An Introduction to Basic Electronics

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Basic Electronic Devices

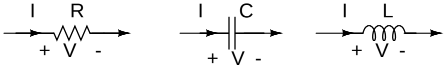
There are three basic devices which shape up the working and design of all electronic circuits. They are:

- Resistor- A resistor works as per Ohm's Law. If V is the voltage across the resistor, I is the current through it and R is the resistance value, then $V = IR$.
- Capacitor- A capacitor is used to store energy in its electric field. It does not have a linear I-V relationship, unlike a resistor.

$$V = \frac{1}{C} \int I.dt$$

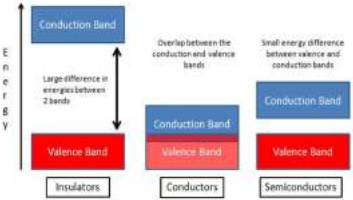
- Inductor- An inductor is used to store energy in its magnetic field. Its behaviour is somewhat analogous to a capacitor, due to its I-V relationship.

$$I = \frac{1}{L} \int V.dt$$



Semiconductor Devices- The Concept of Energy Bands

- Electronic circuits are different from electrical circuits. Electronics depend on the use of semiconductors as well e.g. Silicon, Germanium.
- Semiconductors have electrical conductivity between that of conductors and insulators.
- Every element has energy levels which its electrons can occupy. A range of energy levels which cause some common properties is called an energy band.
- We consider two energy bands- the **valence band (VB)** and the **conduction band (CB)**. The valence electrons occupy the energy levels in the VB.



The Concept of Energy Bands (contd...)

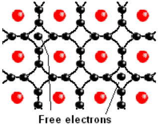
- What does this imply? From the band structure figure, it is clear that even at room temperature, **metals have free electrons in the conduction band**, which make them **good conductors**.
- The difference between the lowest energy level in the CB and the highest energy level in the VB is called a **band-gap**. Larger the band-gap, lesser is the conductivity.
- **Semiconductors are insulators at room temperature**. However, with an externally applied voltage, the valence electrons in the semiconductor may overcome the band-gap and climb to the CB. The band-gap is about 1.1 eV for silicon.

Electrons and Holes

- In pure silicon, the presence four valence electrons is the reason to forming a matrix of silicon atoms in a crystalline structure. This property is called catenation.
- All electrons form a part of the covalent bonds hence there are no free charge carriers at room temperature.
- However, an external electric field may cause some electrons to break the covalent bonds and flow as a mobile charge (overcoming the band-gap). An electron deficiency in the crystal is called a hole.
- What can be said about the concentration of free electrons and holes in a pure semiconductor?
- Pure semiconductors are also called **intrinsic** semiconductors.

Increasing the Carrier Concentration

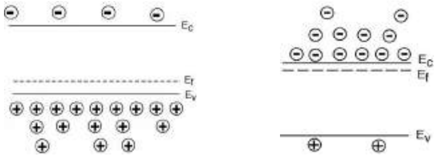
- To increase free electrons at room temperature, impurities can be introduced into the crystal. By diffusing pentavalent element atoms (e.g. phosphorous, arsenic), excess free electrons are created.
- Such kind of semiconductors are called **extrinsic** semiconductors.
- This process is called doping. Pentavalent dopants introduce **donor** atoms in the crystal. Since electrons form the majority of carriers, this material is called an *n*-type semiconductor.



- Can you guess what kind of elements need to be doped into silicon to form a *p*-type semiconductor? What will be the majority carriers here?

Energy Levels in Semiconductors

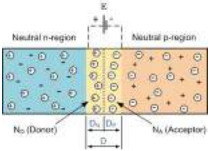
- Every crystalline solid has a characteristic energy level called the **Fermi Level**. It is a hypothetical level which indicates a 50% probability of being occupied by an electron.
- Why hypothetical? Consider the case of pure silicon. It has a band-gap of 1.1 eV, indicating that the Fermi Level at 0K is exactly half-way, i.e. 0.55 eV from both CB and VB.
- The 0.55 eV energy level lies inside the band-gap, which no electron can occupy! Hence, it is only a hypothetical measure.



Energy band diagram in (i) p- and (ii) n-type semiconductor

The p-n Junction under Equilibrium

- Fusing together a p- and an n-type semiconductor results in formation of a p-n junction diode.
- Due to large difference in carrier concentration, the electrons from the n-side tend to diffuse to the p-side, leaving behind positively charged donor atoms behind.
- Likewise, the holes start moving from the p-side, leaving behind negatively charged acceptor atoms.
- As the electrons flow into the p-side, the negatively charged acceptor ions start repelling them (similarly with holes flowing to the n-side). This diffusion process continues until the ionized atoms at the junction repel flow of any more carriers across the junction.
- Hence, a depletion region (devoid of charge carriers) gets formed on either side of the junction, with a built-in potential.



