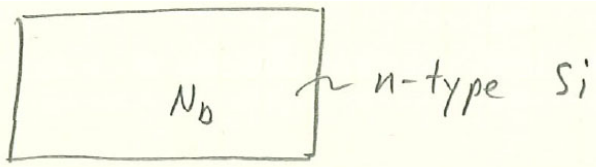
Tuesday, 1/20/26

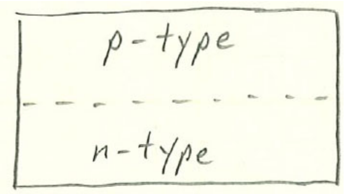
The pn Junction

We are going to review the pn junction, which in addition to forming the diode, is fundamental to photovoltaic devices.

Let’s start with an n-type Si wafer, with donor impurity doping, N_D:

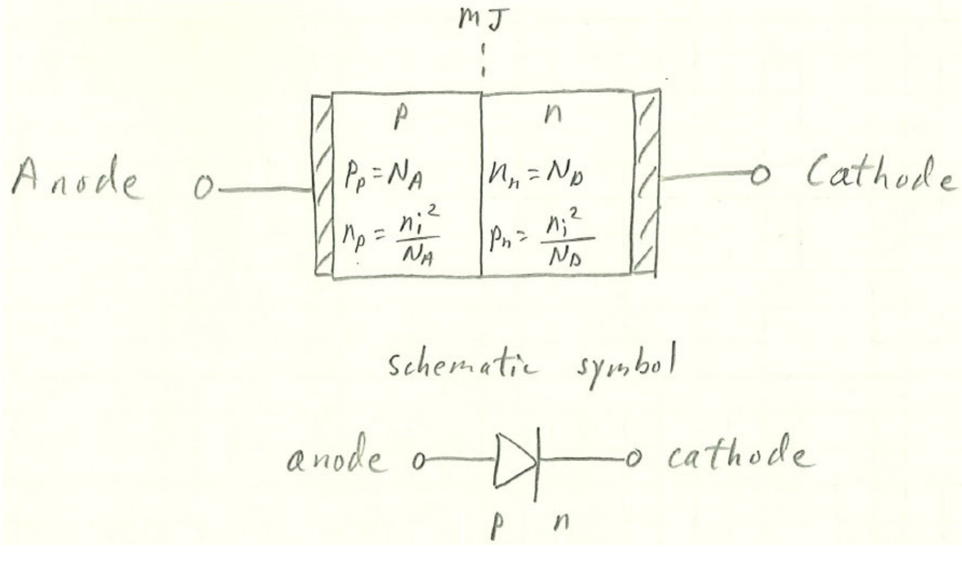


We will selectively dope this wafer with acceptor impurity atoms such that $N_A > N_D$ in that area of the wafer. This makes that section of the wafer p-type:



The dashed line, called the “metallurgical junction (MJ)” is where the bulk Si changes from p-type to n-type.

Next, metallize both sides of the wafer such that good Ohmic contacts are formed, which will form an electrical contact with each side of the device. This forms a pn junction diode:



The charge carrier concentrations on each side of the MJ are represented by p_p, n_p, p_n, and n_n. Typical values for the charge concentrations are:

p-type side	n-type side
$p_p = 10^{17}$ holes/cm^3	$p_n = 10^4$ holes/cm^3
$n_p = 10^3$ e$^-$'s/cm^3	$n_n = 10^{16}$ e$^-$'s/cm^3

Because of the difference in dopant concentrations on each side of the MJ, there is a large concentration of holes on the p-type side and a large concentration of electrons on the n-type side.

Because of the charge carrier difference across the MJ, some mobile holes will diffuse across the MJ to the n-type side, and some electrons will diffuse across the MJ to the p-type side: like charges repel.

On the p-type side of the MJ, immobile negative charged acceptor atoms remain, with a localized negative charge. Likewise, on the n-type side of the MJ, immobile positive charged donor atoms remain, with a localized positive charge.

This results in the development of a Space Charge Region (SCR), depleted of mobile charge carriers around the MJ. This region is also called a Depletion Region or a Depletion Layer.

