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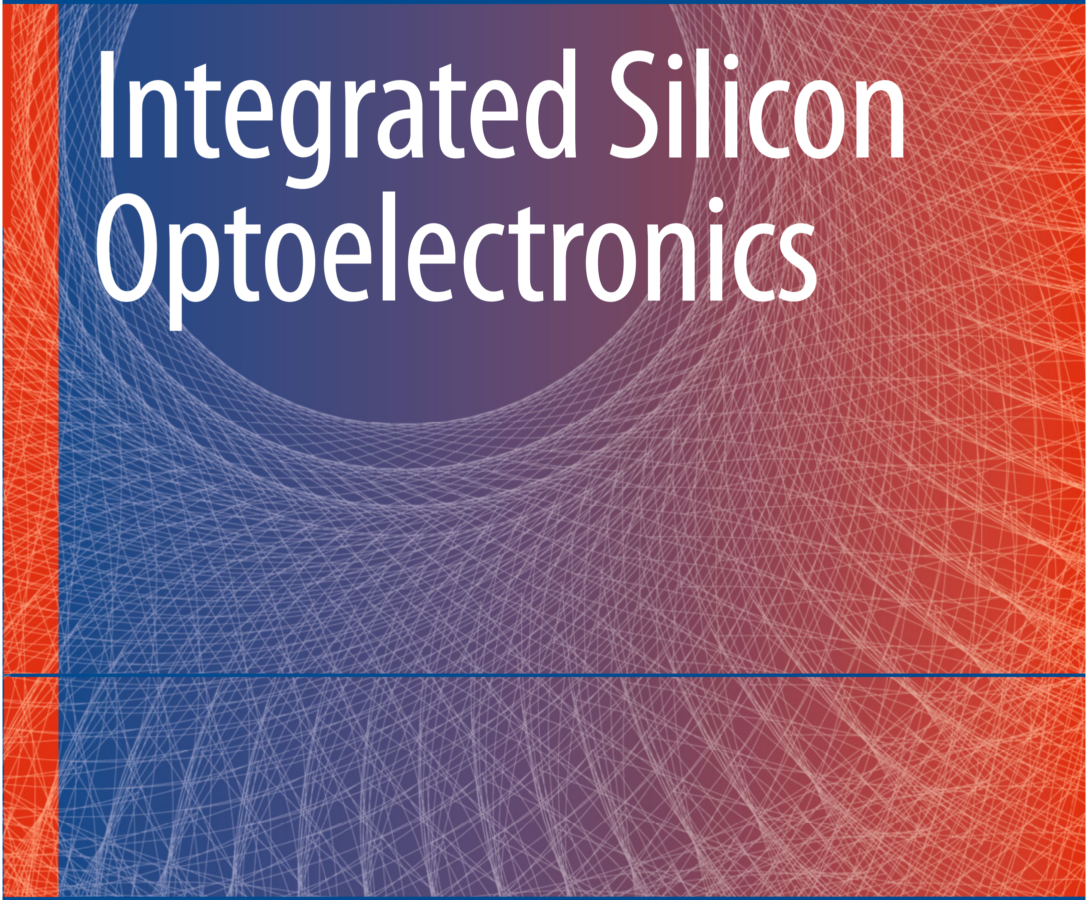

Integrated Silicon Optoelectronics

Second Edition

Springer

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With 321 Figures

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Preface

Since the first edition of this book, a lot of interesting integrated optoelectronic devices were investigated and introduced in numerous publications. Therefore, Springer and me decided to publish this extended edition. Hot topics were avalanche photodiodes and even single-photon avalanche photodiodes in the past years. Lateral PIN photodiodes, for instance, have been improved with the trench technology known from dynamic random access memory (DRAM) technology. In addition, much research was done in the field of Germanium detectors on silicon to extend the detectable wavelength region towards the infrared spectrum and to increase the bandwidth of Silicon-based detectors into the several-ten Giga-Hertz range. A considerable progress has also been achieved with Silicon-based light emitters. Wafer bonding pushed the hybrid Silicon laser. Also, electroluminescence from nanocrystalline silicon experienced huge progress. All these above mentioned topics have been included in this extended edition of *Integrated Silicon Optoelectronics*.

Photonic integrated circuits already became true recently. The integrated-photonics community now works towards a photonics foundry based on advanced Silicon integrated circuit processes to enable the design and fabrication of application specific photonic integrated circuits similar to electronic ASICs (application specific integrated circuits) in semiconductor foundries.

Of course, there was also plenty of research on and progress in optical receiver and optical sensor circuits. But the design and circuit chapter have not been updated in this extended version, since the circuit-oriented book *Silicon Optoelectronic Integrated Circuits* appeared in 2004 also at Springer.

