An Introduction to Semiconductor Radiation Detectors

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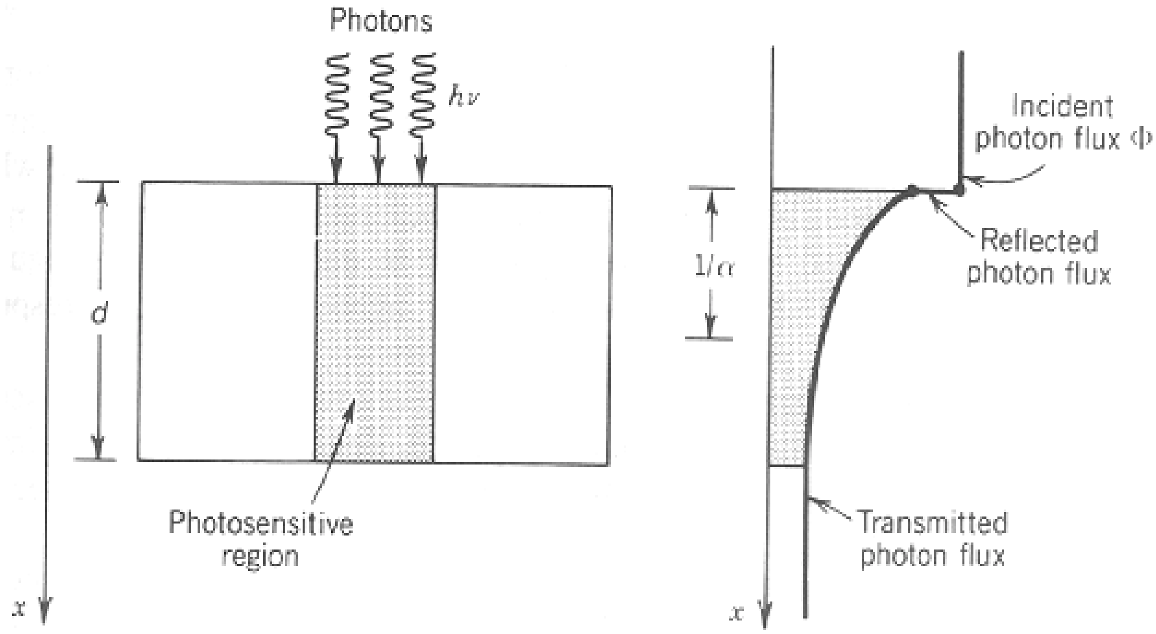
I. Photons and Semiconductors



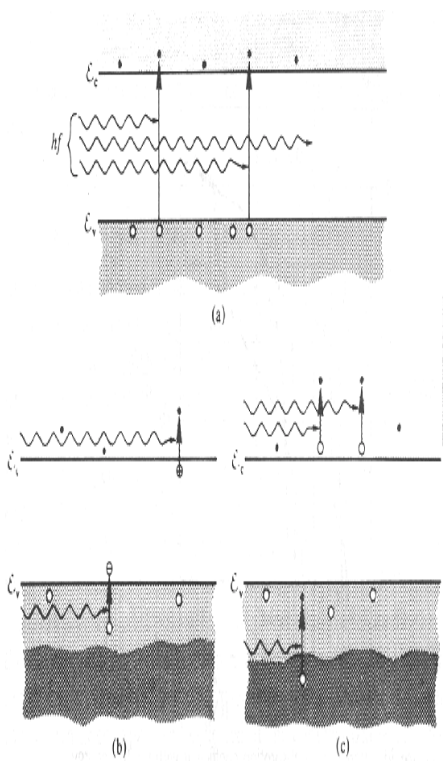
Propagation of an electromagnetic field through an absorbing medium.

1). An electromagnetic field incident on an interface between media with differing dielectric constants will have a fraction R of its intensity reflected from the interface and a fraction T=(1-R) transmitted through the interface. The coefficient of reflection may be calculated from the well known Fresnel equations. Semiconductors, due to their large ε, typically have R≈0.3 for normal incidence from air.

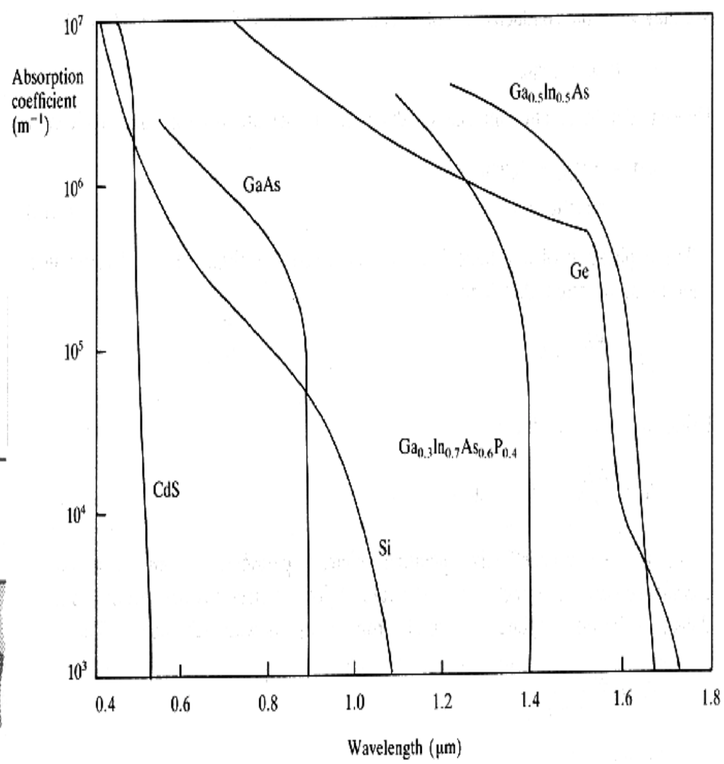
2). Generally, when a photon of frequency ν travels in an absorbing medium, it will travel an average distance of 1/α(ν) before being absorbed, where α(ν) is the absorption coefficient of the material. We may represent this as a differential equation for the intensity of a propagating electromagnetic field:

$$\frac{dI}{dx} = -\alpha(\nu) I \qquad \rightarrow \qquad I(x - x_0) = I(x_0) e^{-\alpha(\nu)(x - x_0)}$$

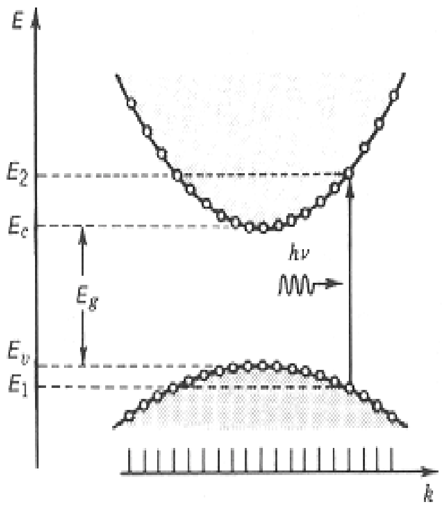
3). In semiconductors, there are several processes that may result in the absorption of an incident photon. Interband transitions (a) may occur when a resonant photon interacts with a valence electron, exciting it to an unoccupied level in the conduction band. Charge transfer transitions (b) may occur in which a photon either excites a valence electron into an empty acceptor state, or excites a donor electron into an empty conduction band state. Intraband transitions (c) may also occur in which a valence electron is excited into an unoccupied valence band state, or a conduction electron is excited into an unoccupied conduction band state.



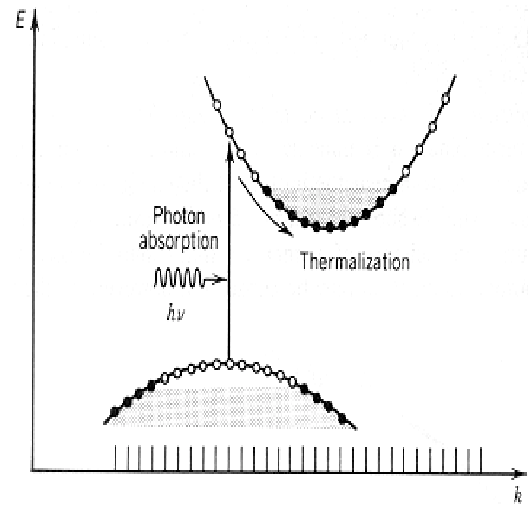
Possible absorption processes in a semiconductor: (a) Interband, (b) Charge Transfer, and (c) Intraband.



Absorption coefficients of common semiconductors.



Absorption in a direct gap semiconductor such as GaAs.



Absorption in an indirect gap semiconductor such as Si. Absorption is immediately followed by a nonradiative transition to the lowest unoccupied conduction band state.

