SIEMENS

General IR and Photodetector Information Appnote 37

1. Detectors (Radiation-sensitive Components)

Charge Carrier Generation in a Photodiode

Figure 1.1 shows the basic design of a planar silicon photodiode with an abrupt pn transition. Due to the differing carrier concentrations, a field region free of mobile carriers, the space charge region, builds up between the p^+ and n region, which only reaches into the n region if there is an abrupt p^+ n transition. The following applies to the width of the space charge region:

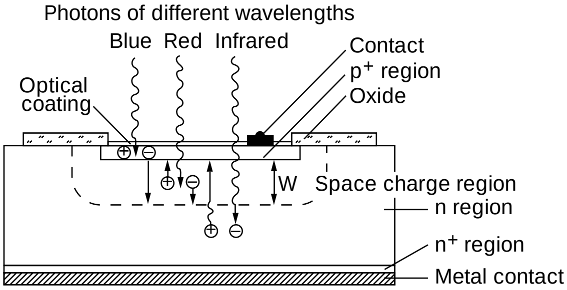


Figure 1.1 Planar Silicon Photodiode (schematic)

(1) $$w \sim \sqrt{\frac{V_D + V}{n_D}}\ .$$

In this case, V_D is the diffusion voltage, V is the external voltage and n_D is the donor concentration on the n side. For the junction capacitance $C_j \sim \frac{1}{w}$ with w from equation (1) the g is obtained:

(2) $$C_j \sim \sqrt{\frac{n_D}{V_D + V}}\ .$$

If photons with an energy $h\nu \geq E_g$ penetrate into the diode, electron hole pairs are generated on both sides of the pn junction. The energy difference $(h\nu - E_g)$ is dissipated to the grid in the form of heat. The electrical field in the space charge region repels the majority carriers and attracts the minority carriers on the other respective side (thus, holes from the n side to the p side and, vice versa, electrons from the p side to the n side). In this way, the charge carrier pairs are separated and a photocurrent flows through an external circuit, also without an additional voltage (photovoltaic effect). Carriers occurring in the space charge region are immediately sucked off due to the field prevailing in this layer. The carriers from the other regions must first of all diffuse into the space charge region in order to be separated. If they recombine beforehand, they are lost with respect to the photocurrent. Thus, the photocurrent I_p consists of a drift current I_{drift} of the space charge region and of a diffusion current I_D from the remaining regions.

Should the p^+ region be far thinner than the penetration depth $\frac{1}{\alpha_\lambda}$ (α_λ = absorption coefficient) of the radiation, the photocurrent from the p^+ region can be neglected and the following relationship can be derived for the photocurrent I_p.

(3) $$I_p = q\Phi_O \left[1 - \frac{e^{-\alpha_\lambda w}}{1 + \alpha_\lambda L_P} \right]$$

L_O is the diffusion length of the holes in the n region, q is the elementary charge and Φ_O the radiant flux. The absorption coefficient α_λ is the only variable in the equation which depends on the wavelength. It predominantly determines the spectral characteristic of the diode's photosensitivity. In accordance with equation (1), the space charge region width w depends on the voltage and the doping which, in addition to the crystal quality, also influences L_D. High sensitivity is achieved with high values for w and/or L_D.

With respect to the electrical mode of operation, we differentiate between diode mode (with bias voltage) and cell mode (without bias voltage). In cell mode, the diode acts as a current generator which converts the radiant energy into electrical energy. If the photodiode is considered as a current source with the photocurrent I_p and a diode of equal polarity is connected in parallel to the load resistance R_{LE} (idealized equivalent circuit diagram), the relationship between the current and voltage can be expressed as follows:

(4) $$I = I_S \left[e^{\frac{V}{n \cdot V_T}} - 1 \right] - I_p\ .$$

In this case, I_p is the photocurrent, I_{sat} the saturation current, V the voltage between the p and n contact, V_T the voltage equivalent of the temperature and n is the diode factor. In the case of $I_p = 0$, equation (4) is reduced to a normal diode equation and describes the dark characteristic ($E_V = 0$). When subjected to light, the characteristic is shifted downwards corresponding to the illuminance. The open-circuit voltage

(5) $$V_L = nV_T \ln \left[1 + \frac{I_p}{I_S} \right]$$

belongs to $I = 0$ ($R_{LE} = \infty$) and the short-circuit current $I_S = -I_p$ belongs to $V = 0$ ($R_{LE} = 0$).

There is a linear relationship, depending on the diode type, between the illuminance E_V and the photocurrent I_p, which covers several powers of ten (eight and more). However, due to $I_p \sim E_V$ and $I_p > I_S$, a logarithmic relationship prevails between the open-circuit voltage V_L and the illuminance E_V. The forward current I_F belonging to the open-circuit voltage V_L is equal to the impressed photocurrent. In diode mode, the photocurrent of one or the other diode type may slightly change together with the applied voltage. This is due to the voltage dependence of the space charge region. In silicon photodiodes, the dark current [first term in equation (4)] once again only plays a role with extremely low illuminances (in the millilux range).

Spectral Sensitivity

Figure 1.2 shows the graph of the spectral sensitivity of a silicon and a germanium photodiode. The positions of the emission maxima of the most important light emitting diodes and the sensitivity of the human eye are also shown.

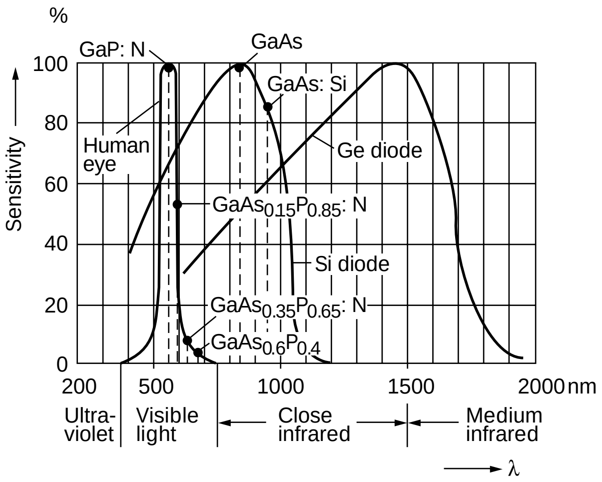


Figure 1.2 Relative Sensitivity of a Silicon and a Germanium Diode

The two photodiodes cover the wavelength band from approximately 300 to 1800 nm. In this case, the silicon diode is of greater significance; it covers the visible range and, with its maximum sensitivity in the near infrared area, is well matched to the GaAs infrared emitting diode, whose best known field of application covers IR remote controls and light barriers.

The sensitivity limit of semiconductor detectors in the long wave spectral wave band λ_g is determined by the energy gap E_g.

$$\lambda_g\,[\mathrm{nm}] = \frac{h \cdot c}{E_g} = \frac{1.24}{E_g\,[\mathrm{eV}]}$$

The run of the spectral sensitivity curve in the remaining wave band is determined by the absorption coefficient α_λ and the recombination relationships in the interior and on the surface of the semiconductor (carrier loss). The drop in the curve towards shorter wavelengths is due to the higher absorption for shortwave radiation; for this reason, carrier pairs are only generated in the regions near the surface but, due to the high prevalent recombination rate, are mostly lost with respect to the photocurrent.

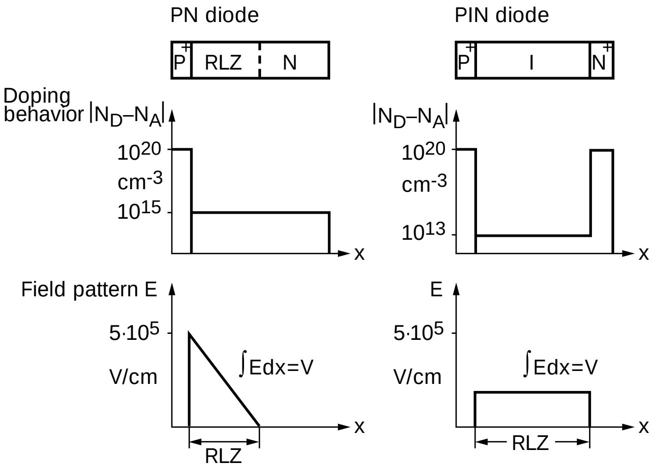


Figure 1.3 Doping Behavior and Field Pattern of Photodiodes

Photodiodes (PN and PIN Diodes)

Photodiodes can optimally be matched to the desired application by choosing the correct mode of operation and by means of a suitable internal structure. In addition to the schematic structure of each individual diode type, Figure 1.3 shows the doping behavior and the field pattern as well as the region in which the avalanche effect takes place at a sufficiently high voltage (ionization region).

