Solid State Detectors

Astronomy 525

Lecture 19

Outline

- Photoconductive detector model
- Limitations of Photoconductors
- Blocked Impurity Band Detectors
- Photovoltaic Detectors

Photoconductive detector model

- Under the influence of an electric field, **E**, the electron-hole pair will each drift.
- The drift velocities will be

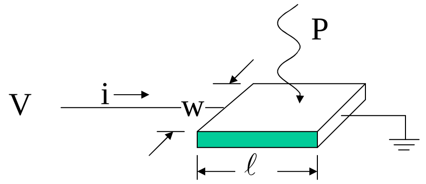
$$\mathbf{v_n} = -\mu_n\mathbf{E}$$
$$\mathbf{v_p} = \mu_p\mathbf{E}$$

  - where μ_n, μ_p = mobilities for negative and positive carriers.
  - At T ~ 290 K, $\mu_n \sim 10^2 - 10^4$ cm^2/V/sec and $\mu_p \sim \mu_n/10$

See Boyd, page 162

PC Detector Model - (cont'd)

- Suppose monochromatic light with power, P, at frequency, ν, falls onto the detector.



- Let S be the surface density of conduction-band electrons (electrons/unit area of detector surface) due to both thermal & photo-electrons.
- Let ΔS be the contribution from photo-excited electrons.

PC Detector Model - (cont'd)

Let τ be the lifetime of the electron in the conduction band

$$\frac{\Delta S}{\Delta t} = \frac{\eta P}{h\nu \ell w} - \frac{\Delta S}{\tau}$$

Which in steady state gives

$$\Delta S = \frac{\eta P \tau}{h\nu \ell w}$$

If the bias voltage is V, then the drift velocity is

$$\mathrm{v}_n = -\mu_n E \qquad \text{where} \quad E = \frac{V}{\ell}$$

The photocurrent is then

$$i = -\Delta S\, e\, \mathrm{v}_n w = \frac{\eta e P G}{h\nu}$$

G, the photoconductive gain, increases with applied voltage

$$G = \frac{|\mathrm{v}_n|\tau}{\ell} = \frac{\mu\tau V}{\ell^2}$$

Limitations of Photoconductors

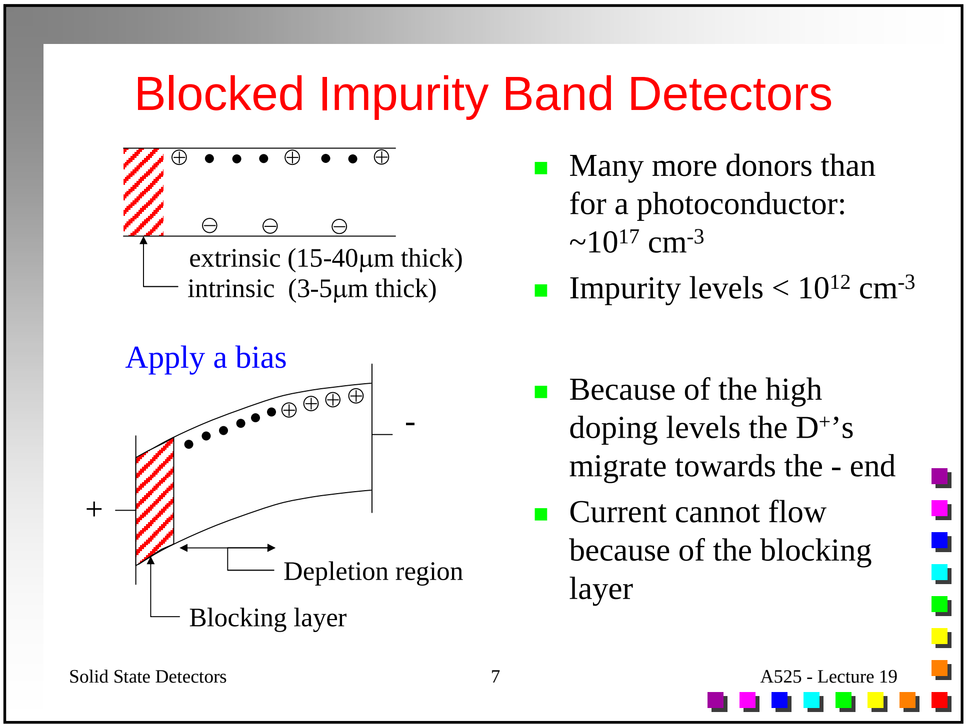
- Cannot dope too high because "dark current" increases due to e- hopping towards + end (hopping current).
  - $N_D \sim 10^{15}$ - 10^{16} cm^{-3}
- To get a high $\eta \Rightarrow$ must make this thick (> 100 μm) to get a high optical depth

