BELL TELEPHONE LABORATORIES SERIES

PRINCIPLES OF ELECTRON TUBES

INCLUDING GRID-CONTROLLED TUBES, MICROWAVE TUBES AND GAS TUBES

JAMES W. GEWARTOWSKI and HUGH A. WATSON
MEMBERS OF THE TECHNICAL STAFF, BELL TELEPHONE LABORATORIES, INCORPORATED
RESEARCH AND DEVELOPMENT UNIT OF THE BELL SYSTEM

This introductory yet comprehensive study of modern electron tubes emphasizes basic physical principles, and gives a clear picture of how electron-field interactions lead to useful device performance. Of special value to engineers concerned with the development or utilization of electron tubes.

THE BELL TELEPHONE LABORATORIES SERIES is a group of books arising out of the broad investigations of the Bell Telephone Laboratories, a research and development organization whose more than 4,000 scientists and engineers deal with every aspect of communications and allied fields. For almost thirty-five years the series has represented some of the most notable contributions to the literature of science and engineering.

Here, clearly and accurately presented, are theoretical and practical texts from one of the world's greatest industrial laboratories. The various authors are recognized leaders in their respective fields.

The continuing authority of the series is assured by careful revision as significant new developments take place. Titles are added as new areas of scientific and technological activity are sufficiently delineated for detailed discussion.

A complete list of titles now available in THE BELL TELEPHONE LABORATORIES SERIES appears on the back panel of this jacket.

PRINTED
IN
U.S.A.

THIS logically arranged book is the most comprehensive study of electron tubes available today. Placing its emphasis on the basic physical principles involved, it avoids complicated and rigorous mathematical analyses when simpler approximate analyses are possible. Each presentation of a tube-type demonstrates the way electron-field interactions lead to useful performance from the device. Detailed descriptions of specific tubes appear as practical embodiments of the principles, and various tube-types are compared to show their relative advantages and disadvantages for particular applications.

The first 13 chapters relate primarily to vacuum tubes. Beginning with a study of electrostatics, magnetostatics, and the basic laws of electron motion, the book goes on to cathodes, electron guns, lenses, and methods of beam confinement. Conventional diodes and grid-controlled tubes are described, and their high-frequency limitations are explored by means of the concept of induced currents. An introduction to microwave circuits is followed by analyses of the microwave tubes. This first section concludes with a consideration of noise phenomena in electron tubes, and the last four chapters are concerned with gas discharge devices including the Townsend discharge in a gas diode, cold-cathode gas tubes, hot-cathode gas tubes, and gas lasers.

The book is a revision and extension of notes prepared by the authors for a course given in the Communications Development Training Program at Bell Telephone Laboratories. Numerous problems are provided to enhance its use as a textbook. Practicing engineers, especially those working on electron-tube development and those using electron tubes as circuit elements, will find this book to be of exceptional usefulness.

1759

THE BELL TELEPHONE LABORATORIES SERIES

THEORY OF VIBRATING SYSTEMS AND SOUND By Irving B. Crandall

SPEECH AND HEARING Second Edition By Harvey Fletcher

PROBABILITY AND ITS ENGINEERING USES Second Edition By Thornton C. Fry

ELEMENTARY DIFFERENTIAL EQUATIONS By Thornton C. Fry

PRINCIPLES OF ELECTRON TUBES By James W. Gewartowski and Hugh A. Watson

TRANSMISSION NETWORKS AND WAVE FILTERS By T. E. Shea

ECONOMIC CONTROL OF QUALITY OF MANUFACTURED PRODUCT By W. A. Shewhart

ELECTROMECHANICAL TRANSDUCERS AND WAVE FILTERS Second Edition By Warren P. Mason

POISSON'S EXPONENTIAL BINOMIAL LIMIT By E. C. Molina

ELECTROMAGNETIC WAVES By S. A. Schelkunoff

NETWORK ANALYSIS AND FEEDBACK AMPLIFIER DESIGN By Hendrik W. Bode

CAPACITORS—THEIR USE IN ELECTRONIC CIRCUITS By M. Brotherton

FOURIER INTEGRALS FOR PRACTICAL APPLICATIONS By George A. Campbell and Ronald M. Foster

APPLIED MATHEMATICS FOR ENGINEERS AND SCIENTISTS Second Edition By S. A. Schelkunoff

EARTH CONDUCTION EFFECTS IN TRANSMISSION SYSTEMS By Erling D. Sunde

THEORY AND DESIGN OF ELECTRON BEAMS Second Edition By J. R. Pierce

PIEZOELECTRIC CRYSTALS AND THEIR APPLICATION TO ULTRASONICS By Warren P. Mason

MICROWAVE ELECTRONICS By John C Slater

TRAVELING-WAVE TUBES By J. R. Pierce

PRINCIPLES AND APPLICATIONS OF WAVEGUIDE TRANSMISSION By George C. Southworth

ELECTRONS AND HOLES IN SEMICONDUCTORS By William Shockley

FERROMAGNETISM By Richard M. Bozorth

DESIGN OF SWITCHING CIRCUITS By William Keister, Alistair E. Ritchie and Seth H. Washburn

