**AN-440**
**Application Note**

# THEORY AND CHARACTERISTICS OF PHOTOTRANSISTORS

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A brief history of the photo-electric effect is discussed, followed by a comprehensive analysis of the effect in bulk semiconductors, pn junctions and phototransistors. A model is presented for the phototransistor. Static and transient data for the MRD300 provide typical phototransistor characteristics. Appendices provide a discussion of the relationship of irradiation and illumination and define terms specifically related to phototransistors.

***MOTOROLA Semiconductor Products Inc.***

# THEORY AND CHARACTERISTICS OF PHOTOTRANSISTORS

## INTRODUCTION

Phototransistor operation is based on the sensitivity of a pn junction to radiant energy. If radiant energy of proper wave-length is made to impinge on a junction, the current through that junction will increase. This optoelectronic phenomenon has provided the circuit designer with a device for use in a wide variety of applications. However, to make optimum use of the phototransistor, the designer should have a sound grasp of its operating principles and characteristics.

## HISTORY

The first significant relationships between radiation and electricity were noted by Gustav Hertz in 1887. Hertz observed that under the influence of light, certain surfaces were found to liberate electrons. This photo-emissive effect was put into theory by Max Planck in 1900. He proposed that light of a frequency f contained energy bundles or packets, which he called photons. Furthermore, the energy content of each photon was directly proportional to the light frequency:

$$E = hf, \qquad (1)$$

where E is the photon energy,
h is Planck's constant, and
f is the light frequency.

Planck theorized that a metal had associated with it a work function, or binding energy for free electrons. If a photon could transfer its energy to a free electron, and that energy exceeded the work function, the electron could be liberated from the surface. The presence of an electric field could enhance this by effectively reducing the work function. Einstein extended Planck's findings by showing that the velocity, and hence the momentum of an emitted electron, depended on the work function and the light frequency.

## PHOTO EFFECT IN SEMICONDUCTORS

### Bulk Crystal

If light of proper wavelength impinges on a semiconductor crystal, the concentration of charge carriers is found to increase. Thus, the crystal conductivity will increase:

$$\sigma = q\,(\mu_e n + \mu_h p), \qquad (2)$$

where $\sigma$ is the conductivity,
q is the electron charge,
$\mu_e$ is the electron mobility,
$\mu_h$ is the hole mobility,
n is the electron concentration, and
p is the hole concentration.

The process by which charge-carrier concentration is increased is shown in Figure 1. The band structure of the semiconductor is shown, with an energy gap, or forbidden region, of Eg electron volts. Radiation from two light sources is shown striking the crystal. Light frequency $f_1$ is sufficiently high that its photon energy, $hf_1$, is slightly greater than the energy gap. This energy is transferred to a bound electron at site one in the valence band, and the electron is excited to a higher energy level, site one in the conduction band, where it is free to serve as a current carrier. The hole left behind at site one in the valence band is also free to serve as a current carrier.

The photon energy of the lower-frequency light, $hf_2$, is less than the band gap, and an electron freed from site two in the valence band will rise to a level in the forbidden region, only to release this energy and fall back into the valence band and recombine with a hole at site three.

The above discussion implies that the energy gap, Eg, represents a threshold of response to light. This is true, however, it is not an abrupt threshold. Throughout the photo-excitation process, the law of conservation of mo-

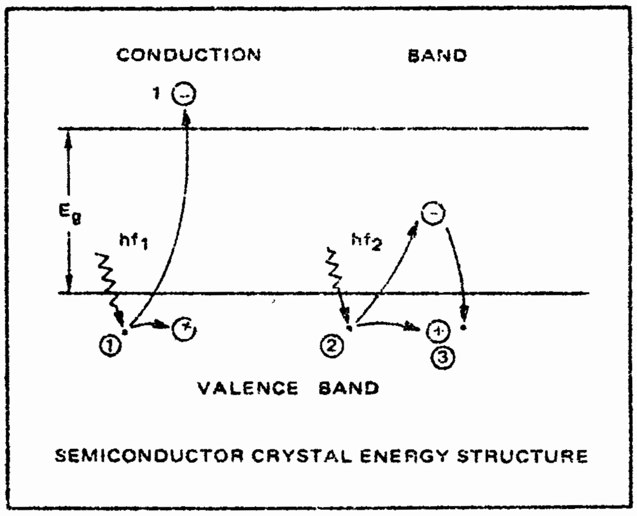

FIGURE 1 – Photoeffect in a Semiconductor

mentum applies. The momentum and density of hole-electron sites are highest at the center of both the valence and conduction bands, and fall to zero at the upper and lower ends of the bands. Therefore, the probability of an excited valence-band electron finding a site of like momentum in the conduction band is greatest at the center of the bands and lowest at the ends of the bands. Consequently, the response of the crystal to the impinging light is found to rise from zero at a photon energy of Eg electron volts, to a peak at some greater energy level, and then to fall to zero again at an energy corresponding to the difference between the bottom of the valence band and the top of the conduction band.

The response is a function of energy, and therefore of frequency, and is often given as a function of reciprocal frequency, or, more precisely, of wave length. An example is shown in Figure 2 for a crystal of cadmium-selenide. On the basis of the information given so far, it would seem reasonable to expect symmetry in such a curve; however, trapping centers and other absorption phenomena affect the shape of the curve[1].

The optical response of a bulk semiconductor can be modified by the addition of impurities. Addition of an acceptor impurity, which will cause the bulk material to become p-type in nature, results in impurity levels which lie somewhat above the top of the valence band. Photoexcitation can occur from these impurity levels to the conduction band, generally resulting in a shifting and reshaping of the spectral response curve. A similar modification of response can be attributed to the donor impurity levels in n-type material.

## PN Junctions

If a pn junction is exposed to light of proper frequency, the current flow across the junction will tend to increase. If the junction is forward-biased, the net increase will be relatively insignificant. However, if the junction is reverse-biased, the change will be quite appreciable. Figure 3 shows the photo effect in the junction for a frequency well within the response curve for the device.

Photons create hole-electron pairs in the crystal on both sides of the junction. The transferred energy promotes the electrons into the conduction band, leaving the holes in the valence band. The applied external bias provides an electric field, $\mathcal{E}$, as shown in the figure. Thus the photo-induced electrons in the p-side conduction band will flow down the potential hill at the junction into the n-side and from there to the external circuit. Likewise, holes in the valence band of the n-side will flow across the junction into the p-side where they will add to the external current.

