Lab Note 3: Motion Extra Reading

Appendix A: Electronics Glossary

In this appendix, we will elaborate upon terms and components we mentioned in the main note whose explanations are too long to fit comfortably in a footnote. **PLEASE NOTE: this material is NOT IN SCOPE, so do not panic if it seems complex.** It is just here to give some additional background to the lab if you would like some.

- **Bipolar Junction Transistor (BJT):** We will give a very minimal introduction to the BJT. This material is VERY out-of-scope, and the device physics is greatly simplified; the version of this material taught in EE 105 is much more in-depth/nuanced, so take that course if this piques your interest :).

  Like a FET (field-effect transistor, e.g. CMOSFET, JFET), a BJT can act as a switch or an amplifier. In this introduction, we will only address the switch application (but you can learn about the amplifier application in EE 105, EE 140, etc.).

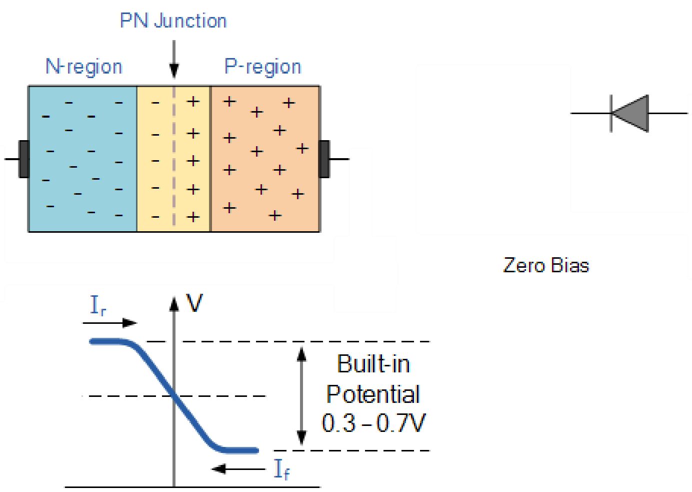
  The BJT is a three-terminal (base, collector, emitter) device in which applying a small current to the base allows a larger current to flow between the collector and emitter. Like the MOSFET, it comes in two types, except for instead of NMOS and PMOS, those types are NPN (negative-positive-negative) and PNP (positive-negative-positive). These names come from the fact that a BJT is essentially made of three layers of semiconductor material: in the NPN case, one layer of positively-doped (p-type) material is sandwiched between two layers of negatively-doped (n-type) material.

  A brief detour: diodes

  Diodes[1] are also semiconductor devices, except they have only two layers (one each of p-type and n-type) instead of three.

  We will define two kinds of charge carriers: electrons carry negative charge, and holes carry an equal and opposite (positive) charge[2]. The p-type material has excess holes, and the n-type material has extra electrons.

  Let's examine how this device behaves in its open circuit condition (i.e., its terminals are not connected to anything). As you might have guessed, the electrons and the holes are attracted to each other, so as they diffuse across the junction, they recombine and neutralize each other, forming a depletion region around the junction.



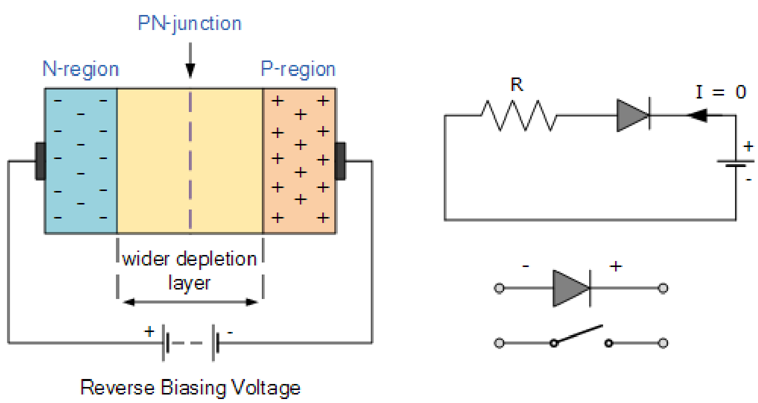
  When a hole diffuses from the p-side to the n-side, it quickly recombines with one of the majority electrons on the n-side and disappears; as this continues to happen, the n-side depletion region loses its free electrons. When an electron is freed from its parent atom and then neutralized by a hole, the parent atom becomes positively charged: therefore, the depletion region on the n-side is positively charged. Similarly, the depletion region on the p-side becomes negatively charged. This creates a potential difference across the depletion region, known

[1] It is important to note that not all diodes are made this way; however, this is the classical example.
[2] If you would like some additional background on this abstraction, see here.

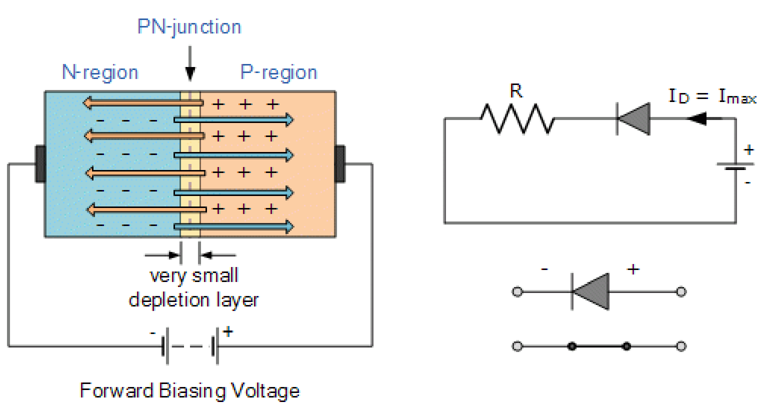
as the **barrier voltage**, which the carriers must overcome to continue to diffuse across the depletion region. As the depletion region grows, so does the barrier voltage, making it more and more difficult for more carriers to diffuse across the depletion region, bringing the system into an equilibrium. With no voltage source connected across the terminals, the currents of electrons and holes are equal in magnitude and opposite in direction.

