Measurement Techniques

Introduction

Characteristics of optoelectronics devices given in data sheets are verified either by 100 % production tests followed by statistic evaluation or by sample tests on typical specimens. These tests can be divided into following categories:

- Dark measurements
- Light measurements
- Measurements of switching characteristics, cut-off frequency and capacitance
- Angular distribution measurements
- Spectral distribution measurements
- Thermal measurements.

Dark and light measurements limits are 100 % measurements. All other values are typical. Basic circuits used for these measurements are shown in following sections. Circuits may be modified slightly to cater for special measurement requirements.

Most of the test circuits may be simplified by use of a Source Measure Unit (SMU), which allows either to source voltage and measure current or to source current and measure voltage.

Dark and Light Measurements

Emitter Devices

IR diodes (GaAs)

Forward voltage, V_F, is measured either on a curve tracer or statically using the circuit shown in figure 1. A specified forward current (from a constant current source) is passed through device and voltage developed across it is measured on a high-impedance voltmeter.

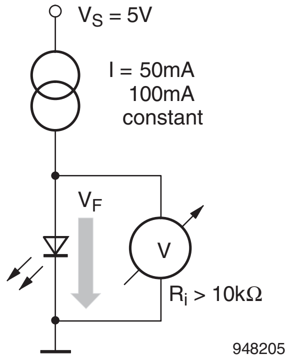

Figure 1.

To measure reverse voltage, V_R, a 10 µA or 100 µA reverse current from a constant current source is impressed through the diode (figure 2) and voltage developed across is measured on a voltmeter of high input impedance (≥ 10 MΩ).

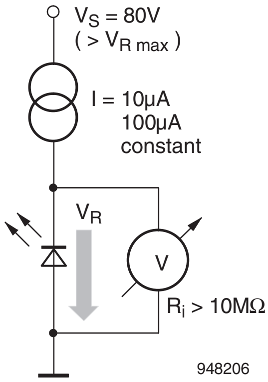

Figure 2.

For most devices, V_R is specified at 10 µA reverse current. In this case either a high impedance voltmeter has to be used, or current consumption of DVM has to be calculated and added to the specified current. A second measurement step will then give correct readings.

In case of GaAs IR diodes, total radiant output power, Φ_e, is usually measured. This is done with a calibrated large-area photovoltaic cell fitted in a conical reflector with a bore which accepts the test item – see figure 3. An alternative test set uses a silicon photodiode attached to an integrating sphere. A constant dc or pulsating forward current of specified magnitude is passed through the IR diode. Advantage of pulse-

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current measurements at room temperature (25 °C) is that results can be reproduced exactly.

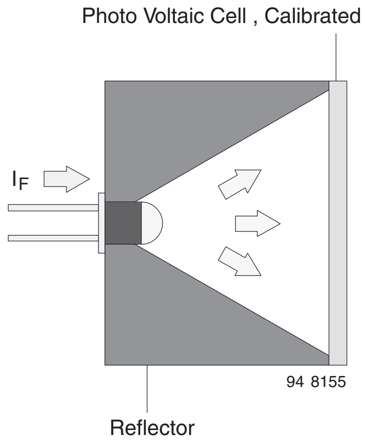


Figure 3.

If, for reasons of measurement economy, only dc measurements (figure 4) are to be made, then energizing time should be kept short (below 1 s) and of uniform duration, to minimize any fall-off in light output due to internal heating

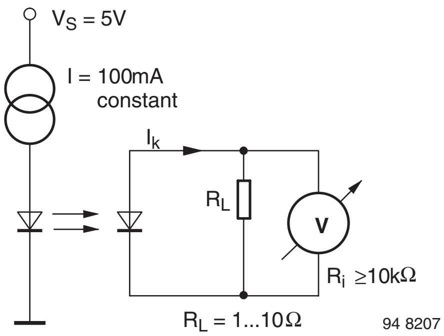


Figure 4.

To ensure that relationship between irradiance and photocurrent is linear, the photodiode should operate near short-circuit configuration. This can be achieved by using a low resistance load ($\leq$ 10 Ω) of such a value that voltage dropped across is very much lower than open circuit voltage produced under identical illumination conditions ($R_{meas} << R_i$). Voltage across load should be measured with a sensitive DVM.

Knowledge of radiant intensity, I_e, produced by an IR emitter enables customers to assess the range of IR light barriers. Measurement procedure for this is more or less the same as used for measuring radiant power. The only difference is that in this case the photodiode is used without a reflector and is mounted at a specified distance from, and on optical axis of, the IR diode (figure 5) so that only radiant power of a narrow axial beam is considered.