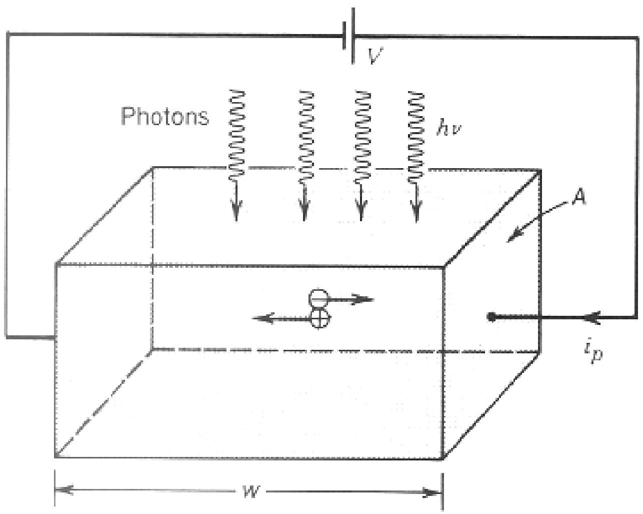
4). The quantum efficiency η of a radiation detector is defined as the probability that a photon incident on the detector will generate a charge carrier pair that may contribute to a current flow through the detector. Thus, if ζ percent of the generated charge carriers contribute to the current and 1-ζ percent suffer immediate recombination or become trapped at localized states, we may write the quantum efficiency as follows:

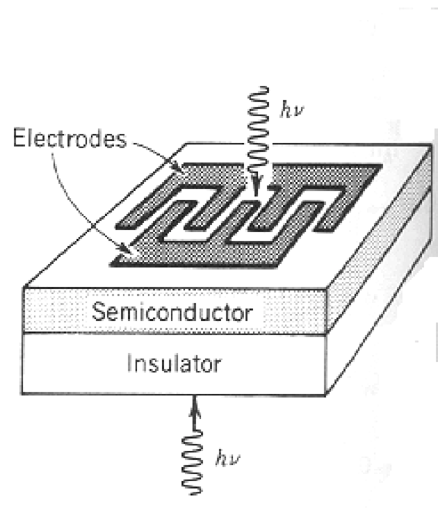
$$\eta = (1-R)\zeta(1-e^{-\alpha(\nu)d})$$

5). The responsivity ℜ is another important parameter used to characterize a radiation detector. The responsivity is defined as the ratio of generated photocurrent to incident electromagnetic power. Since the photocurrent is just the effective carrier charge generated by the absorption of a photon (q=Ge) times the product of the photon flux and quantum efficiency (in steady state), and the power is just the photon flux times the photon energy, we may write an equation for ℜ.

$$\Re = \frac{q\eta}{h\nu} = G\eta\frac{\lambda_{vac}}{1.24}$$

II. Photoconductors





1). The simplest type of semiconductor radiation detector involves observing the change in conductivity in a semiconductor due to the creation of additional charge carriers by an incident electromagnetic field. These devices are commonly known as photoconductors.

2). The conductivity σ in the absence of illumination may be found as follows from the current density J, velocity V, charge density ρ, electric field E, and mobility μ:

$$J = \sigma E \quad \text{, but} \quad J = \rho V \quad \text{where} \quad V = \mu E \quad \Rightarrow \quad \sigma = \mu \rho$$

Now, if μ_e is the electron mobility, μ_h is the hole mobility, N_e is the density of electrons in conduction band, and N_h is the density of holes in the valence band, then

$$\sigma = e(\mu_e N_e + \mu_h N_h)$$

If the material is then illuminated, an excess density of charge carriers $\Delta N_e = \Delta N_h = \Delta N$ will be created by photon absorption and the conductivity will change by

$$\Delta\sigma = e(\mu_e + \mu_h)\Delta N$$

Next, if we assume that the electromagnetic power is uniform throughout a volume V=wA, and that carriers have an average lifetime of τ, we may write a differential equation for the excess charge carriers.

$$\frac{d\Delta N}{dt} = \frac{\eta P}{wAh\nu} - \frac{\Delta N}{\tau}$$

But, in steady state ΔN is constant so that we may find the following:

$$\frac{d\Delta N}{dt} = 0 \qquad \Rightarrow \qquad \Delta N = \frac{\eta P \tau}{wAh\nu} \qquad \rightarrow \qquad \Delta\sigma = \frac{e\eta\tau(\mu_e + \mu_h)}{wAh\nu} P$$

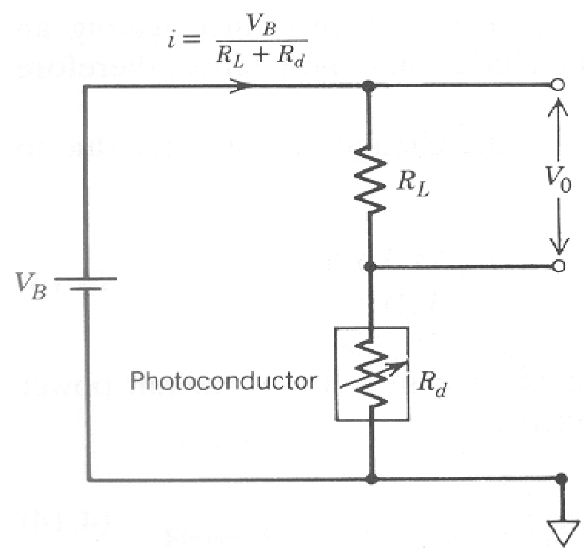
We may now calculate the responsivity from Ohm's law:

$$J_p = \Delta\sigma E \qquad \rightarrow \qquad I_p = AE\Delta\sigma = E\frac{e\eta\tau(\mu_e + \mu_h)}{wh\nu} P = \frac{I}{A\sigma}\frac{e\eta\tau(\mu_e + \mu_h)}{wh\nu} P$$

$$\Re = \frac{I_p}{P} = \frac{Ie\eta\tau(\mu_e + \mu_h)}{\sigma Awh\nu} \qquad \Rightarrow \qquad G = \frac{E\tau(\mu_e + \mu_h)}{w} = \tau\frac{V_e + V_h}{w} = \frac{\tau}{\tau_d}$$

Notice that we may have a gain greater than unity! This implies that a single photon absorption produces τ/τ_d carrier pairs. This is understood by realizing that τ_d represents the time for the charge carriers to traverse the conductor and enter the external circuit. Current continuity and charge conservation requires that new carriers must enter the semiconductor from the external circuit until they eventually recombine after time τ. Thus, the charge carriers effectively traverse the semiconductor τ/τ_d times resulting in gain.

3). In order to detect the change in conductivity, we must place the semiconductor in an external circuit such as the one diagrammed below.



With this detection circuit, a change in the conductivity will result in a change in the current, and therefore a corresponding change in the

voltage drop observed across the load resistor. The zero signal voltage V_0 and the change in the resistance of the semiconductor are given by

$$V_0 = \frac{V_B R_L}{R_L + R_d} \quad \textbf{and} \quad \Delta R = \frac{1}{Aw\Delta\sigma} \quad \Rightarrow \quad V_0(P) = \frac{V_B R_L}{R_L + R_d + \Delta R}$$

4). One of the most important characteristics of a detector is its temporal response to an incident time dependent intensity. A fundamental limit to a detector's response is the lifetime associated with generated charge carriers. For example, if we consider the situation depicted below, a single incident photon generates a charge carrier pair which produce an associated current in the circuit. Although the field was a delta function in both time and space, the resulting current is a pulse extended over the time for the slowest charge carrier to recombine (decay).

