

# Contents

## Page

xv		<b>Introduction</b>
1	1	<b>Physics of Optical Radiation</b>
3	1.1	Optical radiation and light
3	1.1.1	Basic definitions
3	1.1.2	The quantum nature of radiation
4	1.1.3	The dualism of waves and particles
4	1.1.4	Wavelength and propagation speed
5	1.2	Radiation and luminescence phenomena
5	1.2.1	Atomic and band model
8	1.2.2	Luminescence, Fluorescence, Phosphorescence
9	1.2.3	Luminescence phenomena in semiconductors, injection luminescence
13	1.3	Photoelectric effect
13	1.3.1	External photoeffect
14	1.3.2	Internal photoeffect
16	1.3.3	Junction photoeffect
19	2	<b>Principles of calculation in radiation physics and optics</b>
21	2.1	Radiant flux – Luminous flux, Radiant energy – Light quantity
22	2.2	Parameters related to the radiation source
22	2.2.1	Radiant emittance – Luminous emittance
23	2.2.2	Radiant intensity – Luminous intensity
24	2.2.3	Radiance – Luminance
26	2.2.4	Units of luminance
26	2.2.5	Radiant efficiency and luminous efficiency
27	2.3	Parameters related to the receiver
27	2.3.1	Irradiance – Illuminance
28	2.3.2	Irradiation – Light exposure
29	2.3.3	Relationship between irradiance or illuminance and the reflected radiance or luminance
29	2.3.4	Spectral radiation – physical units
33	3	<b>Laws of radiation</b>
35	3.1	Solid angle
36	3.2	Lambert's radiator
36	3.2.1	Fundamental law of photometry
37	3.2.2	Lambert's cosine law
38	3.3	Calculation of radiation with small surface radiators and surface receivers
40	3.3.1	Inverse square law

43	4	<b>Laws of Radiation from a Black Body</b>
45	4.1	Black and "Non-black" bodies
45	4.1.1	Black bodies
46	4.1.2	Non-black bodies
46	4.2	Laws of radiation
46	4.2.1	Planck's law of radiation
47	4.2.2	Stefan-Boltzmann law
48	4.2.3	Wien displacement law
50	4.2.4	Emissivity
51	4.2.5	Kirchhoff's law
51	4.2.6	Radiation isotherms
51	4.2.7	Reduced law of radiation
57	5	<b>General and Photometric Evaluation of Radiation</b>
59	5.1	The human eye
59	5.2	Optical sensitivities
60	5.3	Photometric evaluation of radiation
62	5.3.1	Determination of the conversion constants C and C'
64	5.3.2	Photometric radiation equivalent
67	5.3.3	Photometric radiation equivalent of the photopic sensitivity of the eye
69	5.4	Calculation of the photometric radiation equivalent K for different radiation sources
69	5.4.1	Calculation of the photometric radiation equivalent K of a Planck radiator with the temperature laid down for the definition of the candela
69	5.4.2	Calculation of the photometric radiation equivalent K for standard light A
70	5.4.3	Calculation of the photometric radiation equivalent K of the luminescence radiation from light-emitting diodes
74	5.5	Conversion of radiometric units into photometric, photopic units
74	5.5.1	Conversion of radiometric units into photometric units for Planck radiation
76	5.5.2	Conversion of radiometric units into photometric units for the luminescence radiation from light-emitting diodes
77	5.6	Actinic value
77	5.6.1	Actinic value of a radiation for photodetectors and for the human eye
80	5.6.2	Actinic value of Planck radiation and luminescence radiation for the eye as a photodetector
83	6	<b>Interaction between optical radiation and matter</b>
85	6.1	Absorption, transmission and reflection factors
85	6.2	Spectral transmission factor and spectral absorption factor
86	6.3	Scatter
86	6.4	Reflection of radiation
87	6.4.1	Spectral reflectivity
88	6.5	Basic laws of absorption, attenuation and scatter