Radiant power within a solid angle of Ω = 0.01 steradian (sr) is measured at a distance of 100 mm. Radiant intensity is then obtained by using this measured value for calculating the radiant intensity for a solid angle of Ω = 1 sr.

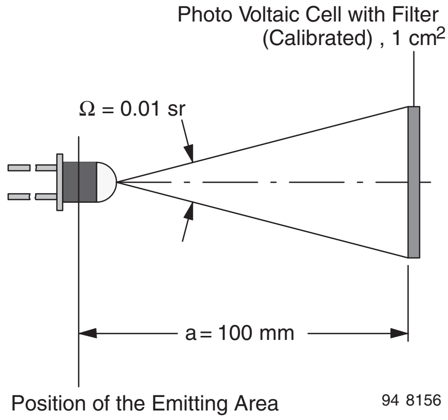


Figure 5.

Detector Devices
Photovoltaic cells, photodiodes

- Dark measurements

Reverse voltage characteristic, V_R, is measured either on a curve tracer or statically using the circuit shown in figure 6. A high-impedance voltmeter, which draws only an insignificant fraction of device's reverse current, must be used.

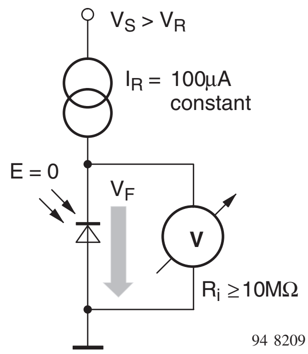


Figure 6.

Dark reverse current measurements, I_{ro}, must be carried out in complete darkness – reverse currents of silicon photodiodes are in the range of nanoamperes only, and an illumination of a few lux is quite sufficient to falsify the test result. If a highly sensitive DVM is to be used, then a current sampling resistor of such a value that voltage dropped across is small in comparison with supply voltage must be connected in series with the test item (figure 7). Under these conditions, any reverse voltage variations of the test samples can be ignored. Shunt resistance (dark resistance) is determined by applying very slight voltage to the photodiode and then measuring dark current. In case of 10 mV or less, forward and reverse polarity will result in similar readings.

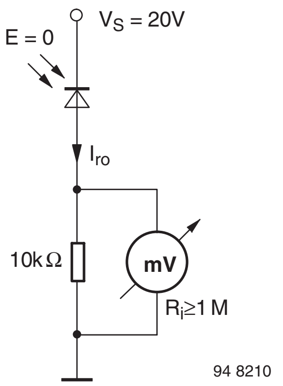


Figure 7.

- Light measurements

The same circuit as used in dark measurement can be used to carry out light reverse current, I_{ra}, measurements on photodiodes. The only difference is the diode is now irradiated and a current sampling resistor of lower value must be used (figure 8), because of higher currents involved.

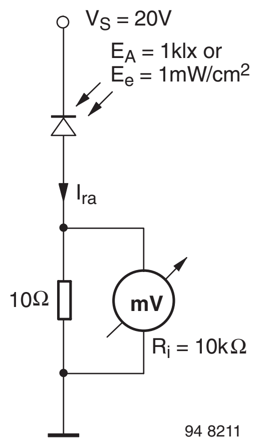


Figure 8.

Open circuit voltage, V_O, and short circuit current, I_k, of photovoltaic cells and photodiodes are measured by means of test circuit shown in figure 9. The value of load resistor used for I_k measurement should be chosen so that voltage dropped across is low in comparison with open circuit voltage produced under conditions of identical irradiation.

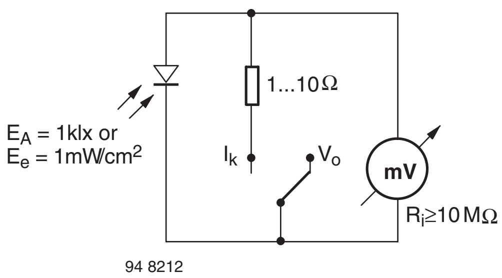


Figure 9.

Light source used for light measurements is a calibrated incandescent tungsten lamp with no filters.

Filament current is adjusted for a color temperature of 2856 K (standard illuminant A to DIN 5033 sheet 7), and specified illumination, E_v, (usually 100 or 1000 lux) is produced by adjusting the distance, a, between lamp and detector on an optical bench. E_v can be measured on a V(λ)-corrected luxmeter, or, if luminous intensity, I_v, of the lamp is known, E_v can be calculated using the formula: $E_v = I_v/a^2$.

