PHOTOVOLTAIC DETECTORS: p-n JUNCTION

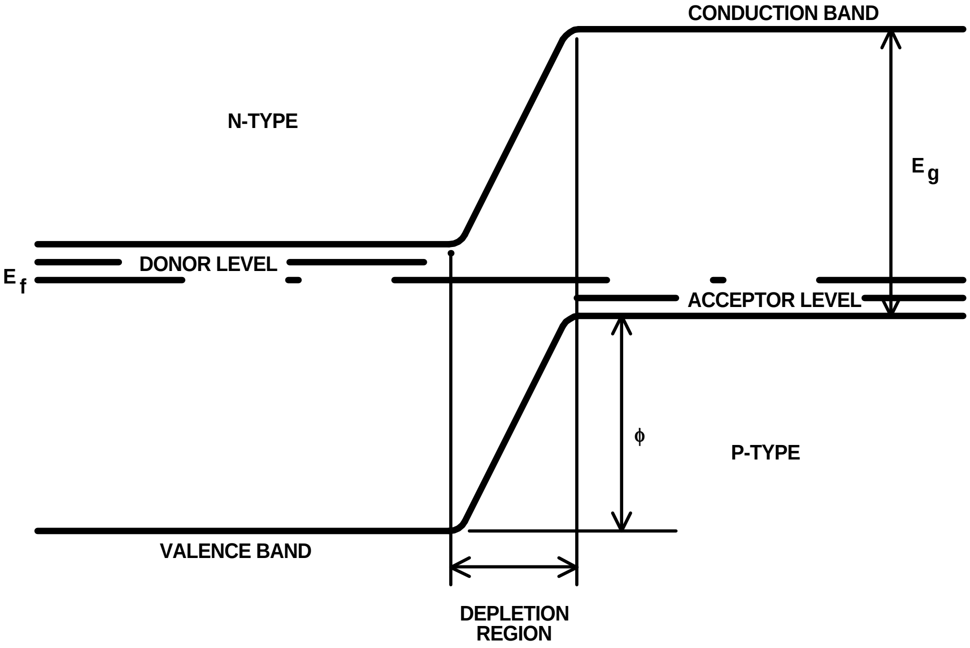
Two opposite impurity-doped semiconductors:

- n-type (donor, As, Sb, P)
  - electrons are majority carriers
  - holes are minority carriers
- p-type (acceptor, Al, B, In, Ga)
  - holes are majority carriers
  - electrons are minority carriers

Majority carriers mobile, minority carriers not.

JUNCTION FORMATION:

1. Free electrons in n-region attracted to positive charge in p-region, drift on over
2. Free holes in p-region attracted to negative charge in n-region, drift on over
3. Leaves n-region with net positive charge and p-region with net negative charge. Whole crystal neutral
4. Potential barrier formed at junction.



Height of potential barrier ϕ depends upon donor and acceptor energy levels and concentrations.

$$f \approx \frac{kT}{q} \ln \frac{n_n p_p}{n_i^2}$$

n_n = electrons in n-region (majority carriers)

p_p = holes in p-region (majority carriers)

n_i^2 = intrinsic carrier concentration

Since n_i is strong function of temperature,

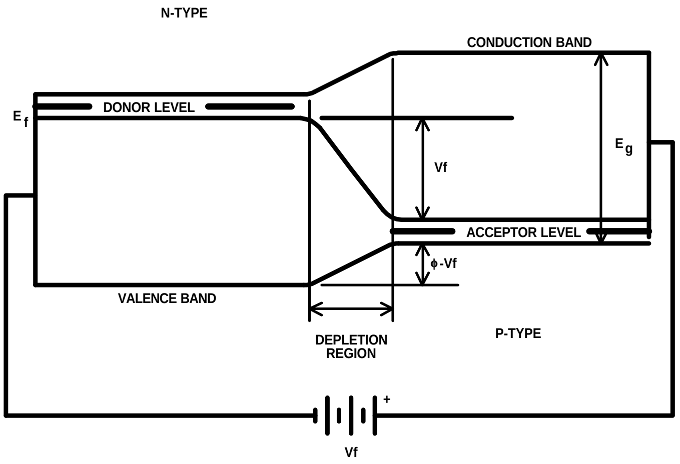
as T↑, ϕ↓

Fermi level constant in equilibrium junction

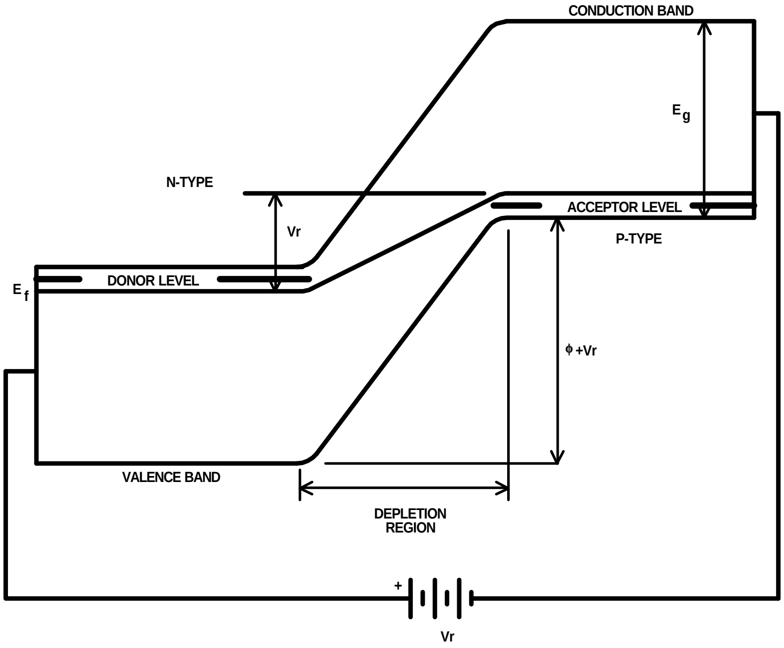
BIASING THE p-n JUNCTION

Apply external bias across junction

FORWARD BIAS: barrier height reduced; high current, due to majority carriers; depletion region narrower