90	6.6	Absorption and transmission spectra
96	6.7	Refraction
101	7	<b>Radiation sources</b>
103	7.1	Natural radiation sources
103	7.1.1	The Sun
104	7.1.2	The Moon
104	7.1.3	Clouds
104	7.2	Artificial radiation sources
104	7.2.1	Open fire
104	7.2.2	Filament lamps
105	7.3	Luminescence radiators
105	7.3.1	Hot gases
105	7.3.2	Discharges through gases
107	7.3.3	Discharge lamps
107	7.3.4	Discharge tubes
109	7.3.5	Xenon lamps
109	7.3.6	Metal-vapour lamps
109	7.3.6.1	Sodium-vapour lamps
109	7.3.6.2	Low-pressure mercury-vapour lamps
109	7.3.6.3	High-pressure mercury-vapour lamps
110	7.3.6.4	Fluorescent lamps
110	7.4	Mixed-light lamps
111	7.5	Flash-discharge tubes in photography
113	7.6	Luminescent diodes
113	7.6.1	Silicon-doped GaAs diodes
113	7.6.2	GaP diodes
114	7.6.3	Zinc-doped GaAsP diodes
114	7.6.4	Considerations on quantum efficiency
117	8	<b>Photodetectors</b>
119	8.1	Photodetectors with external photoeffect
120	8.2	Photodetectors with internal photoeffect
120	8.2.1	Photoconductors or photoresistors
121	8.3	Junction photodetectors
123	9	<b>Parameters of IR Detectors and Junction Photodetectors</b>
125	9.1	Quantum efficiency of junction photodetectors
126	9.1.1	Quantum efficiency and photocurrent gain of avalanche photodiodes
130	9.2	Spectral sensitivity of junction photodetectors
132	9.2.1	Scottky-Barrier PIN photodiodes
132	9.2.2	Planar diffused Si photodiodes
134	9.2.3	Photodiodes by the CDI process
134	9.2.4	Effect of temperature on the spectral sensitivity of photodiodes
134	9.2.5	Possibilities for shifting the spectral sensitivity of photodiodes
136	9.3	Evaluation of radiation by non-amplifying junction photodetectors for monochromatic radiatic

137	9.4	Evaluation of radiation by non-amplifying junction photodetectors for chromatic radiation (mixed radiation)
139	9.5	Evaluation of radiation by amplifying junction photodetectors
144	9.6	Area-dependent sensitivity values for junction photodetectors
145	9.7	Actinic values of IR luminescence radiation from GaAs diodes for silicon junction photodetectors
151	9.8	Dark current of junction photodetectors
153	9.8.1	Dark current of avalanche photodiodes
154	9.9	Sensitivity parameters of IR detectors
159	10	<b>Parameters common to emitters and receivers</b>
161	10.1	Evaluation of the radiation and receiving characteristics of optoelectronic components
167	10.2	Optical tolerances of optoelectronic components
168	10.2.1	Effect of wafer centering, lens quality, distance from lens to wafer, refractive index of epoxy resin and shape of dome and case
170	10.2.2	Effect of internal case reflections and wafer geometry
173	10.2.3	Tolerance levels which occur
176	10.3	Coupling characteristics, transfer ratios and contrast current ratios of short optical links
176	10.3.1	Coupling characteristics and transfer ratios
181	10.3.2	Contrast ratio
184	10.4	Half-power and half-value points
186	10.5	Dynamic data
191	10.6	Reliability of optoelectronic components
205	11	<b>Parameters of Luminescence diodes</b>
207	11.1	Quantum efficiency
213	11.2	Thermal calculations
213	11.2.1	Basic principles
215	11.2.2	Determination of the thermal resistance
217	11.2.3	Loss power calculation for luminescence diodes in plastic packages
217	11.2.4	Loss power calculation for luminescence diodes in metal cans with infinitely large heat-sinks
217	11.2.5	Loss power calculation for luminescence diodes in metal cans without heat-sink
218	11.2.6	Loss power calculation for luminescence diodes in metal cans with heat-sink
218	11.2.7	Calculation of the maximum permissible forward current
220	11.3	Radiant power
223	11.4	Radiant efficiency
224	11.5	Spectral radiant efficiency
226	11.6	Electrical parameters
228	11.7	Pulse operation

231	12	<b>Radiation measurements</b>
233	12.1	General Considerations
233	12.2	Measurement of colour temperature of standard light A
235	12.3	Measurement of radiant power with thermal photodetectors
237	12.4	Measurement of radiant power of standard light A with the thermopile
238	12.5	Measurement of irradiance of standard light A with Si photodetectors
240	12.6	Measurement of a luminescence diode radiation with Si photodetectors
240	12.6.1	General measurement problems
242	12.6.2	Measurement of relative spectral sensitivity with a monochromator
242	12.6.3	Measurement of irradiance of a luminescence diode radiation with Si photodetectors
245	12.7	Measurement of the total radiant power of a luminescence diode
247	13	<b>Optoelectronic couplers</b>
249	13.1	Direct optoelectronic couplers
250	13.2	Reflection optoelectronic couplers
252	13.3	Optocouplers with non-stationary source emission
252	13.4	Simple examples of optocouplers
254	13.5	Optocouplers with lenses
259	13.6	Optocouplers with unmodulated optical radiation
260	13.7	Optocouplers with modulated optical radiation
263	14	<b>Operation of luminescence diodes with direct current</b>
265	14.1	Operation through series resistances
265	14.2	Operation from constant-current sources
269	14.3	Drive with logic circuits
273	15	<b>Photodetector circuits</b>
275	15.1	Principle of operation
276	15.2	Detector circuits for two-pole junction photodetectors
276	15.2.1	Direct relay control with phototransistors
276	15.2.2	Photo-Darlington circuits
277	15.2.3	Control of thyristors and triacs with phototransistors
280	15.2.4	Driving of transistor- and operational amplifiers with phototransistors, photodiodes and photocells
285	15.2.5	Driving of multivibrators with phototransistors
288	15.3	Detector circuits for three-pole phototransistors
288	15.3.1	Operating modes of three-pole phototransistors
288	15.3.1.1	Photocell and photodiode operation of the TIL 81 phototransistor
288	15.3.1.2	Advantages of the TIL 81 phototransistor in photocell and photodiode operation
291	15.3.1.3	Phototransistor operation of the TIL 81
293	15.3.2	Driving of amplifiers with three-pole phototransistors