It should be noted that this inverse square law is only strictly accurate for point light sources, that is for sources where dimensions of source (the filament) are small (≤ 10 %) in comparison with distance between source and detector.

Since lux is a measure for visible light only, near infrared radiation (800 to 1100 nanometers) where silicon detectors have their peak sensitivity, is not taken into account. Unfortunately, near infrared emission of filament lamps of various construction varies widely. As a result, light current measurements carried out with different lamps (but the same lux and color temperature calibration) may result in readings that differ up to 20 %.

The simplest way to overcome this problem is to calibrate (measure the light current) some items of a photodetector type with a standard lamp (OSRAM WI 41 / G) and then use these devices for adjustment of the lamp used for field measurements.

An IR diode is used as a radiation source (instead of tungsten incandescent lamp), to measure detector devices being used mainly in IR transmission systems together with IR emitters (e.g., IR remote control, IR headphone). Operation is possible both with dc or pulsed current.

Adjustment of irradiance, E_e, is similar to the above mentioned adjustment of illuminance, E_v. To achieve a high stability similar to filament lamps, consideration should be given to the following two points:

- IR emitter should be connected to a good heat sink to provide sufficient temperature stability.
- dc or pulse-current levels as well as pulse duration have great influence on self-heating of IR diodes and should be chosen carefully.
- Radiant intensity, I_e, of the device is permanently controlled by a calibrated detector.

Phototransistors, photodarlington transistors

Collector emitter voltage, V_{CEO}, is measured either on a transistor curve tracer or statically using the circuit shown in figure 10. Normal bench illumination does not change measured result.

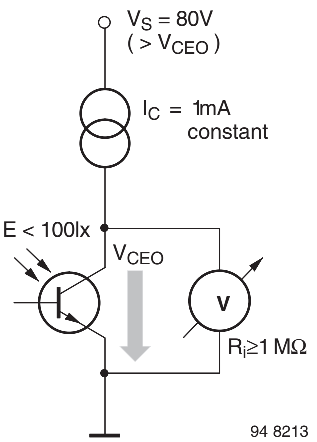


Figure 10.

In contrast, however, the collector dark current, I_{CEO} or I_{CO}, must be measured in complete darkness (figure 11). Even ordinary daylight illumination of the wire fed-through glass seals would falsify measurement result.

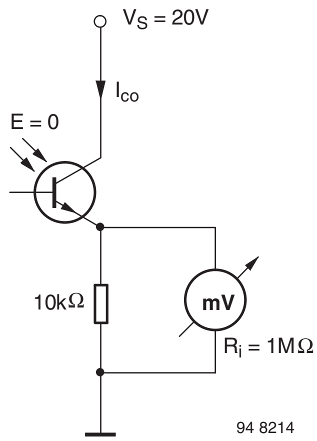


Figure 11.

The same circuit is used for collector light current, I_{ca}, measurements (figure 12). Optical axes of the device is aligned to an incandescent tungsten lamp with no filters, producing a standard-A illuminance of 100 or 1000 lx with a color temperature of T_f = 2856 K. Alternatively an IR irradiance by a GaAs diode is used (refer to the photovoltaic cells and photodiodes section). Note that a lower value sampling resistor is used, in keeping with the higher current involved.

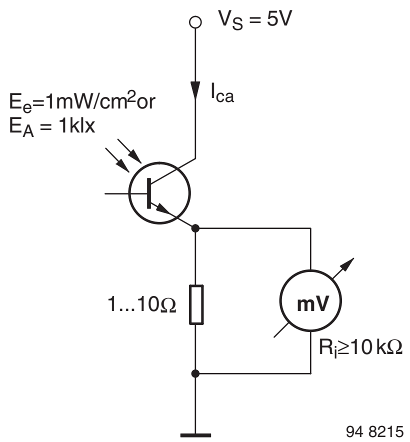


Figure 12.

To measure collector emitter saturation voltage, V_{CEsat}, the device is illuminated and a constant collector current is passed through. The magnitude of this current is adjusted below level of minimum light current, $I_{ca\ min}$, for the same illuminance (figure 13). Saturation voltage of the phototransistor or Darlington stage (approximately 100 mV or 600 mV, respectively) is then measured on a high impedance voltmeter.