$$P_{abs} = 1 - e^{-\tau_a} \qquad \tau_a = N_D \sigma_D \ell_{det}$$

For $\tau_a \sim 1 \Rightarrow \ell_{det} \sim 100$ μm

$N_D = 10^{16}$ cm^{-3}
$\sigma_D = 10^{-14}$ cm^{-2}

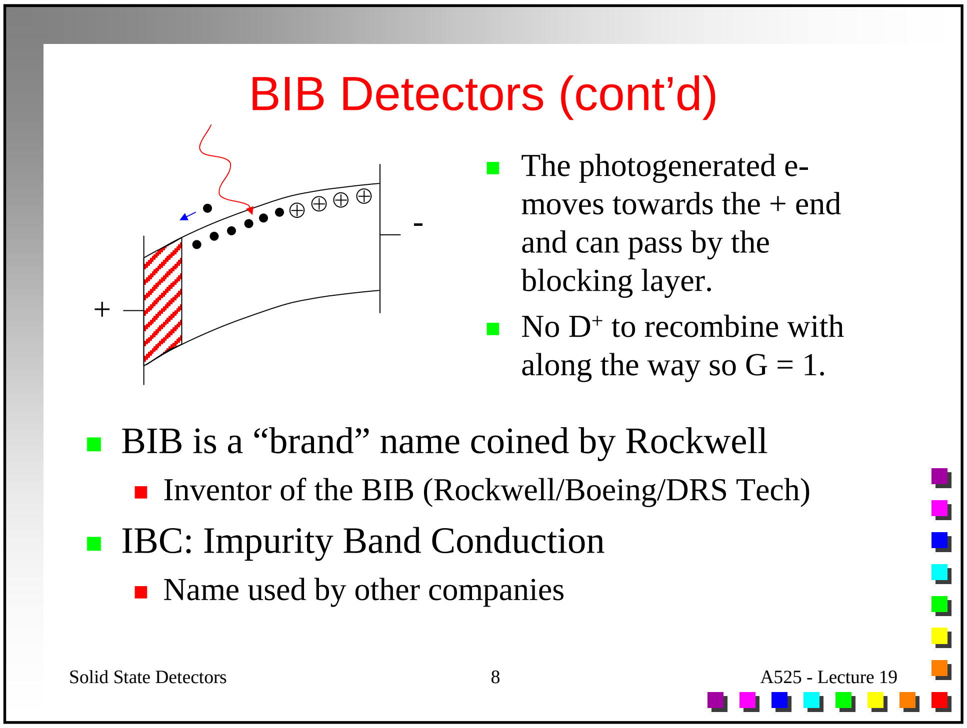
- Show time constant effects (hook response, spiking, etc.)
- Susceptible to ionizing radiation due to size



Blocked Impurity Band Detectors

- Many more donors than for a photoconductor: ~10^{17} cm^{-3}
- Impurity levels < 10^{12} cm^{-3}
- Because of the high doping levels the D^{+}'s migrate towards the - end
- Current cannot flow because of the blocking layer

Solid State Detectors 7 A525 - Lecture 19



BIB Detectors (cont'd)

- The photogenerated e- moves towards the + end and can pass by the blocking layer.
- No D^{+} to recombine with along the way so G = 1.
- BIB is a "brand" name coined by Rockwell
  - Inventor of the BIB (Rockwell/Boeing/DRS Tech)
- IBC: Impurity Band Conduction
  - Name used by other companies

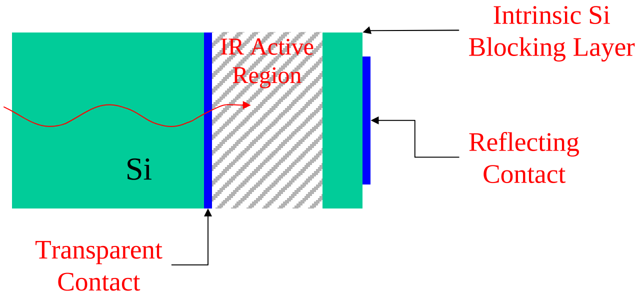
Solid State Detectors 8 A525 - Lecture 19

BIB Advantages

High doping:	good photon absorption broader wavelength coverage
D^+ depletion:	good e- collection efficiency
Intrinsic layer:	blocks dark current
Small size:	easier to make arrays less susceptible to ionizing radiation

BIB Structure

- Back-Illumination for arrays.



