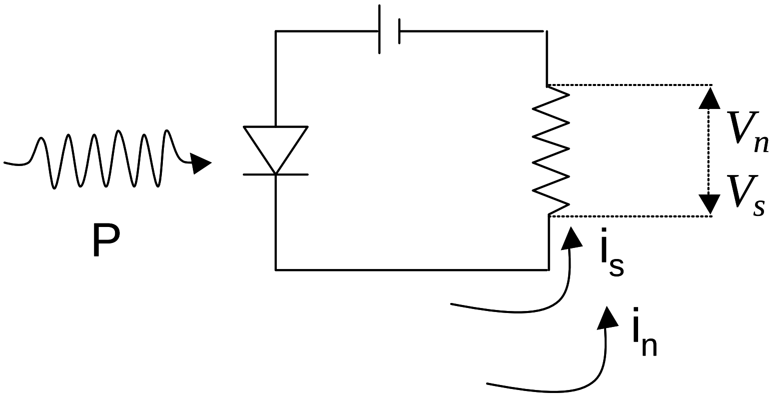
Basic Properties of Photodetectors



1. *Responsivity*: How much signal is obtained per unit of optical power? This is usually specified in Amps/Watt (A/W) or in Volts/Watt (V/W). For example we can write:

$$i_s = PR$$

where P is the optical power, R is the responsivity, and i_s is the signal current generated in the circuit.

2. *Spectral Response*: How the responsivity varies with wavelength.

3. *Sensitivity*: Following “Optical Radiation Detectors” by Dereniak and Crowe we define the following figures of merit for detector sensitivity:

   a. NEP ≡ The “Noise Equivalent Power” ≡ The optical power required to generate a signal current i_s that is equal to the root mean square noise current $i_{rms} = \sqrt{\langle i_n{}^2 \rangle}$.

$$i_{rms} = NEP \times R$$

b. Detectivity, D $\equiv$ 1/NEP (smaller NEP is better but bigger D is better)

c. D^* (pronounced "Dee Star") = $(A\,\Delta f)^{1/2}$ D, where A is the detector area and Δf is the detector bandwidth. The noise in most photodetectors is proportional to $(A\,\Delta f)^{1/2}$, and including this factor in the definition of D^* takes this into account – if two photodetectors have the same D, the one with the larger $(A\,\Delta f)^{1/2}$ is considered better and gets a larger D^*.

4. *Time Response (Frequency Response)*: How fast does the detector respond to a change in signal?

5. Quantum Efficiency: Number of electrons-hole pairs collected (created and separated to the n and p regions) for each photon.

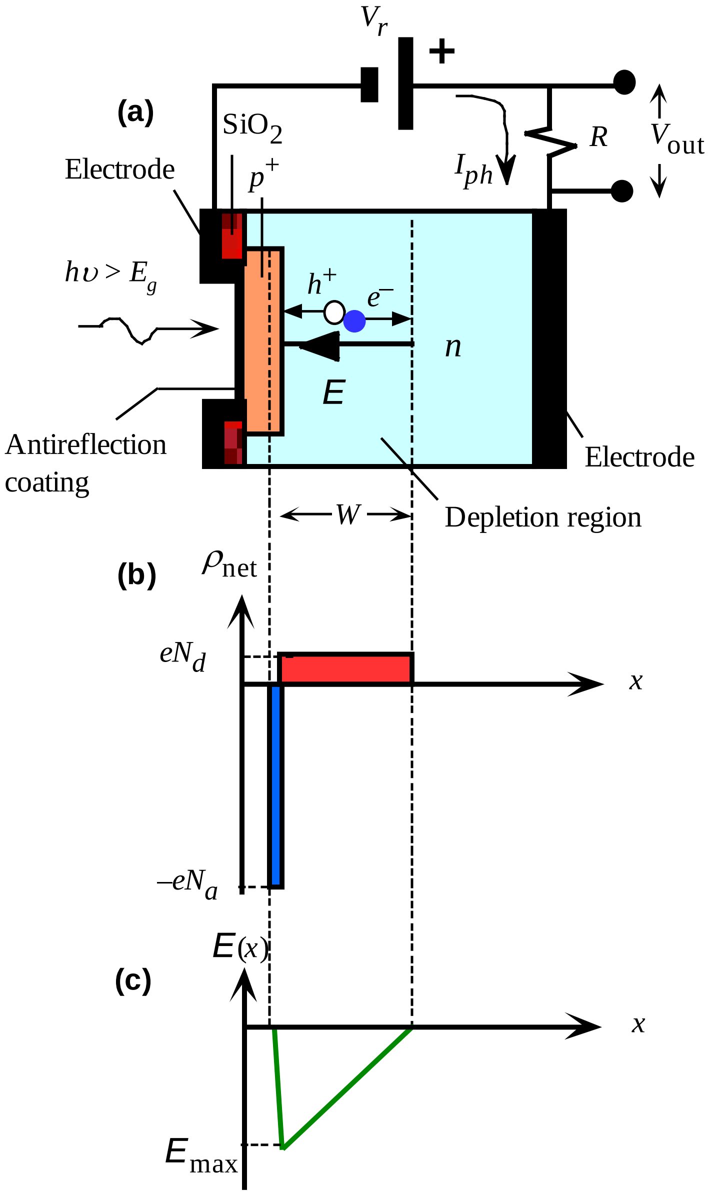
$$QE = \frac{\text{Electron-Hole Pairs Collected}}{\text{Number of Photons}}$$