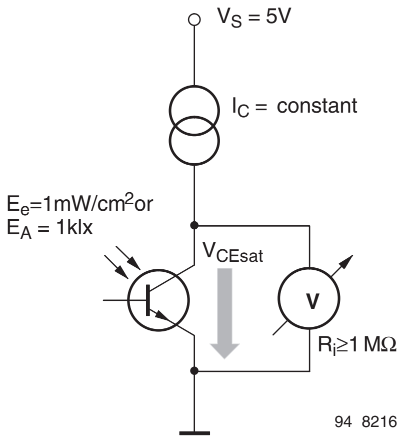


Figure 13.

Switching Characteristics

Definition

Each electronic device generates a certain delay between input and output signals as well as a certain amount of amplitude distortion. A simplified circuit (figure 14) shows how input and output signals of optoelectronic devices can be displayed on a dual-trace oscilloscope.

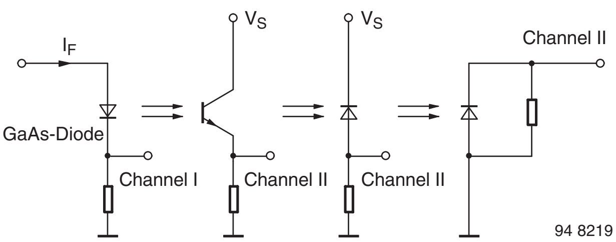
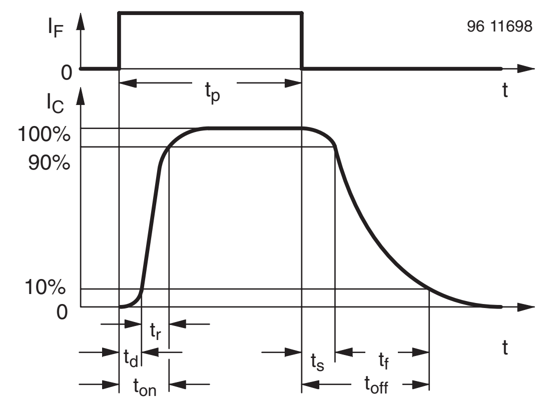


Figure 14.

The switching characteristics can be determined by comparing timing of output current waveform with input current waveform (figure 15).



t_p	pulse duration	t_s	storage time
t_d	delay time	t_f	fall time
t_r	rise time	t_{off} (= $t_s + t_f$)	turn-off time
t_{on} (= $t_d + t_r$)	turn-on time		

Figure 15.

These time parameters also include the delay existing in a luminescence diode between forward current (I_F) and radiant power Φ_e).

Notes Concerning the Test Set-up

Circuits used for testing IR emitting, emitting sensitive and optically coupled isolator devices are basically the same (figure 14). The only difference is the way on which test device is connected to the circuit.

It is assumed that rise and fall times associated with signal source (pulse generator) and dual trace oscilloscope are insignificant, and that switching characteristics of any radiant sensitive device used in set-up are considerably shorter than those of test item. Switching characteristics of IR emitters, for example ($t_r \approx$ 10 to 1000 ns) are measured with aid of a PIN Photodiode detector ($t_r \approx$ 1 ns).

Photo- and darlington transistors and photo- and solar cells ($t_r \approx$ 0.5 to 50 µs) are, as a rule, measured by use of fast IR diodes (t_r < 30 ns) as emitters.

Red light-emitting diodes are used as light sources only for devices which cannot be measured with IR diodes because of their spectral sensitivity (e.g. BPW21R). These diodes emit only 1/10 of radiant power of IR diodes and consequently generate only very low signal levels.

Switching Characteristic Improvements on Phototransistors and Darlington Phototransistors

As in any ordinary transistor, switching times are reduced if drive signal level, and hence collector current, is increased. Another time reduction (especially in fall time t_f) can be achieved by use of a suitable

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base resistor, assuming there is an external base connection, although this can only be done at the expense of sensitivity.

Technical Description – Assembly

Emitter

Emitters are manufactured using the most modern Liquid Phase Epitaxy (LPE) process. By using this technology, the number of undesirable flaws in crystal is reduced. This results in a higher quantum efficiency and thus higher radiation power. Distortions in crystal are prevented by using mesa technology which leads to lower degradation. A further advantage of the mesa technology is that each individual chip can be tested optically and electrically even on the wafer.

Detector

Vishay Semiconductor detectors have been developed to match perfectly to emitters. They have low capacitance, high photosensitivity and extremely low saturation voltage.

Silicon nitride passivation protects surface against possible impurities.

