt
kg	kilogram
kHz	kilohertz
km	kilometer
kPa	kilopascal
K_{Public}	public key
K_{Secret}	secret key
kV	kilovolt
kW	kilowatt
L	liter
$LaAlO_3$	lanthanum aluminate
LaB_6	lanthanum hexaboride
Langasite	lanthanum gallium silicate, $La_3Ga_5SiO_{14}$
LAO	lanthanum aluminate
LC	Inductance–capacitance (circuit)
LCD	liquid crystal display
LCJFET	lateral channel JFET
LCPs	liquid crystal polymers
LDPC	low density parity coding
LEC	liquid encapsulated Czochralski
LED	light-emitting diode
LEO	low earth orbit
LFI	local file inclusion

LGS	lanthanum gallium silicate, $La_3Ga_5SiO_{14}$
Li	lithium
LO	local oscillator
LPCVD	low-pressure chemical vapor deposition
LPF	low-pass filter
LSN	low-stress silicon nitride
LTCC	low temperature co-fired ceramic
LTE	low-temperature electronics
LTO	low-temperature oxide
M1	classically-activated macrophages
M2	wound-healing macrophages
m	meter
mA	milli-ampere
MAC	molecular absorber coating, managed/mandatory access control
MACOR	trademark for a machinable glass ceramic: fluorophlogopite mica (55%) + borosilicate glass (45%)
MAG	maximum available gain
$M_xAl_xSi_{1-x}O_2 \cdot yH_2O$	zeolite, M is a metal or hydrogen ion, $0 < x < 1$ and y is the number of water molecules
MDR	managed detection and response
MEA	more electric aircraft
MEMS	microelectromechanical systems
MESFET	metal–semiconductor FET
meV	milli-electronvolt
Mg	magnesium
Mg^{2+}	magnesium cation
MG	metallurgical grade (polysilicon)
$MgCr_2O_4$–TiO_2	magnesium chromite–titanium dioxide
MgO	magnesium oxide
MHz	megahertz
MISFET	metal–insulator–semiconductor FET
mK	millikelvin
MLI	multilayer insulation
mm	millimeter
MMIC	monolithic microwave IC
Mn	manganese
$Mn(NO_3)_2$	manganese nitrate
MnO_2	manganese dioxide
mΩ	milli-ohm
MΩ-cm	megaohm-centimeter
Mo	molybdenum
MOCVD	metal–organic CVD
MOSFET	metal–oxide–semiconductor FET
$MoSi_2$	molybdenum disilicide
MPa	megapascal
MPC	2-methacryloyloxyethyl phosphorylcholine
MPCVD	microwave plasma-enhanced CVD
MPS	merged PiN/Schottky (diode)
Mregs	regulatory macrophages
MRI	magnetic resonance imaging

mS	millisiemen
MSOC	modern security operations center
MTTF	mean-time-to-failure
MV	megavolt
mV	millivolt
N	nitrogen, north
n	number, neutron
Na^+	sodium cation
Na_2O	sodium oxide
NaOH	sodium hydroxide
NASA	National Aeronautics and Space Administration
Nb	niobium
nC	nanocoulomb
NH_3	ammonia
Ni	nickel
NiCr	nickel–chromium, nichrome
NiO	nickel (II) oxide
nm	nanometer
NMOS	n-channel MOSFET
NO	nitric oxide
NO_2	nitrogen dioxide gas
NO_x	oxides of nitrogen
NP0	negative positive zero
ns	nanosecond
O_2	oxygen
OCVD	open circuit voltage decay
OH^-	hydroxide anion
ONO	silicon oxide–silicon nitride–silicon oxide
OP-AMP	operational amplifier
OSI	open system interconnection (model)
OSP	organic solderability preservative
pA	picoampere
Parylene C	derivative of parylene in which one hydrogen atom in the aryl ring is replaced with chlorine
Pb	lead (plumbum)
pBN	pyrolytic boron nitride
pC	pico Coulomb
PCB	printed circuit board
PCBA	printed circuit board assembly
PCM	phase-change material
Pd	palladium
PDMS	polydimethylsiloxane
PDR	packet delivery ratio
PECVD	plasma-enhanced CVD
PEEK	polyetheretherketone
PEG	polyethylene glycol
pH	potential hydrogen
PH_3	phosphine
pHEMA	poly (2-hydroxyethyl methacrylate)
PKI	public key infrastructure