Consider the rate equation that was derived earlier for a time dependent excess carrier density.

$$\frac{d\Delta N}{dt} = \frac{\eta P}{wAh\nu} - \frac{\Delta N}{\tau} = g - \frac{\Delta N}{\tau}$$

Now, if we solve this for no initial excess charge carriers, we find that a step function incident power produces an exponential rise and fall in the excess charge carriers and thus also in the observed signal.

$$\Delta N(0) = 0 \xrightarrow{P(t)=P} \Delta N(t) = \tau\, g(1 - e^{\frac{-t}{\tau}})$$

$$\Delta N(0) = \Delta N_0 \xrightarrow{P(t)=0} \Delta N(t) = \Delta N_0 e^{\frac{-t}{\tau}}$$

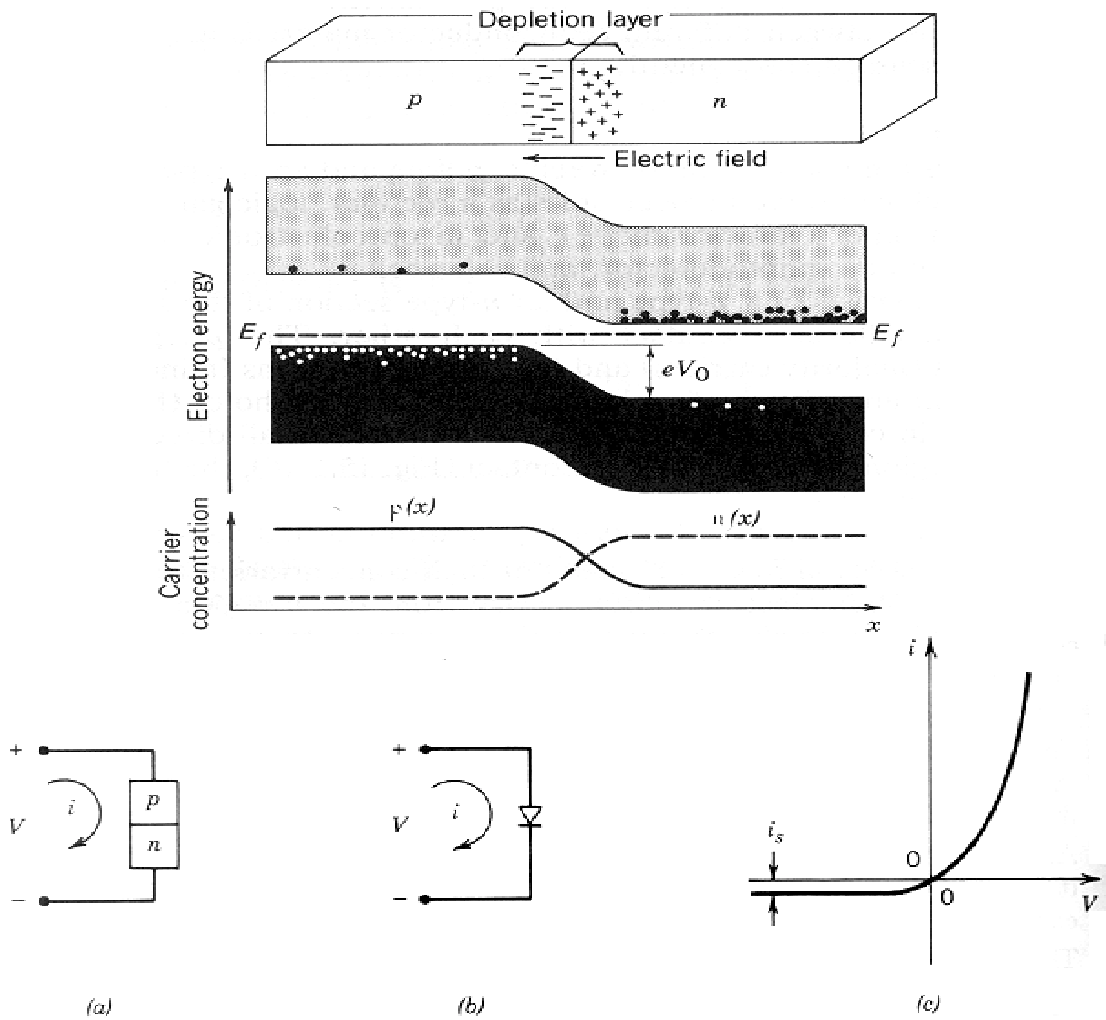
The general frequency response may be found from the Fourier transform of a delta function impulse which gives

$$\Delta N(f) = \frac{2\tau\, g}{\sqrt{1 + (2\pi\ f\tau)^2}}$$

This exhibits the classic 3dB per octave rolloff of a single-pole low-pass filter with an RC time constant of τ. Thus, the ability of the conductor to "store" charge created by an impulse for a time τ acts to reduce the high frequency response of the device in a manner equivalent to an RC low-pass filter.

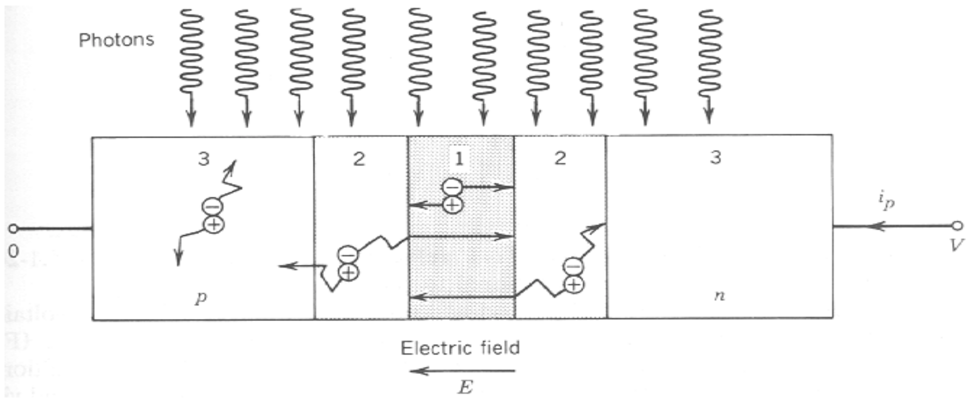
III. P-N Photodiodes

1). Semiconductor junction photodiodes can exhibit dramatically improved performance over simple photoconductor detectors. Photodiodes may be designed with improved response times, greater sensitivity, decreased thermal sensitivity, linearity over 9-10 orders of magnitude, large internal amplification, and may also be used to generate power such as in solar cells.



Schematic representation of an unbiased pn junction and the I-V response under an applied voltage.

2). A p-n junction exhibits an increased resistance due to the reduced number of charge carriers in the space charge region about the junction (the depletion layer). Now, consider light incident upon a p-n junction.

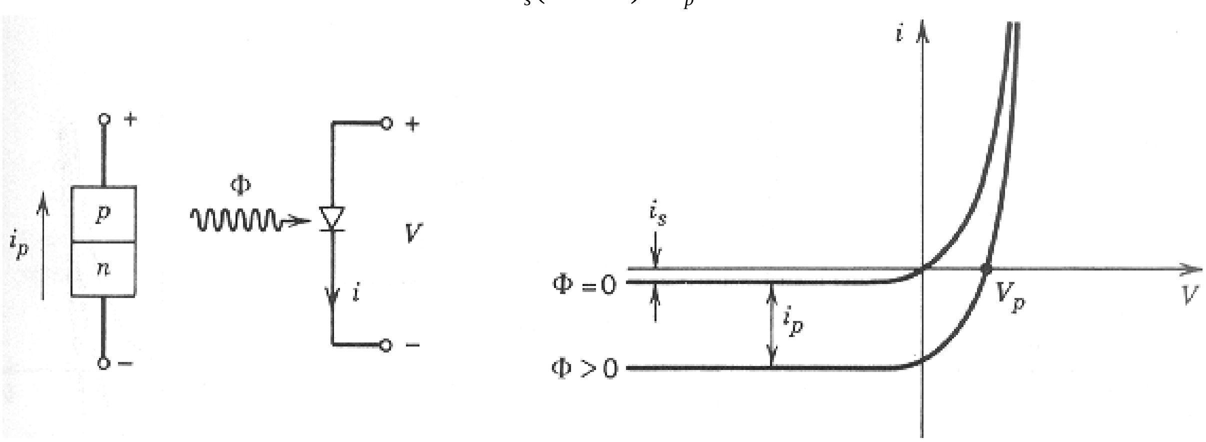


If the light produces charge carriers in region 3, they will randomly move for a time τ before recombining, thus producing no net current (the applied voltage appears almost entirely across the space charge region due to the lack of charge carriers and the resulting large resistance). If the light produces carriers in region 1, the strong internal field of the space charge region will rapidly sweep the carriers across the region, thus resulting in a net current. Also, if light produces charge carriers within a diffusion length of the space charge region (region 2), they may also diffuse into the region and be swept across by the field. The net effect of the photogeneration of charge carriers is that a constant current is created that flows from the n to p regions of the diode (a negative current). This photocurrent is the same as in our earlier expression for the responsivity with G=1 (once carriers leave the space charge region they no longer significantly contribute to the current for the same reasons as given above, thus G=1).