PN photodiode radiation which, as a rule, enters the p^+ region vertically, is absorbed in the mainly quasi-neutral p and n regions due to the narrow space charge region; thus, the photocurrent predominantly consists of the diffusion current. As the characters are diffused relatively slowly, PN diodes are frequently used in applications in which the stress is placed rather more on low dark currents than on high speed. (For complete diffusion of a 5 µm thick p layer, an electron needs 3 ns, and a hole needs 15 ns for the same distance in the n region). Therefore, silicon PN diodes can be found in exposure meters which still operate perfectly under starlight; this presupposes dark currents of less than approximately 10^{-11} A/mm^2. Solar cells also belong to the group of PN photodiodes.

Contrary to the PN diode, most of the light for PIN photodiodes is absorbed in the space charge region. These photodiodes are mostly used in applications requiring high speeds. If possible, in order to achieve a large space charge region, according to equation (2), the semiconductor material must be intrinsic (intrinsic I) (mostly weak n or weak p doped) into which a p^+ region is diffused on the one side and an n^+ region is diffused on the other side.
A $P^+ IN^+$ structure (“sandwich” structure) is obtained. Per equation (3), the junction capacitance C_j is low due to the large space charge region of the PIN diode. C_j values are used between a few picofarad and a few tenths of a picofarad. The product from C_j and R_L (load resistance) is the time constant of the measurement circuit.

To achieve PIN diodes which are as “fast” as possible, the voltage is increased to such an extent that the carriers drift through the space charge region at saturation speed V_{sat}. In silicon and germanium, a saturation speed V_{sat} from 5 x 10^6 to 1 x 10^7 cm/sec is achieved with fields of approximately 2 x 10^4 V/cm. Accordingly, a carrier requires approximately 50 ps to completely drift through a 5 µm thick region.

Photovoltaic Cells

Voltaic cells are active dipole components which convert optical energy into electrical energy without requiring an external voltage source.

The properties of a voltaic cell are essentially characterized by the open-circuit voltage and the short-circuit current. In the case of a short circuit (V = 0), the current I_S is a linear function of the illuminance and thus also proportional to the area subjected to radiation. The open-circuit voltage V_O initially increases logarithmically with the luminous intensity.

This is independent of the size of the cell and amounts to approximately 0.5 V at 1000 lx. In order to extract the maximum amount of energy from a voltaic cell, the load resistance R_L must lie in the order of magnitude of $R_i = \sqrt{V_O / I_S}$. The internal resistance R_i of a voltaic cell should be as low as possible in order to prevent unnecessary loss.

In order to measure the luminous intensity, the proportional relationship between the optical and electrical signals is important, and in practice, this applies up to a load resistance of $R_i \approx V_O / 2\, I_S$.

In principle, voltaic cells can also be operated in diode mode by applying a voltage in reverse direction. Obviously, this voltage must not exceed the maximum reverse voltage.

Phototransistors

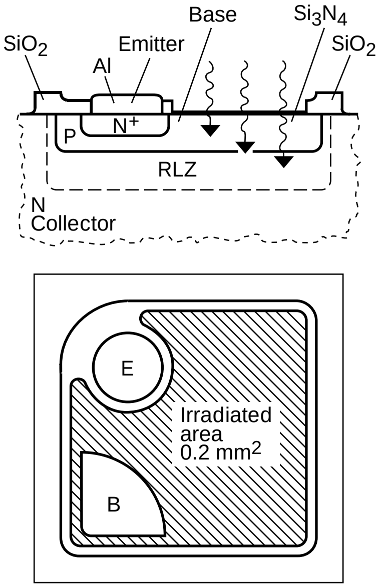


Figure 1.4 Bipolar Phototransistor

In principle, a phototransistor corresponds to a photodiode (collector-base diode) with a series-connected transistor as amplifier. The phototransistor is the simplest integrated photoelectric component. Figure 1.4 shows one of the practical designs of a bipolar phototransistor (cross-section and view) with emitter (n^+), base (p) and collector (n); the latter is mostly subdivided into a weakly doped n and a highly doped n^+ region. As the diffusion length L_D of the holes in the n^+ region is low due to the high amount of doping, only the p and n regions provide the maximum amount to the primary photocurrent I_{CB} of the collector-base diode. This is due to the low photosensitivity (also in comparison with photodiodes) of epitaxial transistors in the long wave band. A large part of the long-wave radiation is absorbed in the n^+ region as the n region is mostly extreme thin (10 to 20 µm) as a result of the requirement for extremely low conductor resistances. The view of the transistor shows a base with a large area in which the emitter and also the base connection are attached to the side; in this way, as uniform as possible a surface sensitivity is achieved. The gain of phototransistors normally lies between 100 and 1000. Gain deviations from the linearity and thus from the linear relationship between the illuminance and the photocurrent amount to (over approximately four powers of ten of the photocurrent I_p, from some 100 nA to some mA) less than 20% and mostly less than 10%. With regard to dynamic behavior, phototransistors are less favorable than photodiodes as, in addition to the collecting and charging processes in photodiodes, there is also a delay due to the amplification mechanism (Miller effect). In addition to the rise and fall times t_r and t_f, the transistor also has the delay time t_d. This is the time required until the photocurrent has reached 10% of its final value after activation of an optical square-wave pulse. For the rise and fall times of a phototransistor, the following relationship applies:

$$t_{r \cdot f} = \sqrt{\left(\frac{1}{2_{f_T}}\right)^2 + a\,(R \cdot C_{CB} \cdot V)^2}$$

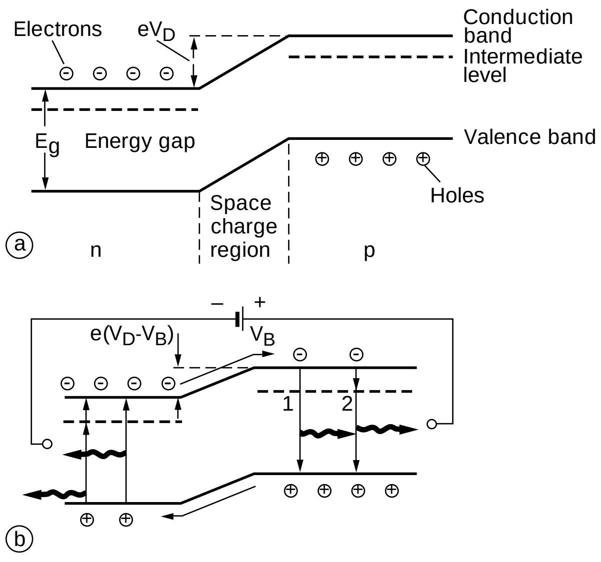
In this case, f_T is the transition frequency, R is the load resistance, C_{CB} is the collector-base capacitance, G is the gain, a is a constant whose value lies between four and five. The rise and fall times of usual phototransistors range from 1 to approximately 30 µs with 1 kOhm load resistance. Therefore, they are particularly suitable for utilization within a frequency range up to some 100 kHz, which suffices for important applications such as light barriers, punch tapes, and punch card readers.

2. Emitters (Radiation Emitting Components)

Principle of Operation and Materials

Light emitting diodes operate in accordance with the principle of injection luminescence. Through a pn junction operated in forward direction, n-type charge carriers are injected into the neutral n and p region where they partially recombine for emission, sending out a photon with the energy $h\nu = hc / \lambda \leq E_g$ (h = Planck’s constant, ν = frequency, c = speed of light, λ = wavelength, E_g = energy gap). This is shown in Figure 2.1, an energy diagram for a pn junction.