294	15.3.3	Photo-trigger circuits and photomultivibrators
298	15.4	Simple optocouplers with filament lamp and two-pole phototransistors
302	15.5	Logic circuits with phototransistors
304	15.6	Photodetector circuits to drive TTL circuits
309	16	<b>Modulated transmitters with luminescence diodes</b>
311	16.1	The simplest modulator circuits for luminescence diodes
312	16.2	Sine-wave-modulated transmitter with luminescence diodes
313	16.2.1	Modulation operation with bias voltage sources
318	16.2.2	Modulation operation with constant-current sources
320	16.3	Pulse-modulated transmitter with luminescence diodes
325	17	<b>Photodetector circuits for modulated radiation</b>
327	17.1	Circuits with phototransistors
328	17.2	Circuits with the TIL 81 photodetector as photodiode and as photocell
335	18	<b>Practical measurement of the photocurrent sensitivity of Si phototransistors</b>
337	18.1	Theoretical circuits of test equipments
338	18.2	Test equipment for measurement of the relative spectral sensitivity of phototransistors
341	19	<b>Light measurement with Si phototransistors in electronic flash units</b>
343	19.1	Principle of an electronic flash unit
344	19.2	Types of exposure control
345	19.3	Circuit of a flash unit
346	19.4	Si phototransistors for the automatic flash exposure control
349	20	<b>Circuits with light-emitting diodes</b>
351	20.1	Simple indicators
352	20.2	Diode tester
352	20.3	Logic tester
354	20.4	Polarity and voltage tester
355	20.5	Large-format seven-segment display unit
355	20.6	Analogue indication of digital values
357	20.7	Analogue measuring instruments with LED indication
361	21	<b>Numeric and alphanumeric display units</b>
363	21.1	Seven-segment display units
365	21.2	Multiplex operation of display units
368	21.3	Numerical display units with integrated logic
371	21.4	Monolithic display units
374	21.5	5 x 7-point matrix display units

381	22	<b>Direction-dependent photocell units</b>
383	22.1	Principle of operation
384	22.2	Direction-dependent counter
385	22.3	Direction-dependent optocouplers
387	22.4	Digital control knob
389	23	<b>Optoelectronic rangefinder</b>
391	23.1	Phase measurement as a measuring principle
394	23.2	Practical circuit of the rangefinder
399	24	<b>Data transmission with optocouplers</b>
401	24.1	Interference on transmission links
401	24.2	Construction and characteristics of optoelectronic couplers
401	24.2.1	Current transfer ratio
402	24.2.2	Mechanical construction
403	24.2.3	Dynamic performance
403	24.2.3.1	Photodiode operation
404	24.2.3.2	Phototransistor operation
404	24.3	Simple transmission links
406	24.4	Improvement of the switching performance of optocouplers
408	24.5	Optocouplers in photodiode operation
409	24.6	Duplex operation with optocouplers
410	24.7	Common-mode suppression of optocouplers
413	25	<b>Light exposure switch for photographic enlarger</b>
413	25.1	Principle of construction of a light exposure switch
416	25.2	The timing system
418	25.3	Practical circuit of the light exposure switch
419	26	<b>Optoelectronic couplers as switches for analogue signals</b>
421	26.1	Semiconductor switches and potential isolation
421	26.2	The phototransistor as a switch in the optocoupler
421	26.2.1	Steady-state performance
423	26.2.2	Dynamic performance
425	26.3	Application of optocouplers in a digital voltmeter
425	26.3.1	Voltage measurement method used
426	26.3.2	Practical circuit of the digital voltmeter
426	26.3.2.1	Analogue section
428	26.3.2.2	Digital section
429	26.3.2.3	Voltage converter
429	26.4	D.C. voltage amplifier with chopper
431	26.5	Line tester
431	26.5.1	Test principle
433	26.5.2	Practical circuit of the line tester