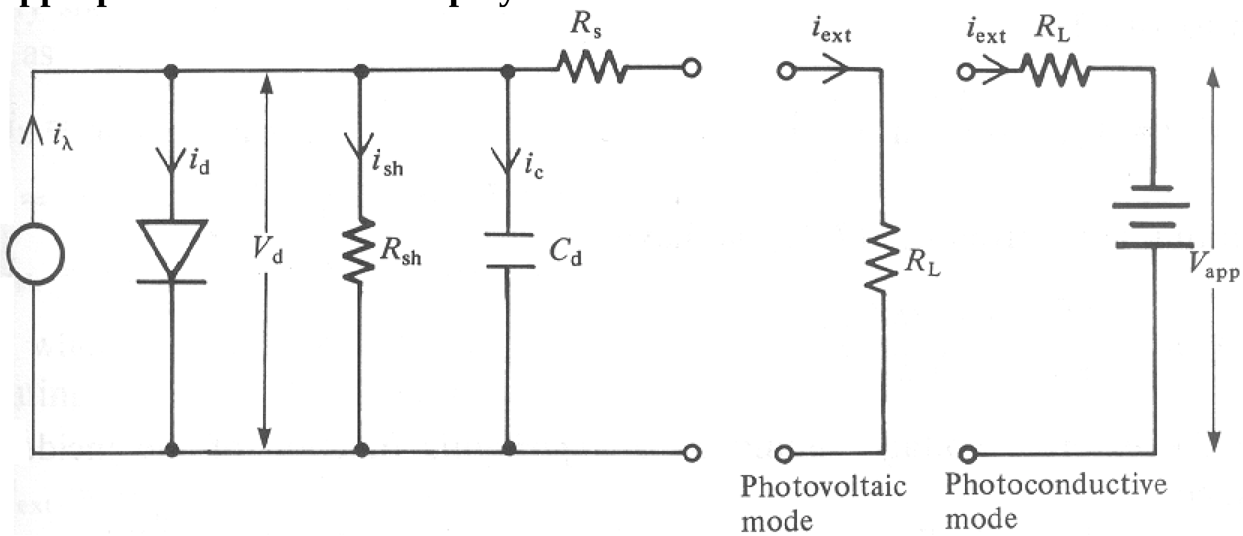
$$I_p = \Re P = \frac{e\eta}{h\nu} P_{abs}$$

This acts to shift the I-V curve downward by I_p resulting in a I-V relationship given by

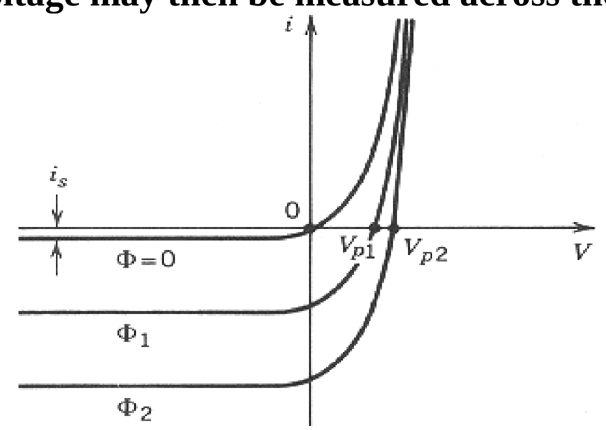
$$I = I_s(e^{\frac{eV}{kT}} - 1) - I_p$$

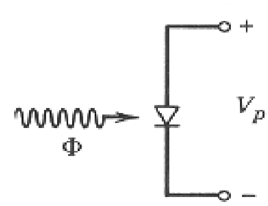


3). There are two fundamental modes of operation for a photodiode: photovoltaic mode and photoconductive mode. The equivalent circuits appropriate for each are displayed below.



4). In photovoltaic mode, the load resistor is chosen very large so that the diode essentially sees an open circuit. The equilibrium current through the diode is nearly zero and thus a positive voltage appears across the diode that cancels the photogenerated current. This induced voltage may then be measured across the load resistor.



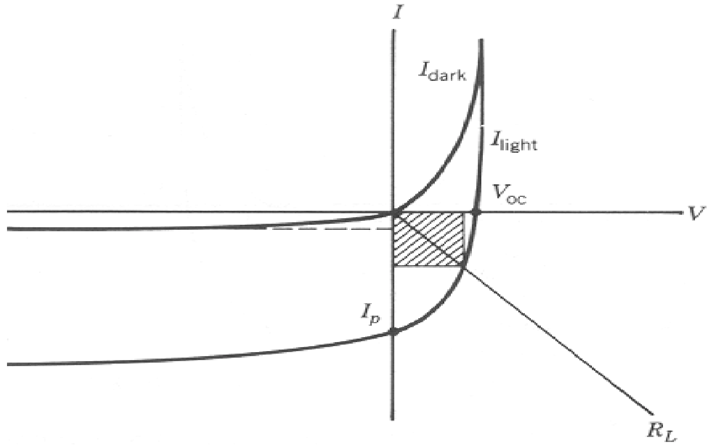


If we consider the photovoltaic circuit, the induced voltage for low frequencies (ignoring the capacitance) and a small shunt resistance is approximately

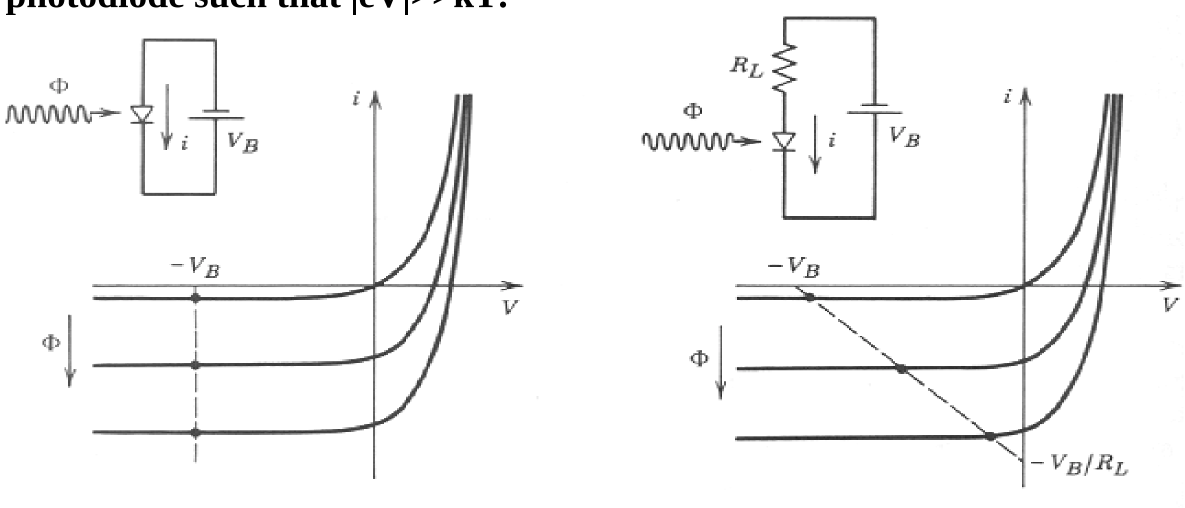
$$V_{ext} = \frac{kT}{e}\ln\left(\frac{eP\eta}{I_s h\nu}\right)$$

(where I_s is the reverse-bias saturation current), thus we see that the voltage varies logarithmically with the absorbed power.

The most common use of the photovoltaic mode is not as a detector, but as a power generator in solar cells. If we consider the load resistor to have a finite value, a current will flow of $I=V/R_L$ which results in a power of $P=V^2/R_L$.



5). In photoconductive mode, a large reverse bias is applied to the photodiode such that |eV|>>kT.



(a) (b)

Thus, we may approximate the current in the diode as

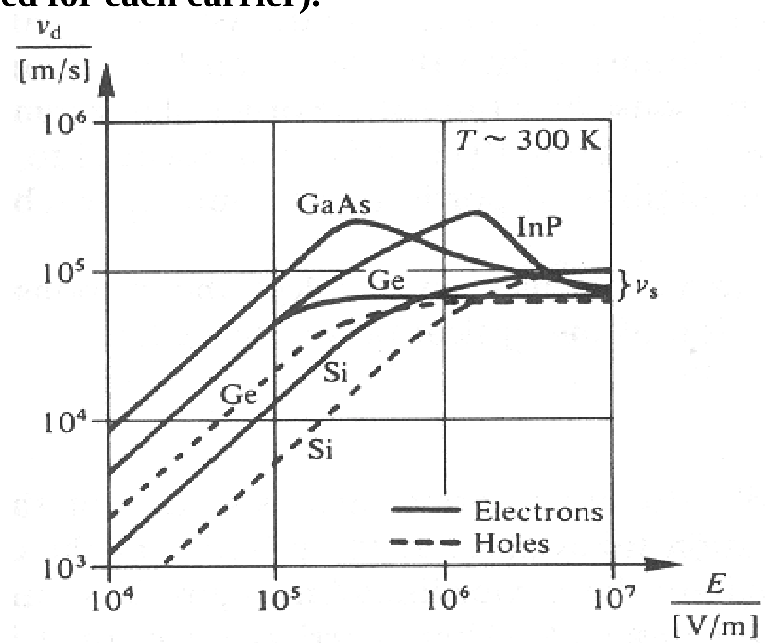
$I = -(I_s + I_p)$ **(but, typically $I_s \sim 10nA << I_p$)** $\rightarrow$ $I_{ext} = -\frac{e\eta}{h\nu} P_{abs}$

which shows that the external current is directly proportional to the incident power. Photoconductivity mode is usually used for photodiode detectors since it exhibits faster response, better stability, and a greater dynamic range. Also, the strong reverse bias increases the carrier velocities, reduces the junction capacitance, and increases the size of the active region (the space charge region).