The probability of radiant recombination essentially depends on the band structure type of the corresponding semiconductor material. In the case of direct semiconductors with GaAs as the most important representative, an electron can



ⓐ without external voltage
ⓑ with externally applied voltage.
Diode operated in forward
direction (1 ≙ direct recombination.
2 ≙ indirect recombination)

Figure 2.1 The pn Junction of a Light Emitting Diode

directly fall from the conduction band into a free state in the valence band (hole), in which case the released energy is given off as a photon (cp Figure 2.2, left). In the case of the so-called indirect semiconductors with Si, Ge, and GaP as the most important representatives, however, this transition is linked with a pulse change of the electron. Recombination is then only possible with the participation of third partners, for example, phonons or impurities. These must ensure pulse compensation. The energy released during the transition is mainly dissipated as heat to the grid. In indirect semiconductors, this leads to the probability of radiant recombination being less by orders of magnitude than in direct semiconductors. Nevertheless, effective radiant recombination can be generated in some indirect semiconductors. This is achieved by doping with isoelectronic impurities. The two most efficient isoelectronic impurities in GaP are the nitrogen atom and the zinc-oxygen pair. Radiant recombination is then achieved by way of the decay of an electron hole pair (exciton) bonded to the isoelectronic impurity (cp Figure 2.2, right).

A high degree of crystal perfection is a precondition for the creation of effectively radiant recombination as crystal defects act as centers for non-radiating recombination. For this reason, the active layers of light emitting diodes are produced epitaxially at temperatures far below the melting point of the semiconductor material.

III-V compound semiconductors and mixtures of these can be used as materials for light emitting diodes as their energy gaps cover wide spectrum and the band structure, contrary to the classical semiconductors Si and Ge, enable the creation of effective radiant recombination. Above all, the semiconductors GaAs, GaP, and the terniary mixtures Ga (As, P) and (Ga, Al) As have practical significance.

Infrared Emitters (IR LEDs)

IR emitters are based on GaAs which has an energy gap of approximately 1.43 eV, corresponding to emission of approximately 900 nm. Higher external quantum efficiencies can be achieved with these diodes than with light emitting diodes for the visible wave band. The left-hand side of Figure 2.3 shows the schematic of the diode body of a silicon-doped GaAs IRED. By means of liquid phase epitaxy (LPE), the active layer with a high crystal perfection can be grown onto a GaAs substrate. Due to the amphoteric characteristic of the silicon impurity, the pn junction forms automatically during the process of epitaxy. Due to the silicon doping, the emission lies at 950 nm and is thus so far underneath the band edge that the radiation created in the diode body is only absorbed to a slight extent. Part of the radiation leaves the diode body on a direct path through the near surface. However, radiation emitted in the direction of the substrate is also useful. For this purpose, the rear of the diode body is mirrored and serves as a reflection surface.

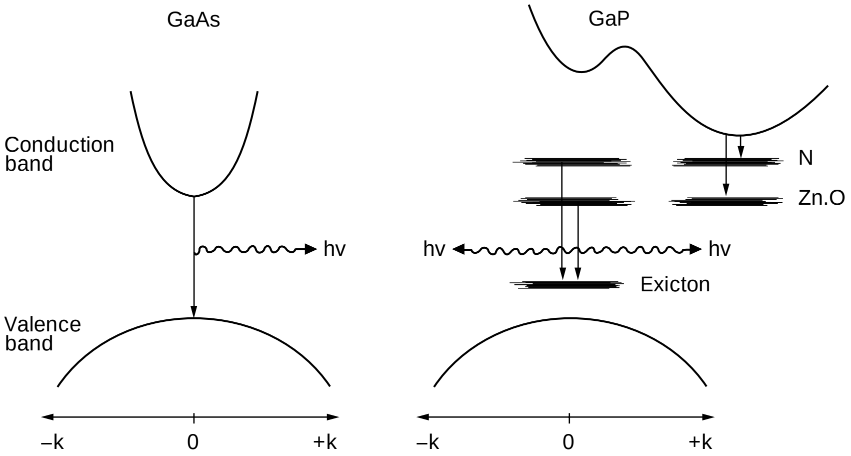


Figure 2.2 Dependence of Energy States on Wave Number Vector k in Direct (GaAs) and Indirect (GaP) Semiconductors

GaAs-IREDs are fitted in plastic packages or in hermetically sealed glass-metal housings.

An essential piece of information for the user is the radiation characteristic. If the light emitting diodes are used in an arrangement without optical lenses, for example, in a punch tape reading head, the radiation should have a small half angle. This is the case with LD260 to 269 and CQY77.

In conjunction with optical lens systems, designs are preferred in which the radiation leaves the component through a flat window (CQY78, SFH402).

Array designs are suitable for a wide range of applications as they can be rowed up in any configuration.

Further developments in the field of silicon-doped liquid phase epitaxial IREDs is aimed at expanding the wave band. The amphoteric character of the silicon doping is retained in the terniary mixed crystal (GaAl) As in that the energy gap can be varied by means of the amount of Al. In this way, it is possible to produce emission wave bands between 850 and 900 nm and to tune the emitter diodes to the maximum detector sensitivity. With selectively sensitive detectors, it would be possible to create transmission systems with two (or more) optically separate channels.

Electrical and Optical Characteristics of IR LEDs

Figure 2.4 shows the emission spectrum of the most important LEDs and the relative spectral contact sensitivity $V\lambda$. With respect to the emission spectrum of the IRED relative to the sensitivity curve of the silicon photodiode (Figure 1.2).

The emission spectrum of the GaP diode ranges from the yellow to the green wave band. By dying the plastic seal, the emission band can be limited in such a way that the emitted light appears yellow ($\lambda_p = 575$ nm) or green ($\lambda_p = 560$ nm) to the viewer.

In the case of GaAs diodes and the red $GaAs_{0.6}P_{0.4}$ diode, the emitted radiation (or luminous intensity, respectively) of IREDs and LEDs changes in the normal operating range in a linear relationship with the forward current while, in the case of TSN diodes and GaP diodes, it rises slightly over proportionally (Figure 2.5).

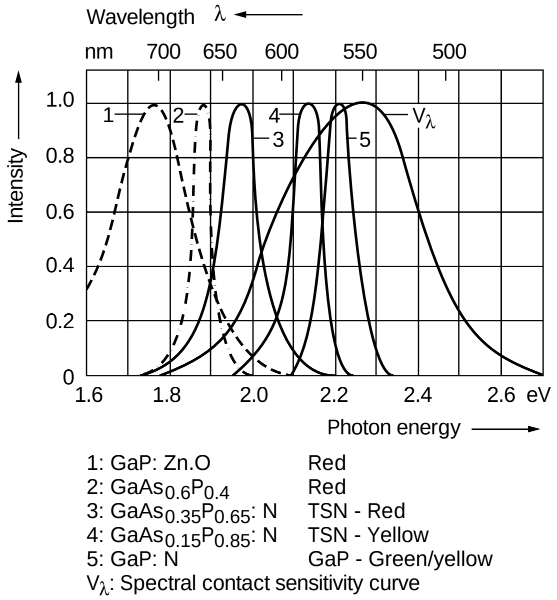
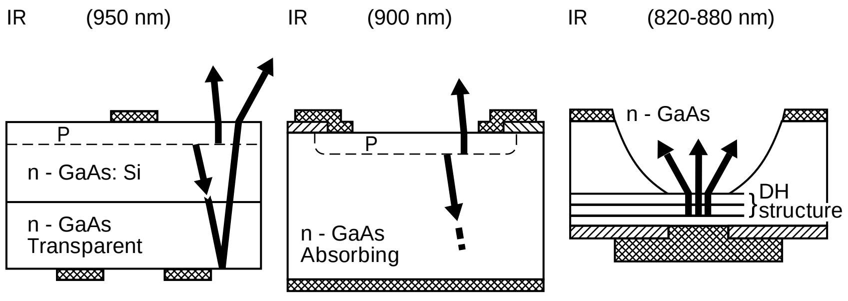


Figure 2.4 Emission Spectra of the Most Important LEDs

If the forward current is very high, the curve asymptotically approaches a threshold value. This is caused by a strong heating of the semiconductor system. The linearity range can be widened by switching from static to pulse operation. Nonlinearity also turns up at small forward currents. It is caused by excess current not contributing to the radiation and cannot be influenced by the customer. Figure 2.6 shows the radiant power versus the forward current.