Back-Illuminated Blocked-Impurity-Band -> BIBIB

InSb Photoconductors: the Problem

- For InSb it is not possible to simultaneously achieve both high G, and large resistance
  - If G is small, signals are small ⇒ likely dominated by amplifier noise
  - If the resistance is small, the system will be dominated by Johnson noise (more later)
- The situation is identical for $Hg_{1-x}Cd_xTe$ detectors, which are an alternative type in the near-IR
- The situation is ameliorated by using the InSb or $Hg_{1-x}Cd_xTe$ materials as photodiodes

Not shown in class

InSb Photoconductors: the Problem

- Consider construction of an InSb intrinsic photoconductor for the 1-5 μm region
  - The carrier lifetime, $\tau_e \approx 10^{-7}$ s, $\mu_e \approx 10^5$ cm^{2}V^{-1}s^{-1}
  - So that:

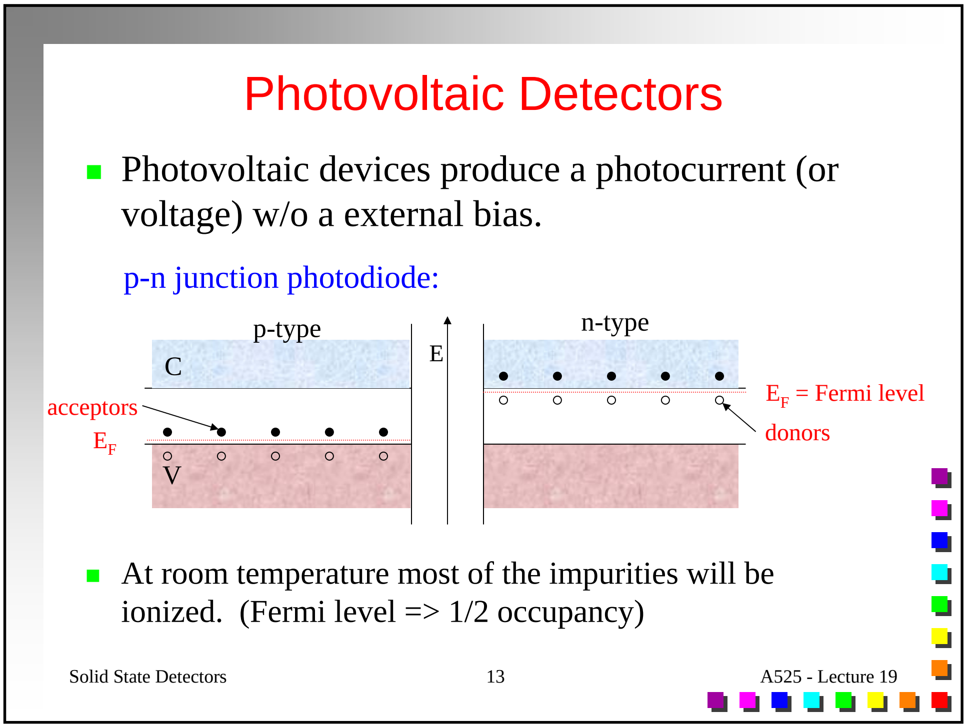
$$G = \tau_e \cdot \mu_e \cdot \varepsilon_x / \ell \approx 10^{-2}\ \mathrm{V}/\ell^2$$

- The breakdown voltage for InSb is small

  ⇒ can only make $G \sim 1$ by making the physical size of the device, ℓ, small.
- However, the detector resistance is:

$$R_d = \ell/(\sigma w d), \text{ where } \sigma = q n_0 \mu_e$$

  - Since the electron mobility in InSb is ~ 100 times that of silicon, it is not possible to achieve high R, with small ℓ