6). The frequency response of the p-n junction is similar to that of the photoconductor, except with additional contributions. The transit time of charge carriers generated in the space charge region reduces the frequency response of the photodiode, but since the transit time is a function of position in the space charge region, the frequency response of the diode will depend upon the illumination conditions. If we assume uniform illumination of the space charge region and a delta function in time, the resulting current flow in the diode will exhibit a linear decay to zero. Thus, the corresponding frequency response is just given by the Fourier transform:

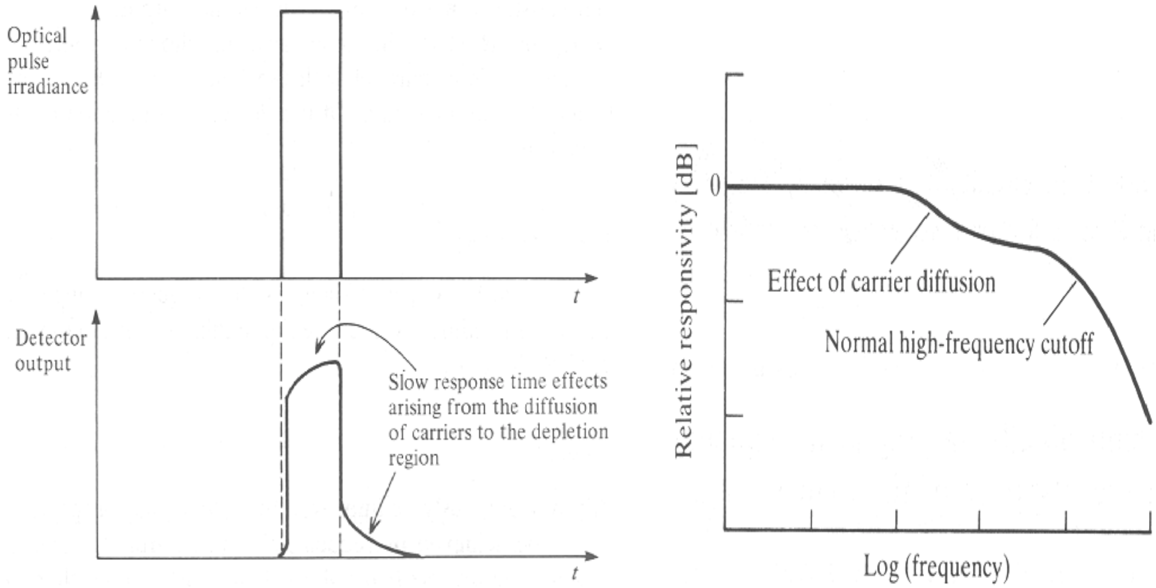
$$I(f)\alpha\frac{1}{f^2}\left[\cos(\pi f \tau)-1\right]+(\pi\tau)^2 sinc(\pi f \tau)$$

where τ is the carrier transit time across the entire space charge region (if the transit times are different for holes and electrons, separate terms must be included for each carrier).



Charge carrier drift velocity as a function of applied field for several semiconductor materials.

7). The current due to charge carriers produced in the diffusion region produces the same frequency rolloff as in the photoconductor, except that the appropriate time is the charge carrier lifetime. Since this is usually much longer than the transit time, this will act to add a long tail onto the response of the diode.



The effect of carrier diffusion on the response of an ideal pn photodiode.

8). In addition to these effects, there is also an additional capacitance due to the charge stored at the junction. For an abrupt p-n junction, the capacitance may be calculated by approximating the junction as a parallel plate capacitor

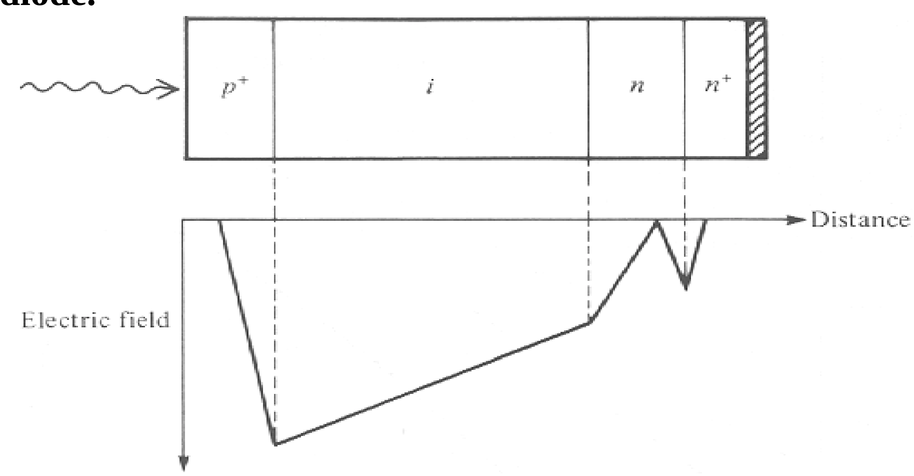
$$C_j = \frac{A\varepsilon\varepsilon_0}{w} = \frac{A}{2}\left[\frac{2e\varepsilon\varepsilon_0}{(V_0 - V)}\left(\frac{N_d N_a}{N_d + N_a}\right)\right]^{\frac{1}{2}}$$

where w is the width of the space charge region, A is the area of the junction, V_0 is the zero current diode potential (the built-in voltage), and N_d (N_a) is the donor (acceptor) concentration. This junction capacitance produces a frequency rolloff with time constant $\tau = R_L C_j$. Note that the capacitance is reduced as the reverse bias voltage is increased.

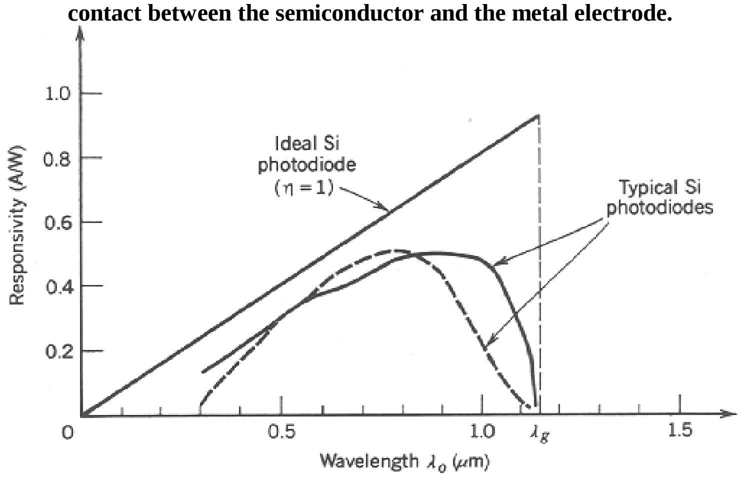
IV. Photodiode Design

1). PIN Diodes—The most common form of photodiode used is the silicon PIN diode in which a thick layer of an intrinsic semiconductor is grown between the n and p layers of the junction. Since there are very few charge carriers in the intrinsic region, the space charge region reaches completely through from the p to the n region. This results in several advantages over the simple p-n photodiode.

- **The width of the space charge region is increased so that the active area of the diode is effectively increased.**
- **The increased width of the junction reduces the junction capacitance.**
- **Since the space charge region is larger, the ratio of the current generated in the space charge region to current generated in the diffusion regions is increased, thus improving the response time of the diode.**



Schematic representation of a PIN photodiode. The presence of a second n^+ layer is to improve the Ohmic contact between the semiconductor and the metal electrode.



Responsivity of common Silicon PIN photodiodes.