REVERSE BIAS: barrier height increased; low current due to minority carriers; depletion region wider


CONDUCTION BAND
E_g
N-TYPE
ACCEPTOR LEVEL
Vr
P-TYPE
E_f
DONOR LEVEL
ϕ +Vr
VALENCE BAND
DEPLETION
REGION
+
Vr

I-V CHARACTERISTICS

Equation of I-V characteristics of p-n junction diode:

$$I = I_o \left[e^{\frac{qV}{bkT}} - 1 \right]$$

where I_o = reverse saturation current,

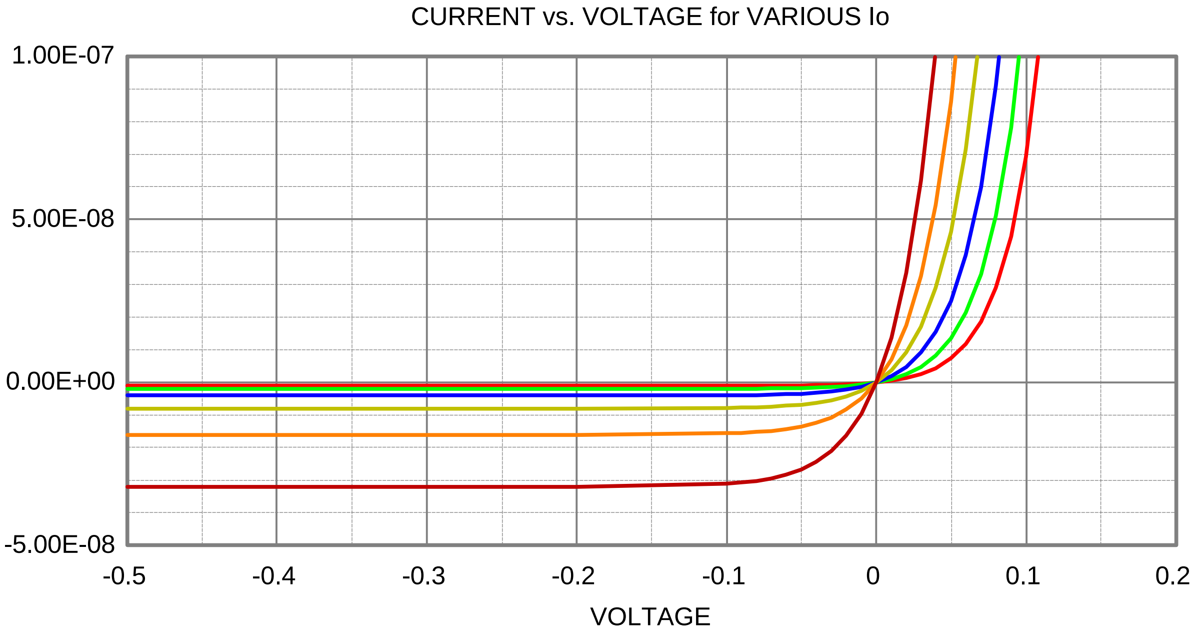
q = electronic charge = 1.602 177 33 (49) $\times 10^{-19}$ C

V = applied voltage

β = "fudge factor," to make the equation fit the data; varies between 1 and 3, voltage dependent.

k = Boltzmann's constant = 1.380658 (12) ×10-23 J/K

T = temperature (K) (q/kT≈38.7 @ 300K)