At constant current, the radiant intensity or luminous intensity, respectively, decreases with rising temperature. The tem-



Epitaxy	LPE	—	LPE (Hetero)
pn junction	LPE	Diffusion	LPE (Hetero)
Technology	GaAs-IRED	Diffused GaAs IRED	Burrus type
Switching time (typical)	1000 ns	50 ns	15 ns

═ Semiconductor ▩ Contact ▨ Contact

LPE = liquid phase epitaxy

Figure 2.3 Structure of the Diode Body of an IRED

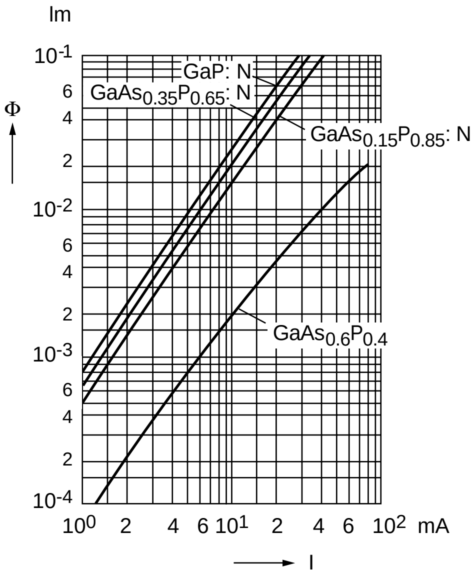


Figure 2.5 Light Current - diode Current Characteristic

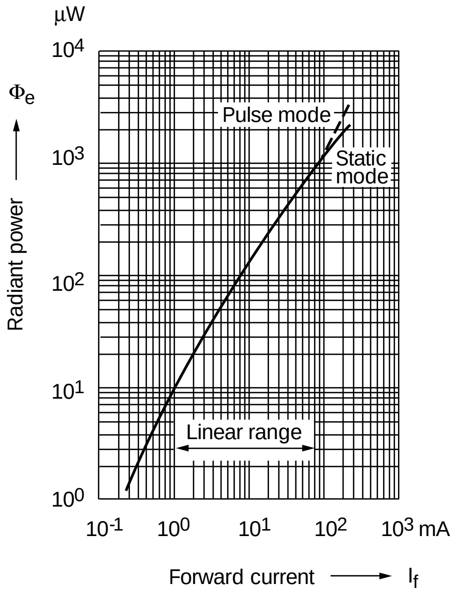


Figure 2.6 Radiant Power versus Forward Current

perature coefficient is – 0.7% per degree for GaAs, – 0.8% per degree for GaAsP, and – 0.3% per degree for GaP. This is negligible for many applications. If the temperature dependence proves disturbing, it can widely be eliminated by compensation circuits.

The radiant power emitted by LEDs declines with increasing length of operation (“aging”). A “life” of components was introduced to describe the degree of degradation. It is defined as the time after which the radiant power has fallen to half the value. In the case of IREDs, for example, the average life dependent on the operating current and ambient temperature is approximately 10^5 h (extrapolated from continuous tests). Refer to Figure 2.7.

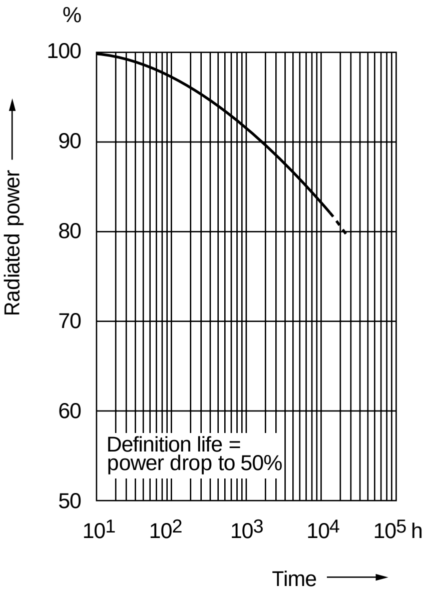


Figure 2.7 Radiated Power versus Operating Life

3. Measuring Technique

Detectors (Radiation Sensitive Components)

Radiation-sensitive semiconductor devices serve to convert radiation energy into an electrical one. Radiation energy can be offered to the component in manifold forms, depending on the source of radiation. For measuring purposes only such radiation sources can be taken into consideration which, in their spectral energy distribution, can easily be covered and are reproducible, i.e. thermic radiation sources like the tungsten filament lamp, which at least in the wavelength range here of interest comes very close to the black body and monochromatic light sources that means those emitting radiation of only one wavelength or at least of a very narrow wavelength range, above all light emitting diodes and a combination of whatever emitters with narrow band filters. Especially for applications with infrared emitting diodes (IREDs), this measurement of the spectral photosensitivity is increasingly gaining significance and is taking the place of integral measurement with standard light A. Because of its high energy, the tungsten filament lamp is mainly used for measuring the radiation sensitivity when set to a “color temperature” of 2856 K, corresponding to standard light A as per IEC306 -1 part 1 and DIN5033 while light emitting diodes are primarily employed for cut-off frequency and switching time measurements as they can be modulated or pulsed up to high frequencies. At this instance, we want to draw your attention to the following. The definition “color temperature” is limited in its use for the optoelectronic measuring technique, quasi only as auxiliary. But unfortunately the term has come to stay. In practice the lamps are not calibrated to color temperature but to “relative temperature in the visible range”, mostly to a green-red relation. An extension to a red-green-infrared relation and thus an approach to the, for our measuring technique solely correct, “distribution temperature” in the wavelength range 350 to 1200 nm, or even better 300 to 1800 nm, is worth aspiring after. This still meets with objections on the part of lamp manufacturers to extend their calibration equipment and the relatively small quantity of lamps required.

The tungsten filament lamps used for measuring purposes have to be set to a relative spectral energy distribution that corresponds to that of the black body at a temperature of normally 2856 K at least in the wavelength range 350 to 1200 nm, and have to be operated under very stable conditions. It is necessary to have the lamp operated with constant current, the deviation from the rated value must be kept less than ±0.1%. This requirement seems to be very high, but one has to consider that a deviation of the lamp current by 0.1% brings about a change of the radiant intensity by 0.7% and, of the color temperature, by 2 K. Naturally, the lamp can also be operated with constant voltage but this is hard to realize in practice because of the inevitable and varying contact resistances in the lamp socket, therefore an operation with constant current is to be preferred.

A lamp voltage check at the same time permits a control of the lamp with regard to a change in its characteristics, for example, by evaporating of coiled filament material which would point to the fact that the lamp is no longer suitable for measuring purposes and has either to be replaced or calibrated anew. This check is mainly recommended for the “standard lamps” which are standard for color temperature, radiant and/or luminous intensity.

For general measuring purposes, serial measurements in particular, the standard lamps gauged by the PTB or the manufacturer are usually not used because of the calibration costs. Therefore, the service lamps are set to the given ratings by a comparison with these standard lamps.

Photosensitivity

For photosensitivity measurements (photocurrent or photovoltage) the components to be measured are placed at the position predetermined for the specific irradiance and there they are held in such a way that the radiant sensitive surface of the semiconductor chip is vertical to the direction of light. Cylindric components such as in TO18, TO5 or similar plastic packages are put up so that the package axis coincide with the direction of radiation. This is of prime importance for components with a highly focusing lens. A holder with a sliding socket for the terminal wires proved useful (see Figure 3.1).

Solid Angle

The solid angle is a part of space. It is limited by all the beams which radiate conically from one point (radiation source) and which end on a closed curve in the space. If this closed curve lies on the unitary sphere (radius R = 1 m) and envelopes an area of 1 m^2, and if all rays originate from the center point of the unitary sphere, the solid angle has one sterad (sr).

Short-circuit Current

When measuring the short-circuit current I_S of photovoltaic cells care has to be taken that the internal resistance of the measuring instrument used is small enough compared to the internal resistance of the photovoltaic cell. The same applies to measuring the open circuit, the internal resistance of the measuring instrument is large compared to the internal resistance of the photovoltaic cell.