Assembly

Components are fitted onto lead frames by fully automatic equipment using conductive epoxy adhesive. Contacts are established automatically with digital pattern recognition using well-proven thermosonic technique. All component are measured acc. compliance of parameter limits confirmed in data sheet.

Applications

Silicon photodetectors are used in manifold applications, such as sensors for radiation from near UV over visible to near infrared. There are numerous applications in measurement of light, such as dosimetry in UV, photometry, and radiometry. A well known application is shutter control in cameras.

Another large application area for detector diodes and especially phototransistors, is position sensing.

Examples are differential diodes, optical sensors, and reflex sensors.

Other types of silicon detectors are built-in as parts of optocouplers.

One of the largest application area is remote control of TV sets and other home entertainment appliances.

Different applications require specialized detectors and also special circuits to enable optimized functioning.

Equivalent circuit

Photodetector diodes can be described by electrical equivalent circuit shown in figure 16.

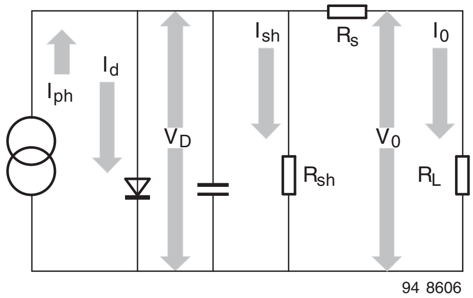


Figure 16.

$$I_O = I_{ph} - I_D - I_{sh} \quad (1)$$

$$I_O = I_{ph} - I_s\left(\exp\frac{qV_D}{kT} - 1\right) - I_{sh}$$

$$V_{OC} = V_T \times \ln\left(\frac{s(\lambda) \times \phi_e - I_{sh}}{I_s} + 1\right) \quad (2)$$

As described in chapter 'I-V Characteristics of illuminated pn junction', the incident radiation generates a photocurrent loaded by a diode characteristic and load resistor, R_L. Other parts of the equivalent circuit (parallel capacitance, C, combined from junction, C_j, and stray capacitances, serial resistance, R_S, and shunt resistance, R_{sh}, representing an additional leakage) can be neglected in most of standard applications, and are not expressed in equations 5 and 7 (see „Physics and Technology“). However, in applications with high frequencies or extreme irradiation levels, these parts must be regarded as limiting elements.

Searching for the right detector diode type

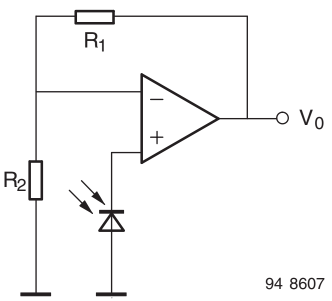
Photodiode BPW 20 RF is based on rather highly doped n-silicon, while BPW34 is a PIN Photodiode based on very lightly doped n-silicon. Both diodes have the same active area and spectral response as a function of wavelength is very similar. These diodes differ in the junction capacitance and shunt resistance. Both can influence performance of the application.

Detecting very small signals is the domain of Photodiodes with their very small dark currents and dark/shunt resistances.

With a specialized detector technology, these parameters are very well controlled in all Vishay photodetectors.

Very small leakage currents of Photodiodes are offset by higher capacitances and smaller bandwidths in comparison to PIN Photodiodes.

Photodiodes are often operated in photovoltaic mode (especially in light meters), as depicted in circuit of figure 17, where a strong logarithmic dependence of open circuit voltage on input signal is used.



$$V_O \approx V_{OC} \times [1 + R_1 / R_2] \text{ with} \quad (3)$$

$$V_{OC} = V_T \times \ln(s(\lambda) \times \phi_e / I_s + 1) \quad (2)$$

Figure 17. Photodiode in the photovoltaic mode operating with a voltage amplifier

It should be noted that extremely high shunt/dark resistance (more than 15 GΩ) combined with a high-impedance operational amplifier input and a junction capacitance of about 1 nF can result in slow switch-off time constants of some seconds. Some instruments therefore have a reset button for shortening the diode before starting a measurement.

Photovoltaic mode of operation for precise measurements should be limited to the range of low ambient temperatures, or a temperature control of the diode (e.g., using a Peltier cooler) should be applied. At high temperatures, dark current is increased (see figure 18) leading to a non-logarithmic and temperature dependent output characteristic (see figure 19). Curves shown in figure 18 represent typical behavior of these diodes. Guaranteed leakage (dark reverse current) is specified with I_{ro} = 30 nA for standard types. This value is far from that one which is typically measured. Tighter customer specifications are available on request. Curves of figure 19 show open circuit voltage as a function of irradiance with dark reverse current, I_S, as parameter (in a first approximation increasing I_S and I_{sh} have the same effect). The parameter shown cover possible spread of dark current. In combination with figure 18 one can project the extreme dependence of open circuit voltage at high temperatures (figure 20).