I thank Dr. Ascheron from Springer for initiating this extended edition and his team for technical support with the text processor in a good cooperation. My deepest gratitude, again, is directed to my wife, my daughters Luise and Lina, as well as my son Frieder, whose patience was really huge during the preparation of this extended version.

Vienna
June 2009

Horst Zimmermann

Preface of the First Edition

This book is intended as a bridge between microelectronics and optoelectronics. Usually, optoelectronics plays a minor role in electrical engineering courses at universities. Physicists are taught optics but not very much semiconductor technology and chip design. This book covers the missing information for engineers and physicists who want to know more about integrated optoelectronic circuits (OEICs) in silicon technologies and about their emerging possibilities.

Optoelectronics usually implies that III/V semiconductor materials are involved. This is the case when ultra-high-speed photodetectors or efficient light emitters are needed. For other applications, the price of III/V photodetectors and OEICs is simply too high. Silicon photodectectors and receiver OEICs, therefore, are the only choice when high volumes are needed and the price has to be low as, for instance, in consumer electronics. Such high volumes of silicon OEICs are, for example, needed in optical storage systems like audio CD, magneto-optical disk, CD-ROM, and Digital-Video-Disk or Digital-Versatile-Disk (DVD) systems. The market for DVD systems and therefore, for DVD OEICs is estimated to be 120 million pieces in the year 2001.

OEICs are key devices for advanced optical storage systems and for the enhancement of their speed and data rate. This importance of OEICs is due to the following advantages of monolithic optoelectronic integrated circuits: (a) good immunity against electromagnetic interference (EMI) because of very short interconnects between photodetectors and amplifiers; (b) reduced chip area due to the elimination of bondpads; (c) improved reliability due to the elimination of bondpads and bond wires; (d) cheaper mass production compared to discrete circuits, wire-bonded circuits, and hybrid integrated circuits; and (e) larger $-3\,\mathrm{dB}$ bandwidth compared to discrete circuits, wire-bonded circuits, and some hybrid integrated circuits due to the avoidance of parasitic bondpad capacitances.

Even in the domain of light emission, silicon is being investigated intensively to make silicon a competitor of III/V semiconductor materials. Much effort is made to let silicon emit light, and these attempts will be described in this book.

This book was written in parallel with the development of OEICs in CMOS and in BiCMOS technologies for optical storage systems and for optical interconnect technologies. It describes the state of the art in OEIC design and the approaches to this topic reported recently in the literature.

Parts of the book have their origin in an "Optoelectronics" lecture I have given since 1994. It, however, dives much deeper into the topic. The possibilities of integrated silicon optoelectronics are investigated thoroughly and I have tried to initiate a link between microelectronics and photonics. The term *photonics* has come into use more and more in the last decade. This term, which was coined in analogy with electronics, reflects the growing link between optics and electronics forged by the increasing role of semiconductor materials and devices in optical systems.

As the term *electronics* already expresses, it is based on the control of electrons and of electric charge flow. Photonics is based on the control of photons, and the term photonics reflects the importance of the photon nature of light in describing the operation of many optical devices. The overlap between the two disciplines is obvious, since electrons often control the flow of photons and, conversely, photons control the flow of electrons. The term photonics is used broadly to encompass: (a) the generation of light by LEDs and lasers; (b) the transmission of light in free space, through conventional optical lenses, apertures, and imaging systems, and through optical fibers and waveguides; (c) the modulation, switching, and scanning of light by the use of electrically, acoustically, or optically controlled devices; (d) the amplification and frequency conversion of light by the use of wave interaction in nonlinear materials; and (e) the detection of light.

These areas have found steadily increasing applications in optical communication, signal processing, computing, sensing, display technology, printing, and energy transport. Items (a)–(c) and (e) can be covered by silicon and will be discussed in this book.

Integrated optoelectronic receiver circuits have already made their way into microelectronics, which is dominated by silicon technology. I think it is only a question of time before true microphotonic silicon-based circuits with electronic circuits, light detectors, waveguides, grating couplers, holographic lenses, and efficient light emitters are developed and enter the market.

I would like to thank Prof. Dr.-Ing. P. Seegebrecht for the generous possibility to develop OEICs independently and for several helpful comments concerning a part of the text used to acquire the title "habilitatus". I am also indebted to Prof. Dr. H. Föll, who offered a waferprober for the characterization of the OEICs. The work of the OEIC group members, A. Ghazi, T. Heide, K. Kieschnick, and G. Volkholz, is highly appreciated. Three students, N. Madeja, F. Sievers, and U. Willecke, carefully performed simulations and measurements. M. Wieseke and F. Wölk helped with the preparation of numerous drawings. Special thanks go to R. Buchner from the Fraunhofer-Institute for Solid-State Technology in Munich and H. Pless from Thesys Microelectronics in Erfurt for their engagement in the fabrication of CMOS

OEICs and BiCMOS OEICs, respectively. Last but not the least I would like to gratefully acknowledge the funding of the projects by the German Ministry for Education, Science, Research, and Technology (BMBF) within the leading project "optical memories."