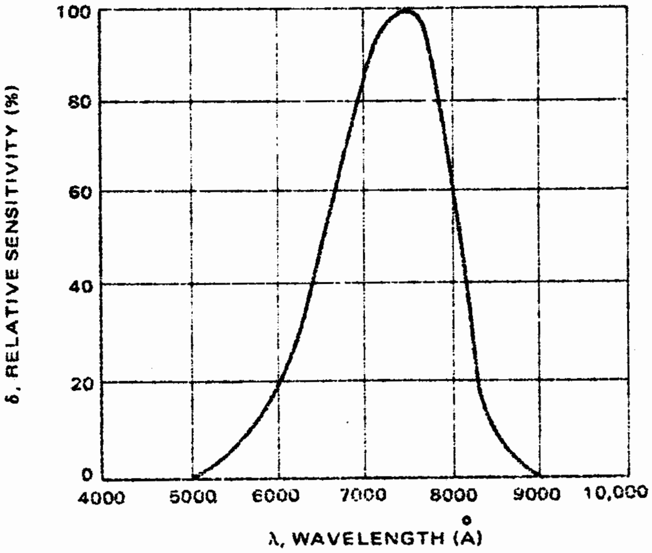

FIGURE 2 – Spectral Response of Cadmium Selenide

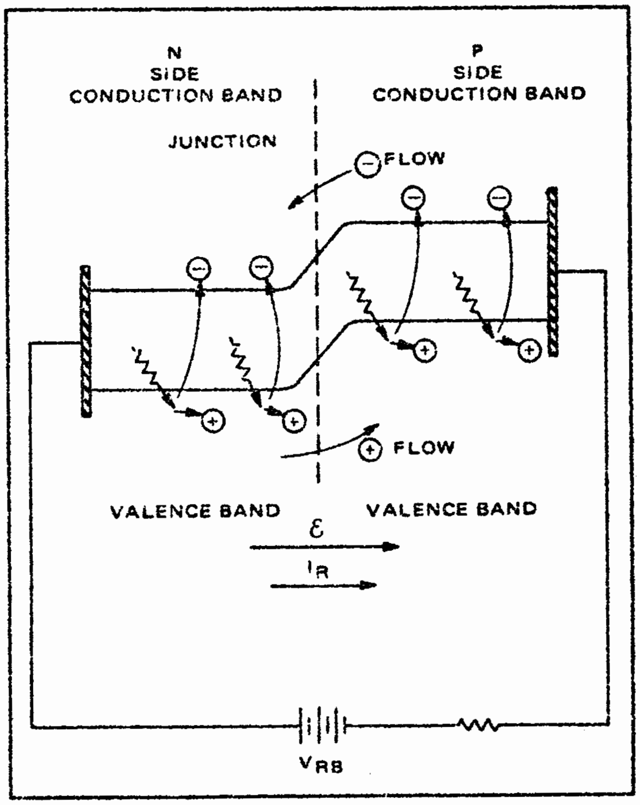

FIGURE 3 – Photo Effect in a Reverse-Biased PN Junction

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[1] See references for a detailed discussion of these.

Under dark conditions, the current flow through the reverse-biased diode is the reverse saturation current, $I_O$. This current is relatively independent of the applied voltage (below breakdown) and is basically a result of the thermal generation of hole-electron pairs.

When the junction is illuminated, the energy transferred from photons creates additional hole-electron pairs. The number of hole-electron pairs created is a function of the light intensity.

For example, incident monochromatic radiation of H (watts/cm$^2$) will provide P photons to the diode:

$$P = \frac{\lambda H}{hc}, \qquad (3)$$

where $\lambda$ is the wavelength of incident light,

h is Planck's constant, and

c is the velocity of light.

The increase in minority carrier density in the diode will depend on P, the conservation of momentum restriction, and the reflectance and transmittance properties of the crystal. Therefore, the photo current, $I_\lambda$, is given by

$$I_\lambda = \eta F q A, \qquad (4)$$

where $\eta$ is the quantum efficiency or ratio of current carriers to incident photons,

F is the fraction of incident photons transmitted by the crystal,

q is the charge of an electron, and

A is the diode active area.

Thus, under illuminated conditions, the total current flow is

$$I = I_O + I_\lambda. \qquad (5)$$

If $I_\lambda$ is sufficiently large, $I_O$ can be neglected, and by using the spectral response characteristics and peak spectral sensitivity of the diode, the total current is given approximately by

$$I \approx \delta S_R H, \qquad (6)$$

where $\delta$ is the relative response and a function of radiant wavelength,

$S_R$ is the peak spectral sensitivity, and

H is the incident radiation.

The spectral response for a silicon photo-diode is given in Figure 4.

Using the above relations, an approximate model of the diode is given in Figure 5. Here, the photo and thermally generated currents are shown as parallel current sources. C represents the capacitance of the reverse-biased junction while G represents the equivalent shunt conductance of the diode and is generally quite small. This model applies only for reverse bias, which, as mentioned above, is the normal mode of operation.

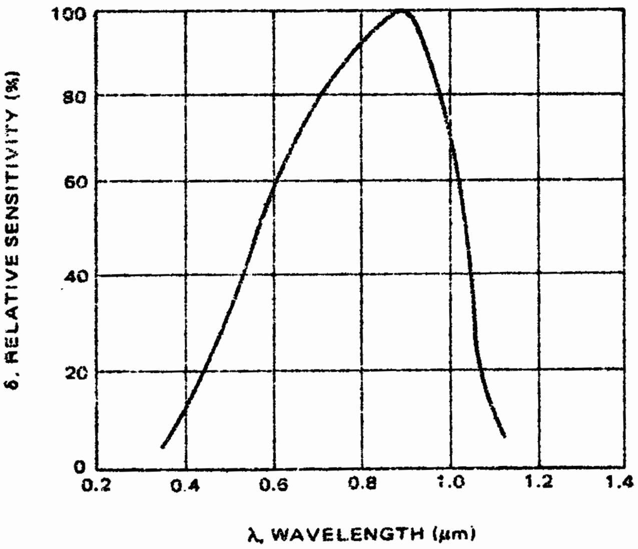


FIGURE 4 – Spectral Response of Silicon Photodiode

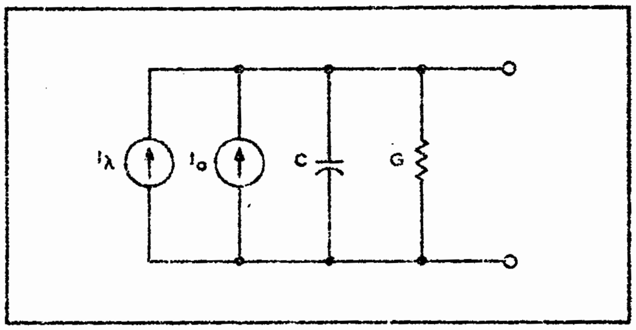


FIGURE 5 – Approximate Model of Photodiode

**Photo Transistor**

If the pn junction discussed above is made the collector-base diode of a bipolar transistor, the photo-induced current is the transistor base current. The current gain of the transistor will thus result in a collector-emitter current of

$$I_C = (h_{fe} + 1) I_\lambda, \qquad (7)$$

where $I_C$ is the collector current,

$h_{fe}$ is the forward current gain, and

$I_\lambda$ is the photo induced base current.

The base terminal can be left floating, or can be biased up to a desired quiescent level. In either case, the collector-base junction is reverse biased and the diode current is the reverse leakage current. Thus, photo-stimulation will result in a significant increase in diode, or base current, and with current gain will result in a significant increase in collector current.

The energy-band diagram for the photo transistor is shown in Figure 6. The photo-induced base current is returned to the collector through the emitter and the external circuitry. In so doing, electrons are supplied to the base region by the emitter where they are pulled into the collector by the electric field $\mathcal{E}$.

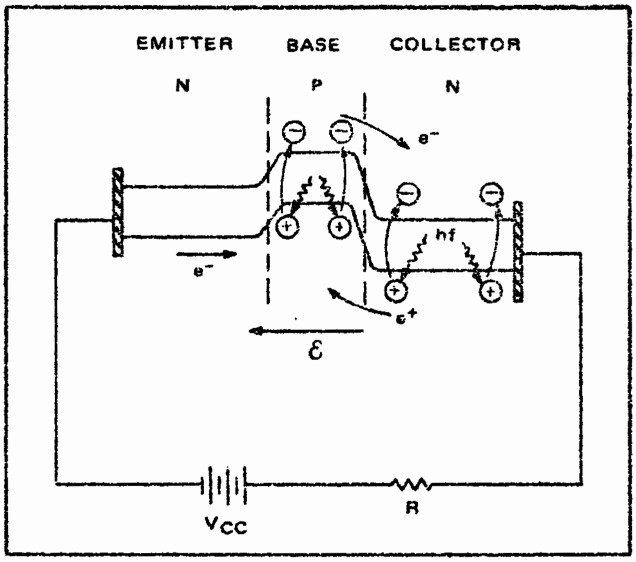


FIGURE 6 — Photoeffect in a Transistor

The model of the photo diode in Figure 5 might also be applied to the phototransistor, however, this would be severely limited in conveying the true characteristics of the transistor. A more useful and accurate model can be obtained by using the hybrid-pi model of the transistor and adding the photo-current generator between collector and base. This model appears in Figure 7.