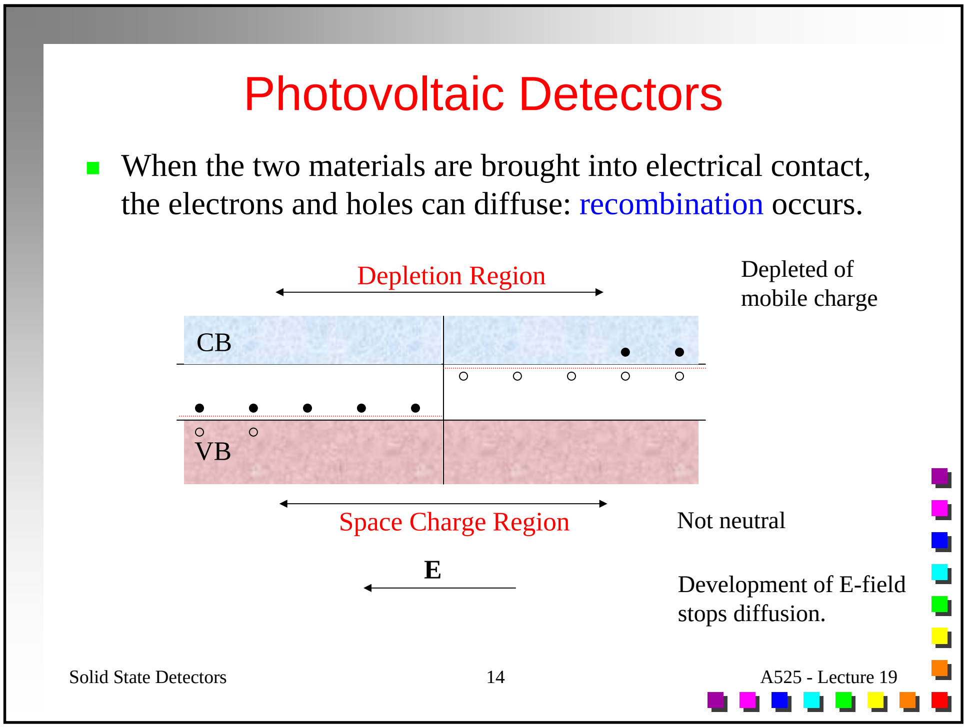


Photovoltaic Detectors

- Photovoltaic devices produce a photocurrent (or voltage) w/o a external bias.

p-n junction photodiode:

- At room temperature most of the impurities will be ionized. (Fermi level => 1/2 occupancy)



Photovoltaic Detectors

- When the two materials are brought into electrical contact, the electrons and holes can diffuse: recombination occurs.

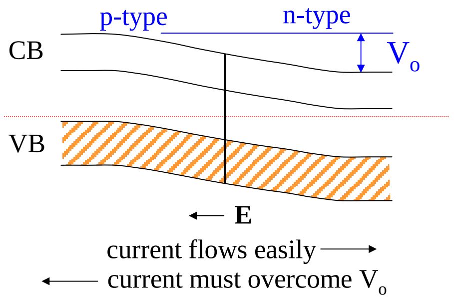
Depleted of mobile charge

Not neutral

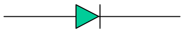
Development of E-field stops diffusion.

PV Detectors (cont'd)

- The electric field creates a potential difference, V_o, between the p- and n-type materials.

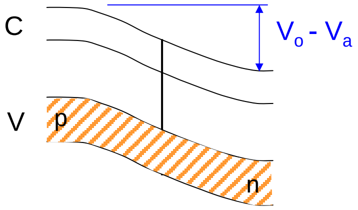


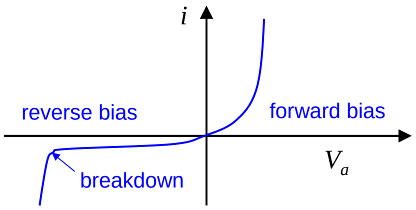
Electrons flow between the materials until the Fermi levels are in equilibrium

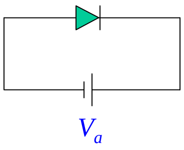


A diode

Diode behavior – Reverse Bias







- If we add to the contact potential (+ voltage applied to n-type material) this is *termed reversed bias*
- The voltage drop appears across the depletion layer because this region has a large resistance (due to the depletion of mobile charges)
  - The increased V increases the width of the depletion zone, and $R_{junction}$
  - Eventually the junction breaks down and becomes highly conducting

Not shown in class

Diode behavior – Reverse Bias, 2

- At modest reverse biases, breakdown can occurs via tunneling:
  - If the conduction band in the n-type is brought below the energy level of the valence band in the p-type material, and the width of the depletion region is small enough that the electron's wave function can extend across it.
- At high reverse biases, breakdown occurs by avalanching:
  - The strong field accelerates a free electron in the p-type region so strongly that it then can create additional conduction electrons through collisions