I extend my sincere thanks to Dr. Ascheron and his team at Springer for the good cooperation and their technical support with the text processor. My deepest gratitude, however, is directed to my wife and my daugthers, Luise and Lina, who supported this book project with their encouragement and patience during many evenings and weekends.

Kiel *Horst Zimmermann*
January 2000

Contents

List of Symbols

Symbol	Description	Unit
a	Lattice constant	nm
A	Area	cm^2
A_0	Low-frequency open loop gain	
$A(\omega)$	Frequency-dependent gain	
c	Speed of light in a medium	$\mathrm{cm\,s}^{-1}$
c_0	Speed of light in vacuum	$\mathrm{cm\,s}^{-1}$
c_{bd}	Small-signal bulk–drain capacitance	F
c_{bs}	Small-signal bulk–source capacitance	F
c_{cs}	Small-signal collector–substrate capacitance	F
c_{gb}	Small-signal gate–bulk capacitance	F
c_{gd}	Small-signal gate–drain capacitance	F
c_{gs}	Small-signal gate–source capacitance	F
c_{ws}	Small-signal well–substrate capacitance	F
c_{je}	Small-signal emitter–base capacitance	F
c_{μ}	Small-signal base–collector capacitance	F
C_{e}	Doping concentration of epitaxial layer	cm^{-3}
C_{B}	Capacitance of bondpad	F
C_{BE}	Base–emitter capacitance	F
C_{C}	Base–collector space-charge capacitance	F
C_{D}	Depletion capacitance of photodiode	F
C_{E}	Total base–emitter capacitance of bipolar transistor	F
C_{F}	Feedback capacitance of transimpedance amplifier	F
C_{I}	Input capacitance of amplifier	F
C_{L}	Load capacitor	F
C_{P}	Capacitance of chip package	F
$C_{\mathrm{R_F}}$	Parasitic capacitance of feedback resistor	F
C_{S}	Parasitic capacitance of signal line	F
C_{SE}	Base–emitter space-charge capacitance	F

Symbol	Description	Unit
d_e	Thickness of epitaxial layer	µm
d_I	Thickness of intrinsic region	µm
d_p	Thickness of P-type region	µm
D	Diffusion coefficient	$\mathrm{cm^2\,s^{-1}}$
D_n	Diffusion coefficient of electrons	$\mathrm{cm^2\,s^{-1}}$
D_p	Diffusion coefficient of holes	$\mathrm{cm^2\,s^{-1}}$
DR	Data rate	$\mathrm{Mb\,s^{-1}}$
E_C	Bottom of conduction band	eV
E_F	Fermi energy level	eV
E_g	Energy bandgap	eV
E_p	Phonon energy	eV
E_t	Energy level of recombination center	eV
E_V	Top of valence band	eV
E	Photon energy	eV
$\boldsymbol{E}$	Electric field	$\mathrm{V\,cm^{-1}}$
f	Frequency	Hz
f_g	Bandwidth, −3 dB frequency	Hz
f_T	Transit frequency (gain-bandwidth product)	Hz
f_GP	Frequency of gain-peak	Hz
G	Photogeneration (e–h–p)	$\mathrm{cm^{-3}\,s^{-1}}$
$G(\omega)$	Frequency response function	$\mathrm{V\,A^{-1}}$
g_m	Transconductance	$\mathrm{A\,V^{-1}}$
h	Planck constant	J s
$\hbar$	$h/2\pi$	J s
$h\nu$	Photon energy	eV
I	Current	A
I_ph	Photocurrent	A
I_th	Threshold current	A
I_B	Base current	A
I_C	Collector current	A
I_D	Drain current	A
I_E	Emitter current	A
I_S	Source current	A
j	Current density	$\mathrm{A\,cm^{-2}}$
$\boldsymbol{k}$	Wave vector	$\mathrm{cm^{-1}}$
k_B	Boltzmann constant	$\mathrm{J\,K^{-1}}$
$k_\mathrm{B}T$	Thermal energy	eV
L	Length	µm
L_n	Diffusion length of electrons	µm
L_p	Diffusion length of holes	µm
L_B	Inductance of bond wire	H
L_G	Gate length	µm
L_W	Inductance of lead wire	H