Assuming a temperature of 25°C, and a radiation source at the wave length of peak response (i.e., $\delta = 1$), the following relations apply:

$$I_\lambda \approx S_{RCBO} \cdot H, \qquad (8a)$$

$$g_m = 40\, i_c, \text{ and} \qquad (8b)$$

$$r_{be} = h_{fe}/g_m, \qquad (8c)$$

where $S_{RCBO}$ is the collector-base diode radiation sensitivity with open emitter,

$g_m$ is the forward transconductance,

$i_c$ is the collector current, and

$r_{be}$ is the effective base-emitter resistance.

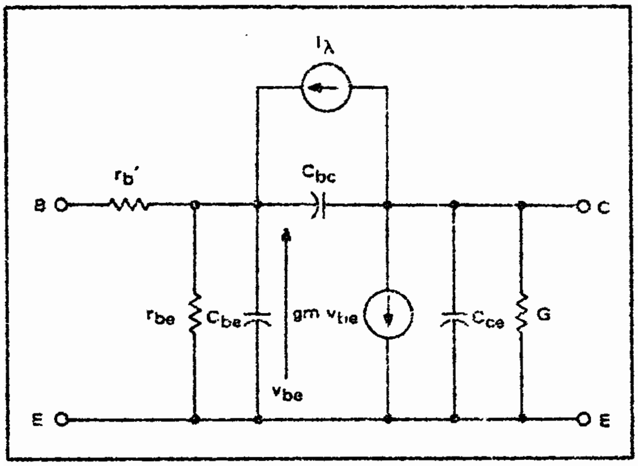


FIGURE 7 — Hybrid-pi Model of Phototransistor

In most cases $r'_b \ll r_{be}$, and can be neglected. The open-base operation is represented in Figure 8. Using this model, a feel for the high-frequency response of the device may be obtained by using the relationship

$$f_t \approx \frac{g_m}{2\pi C_{BE}}, \qquad (9)$$

where $f_t$ is the device current-gain-bandwidth product.

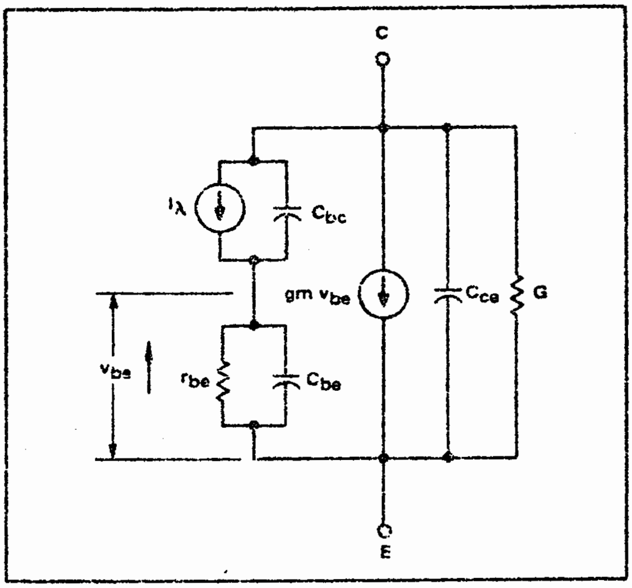


FIGURE 8 — Floating Base Approximate Model of Phototransistor

## STATIC ELECTRICAL CHARACTERISTICS OF PHOTOTRANSISTORS

### Spectral Response

As mentioned previously, the spectral response curve provides an indication of a device's ability to respond to radiation of different wave lengths. Figure 9 shows the spectral response for constant energy radiation for the Motorola MRD300 phototransistor series. As the figure indicates, peak response is obtained at about 8000 Å (Angstroms), or 0.8 $\mu$m.

