APPLIED ELECTRONICS

SECOND EDITION

Truman S Gray

Applied Electronics

A FIRST COURSE IN
ELECTRONICS, ELECTRON TUBES,
AND ASSOCIATED CIRCUITS

SECOND EDITION

by

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Foreword

The staff of the Department of Electrical Engineering at the Massachusetts Institute of Technology has for some years been engaged in an extensive program of revising as a unit its entire presentation of the basic technological principles of electrical engineering. This new edition of *Applied Electronics* covers a part of that presentation.

The decision to undertake so comprehensive a plan rather than to add here and patch there came from the belief that the Department's large staff, with its varied interests in teaching and related research, could effect a new synthesis of educational material in the field of electrical engineering and evolve a set of textbooks with a breadth of view not easily approached by an author working individually.

Such a comprehensive revision, it was felt, should be free from the duplications, repetitions, and unbalances so often present in an unintegrated program. It should possess a unity and breadth arising from the organization of a subject as a whole. It should appeal to the student of ordinary preparation and also provide a depth and rigor challenging to the exceptional student and acceptable to the advanced scholar. It should comprise a basic course adequate for all students of electrical engineering regardless of their ultimate specialty. Restricted to material which is of fundamental importance to all branches of electrical engineering, the course should naturally lead into any one branch.

This book and the reorganized program of teaching out of which it has grown are thus products of a major research project to improve educational methods. The rapid development of electronics brought about by the impetus of the recent wars has made desirable revision of the original book to include new and improved devices, techniques, and methods of presentation. During these developments it has become clear that revision of this treatment and extension of it to new areas such as are included in this book should become more and more the responsibility of individual authorities who could relate their work to the over-all structure.

KARL T. COMPTON

Preface

During the years since the first edition of this book was published, electronics has truly come of age. We now rely on it for our comfort, our convenience, and even our lives in diverse fields such as energy conversion, communication, and control. We look to it with justified expectancy for new useful developments of benefit to mankind. The importance of electronics in science and engineering and, correspondingly, in technological education, has thus become even more clearly established than ever before. To facilitate such education, this book aims to lay a foundation for effective engineering application of the basic phenomena of electronics.

The extent of the use of electronics in the different branches of electrical engineering—power, communications, measurement, control, and others—precludes a complete treatment of the subject in a single volume. Hence, this book is not exhaustive; details of application are expected to follow in courses designed for specialization by students in the different branches. This book is for a first basic course. Rigor of thought and analysis, rather than extensiveness of scope, is its intended feature.

New devices, new principles, and new methods of analysis have extended the possibilities for application of electronics. The basic pattern of the field, and hence of this book, remains, however, essentially unchanged from that of the original edition. On the premise that proper application of electronic apparatus requires a working knowledge of the physical phenomena involved in the apparatus, the first part of the book is a discussion of those phenomena. The second part is an explanation of the way the phenomena combine to govern the characteristics, ratings, and limitations of electronic devices, and the third is a consideration of applications common to the several branches of electrical engineering. Finally, the fourth part is a treatment of semiconductor devices, primarily the transistor, in a manner parallel to the previous treatment of vacuum tubes. This arrangement makes practicable use of the book as a textbook in a number of different ways. In its entirety, it is intended to be suitable for a two-semester course. Assigning the early chapters and certain of the later chapters as reference material for reading only, with resultant emphasis upon the chapters that treat the circuit applications of electron tubes and semiconductor devices, makes possible use of the book for a one-semester course. To provide for additional study by particularly apt or advanced students, more material than is usually covered in a first course is presented; and to aid independent study outside the classroom, graphical data on typical electron tubes and answers to representative problems stated at the ends of the chapters are included in appendices.