PLD	pulsed laser deposition
PLGA	poly(lactic-co-glycolic) acid
PMOS	p-channel MOSFET
PMU	power management unit
PO_4^{3-}	phosphate anion
P_2O_5	phosphorous pentoxide
$POCl_3$	phosphorous oxychloride
Poly-SiC	polycrystalline silicon carbide
ppm K^{-1}	parts per million Kelvin^{-1}
ps	picosecond
PSG	phosphosilicate glass
Pt	platinum
PTFE	polytetrafluoroethylene
PTH	plated-through-hole
PVA	poly(vinyl alcohol)
PVDF	polyvinylidene fluoride
QUAD	quadruple
rad	radiation absorbed dose
RADAR	radio detection and ranging
RAM	random-access memory
RBAC	role-based access control
RCE	remote code execution
ReBCO	rare-earth barium copper oxide
RF	radio frequency
RFBG	regenerated fiber Bragg grating
RFI	remote file inclusion
RFID	radio-frequency identification
RH	relative humidity
RHBD	radiation hardening by design
RHBP	radiation hardening by process
RoHS	restriction of hazardous substances
RPCVD	reduced pressure CVD
R–S	reset–set (flip-flop)
RSFQ	rapid single flux quantum
R_2SiO	structural unit of silicone where R is an organic group
RTA	rapid thermal annealing
RTP	reversible thermal panel
RTV	room temperature vulcanization
Ru	ruthenium
s	second
S	sulfur, siemen
SAE International	Society of Automotive Engineers International
Sapphire	Al_2O_3
SAW	surface acoustic wave
SBD	Schottky barrier diode
SBMA	sulfobetaine methacrylate
SCPs	satellite control processors
SCS	switched capacitor system
Se	selenium

SEB	single event burnout
SEE	single event effect
SEFI	single event functional interrupt
SEGR	single event gate rupture
SEI	Sumitomo Electric Industries Ltd
SEJFET	static expansion channel JFET
SEL	single event latchup
SES	single event snapback
SET	single event transient
SEU	single event upset
SFBG	sapphire fiber Bragg grating
SFCL	superconducting FCL
Si	silicon
SIAFET	static induction-injected accumulated FET
SiC	silicon carbide
SIEM	security information and event management
SiGe	silicon–germanium (alloy)
$Si_{1-x}Ge_x$	silicon–germanium (alloy) where x is the mole fraction of germanium in the alloy with a value from 0 to 1
SiH_4	silane
$SiHCl_3$	trichlorosilane
SiH_2Cl_2	dichlorosilane
SiO_2	silicon dioxide
SMD	surface mount device
Si_3N_4	silicon nitride
$Si(OC_2H_5)_4$	tetraethylorthosilicate (TEOS)
$Si_xO_yN_z$	silicon oxynitride
SISO	spiral in/spiral out (resonator)
SLD	superluminescent diode
Sm	samarium
$s\ m^{-1}$	second meter^{-1}
SMF-28	single mode optical fiber-28, a standard telecom fiber
SMLI	stateful multilayer inspection (firewall)
Sn	tin (stannum)
SO_4^{2-}	sulphate anion
SOI	silicon-on-insulator
SPF	sender policy framework
SQUID	superconducting quantum interference device
SRH	Shockley–Read–Hall (recombination)
SS	subthreshold swing
STI	shallow trench isolation
STP	shielded twisted pair (cable)
SYN	synchronize
SYN-ACK	synchronize-acknowledge
T	tesla
Ta	tantalum
TaN	tantalum nitride
Ta_2O_5	tantalum pentoxide
$TaSi_2$	tantalum disilicide
TBCCO	thallium–barium–calcium–copper oxide