The Built-in Potential

Consider a p-n junction formed with donor doping concentration N_D, acceptor doping concentration N_A and an intrinsic carrier concentration n_i. If the number of mobile carriers are n and p for electrons and holes, then as per the Law of Mass Action, we have

$$n_i^2 = n.p$$

We know that the Fermi Levels in n-type ($E_{f,n}$) and p-type ($E_{f,p}$) semiconductors are different. The built-in junction potential is equivalent to the difference in the Fermi Levels. We have,

$$E_{f,n} = kT \ln(\frac{N_D}{n_i}) \qquad E_{f,p} = kT \ln(\frac{n_i}{N_A})$$

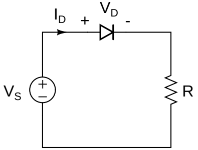
where k is the Boltzmann constant and T is the temperature in Kelvin. But, electric potential $\phi = E/q$, where q is the electron charge. Then the built-in potential V_γ is

$$V_\gamma = \frac{E_{f,n} - E_{f,p}}{q} = \frac{kT}{q} \ln(\frac{N_A N_D}{n_i^2})$$

Exercise: Calculate the built-in potential of a silicon diode with $n_i = 10^{10}/cm^3$, $N_D = 10^{16}/cm^3$ and $N_A = 10^{15}/cm^3$ at room temperature 27°C. Vary n_i, N_D and N_A to study how V_γ varies.

Diode Biasing

The following figure shows a *forward-biased* diode. Note that, the anode of the supply is connected to that of the diode, and similar for the cathodes.



The current through the diode I_D is given by Shockley's equation

$$I_D = I_S(e^{\frac{V_D}{V_T}} - 1)$$

- Here, V_D is the voltage across the diode, $V_T = kT/q$ and I_s is the reverse saturation current.
- The equation indicates that when V_D increases, the diode current increases exponentially. When $0 < V_D \ll V_T$, the current is negligibly small.
- When V_D is negative (*reverse-bias*), the current is negative, but of small value.
- If the reverse bias voltage is increased, the diode may break down, causing a large reverse bias current. Shockley's equation does not hold in this region.

What happens during forward bias?

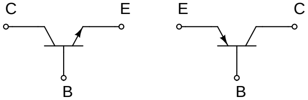
- The majority carriers (holes in p-type and electrons in n-type) are pushed towards the junction due to the externally applied voltage.
- At the p-n junction, there are two opposing electric fields acting. One is the built-in field across the junction and the other is the influence of the externally applied voltage.
- The result is that the net field is less than the equilibrium field value, hence the electrons from the n-side move to the p-side, resulting in a forward-bias current.
- The conventional current direction is always opposite to that of the flow of electrons, hence the forward current is from the anode (p) to the cathode (n).
- As evident from Shockley's equation, the current increases with increase in V_D. This is assuming that $V_D < V_\gamma$. Since the electric field in the diode is strongest at the junction, nearly all of the applied voltage is seen at the junction itself.

Exercise: Work out what happens during reverse bias. Why is the current low? Why does breakdown occur?

The Bipolar Junction Transistor (BJT)

The BJT has two p-n junctions.

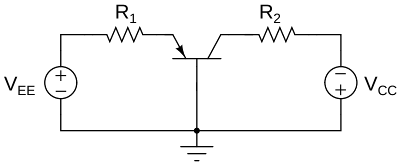
- Since the BJT has two junctions, it can be a p-n-p or an n-p-n device.
- The three terminals are named Emitter (E), Base (B) and Collector (C).
- Usually, the emitter is highly doped, the base is lightly doped (and narrow in size) and the collector is moderately doped.
- The BJT has three regions of operation, based on the biasing of the two junctions.
  - Cutoff region- Here, the B-E junction is reverse biased, irrespective of the C-B junction.
  - Forward-active region- Here, the B-E junction is forward biased, and the C-B junction is reverse biased. This is the most commonly used region of operation.
  - Saturation region- Here, both B-E and C-B junctions are forward biased.



Symbols for (i) NPN and (ii) PNP transistor

Example- Working of a PNP transistor

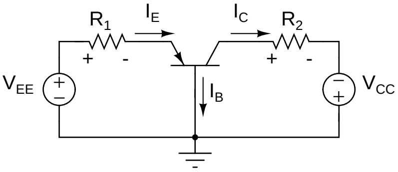
Consider the figure shown below. The transistor is in forward-active region.