Symbol	Description	Unit
$\bar{n}$	Refractive index	
$\bar{n}_{\mathrm{s}}$	Refractive index of surroundings	
$\bar{n}_{\mathrm{sc}}$	Refractive index of semiconductor	
$\bar{n}_{\mathrm{ARC}}$	Refractive index of antireflection coating	
n	Density of free electrons	cm^{-3}
n_{i}	Intrinsic density	cm^{-3}
N	Impurity concentration	cm^{-3}
N_{A}	Acceptor concentration	cm^{-3}
N_{D}	Donor concentration	cm^{-3}
N_{t}	Concentration of recombination centers	cm^{-3}
p	Density of free holes	cm^{-3}
Q_{E}	Minority-carrier charge in the base	$\mathrm{A\,s}$
Q_{pix}	Charge on pixel storage capacitor	$\mathrm{A\,s}$
QE	Quantum efficiency	%
$\boldsymbol{p}$	Momentum	$\mathrm{J\,s\,m}^{-1}$
P_{opt}	Incident optical power	W
$\bar{P}$	Optical power in a semiconductor	W
q	Magnitude of electronic charge	$\mathrm{A\,s}$
r_{b}	Base series resistance	Ω
r_{o}	Small-signal output resistance	Ω
r_{c}	Small-signal collector series resistance	Ω
r_{ex}	Small-signal emitter series resistance	Ω
r_{d}	Small-signal drain series resistance	Ω
r_{s}	Small-signal source series resistance	Ω
R	Responsivity	$\mathrm{A\,W}^{-1}$
R_{bb}	Responsivity to black-body radiation	$\mathrm{A\,W}^{-1}$
R_{D}	Parallel resistance	Ω
R_{F}	Feedback resistance	Ω
R_{S}	Series resistance	Ω
R_{I}	Input resistance of amplifier	Ω
R_{L}	Load resistance	Ω
$\bar{R}$	Reflectivity	
t	Time	s
t_{d}	Drift time	s
t_{diff}	Diffusion time	s
t_{f}	Fall time	s
t_{r}	Rise time	s
t_{gd}	Group delay	s
T	Absolute temperature	K
U	Voltage	V
U_{BE}	Base–emitter voltage	V
U_{D}	Built-in voltage	V
U_{DS}	Drain–source voltage	V

Symbol	Description	Unit
U_{Ea}	Early voltage	V
U_{GS}	Gate–source voltage	V
U_{T}	Thermal voltage $\mathrm{k_B T/q}$	V
U_{th}	Thermal generation/recombination rate	$\mathrm{cm^{-3}s^{-1}}$
U_{Th}	Threshold voltage	V
V_{det}	Detector bias	V
V_{o}	Output voltage	V
V_{rev}	Reverse voltage	V
v	Carrier velocity	$\mathrm{cm\,s^{-1}}$
v_{s}	Saturation velocity	$\mathrm{cm\,s^{-1}}$
v_{th}	Thermal velocity	$\mathrm{cm\,s^{-1}}$
W	Width of space-charge region	µm
W_{B}	Base thickness	µm
W_{G}	Gate width	µm
Z_{F}	Feedback impedance of transimpedance amplifier	Ω
x	x direction	µm
y	y direction	µm
α	Absorption coefficient	$\mathrm{\mu m^{-1}}$
β	Current gain of bipolar transistor	
η_{e}	External (total) quantum efficiency	%
η_{i}	Internal quantum efficiency	%
η_{o}	Optical quantum efficiency	%
η_{mc}	Emission enhancement factor in microcavity	
ϵ_0	Permittivity in vacuum	$\mathrm{F\,cm^{-1}}$
ϵ_{d}	Relative permittivity of passivation layer	
ϵ_{r}	Relative permittivity	
ϵ_{s}	Semiconductor permittivity	$\mathrm{F\,cm^{-1}}$
$\bar{\epsilon}$	Dielectric function	
σ	Carrier capture cross section	$\mathrm{cm^{-2}}$
τ	Lifetime	s
τ_{n}	Electron lifetime	s
τ_{p}	Hole lifetime	s
τ_{B}	Base transit time	s
$\bar{\kappa}$	Extinction coefficient	
λ	Wavelength in a medium	nm
λ_0	Wavelength in vacuum	nm
λ_{c}	Wavelength corresponding to E_{g}	nm
λ_{d}	Design wavelength of a DBR	nm
λ_{ch}	Channel length modulation parameter	$\mathrm{V^{-1}}$
ν	Frequency of light	Hz
μ	Mobility	$\mathrm{cm^2\,V^{-1}\,s^{-1}}$
μ_{n}	Electron mobility	$\mathrm{cm^2\,V^{-1}\,s^{-1}}$
μ_{p}	Hole mobility	$\mathrm{cm^2\,V^{-1}\,s^{-1}}$