TC	temperature coefficient
TCP SYN	transmission control protocol synchronize
TCR	TC of resistance
TCS	trichlorosilane
Te	tellurium
TEOS	tetraethylorthosilicate
Ti	titanium
Ti-6Al-4V	90% Ti, 6% aluminum and 4% vanadium alloy
TID	total ionizing dose
TiN	titanium nitride
TiO_2	titanium dioxide
TiO_2–ZrO_2	titanium dioxide–zirconium dioxide
$TiSi_2$	titanium disilicide
TMB	trimethylboron
TMR	triple modular redundancy
TP	twisted pair (cable)
TPTS	two-phase thermal switch
TPU	thermoplastic polyurethane
TTL	transistor–transistor logic
TV	television
UHVCVD	ultra-high vacuum CVD
UMOSFET	U-shaped MOSFET
URL	uniform resource locator
UTP	unshielded twisted pair (cable)
UV	ultraviolet
V	volt
VAPT	vulnerability assessment and penetration testing (tool)
VCI	volatile corrosion inhibitor (coating)
V_2O_5	vanadium pentoxide
VTJFET	vertical trench JFET
W	tungsten, watt
Wb	weber, the SI unit of magnetic flux. Weber per second = Volt
WI-FI	not the short form of 'wireless fidelity'; a registered trademark of WI-FI alliance; a family of wireless protocols based on IEEE 802.11 standard; a local area networking technology for high-speed data exchange between digital devices over short distances through radio communication by internet
WN_x	tungsten nitride
WSi_2	tungsten disilicide
w/v	weight by volume concentration
w/w	weight by weight concentration
XML	extensible markup language
XSS	cross-site scripting
$YBa_2Cu_3O_7$	YBCO
YBCO	yttrium barium cuprate
$YCa_4O(BO_3)_3$	yttrium calcium oxoborate
YCOB	$YCa_4O(BO_3)_3$
YIG	yttrium iron garnet
Y_2O_3	yttrium oxide
YSZ	yttria stabilized zirconia

Z	atomic number
Zn	zinc
Zr	zirconium
ZrO_2	zirconium oxide, zirconia
ZTC	zero temperature coefficient biasing point of a MOSFET

Roman alphabet symbols

a	depth of the active region in MESFET
A	parameter in the model of Quay *et al*, area, amplitude of signal
$\mathbf{A}$	magnetic vector potential
A^*	effective Richardson constant
A, B, C	parameters of the Bludau *et al* model
A_{V}	voltage gain
b	parameter in Arora–Hauser–Roulston equation, parameter in Chynoweth equations
B	bandwidth of the original signal in FHSS
$B(0)$	magnetic induction at the surface
B_{FHSS}	bandwidth determined by the spacing between the M carrier frequencies of FHSS signal
b_{i}	the *i*th data bit
BV_{CBO}	collector–base breakdown voltage of a bipolar transistor with emitter open
BV_{CEO}	collector–emitter breakdown voltage of a bipolar transistor with base open
BV_{DSS}	drain–source breakdown voltage of a MOSFET with gate shorted to source
$B(x)$	magnetic induction along the x-direction
C_1, C_2, C_3	parameters in the model of threshold ionization energy
C	capacitance
c	velocity of light, damping coefficient (vibration theory)
C_{ds}, C_{DS}	drain–source capacitance
C_{gd}	gate–drain capacitance
C_{iss}	intrinsic capacitance
C–L	capacitance–inductance
C–L–C	capacitance–inductance–capacitance
C_{rss}	reverse transfer capacitance
C_{ox}	oxide capacitance per unit area
$c(t)$	chipping signal
D	diffusion coefficient of carrier, diffusion coefficient of dopant
d	diameter, thickness, length, deformation
$d\mathbf{l}$	linear element
D_{nB}	diffusion constant of electrons in the p-base
$\widetilde{\boldsymbol{D}}_{\mathrm{nB}}$	position-averaged diffusion coefficient across the base profile
$D_{\mathrm{nB}}(x)$	position-dependent diffusion coefficient of electrons in the base
D_{pB}	diffusion constant of holes in the base
D_{pE}	diffusion constant of holes in the n^+-emitter
$d\mathbf{s}$	areal element
$d(t)$	discrete function
E	electric field
e	electronic charge
E_{C}	energy of conduction band edge
E_{g}, E_{G}	energy bandgap
E_{gB0}	silicon bandgap at zero doping of the base layer (in an HBT)