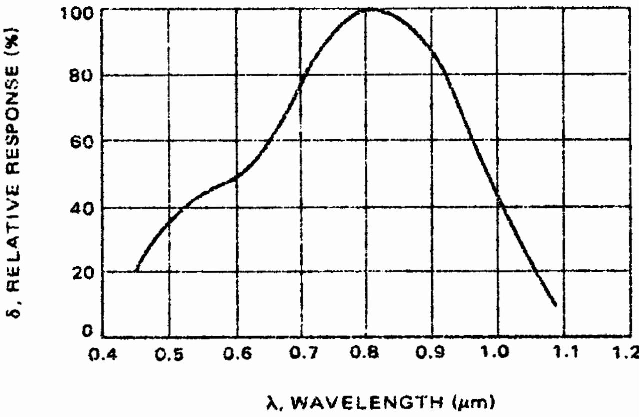


FIGURE 9 — Constant Energy Spectral Response for MRD300

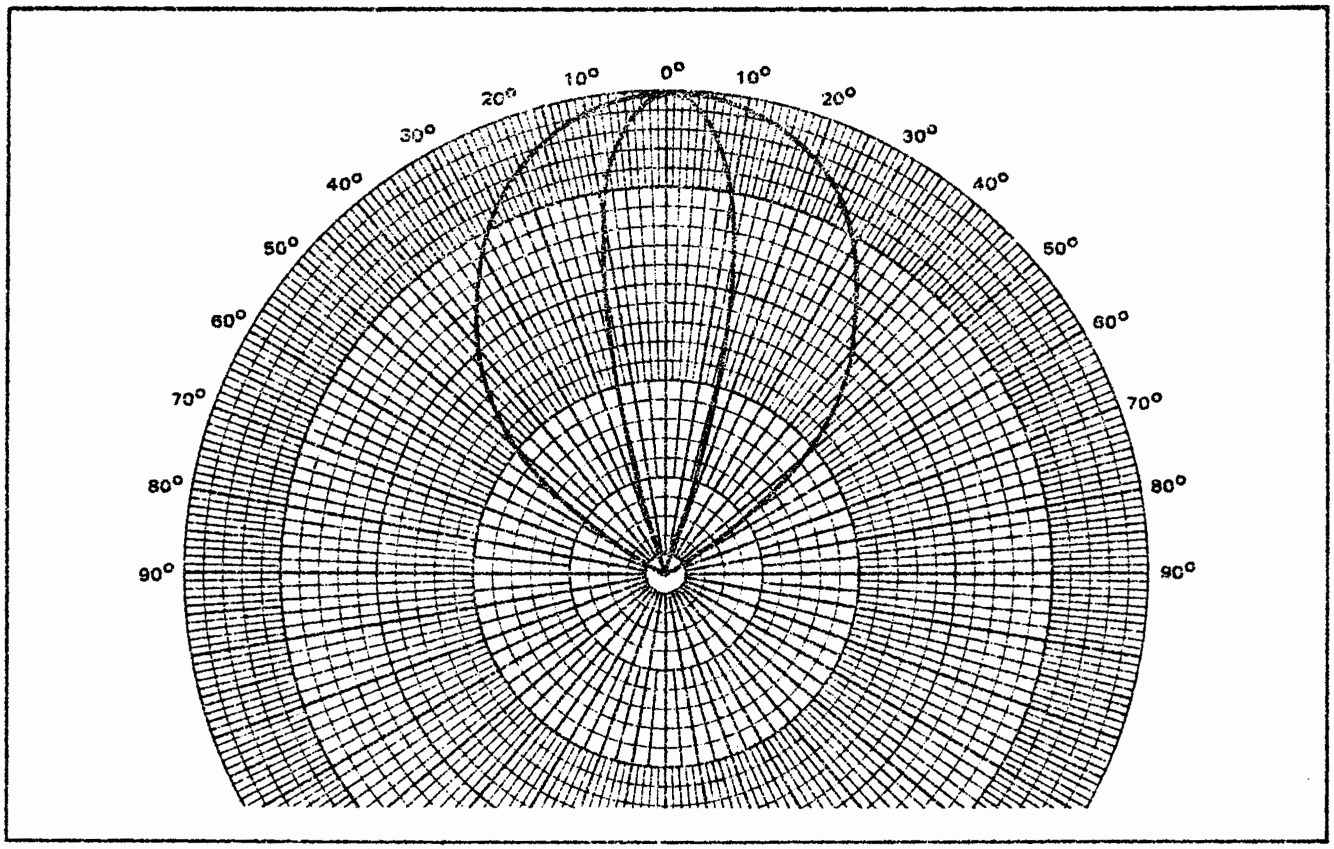


FIGURE 10 – Polar Response of MRD300. Inner Curve with Lens, Outer Curve with Flat Glass.

## Angular Alignment

Lambert's law of illumination states that the illumination of a surface is proportional to the cosine of the angle between the normal to the surface and the direction of the radiation. Thus, the angular alignment of a phototransistor and radiation source is quite significant. The cosine proportionately represents an ideal angular response. The presence of an optical lens and the limit of window size further affect the response. This information is best conveyed by a polar plot of the device response. Such a plot in Figure 10 gives the polar response for the MRD300 series.

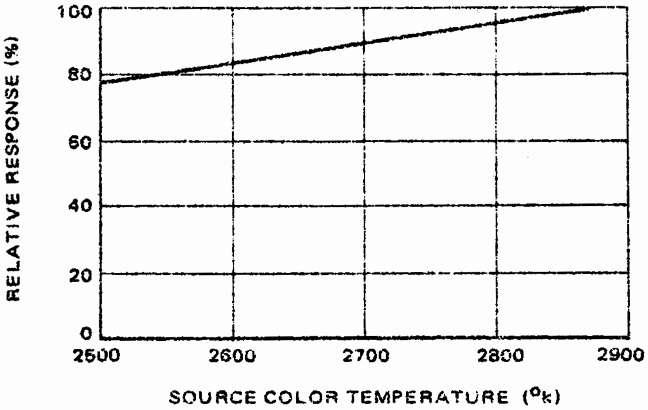


FIGURE 12 – Relative Response of MRD300 versus Color Temperature

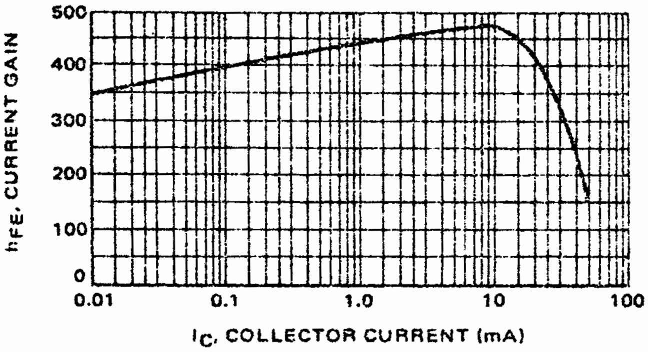


FIGURE 11 – DC Current Gain versus Collector Current

## DC Current Gain

The sensitivity of a photo transistor is a function of the collector-base diode quantum efficiency and also of the dc current gain of the transistor. Therefore, the overall sensitivity is a function of collector current. Figure 11 shows the collector current dependence of dc current gain.

## Color Temperature Response

In many instances, a photo transistor is used with a broad band source of radiation, such as an incandescent lamp. The response of the photo transistor is therefore dependent on the source color temperature. Incandescent sources are normally operated at a color temperature of 2870°K, but, lower-color-temperature operation is not uncommon. It therefore becomes desirable to know the result of a color temperature difference on the photo sensitivity. Figure 12 shows the relative response of the MRD300 series as a function of color temperature.

### Temperature Coefficient of Ip

A number of applications call for the use of phototransistors in temperature environments other than normal room temperature. The variation in photo current with temperature changes is approximately linear with a positive slope of about 0.667%/°C.

The magnitude of this temperature coefficient is primarily a result of the increase in $h_{FE}$ versus temperature, since the collector-base photo current temperature coefficient is only about 0.1%/°C.

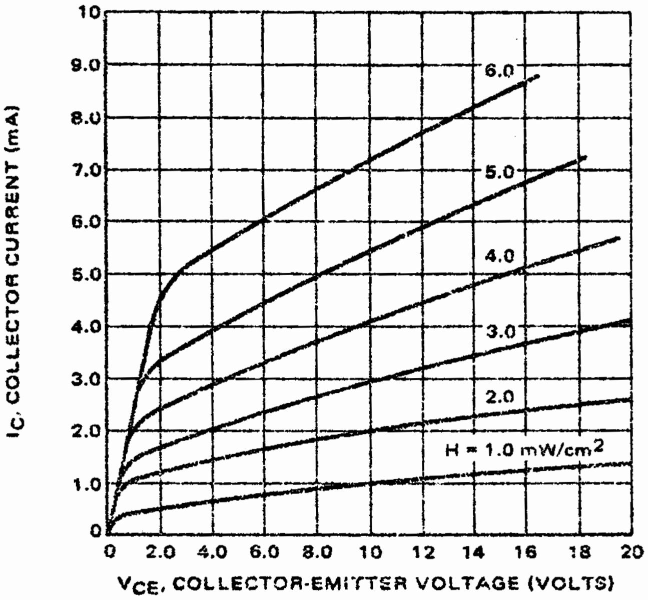


FIGURE 13 – Collector Characteristics for MRD300

### Collector Characteristics

Since the collector current is primarily a function of impinging radiation, the effect of collector-emitter voltage, below breakdown, is small. Therefore, a plot of the $I_C - V_{CE}$ characteristics with impinging radiation as a parameter, are very similar to the same characteristics with $I_B$ as a parameter. The collector family for the MRD300 series appears in Figure 13.

### Radiation Sensitivity

The capability of a given phototransistor to serve in a given application is quite often dependent on the radiation sensitivity of the device. The open-base radiation sensitivity for the MRD300 series is given in Figure 14. This indicates that the sensitivity is approximately linear with respect to impinging radiation. The additional capability of the MRD300 to be pre-biased gives rise to interest in the sensitivity as a function of equivalent base resistance. Figure 15 gives this relationship.