The SCR has an electric field across the MJ that limits additional charge carrier diffusion across the MJ. This results in a built-in potential across the pn junction:

$$\phi_j = -\int E(x)dx\ , \quad [\phi_j] = \mathrm{V}$$

Solving the equation for ϕ_j yields:

$$\phi_j = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

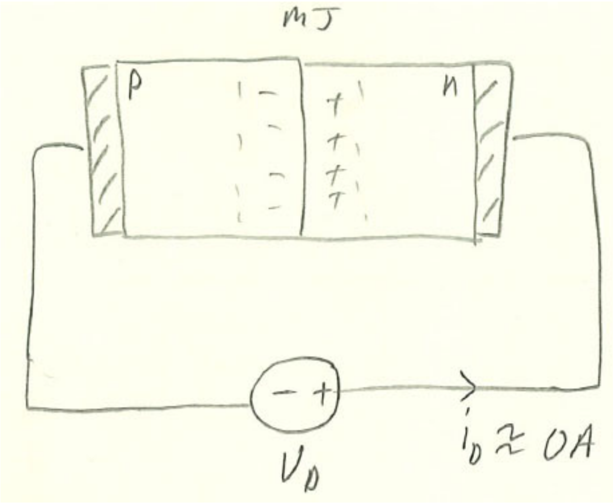
The SCR has a width, extending into the n-type region from the MJ, x_n, and into the p-type region across the MJ, x_p. This width is called w_{do}:

$$w_{do} = x_n + x_p = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\phi_j}$$

$$[w_{do}] = \mathrm{m}$$

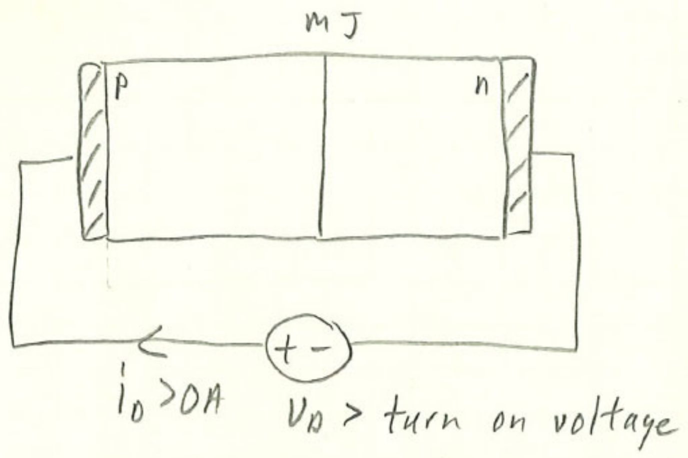
The SCR electric field results in drift currents in opposite direction to diffusion currents, so that they balance out.

1. Reverse Bias Operation



The applied negative voltage, V_D, increases the potential barrier to a net of charge carriers moving across the MJ: $i_D \approx 0A$.

2. Forward Bias Operation



The applied positive voltage, V_D, reduces the potential barrier:

$$i_D = I_s \left[e^{\left(\frac{v_D}{nV_T}\right)} - 1 \right],$$

where: I_s = reverse saturation current, typically 10^{-18} A $\leq I_s \leq 10^{-9}$ A

n = a nonideality factor, typically $1 \leq n \leq 1.1$

V_T = thermal voltage: $V_T = \frac{KT}{q}$

Note: if T ↑ then v_D ↑ for a constant i_D, according to this equation. However, I_s also increases as T ↑. So, v_D might increase or decrease as T ↑, depending on the sensitivity of I_s for a particular diode to changes in T.

In the forward bias condition:

p-type Si contributes holes across the MJ,

n-type Si contributes electrons across the MJ.

Therefore, the pn junction diode is a <u>majority carrier</u> device.