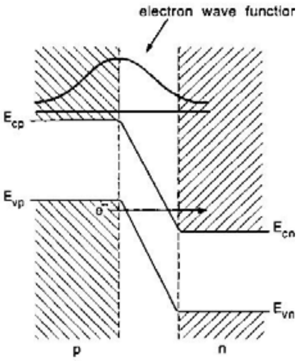
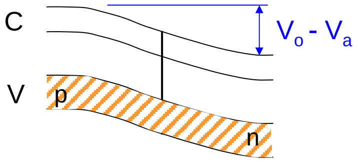
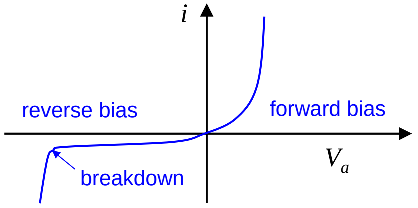
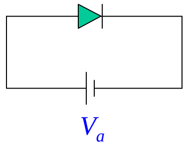


Figure 4.3 in Reike: tunneling through a junction

Diode behavior – Forward Bias

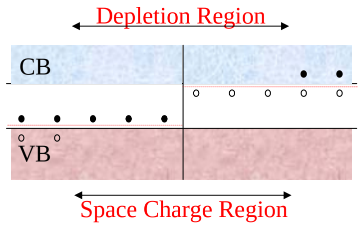






- If we subtract from the contact potential (+ voltage applied to the p-type material), this is termed forward bias
  - This decreases the width of the depletion zone
  - If the bias voltage is larger than V_o, then the junction becomes strongly conducting.

PV Depletion Region Size



Poisson's eq'n:

$$\nabla^2 V = -\frac{\rho}{\varepsilon} \qquad (E = -\nabla V)$$

N_A = acceptor density
N_D = donor density
ℓ_p = width of acceptor region
ℓ_n = width of donor region

Assume 1) junction at $x = 0$
2) N_A = constant, $x < 0$
3) N_D = constant, $x > 0$

We also have $$E = -\frac{dV}{dx} = 0 \qquad x \le -\ell_p,\ x \ge \ell_n$$

and $$V(\ell_n) - V(-\ell_p) = V_o - V_a$$

PV Depletion region size (cont'd)

Poisson's Eq'n is then:

$$\frac{d^2V}{dx^2} = \begin{cases} \dfrac{eN_A}{\varepsilon} & -\ell_p < x < 0 \\ -\dfrac{eN_D}{\varepsilon} & 0 < x < \ell_n \\ 0 & \text{otherwise} \end{cases}$$

Solving gives:

$$V = \begin{cases} \dfrac{eN_A}{2\varepsilon}\left(x^2 + 2\ell_p x\right) & -\ell_p < x < 0 \\ -\dfrac{eN_D}{2\varepsilon}\left(x^2 - 2\ell_n x\right) & 0 < x < \ell_n \end{cases}$$

where

$$\ell_p = \left[\frac{2\varepsilon}{e}\,\frac{N_D/N_A}{N_A + N_D}\left(V_o - V_a\right)\right]^{1/2} \qquad \ell_n = \left[\frac{2\varepsilon}{e}\,\frac{N_A/N_D}{N_A + N_D}\left(V_o - V_a\right)\right]^{1/2}$$

PV Depletion region size (cont'd)