   a. External Quantum Efficiency – We calculate with the number of photons incident on the front surface of the detector.

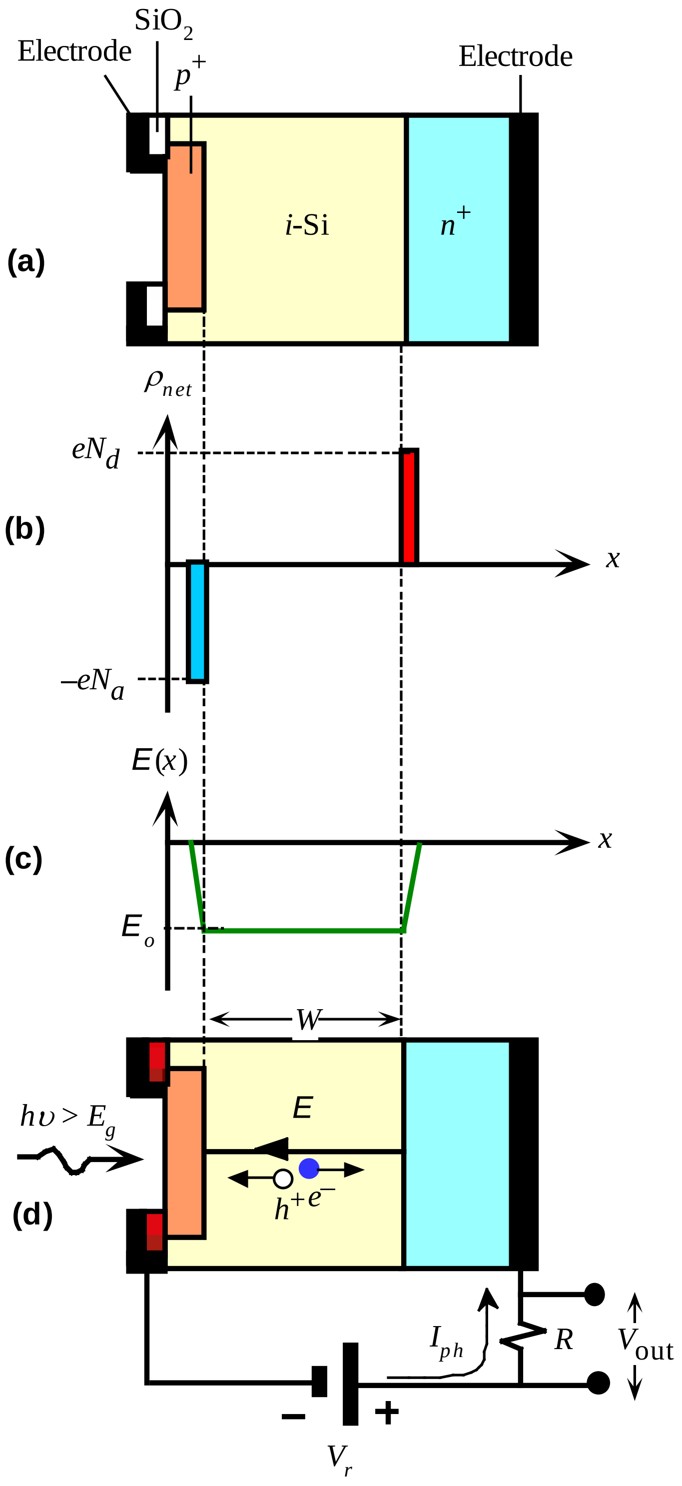
   b. Internal Quantum Efficiency – We calculate with the number of photons that enter the photodetector.