3. Reverse Breakdown

If the reverse bias voltage in large enough, the reverse current flow will become significant. The voltage where this occurs is called the <u>reverse breakdown voltage</u>, V_{BR}. Reverse breakdown can happen by two mechanisms.

a. Avalanche Breakdown

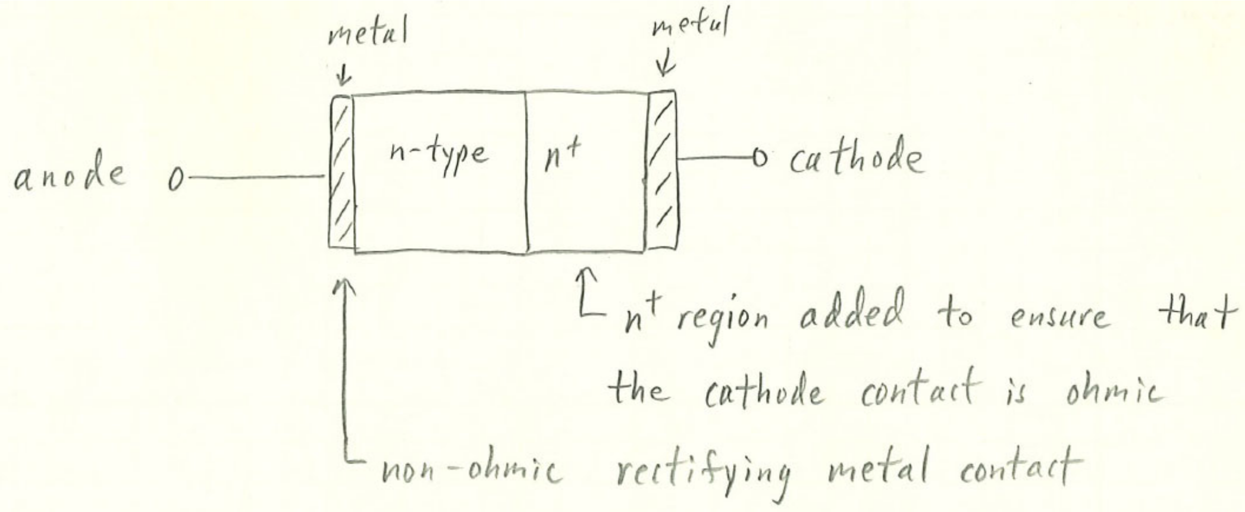
This is an impact-ionization process. The depletion layer increases under reverse bias until the electric field across it is strong enough to accelerate electrons to a velocity fast enough to break covalent bonds upon impact, creating electron-hole pairs. In room temperature Si diodes, $V_{BR} > 5.6$ V typically.

b. Zener Breakdown

This reverse breakdown process occurs because of induced carrier tunneling directly between conduction and valence energy bands in heavily doped diodes. In room temperature Si diodes, $V_{BR} < 5.6$ V typically.

4. Schottky Barrier Diode

A diode can be realized by placing a doped semiconductor in contact with a metal layer. Typically, this is done with n-type Si and a metal layer, where the metal layer replaces the p-type Si. Consider this device's structure below:



Typically, the Schottky diode has a lower turn-on voltage than a pn junction diode, and switches on and off very fast.

P-type Si with a metal layer will also form a Schottky diode, but this structure often has a very low turn-on voltage and an excessively large reverse leakage current.

The Schottky diode will behave as a photodiode when exposed to light.

5. The Amazing pn Junction

Consider the various uses for the pn junction:

(1) Rectifier

(2) Photovoltaic device

(3) LEDs and semiconductor lasers

(4) Thermoelectric cooler (TEC): solid state heat pump or power generator: uses the Peltier effect

(5) Photodiode

(6) Temperature sensor (PTAT)

(7) BJT transistor, SCR, TRIAC

6. History of the pn Junction

Invented in 1939 at Bell Labs by Russell Ohl.

Russell Ohl (1898 – 1987), went to Penn State at age 16.

He observed that when light shines on a Si pn junction, electricity is produced. He thus invented the Si solar cell: U.S. patent 2402662, “Light Sensitive Device,” granted in 1946.