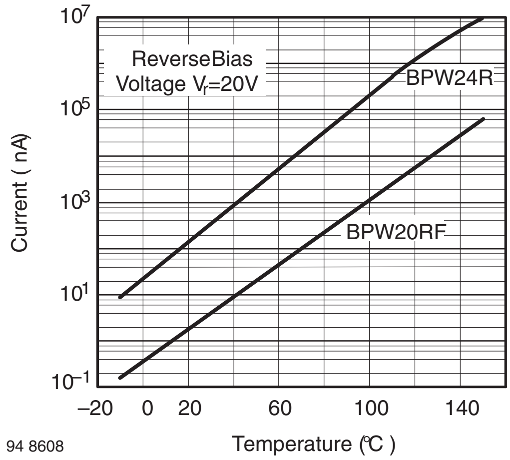


Figure 18. Reverse dark current vs. temperature

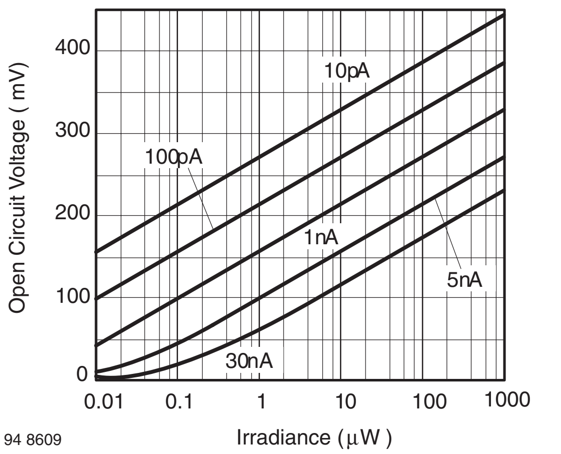


Figure 19. Open circuit voltage vs. irradiance, parameter: dark reverse current, BPW20RF

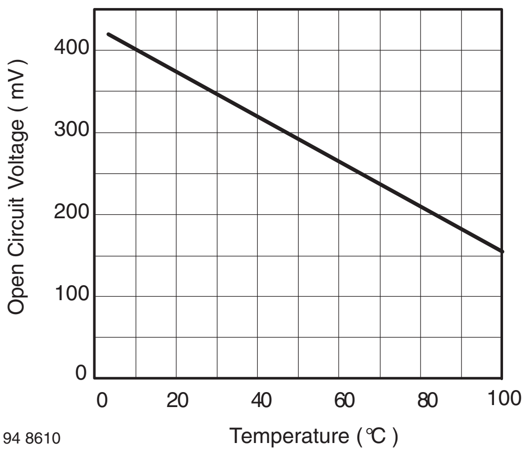


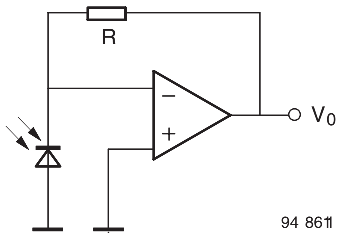
Figure 20. Open circuit voltage vs. temperature, BPW46

Operating modes and circuits

Advantages and disadvantages of operating a photodiode in open circuit mode have been discussed.

For operation in short circuit (see figure 21) or photoconductive (see figure 22) mode, current-to-voltage converters are typically used. In comparison with photovoltaic mode, temperature dependence of output signal is much lower. Generally temperature coefficient of light reverse current is positive for irradiation with wavelengths > 900 nm, rising with increasing wavelength. For wavelengths < 600 nm, a negative temperature coefficient is found, likewise with increasing absolute value to shorter wavelengths.