$\Delta E_{\mathrm{gB,A}}$	bandgap narrowing of base layer due to acceptor impurity doping effect (in an HBT)
$\Delta E_{\mathrm{gBGe}}(x = 0)$	bandgap offset of base layer at $x = 0$ (in an HBT)
$\Delta E_{\mathrm{gB,Ge}}(x = W_{\mathrm{B}})$	bandgap offset of base layer at $x = W_{\mathrm{B}}$ (in an HBT)
$E_{\mathrm{gB}}(x)$	position-dependent energy bandgap of SiGe base layer (in an HBT)
E_{F}	Fermi energy level
E_{fn}	quasi-Fermi level of electrons
E_{fp}	quasi-Fermi level of holes
E_{g}	energy bandgap
$E_{\mathrm{g}}(0)$	energy bandgap at 0 K
$\langle E_{\mathrm{p}} \rangle$	average energy loss due to phonon scattering
E_{V}	energy of valence band edge
F	force, free energy
f	frequency of the signal
F_0	peak value of the force waveform
f_0	frequency of the carrier signal in FHSS
F1, F2, F33, F4, F5, F6, F7, F8	frequencies corresponding to the 8 k-bit patterns: 000, 001, 010, 011, 100, 101, 110, 111
$f_1 = f_0$	low frequency for binary 0 in FHSS
$f_2 = f_0 + \Delta f$	high frequency for binary 1 in FHSS
f_{c}	carrier frequency in MFSK-FHSS, frequency of the carrier wave in BPSK
f_{d}	difference frequency in MFSK-FHSS
f_i	frequency of the spreading signal during ith hopping period in FHSS
f_{max}	maximum frequency of oscillation
f_{n}	natural frequency
f_{T}	transition frequency (unity-gain frequency)
G	processing gain
g	acceleration due to gravity
g_{d}	output conductance
g_{m}	transconductance of MOSFET
g_{m0}	transconductance value (maximum) at $V_{\mathrm{GS}} = 0$
g_{mb}	body-effect conductance
g_{ms}	transconductance of MOSFET in saturated condition
h	Planck's constant
$\hbar$	reduced Planck's constant = $h/2\pi$
H_{C}	critical magnetic field of a superconductor
h_{FE}	current gain of a bipolar transistor in a common-emitter connection
I, i	current
I_{A}	current in circuit A
I_{B}	base current of a bipolar transistor, current flowing through load resistance of circuit B
I_{b}	biasing current (superconductor, Josephson junction, SQUID)
I_{C}	collector current of a bipolar transistor, critical current (superconductor)
I_{CBO}	collector–base reverse current of a bipolar transistor with emitter open