Photodiodes

Photodiodes are compact, inexpensive, sensitive, and fast; but they have limited spectral response.

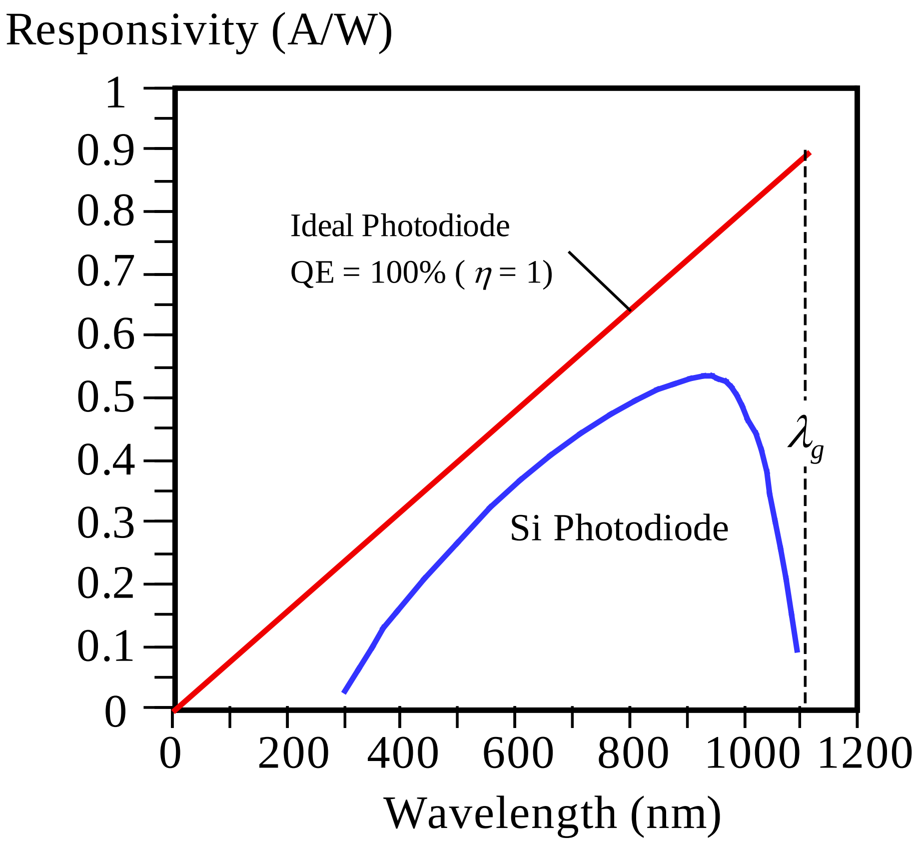


(a) A schematic diagram of a reverse biased *pn* junction photodiode. (b) Net space charge across the diode in the depletion region. N_d and N_a are the donor and acceptor concentrations in the p and n sides. (c). The field in the depletion region.



The schematic structure of an idealized *pin* photodiode (b) The net space charge density across the photodiode. (c) The built-in field across the diode. (d) The *pin* photodiode in photodetection is reverse biased.

Responsivity for a Photodiode:



Responsivity (*R*) vs. wavelength (λ) for an ideal photodiode with QE = 100% ($\eta = 1$) and for a typica commercial Si photodiode.