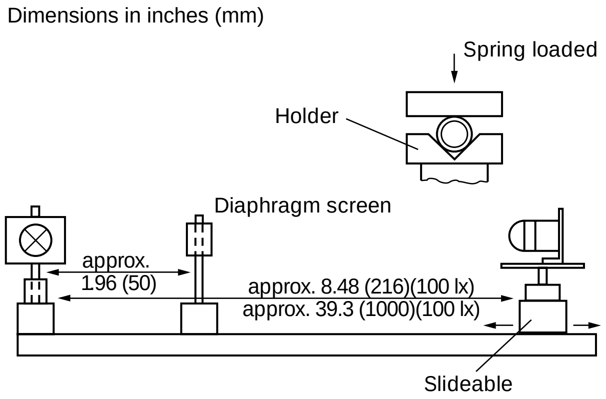


Figure 3.1 Ip Test Set-up for Photoelectric Devices

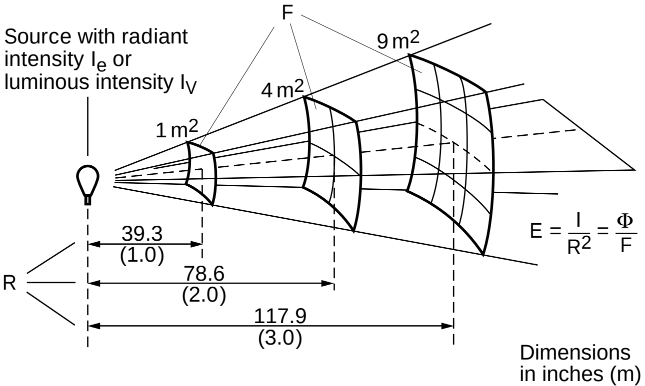


Figure 3.2 Solid Angle (1 sterad)

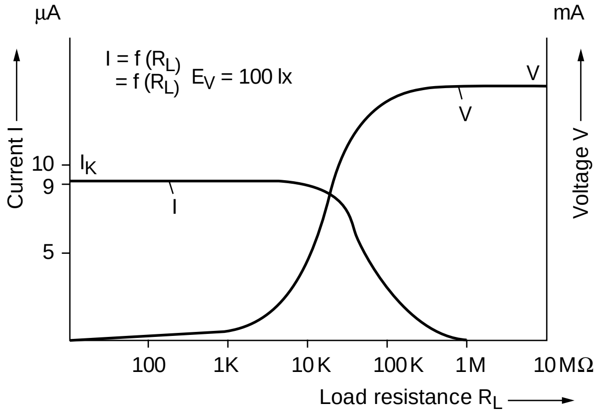


Figure 3.3 I or V versus Load Resistance for Photovoltaic Cell BPY11

Switching Times

The switching times are measured oscillographically by a set-up as shown in the circuit diagram below (Figure 3.4) by means of a pulsed infrared emitting GaAs diode as a measuring source and a double-beam oscillograph. The switching times of the GaAs must, of course, be small compared to the switching times of the component to be measured.

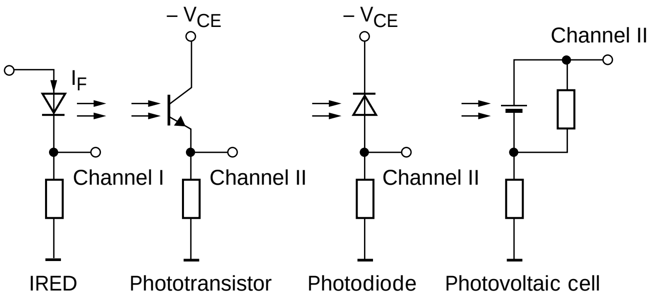
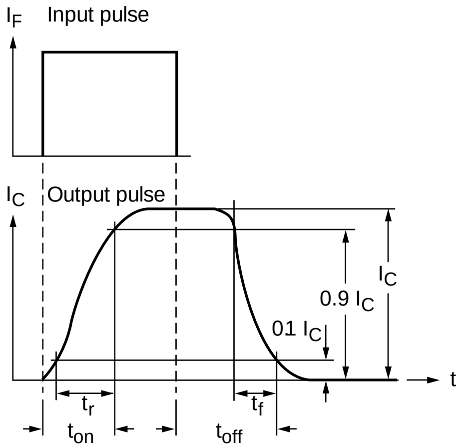


Figure 3.4 “Measuring the Switching Times of Detectors”



Turn-on time t_{on}:
The time in which the collector current I_C rises to 90% of its maximum value after activation of the drive current I_F.

Rise time t_r:
The time in which the collector current I_C rises from 10% to 90% of its final value.

Turn-off time t_{off}:
The time in which the collector current I_C drops to 10% of its maximum value after deactivation of the drive current I_F.

Fall time t_f:
The time in which the collector current I_C drops from 90% to 10% of its maximum value.

Figure 3.5 Switching Time Definitions

Radiation in the Infrared Range

The radiant intensity I_e in the direction of the case axis should be measured by a wavelength independent detector (thermocouple element) but low sensitivity, inertia, and temperature sensitivity cause difficulties. For this reason, one usually measures with a correspondingly calibrated photovoltaic cell. In such case, the spectral sensitivity curve of the photovoltaic cell has to be considered and the measuring result corrected with regard to the deviations in the emitted wavelength of the radiator to be measured (for example IRED with different production technology). If the total radiation of the component shall be measured, the IRED has to be fitted in a parabolic like reflector to ensure that all radiation emitted by the component reaches the photovoltaic cell that forms the end of the parabola.

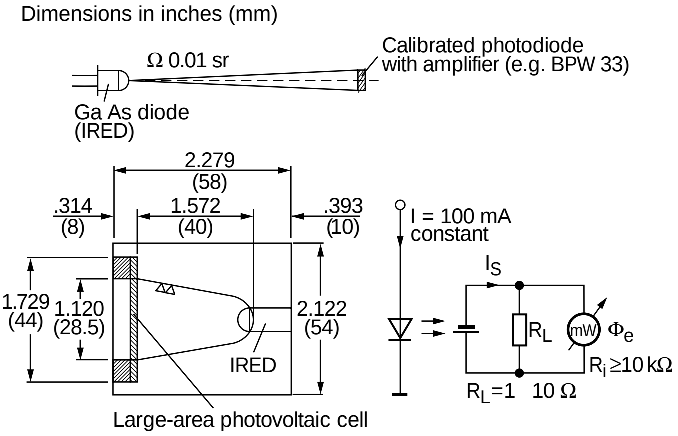


Figure 3.6 Calibrated Photodiode with Amplifier (for example BPW33)

Figure 3.6 shows the outline of such a measuring parabola. As for the rest, the same requirements apply as for radiant intensity measurements.

In cases where IRED emitting diodes are used in connection with mirrors or lenses, for example in light barriers, it can prove useful to state the radiant power (radiation capacity) Φ_e defined in a cone with the half angle φ, or the curve $\Phi_e = f(\varphi)$, respectively (see Figure 3.7).

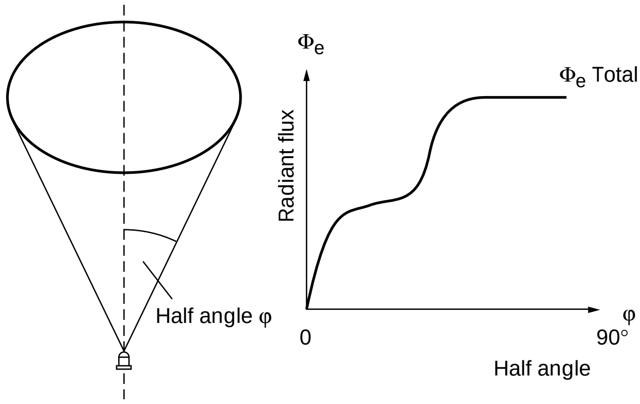
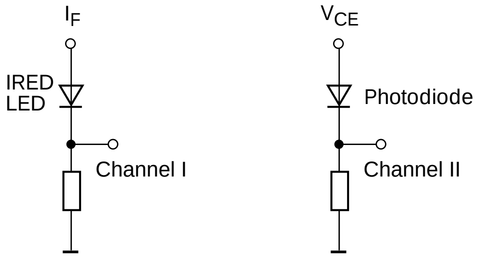


Figure 3.7 Radiation Cone and Radiant Flux Φ_e versus Half Angle

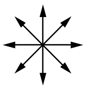
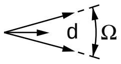
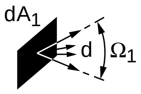
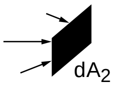
Switching Times

For measuring the switching times the same applies as to the radiant sensitive components except that now a photodiode serves as detector and its switching time must be small compared to that of the IRED or LED to be measured.