I_{CCH}	current drawn from the supply during logic high output state
I_{CEO}	collector–emitter reverse current of a bipolar transistor with base open
I_{d}	current in SBD
I_{D0}	reverse saturation current (leakage current) of SBD
I_{DS}	drain–source current of a MOSFET
I_{DSS}	drain–source leakage current of a MOSFET with the gate shorted to the source, the saturated drain current of a MESFET at $V_{\mathrm{GS}} = 0$
I_{E}	emitter current of a bipolar transistor
I_{F}	forward current
I_{fc}	full saturation current
I_{IL}	input low current
I_{nB}	electron current from the n^+-emitter to the p-base
I_{OFF}	off-state current
I_{ON}	on-state current
I_{p}	persistent current (superconductor)
I_{pE}	hole current from the p-base to the n^+-emitter of a bipolar transistor
I_{R}	reverse current
I_{S}	saturation current, screening current (superconductor)
J, j	current density
J_{B}	base current density
$J_{\mathrm{C}}, j_{\mathrm{C}}$	collector current density of a bipolar transistor, critical current density of a superconductor
J_{n}	Bessel functions of the first kind
K	stiffness, spring constant
k	number of bits in a binary word
K, K_1, K_2	constants
k_{B}	Boltzmann constant
K_{FE}	damage coefficient related to current gain
K_{τ}	damage coefficient associated with carrier lifetime
L	length, diffusion length of carrier, channel length of an FET, inductance, number of bits per signal element (in FHSS)
L_{nB}	diffusion length of electrons in the base
L_{pE}	diffusion length of holes in the emitter
M	number of equivalent valleys in the conduction band of SiC, collector multiplication factor, a digit for the number of levels or groupings likely for an assigned number of binary variables, number of signal elements in MFSK-FHSS, index in MOSFET drain current equation in Shoucair's analysis
m_0	rest mass of electron = 9.11×10^{-31} kg
$m_{\mathrm{n}}{}^*$, $m_{\mathrm{p}}{}^*$	effective masses of electrons and holes for density-of-state calculations
N	dopant concentration
n	electron concentration, ideality factor of SBD
$\widetilde{N}$	position-averaged ratio of effective densities of states in SiGe and Si, across the base profile
N_{A}	total acceptor impurity concentration
$N_{\mathrm{A}}{}^-$	ionized acceptor impurity concentration
N_{AB}	acceptor concentration in the p-base layer

N_C, N_V	effective densities of states in the conduction and valence bands of a semiconductor
N_crit	critical impurity density
$N_\mathrm{C,SiGe}\,(x)$	position-dependent effective density of states in the conduction band of SiGe
N_D	total donor impurity concentration
$N_\mathrm{D}{}^+$	ionized donor impurity concentration
N_DE	doping concentration in the n-emitter layer
$N_\mathrm{D(g)}$	doping concentration of polysilicon gate
N_I	density of charged impurities, trap density
n_i	intrinsic carrier concentration (of a semiconductor)
$n_\mathrm{iB}(x)$	position-dependent intrinsic carrier concentration in the base
n_pB	number of electrons in the p-base
$N(t)$, $n(t)$	noise as a function of time
$N_\mathrm{V,SiGe}\,(x)$	position-dependent effective density of states in the valence band of SiGe
P	pressure
$\mathbf{p}$	canonical momentum of a classical particle
p	hole concentration
P_0	amplitude of the transmitted force
p_0	TC of threshold voltage
$p_\mathrm{B}(x)$	position-dependent hole concentration in the base varying with position x
$p_\mathrm{H_2O}$	partial pressure of water vapor present in air
$p^*_\mathrm{H_2O}$	equilibrium vapor pressure of water vapor
P_I	incident power
P_J	jammer power
p_nE	number of holes in the n^+-emitter
P_T	transmitted power
$p(t)$	product or spread signal in FHSS
Q	total electronic charge
q	electronic charge
Q_0	heat of compression
q_0	parameter in Shoucair's threshold voltage equation (the value of V_Th at 0 K, as found by extrapolation)
$Q_\mathrm{a}(T)$	conducting channel charge
Q_C	heat absorbed from the cold environment at temperature T_C
Q_f	fixed charge in the silicon dioxide
R	resistance, the bit rate in the input information signal in DSSS
R_1, R_2, R_3	three reflected beams
R_1, R_3	resistors formed at the junctions between the beams and the support frame
R_2, R_4	resistors made at the junctions between the beams and the proof mass
R_A	resistance connected to voltage source V_A
R–C	resistance–capacitance
R_c	bit rate in the spread signal in DSSS
R_CHANNEL	resistance of channel region of a MOSFET
$r_\mathrm{Corrected}(t)$	received corrected signal
R_DRIFT	resistance of drift region of a MOSFET