Most of the functional methods by which electronics is employed in engineering are included. To make the book adequate as a point of departure into independent study and analysis of specialized applications of electronics, emphasis is placed on care in reasoning, with the thought that ease of understanding is synonymous with clarity of conception. Attempt is made to point out all links in the chain of reasoning in order to avoid those gaps that are so easily spanned intuitively by experienced engineers, but are so disturbing to the careful but inexperienced student. In addition to exact logic, this effort involves not advanced mathematics, but rather scrupulous attention both to aids to clearness of thought and to apparently minor details that are elementary but essential. One important aid is precise definitions of symbols and interpretation of them in terms of physical quantities. Among the elementary details requiring attention are the algebraic signs associated with the distinction between actual and reference directions of quantities, and avoidance of the common error of mixing complex numbers and time functions in the same equation. The three categories of mathematical quantities—scalars, complex numbers, and vectors—are distinguished by distinctive type, in accordance with the ASA American Standard Letter Symbols for Electrical Quantities. Since some of the rules for mathematical manipulation of quantities in each of these categories differ from the rules for quantities in the other two categories, such a distinction is essential for clarity. Symbols for the various component currents and voltages in electron-tube circuits are consistent with the recently revised standard for those quantities, and rationalized meter-kilogram-second units for physical quantities are used throughout the book, in accordance with almost universal present-day practice.

During preparation of this revision, it has been a pleasure to recall the contributions of colleagues who shared in supplying preliminary drafts of sections of the original edition. Many of them are now at other educational institutions or with industrial organizations; some, however, are still my close associates. The fact that many of the ideas and concepts in those early drafts continue to be regarded as fundamental and are hence retained in this revised book attests to the soundness of their judgment. I have been greatly aided by discussions with and suggestions from my present colleagues. In particular, I wish especially to thank Professor A. B. Van Rennes and Professor E. F. Buckley for their many

constructive suggestions throughout the book, and their able, generous, and untiring aid in reading all the manuscript and the proof. I am also indebted to Professor S. J. Mason and Professor R. E. Scott for their suggestions regarding circuit analysis, and to Professor R. B. Adler for his advice regarding the chapter on semiconductor devices. Dean F. G. Fassett, Jr., has been ever helpful with counsel on presentation and style, and Dean H. L. Hazen and Professor G. S. Brown have provided continual inspiration by their encouragement and support of this work. To all these individuals, and to my wife Isabel for her constant encouragement, assistance, and forbearance, I extend my thanks, with the hope that their helpfulness will be reflected in increased usefulness of the book to students.

TRUMAN S. GRAY

October 27, 1953

Table of Symbols

In this book a **boldface roman-type** or **script letter** is used to represent a space vector, and an ordinary *italic* or *script letter* to represent its magnitude, for example: **B**, **ℰ**, B, $\mathcal{E}$. Similarly, a ***boldface italic letter*** is used to represent a complex number, and an *italic letter* its magnitude, for example: $\boldsymbol{E}$, E. Ordinary italic or script letters are used to represent the ordinary real scalar quantities. For voltage, current, and charge, capital letters generally represent fixed quantities, and lower-case letters represent variable quantities. For transistors, however, an exception is made, as is explained in Art. 4, Ch. XIII. In general, each letter stands for a quantity of a particular kind, and subscripts are used to distinguish several quantities of the same kind from one another. For example, i is used for instantaneous current, and i_b specifies the instantaneous plate current in an electron tube.

The notation used in this book conforms to that standardized by the Institute of Radio Engineers[1] for use with electron tubes and their circuits. In order to make this conformity possible no distinction is made between e and v, or E and V. Any one is used to represent a voltage whether it be that of a source or not.

In the table that follows are listed the more important symbols used in this book. Many of the special symbols obtained through adding subscripts to the letters listed are omitted from this list, but are defined in the text where used. The standardized symbols used to designate voltage and current components encountered in electron-tube circuits are omitted from the main list and appear instead in a table at the end of the list. This table is repeated in Art. 20, Ch. VIII.

Abbreviations used in this book are, in general, those approved by the American Standards Association.[2]

[1] *Standards on Abbreviations, Graphical Symbols, Letter Symbols, and Mathematical Signs, 1948* (New York: The Institute of Radio Engineers, 1948), 1–9.