MODULATION THEORY By Harold S. Black

SWITCHING RELAY DESIGN By R. L. Peek, Jr. and H. N. Wagar

TRANSISTOR TECHNOLOGY Vol. I Edited by H. E. Bridgers, J. H. Scaff and J. N. Shive

TRANSISTOR TECHNOLOGY Vol. II Edited by F. J. Biondi

TRANSISTOR TECHNOLOGY Vol. III Edited by F. J. Biondi

PHYSICAL ACOUSTICS AND THE PROPERTIES OF SOLIDS By Warren P. Mason

THE PROPERTIES, PHYSICS AND DESIGN OF SEMICONDUCTOR DEVICES By John N. Shive

D. VAN NOSTRAND COMPANY, Inc.
120 Alexander Street Princeton, New Jersey
105

Principles of Electron Tubes

THE BELL TELEPHONE LABORATORIES SERIES

PROBABILITY AND ITS ENGINEERING USES. *By* THORNTON C. FRY. Second Edition.
TRANSMISSION NETWORKS AND WAVE FILTERS. *By* T. E. SHEA.
ECONOMIC CONTROL OF QUALITY OF MANUFACTURED PRODUCT. *By* W. A. SHEWHART.
ELECTROMECHANICAL TRANSDUCERS AND WAVE FILTERS. *By* WARREN P. MASON. Second Edition.
POISSON'S EXPONENTIAL BINOMIAL LIMIT. *By* E. C. MOLINA.
ELECTROMAGNETIC WAVES. *By* S. A. SCHELKUNOFF.
NETWORK ANALYSIS AND FEEDBACK AMPLIFIER DESIGN. *By* HENDRICK W. BODE.
CAPACITORS—THEIR USE IN ELECTRONIC CIRCUITS. *By* M. BROTHERTON.
FOURIER INTEGRALS FOR PRACTICAL APPLICATIONS. *By* GEORGE A. CAMPBELL and RONALD M. FOSTER.
APPLIED MATHEMATICS FOR ENGINEERS AND SCIENTISTS. *By* S. A. SCHELKUNOFF. Second Edition.
EARTH CONDUCTION EFFECTS IN TRANSMISSION SYSTEMS. *By* ERLING D. SUNDE.
THEORY AND DESIGN OF ELECTRON BEAMS. *By* J. R. PIERCE. Second Edition.
PIEZOELECTRIC CRYSTALS AND THEIR APPLICATION TO ULTRASONICS. *By* WARREN P. MASON.
MICROWAVE ELECTRONICS. *By* JOHN C. SLATER.
PRINCIPLES AND APPLICATIONS OF WAVEGUIDE TRANSMISSION. *By* GEORGE C. SOUTHWORTH.
TRAVELING-WAVE TUBES. *By* J. R. PIERCE.
ELECTRONS AND HOLES IN SEMICONDUCTORS. *By* WILLIAM SHOCKLEY.
FERROMAGNETISM. *By* RICHARD M. BOZORTH.
THE DESIGN OF SWITCHING CIRCUITS. *By* WILLIAM KEISTER, ALASTAIR E. RITCHIE, and SETH H. WASHBURN.
SPEECH AND HEARING IN COMMUNICATION. *By* HARVEY FLETCHER. Second Edition.
MODULATION THEORY. *By* HAROLD S. BLACK.
SWITCHING RELAY DESIGN. *By* R. L. PEEK, JR., and H. N. WAGAR.
TRANSISTOR TECHNOLOGY, Volume I. *Edited by* H. E. BRIDGERS, J. H. SCAFF, and J. N. SHIVE.
TRANSISTOR TECHNOLOGY, Volume II. *Edited by* F. J. BIONDI.
TRANSISTOR TECHNOLOGY, Volume III. *Edited by* F. J. BIONDI.
PHYSICAL ACOUSTICS AND THE PROPERTIES OF SOLIDS. *By* WARREN P. MASON.
THE PROPERTIES, PHYSICS AND DESIGN OF SEMICONDUCTOR DEVICES. *By* J. N. SHIVE.
PRINCIPLES OF ELECTRON TUBES. *By* J. W. GEWARTOWSKI and H. A. WATSON.