$R_{\mathrm{D}}^{\mathrm{Si}}$	on-resistance of Si diode
$R_{\mathrm{D}}^{\mathrm{SiC}}$	on-resistance of SiC diode
$R_{\mathrm{DS(ON)}}$	drain–source on-resistance of a MOSFET
R_{G}	resistance of the current path to ground
R_{LA}	resistance of load resistance of circuit A
R_{LB}	resistance of load resistance of circuit B
R_{n}	external resistor shunting a JJ
R_{Return}	resistance of return path of current
R_{SA}	resistance of voltage source of circuit A
R_{SB}	resistance of voltage source of circuit B
R_{s}, R_{S}	series resistance of the source
$r(t)$	received signal
S, s	cross-section, area
$s_{\mathrm{Corrected}}(t)$	corrected signal $s(t)$ in DSSS (by including noise)
$s_{\mathrm{Corrected\text{-}Jamming}}(t)$	corrected signal $s(t)$ in DSSS (by including noise as well as jamming)
$s_{\mathrm{d}}(t)$	transmitted digital signal with respect to time, BPSK signal
$s_{\mathrm{i}}(t)$	transmitted digital signal for one signal element with respect to time (in MFSK-FHSS)
S_{Jammer}	power of jammer
$S_{\mathrm{Jamming(Filter)}}$	power of the jamming signal entering the filter
$s_{\mathrm{Jamming}}(t)$	jamming signal as a function of time
$s(t)$	spread signal in FHSS
T	temperature in the Kelvin scale, periodic time of clock signal, transmissibility, bit period in MFSK-FHSS, bit width in DSSS
t	time
T_0	ambient temperature
T_{C}	temperature of the cold environment
T_{c}	time taken for translation of the MFSK signal to a new frequency in MFSK-FHSS, bit width of the pseudorandom noise signal in DSSS
t_{H}	hop period
T_{L}	lattice temperature
t_{ox}	oxide thickness
T_{s}	time occupied by each signal element in MFSK-FHSS
U_1, U_2	states of lowest energy on the opposite sides of the tunnel barrier
V, v	voltage
v	velocity of electron
V_0	amplitude of sinusoidal voltage
V_+, V_-	two signals equal in magnitude but opposite in phase (ϕ_+, ϕ_-)
V_1, V_2	voltage magnitudes
V_{a}	early voltage
V_{A}, V_{B}	voltage sources of circuits A and B
V_{a}, V_{b}, V_{c}	potentials at the ground points a, b, c of circuits A, B, C
V_{AC}	AC voltage
v_{BC}	base–collector voltage
v_{BE}	base–emitter voltage
V_{bi}	built-in potential
V_{CE}	collector–emitter voltage, voltage conversion efficiency
v_{CES}	collector–emitter voltage in saturation mode

