Physics of Semiconductor Laser Devices

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Preface

In the fifteen or so years since its invention the semiconductor injection laser has evolved almost beyond recognition. From the original rather crude component based on a simple p–n junction it has grown and diversified into a whole range of sophisticated opto-electronic devices specifically designed for a variety of potentially important applications. The considerable amount of research that has been necessary to reach this position has also contributed greatly to the more general understanding of opto-electronic processes in semi-conductors and has generated much fruitful inter-disciplinary cross fertilization.

Recent years have seen a spate of new ideas in the semiconductor laser field and much re-assessment of older concepts. However, the flood now seems to be passing its peak. Although there is still no diminution in the rate at which new literature appears, one senses a change in emphasis. The present papers are directed mainly to describing the improved technological realization of known ideas rather than to putting forward new fundamental concepts. A period of consolidation and exploitation seems to be at hand. The semiconductor laser is now poised and ready for wide practical application in a number of fields, such as optical fibre communication, military systems, information read-out and printing. The near future should predominantly see a refinement of existing devices rather than a diversification, and the present seems a suitable time for making a critical survey of the more fundamental aspects of the subject.

This book deals specifically with the physics of the semiconductor laser. The basic phenomena that control the operation of the device are analysed and described in considerable detail. The treatment has been keyed particularly to fundamental concepts and kept general in order to avoid being overtaken by events. In the places where the mathematical formalism becomes cumbersome, and analytic methods fail, approximate methods have been employed in preference to computer simulation in order to give a broader picture and a better understanding. Curves have been used freely for presenting the information, frequently in normalized form for wider applicability. The range of phenomena in a semiconductor laser involve a number of scientific disciplines. To cater for the reader who is not already a specialist in all of these I have endeavoured, in the chapters on fundamental behaviour, to provide in a readable form the minimum background that is needed to understand the more specialized part of the text.

The plan of the book is as follows. The first part deals with fundamental principles. After an introduction in Chapter 1, Chapter 2 gives a full account of light emission in semiconductors. This starts with the Einstein emission/absorption relations, applied specifically to semiconductors, and with electron transition probabilities and leads up to an analysis of threshold current, incremental efficiency, and the spectral mode distribution in lasers. Chapter 3 deals with carrier injection processes at semiconductor heterojunctions and with the effect of temperature on carrier confinement. Chapter 4 deals with the processes by which light is confined within the very small dimensions of the semiconductor laser chip. Deliberate dielectric light-guides are provided for this purpose within the semiconductor and advantage is also taken of 'waveguiding by gain'. The principles of the dielectric light-guide are introduced briefly for the non-specialist using both ray and wave treatments and the results are applied generally to all types of heterostructure light-guide. More particular attention is applied to the alternative process of gain-guiding. This process, which is largely specific to semiconductor lasers and is seldom treated elsewhere, is analysed in considerable detail. The waveguide theory is also applied in treating the transverse modes of the laser resonator.

The second part of the book deals with specific characteristics of semiconductor lasers. The main topics comprise: the properties of the various broad contact heterostructure lasers in Chapter 5; a comprehensive discussion of 'stripe lasers' and their mode of operation in Chapter 6; dynamic characteristics of lasers in Chapter 7, including modulation, delay, stability, and noise; and distributed-feedback and distributed-Bragg-reflecting lasers in Chapter 8. In all these chapters the bulk of the examples refer to GaAs/(GaAl)As lasers because only these devices are at present sufficiently well characterized to give a good illustration of the general principles. The main subject matter, however, is much more general.

In order to provide a setting for the more analytical material in the rest of the book, Chapter 1 gives a general review of the whole contemporary field of semiconductor lasers and the associated technology. Not only are the different laser types and materials described but also their fabrication processes and the factors that control operating life. The possible future role of the semiconductor laser in integrated optics is also discussed. Particular applications are not, however, considered.

No attempt has been made to provide an exhaustive set of references to research papers or necessarily to note the first contribution in each field. The references that are supplied have been chosen both for the way in which they add to the general understanding of the subject and to complement the text in places where the reader may require additional information. Various review articles exist from which a more comprehensive list can be obtained.

I am indebted to many colleagues at STL and elsewhere who have helped me in the layout and preparation of this book. Especially I would like to thank J. E. A. Whiteaway, A. G. Steventon, J. E. Carroll, K. Unger, S. E. H. Turley, R. G. Plumb, and L. D. Westbrook for critical reading of the manuscript and useful suggestions. I am very grateful to the management at STL both for the facilities they have provided for laser research and for support during the preparation of the book. Particular thanks are due to F. Kerry for editing and correcting the material and to Mrs Cheryl Vaughan for typing the various versions of the text.