REVERSE SATURATION CURRENT

$$I_o = qA\left(\frac{n_p D_n}{L_n} + \frac{p_n D_p}{L_p}\right)$$

where

q = electronic charge

n_p = minority carrier concentration (electrons)
in p-region

D_n = Einstein diffusion constant of electrons

L_n = minority carrier diffusion length (electrons)
in p-region

p_n = minority carrier concentration (holes)
in n-region

D_p = Einstein diffusion constant of holes

L_p = minority carrier diffusion length (holes)
in n-region

A = area

Einstein diffusion constant

$$D = \frac{kT}{q}\mu$$

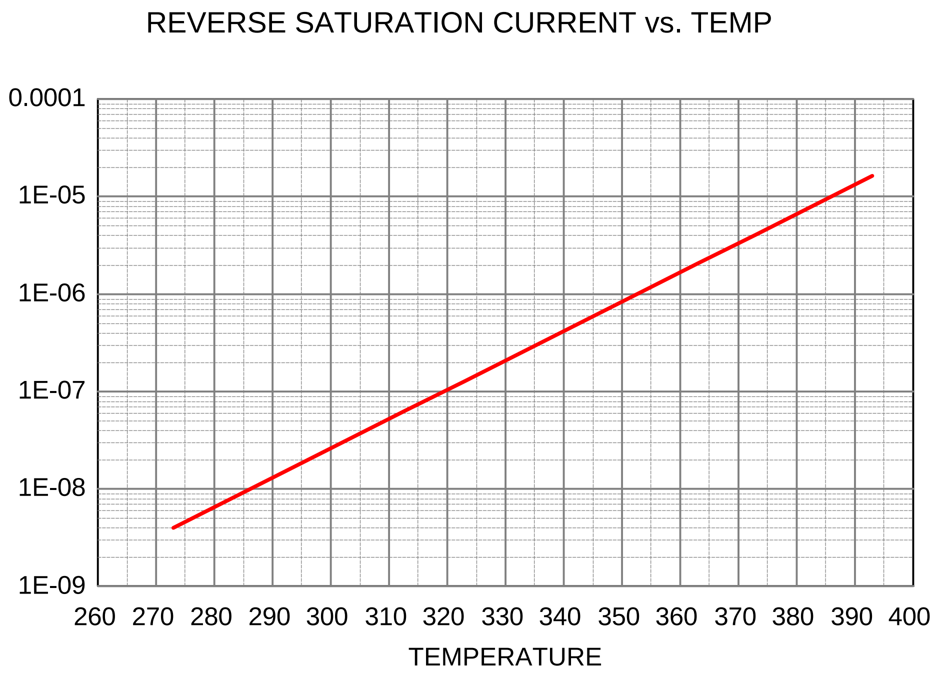
where μ is mobility

Minority carrier diffusion length

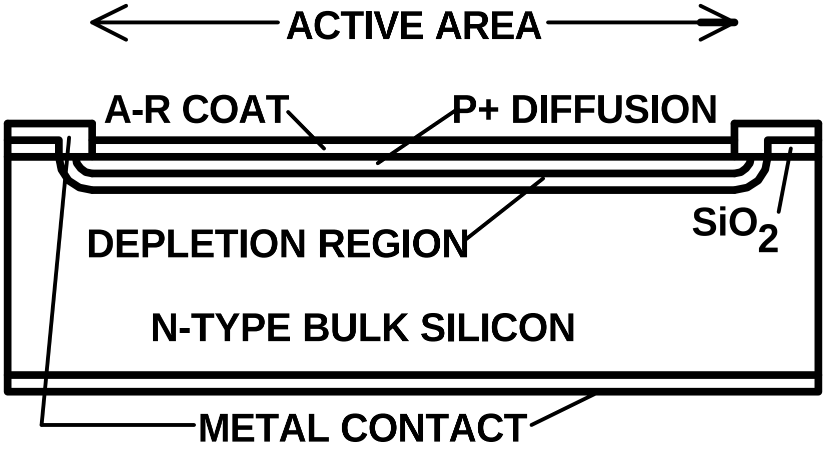
$$L = \sqrt{Dt}$$

where τ is minority carrier lifetime

Strongly temperature dependent through minority carrier concentrations.



p-n JUNCTION PHOTODIODE



Photon with energy >E_g creates electron-hole pair.

$$\lambda_c = \frac{1.2398}{E_g} \quad (\lambda \text{ in } \mu m)$$

Carriers generated within depletion region are immediately separated by potential across barrier.

Carriers generated outside depletion region may diffuse to junction to be separated by potential barrier. Governed by minority carrier diffusion length and carrier lifetime.

Result: voltage generated across barrier; magnitude related to potential barrier height ϕ and amount of light.

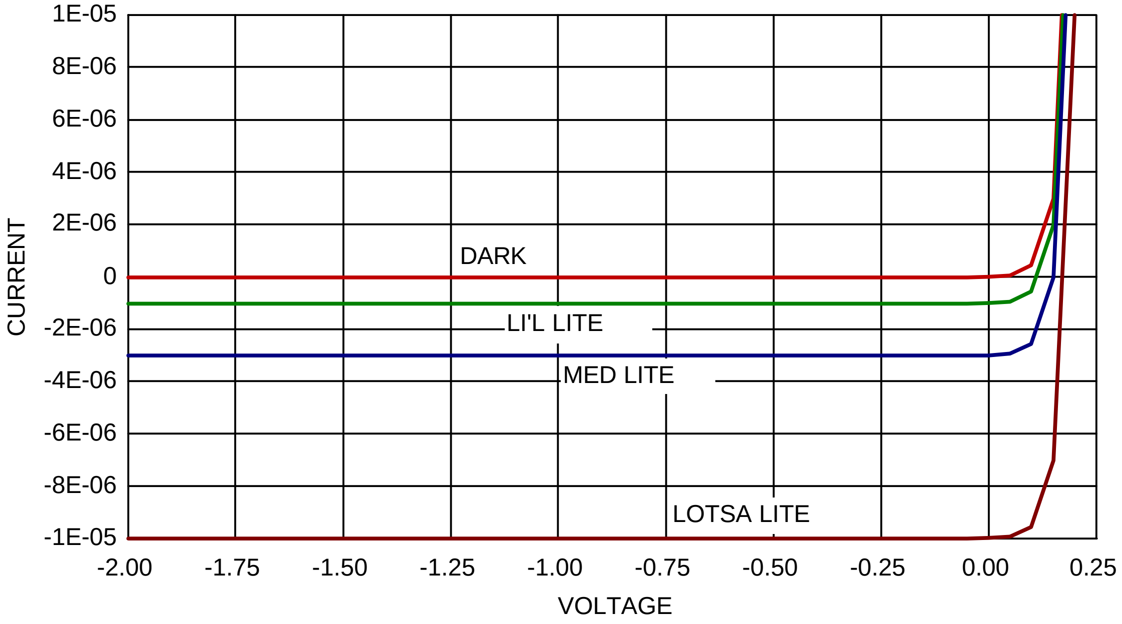
EQUATION OF PHOTODIODE

Current generated due to light, which adds to dark current

$$\boxed{I = I_o \left(e^{\frac{qV}{bkT}} - 1 \right) - I_g}$$

where

$$\mathrm{I_g} = \; h\mathrm{q}\Phi_{\mathrm{p}} = h\mathrm{q}\frac{l}{\mathrm{hc}}\Phi$$



QUANTUM EFFICIENCY

Photons with $\lambda > \lambda_c$ not absorbed

Electron-hole pairs created outside depletion region not all utilized

Electron-hole pairs created beyond diffusion length not utilized (increase depletion width via reverse bias)

Surface recombination (passivate)

Optical losses [reflection (A-R coat) and transmission]

Most photons have more energy than needed to create electron-hole pair - excess energy just heats