V_{CM}	common-mode voltage
V_{d}	voltage across SBD
V_{DC}	DC voltage
V_{DD}	drain supply
V_{DM}	differential-mode voltage
V_{DS}	drain–source voltage
$V_{\mathrm{D}}^{\mathrm{Si}}$	forward voltage of Si diode
$V_{\mathrm{D}}^{\mathrm{SiC}}$	forward voltage of SiC diode
V_{FB}	flatband voltage
V_{G}	voltage drop produced across resistor R_{G}
V_{GS}	gate–source voltage
V_{GS} (ZTC)	V_{GS} at ZTC point
$V_{\mathrm{IN+}}$, $V_{\mathrm{IN-}}$	input voltage terminals of the Wheatstone bridge
v_{nB}	velocity of electrons at the emitter end of the base
V_{NMH}	high-level noise margin
V_{NML}	low-level noise margin
V_{OH}	output high voltage
V_{OL}	output low voltage
V_{OUT}	output voltage of the Wheatstone bridge
$V_{\mathrm{OUT+}}$, $V_{\mathrm{OUT-}}$	output voltage terminals
V_{Output}	voltage of the output signal
V_{peak}	peak voltage
V_{po}	pinch-off voltage of MESFET
v_{pE}	velocity of holes at the base end of the emitter
V_{R}	reverse bias
V_{RLA}	voltage across the load resistance R_{LA} of the source circuit A
V_{RLB}	voltage across the load resistance R_{LB} of the receptor circuit B
V_{SA}	voltage source of circuit A
V_{SB}	substrate bias, voltage source of circuit B
V_{Signal}	voltage of the signal
V_{SS}	source supply
$V(t)$	time-dependent voltage
V_{sub}, $V_{\mathrm{substrate}}$	substrate voltage
V_{Th}	threshold voltage of a MOSFET
V_{Thermal}	thermal voltage
v_{sat}	saturation velocity of carrier
$v_{\mathrm{n}}^{\mathrm{sat}}$	saturation velocity of electron
$v_{\mathrm{p}}^{\mathrm{sat}}$	saturation velocity of hole
W	bandwidth of the input information signal in DSSS
w	depletion layer width
W, W_{B}	base width of a bipolar transistor, channel width of an FET
W_0	work done at room temperature
W_{C}	work done by the gas during expansion in the engine at temperature T_{C}
W_{D}	depletion region thickness at the drain
W_{d}	bandwidth of the input data signal in MFSH-FHSS
W_{I}	threshold ionization energy
W_{S}	depletion region thickness at the source
W_{s}	bandwidth of the spread signal in MFSH-FHSS, the bandwidth of the spread signal in DSSS

X_{C}	capacitive reactance
X_{L}	inductive reactance
$Xtalk_{\mathrm{BA}}$	crosstalk parameter between receptor circuit B and source circuit A
$Z_{\mathrm{A}}, Z_{\mathrm{B}}, Z_{\mathrm{C}}, \ldots, Z_N$	impedances of wires $\mathrm{W}_{\mathrm{A}}, \mathrm{W}_{\mathrm{B}}, \mathrm{W}_{\mathrm{C}}, \ldots, \mathrm{W}_N$

Greek/other symbols

α	fitting parameter in the Varshini equation, index of temperature for mobility variation, ionization coefficient, current gain of a bipolar transistor in the common-base configuration, an empirical constant determining the saturation voltage of the drain current of a MESFET
α_{it}	coefficient for interface states
α_{n}	ionization coefficient of an electron
α_{ot}	coefficient for oxide-trapped charges
α_{p}	ionization coefficient of a hole
α_{T}	base transport factor
β	fitting parameter in the Varshini equation, current gain of a bipolar transistor in the common-emitter configuration, transconductance parameter of a MESFET containing the electron mobility μ_{n}
β_{max}	maximum current gain
β_{NPN}	current gain of n–p–n transistor
β_{PNP}	current gain of p–n–p transistor
β_{Si}	current gain of Si BJT
$\beta_{\mathrm{Si/SiGe}}(T)$	current gain of Si/SiGe HBT as a function of temperature T
γ	emitter injection efficiency of a bipolar transistor, the effective threshold voltage displacement with V_{DS} for a MESFET
δ	phase difference
ΔC	change in capacitance
ΔE_{A}	activation energy of acceptor impurity
ΔE_{D}	activation energy of donor impurity
ΔE_{g}	energy bandgap difference between the emitter and base semiconductor materials
ΔE_{gB}	bandgap narrowing of the base
ΔE_{gE}	bandgap narrowing of the emitter
$(\Delta E_{\mathrm{g}})_{\mathrm{Si/SiGe}}$	difference between energy bandgaps of the Si emitter and $\mathrm{Si}_x\mathrm{Ge}_{1-x}$ base
ΔE_{V}	valence band offset
Δf	difference between frequencies f_1 and f_2
ΔN_{it}	interface trap density
ΔN_{ot}	oxide-trapped charge density
ΔR	change in resistance
Δt	time interval
$\Delta\xi_{\mathrm{g}}$, $\Delta\xi_{\mathrm{gBE}}$	decrease in bandgap of the emitter relative to base
$\Delta\Phi$	phase difference between junctions A, B in a SQUID
ε	dielectric constant
ε_0	permittivity of free space
$\varepsilon_{\mathrm{ox}}$	relative permittivity of silicon dioxide
ε_{s}	relative permittivity of silicon
η	emission coefficient or ideality factor in diode equation, shielding efficiency
η_{A}	efficiency of absorption
η_{a}, η_{b}	empirical constants
η_{MR}	efficiency of multiple reflections
η_{R}	efficiency of reflection
θ	gauge-invariant phase difference, contact angle at solid–liquid interface
$\theta(\mathbf{r})$	phase of the wave function