So, did we just break the first law of thermodynamics? Didn't we just generate a voltage out of thin air? Not quite. The voltage we have been discussing is the voltage *across the depletion region*, not across the junction terminals. Actually, the contact voltages at the metal-semiconductor junctions at the device's terminals perfectly balance out the barrier voltage so that when you measure the voltage across the open-circuited diode's terminals, you will read a voltage of 0V.

Now that we have explored the p-n junction diode's open circuit behavior, we are ready to see how it performs under an applied voltage. If we apply the voltage across the diode so that the p-side terminal is more positive than the n-terminal, the diode is said to be **forward-biased**, whereas if we apply the voltage so that the n-side terminal is more positive than the p-terminal, we say the diode is **reverse-biased**.



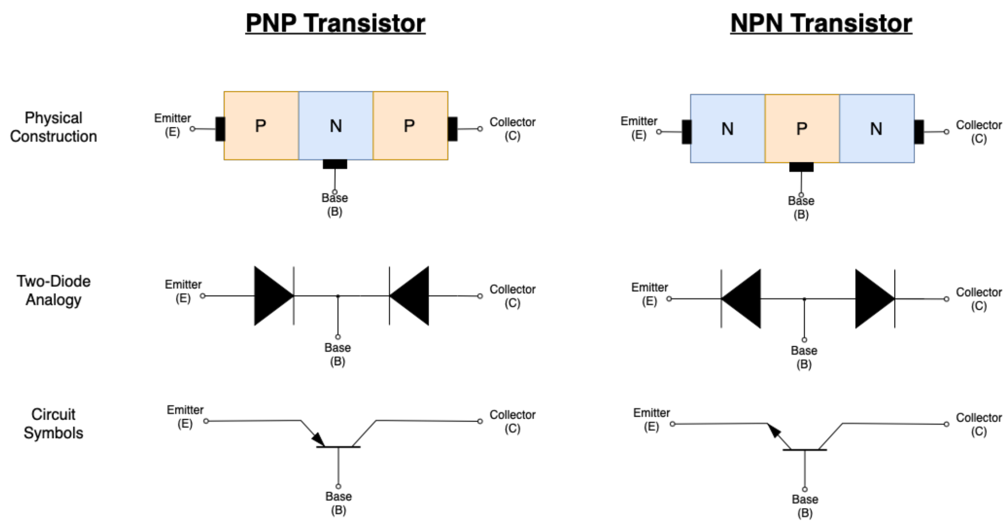
In the reverse-biased case, the external voltage is applied in the same direction as the barrier voltage, so it adds to the barrier voltage, making the effective barrier voltage the sum of the open-circuit barrier voltage and the applied voltage. This makes it much more difficult for electrons and holes to diffuse across the depletion region, so the device allows only a very small amount of current to flow: for the ideal diode abstraction, we consider this current to be 0.



In the forward-biased case, the external voltage is applied in the opposite direction as the barrier voltage, so it *subtracts* from the barrier voltage, greatly reducing the effective barrier voltage. This allows electrons and holes to diffuse more freely across the depletion region and therefore enables a substantial current to flow through the device. Since our voltage/current convention says that current flows from high voltage to low, we conclude that the current flows from the p-side to the n-side.

Back to BJTs

Now that we've been introduced to the underlying physics of the p-n junction diode, we can see that an NPN BJT is essentially two diodes connected back-to-back, where the base is connected to the p-region (shared by both diodes) and the emitter and collector are each connected to one of the n-regions:



Let's now explore how we can bias this component so we can use it as a switch. We want the current between the collector and the emitter to be controlled by the current between the emitter and the base.

Let's see how we can bias the BJT so that it does not conduct; i.e., so that the switch is off[3]. We will set the voltage at the base to be equal to the voltage at the emitter (0V in our lab), and we will set the collector voltage to a significantly greater value. This reverse-biases the collector-base diode so that essentially no current can flow through it. Even though the base-emitter diode is not technically reverse-biased, (1) the fact that the collector-base diode is reverse-biased means essentially no current reaches the base anyway, and (2) the fact that the base and the emitter are at the same voltage means that there is no potential difference between them to incite current flow.[4]

Now, let's see how we can bias the BJT to turn it on[5]. We want both diodes to be forward-biased, so we will set the base voltage to be higher than both the emitter and the collector. Notice that the collector in our circuit is not connected to 9V but rather to the motor: almost all of the 9V is dropped across the motor, so even though the 5V at the base is much lower than 9V, the base voltage is still higher than the voltage at both the emitter and the collector, so both diodes are still forward-biased.

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[3] If you look this up to explore further, we are trying to operate the BJT in cutoff mode.

[4] Note that technically, the condition for the BJT to be in cutoff is that both the collector-base and base-emitter diodes are reverse-biased. We used the example of reverse-biased collector-base diode and unbiased base-emitter diode because that is how our actual motor controller circuit works.

[5] If you look this up to explore further, we are trying to operate the BJT in saturation mode.

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Edited by Steven Lu, Yi-Hsuan Shih (2021). Version 2.0, 2021.