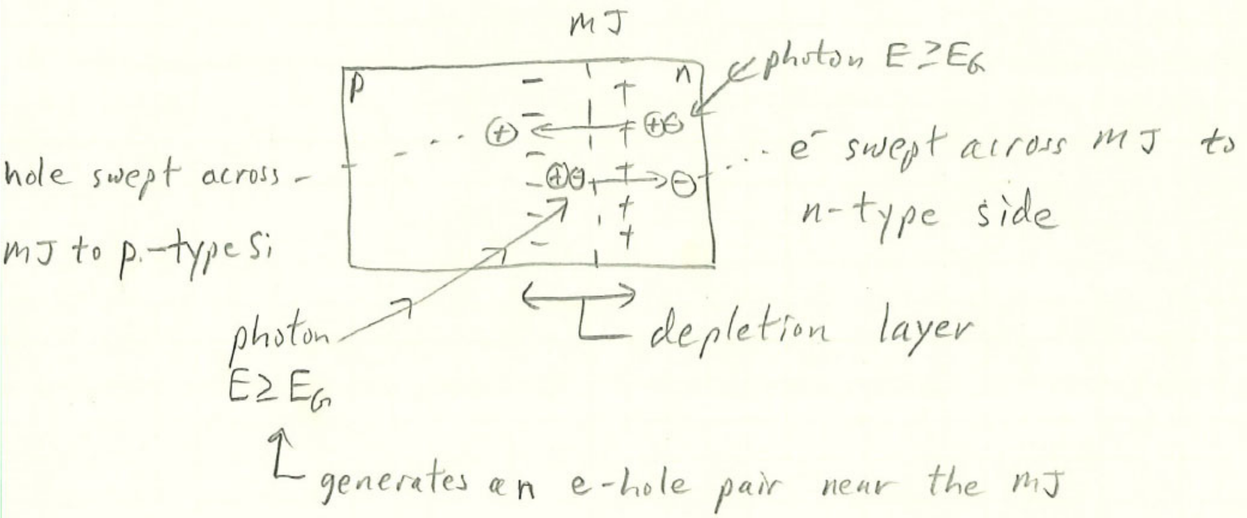
Also, U.S. patent 2443542, “Light-sensitive Electric Device Including Silicon,” granted in 1948.

Think about what an impact his work has had!

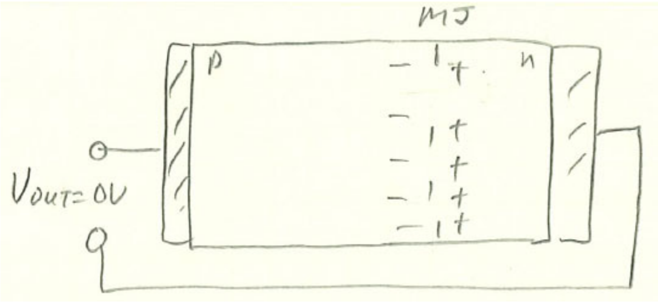
Solid State Physics of PV Semiconductors

We will assume the semiconductor material is Si for now.

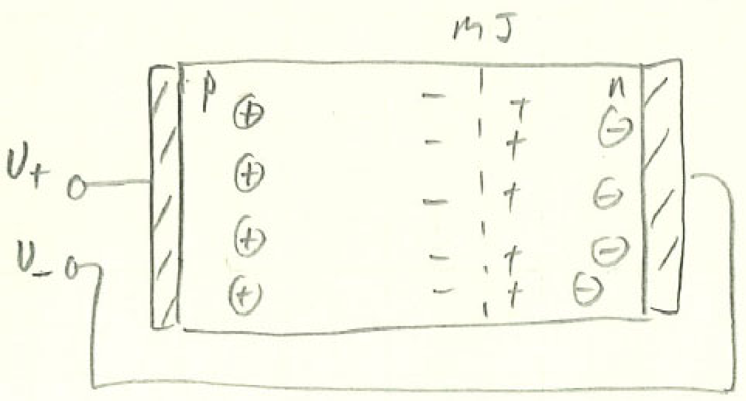
Assume that a photon with energy, E, where $E \geq E_G$, strikes the pn junction in or near the SCR (depletion region), creating an electron-hole pair. The electric field from the immobile charges on both side of the MJ will attract electrons to the n-type side and holes to the p-type side:



When the pn junction is in the dark, a state of charge carrier equilibrium exists: drift currents = diffusion currents. As a result, $V_{out} = 0$ V.