Barrier height less than E_g

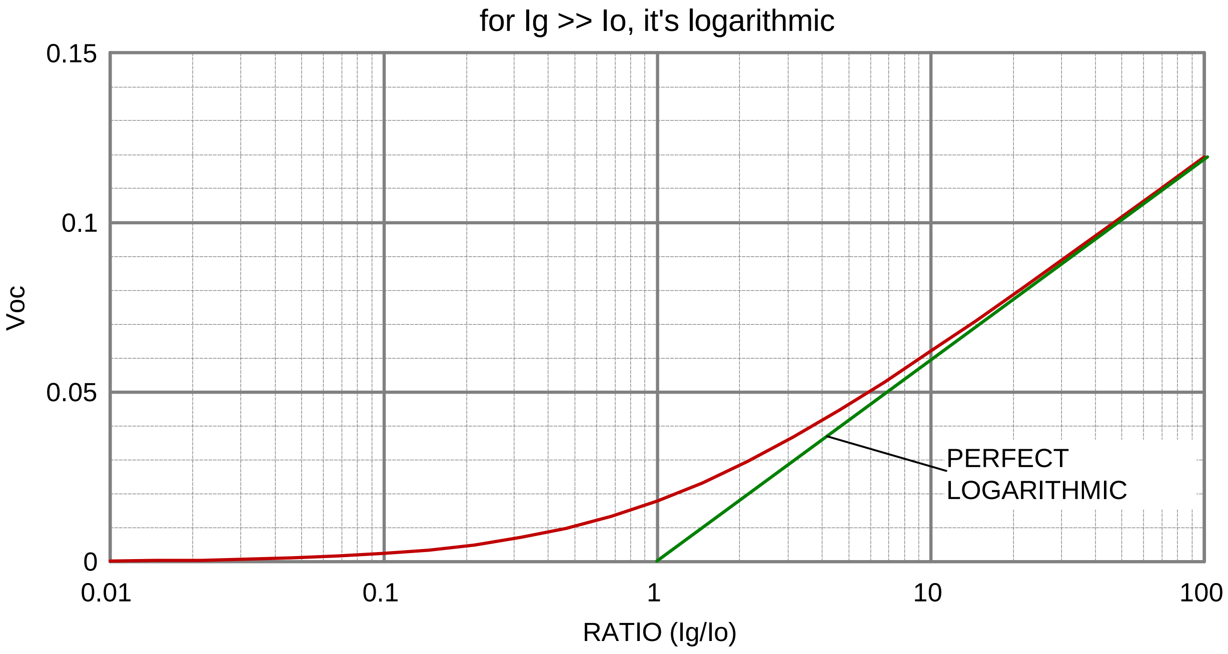
OPERATING POINTS

SHORT-CIRCUIT CURRENT: At $V = 0$, $I = -I_g$ which is linear with incident radiant power.

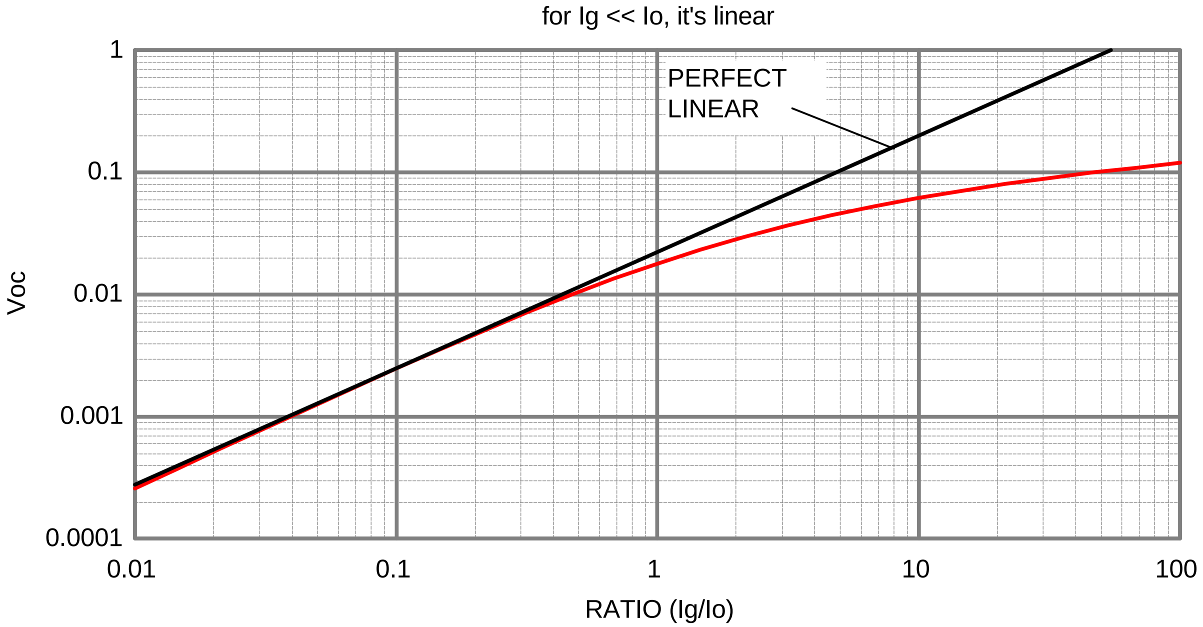
OPEN-CIRCUIT VOLTAGE: At $I = 0$, then

$$V_{oc} = \frac{b\,kT}{q}\ln\left(\frac{I_o + I_g}{I_o}\right)$$

If $I_g \gg I_o$, V_{oc} is logarithmic with radiant power.



If $I_g << I_o$, V_{oc} is linear with radiant power.



If $I_o \approx I_g$, operation intermediate between linear and logarithmic.