GENERAL PURPOSE PIN PHOTODIODES

SPECIFICATIONS

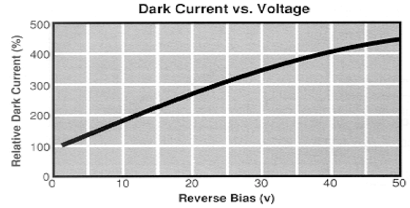
Responsivity: 0.32 A/W minimum, 0.36 A/W typical @ 632.8nm; 0.50 A/W minimum, 0.55 A/W typical @ 900nm

Series Resistance: 100Ω maximum (measured by applying +10mA to photodiode and measuring voltage across anode and cathode)

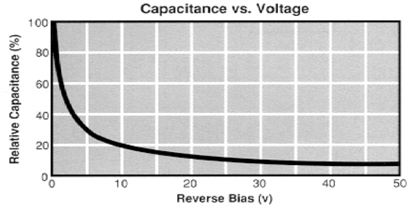
Part Number	Total Area	Active Area	Storage & Operating Temp.	Shunt[1] Resistance	Dark Current[1] at 5V		Breakdown Voltage[2] @ 10µA	Capacitance[3] (typ)		NEP[4]	Max.[5] Linear Current	Response Time[6] @ 10V
				(min)	Typ.	Max.	(typ)	at 0V	at 10V	(typ)	(typ)	(typ)
	(mm²)	(in)	(°C)	(M-Ohm)	(nA)	(nA)	(V)	(pF)	(pF)	(W/ √Hz)	(mA)	(nsec)
SD 057-11-21-015	1.67	0.051 x 0.051	-20 to 75	800	0.5	2.0	50	28	6	2.8×10^{-14}	0.17	7
SD 057-11-21-011	1.67	0.051 x 0.051	-40 to 110	800	0.5	2.0	50	28	6	2.8×10^{-14}	0.17	7
SD 076-11-21-011 (isolated) -211	2.91	0.105 x 0.043	-40 to 110	450	0.9	3.5	50	50	10	3.2×10^{-14}	0.29	8
SD 100-11-21-021 (isolated) -221	5.1	0.100 (dia.)	-40 to 110	300	1.6	6.4	50	87	18	4.0×10^{-14}	0.51	10
SD 125-11-21-021	7.95	0.111 x 0.111	-40 to 110	180	2.5	10.0	50	135	28	5.2×10^{-14}	0.80	15
SD 172-11-21-021 (isolated) -221	15.4	0.185 x 0.125	-40 to 110	100	5.0	20.0	50	255	53	7.0×10^{-14}	1.5	30
SD 200-11-21-041 (isolated) -241	20.3	0.200 (dia.)	-40 to 110	70	6.5	26.0	50	345	71	8.6×10^{-14}	2.03	32
SD 290-11-21-041 (isolated) -241	42.6	0.300 x 0.220	-40 to 110	35	13.0	52.0	50	725	150	1.2×10^{-13}	4.26	70
SD 445-11-21-305	100	0.394 x 0.394	-20 to 75	15	30.0	120	50	1700	350	2.0×10^{-13}	10.0	140

1. Dark Current and Shunt Resistance vary with temperature as follows: for T>23°C, $I_D = 1.09^{\Delta T} I_{D23}$, $R_{SH} = 0.9^{\Delta T} R_{SH23}$ and for T<23°C, $I_D = I_{D23}/1.09^{\Delta T}$, $R_{SH} = R_{SH23}/0.9^{\Delta T}$, where ΔT is the temperature difference from 23°C, and I_{D23} and R_{SH23} are the dark current and shunt resistance at 23°C.
2. Typical values listed. Minimum value shall be 50% of typical.
3. Typical values are listed in the table. Maximum value is 20% higher than the typical value.
4. Test conditions are V_B=-5V and 950nm.
5. Maximum linear current specifies the level above which the output current deviates more than 10%. Short circuit current saturates at approximately 10 times this level.
6. Response times listed are for the rising or falling edge, and were measured at 950nm with a 50Ω load. Shorter wavelengths will result in faster rise and fall times.

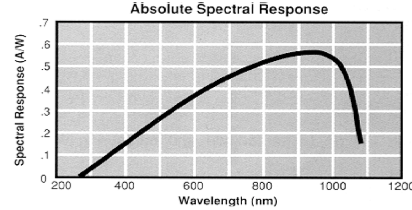
Dark Current vs. Voltage



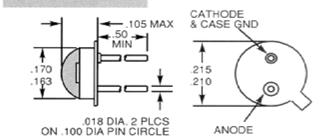
Capacitance vs. Voltage



Absolute Spectral Response

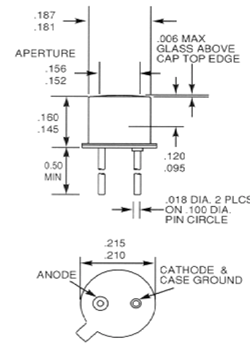


SD 057-11-21-015

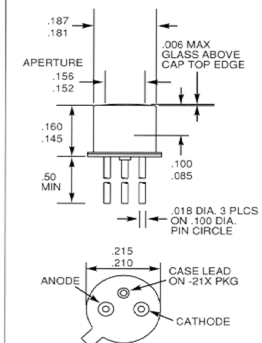


SD 057-11-21-011

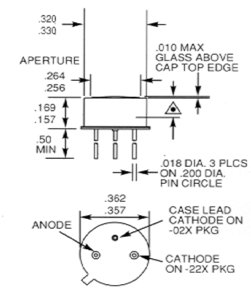
SD 076-11-21-011



SD 076-11-21-211

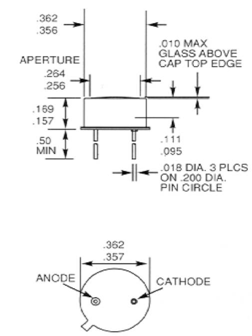


SD 100-11-21-021	.111 .095
SD 100-11-21-221	.098 .078
SD 172-11-21-021	.111 .095
SD 172-11-21-221	.098 .078

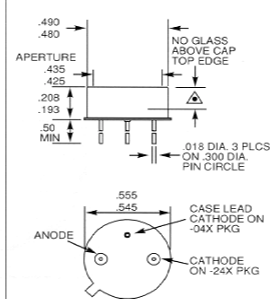


SD 125-11-21-021

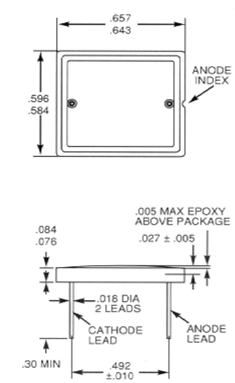
SD 125-11-21-221



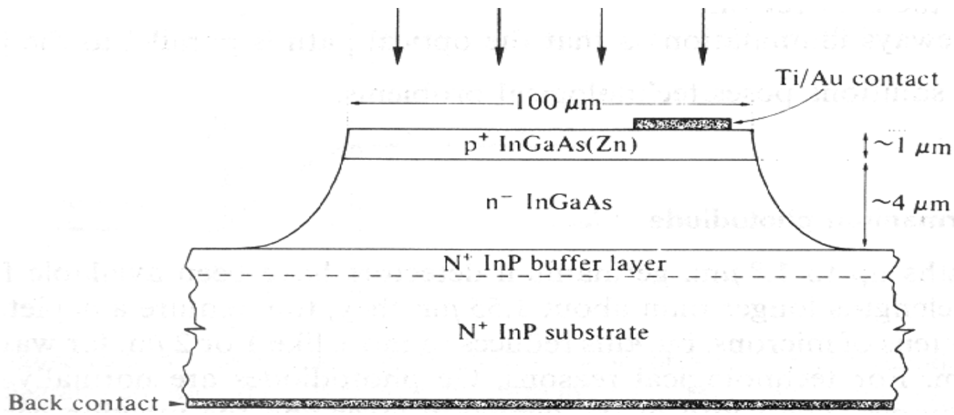
SD 200-11-21-041	.136 .095
SD 200-11-21-241	.111 .115
SD 290-11-21-041	.136 .095
SD 290-11-21-241	.111 .115



SD 445-11-21-305

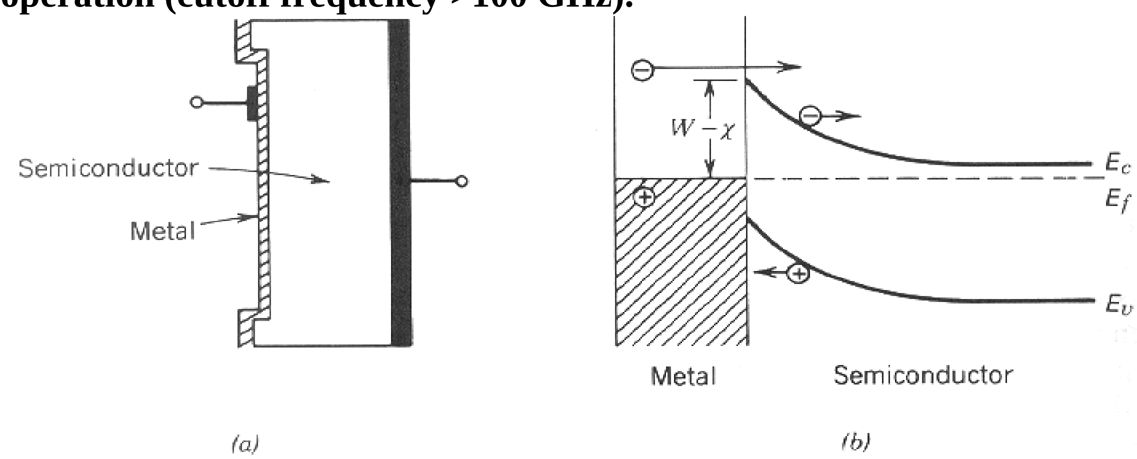


2). Heterojunction Diodes—For photodiode designs that involve light incident normal to the junction, absorption in the layer before the space charge region (usually the p doped region) may be a significant problem for wavelengths that are strongly absorbed. For this reason, most photodiode designs employ a very narrow layer of highly doped p material in order to minimize this absorption loss. Heterojunctions may also be employed to eliminate this effect by using a p material that has a larger bandgap than the energy of the photons being detected, thus acting as a transparent window to the incident light.



