**LEDs, Solar Cells, and MOSFETs**

Now want to briefly consider how such diodes emit light, how they are used in solar cells, etc. Maybe I’ll do MOSFETs too? Maybe not.

**Light Emitting Diodes**

So let’s go back to our pn junction with a battery attached, as before, in the forward direction.

Histogram

Description automatically generated with medium confidence

And recall our formulas for the steady state current densities in the conduction and valence bands.

where nc is density of electrons in conduction band, pv is density of holes in valence band, and where nc(0), pv(0) are the equilibrium distributions, displayed below, and where **j**c,v is the current density in the conduction and valence bands.

Diagram

Description automatically generated with medium confidence

And here is the current we got:



Okay anyway, so when we apply an electric field (battery) to our diode, the electric field will impart energy to the electrons/holes – to accelerate them or to bump them up from valence to conduction band, and this energy is dissipated via scattering (quantified via τsc), but also by electrons dropping out of the conduction band and into the valence band (quantified via τgr). The former process will transform the energy acquired by the electric field into heat, while the latter will transform it into light, of frequency roughly equal to f = Eg/h, where Eg is the band gap energy. We can see that this latter process will only occur within the depletion + diffusion zone, since only there is (n – nc(0))/τgrc or (p – pv(0))/τgrv signficiant.

On a practical note, should mention that it can be difficult to see the light emitted from the diode. If Eg/h is not in the visible spectrum, then of course you won’t see it. But even if it is, a lot of the light that would get emitted from the depletion zone tends to get reflected back into the depletion zone, and reabsorbed eventually because the index of refraction of the homoegneous zone is higher than that of the depletion zone. Homogeneous zone has higher index of refraction, due to larger polarizability, say, or due to larger number of mobile electrons. So one has to make one end of the diode small so photons have better chance of transmitting through.

**Solar Cells**

A solar cell is basically an LED in revese. So consider the pn junction sans battery.

Diagram

Description automatically generated with medium confidence

Thinking about the current in the **first way** (see last file jgen ~ jdrift and jrec ~ jdiff), no net current will flow w/o light impinging on the N guy as, in equilibrium, the diffusion current of thermally excitated holes going over the potential barrier (from p to n) is canceled by the drift current of holes being dragged down the barrier by φ (from n to p). And similarly for electrons. But if we shine light on the N guy, then this can excite electrons from the valence band into the conduction band. So what happens then? Well recall our formula for the currents,



When we bump an N electron into the conduction band, we are increasing pv, and visually it would seem, also decreasing ∇pv across the depletion zone. The increase in pv would increase |jdrift|, increasing current to left, while the decrease in ∇pv would decrease |jdiff|, also increasing the current to the left (remember e is negative, and ∇pv is negative). So this would seem to encourage flow of current from N to P. Apropos the electrons, we are increasing nc, and it seems, also increasing ∇nc across the depletion zone. The increase in nc would increase |jdrift|, increasing current to left, while the increase in ∇nc would increase |jdiff|, increasing the current to the right (remember e is negative). Well since three of the four currents got increased to the left, I’m going to go with the net current moving to the left. So,



Apropos the light, we’ll note that of course its frequency must be large enough to bump the electrons up from the valence band to the conduction band, so f = Eg/h, basically. Energies less than this won’t work of course. But energies in great excess of this are not efficient, as the excess energy typically gets dissipated as heat. We can model the pn-junction/cell as a battery with an internal resistance. The emf ξcell = Eg/|e|, the gap potential difference basically. But the potential difference across the terminals of the cell will be ΔVcell = ξcell­ – Ir, where I is the current through the cell, and r its internal resistance, which models the dissipation of excess energy given by the photons to the electrons.