List of Principal Symbols

A = amplitude of forward wave in corrugated waveguide

$[A]$ = $A \exp(-j\beta_b z)$

A_b = forward wave component associated with backward wave component B in composite backward eigen solution for corrugated waveguide

A_{21} = Einstein coefficient for rate of spontaneous transitions per unit volume per unit energy interval of $h\nu$

B = $\{\pm(b^2 + 1)^{1/2} - b\}^{1/2}$ anti-focusing parameter

B = (also) amplitude of backward wave in corrugated waveguide

$[B]$ = $B \exp(j\beta_b z)$

B_b = backward wave component associated with forward wave component A in composite forward eigen solution for corrugated waveguide

$B_{21}(E_c, E_v)$ = Einstein coefficient for stimulated radiative transitions of electrons from energy E_c to E_v

C = proportion of spontaneous emission coupled to lasing modes

D = normalized width of centre layer of slab dielectric waveguide = $\beta_0 \delta\epsilon^{1/2} d$

D = (also) diffusion coefficient of minority carriers

D = (in Chapter 8) real part of eigen wave propagation coefficient β_e

E with subscripts x, y, etc. = component of optical electric field

E = energy of electron

E_c = energy of electron in conduction band

E_v = energy of hole in valence band

E_g = energy interval of forbidden band-gap

E_t = energy characterizing depth of band-tail

F = photon flux per unit area

F = (also) $\Delta\epsilon_f/\Delta\epsilon_m + 1$

F_x = Fourier component of E_x

G = stimulated emission per photon per mode

G' = $\mathrm{d}G/\mathrm{d}n$ = derivative of gain with respect to minority carrier concentration

G = (in Chapter 8) imaginary component of eigen wave propagation coefficient β_e

H with subscripts x, y, etc. = component of optical magnetic field

I = current

I_th = threshold current

J = current density per unit volume (carriers per second)

J_c = current density per unit area at contact

J_0 = threshold current density per unit area of wide laser

J_n = nominal current density per unit area referred to standard thickness of 1 μm (or more generally thickness of d_n)

J_t = current density per unit volume that gives zero gain

J_th = threshold current density per unit volume

J_th0 = threshold current density per unit volume of very long laser

K = degrees Kelvin

K_0 = wave vector of corrugation in corrugated guide

L = length of laser

L = (also) dynamic diffusion length

L_s = screening length

M $= \frac{1}{2} \times$ effective number of longitudinal modes in gain spectrum

M = (also) matrix element of momentum operator for calculating radiative transition probabilities

M_{bb} = band-to-band matrix element

M_{bi} = band-to-impurity matrix element

N = total number of possible optical modes in laser cavity over effective spectral width of gain

N_{A} = acceptor concentration

N_{D} = donor concentration

P = normalized transverse optical decay coefficient $(=p/\delta\epsilon^{1/2}\beta_0)$

Q = normalized transverse optical propagation coefficient $(=q/\delta\epsilon^{1/2}\beta_0)$

R = normalized transverse optical decay coefficient $(=r/\delta\epsilon^{1/2}\beta_0)$

R = (also) reflection coefficient for optical intensity

R = (also) radius of curvature of wavefront

$\left.\begin{array}{l} R_{\text{eff}} \\ R_{\text{e1}}, \\ R_{\text{e2}}, \text{ etc.} \end{array}\right\}$ = effective reflection coefficient of composite eigen waves in corrugated waveguides

S = normalized effective width of optical distribution in slab dielectric waveguide $(=\beta_0\delta\epsilon^{1/2}s)$

S = (also) normalized effective width of gain distribution in parabolic guide $(=s/(2n+1)|B|s_0)$

S_{eff} = normalized effective width of optical distribution in parabolic guide $(=s_{\text{eff}}/(2n+1)|B|s_0)$

S_1 $= s/(2n+1)s_0$

T = absolute temperature

T_{12} = transmission coefficient of composite eigen waves in corrugated waveguides