# **1 Physics of Optical Radiation**

- 1.1     Optical Radiation and Light**
  - 1.1.1   Basic Definitions**
  - 1.1.2   The Quantum Nature of Radiation**
  - 1.1.3   The Dualism of Waves and Particles**
  - 1.1.4   Wavelength and Propagation Speed**
- 1.2     Radiation and Luminescence Phenomena**
  - 1.2.1   The atomic and band model**
  - 1.2.2   Luminescence, Fluorescence,  
         Phosphorescence**
  - 1.2.3   Luminescence phenomena in  
         semiconductors, injection luminescence**
- 1.3     Photoelectric effect**
  - 1.3.1   External photoeffect**
  - 1.3.2   Internal photoeffect**
  - 1.3.3   The junction photoeffect**





## Physics of Optical Radiation

### 1.1

#### Optical Radiation and Light

Wavelength range	Designation of Radiation
100 nm – 280 nm	UV – C
280 nm – 315 nm	UV – B
315 nm – 380 nm	UV – A
380 nm – 440 nm	Light – violet
440 nm – 495 nm	Light – blue
495 nm – 558 nm	Light – green
580 nm – 640 nm	Light – yellow
640 nm – 750 nm	Light – red
750 nm – 1 400 nm	IR – A
1.4 $\mu\text{m}$ – 3 $\mu\text{m}$	IR – B
3 $\mu\text{m}$ – 1 000 $\mu\text{m}$	IR – C

Table 1.1  
Subdivision of the optical radiation spectrum according to DIN 5031

### 1.1.1

#### Basic Definitions

Optical radiation is understood to mean electromagnetic radiation in the range of wavelengths between 10 nm and 1 mm. This range is illustrated in Figure 1.1 as part of the whole electromagnetic spectrum. The optical radiation band consists of the sub-ranges *UV* (Ultraviolet), *visible* radiation (Light) and *IR* (infra-red). The transitions between the individual ranges are fluid. According to DIN 5031, Part 7, the UV range starts at 100 nm. The UV and IR ranges are divided into sub-groups A, B and C and the visible range into the relevant colours, as shown in Table 1.1. The expression "Light" only relates to the optical radiation perceived and evaluated by the human eye.

### 1.1.2

#### The quantum nature of radiation

Until the beginning of this century, electromagnetic radiation, including optical radiation, was considered to be continuous trains of waves.

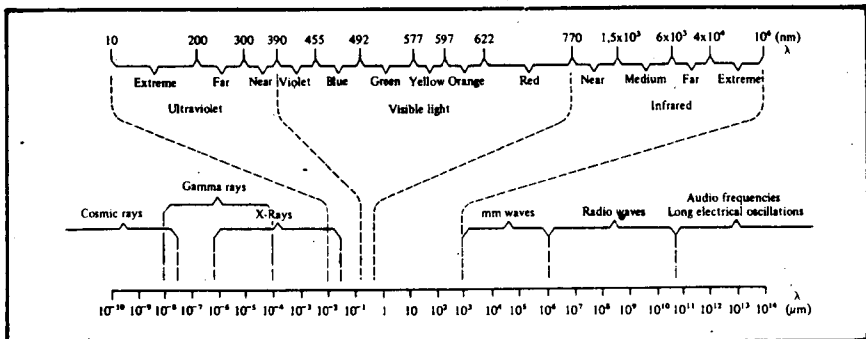


Figure 1.1  
Electromagnetic Radiation Spectrum

Physical investigations and considerations on the phenomena of the external photo-electric effect led, however, to the recognition of the fact that radiation does not interact with matter continuously, but in small portions which cannot be further sub-divided, the so-called *quanta*. Such a radiation quantum, also called a *photon*, corresponds to a certain amount of energy, dependent on the frequency of the radiation, which has a minimum value for any given frequency. For the relationship between the energy and the frequency of a quantum of radiation, the equation

$$W_{\text{ph}} = h \cdot \nu \quad (1.1)$$

applies, where  $h = 6.62 \cdot 10^{-34}$  watt. sec<sup>2</sup> (W.s<sup>2</sup>) Planck's constant and  $\nu$  = the frequency of the radiation in Hz.

In the optical range, the amounts of energy in the individual quanta are so small that the quantum structure of such radiation is beyond the limits of most conventional measurement methods and observations.

All quanta arise from changes in energy in atoms and molecules. The radiations which are of importance for opto-electronics have their origin in the outer electron orbits of the atoms. In the normal state, each electron is in the physically lowest possible level, where it has a certain amount of potential and kinetic energy. By excitation processes, e.g., by the introduction of electrical, thermal or radiant energy, electrons can temporarily leave their basic state and occupy a higher level with a correspondingly higher energy content. This state is not stable; therefore after a very short time the excited electrons fall back to the basic state, while emitting a quantum of radiation, the frequency of which, as shown in formula (1.1), corresponds to the energy difference between the two levels.