An example of a heterojunction photodiode.

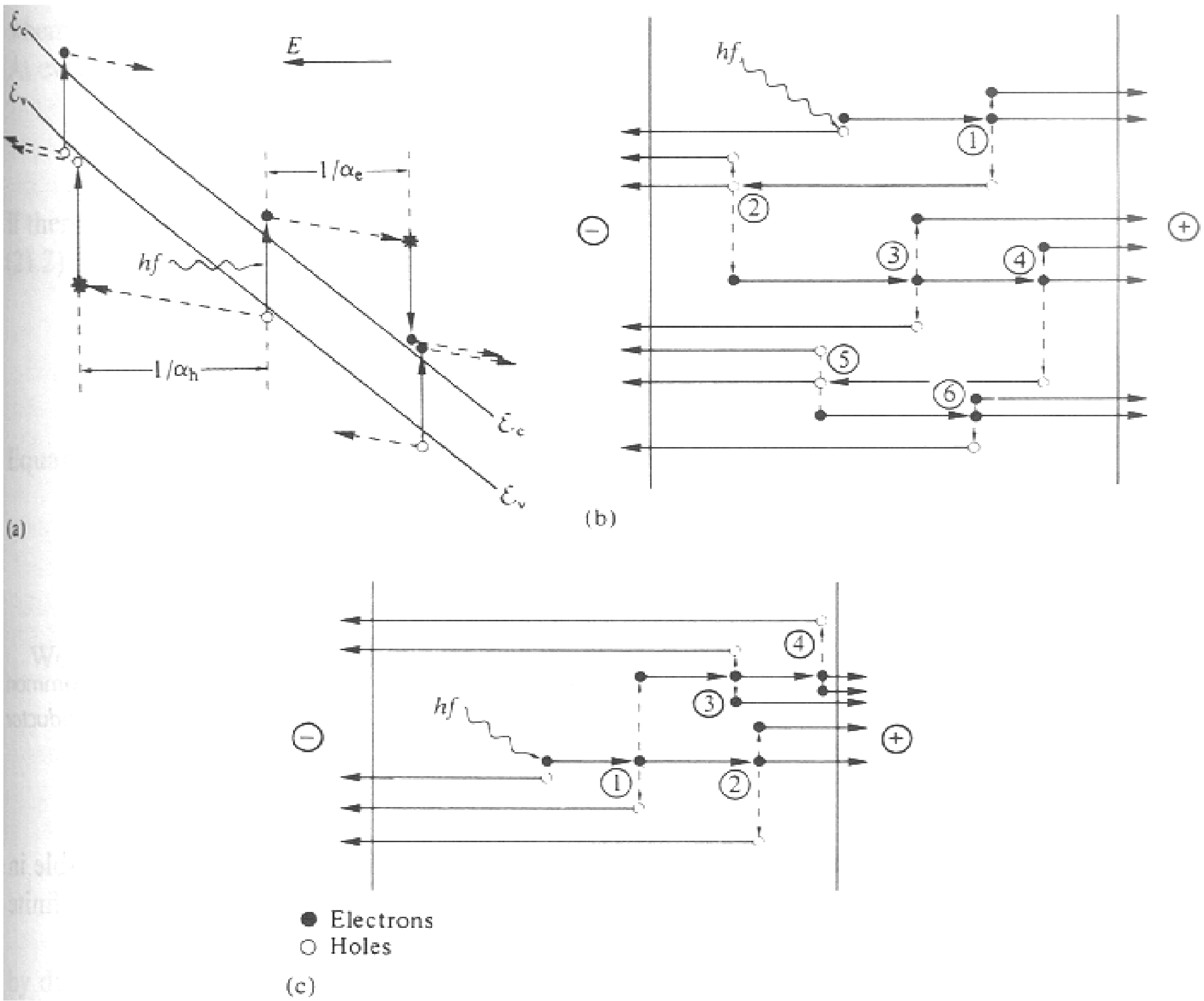
3). Schottky Diodes—Schottky-barrier photodiodes replace the p-n junction with a metal-semiconductor junction in which the metal layer is thin enough to be transparent to the incident radiation (which may also simultaneously act as an anti-reflection coating for the diode). Since the junction essentially occurs at the surface of the diode, all of the incident light is absorbed in the active region, and the charge carrier transit time is dramatically reduced allowing high-frequency operation (cutoff frequency >100 GHz).



(a) A simple Schottky diode and (b) the corresponding band diagram.

V. Avalanche Diodes

1). Avalanche photodiodes (APD) exhibit internal gain such that a single photon may produce hundreds of charge carrier pairs. Since the internal gain generally produces less noise than an equivalent external amplifier, APD's are useful for very low light conditions in which minimization of the noise is critical.



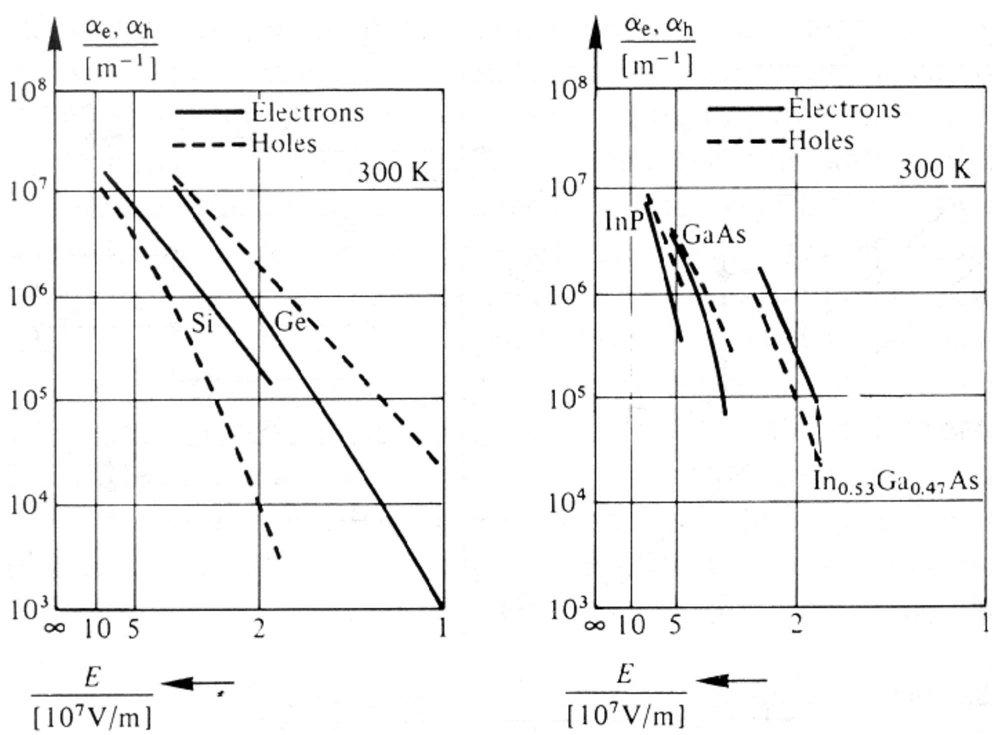
Avalanche multiplication in semiconductors: (a) impact ionization process in a uniform electric field depicted on an energy band diagram, (b) avalanche multiplication with positive feedback, and (c) without feedback for k=0.

2). APD's utilize the phenomenon of avalanche breakdown in which the field within the junction is made very large by applying a strong reverse bias. The charge carriers then may gain enough energy from the field to create additional charge carrier pairs through impact ionization.