V = volume

V = (also) voltage

X = normalized position co-ordinate $(=y\delta\epsilon^{1/2}\beta_0)$

Y = normalized admittance

Y_0 = characteristic admittance of free space

Z = characteristic impedance of free space

Z = (also) density of optical modes per unit volume per unit spectral bandwidth

a = coefficient for describing intensity distribution in guide with parabolic distribution of dielectric constant $(= \exp(-a/x^2))$

a = (also) $2\pi/w$

a_1 and a_2 = real and imaginary parts of a

b = ratio of real to imaginary part of dielectric constant due to injected carriers

c = velocity of light

d = thickness of active layer of heterostructure

e = electronic charge

f = shape factor of optical distribution (Chapter 7)

f_c = fractional occupation of states in conduction band

f_v = fractional occupation of states in valence band

f_r = ringing frequency in transient oscillation

g = electrical conductivity

g = (also) gain coefficient per unit length of optical intensity, except in Chapter 8 where g is the amplitude rather than intensity gain coefficient

g_z = mode gain at threshold

g_m = peak gain at centre of stripe

g_+ = positive contribution to mode gain g_z

g_- = negative contribution to mode gain g_z

h = Planck's constant, $\hbar = h/2\pi$

h = (also) $\Delta\epsilon_m/\Delta\epsilon_z - 1$

$\mathbf{k}$ = wave-vector, particularly for electron wave-function

$\mathbf{k}_c$ = wave-vector of electron in conduction band

$\mathbf{k}_{\mathrm{v}}$ = wave-vector of hole in valence band

k = coupling coefficient for region of gain in slab-dielectric waveguide

k = (also) coupling coefficient per unit length in corrugated guide

l = diffusion length of injected carriers

l_{s} = spreading length in stripe laser

l_{eff} = effective diffusion length (due to diffusion + spreading)

l' = l_{eff}/s_1

m = longitudinal mode number

m_{eff} = effective number of longitudinal modes $\times \frac{1}{2}$

m_{eff} = (also) effective mass of carrier

m_{c} = effective mass of electron

m_{v} = effective mass of hole

n = electron concentration

n = (also) number of transverse mode perpendicular to junction

n_{th} = electron concentration at threshold

n_0, n_1 = (in dynamic analysis) steady state and oscillatory components of n

n_{m} = maximum effective concentration of one type of carrier with which a carrier of the opposite type can recombine

p = hole concentration

p = (also) transverse decay constant for electric field in outer layer of dielectric slab waveguide

q = transverse propagation constant for electric field in centre layer of dielectric slab waveguide

q = (also) transverse mode number in junction plane

r = radial position co-ordinate

r = (also) transverse decay constant for electric field in outer layer of lower dielectric constant in asymmetric dielectric-slab waveguide

r_{stim} = net rate of stimulated emission per unit volume per unit bandwidth

r_{spon} = rate of spontaneous emission per unit volume per unit bandwidth

s = effective width of optical distribution in dielectric-slab waveguide

s = (also) width of gain distribution in gain guide

s = (in Chapter 8) ratio of backward to forward wave amplitude in eigen solutions for corrugated waveguide

s_{eff} = width to $1/e^2$ points of optical intensity in Gaussian distribution and $1/\cosh^u$ distributions of optical intensity

s_0 = characteristic gain-guide dimension $(= 1/\beta_0 \Delta\epsilon_z^{1/2})$

s_1 = characteristic gain-guide dimension modified for antiguiding and slope of gain/current characteristic $(=\beta^{1/2} B s_0)$

s_2 = characteristic gain-guide dimension further modified to take diffusion into account $(=(4 l_{\mathrm{eff}} s_1/3)^{1/2})$

t = time

t = (also) thickness of layer of heterostructure in which current spreading occurs in stripe lasers

t_{d} = delay time for laser switch on

u = coefficient for describing field distribution in guide with $\cosh^{-2}$ distribution of dielectric constant

u_1 and u_2 = real and imaginary parts of u

$u(r)$ = Bloch function of crystal lattice

w = width of stripe

w_0 = width of Gaussian beam at waist

w_0 = (also) fictional width of stripe for evaluating peak injected carrier concentration in terms of current

w_{eff} = fictional width of stripe for evaluating threshold current in terms of threshold current density of broad laser

w' = w/s_1

w_{stim} = rate of stimulated emission per photon per mode $(=r_{\mathrm{stim}}/\phi)$

w_{spon} = rate of spontaneous emission per mode

$\left.\begin{matrix} x \\ y \\ z \end{matrix}\right\}$ = (mainly) position co-ordinates

z_{f} = position of virtual waist of Gaussian emitted beam behind front face of stripe laser