[2] *American Standard Abbreviations for Scientific and Engineering Terms — ASA No. Z10.1* (New York: American Society of Mechanical Engineers, 1941).

English Letter Symbols

Symbol: Complex	Symbol: Scalar	Symbol: Vector	Description	Defined or First Used: Page
	A		Coefficient in Richardson's equation	77
	A		Heating current for a tungsten filament	88
	A		Constant of integration	320
$\mathbf{A}$	A		Voltage amplification of an amplifier	413
	A		Amplitude of a wave	691
	A'		Heating current for a unit tungsten filament	88
	A_c		Amplitude of carrier wave	692
$\mathbf{A}_{fb}$	A_{fb}		Voltage amplification of feedback amplifier	573
$\mathbf{A}_{gg}$			Loop transmission	575
	A_m		Amplitude of modulating wave	692
	A_{oc}		Open-circuit voltage amplification	804
$\mathbf{A}_{so}$			Direct transmission	575
$\mathbf{A}_t$			Complex no-load voltage amplification of a feedback amplifier	589
	$A(t)$		Instantaneous amplitude of modulated wave	692
	a	$\mathbf{a}$	Acceleration	8
	a		Coefficient in power series	440
	a		Transformer turns ratio	457
	a		A constant	735
	a		Amplitude of interfering signal	769
	a_1		Instantaneous current in anode 1 of polyphase rectifier	309
	B	$\mathbf{B}$	Magnetic flux density	30
	B_g		Input susceptance of vacuum tube	422
	BW		Bandwidth	495
	b		Constant in Richardson's equation	77
	b		Coefficient in power series	440
	C		Constant of integration	16
	C		Capacitance	317
	C_c		Capacitance of coupling capacitor	509
	C_g		Capacitance of grid capacitor	642
	C_g'		Total interstage shunt capacitance in a cascade amplifier	515
	C_{gk}		Grid-to-cathode interelectrode capacitance	420
	C_{gp}		Grid-to-plate interelectrode capacitance	420

Symbol			Description	Defined or First Used
Complex	Scalar	Vector		Page
	C_k		Capacitance of cathode by-pass capacitor . .	398
	C_{pk}		Plate-to-cathode interelectrode capacitance .	420
	c		Speed of propagation of electromagnetic waves in free space	4
	D	$\mathbf{D}$	Electric flux density	128
	d		A distance	6
	d		Diameter	141
	d		Coefficient in power series	743
	E		Constant voltage	8
$\mathbf{E}$	E		Effective value of alternating voltage . . . (See also table at end of this list for standardized symbols for voltages encountered in electron-tube circuits.)	289
	E_b		Constant, or average, plate voltage of electron tube	22
	E_{bb}		Plate-supply voltage	118
	E_{cc}		Grid-bias supply voltage	370
	E_{dc}		Average value of rectifier load voltage . . .	289
	E_{d0}		Average value of rectified voltage	304
	E_f		Filament voltage of electron tube	172
	E_m		Amplitude of alternating grid voltage . . .	377
$\mathbf{E}_n$	E_n		Extraneous or noise voltage	495
$\mathbf{E}_o$	E_o		Output voltage	571
	E_s		Breakdown voltage of a gas	153
$\mathbf{E}_s$	E_s		Effective value of source voltage	304
	E_{sm}		Maximum instantaneous value of source voltage	282
	E_0		Voltage intercept for approximate plate characteristics	200
	E_0		Constant voltage drop in gas-type rectifier when conducting	284
	$\mathcal{E}$	$\boldsymbol{\mathcal{E}}$	Electric field intensity	8
	e		Instantaneous voltage	13
	e_b		Instantaneous plate voltage of electron tube .	12
	e_c		Instantaneous grid voltage of electron tube .	184
	e_c		Instantaneous voltage across capacitor . . .	719
	e_{cn}		Instantaneous grid-to-ground voltage . . .	429