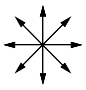
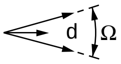
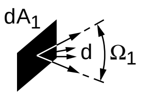
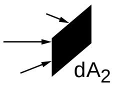


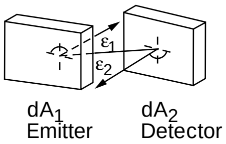
4. Terms and Definitions

Radiation and Light Measurement

	Radiometric terms				
No.	Term	Sym-bol	Unit	Relation	Simplified definition
1 	Radiant power	Φ_e, P	W		Radiant power is the total power given in the form of radiation
	Emitter				
2 	Radiant intensity	I_e	$\frac{W}{sr}$	$I_e = \frac{d\Phi_e}{d\Omega_1}$	Radiant intensity is radiant power per solid angle
3 	Radiance	L_e	$\frac{W}{m^2\,sr}$	$L_e = \frac{d^2\Phi_e}{dA_1 \cdot d\Omega_1}$	Radiance is radiant power per area and solid angle
	Sensor				
4 	Irradiance	E_e	$\frac{W}{m^2}$	$E_e = \frac{d\Phi_e}{dA_2}$	Irradiance is incident radiant power per (sensor) surface

Indices “e” (= energetic) and “v” (= visual) may be omitted unless danger of confusion
DIN 1301, DIN 1304, DIN 5031, DIN 5496
International Dictionary of Light Engineering, 3rd Ed. publ. by CIE and IEC

	Spectral Radiometric terms			Photometric terms		
No.	Term	Sym-bol	Unit	Term	Sym-bol	Unit
1 	Spectral radiant power distribution	$\Phi_{e\lambda}$	$\frac{W}{nm}$	Luminous flux	Φ_v	lm Lumen
	Emitter					
2 	Spectral radiant intensity distribution	$I_{e\lambda}$	$\frac{W}{sr\ nm}$	Luminous intensity	I_v	$\frac{lm}{sr} = cd$ Candela
3 	Spectral radiance distribution	$L_{e\lambda}$	$\frac{W}{cm^2 sr\ nm}$	Luminance	L_v	$\frac{cd}{cm^2} = sb$ Stilb
	Sensor					
4 	Spectral irradiance distribution	$E_{e\lambda}$	$\frac{W}{m^2\ nm}$	Illuminance	E_v	$\frac{lm}{m^2} = lx$ Lux



dA_1 = element of area of emitter
dA_2 = element of area of detector
ε_1 = angle of radiation

Photometric Basic Law

$$d^2\Phi = L\frac{dA_1 \cdot \cos\varepsilon_1 \cdot dA_2 \cdot \cos\varepsilon_2}{R^2}\Omega_0$$

Inverse Square Law

$$E = \frac{I}{R^2}\cos\,\varepsilon_1\Omega_0$$

(r should be 10 times the max. spacing of emitter-detector to keep error below 1%).

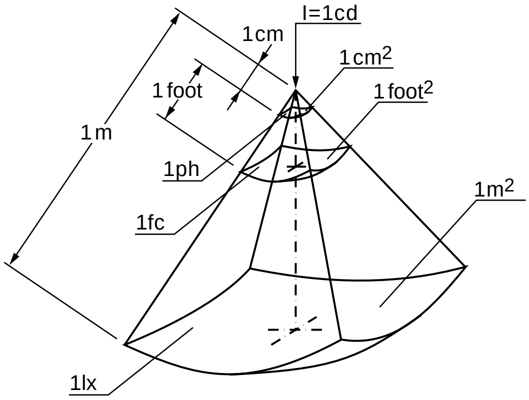
ε_2 = angle of irradiation
R = spacing emitter-detector
Ω_0 = sr

Radiation Characteristic

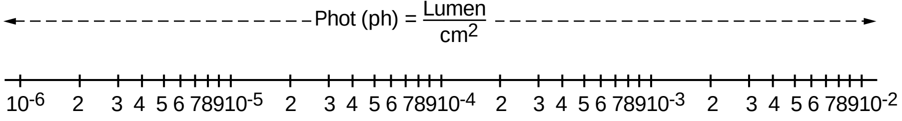
Designation	Symbol	Meas. quant.	Abbr.	Definition
Quantity of radiation	Q	Joule Wattsecond	J Ws	Quantity of radiation through a surface
Radiant power	Φ	Watt	W	Quantity of radiation Q per second through a surface
Point source of radiation	–	–	–	...is a source viewed from such a great distance R that all rays seem to emanate from one point. The max. linear expansion of the source must be substantially smaller than the distance R (example: sun for observer on earth).
Solid Angle	Ω	Sterad	sr	$\Omega = \frac{A_1}{R_1^2} = \frac{A_2}{R_2^2} = \frac{A_3}{R_3^2} = \frac{A}{R^2}$ the radiant power Φ[W] of a point source is constant in solid angle. (Prerequisite: homogenous, undamping medium.) $\Omega = 1$ is $A = R^2$ so that $\Omega_{\text{hemisphere}} = \Omega_{\frown} = 2\pi$ sr; $\Omega_{\text{full sphere}} = \Omega_{\ominus} = 4\pi$ sr
Radiant intensity	I	$\frac{\text{Watt}}{\text{sterad}}$	$\frac{\text{W}}{\text{sr}}$	...is the solid angle density of the radiant power $\left(\frac{d\Phi}{d\Omega}\right)$ I of one source generally varies depending upon viewing direction. I only defined when $R \rightarrow \infty$
Total radiant power of a source	Φ_{tot}	Watt	W	$\Phi_{tot} = \int_0^{4.7} I \, d\Omega$
Irradiance	E	$\frac{\text{Watt}}{\text{meter}^2}$	$\frac{\text{W}}{\text{m}^2}$	...is the surface density of the radiant power (spherical surface) for a point source. $E = \frac{d\Phi}{dA}$; $dA = R^2 \, d\Omega$ $E = \frac{d\Phi}{d\Omega \, R^2} = \frac{I}{R^2}$; $I = ER^2$
Radiance	L	$\frac{\text{Watt}}{\text{m}^2 \text{ sterad}}$	$\frac{\text{W}}{\text{m}^2 \text{ sr}}$	...is the radiant intensity referred to the radiant surface viewed by the observer. (Surface projection $A_p = \cos\varepsilon$, when ε is the angle by which the radiant surface is rotated against the connecting line to viewer. $L = \frac{I}{A_p} = \frac{I}{A\cos\varepsilon}$). Important optical quantity. 1) In an undamped beam path L is maintained and cannot be increased by any optical measure 2) The human eye sees differences in radiance as differences in brightness.
Sensitivity of detector	$S = \frac{I}{E}$	$\frac{\text{Ampere}}{\text{irradiance}}$	$\frac{\text{A} \cdot \text{m}^2}{\text{W}}$	Electrical quantity (current, voltage or resistance) in relation to irradiance

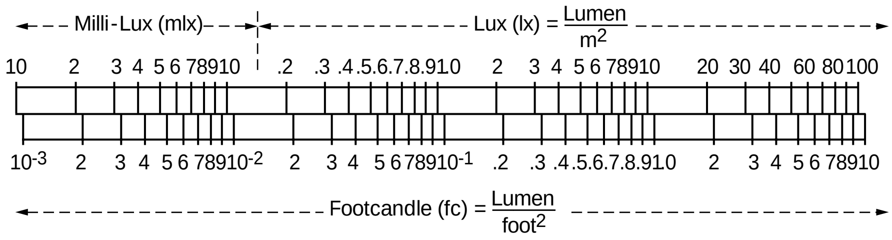
Illuminance (Units and Conversion Factors)

		lx	mlx	ph	fc
1 Lux = lx	=	1	10^{-3}	10^{-4}	9.29×10^{-2}
1 Millilux = mlx	=	10^{-3}	1	10^{-7}	9.29×10^{-5}
1 Phot = ph	=	10^{4}	10^{7}	1	929
1 Footcandle = fc1)	=	10.76	10760	1.076×10^{-3}	1



Illuminance





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1) equivalent footcandle / apparent footcandle } footlambert (Luminous density) $\hat{=}$ footcandle (illuminance).