Symbol	Description	Unit
ω	Angular frequency	s^{-1}
ω_T	$2\pi f_T$	s^{-1}
ω_{GP}	$2\pi f_{GP}$	s^{-1}
ρ	Charge density	$A\,s\,cm^{-3}$
Φ	Photon flux density	$cm^{-2}s^{-1}$
Φ_B	Barrier height	eV
Φ_{bi}	Built-in potential	V
Ψ	Potential	V
Θ	Angle	$^\circ$
Θ_c	Critical angle for total reflection	$^\circ$
Θ_i	Incidence angle	$^\circ$

1

Basics of Optical Emission and Absorption

Optical emission and absorption are fundamental processes which are exploited when electrical energy is converted into optical energy and vice versa. Optoelectronics is based on these energy conversion processes. Light emitters such as light-emitting diodes (LEDs) and diode lasers convert electrical energy into optical energy. Photodetectors convert optical energy into electrical energy. In this chapter, the most important factors needed for the comprehension of light emitters and photodetectors will be summarized in a compact form. For a detailed description of the basics of optical emission and absorption, the book [1] can be recommended. Here, emphasis will, of course, be placed on silicon devices. First we will introduce photons and the properties of light. Then, the consequences of the band structure for optical emission and absorption will be dealt with. Photogeneration will be defined. Furthermore, optical reflection and its consequences on the efficiency of photodetectors will be described.

1.1 Properties of Light

Due to the work of Max Planck and Albert Einstein it is possible to describe light not only by a wave formalism, but also by a quantum-mechanical particle formalism. The smallest unit of light intensity is a quantum-mechanical particle called a photon. The photon, consequently, is the smallest unit of optical signals. Photons are used to characterize electromagnetic radiation in the optical range from the far infrared to the extreme ultraviolet spectrum. The velocity of photons c in a medium with an optical index of refraction $\bar{n}$ is

$$c = \frac{c_0}{\bar{n}}, \tag{1.1}$$

where c_0 is the velocity of light in vacuum. Photons do not possess a quiescent mass and, unfortunately for the construction of purely optical computers, cannot be stored. Photons can be characterized by their frequency ν and by their wavelength λ:

$$\lambda = \frac{c}{\nu}. \tag{1.2}$$

The frequency of a photon is the same in vacuum and in a medium with index of refraction $\bar{n}$. The wavelength λ in a medium, therefore, is shorter than the vacuum wavelength λ_0 ($\lambda = \lambda_0/\bar{n}$). As a consequence, the vacuum wavelength is used to characterize light sources like light-emitting diodes (LEDs) or semiconductor lasers, because it is independent of the medium in which the light propagates.

Photons can also be characterized by their energy E (h is Planck's constant):

$$E = h\nu = \frac{hc}{\lambda} = \frac{hc_0}{\lambda_0}. \tag{1.3}$$

A useful relation is given next which allows a quick calculation of the energy for a certain wavelength and vice versa:

$$E = \frac{1{,}240}{\lambda_0} \tag{1.4}$$

where E is in eV and λ_0 in nm. Let us define the flux density Φ as the number of photons incident per time interval on an area A. The optical power P_{opt} incident on a detector with a light sensitive area A, then, is determined by the photon energy and by the flux density:

$$P_{\mathrm{opt}} = E\Phi A = h\nu\Phi A. \tag{1.5}$$

The magnitude of the momentum of a photon p in a medium is determined by its wavelength in this medium:

$$p = \frac{h}{\lambda}. \tag{1.6}$$

The wave number k is the magnitude of the wave vector $\boldsymbol{k}$, which defines the direction of the motion of the photon:

$$k = \frac{2\pi}{\lambda}. \tag{1.7}$$

The momentum of a photon $\boldsymbol{p}$ is proportional to the wave vector

$$\boldsymbol{p} = \hbar\boldsymbol{k}, \tag{1.8}$$

where $\hbar = h/(2\pi)$.

1.2 Energy Bands of Semiconductor Materials

The energy-band structure of a semiconductor determines not only its electrical properties but also its optical properties such as the absorption of photons and the probability of radiative transitions of electrons from the conduction band to the valence band. The absorption of photons, which is important for photodetectors, will be dealt with in the next section. Here, we will just point out the consequences of the kind of energy-band structure for the applicability of a semiconductor material when we want to obtain efficient light emitters.