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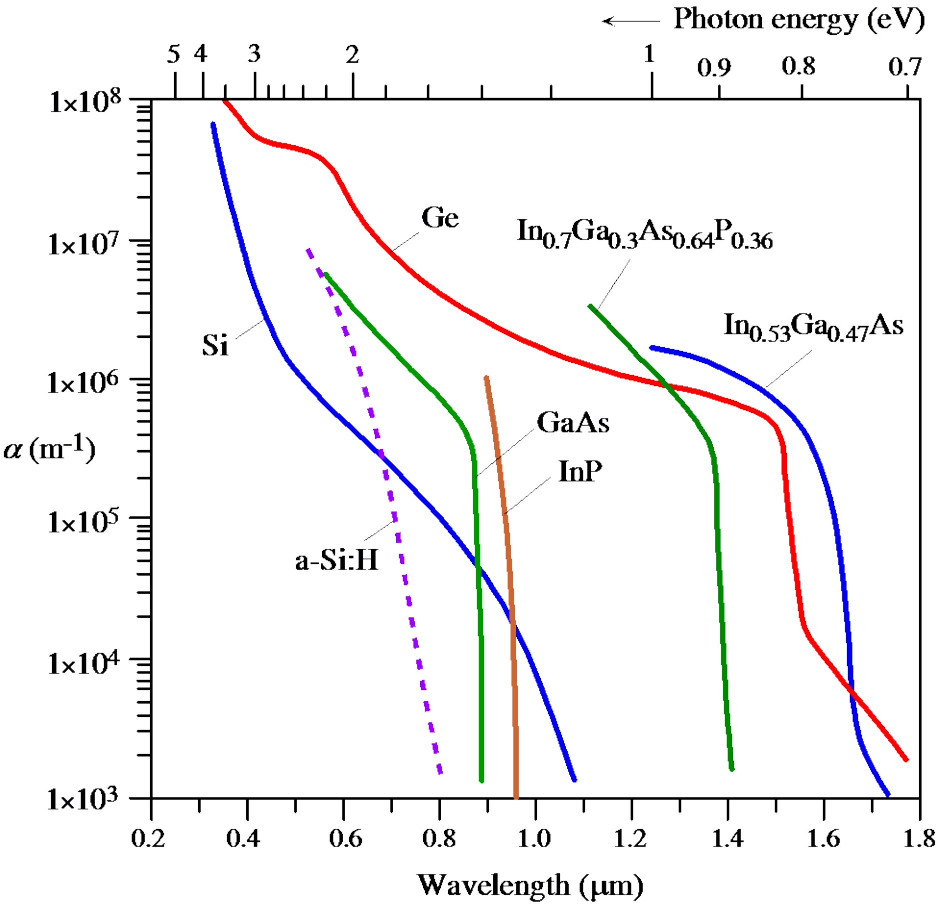
Note 1. R is small beyond a cut-off wavelength corresponding to the semiconductor band gap.

Note 2. R decreases at shorter wavelengths because the number of photogenerated electrons = $\eta P/h\nu = \eta P\lambda/hc$, which decreases with wavelength.

Note 3. Choosing the correct semiconductor material for a photodiode includes selecting one with a small enough band gap but sensitivity must also be taken into account (see next section)



Absorption coefficient (α) vs. wavelength (λ) for various semiconductors
(Data selectively collected and combined from various sources.)