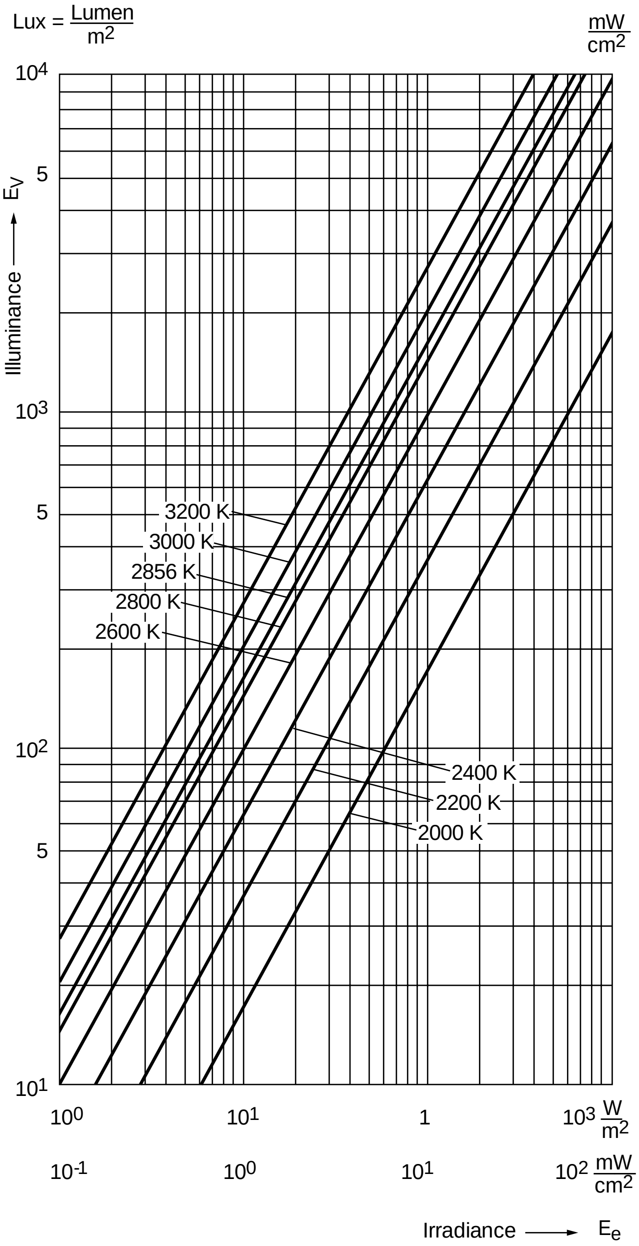


Figure 5.1 Conversion of Illuminance E_V into Irradiance E_e (Planck's Black Body)

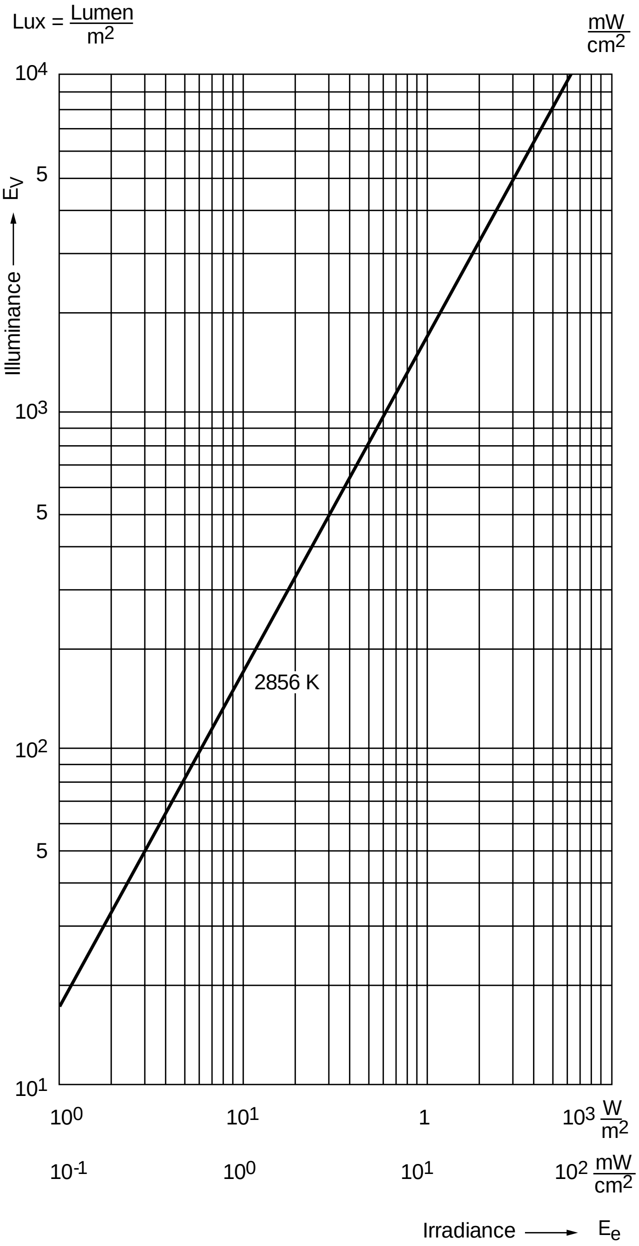
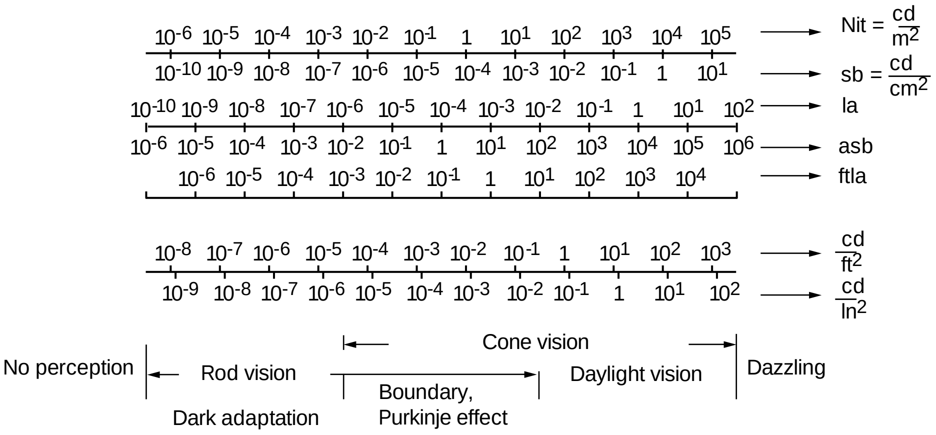


Figure 5.2 Conversion of Illuminance E_V into Irradiance E_e at 2856 K (Planck's Black Body)

Luminous Density (Units and Conversion Factors)

Units		sb	cd/m^2	cd/ft^2	cd/in^2	asb	L	Lm	ftL
1 Stilb = cd/cm^2 = sb	=	1	10^4	929	6.45	31400	3.14	3140	2920
1 cd/m^2 = Nit = nt	=	10^{-4}	1	9.29×10^{-2}	6.45×10^{-4}	3.14	3.14×10^{-4}	0.314	0.292
1 cd/ft^2	=	1.076×10^{-3}	10.76	1	6.94×10^{-3}	33.8	3.38×10^{-3}	3.38	3.14
1 cd/in^2	=	0.155	1550	144	1	4870	0.487	487	452
1 Apostilb = asb	=	3.18×10^{-5}	0.318	2.96×10^{-2}	2.05×10^{-4}	1	10-4	0.1	9.29×10^{-2}
1 Lambert = L or la	=	0.318	3183	296	2.05	10^4	1	10^3	929
1 mL or mla	=	3.18×10^{-4}	3.18	0.296	2.05×10^{-3}	10	10-3	1	0.929
1 footlambert	=								
1 equivalent footcandle	=								
1 apparent footcandle ftL or ftla	=	3.43×10^{-4}	3.43	0.318	2.21×10^{-3}	10.76	1.076×10^{-3}	1.076	1