Since the overall charge is neutral

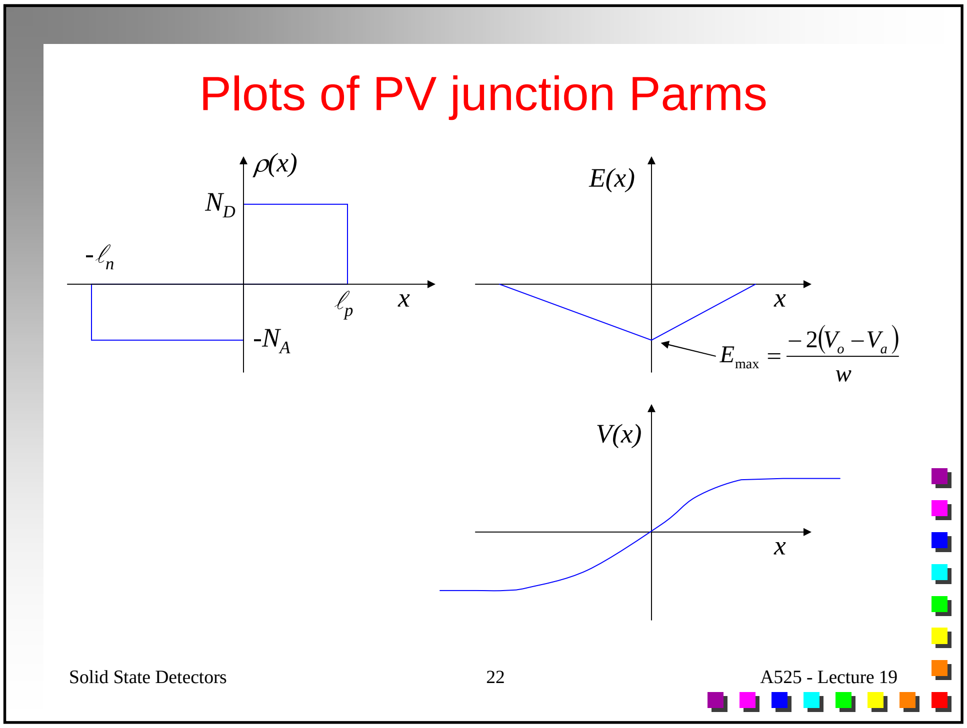
$$N_A \ell_p = N_D \ell_n$$

The total width of the region is ($\ell_p + \ell_n$):

$$w = \left[\frac{2\varepsilon}{e} \frac{N_A + N_D}{N_A N_D} \left(V_o - V_a\right) \right]^{1/2}$$

Differentiating the voltage to get the electric field gives

$$E = \begin{cases} -\dfrac{eN_A}{\varepsilon}\left(\ell_p + x\right) & -\ell_p < x < 0 \\ -\dfrac{eN_D}{\varepsilon}\left(\ell_n - x\right) & 0 < x < \ell_n \end{cases}$$



Plots of PV junction Parms

Junction Capacitance

- Photodiodes have relatively high capacitance since the distribution of oppositely charged particles across the junction forms a parallel plate capacitor with a small separation between the plates
- This large capacitance limits the frequency response of the photodiode, and thereby drives the limiting noise of the readout electronics.
- A faster junction is a PIN diode
  - p-type – intrinsic (insulator) – n-type junction

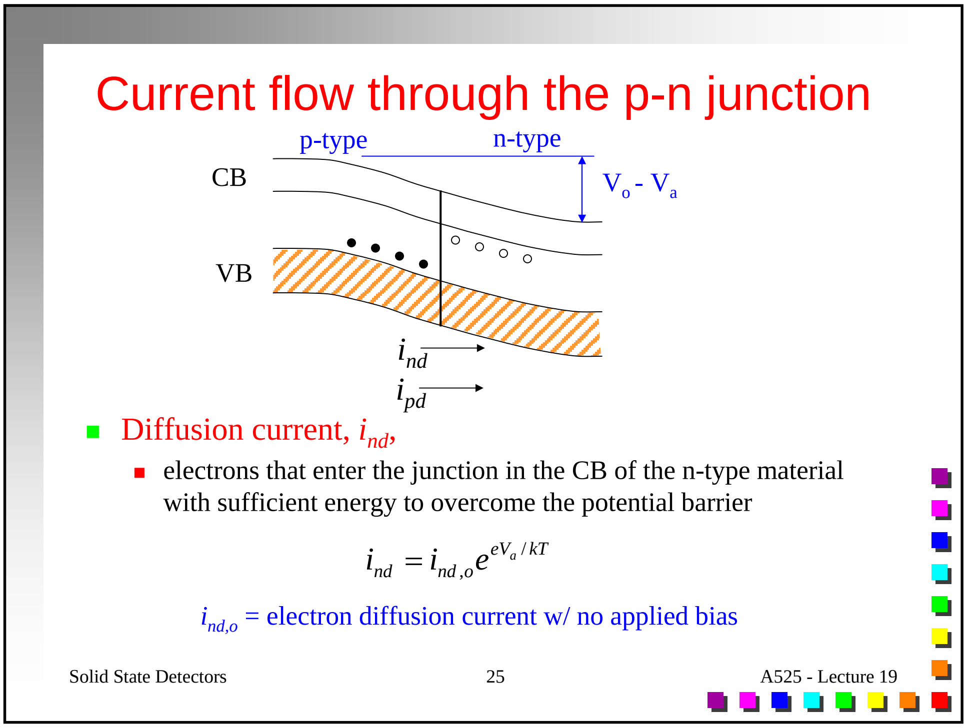
Junction Capacitance

- Stored charge per unit area
  - $Q = eN_A\ell_p$ in p-type region
  - $-Q$ in n-type region
- The p-n junction has a junction capacitance
- For junction area, A, the differential capacitance is

$$C = A\frac{dQ}{dV} = AeN_A\frac{d\ell_p}{dV}$$

$$= A\left[\frac{\varepsilon e}{2}\frac{N_A N_D}{N_A + N_D}\frac{1}{V_o - V_a}\right]^{1/2} = \frac{\varepsilon A}{w}$$

Note that the capacitance decreases for an increasing negative bias.