Symbol: Complex	Symbol: Scalar	Symbol: Vector	Description	Defined or First Used: Page
	e_{c1}		Instantaneous control-grid voltage of electron tube	203
	e_{c2}		Instantaneous screen-grid voltage of electron tube	202
	e_{crit}		Critical grid voltage of a thyratron	366
	e_{d0}		Instantaneous rectified voltage	304
	e_{gna}		Sum component in grid-to-ground voltage	505
	e_{gnd}		Difference component in grid-to-ground voltage	505
	e_h		Instantaneous carrier voltage	738
	e_i		Instantaneous input voltage	339
	e_k		Instantaneous cathode-to-ground voltage	429
	e_m		Instantaneous modulating voltage	739
	e_o		Instantaneous output voltage	431
	e_o		Local oscillator voltage	758
	e_s		Instantaneous value of alternating source voltage	280
	e_s		Input signal voltage	430
	e_t		Total radiation emissivity	82
	e_0		Instantaneous control voltage of a triode	667
	e_1		Instantaneous source voltage for anode 1 of polyphase rectifier	304
	F	$\mathbf{F}$	Force	4
	F		Noise figure	816
	f		A function	58
	f		Frequency	111
	f		Fractional quantity	143
	f_0		Geometric mean frequency	519
	f_1		Lower half-power frequency	515
	f_2		Upper half-power frequency	516
	G		Conductance	422
	$G(f)$		Frequency spectrum of a wave	746
	G_g		Input conductance of vacuum tube	422
	$G(\omega)$		Angular-frequency spectrum of a wave	702
	g_m		Mutual conductance, or control-grid-to-plate transconductance of vacuum tube	194
	h		Planck constant	5
	I		Constant current	80

Symbol			*Description*	*Defined or First Used*
Complex	*Scalar*	*Vector*		*Page*
I	I		Effective value of alternating current . . . (See also table at end of this list for standardized symbols for currents encountered in electron-tube circuits.)	290
	I_a		Effective value of rectifier anode current . .	309
	I_b		Instantaneous transistor base current . .	797
	I_c		Instantaneous transistor collector current .	789
	I_{dc}		Average rectifier load current	288
	I_e		Instantaneous transistor emitter current .	789
	I_f		Filament current of electron tube	171
	I_L		Effective value of current in inductor . . .	664
	I_n		Rms shot noise current	496
I_o			Output current	573
	I_s		Saturation thermionically emitted current .	80
	i		Angle of incidence.	27
	i		Instantaneous current	30
		$\mathbf{i}$	Vector indicating magnitude and direction of current in a stream.	32
	i_b		Instantaneous plate current of electron tube .	119
	i_c		Instantaneous grid current of electron tube. .	190
	i_c		Instantaneous capacitor current.	317
	i_{c2}		Instantaneous screen-grid current of electron tube	204
	i_d		Instantaneous plate current of composite tube	468
	i_i		Instantaneous input current	338
	J		Current density	77
	J_s		Saturation current density	77
	$J_n(\delta)$		Bessel function of order n and argument δ. .	763
	j		$\sqrt{-1}$	46
	K		Stefan-Boltzmann constant	82
	K		Constant of proportionality	130
	k		Boltzmann constant	68
	k		Constant of proportionality	692
	k		An integer	633
	L		Inductance	46
	l	$\mathbf{l}$	Length	8
	M		Rate of evaporation of a tungsten filament .	88