Electromagnetic Radiation

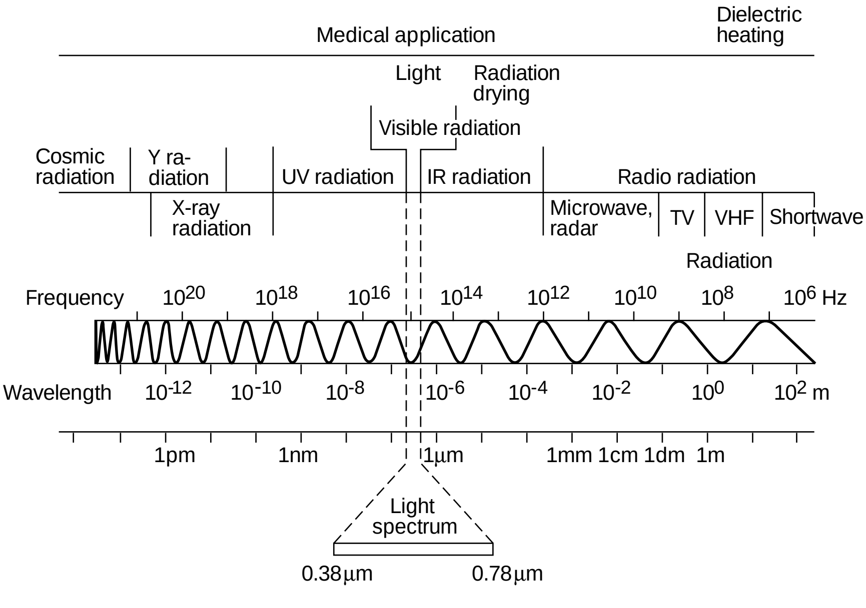


Figure 5.3 Frequency and Wave Bands

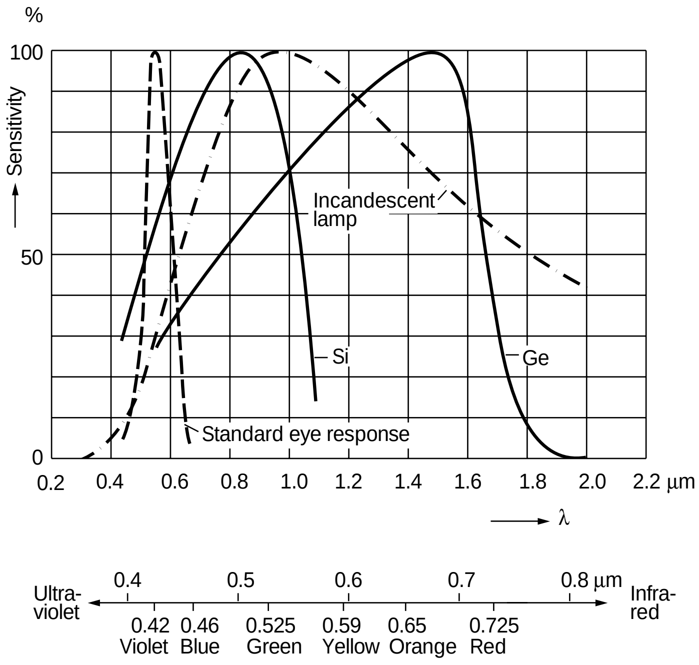


Figure 5.4 Relative Sensitivity of Different Light - sensitive Detectors

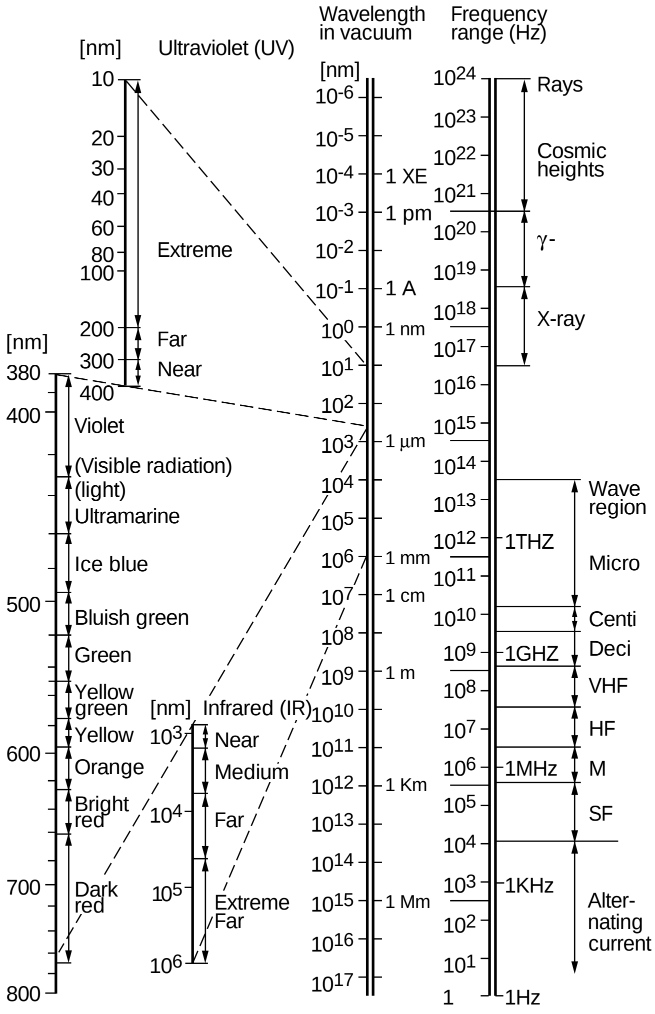


Figure 5.5 Nomogram for Electromagnetic Radiation

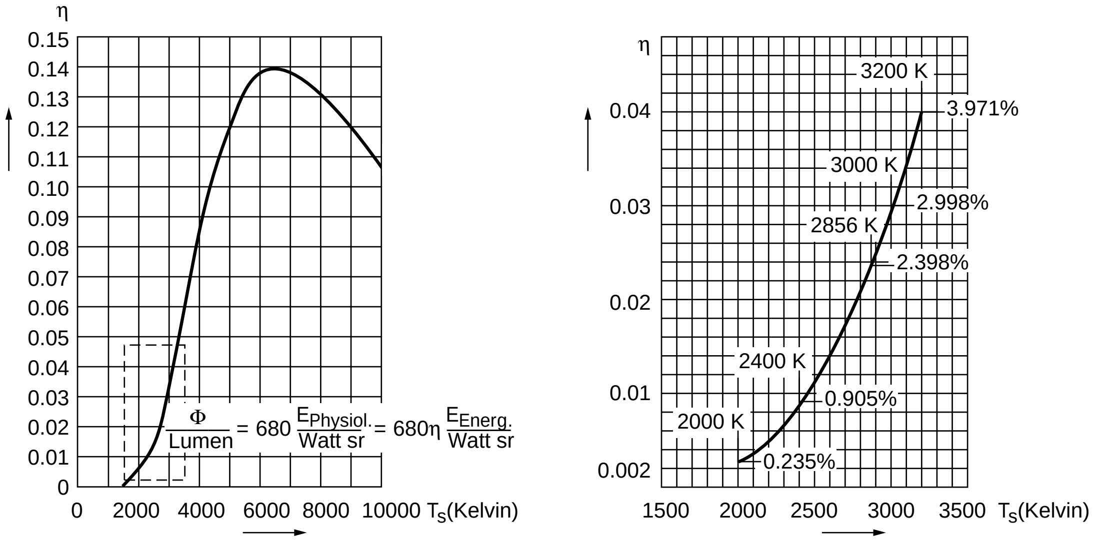


Figure 5.6 Visual Efficiency µ of the Total Radiation of a Black Body versus Temperature