Principles of Electron Tubes

Including Grid-Controlled Tubes, Microwave Tubes, and Gas Tubes

by

J. W. GEWARTOWSKI and H. A. WATSON
Members of the Technical Staff
Bell Telephone Laboratories

D. VAN NOSTRAND COMPANY, INC.
PRINCETON, NEW JERSEY
Toronto New York London

D. VAN NOSTRAND COMPANY, INC.
120 Alexander St., Princeton, New Jersey (*Principal office*)
24 West 40 Street, New York 18, New York

D. Van Nostrand Company, Ltd.
358, Kensington High Street, London, W.14, England

D. Van Nostrand Company (Canada), Ltd.
25 Hollinger Road, Toronto 16, Canada

Published simultaneously in Canada by
D. Van Nostrand Company (Canada), Ltd.

PRINTED IN THE UNITED STATES OF AMERICA

To Our Parents

PREFACE

This book is a revision and extension of notes prepared by the authors for courses given to the Communications Development Training Program at Bell Telephone Laboratories. This study program is given to all new members of the technical staff who have completed their university training at the B.S. or M.S. level. Thus the book is primarily intended for use at the senior or first-year graduate level.

The book should also be useful to graduate engineers working on electron-tube development and manufacture and to engineers using electron tubes as circuit elements. Detailed descriptions are included of practical electron tubes as examples.

Throughout the text an effort has been made to present a coherent picture of the use of electron-field interactions to obtain useful device performance. The first 13 chapters relate primarily to vacuum tubes, and the last four chapters are concerned with gas-discharge devices. The text first considers the basic laws of electron motion in fields and electron emission. This is followed by a discussion of electron lenses and electron guns. Next, grid-controlled vacuum tubes are examined, and their equivalent circuits are derived. High-frequency limitations of grid-controlled tubes are explored through the concept of induced currents. This is followed by a detailed study of microwave tubes. A final chapter on vacuum tubes considers the noise performance of these devices. The last four chapters of the text consider first the Townsend discharge in a gas diode, followed by a discussion of cold-cathode and hot-cathode gas tubes, and finally a description of gas lasers.

Although considerable mathematical detail is included, an effort has been made to stress the physical principles of each device. Problems are included at the ends of most of the chapters to illustrate further concepts relative to the text material. References are cited for those who wish to pursue particular subjects in more detail. A notation has been adopted which is consistent with the symbols used in the literature, insofar as this is possible in a coherent presentation. No attempt has been made to include any historical comments concerning electron tubes. For the most part, tubes are discussed in configurations that are in practical use today rather than in those originally conceived.

The authors wish to thank their many associates at Bell Telephone Laboratories who provided information, drawings, and criticism of the manuscript. Dr. T. B. Ramachandran of Lehigh University carefully reviewed the earlier chapters and made a number of helpful suggestions concerning later chapters while these were in preparation. The authors also wish to express their appreciation to four secretaries who typed the manuscript and its many revisions: Miss J. Mishko, Miss D. J. Delong, Mrs. S. T. Otto, and Mrs. J. K. Ziegler.

J.W.G. AND H.A.W.

CONTENTS

APPENDICES

LIST OF PRINCIPAL SYMBOLS

A = area
A_1 = initial loss factor, see Equation (10.1-62)
A_2 = space charge loss factor, see Equation (10.1-68)
a = radius of a helix-type slow-wave circuit
B, $\mathbf{B}$ = magnetic flux density; B = amplifier bandwidth
B_m = magnetic flux density within a permanent magnet material
b = susceptance term in electron beam admittance; velocity parameter, see Equation (10.1-40)
C = capacitance; small-signal gain parameter, see Equation (10.1-36)
c = velocity of light in free space
D, $\mathbf{D}$ = electric flux density; D = diffusion coefficient
d = molecular diameter; electrode spacing in a planar device; circuit loss parameter, see Equation (10.1-41)
E, $\mathbf{E}$ = electric field intensity
$\mathbf{E}_1(x,y,z)$ = a vector function of position having the dimensions of $(\text{meters})^{-1}$, see Equation (6.1-5)
$-e$ = electric charge of the electron
F = noise figure; F_1, F_2 = focal points of an electron lens
f = frequency of a sinusoidally varying quantity; f_1, f_2 = focal lengths of an electron lens
G = conductance; average number of metastables striking the cathode for each electron leaving the cathode (Chapter 14)
$\mathcal{G}$ = available power gain
g = conductance term in electron beam admittance
g_m = transconductance
$g_o = I_o/V_o$ = ratio of dc beam current to dc beam voltage
H, $\mathbf{H}$ = magnetic field intensity; H = average number of metastables produced by the release of a single electron from the cathode (Chapter 14)
H_m = magnetic field intensity in a permanent magnet material
h = Planck's constant; hub thickness in a magnetron
I = electric current; average number of ions generated by the release of a single electron from the cathode (Chapter 14)