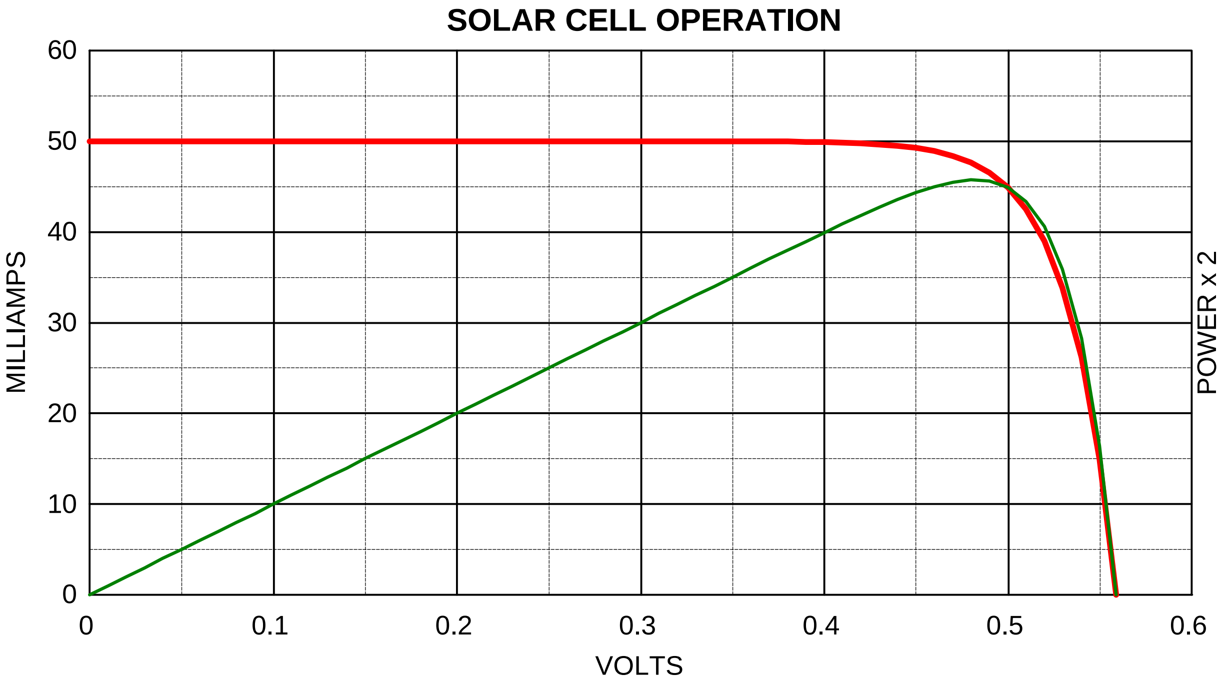
POWER GENERATION

If load resistor R_L placed directly across detector,

I-V characteristic encloses an area

Current and voltage available simultaneously

Power generation capability (solar cell)

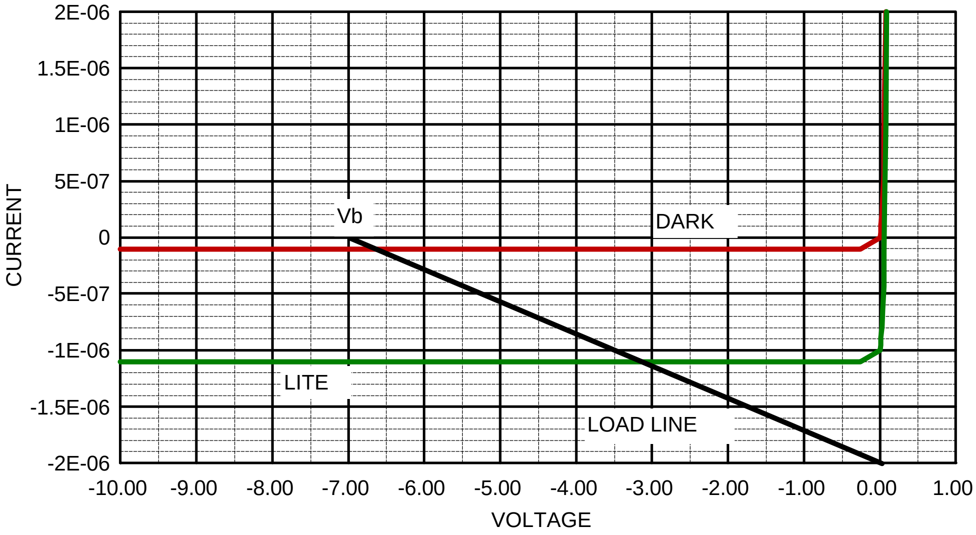


Parasitic resistances (series and shunt) become loss

elements for power generation

REVERSE BIASING THE PHOTODIODE

Bias into third quadrant; requires voltage source and load resistor



$$I = -I_o - I_g$$

ADVANTAGES:

1. **Better long-wavelength response due to less recombination**
2. **Increased speed due to electric field which sweeps carriers out**
3. **Increased speed due to lower junction capacitance $C = const\,(V-0.6)^n$, $-1/2<x<-1/3$**