There are two requirements for transitions of electrons between the valence and the conduction band and vice versa: (a) the energy has to be conserved and (b) the momentum has to be conserved. The conservation of energy usually is not a problem in direct and in indirect semiconductors. For an electron transition between the maximum of the valence band and the minimum of the conduction band, or vice versa, the conservation of momentum, however, cannot be fulfilled with the absorption or emission of a photon alone in an indirect semiconductor, because the magnitude of the momentum of a photon is several orders of magnitude smaller than that of an electron in a semiconductor. The same large difference holds between the wave vectors of a photon and an electron in a crystal. It is, therefore, possible to compare the momentums or the wave vectors. The energy bands in dependence on the wave vector are calculated from the Schrödinger equation with a periodic potential that is characteristic for a certain semiconductor. The wave vector of an electron in a crystal is between approximately 0 and $2\pi/a$, i.e., between the k values at the boundaries of the first Brillouin zone, where a is the lattice constant. The minimum of the conduction band in the first Brillouin zone in silicon, for instance, is at $0.85 \times 2\pi/a$ [1]. The momentum of an electron in the minimum of the conduction band of Si with $a = 0.543\,\mathrm{nm}$, therefore, can reach $0.85 \times 2h/a = 2 \times 10^{-24}\,\mathrm{Js\,m^{-1}}$, whereas the momentum of a photon with $E = 1\,\mathrm{eV}$ is only $5.3 \times 10^{-28}\,\mathrm{Js/m}$. In addition to a photon, a phonon has to be absorbed or emitted in order to conserve the momentum. Phonons are quantized lattice vibrations. They possess small energies (up to approximately 100 meV) and a momentum of the order of that of an electron in a semiconductor. Many phonons are present in crystals like semiconductors at room temperature.

Let us first consider GaAs, which has a direct bandgap (Fig. 1.1), where the minimum of the conduction band (CB) is above the maximum of the valence band (VB). No phonon is needed for the conservation of the momentum when an electron makes a transition from the minimum of the conduction band to the maximum of the valence band (recombining with a hole) and when a photon with the energy of the bandgap is emitted.

Silicon is known to have an indirect bandgap. A phonon is needed for the conservation of the momentum in order to enable the radiative transition of an electron from the minimum of the conduction band to the maximum of the

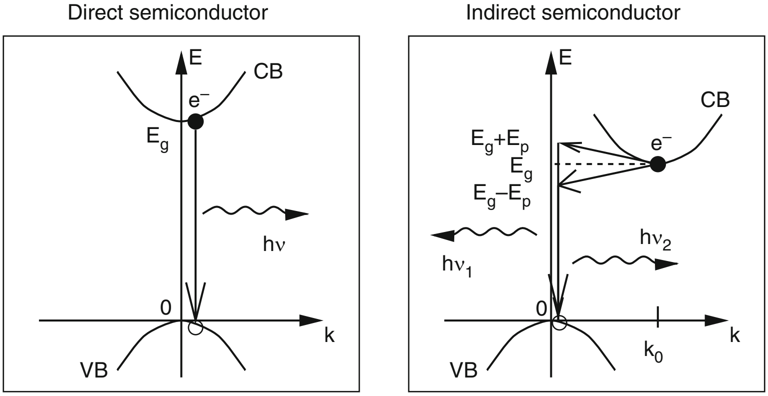

Fig. 1.1. Electron transitions in direct (*left*) and indirect (*right*) semiconductors as, for instance, GaAs and Si, respectively

valence band. A phonon has to be consumed or created when a photon with an energy of approximately E_{g} is emitted (see Fig. 1.1). The photon energy is exactly (E_{p} is the phonon energy)

$$E = h\nu = \frac{hc}{\lambda} = E_{\mathrm{g}} \pm E_{\mathrm{p}}. \tag{1.9}$$

The generation of a phonon possesses a larger probability than the consumption of a phonon in connection with an electron transition in an indirect semiconductor. Therefore, more photons will have the energy $E_{\mathrm{g}} - E_{\mathrm{p}}$ than $E_{\mathrm{g}} + E_{\mathrm{p}}$. From quantum mechanics it is, however, known that the probability of all electron transitions combined with phonon transitions is very small. The probability of radiative transitions in indirect semiconductors in fact is four to six orders of magnitude lower than that in direct semiconductors. Silicon devices, therefore, are usually very poor light emitters. This work will summarize the attempts to obtain more efficient silicon light emitters and it will, of course, focus on silicon photodectors.

1.3 Optical Absorption of Semiconductor Materials

The energy of a photon can be transferred to an electron in the valence band of a semiconductor, which is brought to the conduction band, when the photon energy is larger than the bandgap energy E_{g}. The photon is absorbed during this process and an electron–hole pair is generated. Photons with an energy smaller than E_{g}, however, cannot be absorbed and the semiconductor is transparent for light with wavelengths longer than $\lambda_{\mathrm{c}} = hc_0/E_{\mathrm{g}}$.