In the presence of light with E ≥ E_G, a non-equilibrium condition exists: holes accumulate on the p-type side of the MJ and electrons accumulate on the n-type side.



Now a voltage difference exists between the anode and the cathode: $V_+ - V_- > 0$ V.

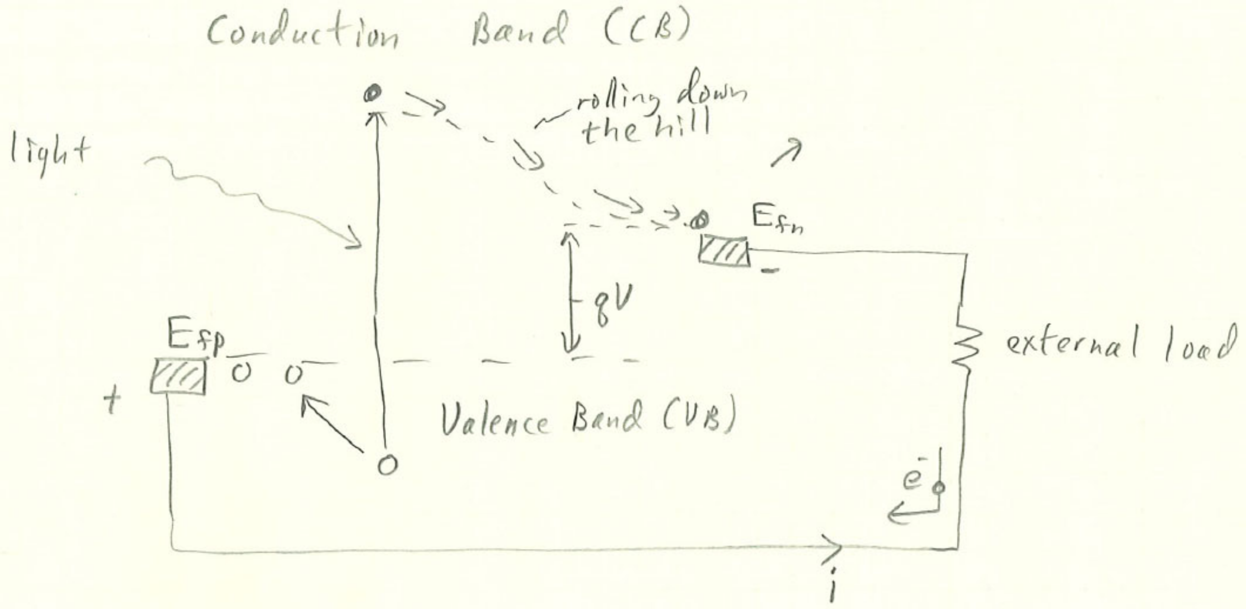
Electrons in the p-type Si (minority carrier) flow across the MJ to the n-type Si.

Holes in the n-type Si (minority carrier) flow across the MJ to the p-type Si.

Therefore, the semiconductor PV device is a minority carrier device.

1. Energy Band Model of the PV Device

Consider the energy band model for a PV device:



Light of sufficient energy creates and electron-hole pair (i.e. an electron moves to the CB).

The CB electron on the p-side of the MJ is swept across the junction by the electric field in the depletion region (i.e. "it rolls down the hill": it loses potential energy).

The output voltage depends on the chemical potentials of electrons and holes in the CB and the VB (horizontal dotted lines in the figure above), called the Fermi Levels (chemical potential for electrons to do work).

The Fermi level of holes on the p-side: E_{fp}.

The Fermi level of electrons on the n-side: E_{fn}.

Keep in mind that voltage, V, is:

$V = \frac{potential\ energy}{charge} = \frac{E}{q} = \frac{qV}{q}$, where E is in eV.

Therefore: $[V] = \frac{N \cdot m}{C}$, and V is the difference in electric potential energy between two points.