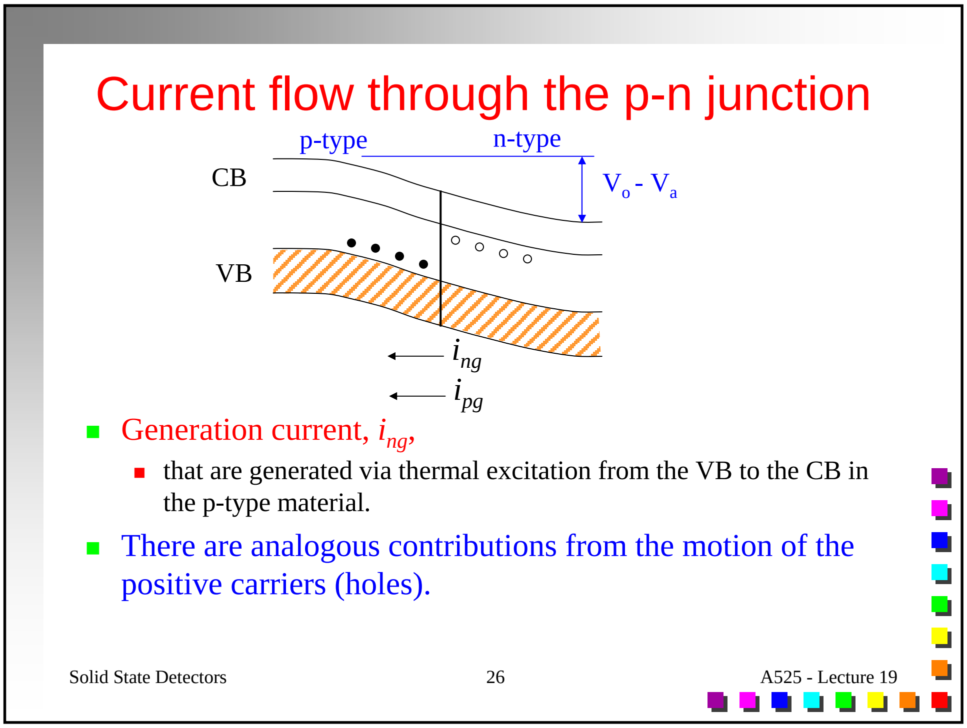


Current flow through the p-n junction

- Diffusion current, i_{nd},
  - electrons that enter the junction in the CB of the n-type material with sufficient energy to overcome the potential barrier

$$i_{nd} = i_{nd,o} e^{eV_a/kT}$$

$i_{nd,o}$ = electron diffusion current w/ no applied bias



Current flow through the p-n junction

- Generation current, i_{ng},
  - that are generated via thermal excitation from the VB to the CB in the p-type material.
- There are analogous contributions from the motion of the positive carriers (holes).

Current flow (cont'd)

- The total current is the sum of each contribution

$$\begin{aligned} i &= i_{pd} + i_{nd} - i_{pg} - i_{ng} \\ &= \left(i_{pd,o} + i_{nd,o}\right)e^{eV_a/kT} - \left(i_{pg} + i_{ng}\right) \end{aligned}$$

- When the bias is zero, there can't be any current flowing through the junction (i_{sat} = saturation current).

$$\begin{aligned} \Rightarrow i_{pg} + i_{ng} &= i_{pd,o} + i_{nd,o} \\ &\equiv i_{sat} \end{aligned}$$

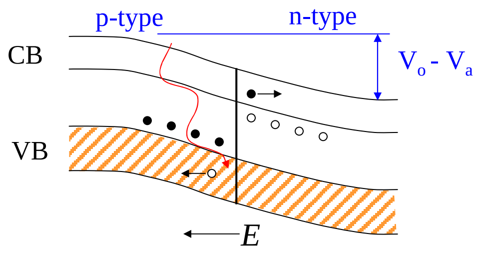
So that

$$i = i_{sat}\left(e^{eV_a/kT} - 1\right)$$

i_{sat} depends upon
1) area of junction
2) carrier mobilities
3) recombination rates
4) temperature

Typical $i_{sat} \sim 10^{-7}$-10^{-9} A for Si photodiodes at room temp.