The optical absorption coefficient α is the most important optical constant for photodetectors. The absorption of photons in a photodetector to produce

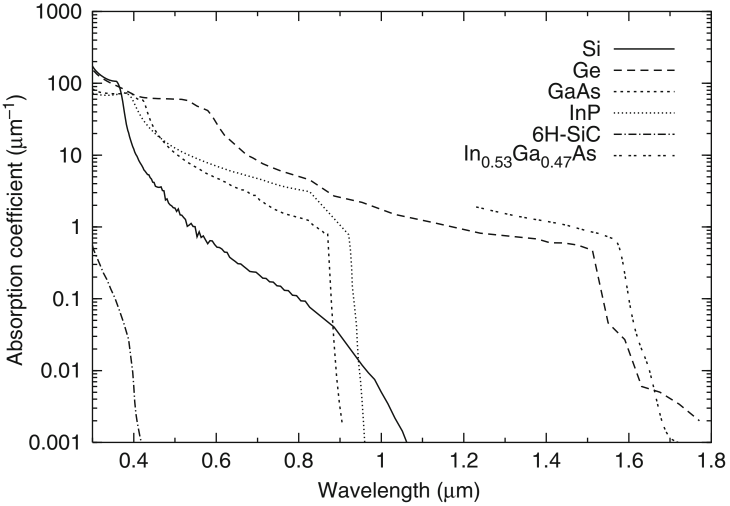

Fig. 1.2. Absorption coefficients of important semiconductor materials versus wavelength

carrier pairs and thus a photocurrent, depends on the absorption coefficient α for the light in the semiconductor used to fabricate the detector. The absorption coefficient determines the penetration depth $1/\alpha$ of the light in the semiconductor material according to Lambert–Beer's law:

$$I(\bar{y}) = I_0 \exp(-\alpha \bar{y}). \tag{1.10}$$

The optical absorption coefficients for the most important semiconductor materials are compared in Fig. 1.2. The absorption coefficients strongly depend on the wavelength of the light. For wavelengths shorter than λ_c, which corresponds to the bandgap energy ($\lambda_c = hc_0/E_g$), the absorption coefficients increase rapidly according to the so-called *fundamental absorption*. The steepness of the onset of absorption depends on the kind of band–band transition. This steepness is large for direct band–band transitions as in GaAs ($E_g^{dir} = 1.42$ eV at 300 K), in InP ($E_g^{dir} = 1.35$ eV at 300 K), in Ge ($E_g^{dir} = 0.81$ eV at 300 K), and in $In_{0.53}Ga_{0.47}As$ ($E_g^{dir} = 0.75$ eV at 300 K). For Si ($E_g^{ind} = 1.12$ eV at 300 K), for Ge ($E_g^{ind} = 0.67$ eV at 300 K), and for the wide bandgap material 6H–SiC ($E_g^{ind} = 3.03$ eV at 300 K) the steepness of the onset of absorption is small.

$In_{0.53}Ga_{0.47}As$ and Ge cover the widest wavelength range including the wavelengths 1.3 and 1.54 μm which are used for long distance optical data transmission via optical fibers. The absorption coefficients of GaAs and InP are high in the visible spectrum (≈400–700 nm). Silicon detectors are also appropriate for the visible and near infrared spectral range. The absorption coefficient of Si, however, is one to two orders of magnitude lower than that of

Table 1.1. Absorption coefficients α of silicon and intensity factors I_0 (ehp cm^{-3} means electron–hole pairs per cm^3) for several important wavelengths for a constant photon flux density of $\Phi = I_0/\alpha = 1.58 \times 10^{18}$ photons/cm^2

Wavelength (nm)	α (µm^{-1})	I_0 (ehp cm^{-3})
980	0.0065	1.03×10^{20}
850	0.06	9.50×10^{20}
780	0.12	1.89×10^{21}
680	0.24	3.79×10^{21}
635	0.38	6.00×10^{21}
565	0.73	1.16×10^{22}
465	3.6	5.72×10^{22}
430	5.7	9.00×10^{22}

the direct semiconductors in this spectral range. For Si detectors, therefore, a much thicker absorption zone is needed than for the direct semiconductors. We will, however, see in this work that with silicon photodiodes GHz operation is nevertheless possible. Silicon is the economically most important semiconductor and it is worthwhile to investigate silicon optoelectronic devices and integrated circuits in spite of the nonoptimum optical absorption of silicon.