Symbol: Complex	Symbol: Scalar	Symbol: Vector	Description	Defined or First Used: Page
	M		Atomic weight	263
	M		Mutual inductance	558
	M'		Rate of evaporation of a unit tungsten filament	88
	m		Mass	4
	m		An integer	307
	m		Modulation factor	698
	m_e		Rest mass of an electron	3
	N		Number	45
	N		Number of turns	295
	$N(W)$		Distribution function for kinetic energies	68
	$N_x(W_x)$		Distribution function for x-associated kinetic energies	72
	n		Number per unit volume, area, length, or time	31
	n		An integer	307
	P		Average power	82
	P		Output power	310
	P_{ac}		Alternating-current power to load	446
	P_B		Power radiated by plate of electron tube	172
	P_b		Quiescent power input to plate of electron tube	445
	P_{bb}		Power from plate power supply	445
	P_{bs}		Power input to plate of electron tube	616
	P_{cs}		Power input to grid of electron tube	637
	P_{dc}		Direct-current power to load	290
	P_g		Power supplied by source of grid-signal voltage	641
	P_h		Power contained in carrier wave	710
	P_{in}		Input power	290
	P_L		Power to load	445
	P_m		Power output of modulating amplifier	710
	P_p		Plate power dissipation	290
	P_2		Rating of transformer secondary windings	310
	p		Pressure	142
	p		Number of phases	306
	Q		Constant electric charge	6
	Q		Quiescent operating point	196
	Q		Ratio of reactance to resistance for an inductor	340
	Q_e		Magnitude of charge of electron	3

Symbol (Complex)	Symbol (Scalar)	Symbol (Vector)	Description	Defined or First Used (Page)
	Q_0		Figure of merit of a tuned circuit	549
	q		Instantaneous electric charge	46
	R		Resistance	46
	R		Resistance of a tungsten filament	88
	R'		Resistance of a unit tungsten filament	88
	R_b		Apparent resistance of plate circuit of Class C amplifier	712
	R_b		External base resistance	794
	R_c		Core-loss resistance	536
	R_{eq}		Equivalent noise resistance	497
	R_{eq}		Equivalent shunt resistance in amplifier	514
	R_{eq}'		Equivalent series resistance in amplifier	514
	R_g		Resistance of grid resistor	509
	R_{in}		Input resistance	805
	R_k		Resistance of cathode resistor	398
	R_L		Resistance of load resistor	394
	R_{out}		Output resistance	805
	R_p		Effective primary-winding resistance to alternating current	536
	R_{pp}		Plate-to-plate load resistance for push-pull amplifier	463
	R_{pri}		Primary-winding resistance	458
	R_S		Resistance of screen-grid voltage supply	426
	R_s		Internal resistance of source of grid signal	789
	R_s		Effective secondary-winding resistance to alternating current	536
	R_t		Tuned resistance of parallel-tuned circuit	550
	R_X		Resistance of filter inductor	340
	$R(\lambda)$		Photoelectric response function	114
	R_0		Resistance of vacuum-type rectifier when conducting	284
	R_1		Series grid resistor for thyratron	370
	r		Angle of refraction	27
	r		Radius	33
	r_b		Base incremental resistance	801
	r_c		Collector incremental resistance	801
	r_e		Emitter incremental resistance	801

Symbol: Complex	Symbol: Scalar	Symbol: Vector	Description	Defined or First Used: Page
	r_k		Radius of cathode of electron tube	50
	r_m		Mutual incremental resistance	801
	r_p		Radius of plate of electron tube	50
	r_p		Dynamic, or incremental, or variational, plate resistance of vacuum tube	194
	r_{11}		Incremental self-resistance	799
	r_{12}		Incremental transfer resistance	799
	r_{21}		Incremental transfer resistance	799
	r_{22}		Incremental self-resistance	799
	s		Area of a surface	128
	s_p		Area of plate of electron tube	132
	T		Absolute temperature	68
	T		Period of sinusoidal wave	447
	t		Time	8
$\mathbf{u}$			Complex variable representing velocity in a plane	46
	u		A fraction	143
	u		Variation in rectified voltage	355
	V		Voltage across tungsten filament	88
	V'		Voltage across unit tungsten filament	88
	V_b		Instantaneous base-to-emitter voltage drop	797
	V_{bb}		Base-bias supply voltage	796
	V_c		Instantaneous collector-to-base voltage drop	793
	V_{cc}		Collector-bias supply voltage	793
	V_e		Instantaneous emitter-to-base voltage drop	793
	V_{ee}		Emitter-bias supply voltage	789
	V_{en}		Instantaneous emitter-to-ground voltage drop	795
	v		Speed	4
		$\mathbf{v}$	Velocity	32
	v_{nc}		Collector noise voltage	814
	v_{ne}		Emitter noise voltage	814
	v_s		Signal source voltage	789
	W		Energy	63
	W		Power input to a tungsten filament	88
	W'		Power input to a unit tungsten filament	88
	W_a		Potential-energy barrier at surface of a metal	72
	W_i		Energy level at top of Fermi band	68