Between these wavelength boundaries the output is almost independent of temperature. By using this mode of operation, reverse biased or unbiased (short circuit conditions), output voltage, V_O, will be directly proportional to incident radiation, ϕ_e (see equation in figure 21).



$$V_O = -R \times \Phi_e \times s(\lambda) \quad (4)$$

$$V_O = -I_{sc} \times R \quad (5)$$

Figure 21. Transimpedance amplifier, current to voltage converter, short circuit mode

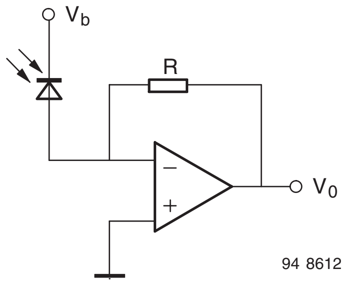


Figure 22. Transimpedance amplifier, current to voltage converter, reverse biased photodiode

Circuit in figure 21 minimizes the effect of reverse dark current while circuit in figure 22 improves the speed of detector diode due to a wider space charge region with decreased junction capacitance and field increased velocity of the charge carrier transport.

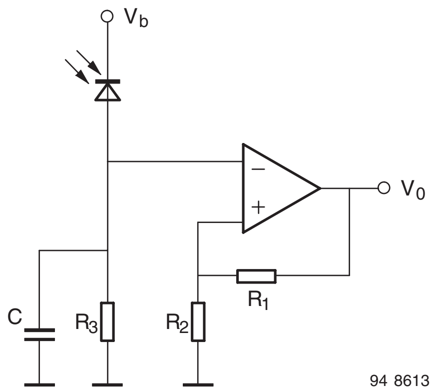
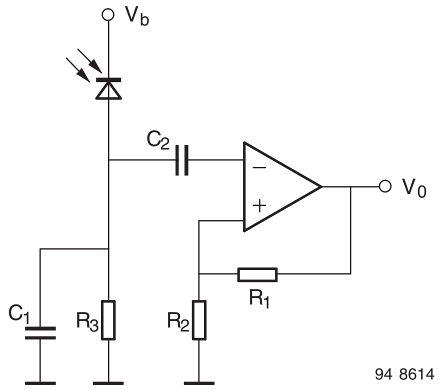


Figure 23. RC-loaded photodiode with voltage amplifier

Figure 23 shows photocurrent flowing into an RC load, where C represents junction and stray capacity while R_3 can be a real or complex load, such as a resonant circuit for the operating frequency.



$$V_O \approx \phi_e \times s(\lambda) \times R_3 \times [1 + R_1 / R_2] \quad (6)$$

Figure 24. AC-coupled amplifier circuit

Circuit in figure 24 is equivalent to figure 23 with a change to AC coupling. In this case, influence of background illumination can be separated from a modulated signal. Relation between input signal (irradiation, ϕ_e) and output voltage is given by the equation in figure 24.

Frequency response

Limitations of switching times in Photodiodes are determined by carrier lifetime. Due to absorption properties of silicon, especially in Photodiodes, most of incident radiation at longer wavelengths is absorbed outside space charge region. Therefore, a strong wavelength dependence of the switching times can be observed (figure 25).

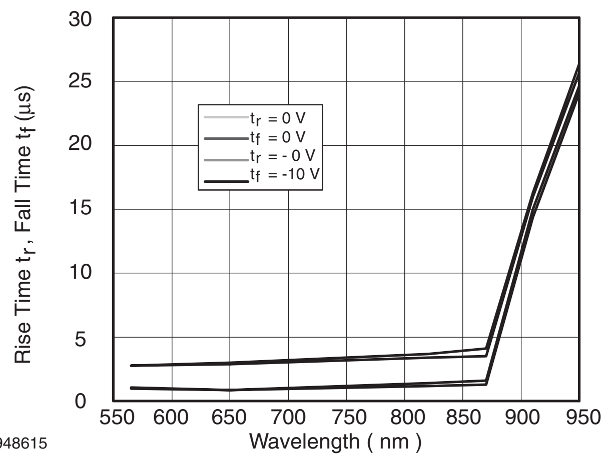


Figure 25. Switching times vs. wavelength for photodiode BPW20RF

A drastic increase in rise and fall times is observed at wavelengths > 850 nm. Differences between unbiased and biased operation result from widening of the space charge region.

However, for PIN Photodiodes (BPW34/ TEMD5000 family) similar results with shifted time scales are found. This behavior, in this case in frequency domain, is presented in figure 26 for a wavelength of 820 nm and figure 27 for 950 nm.