I_o = dc beam current; I_{ST} = dc starting current in a backward-wave oscillator
$i = Re I \epsilon^{j\omega t}$ = instantaneous current, where I is a phasor quantity having magnitude, phase, and the dimensions of an electric current
i = electron convection current phasor (Chapters 10,11)
J = current density; J_o = dc beam current density; cathode emission current density; J_T = total current density (convection + displacement)
$j = \sqrt{-1}$
K = beam-coupling impedance
k = Boltzmann's constant; wave number, $k = \omega\sqrt{\mu\mu_o\varepsilon\varepsilon_o}$
L = inductance; periodic length; mean free path
l = length
M = mutual inductance; beam-coupling coefficient
$M_{1(n)}$ = gap factor for the nth space harmonic; see Equation (10.2-20)
$M_{2(n)}$ = impedance reduction factor for the nth space harmonic, see Equation (10.2-21)
m = mass of the electron
N = number of wavelengths, see Equation (10.1-70); number of molecules in one gram molecular weight
n = index of refraction; number of atoms or molecules per unit volume
P = average power; probability; pressure in mks units
p = pressure in mm of Hg
Q = a measure of quality of a resonant circuit or resonant cavity, see Equation (6.4-2); Q_e = external Q; Q_l = loaded Q; Q_u = unloaded Q
QC = space-charge parameter, see Equation (10.1-37)
q = electric charge
R = resistance; universal constant for one mole of gas, $R = Nk = PV/T$
r = radius; $\mathbf{r}$ = a radial vector of length r
r_a = dynamic anode resistance, or "plate" resistance
$\dot{r} = dr/dt$; $\ddot{r} = d^2r/dt^2$; $r' = dr/dz$; $r'' = d^2r/dz^2$
S = surface area; beam cross-sectional area
$\mathbf{S}$ = Poynting vector
T = temperature in °K; T_e = electron temperature; T_o = standard reference temperature of 290°K
t = time
u, $\mathbf{u}$ = velocity; u_o = dc beam velocity
V = electric potential, voltage; volume

V_o = dc beam voltage

$v = ReV\epsilon^{j\omega t}$ = instantaneous voltage, where V is a phasor quantity having magnitude, phase, and the dimensions of voltage

v_g = group velocity; v_p = phase velocity

W = energy, average stored energy; W_T = electron-volt equivalent of kT; W_t = emission energy parallel to the cathode surface; W_n = emission energy normal to the cathode surface; W_L = average stored energy in a unit cell of length L; W_l = average stored energy per unit length

X = bunching parameter, see Equation (9.2-9).

x_1 = rate of growth of the growing wave (Chapter 10)

Y = admittance

Z = impedance; Z_o = characteristic impedance

α = ionization coefficient per centimeter; circuit attenuation per unit length

β = phase shift per unit length along the axis of a slow-wave circuit; coefficient expressing the average number of metastables produced by a single electron in advancing one centimeter through a gas under the influence of an applied field (Chapter 14)

$\beta_e = \omega/u_o$; β_n = propagation constant for the nth order space harmonic; $\beta_q = \omega_q/u_o$

Γ = complex propagation coefficient

Γ^2 = space-charge smoothing factor for shot noise

γ = average number of electrons emitted from a cold cathode per incident ion

$\gamma_n = \sqrt{\beta_n{}^2 - k^2}$ = transverse decay parameter for the fields in a slow-wave structure

δ = ratio of secondary electrons emitted from a surface to primary electrons; skin depth; dimensionless complex growth constant of a wave (Chapters 10 and 11); gap length in a periodic structure (Chapters 10 and 11)

ε = relative dielectric constant; ε_o = permittivity of free space

ϵ = base for natural logarithms

η = efficiency; ionization coefficient per volt; $\eta = e/m$ = ratio of charge to mass of an electron; η_e = electronic efficiency; η_c = circuit efficiency

θ = angular coordinate in a cylindrical or spherical coordinate system; dc transit angle in a klystron amplifier

λ = wavelength; λ_o = wavelength in free space; λ_z = guide wavelength; λ_c = free-space wavelength at the cutoff frequency

μ = relative permeability; amplification factor; a dimensionless coordinate which varies from zero on the beam axis to unity at the beam edge (Chapter 4); ion mobility; μ_o = permeability of free space; μ_{es} = electrostatic amplification factor

ν = frequency of light radiation

ρ = charge per unit volume

σ = charge per unit area; conductivity of a medium; distance from the trajectory of a nonthermal electron to the trajectory of a thermal electron emitted from the same point on the cathode with transverse velocity $\sqrt{kT/m}$ (Chapter 4)

τ = charge per unit length

ϕ = work function in electron volts; magnetic flux

ψ = magnetic potential; pitch angle of a helix

$\omega = 2\pi f$ = radian frequency; ω_p = plasma frequency in radians/sec, see Equation (9.3-23); ω_q = reduced plasma frequency in radians/sec, see Equation (9.3-30); $\omega_c = eB/m$ = radian cyclotron frequency