The absorption coefficients of silicon for wavelengths which are the most important ones in practice are listed in Table 1.1 [2,3]. In order to compare the quantum efficiencies of photodetectors for different wavelengths, it is advantageous to use the same photon flux for the different wavelengths. The photocurrents of photodetectors are equal for the same fluxes of photons with different energy, i.e., for different light wavelengths, when the quantum efficiency of the photodetector is the same for the different photon energies or wavelengths, respectively. According to the Lambert–Beer law, different intensity factors I_0 result for a constant photon flux. As an example, intensity factors are listed for the most important wavelengths in Table 1.1 for a certain arbitrary photon flux density.

1.4 Photogeneration

The Lambert–Beer law can be formulated for the optical power $\bar{P}$ analogously to (1.10):

$$\bar{P}(\bar{y}) = P_0 \exp(-\alpha \bar{y}). \tag{1.11}$$

The optical power at the surface of the semiconductor $\bar{P}(\bar{y} = 0)$ is $P_0 = (1 - \bar{R})$ (see Fig. 1.3). The optical power of the light penetrating into a medium decreases exponentially with the penetration coordinate $\bar{y}$ in the medium (compare Fig. 2.1).

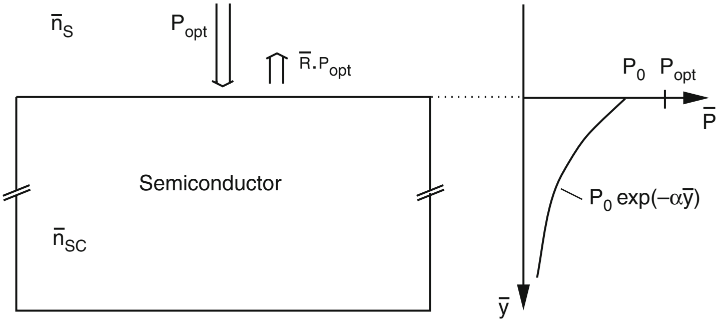

Fig. 1.3. Reflection at a semiconductor surface and decay of the optical power in the semiconductor ($P_0 = (1 - \bar{R})P_{\mathrm{opt}}$)

The absorbed light generates electron–hole pairs in a semiconductor due to the internal photoeffect provided that $h\nu > E_{\mathrm{g}}$. Therefore, we can express the generation rate per volume $G(\bar{y})$ as:

$$G(\bar{y}) = \frac{\bar{P}(\bar{y}) - \bar{P}(\bar{y} + \triangle\bar{y})}{\triangle\bar{y}} \frac{1}{Ah\nu}. \tag{1.12}$$

In this equation, A is the area of the cross section for the light incidence and $h\nu$ is the photon energy. For $\triangle\bar{y} \to 0$, we can write $(\bar{P}(\bar{y}) - \bar{P}(\bar{y} + \triangle\bar{y}))/\triangle\bar{y} = -\mathrm{d}\bar{P}(\bar{y})/\mathrm{d}\bar{y}$. From (1.11), $\mathrm{d}\bar{P}(\bar{y})/\mathrm{d}\bar{y} = -\alpha\bar{P}(\bar{y})$ then follows and the generation rate is

$$G(\bar{y}) = \frac{\alpha P_0}{Ah\nu} \exp(-\alpha\bar{y}). \tag{1.13}$$

1.5 External Quantum Efficiency and Responsivity

The external or overall quantum efficiency η is defined as the number of photogenerated electron–hole pairs, which contribute to the photocurrent, divided by the number of the incident photons. The external quantum efficiency can be determined, when the photocurrent of a photodetector is measured for a known incident optical power.

A fraction of the incident optical power is reflected (see Fig. 1.3) due to the difference in the index of refraction between the surroundings $\bar{n}_{\mathrm{s}}$ (air: $\bar{n}_{\mathrm{s}} = 1.00$) and the semiconductor $\bar{n}_{\mathrm{sc}}$ (e.g., Si, $\bar{n}_{\mathrm{sc}} \approx 3.5$). The reflectivity $\bar{R}$ depends on the index of refraction $\bar{n}_{\mathrm{sc}}$ and on the extinction coefficient $\bar{\kappa}$ of an absorbing medium, for which the dielectric function $\bar{\epsilon} = \bar{\epsilon}_1 + \mathrm{i}\bar{\epsilon}_2 = (\bar{n}_{\mathrm{sc}} + \mathrm{i}\bar{\kappa})^2$ is valid ($\bar{n}_{\mathrm{s}} = 1$) [2].

$$\bar{R} = \frac{(1 - \bar{n}_{\mathrm{sc}})^2 + \bar{\kappa}^2}{(1 + \bar{n}_{\mathrm{sc}})^2 + \bar{\kappa}^2}. \tag{1.14}$$