### 1.1.3

#### The dualism of waves and particles

If the nature of electromagnetic radiation is

investigated, then dependent upon the experimental conditions, sometimes it appears to behave like a wave, but at other times like a stream of particles (corpuscles). Therefore, when describing radiation, these two aspects are considered.

Electromagnetic radiation can be demonstrated to exhibit typical wave characteristics such as interference, refraction and polarisation, which can obviously be interpreted by the periodic nature of a wave-train. In theoretical physics, the propagation of electromagnetic radiation is derived from a wave process with the aid of Maxwell's equations.

From the corpuscular viewpoint, radiation takes on the character of a stream of particles. Each photon is then considered as an elementary particle with zero stationary mass, moving at the speed of light. The shorter the wavelength of radiation, the more prominent does the corpuscular nature become in comparison with the wave character. In the range of gamma rays, therefore, their particle nature becomes the predominant characteristic.

### 1.1.4

#### Wavelength and propagation speed

The speed of propagation of light in vacuo, and also approximately in the atmosphere, is  $c_0 = 2.998 \cdot 10^8$  m/s.

For practical calculations, the rounded value of  $c_0 = 3 \cdot 10^8$  m/s is adequate. The relationship between the three fundamental values, speed of light  $c_0$ , wavelength  $\lambda$  and frequency  $\nu$  is given by

$$c_0 = \lambda \cdot \nu \quad (1.2)$$

By combining the equations (1.1) and (1.2), the wavelength of a photon can be calculated, if the photon energy  $W_{\text{ph}}$  is known.

$$\lambda = \frac{c_0 \cdot h}{W_{\text{ph}}} \quad (1.3)$$

The photon energy is usually stated in electron volts (eV). One electron volt corresponds to the kinetic energy received by an electron through acceleration in an electric field with a potential difference of one volt.

For the conversion of eV into the SI unit Ws or J:

$$1 \text{ eV} = 1.602 \cdot 10^{-19} \text{ Watt secs (Ws)}$$

$$1 \text{ eV} = 1.602 \cdot 10^{-19} \text{ Joules (J)}$$

The equation (1.3) can be simplified as a numerical equation, if the numerical values of the natural constants and the conversion factor for eV into Ws are inserted:

$$\lambda = \frac{3 \cdot 10^8 \cdot 6.62 \cdot 10^{-34}}{W_{ph} \cdot 1.6 \cdot 10^{-19}}$$

Where  $\lambda$  is measured in  $\mu\text{m}$   
 $C$  is measured in  $\text{ms}^{-1}$   
 and  $W_{ph}$  is measured in eV

This results in the numerical equation

$$\lambda = \frac{1.24}{W_{ph}} \quad (1.4)$$

From these equations it can be seen, that the greater the energy of the photons, the shorter does the wavelength of the electromagnetic wave becomes.

## 1.2

### Radiation and Luminescence Phenomena

#### 1.2.1

##### Atomic and Band Model

For the physical explanation of radiation phenomena and also of the photoemission which is described later, an understanding of the atom and band models is necessary. The atomic model describes, in a simplified representation, the spatial structure of an atom, while the band model gives information on the energy content of electrons,

both in single atoms and also in combinations of several atoms, e.g., in a crystal lattice. In Figure 1.2, the atomic model for germanium is shown as an example.

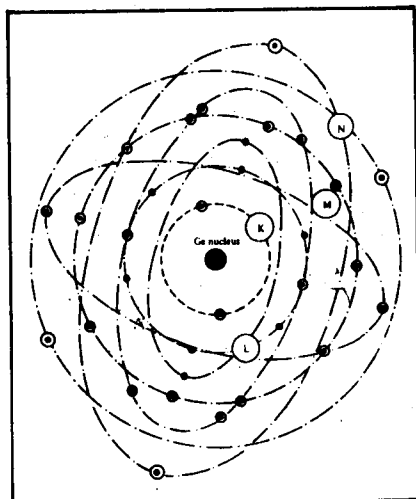


Figure 1.2  
Model of germanium atom

Recent work has shown the atom to be extremely complex but for simplicity it can be considered to be composed of negatively charged electrons, orbiting around a charged nucleus. The atomic nucleus itself consists of positively charged protons bound together with neutral particles called neutrons. The number of protons determines which chemical element is concerned. In an electrically neutral atom, the number of electrons and protons is equal. The electrons are located in specific orbits around the nucleus, and these are grouped into so-called shells; in Figure 1.2 these shells are shown with their normal designations K, L, M and N.