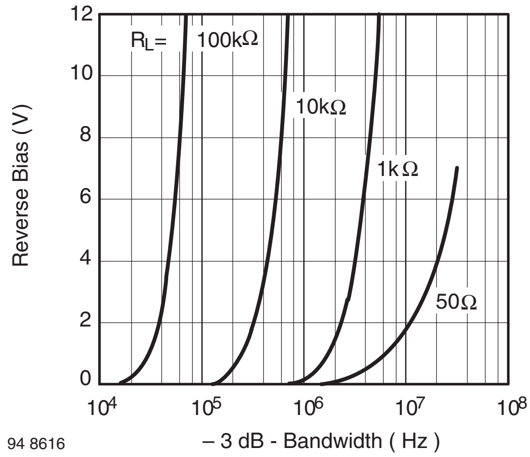


Figure 26. BPW34-family, bandwidth vs. reverse bias voltage, parameter: load resistance, λ = 820 nm

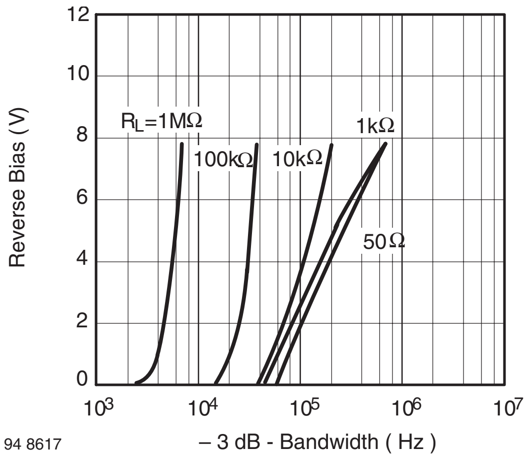


Figure 27. BPW41-family, bandwidth vs. reverse bias voltage, parameter: load resistance λ = 950 nm

Below about 870 nm, only slight wavelength dependence can be recognized, while a steep change of cut-off frequency takes place from 870 nm to 950 nm (different time scales in figure 26 and figure 27). Additionally, influence of load resistances and reverse bias voltages can be taken from these diagrams.

For cut-off frequencies greater 10–20 MHz, depending on the supply voltage available for biasing the detector diode, PIN Photodiodes are also used. However, for this frequency range, and especially when operating with low bias voltages, thin epitaxially grown intrinsic (i) layers are incorporated into PIN Photodiodes.

As a result, these diodes (e.g., Vishay's TESP5700) can operate with low bias voltages (3 to 4 V) with cut-off frequencies of 300 MHz at a wavelength of 790 nm. With application-specific optimized designs, PIN Photodiodes with cut-off frequencies up to 1 GHz at only a 3 V bias voltage with only an insignificant loss of responsivity can be generated.

Main applications for these photodiodes are found in optical local area networks operating in the first optical window at wavelengths of 770 nm to 880 nm.

Which type for which application?

In table 1, selected diode types are assigned to different applications. For more precise selection according to chip sizes and packages, refer to the tables in introductory pages of this data book.

Detector application	PIN Photodiode	Photodiode	epi PIN Photodiode
Photometry, light meter		BPW21R	
Radiometry	BPW34, ... BPW24R	BPW20RF	
Light barriers	BPW24R		
Remote control, IR filter included, λ > 900 nm	BPV20F, BPV23F, BPW41N, S186P, TEMD5100		
IR Data Transmission fc < 10 MHz IR filter included, λ > 820 nm	BPV23NF, BPW82, BPW83, BPV10NF, TEMD1020/ 5100		
IR Data Transmission, fc > 10 MHz, no IR filter	BPW34, BPW46, BPV10, TEMD5000		TESP5700
Fiber optical receiver	frequencies < 20 MHz BPW24R		high frequencies TESP5700
Densitometry	BPW34, BPV10, TEMD5000	BPW20RF, BPW21R	
Smoke detector	BPV22NF, BPW34, TEMD5000		

Table 1: Photodiode reference table

Phototransistor Circuits

A phototransistor typically operates in a circuit shown in figure 28. Resistor R_B can be omitted in most applications. In some phototransistors, base terminal is not connected. R_B can be used to suppress background radiation by setting a threshold level (see equation 7 and 8)

$$V_O = V_S - B \times \phi_e \times s(\lambda) \times R_L \quad (7)$$
$$V_O \approx V_S - (B \times \phi_e \times s(\lambda) - 0.6/R_B) \times R_L \quad (8)$$

For the dependence of rise and fall times on load resistance and collector-base capacitance we refer on chapter 'Properties of Silicon Phototransistors'.

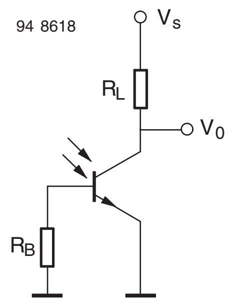


Figure 28. Phototransistor with load resistor and optional base resistor