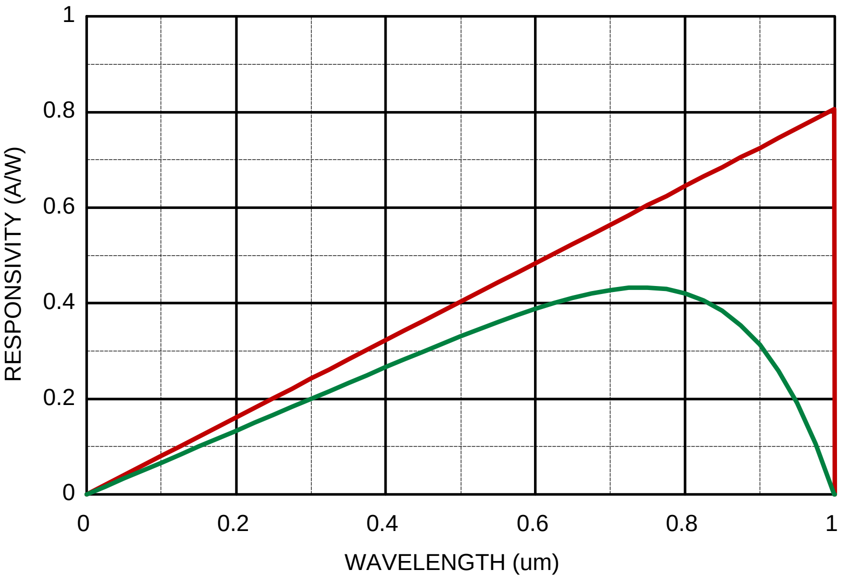
DISADVANTAGES:

1. **Presence of I_o and its temperature dependence**
2. **Requires relatively stable, quiet voltage source**

PHOTOVOLTAIC DETECTOR CHARACTERISTICS

Responsivity

$$\Re = hq\frac{l}{hc}$$



Noises

Shot due to current (signal, background, dark)

$$i_S = \sqrt{2q(i_{sig} + i_{bkgnd} + i_{dark})B}$$

Johnson (dynamic resistance)

$$i_J = \sqrt{\frac{4kTB}{R_{dyn}}}$$

1/f (contacts)

$$i_{1/f} = \sqrt{\int \frac{const \cdot I_{dc}\, df}{f}}$$

LIMITING NOISE IN PHOTOVOLTAICS

Signal equation

$$i_s = \Phi\Re = hq\frac{l}{hc}\Phi = hq\Phi_p$$

Shot noise due to current flow limits

$$\overline{i_n^2} = 2qi_{DC}B$$

i_{DC} from signal (visible) and background (infrared)

$$\overline{i_n^2} = 2hq^2\frac{l}{hc}\Phi B = 2hq^2\Phi_p B$$

$$D^*_{BLIP} = \frac{i_s}{i_n}\cdot\frac{\sqrt{AB}}{\Phi} = \sqrt{\frac{h\,l}{2hcE}} = \frac{l}{hc}\sqrt{\frac{h}{2E_p}}$$

Better than photoconductive detector by $\sqrt{2}$.

No recombination noise

PHOTOVOLTAIC DETECTOR CHARACTERISTICS
II

Linearity

At short-circuit current for high-quality photodiodes, easy to demonstrate linear over seven decades, claimed linear to 14 decades

Dynamic resistance

$$R_d = \frac{dV}{dI} = \frac{b\,kT}{qI_o} e^{-qV/AkT}$$

At zero bias it becomes

$$R_d = \frac{dV}{dI} = \frac{b\,kT}{qI_o}$$

As T↑, R_d↓

- **For minimum Johnson noise current due to detector resistance, need high R.**
- **Longer λ photodiodes have lower E_g, higher I_o, lower R_d, and are noisier.**

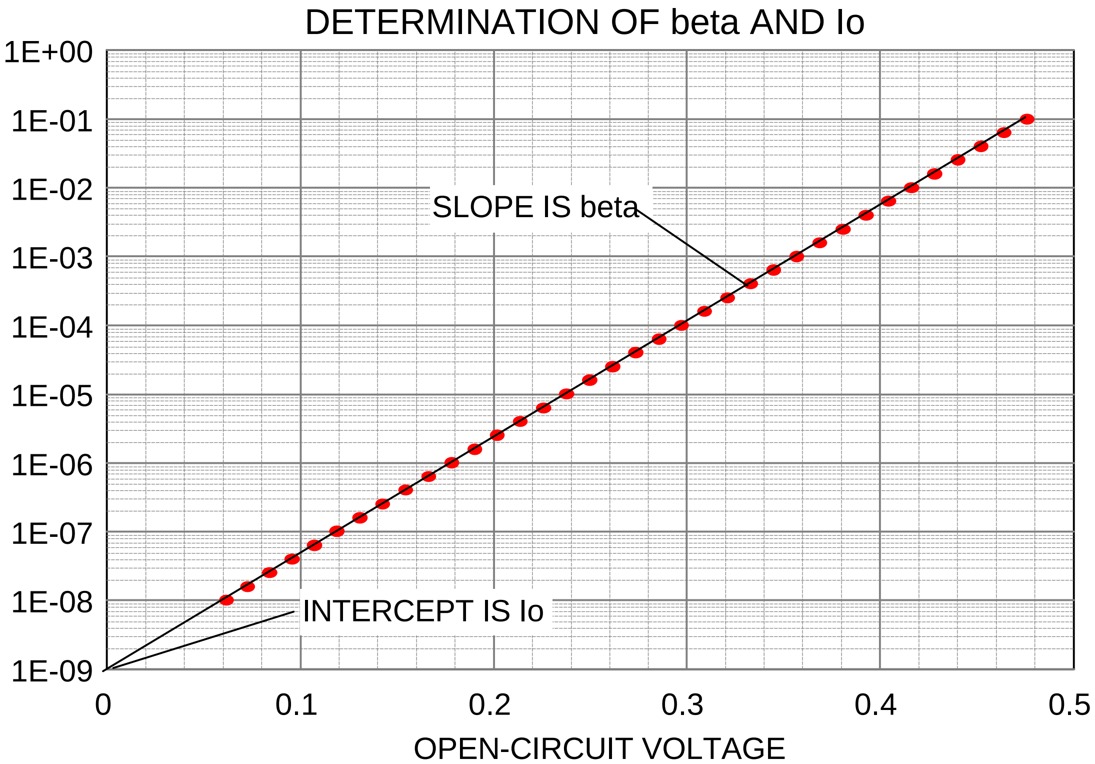
DETERMINATION OF β AND I_o

Determine short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) as a function of light level