Symbol: Complex	Symbol: Scalar	Description	Defined or First Used: Page
	W_x	x-associated kinetic energy	71
	X	Reactance	325
	X_c	Reactance of capacitor	325
	X_L	Load reactance	409
	x	A position co-ordinate	9
$\mathbf{Y}_g$	Y_g	Input admittance of a vacuum tube	422
	y	A position co-ordinate	9
	Z	Atomic number	63
$\mathbf{Z}$	Z	Impedance	340
$\mathbf{Z}_{fb}$	Z_{fb}	Driving-point impedance with feedback	586
$\mathbf{Z}_i$	Z_i	Input impedance	433
$\mathbf{Z}_k$	Z_k	Impedance in cathode circuit	417
$\mathbf{Z}_L$	Z_L	Load impedance	409
$\mathbf{Z}_t$	Z_t	Impedance of a tuned circuit	549
$\mathbf{Z}_t$		Complex internal impedance of a feedback amplifier	589
$\mathbf{Z}_\beta$		Feedback transfer impedance	573
	z	A position co-ordinate	9

Greek Letter Symbols

Symbol: Complex	Symbol: Scalar	Description	Defined or First Used: Page
	α Alpha	Ratio of voltage drop in gas-type rectifier to peak value of supply voltage	298
	α	A fraction	358
	α	Short-circuit current amplification	799
	α_e	Current ratio	801
	β Beta	Constant in three-halves-power equation for cylindrical diode	133
$\boldsymbol{\beta}$	β	Feedback voltage ratio	571
	γ Gamma	Ripple factor	291
	δ Delta	A ratio	45
	δ	Fractional deviation from resonant frequency	550
	δ	A small error in experimental data	728
	δ	Modulation index	763
	ε Epsilon	Dielectric constant	129
	ε_v	Dielectric constant of free space	6
	ϵ	Naperian base (2.71828...)	46
	η Eta	Index of refraction	27

Symbol	*Description*	*Defined or First Used*
Scalar		*Page*
η	Efficiency	290
η_p	Plate efficiency of a vacuum tube	448
θ Theta	An angle	36
ϑ	Impedance angle	409
θ_A	Angle of complex voltage amplification	413
λ Lambda	Wavelength	5
λ	Mean free path	141
μ Mu	Amplification factor of vacuum tube	189
ν Nu	Volume	128
ν	Number of collisions per centimeter	142
π Pi	Ratio of circumference to diameter of circle (3.14159...)	6
ρ Rho	Charge density	128
ϕ Phi	An angle	30
ϕ	Phase angle of current	410
ϕ	Voltage equivalent of work function	73
ϕ_c	Contact potential difference	75
$\phi(t)$	Instantaneous phase angle of modulated wave	691
ψ Psi	Phase angle of voltage	55
ω Omega	Angular frequency	55
ω_c	Angular frequency of carrier wave	692
ω_m	Angular frequency of modulating wave	692
$\omega(t)$	Instantaneous angular frequency of modulated wave	693
ω_0	Resonant angular frequency	548

Other Symbols

$\approx$	Approximately equal to	327
$\equiv$	Defined as	193
$\gg$	Large compared with	341
$\ll$	Small compared with	341
Σ	Sum of	636
$\|A\|$	Magnitude of A	307
Δ	Increment of	29
$\cdot$	Dot product	10
$\times$	Cross product	32
grad	Gradient of	8