Adding photons



- If $h\nu > E_B$ (band gap energy), the a photon will generate an electron-hole pair.

$$\Rightarrow i = -\frac{\eta eP}{h\nu} + i_{sat}\left(e^{eV_a/kT} - 1\right)$$

- Want to keep i_{sat} small => less noise
- Best to lower T rather than apply negative bias (keep small)

Not shown in class

Photodetection in a diode

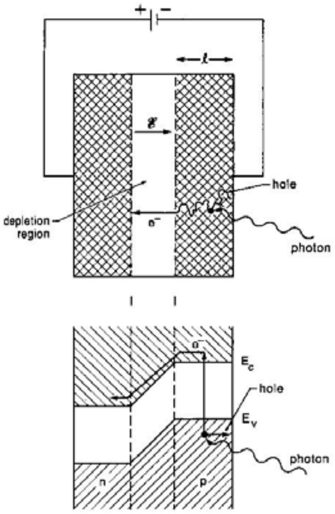
- Free carriers that are generated or recombine in either the n or the p-type regions produce little net current because of the low R in these regions
- One needs creation of a charge carrier within or very near to a unbiased, or reverse-biased junction, so that it can be driven across the junction by the junction field to produce a net current
- Charge carriers can be produced thermally or by photons – we presume that we can freeze out thermal electrons by cooling the device

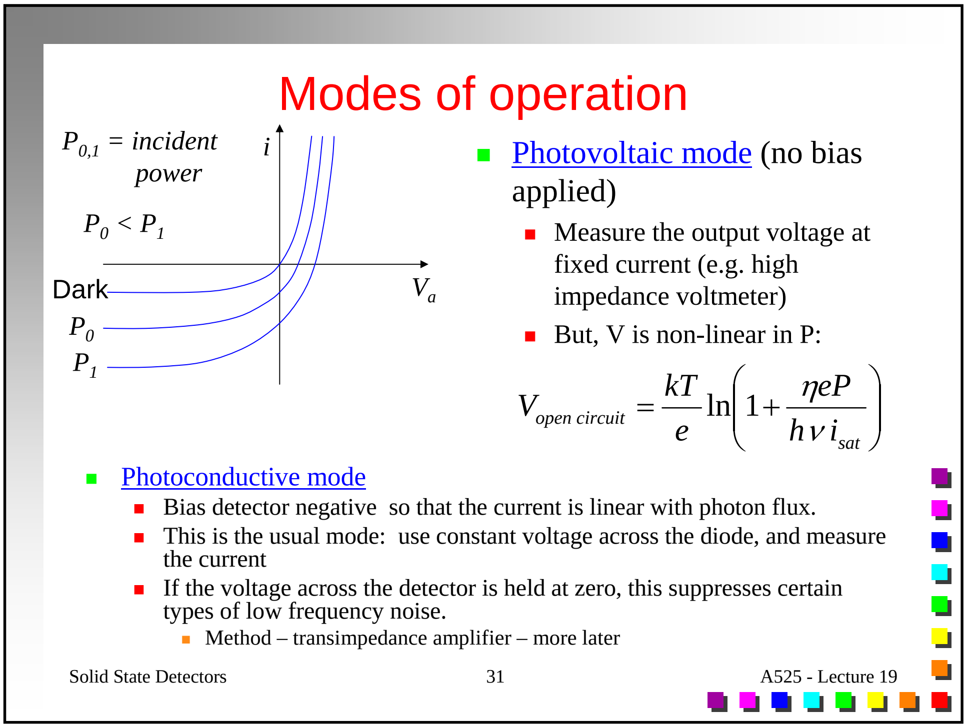
---

Not shown in class

Photodetection in a diode – 2

- The photodetection process is illustrated to the right (Rieke F4.5):
  - A photon is absorbed and excites and e-/hole pair
  - The hole drifts towards the negative electrode or recombines
  - The e- diffuses through the material (remember the field drop only occurs across the depletion zone)
  - If it enters the depletion zone, it is accelerated across the region by the junction potential, creating the photocurrent
  - The process is the same if the n-type material is illuminated (with e-/hole role reversal)





Modes of operation

- Photovoltaic mode (no bias applied)
  - Measure the output voltage at fixed current (e.g. high impedance voltmeter)
  - But, V is non-linear in P:

$$V_{open\ circuit} = \frac{kT}{e}\ln\left(1+\frac{\eta e P}{h\nu i_{sat}}\right)$$

- Photoconductive mode
  - Bias detector negative so that the current is linear with photon flux.
  - This is the usual mode: use constant voltage across the diode, and measure the current
  - If the voltage across the detector is held at zero, this suppresses certain types of low frequency noise.
    - Method – transimpedance amplifier – more later

Solid State Detectors 31 A525 - Lecture 19