Plot log(I_{sc}) vs. V_{oc}

Slope of best-fit straight line is β

Current at intercept (V=0) is I_o

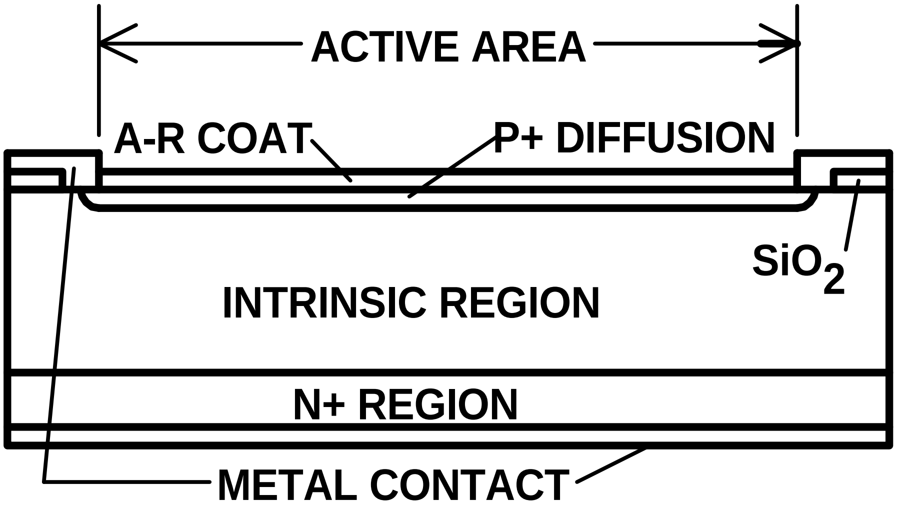


PHOTOVOLTAIC DETECTOR MATERIALS

MATERIAL	Eg (eV)	λc (μm)	NOTES
GaP	2.4	0.52	
GaAs	1.4	0.93	
Si	1.12	1.1	indirect
InGaAs	0.73	1.7	
Ge	0.68	1.82	indirect
InGaAs	0.59	2.1	
InGaAs	0.50	2.5	
InAs	0.28	3.5	
InSb	0.16	5.5	
HgCdTe	variable	variable	variable
PbSnTe	variable	variable	variable

P-I-N PHOTODIODES

Fabricated with wide depletion layer, occupies most of structure



Needs reverse bias for electric field to sweep out carriers

Low capacitance (<5pF)

Fast! (to 60 GHz)

Available in small (25 μm) to medium (1 mm) sizes

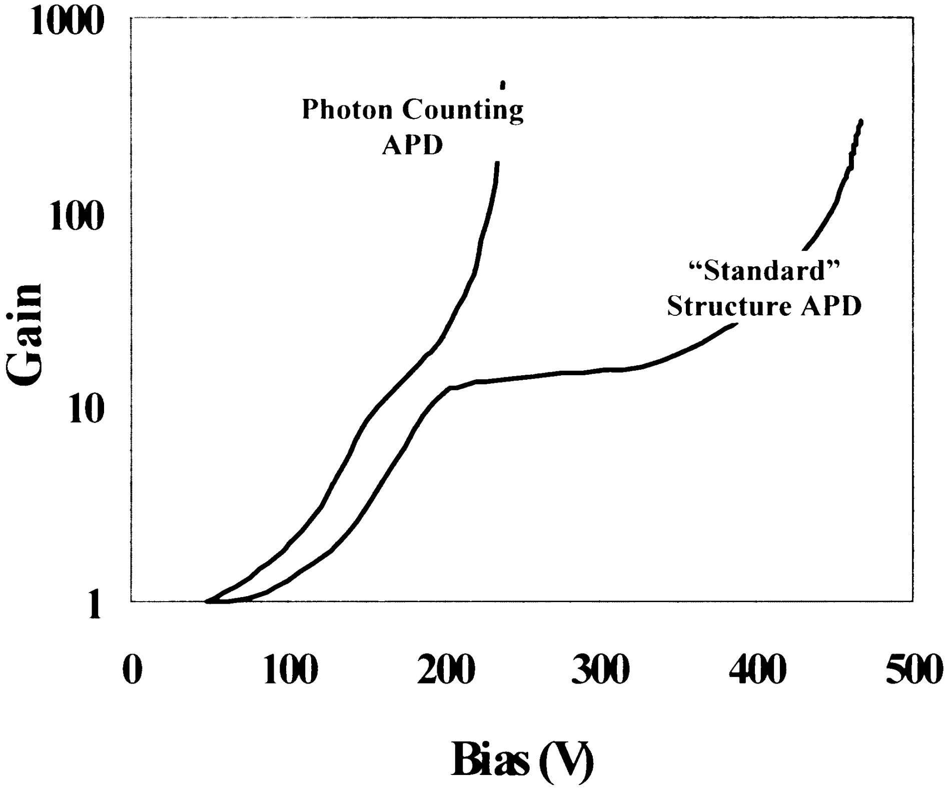
Materials: Si, InGaAs/InP (point, fiber pigtail)

AVALANCHE PHOTODIODE

Operate at high reverse bias below breakdown; carriers moving through intrinsic region can free others

Gain up to 1000 is available, voltage dependent.