Γ = spreading or 'dilution' factor for gain in centre layer of slab-dielectric waveguide

$\Delta\epsilon_f$ = imaginary part of dielectric constant of unpumped semiconductor far from centre of stripe. However, for parabolic transverse distribution of dielectric constant a nominal value of $\Delta\epsilon_f$ is defined at arbitrary points $s/2$ from centre of distribution

$\Delta\epsilon_m$ = maximum or minimum value of imaginary part of dielectric constant at centre of transverse distribution

$\Delta\epsilon_z$ = imaginary part of effective dielectric constant of guided mode (corresponds to mode gain with $\Delta\epsilon_z = g_z/2\beta_z$)

Λ = corrugation length in corrugated waveguide

Λ_b = wave length for Bragg reflection in corrugated waveguide (multivalued)

Φ = normalized emission angle of output wave (= $\sin\theta/\delta\epsilon^{1/2}$)

$\Phi_{1/2}$ = normalized half angle of emission (= $\sin\theta_{1/2}\delta\epsilon^{1/2}$)

α = optical absorption coefficient per unit length (intensity)

β = $(1 - J_t/J_{\mathrm{th}})$ for describing steepness of gain/current characteristic

β = (also) wave propagation coefficient

β = (also) coefficient for obtaining recombination rate from product of electron and hole concentration

β_{o} = propagation coefficient in free space

β_b = Bragg wave vector for corrugated waveguide

β_e = propagation coefficient for composite eigen wave solution for corrugated waveguide

β_z = propagation coefficient along z axis (axis of waveguide)

γ = $w_{\mathrm{spon}}(\max)/w_{\mathrm{stim}}(\max)$

γ = (also) ratio of dielectric constant of built-in waveguide to imaginary dielectric constant due to gain (Chapter 6)

δ = phase error per unit length between propagation coefficient of guided wave and Bragg wave-vector in corrugated waveguide

δ_m = spontaneous emission rate in photons per unit volume in mode m

ϵ = dielectric constant

ϵ_0 = permittivity of free space

ϵ_1 = real part of ϵ (or dielectric constant in region 1)

ϵ_2 = imaginary part of ϵ (or dielectric constant in region 2)

ϵ_{eff} = effective dielectric constant of slab waveguide $(=\beta_z^2/\beta_0^2)$

ϵ_z = effective dielectric constant of guide in junction plane

ζ = $D_1 l_2/D_2 l_1$ to determine transverse distribution of injected carriers

η = $(\epsilon_1 - \epsilon_3)^{1/2}/(\epsilon_1 - \epsilon_2)^{1/2}$ to describe symmetry of slab waveguide

η = (also) external incremental quantum efficiency

η_0 = internal incremental quantum efficiency

η_{sp} = internal spontaneous quantum efficiency

θ = angle or phase

$\theta_{1/2}$ = half angle of emitted beam to half intensity points

θ_0 = angle to the normal of far-field peak for waveguide with $\cosh^{-2}$ distribution of dielectric constant

λ = wavelength

λ_{b} = Bragg wavelength

λ_0 = wavelength in free space

μ = refractive index

$\bar{\mu}$ = $\mu + E\mathrm{d}\mu/\mathrm{d}E = \mu - \lambda\mathrm{d}\mu/\mathrm{d}\lambda$ = refractive index modified for dispersion (i.e. group refractive index)

μ_0 = permeability of free space

ν = frequency

ξ = $(J/J_{\text{th}} - 1)/\beta$

ρ = (Chapter 7) shape factor of current distribution

ρ = density of electronic states per unit energy interval

ρ_{c} = density of electronic states for conduction band

ρ_v = density of electronic states for valence band

ρ_{red} = $\frac{1}{2}(1/\rho_c + 1/\rho_v)^{-1}$ (applying to states with one spin direction only)

σ = photon lifetime in resonant cavity

τ = lifetime of minority carrier

τ_1 = damping time constant for oscillatory modulation

τ_{tr} = damping time constant for envelope of transient oscillation

ϕ = phase angle

ϕ = (also) photon density per mode in laser resonator

ϕ_0 = steady state component of ϕ (in dynamic analysis)

ϕ_1 = oscillatory component of ϕ (in dynamic analysis)

ψ_1 = wave-function of electronic state in valence band

ψ_2 = wave-function of electronic state in conduction band

ω = angular frequency

ω_0 = resonant angular frequency of laser modulation.

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