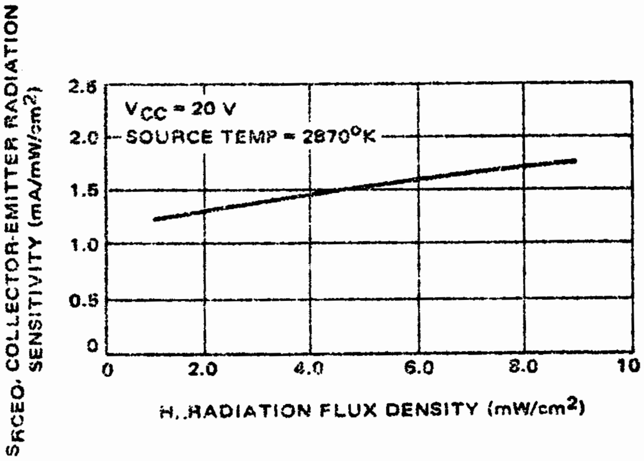


FIGURE 14 – Open Base Sensitivity versus Radiation for MRD300

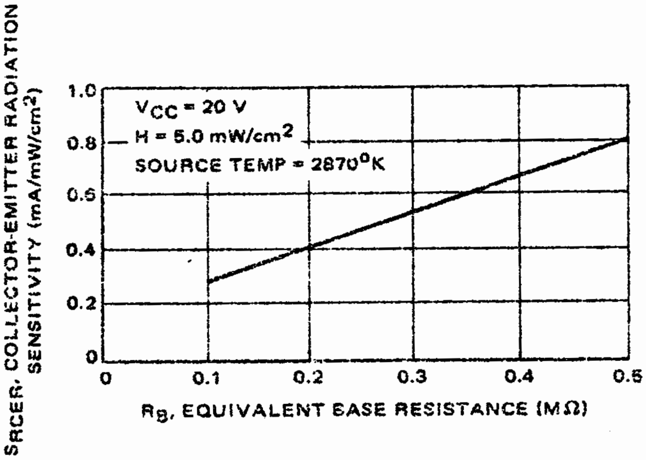


FIGURE 15 – Effect of Base Resistance on Sensitivity of MRD300

### Capacitance

Junction capacitance is the significant parameter in determining the high frequency capability and switching speed of a transistor. The junction capacitances of the MRD300 as a function of junction voltages are given in Figure 16.

## DYNAMIC CHARACTERISTICS OF PHOTOTRANSISTORS

### Linearity

The variation of $h_{FE}$ with respect to collector current results in a non-linear response of the photo transistor over

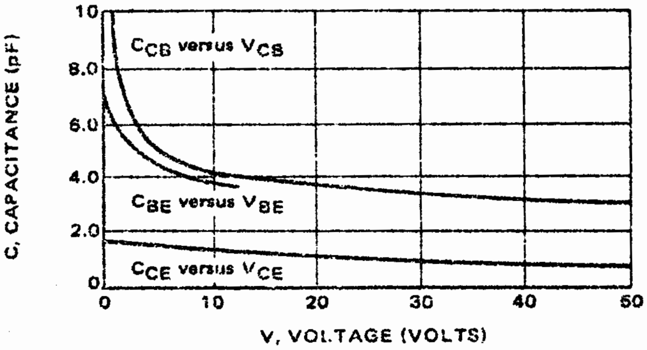


FIGURE 16 – Junction Capacitances versus Voltage for MRD300

large signal swings. However, the small-signal response is approximately linear. The use of a load line on the collector characteristic of Figure 13 will indicate the degree of linearity to be expected for a specific range of optical drive.

### Frequency Response

The phototransistor frequency response, as referred to in the discussion of Figures 7 and 8, is presented in Figure 17. The device response is flat down to dc with the rolloff frequency dependent on the load impedance as well as on the device. The response is given in Figure 17 as the 3-dB frequency as a function of load impedance for two values of collector current.

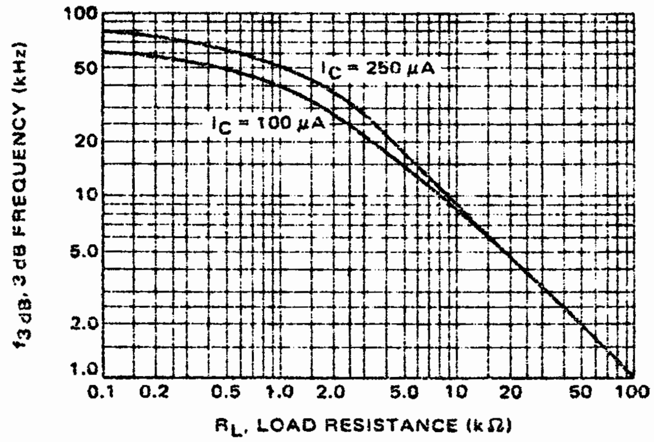


FIGURE 17 – 3 dB Frequency versus Load Resistance for MRD300

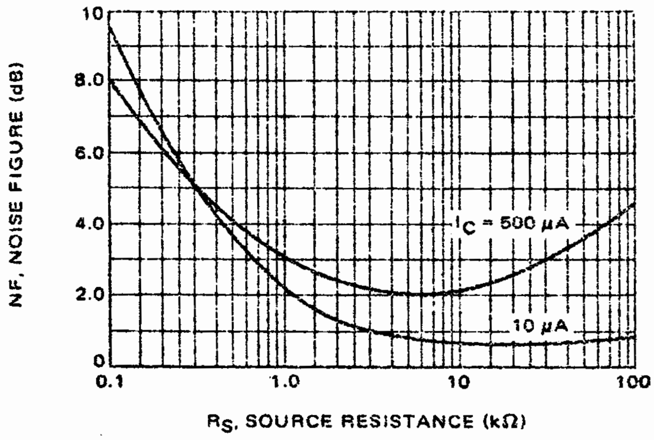


FIGURE 18 – MRD300 Noise Figure versus Source Resistance

### Noise Figure

Although the usual operation of the phototransistor is in the floating base mode, a good qualitative feel for the device's noise characteristic can be obtained by measuring noise figure under standard conditions. The 1 kHz noise figure for the MRD300 is shown in Figure 18.

### Small Signal h Parameters

As with noise figure, the small-signal h-parameters, measured under standard conditions, give a qualitative feel for the device behavior. These are given as functions of collector current in Figure 19. With this information, the device can be analyzed in the standard hybrid model of Figure 20(a); by use of the conversions of Table I, the equivalent r-parameter model of Figure 20(b) can be used.

TABLE I – Parameter Conversions

$$h_{fb} = \frac{h_{fe}}{1 + h_{fe}}$$

$$r_c = \frac{h_{fe} + 1}{h_{oe}}$$

$$r_e = \frac{h_{re}}{h_{oe}}$$

$$r_b = h_{ie} - \frac{h_{re}(1 + h_{fe})}{h_{oe}}$$

## SWITCHING CHARACTERISTICS OF PHOTOTRANSISTORS

In switching applications, two important requirements of a transistor are:

(1) speed

(2) ON voltage

Since some optical drives for phototransistors can provide fast light pulses, the same two considerations apply.

### Switching Speed

If reference is made to the model of Figure 8, it can be seen that a fast rise in the current $I_\lambda$ will not result in an equivalent instantaneous increase in collector-emitter current. The initial flow of $I_\lambda$ must supply charging current to $C_{CB}$ and $C_{BE}$. Once these capacitances have been charged, $I_\lambda$ will flow through $r_{bc}$. Then the current generator, $g_m \cdot v_{be}$, will begin to supply current. During turn-off, a similar situation occurs. Although $I_\lambda$ may instantaneously drop to zero, the discharge of $C_{CB}$ and $C_{BE}$ through $r_{be}$ will maintain a current flow through the collector. When the capacitances have been discharged, $V_{be}$ will fall to zero and the current, $g_m \cdot V_{be}$, will likewise drop to zero. (This discussion assumes negligible leakage currents). These capacitances therefore result in turn-on and turn-off delays, and in rise and fall times for switching applications just as found in conventional bipolar switching transistors. And, just as with conventional switching, the times are a function of drive. Figure 21 shows the collector current (or drive) dependence of the turn-on delay and rise times. As indicated the delay time is dependent on the device only; whereas the rise-time is dependent on both the device and the load.