From <u>Optoelectronics and Photonics</u>, Kasap

Photodiode Sensitivity

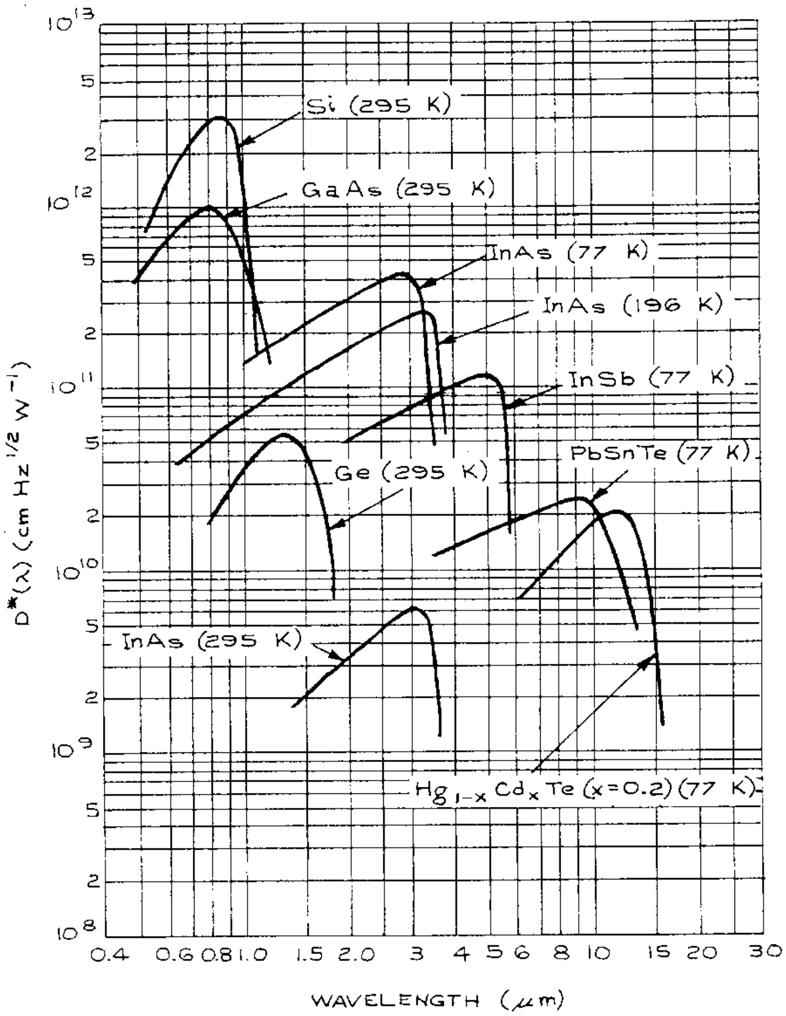


Figure 4.137 D^* as a function of wavelength for various photovoltaic detectors. (Courtesy of Hughes Aircraft Company.)

From Building Scientific Apparatus,1st Edition, Moore et al., Figure 4.137

Note: The peak D^* is larger for photodiodes made from semiconductors with larger band gap because there is less generation of electrons-hole pairs across the gap by background radiation.

Time Response for a Photodiode

The temporal response is limited by:

1. Drift Time
2. Diffusion Time

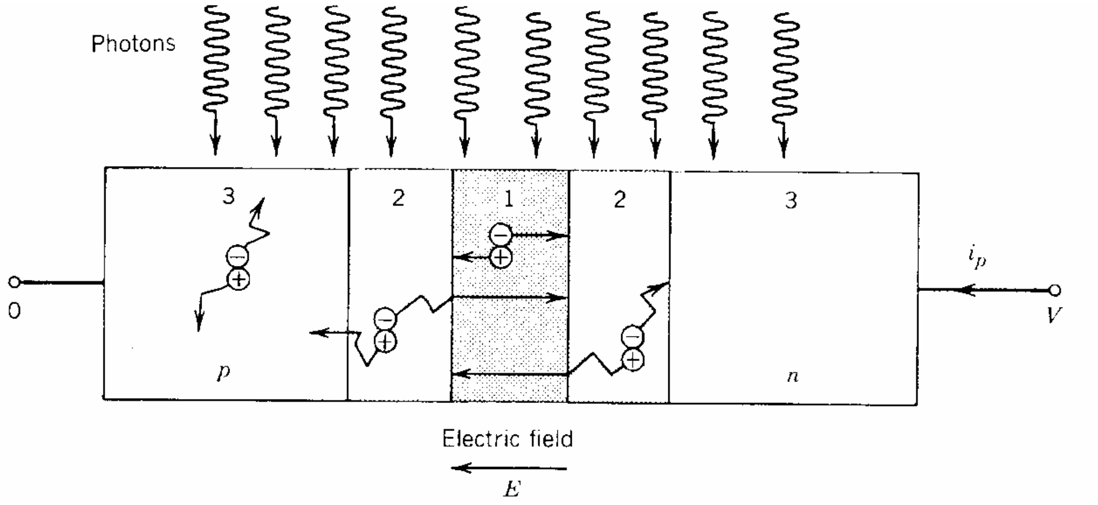


Figure 17.3-1 Photons illuminating an idealized reverse-biased p-n photodiode detector. The drift and diffusion regions are indicated by 1 and 2, respectively.

From Photonics, Saleh and Teich.