κ	TC of threshold voltage
λ	mean free path of carrier, channel length modulation parameter of MESFET, wavelength of the wave, air–fuel ratio in the combustion chamber of automobile
λ or λ_L	London penetration length/depth
λ_0	high-energy low-temperature asymptotic phonon mean free path
μ	mobility of carrier, permeability of the material
μ_0	vacuum permeability
μA	microampere
μ_I	ionized impurity scattering-limited mobility
μ_i	initial mobility
μ_f	final mobility
μJ	microJoule
μ_L	lattice scattering-limited mobility
μm	micron (micrometer)
μ_n	mobility of an electron
μ_{nB}	mobility of electrons in the base
μ_p	mobility of a hole
μ_{pE}	mobility of holes in the emitter
μV	microvolt
μW	microwatt
ξ	coherence length (for Cooper pairs)
ξ_g	bandgap in the emitter
Ξ	an integer
ρ	resistivity of a substance
ρ_1, ρ_2	densities of the Cooper pairs
ρ_{ox}	charge density in the oxide
$\rho(\mathbf{r})$	Cooper pair concentration in the superconductor where $\mathbf{r}$ is the position vector
σ	conductivity
σ_v	an empirical constant
τ	carrier lifetime, time constant
τ_B	base transit time
τ_E	emitter transit time
τ_F	forward transit time, final lifetime
τ_{HL}	high-level lifetime
τ_I	initial lifetime
τ_{LL}	low-level lifetime
τ_p	lifetime of holes
τ_{pE}	lifetime of holes in the emitter
Φ	magnetic flux threading a loop
Φ_0	magnetic flux quantum (fluxon)
ϕ	fluence, phase difference between the wavefunctions ψ_1 and ψ_2; $\phi = \phi_2 - \phi_1$
ϕ_0	phase difference when $V = 0$
ϕ_1, ϕ_2	phases of the wavefunctions of Cooper pairs, phases of two signals V_1, V_2
Φ_{A1}, Φ_{A2}	phases adjacent to the junction A in a SQUID
Φ_{B1}, Φ_{B2}	phases adjacent to the junction B in a SQUID
Φ_A, Φ_B	phase differences across the JJs A and B in a SQUID
ϕ_B	Schottky barrier height
Φ_{bn}	Schottky barrier height of metal–semiconductor interface
$\Phi_{External}$	external magnetic flux

ϕ_F	bulk potential
ϕ_ms	metal–semiconductor work function
ψ	wavefunction
ψ_1 and ψ_2	wavefunctions of Cooper pairs
$\psi(\mathbf{r})$	wavefunction of Cooper pair electron where $\mathbf{r}$ is the position vector
ω	angular frequency
Ω	ohm
Ω-cm	ohm-centimeter
ω_n	natural angular frequency
Ω_s	excitation frequency
∇	nabla (differential operator)