If a high-intensity source, such as a xenon flash lamp, is used for the optical drive, the device becomes optically saturated unless large optical attenuation is placed between source and detector. This can result in a significant storage time during the turn off, especially in the floating-base mode since stored charge has no direct path out of the

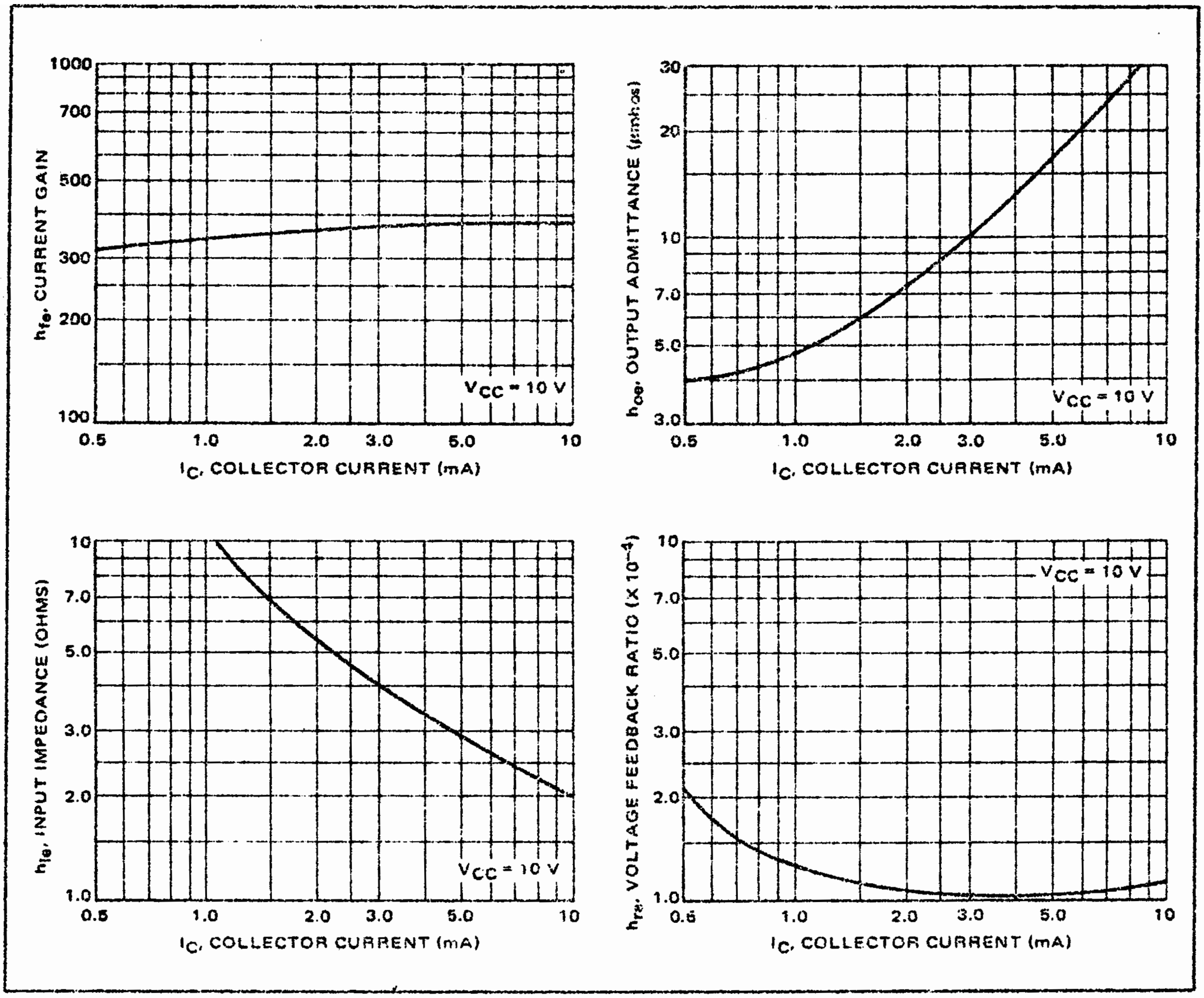
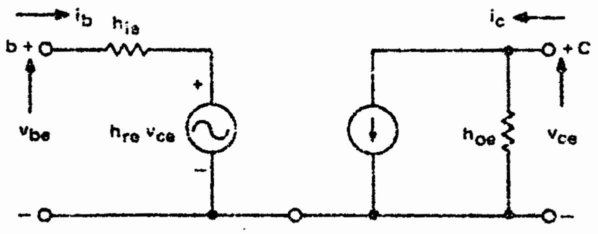
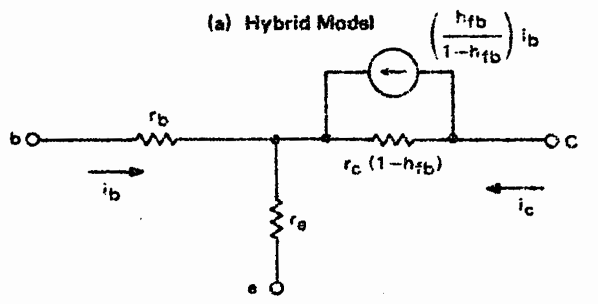


FIGURE 19 — 1 kHz h-Parameters versus Collector Current for MRD300



(a) Hybrid Model



(b) r-Parameter Model

FIGURE 20 — Low Frequency Analytical Models of Phototransistor Without Photo Current Generator

base region. However, if a non-saturating source, such as a GaAs diode, is used for switching drive, the storage, or turn-off delay time is quite low as shown in Figure 22.

## Saturation Voltage

An ideal switch has zero ON impedance, or an ON voltage drop of zero. The ON saturation voltage of the MRD300 is relatively low, approximately 0.2 volts. For a given collector current, the ON voltage is a function of drive, and is shown in Figure 23.

## APPLICATIONS OF PHOTOTRANSISTORS

As mentioned previously, the phototransistor can be used in a wide variety of applications. Figure 24 shows two phototransistors in a series-shunt chopper circuit. As $Q_1$ is switched ON, $Q_2$ is OFF, and when $Q_1$ is switched OFF, $Q_2$ is driven ON.

Logic circuitry featuring the high input/output electrical isolation of photo transistors is shown in Figure 25.

Figure 26 shows a linear application of the phototransistor. As mentioned previously, the linearity is obtained for small-signal swings.