Nearly all atomic nuclei with more than 82 protons and a few smaller nuclei are unstable and disintegrate, through a process known as nuclear fission, spontaneously over varying periods of time. Through this

fission process the basic elements are converted into others. Radium, for example, disintegrates to form the stable element Lead, with the emission of radiation from the nucleus which is characterised into  $\alpha$ ,  $\beta$ , and the short-wave  $\gamma$ -rays. While this radiation originates in the nucleus of the atom, the emission and absorption of optical radiation takes place within the cloud of electrons surrounding the nucleus.

The energy state of the electrons is described by four quantum numbers. The quantum numbers are designated by small letters:

- 1  
n = Principal quantum number (associated with a particular shell)
- 2  
l = Secondary quantum number (sub-group is the shell and shape of the electron orbit)
- 3  
m = Magnetic quantum number (location in space of the angular momentum vector of the orbit)
- 4  
s = Spin quantum number (angular momentum of the electron itself about an imaginary axis)

All electrons associated with an atom or a molecule differ from one another in at least one quantum number. This principle of exclusion of two identical electron states, the so-called Pauli exclusion principle, determines the maximum number of electrons within a given shell, an intermediate shell or an energy level. If all the electrons of an atom are at their lowest possible energy level, that is, in the innermost shells, then the atom is in its basic state.

With the single atom, the electrons adopt exactly defined, discrete energy states. In a

crystal, on the other hand, because of the interaction of the electrons belonging to the different atomic nuclei, the previous discrete bands divide into ranges, the *energy bands*. These ranges are illustrated in the so-called band model, while in semiconductor technology one restricts oneself to the *valency band* and the *conduction band*, which are of interest here, with a "forbidden gap or band" between them. *Figure 1.3* shows a few examples.

In the cases of metals and insulators, the valency band is occupied by electrons, which are fixed in their places. Thus, no movable electrical charges are possible within the valency band. In the case of insulators, the conduction band is unoccupied, i.e., it is free of charge carriers, while in the case of a metal each atom gives up one or more electrons into this band. These electrons are then very loosely bound to a given atomic nucleus and are therefore free to move in the crystal lattice. Their number and mobility in the conduction band determines the conductivity of the substance. In contrast to the metals, which are known to be good electrical conductors, the semiconductor, at low temperatures has almost all electrons in the valency band, so that it is then almost an insulator. With rising temperature, more and more covalent bonds<sup>1</sup> break apart, since through the external supply of energy in the form of heat, a certain number of electrons can leave the valency band and move up into the conduction band. This is possible without difficulty with semiconductors, since the width of the forbidden band is very narrow in comparison with that of insulators. A hole, is then produced in the valency band and behaves like a positively charged particle which can migrate within the band. *The presence of holes in the valency band and electrons in the conduction band causes the conductivity of semiconductor materials to lie somewhere between those of metals and insulators.* The width of the forbidden band, which is

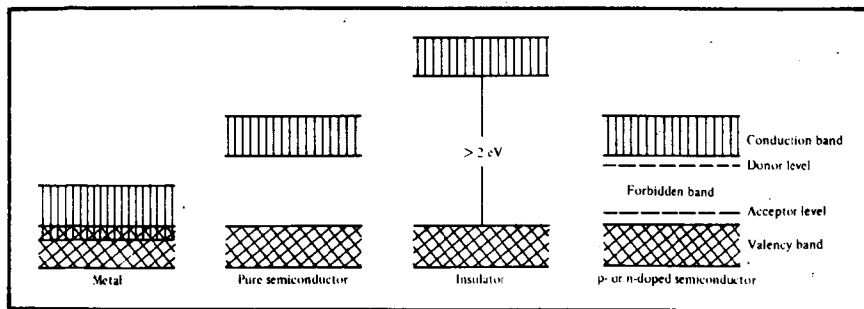


Figure 1.3

### Energy bands of a few materials

generally stated in eV, determines the necessary minimum energy, which must be supplied to an electron, in order to raise it from the valency band to the conduction band.

In the preparation of semiconductor devices "impurities" are intentionally added in small, defined quantities to the undoped or "intrinsic" semiconductor material. Silicon and germanium are two quadrivalent or group IV semiconductors which are commonly used for producing useful electrical devices. However, semiconducting compound materials such as gallium arsenide can also have characteristics which can be readily utilised. The conductivity of the basic material is modified as required by adding either trivalent (group III) atoms, so called "acceptors," to give P-material or pentavalent (group V) atoms, so called "donors," to give N-material. Since the donor level is close, in energy, to the conduction band, a very small amount of energy is sufficient to raise an electron of the donor substance into the conduction band. Therefore, the pentavalent donors, with one electron which is only loosely bound to the atom, increase the basic conductivity. The acceptors in turn attract either loosely bound or free electrons, in order to fill the gaps (holes) caused by their addition. The acceptor level is close, in energy, to the valency band.