Bias (100-300V) and gain temperature sensitive, use regulated current bias for best stability



Noise greater than pin photodiode, goes as G^x, x<1<2

AVALANCHE PHOTODIODE II

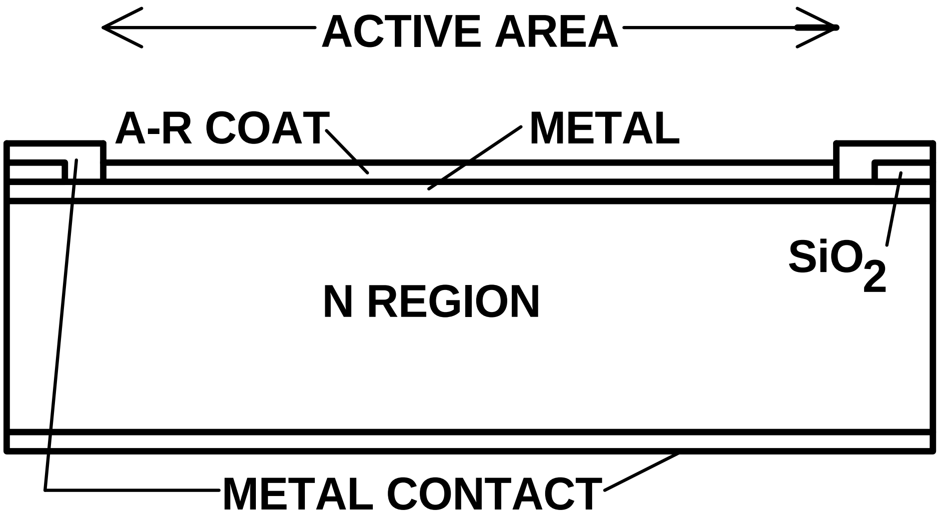
Can count individual photons if cooled (77K) and biased beyond breakdown (Geiger mode)

Silicon, germanium and some mixed heterojunction photodiodes (InGaAs)

Speed: to 1 Ghz (slower than pin, gain mechanism takes time)

Application: Fast detectors with gain, for digital fiber optic communications systems when limiting noise comes from support electronics.

SCHOTTKY-BARRIER PHOTODIODES



Thin semitransparent metal electrode forms potential barrier

Typical structure has thin Au (~10 nm), transparent at wavelengths shorter than 500 nm

Creates depletion layer (potential barrier), behaves like junction ($V_{oc} \approx \phi$)

Fast due to low capacitance (like PIN)

Can operate as avalanche photodiode

Useful for large-area UV detectors.

Used with thin platinum silicide (PtSi, $\lambda c \approx 6\mu m$), palladium silicide ($3.6\mu m$) or indium silicide; all on p-type Si, back illuminated for infrared. quantum efficiency (<10%), extremely uniform, need 77K.

ULTRAVIOLET PHOTODIODES

Silicon displays impact ionization (gain) for $\lambda<360$nm, quantum efficiency appears >1

Schottky barriers have been popular in UV. New front-illuminated Pt-Si stable and uniform.

INVERSION LAYER PHOTODIODES:

Dope top SiO_2 passivation layer (on p-type silicon) with material having positive charge

Attracts electrons to interface, inverting the material

Not a stable (metallurgical) junction, needs additional bias to maintain at high flux

Quantum efficiency approaches 1 at short wavelengths

UV HETEROJUNCTION PHOTODIODES

$$Al_xGa_{1-x}N$$

Tunable depending on x

at x = 0 (GaN), λ_c = 365nm

at x = 1 (AlN), λ_c = 200nm

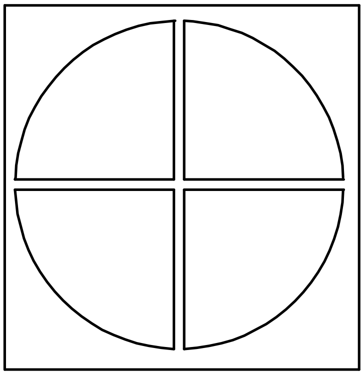
PHOTODIODES IN THE INFRARED

- **Common IR photovoltaic materials include InGaAs (several formulations), InAs, InSb, HgCdTe and PbSnTe.**
- **Operating speeds higher than photoconductors**
- **Theoretical limiting noise (shot) lower by √2 than photoconductors.**

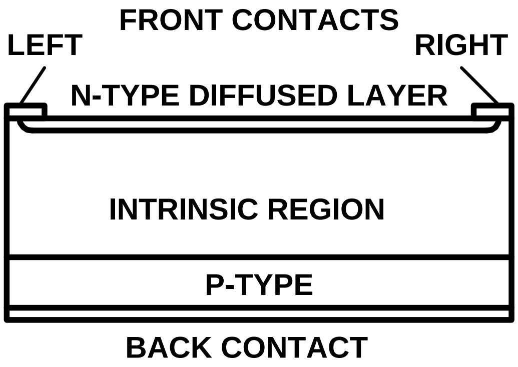
  Due to generation but no recombination noise
- **Infrared devices need cooling**
- **Silicide class detectors have low RQE but exceptional uniformity**
- **IBC (Impurity Band Conduction) and SSPM (Solid State PhotoMultiplier) lang-wave devices under development**

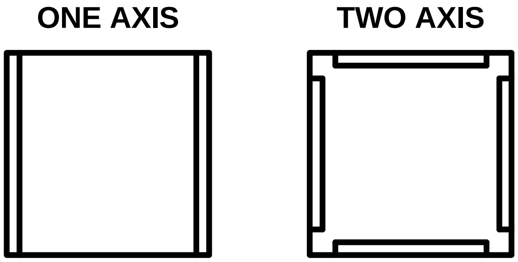
POSITION-SENSING PHOTODIODES

Quad detectors - four individual detectors, used for centering



Lateral-effect photodiode: diffused or Schottky, one or two-axis, current generated at a spot divides according to position





APPLICATIONS OF PHOTOVOLTAIC DETECTORS

Photovoltaic detectors are used across the spectrum, with silicon the clear choice in the visible and near-infrared. When operated at zero-bias, they have low noise, remarkable linearity over many decades and good stability.