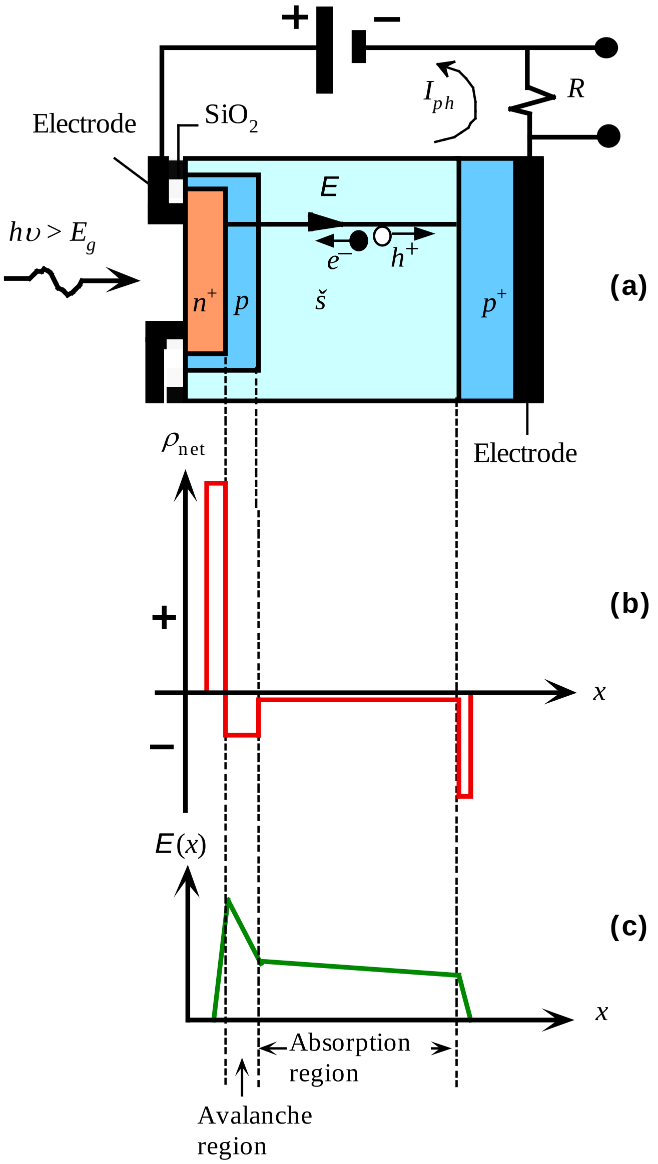
3. RC Time Constant, $\tau = RC$

For high-speed operation, diffusion is minimized and photodiode area is kept small to minimize the RC Time Constant.

Commercial photodiodes have bandwidth up to 40 GHz (InGaAs pin photodiodes available from Opto Speed).

Avalanche Photodiodes (APDs)

→ A photodiode with built-in gain



(a) A schematic illustration of the structure of an avalanche photodiode (APD) biased for avalanche gain. (b) The net space charge density across the photodiode. (c) The field across the diode and the identification of absorption and multiplication regions.

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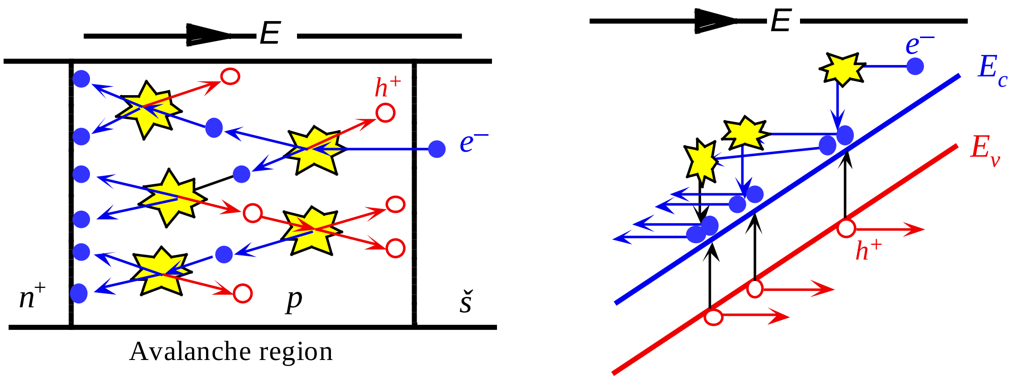

(a) **(b)**

(a) A pictorial view of impact ionization processes releasing EHPs and the resulting avalanche multiplication. (b) Impact of an energetic conduction electron with crystal vibrations transfers the electron's kinetic energy to a valence electron and thereby excites it to the conduction band.

$$M \equiv \frac{I_{APD}}{I_{ph}} \quad \text{("Multiplication Factor", } \sim \text{ 10-100)}$$

$$R_{APD} = MR_0$$

Note that the quantum efficiency for an “APD” can be greater than one.