The charge carriers created by the absorption of a photon are accelerated in the electric field until after an average distance of 1/α they gain enough energy to excite a new pair of charge carriers, where α_e is the electron ionization coefficient and α_h is the hole ionization coefficient. Thus, as the multiplication process continues across the junction, the current grows exponentially with a characteristic length of 1/α. The ratio $k=\alpha_h/\alpha_e$ is known as the ionization ratio and represents the relative effectiveness of holes and electrons to ionize new carriers.

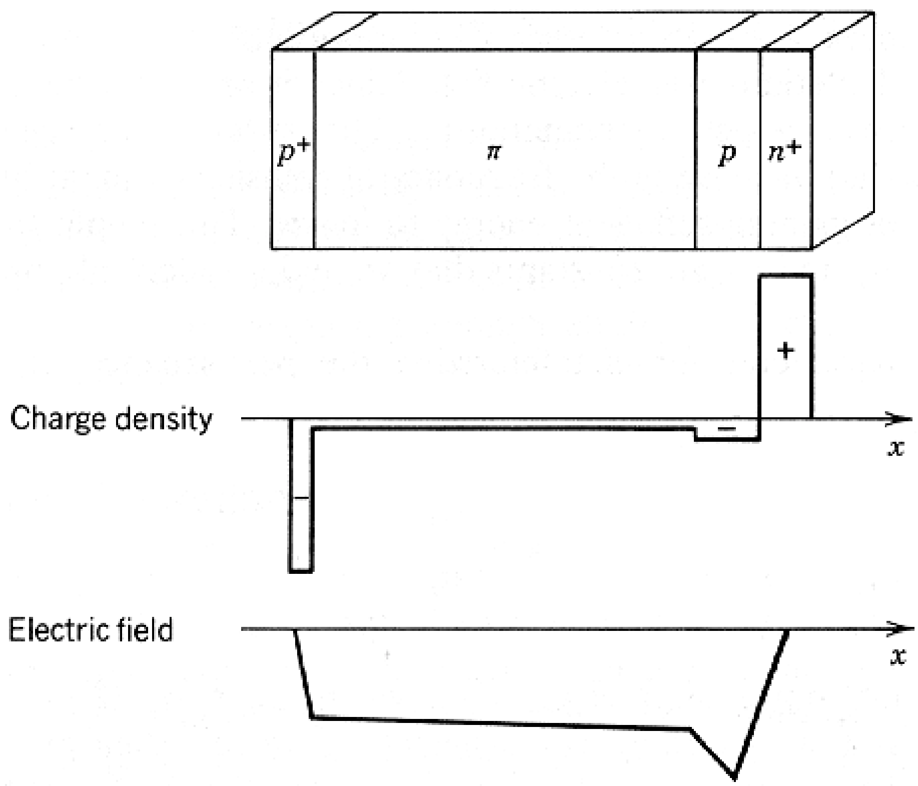
3). Since the ionization coefficients increase rapidly with field strength, a breakdown field E_B and voltage V_B are usually defined such that for fields larger than the breakdown value the ionization coefficient is greater than ~10^6 m^{-1}.

4). If both holes and electrons may ionize new carrier pairs, the multiplication exhibits positive feedback and the possibility of an infinite gain. For high performance APD's, we would like to eliminate all of the feedback due to the instability, noise, and reduced frequency response that results from the feedback. Thus, APD materials and bias voltages are chosen so that k<<1 or k>>1.



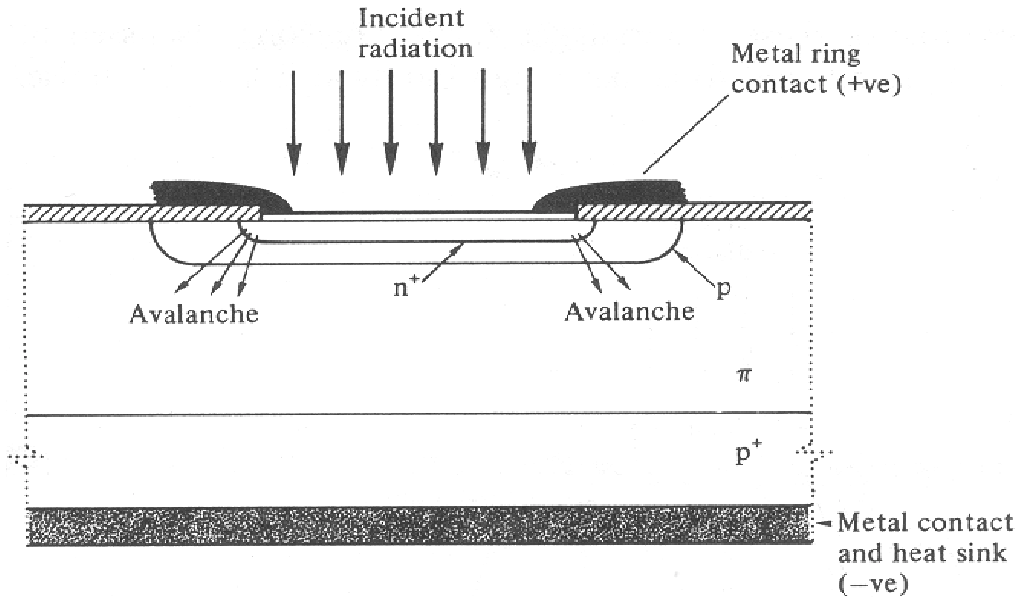
Ionization coefficients as a function of electric field strength.

5). In an APD, we would like to have the largest active area as possible in order to maximize the useful absorption, but we would also like to minimize the size of the multiplication region in order to reduce instabilities in the avalanche process due to excessive local electric fields (greater field uniformity may be obtained in a thin region). The simplest type of APD that satisfies these conditions is based on the "reach-through" p-π-p-n design. In this design, a lightly doped p region π is used as the active absorption region of the junction, and an additional p region is grown next to the n region in order to increase the field strength to the point of avalanche breakdown near the p-n junction.

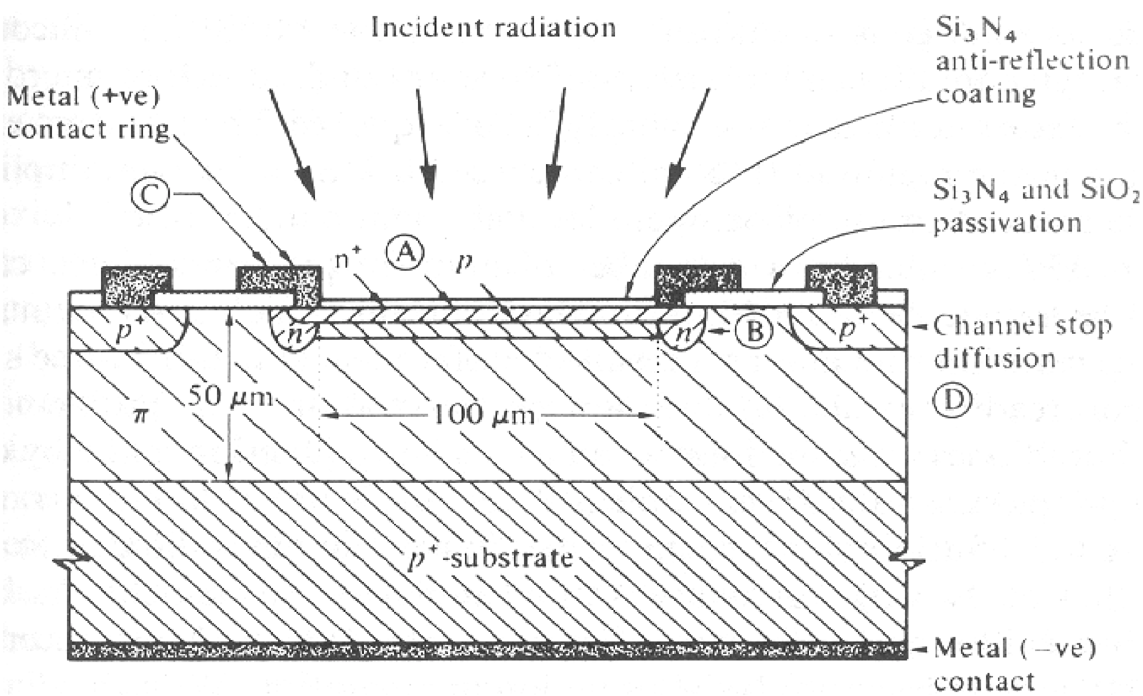


The "reach-through" p-π-p-n avalanche photodiode structure.

6). In APD's, extra care must be taken to design junctions that create the most uniform electric fields within the diode, otherwise breakdown may occur unevenly across the junction.



In this APD, the charge concentration at the corners produce a higher local electric field and thus breakdown will occur there first.



This design overcomes this problem by including a lightly doped n "guard ring" about the edge of the multiplication region that acts to reduce the electric field at the corners.