The conductivity of the doped semiconductor can be altered by the presence of an external energy source.

The excitation energy can be supplied in the form of heat, by photons (light energy) or by the application of an external voltage (electrical energy). If the excitation takes place through photons (irradiation), the term "internal photoeffect" is used. If an excited electron is in the conduction band, this state of excitation is not stable. After a certain time, the electron falls back again and recombines with a hole. Electromagnetic radiation, corresponding to the energy difference liberated, can then be emitted.

Under certain conditions, electrons can be released completely, by energetic excitation, from their parent substance, for example, from alkali metals or certain oxides, and can move freely in space. This process is called emission. If this emission is caused by light quanta, then the term "external photo-effect" is also used.

On the basis of our knowledge of the atomic model, we know that excited electrons are located in orbits with higher energy levels and that on their return to the basic state, electromagnetic radiation can be emitted. A distinction can be made between three kinds of radiation:

- a  
Radiation, which occurs through the return of the electron to the basic state by direct recombination.
- b  
Fluorescence radiation.

c  
Phosphorescence radiation.

From the band model, a distinction is made between four kinds of recombination:

1  
Recombination between free electrons of the conduction band and free holes of the valency band.

2  
Recombination between free electrons of the conduction band and bonded holes of the acceptor level.

3  
Recombination between electrons of the donor level and free holes of the valency band.

4  
Recombination between electrons of the donor level and bonded holes of the acceptor level.

The kind of recombination is determined by the characteristics of the semiconductor and its doping.

### 1.2.2 Luminescence, Fluorescence, Phosphorescence

For all cases of light emission, which do not have their cause solely in the temperature of the material, E. Wiedemann introduced the term "Luminescence" as long ago as 1889. This is understood to mean radiation phenomena in the visible range. In a broader sense, it is also understood, in the literature, to mean the optical radiation range. Depending on the kind of excitation energy, which causes the luminescence phenomenon, distinctions are made, among others, between:

a  
Thermoluminescence:  
Excitation by raising the temperature of

crystals, in which electrons have been raised in energy by absorbed light do not return at once to the basic state, with emission of the luminescent light, but are stored in energy levels, which are somewhat below the starting energy needed for luminescence.

b  
Bioluminescence:  
Is part of chemiluminescence. It occurs in nature, e.g., in glow-worms and fireflies.

c  
Chemiluminescence:  
Occurs through certain chemical reactions, in which energy is liberated and emitted as radiation, e.g., phosphorus glows through oxidation in the air.

d  
Cathodoluminescence:  
Occurs through accelerated fast electrons, which, on collision with atoms, excite the corresponding valency electrons and cause the emission of radiation or light. Typical examples are television and oscilloscope tubes.

e  
A.C. Electroluminescence:  
Obtains the excitation energy through an electric field, e.g., in the dielectric of a capacitor (Destriau effect). The luminescent capacitor contains the thin luminescent dielectric and also a transparent electrode.

f  
Photoluminescence:  
Is caused by fluorescence. The exciting radiation, for example, UV, is more energetic than the radiation emitted in the visible range.

g  
Radioluminescence:  
Obtains the excitation energy through X-rays or gamma rays.

h  
Betoluminescence:  
The excitation energy is beta radiation.

i

#### Crystal luminescence:

Is produced by the deformation of certain crystals.

k

#### Triboluminescence:

Occurs through the supply of mechanical energy with certain crystals. For example, quartz or zinc sheets glow with a faint light through rubbing, drilling, scratching etc.

As well as classification by the excitation energy, luminescence phenomena are also classified according to the way in which they occur:

a

#### Fluorescence:

With this type of radiation, the excited electrons fall back, in one or more steps, within about  $10^{-8}$  seconds, to the basic state and light is emitted. In this process, the excitation energy generally has a higher quantum energy than the radiation emitted. Fluorescent substances act, to a certain extent, as frequency converters. In contrast to phosphorescence, fluorescence only gives an emission, as long as an external supply (e.g., radiation) is maintained.

b

#### Phosphorescence:

A radiation, with which the excited electrons at first remain in a metastable state. This metastable state occurs under the influence of activators (foreign metallic atoms in small concentrations in the basic material), while the electrons fall back into the basic state after a dwell time of varying duration. Phosphorescent materials radiate both during the presence of the excitation energy and also after this excitation energy is switched off, according to the after-glow time.