**Transistors**

A transistor functions as a switch that allows you to basically turn on or off the current flowing through an npn junction by applying an external voltage. We’ll discuss the MOSFET (Metal-Oxide-Semiconductor-Field-Effect-Transistor). Here’s a picture I stole,

Diagram

Description automatically generated

So it’s basically an npn junction, with a metal ‘gate’ attached via an SiO2 insulator/dielectric. The SiO2 is there to prevent leakage of mobile electrons from the gate into the p-type. And the metal gate is there to apply a potential difference to the p-type (and n-types a little). When the applied potential difference to the metal gate is large (say φgate ~ Eg/|e|), then current can flow between source and drain (n→p→n); otherwise not. The circuitry attached to the metal gate allowing application of said potential difference is not shown. Though I say with no gate voltage, current won’t flow, I guess a little bit of current could still flow. Maybe with the battery hooked up the way it is, current would tend to flow between body (p-type Si) and drain, but it would have to also flow between source and body. Now body-drain is a pn connection, which is the way current would normally flow. But source-body is an np connection. And that’s the revese connection for a transistor, so generally wouldn’t get anything beyond the saturation current I guess. Here’s a rough picure. Let’s turn off the potential difference between drain and source, and just consider the transistor by itself.

A picture containing text

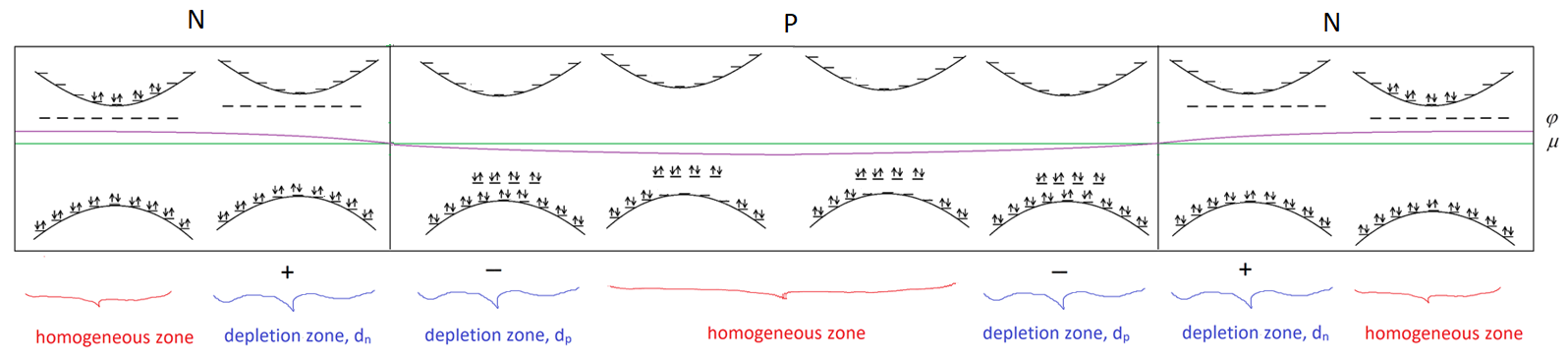
Description automatically generated

When we first put the npn junction together, the N’s are at a higher chemical potential, as usual.

A picture containing chart

Description automatically generated

So electrons will migrate into the P, resulting in a depletion zone on either side of P.



So in this configuration, no current can flow from N→P→N (beyond saturation current I guess?). Then when we apply an electric field in the z-direction (gate Voltage).

Diagram

Description automatically generated

This lowers the energy levels in the p-type/body (and near the edges of the n-types). The amount of lowering would be proportional to the gate voltage potential. So it will be substantial at z = 0, and drop to zero as z increases. The new energy levels for some z close to z = 0, would look like this (the purple φ here below is the same φ as above and is *not* φeff = φ + φgate) :

A picture containing diagram

Description automatically generated

I didn’t really show this in my picture, but typically the applied gate voltage would be large enough to pull the p-type conduction bands below the chemical potential (at least near the gate electrode). So φgae ~ Eg. And so of course electrons in the n-type conduction bands will drop into the p-type conduction bands. And electrons in the n-type valence bands will drop into the p-type valence bands (or could say holes in the p-type valence bands will ‘drop’ upwards into the n-type valence bands).

Chart, histogram

Description automatically generated

And so now the bands can conduct. And application of a potential difference between the source and drain will result in a current flow between them, and through the p-type. Note that since the energy band lowering won’t be too substantial for higher z’s, the region of conducting electrons will be limited to an effectively 2D region around the SiO2 insulator. So this is one way we can create and explore a 2D electron ‘gas’.