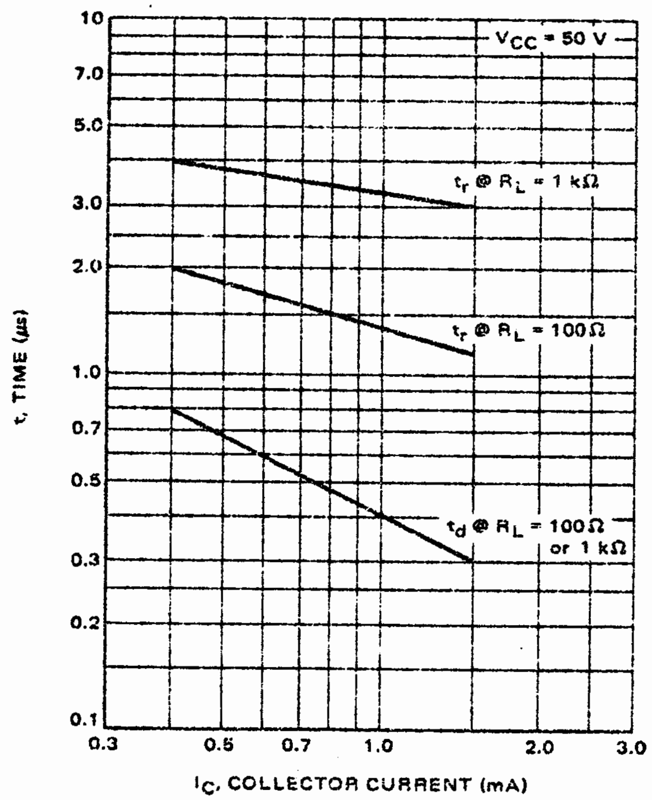


FIGURE 21 – Switching Delay and Rise Times for MRD300

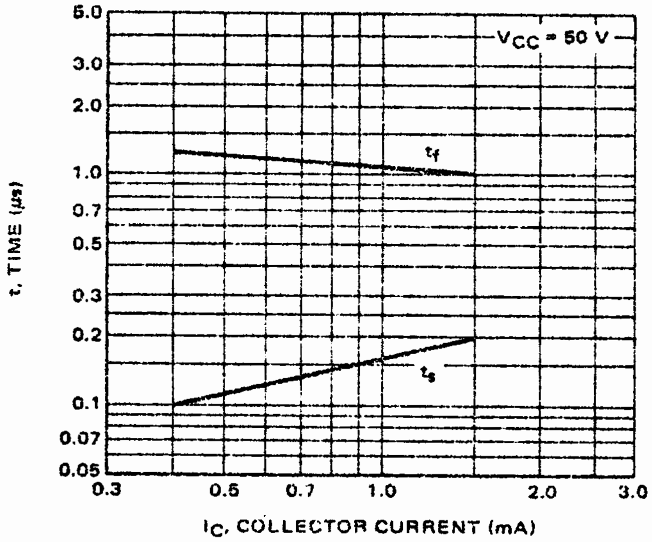


FIGURE 22 – Switching Storage and Fall Times for MRD300

A double-pole, single-throw relay is shown in Figure 27.

In general, the phototransistor can be used in counting circuitry, level indications, alarm circuits, tachometers, and various process controls.

## Conclusion

The phototransistor is a light-sensitive active device of moderately high sensitivity and relatively high speed. Its response is both a function of light intensity and wavelength, and behaves basically like a standard bipolar transistor with an externally controlled collector-base leakage current.

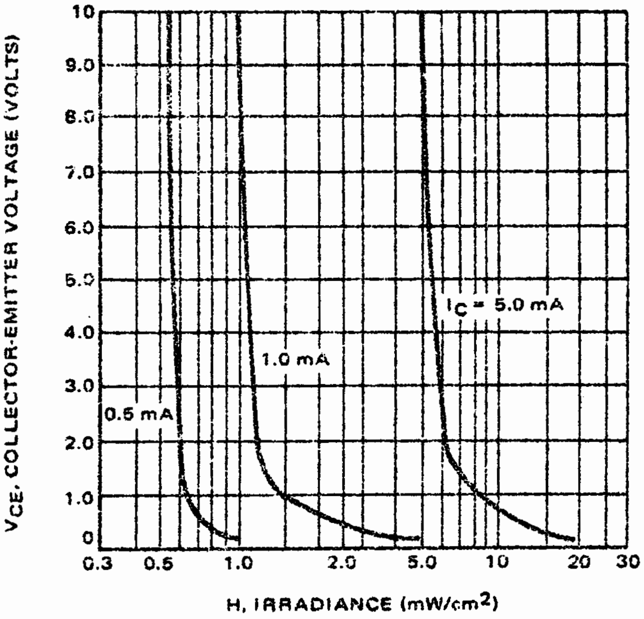


FIGURE 23 – Collector Emitter Saturation Voltage as a Function of Irradiance for MRD300

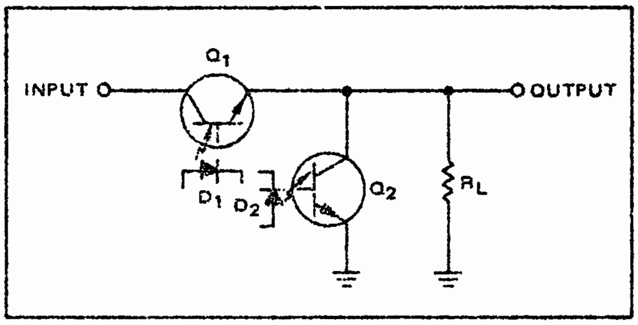


FIGURE 24 – Series-Shunt Chopper Circuit Using MRD300 Phototransistors and GaAs Light Emitting Diodes (LEDs)

## APPENDIX I

Radiant energy covers a broad band of the electromagnetic spectrum. A relatively small segment of the band is the spectrum of visible light. A portion of the electromagnetic spectrum including the range of visible light is shown in Figure I-1.

The portion of radiant flux, or radiant energy emitted per unit time, which is visible is referred to as luminous flux. This distinction is due to the inability of the eye to respond equally to like power levels of different visible wavelengths. For example, if two light sources, one green and one blue are both emitting like wattage, the eye will perceive the green light as being much brighter than the blue. Consequently, when speaking of visible light of varying color, the watt becomes a poor measure of brightness. A more meaningful unit is the lumen. In order to obtain a clear understanding of the lumen, two other definitions are required.

The first of these is the standard source (Fig. I-2). The standard source, adopted by international agreement, con-