### 1.2.1

Luminescence phenomena in semiconductors, Injection luminescence\*

In a semiconductor diode operated in the forward direction, the junction region is enriched with electrons and holes. These two kinds of charge carrier recombine with one another, and at every recombination an electron is transferred from the conduction band into the valency band. At the same time it gives up the amount of energy, which corresponds to the difference in energy between the conduction band and the valency band.

Depending on the given conditions, the energy thus liberated can be converted into radiant energy (photons) or into heat (lattice vibrations of the crystal, also called phonons). If a photon conversion takes place in the semiconductor materials known up to the present day, radiation in the range from infrared to the visible range appears. Since they are caused injection of charge carriers into a junction region, radiation phenomena of this kind are called *injection luminescence*. The probability of photon radiation taking place depends to a great extent on whether the material used is a "direct" or an "indirect" semiconductor.

Both on the basis of the wave-particle dualism and also according to the theory of wave mechanics, a wave function can be ascribed to a particle of matter. In this process, a moving particle, e.g., either an electron or a hole, can be treated mathematically like a wave. From this wave function, a term which is important for semiconductor considerations can be derived by quantum mechanics which is the wave-number vector  $\vec{K}$ . This value, which is also known as the propagation vector, is proportional to the momentum ( $p = m \cdot v$ ) of the moving charge-carrier, as long as the particle can be considered to be "free". In this case it can also be proved that the energy  $W$  of the particle is a quadratic function of  $\vec{K}$ . In a crystal with its periodic three-dimensional lattice the conditions are more complicated, through the interactions of the lattice components with the moving charge carriers. Here, the



function  $W = f(\vec{K})$  is no longer a quadratic function, as before, but the curve which is now produced can contain several maxima and minima. Also, the shape of the curve depends on the geometrical crystal direction, in relation to the major crystal axes, in which the "particle wave" is moving. A few examples are shown in Figure 1.4. In these, the holes always have an energy maximum at  $\vec{K} = 0$ , while the curve shapes differ for electrons.

The probability that an electron will remain is always highest, where its energy becomes a minimum, while the holes endeavour to reach a level with the maximum possible energy in the valency band. At the points, where a minimum of electron energy is directly opposite a maximum of hole energy, the electron can fill the hole, in a recombination, without a change of the wave-number vector  $\vec{K}$  or of its momentum. Semiconductors, where this recombination is possible, are called "direct semiconductors". If the electron energy minimum and the hole energy maximum are not directly opposite, then a recombination can only take place with a simultaneous change of  $\vec{K}$ . In this case, we speak of an "indirect semiconductor".

The physical law of the conservation of momentum in a self-contained system requires, that when a light quantum is either absorbed or emitted from a semiconductor, the momentum of the light quantum causes a corresponding change in momentum in the crystal system. If the momentum values are calculated, both of a moving charge carrier and of a light quantum in the wavelength range which is of interest, it is found, that the momentum of the light quantum is negligibly small in comparison with that of the charge carrier, so that in practice, only the changes of momentum of the charge carriers need to be taken into account, even though light quanta are involved in the process.

Electron transitions in direct semiconductors take place without significant change of momentum, so with recombinations in these materials the probability of the emission of radiation is high. Things are different with indirect semiconductors. In the case of a recombination, here, as well as the energy given up, a change in momentum must also be taken into account. Under these conditions, the production of phonons is again probable, since as well as the energy, these also take up a momentum

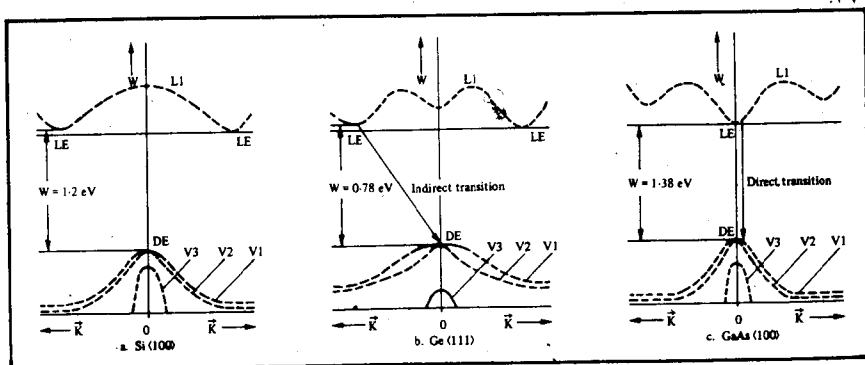


Figure 1.4

Band diagrams in the energy-momentum graph. The abbreviations denote LE = Conduction electron, DE = hole,  $W$  = Energy,  $\vec{K}$  = wave number vector, L1 = Conduction band, V1, V2, V3 = Valency bands, (100), (111) = Miller's indices.<sup>1</sup>

1 Miller's indices are the reciprocal values of the points of intersection of the crystal axes with cut surface.