So, the PV device output voltage is the change in chemical potential necessary to raise an electron through 1 V (i.e. 1 eV).

Therefore: $|V_{out}| = \frac{|E_{fn}|-|E_{pn}|}{q}$, where E is in eV.

So then, the energy output from the PV device is the work done to separate the electron and hole from the incoming photon:

$P = V_{out}I = V_{out}(q/t)$

$W = Pt = V_{out}q = |Efn| - |Efp|$

If we were to dive into quantum mechanics and thermodynamics applied to PV devices, we would discover:

Theoretical highest PV conversion efficiency (single junction): 33% efficiency and $V_{out(OL)} = 0.85V$.

Note the textbook has a 45% maximum efficiency <error>.

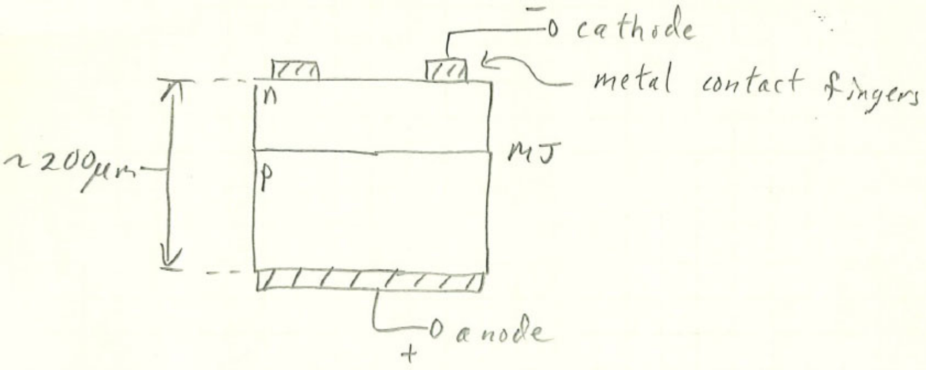
In AM1.5 sunlight and more realistic modeling: 27% maximum efficiency.

Best laboratory Si PV: 26.6% efficiency with $V_{out(OL)} = 0.65V$ to 0.7V (latest NREL chart).

2. Losses in PV Devices

Consider strong sunlight hitting a 6" diameter PV cell: > 10^{19} photons/s.

So where do they all go? To answer this question, consider a typical Si PV cell:



Photon loss mechanisms:

(1) Reflection off the topside contact fingers.

(2) Reflection off the top Si surface.

(3) Reflection off of the bottom surface.

(4) Creation of electron-hole pairs in the Si a long way from the MJ:

→ electrons wander around in the p-type Si

→ if electrons reach the SCR, they get swept across the MJ

→ if an electron encounters a hole first, the charge carrier experiences recombination and is annihilated.

The longer a minority carrier wanders around, the greater its distance of wandering is and the more likely it is to experience recombination.

Carrier Lifetime: the average time between electron-hole generation and recombination: in Si, about 1 μs.

Diffusion Length: the average distance a carrier travels from the point of generation to the point of recombination: in Si, about 200 μm (about the thickness of a Si PV device).

Recombination results in light emission (luminescence: a photon is generated) or heat (non-radiative recombination: lattice vibrations).

Bulk Recombination: takes place as the charge carriers wander around in the body of the cell.

However, most recombinations occur at impurities or at defects in the crystal structure near a cell's surfaces, edges, and metal contacts. These sites allow intermediate energy levels between the VB and the CB, allowing electrons to fall through intermediate energy levels from the CB to the VB.

Indirect Semiconductors

Such as Si.

Recombination is more likely to produce heat in the lattice structure than an emitted photon (compared to a direct semiconductor).

An electron's transition from the CB to the VB requires electron energy level change (from the photon) *and* momentum change (from interaction with a lattice vibration called a phonon).

Direct Semiconductor

Such as GaAs.

An electron’s transition from the CB to the VB occurs faster and requires very little momentum change compared to indirect semiconductors: therefore, not requiring conversion process mediation from phonons.

This is why direct semiconductors are used to make LEDs: recombination produces photons.

Reducing recombination can increase achieved PV efficiency.