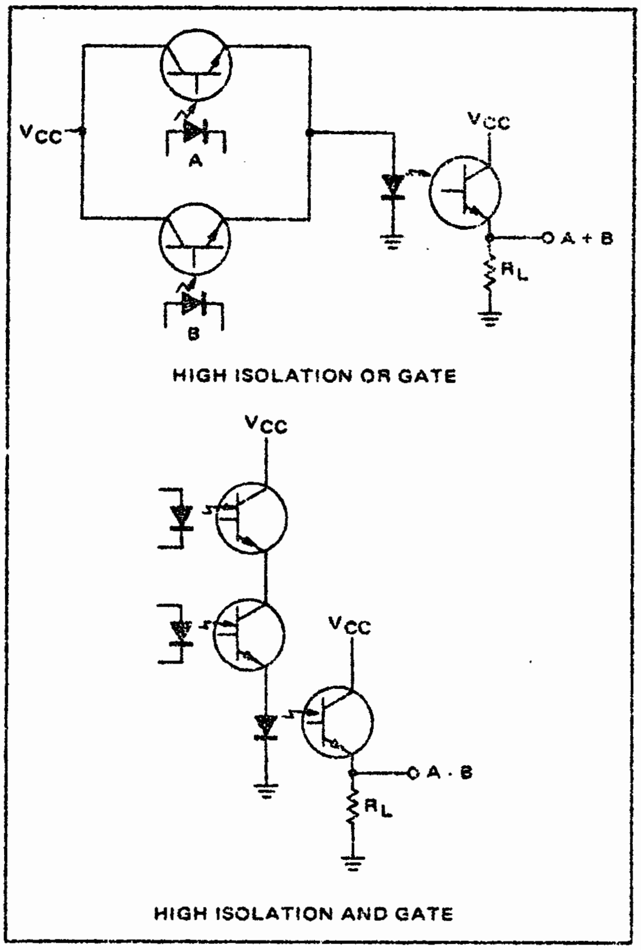


FIGURE 25 – Logic Circuits Using the MRD300 and LEDs

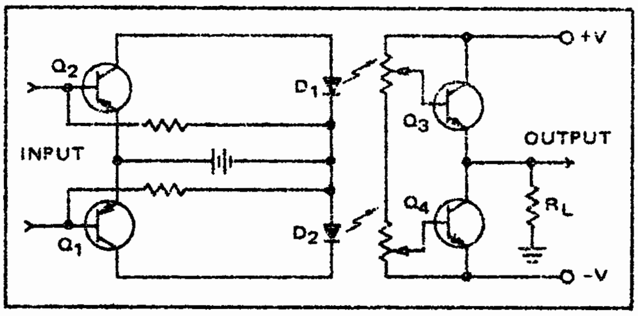


FIGURE 26 – Small Signal Linear Amplifier Using MRD300 and LEDs

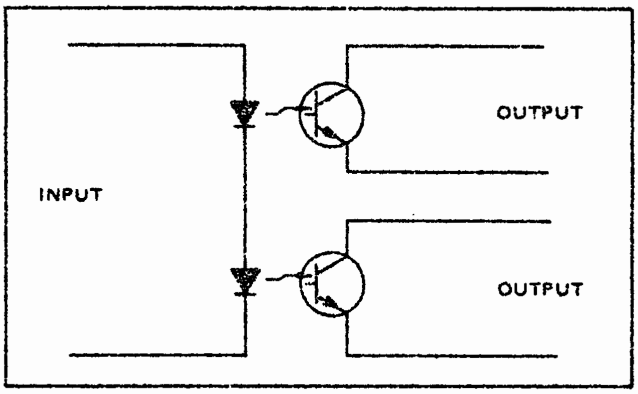


FIGURE 27 – DPST Relay Using MRD300s and LEDs

sists of a segment of fused thoria immersed in a chamber of platinum. When the platinum is at its melting point, the light emitted from the chamber approximates the radiation of a black body. The luminous flux emitted by the source is dependent on the aperture and cone of radiation. The cone of radiation is measured in terms of the solid angle.

The concept of a solid angle comes from spherical geometry. If a point is enclosed by a spherical surface and a set of radial lines define an area on the surface, the radial lines also subtend a solid angle. This angle, $\omega$, is shown in Figure I-3, and is defined as

$$\omega = \frac{A}{r^2}, \qquad \text{(I-1)}$$

where A is the described area and r is the spherical radius.

If the area A is equal to $r^2$, then the solid angle subtended is one unit solid angle or one steradian, which is nothing more than the three-dimensional equivalent of a radian.

With the standard source and unit solid angle established, the lumen can be defined.

A lumen is the luminous flux emitted from a standard source and included within one steradian.

Using the concept of the lumen, it is now possible to define other terms of illumination.

**Illuminance**

If a differential amount of luminous flux, dF, is impinging on a differential area, dA, the illuminance, E, is given by

$$E = \frac{dF}{dA}. \qquad \text{(I-2)}$$

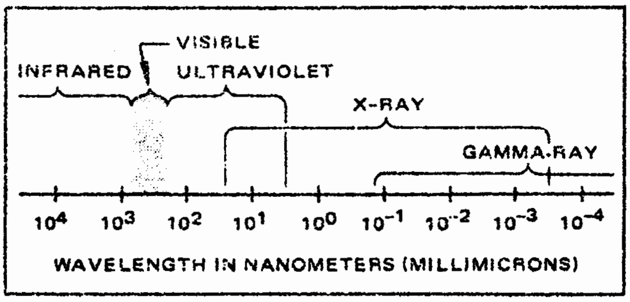


FIGURE I–1 – Portion of Electromagnetic Spectrum

Illuminance is most often expressed in lumens per square foot, or foot-candles. If the illuminance is constant over the area, (I-2) becomes

$$E = F/A. \qquad \text{(I-3)}$$

**Luminous Intensity**

When the differential flux, dF, is emitted through a differential solid angle, $d\omega$, the luminous intensity, I, is given by

$$I = \frac{dF}{d\omega}. \qquad \text{(I-4)}$$

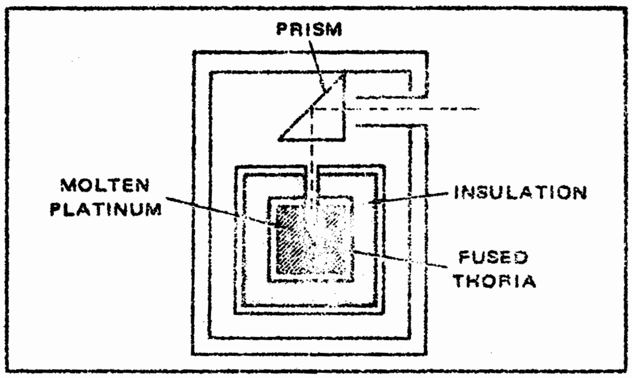


FIGURE I–2 – International Standard Source

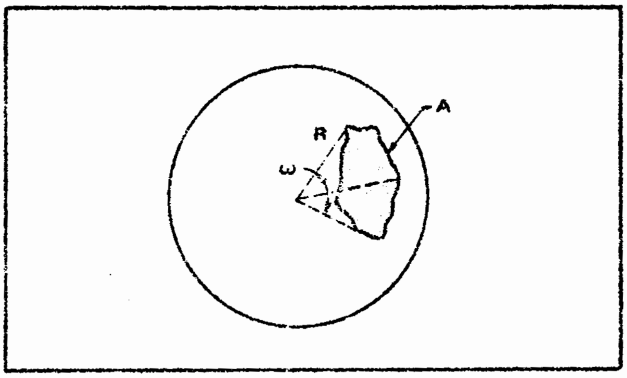


FIGURE I–3 – Solid Angle, ω

Luminous intensity is most often expressed in lumens per steradian or candela. If the luminous intensity is constant with respect to the angle of emission, (I-4) becomes:

$$I = \frac{F}{\omega}. \qquad \text{(I-5)}$$

If the wavelength of visible radiation is varied, but the illumination is held constant, the radiative power in watts will be found to vary. This again illustrates the poor quality of the watt as a measure of illumination. A relation between illumination and radiative power must then be specified at a particular frequency. The point of specification has been taken to be at a wavelength of 0.555 µm, which is the peak of spectral response of the human eye. At this wavelength, 1 watt of radiative power is equivalent to 680 lumens.

## APPENDIX II
## OPTOELECTRONIC DEFINITIONS

F, Luminous Flux: Radiant flux of wavelength within the band of visible light.

Lumen: The luminous flux emitted from a standard source and included within one steradian (solid angle equivalent of a radian).

H, Radiation Flux Density (Irradiance): The total incident radiation energy measured in power per unit area (e.g., mW/cm$^2$).

E, Luminous Flux Density (Illuminance): Radiation flux density of wavelength within the band of visible light. Measured in lumens/ft$^2$ or foot candles. At the wavelength of peak response of the human eye. 0.555 µm (0.555 X 10$^{-6}$m). 1 watt of radiative power is equivalent to 680 lumens.

$S_R$, Radiation Sensitivity: The ratio of photo-induced current to incident radiant energy, the latter measured at the plane of the lens of the photo device.

$S_I$, Illumination Sensitivity: The ratio of photo-induced current to incident luminous energy, the latter measured at the plane of the lens of the photo device.

Spectral Response: Sensitivity as a function of wavelength of incident energy. Usually normalized to peak sensitivity.

### Constants

Planck's constant: $h = 4.13 \times 10^{-15}$ eV-s.
electron charge: $q = 1.60 \times 10^{-19}$ coulomb.
velocity of light: $c = 3 \times 10^{8}$ m/s.

### Illumination Conversion Factors

| Multiply | By | To Obtain |
|---|---|---|
| lumens/ft$^2$ | 1 | ft. candles |
| lumens/ft$^2$* | $1.58 \times 10^{-3}$ | mW/cm$^2$ |
| candlepower | 4π | lumens |

*At 0.555 µm.

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