- As the B-E junction is forward biased, holes move across to the base (**emitter current**). Since the base is narrow and lightly doped, the minority electron-hole recombinations are less.
- Due to the large carrier concentration gradient in the B-E region, majority of the holes diffuse across the base into the C-B junction.
- Since the C-B junction is reverse biased, the junction electric field sweeps out the holes into the collector (**collector current**).
- A small minority of electrons flow from the base to the emitter. Also, a small number of holes coming from the emitter recombine with electrons in the base. New electrons from the supply flow into the base to replace the the lost electrons. These two components form the **base current**.

Transistor Currents

Shown in the figure below are the emitter (I_E), base (I_B) and collector (I_C) currents and their directions. These are inferred from the discussions in the previous slide.



This also gives us an idea why transistors' symbols are the way they are! The following relationships are valid for a BJT.

$$I_E = I_B + I_C$$ As a consequence of Kirchhoff's Current Law

$$\frac{I_C}{I_B} = \beta$$ β is defined as the common-emitter current gain.

$$\frac{I_C}{I_E} = \alpha$$ α is defined as the common-base current gain.

A Quick Quiz- and an Exercise!

Based on what we've learnt so far, try to answer these questions.

1. What are the possible values α can take?
2. Would we like β to be large or small? Why?
3. Mentally, try to find out a relation between α and β.
4. Suggest some applications of diodes.

Exercise 1: Similar to the way we worked out for a PNP transistor, familiarize yourself with the working of an NPN transistor.

Exercise 2: Find out what happens in the saturation region. Do the above current relations still hold?

Introduction to Signals

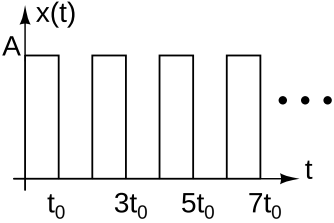
- A signal is a time-dependent piece of information. It is something that removes uncertainty in some manner.
- In electronics we use two kinds of signals- voltage and current. We will mostly be working with voltages.

Let us look at some properties of signals.

- Periodicity- If $x(t)$ is a signal and $x(t+T) = x(t) \;\; \forall \;\; t$, then $x(t)$ is said to be periodic with period T.
- Continuity- If a signal has a defined value at all points in time, it is a continuous-time (CT) signal. Else, it is a discrete-time (DT) signal.
- There are several other signal properties- determinism, causality, energy/power properties.

Frequency Components of Signals

Let's answer this simple question. Consider a signal $x(t)$ as shown.



Q: What is the frequency of x(t)?

Frequency Components of Signals

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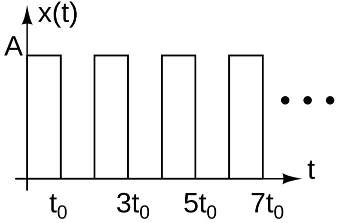


Q: What is the frequency of x(t)?

A: Looks simple- $1/2t_0$, isn't it? But not entirely! Let us see why.

Frequency Components of Signals (contd...)

- $x(t)$ actually has infinite number of frequencies! Fourier analysis tells us how many frequency components are present in a signal. Any periodic signal is expressed as a superposition of finite or infinite number of frequencies, which are integral multiples of a fundamental frequency. $x(t)$ has a fundamental frequency of $1/2t_0$.
- So the next question is, which signal comprises of a single frequency? The answer is a sine wave. Recall the equation for a sine wave

$$x(t) = A\sin(2\pi f_0 t)$$

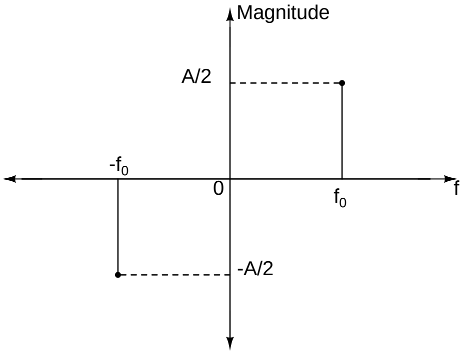
- Sine waves form a **basis** for the Fourier analysis (and for every signal!).

Let's revisit some complex number mathematics. Using Euler's entity, $x(t)$ can be represented as

$$x(t) = A\frac{e^{j2\pi f_0 t} - e^{-j2\pi f_0 t}}{2j}$$

Each exponential term is a Fourier coefficient. The frequency of each component is given by the power. Thus, mathematically, a sine wave has two frequencies!

Frequency Components of Signals (contd...)



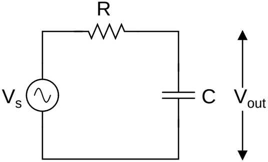
Introduction to Basic Filters

Based on what we have learnt about signals and basic electronic devices, we will now study filters.

- A filter is a **frequency-selective** circuit. This means the filter will behave differently at different frequencies.
- One which passes low frequencies but rejects high frequencies is called a low-pass filter. Now you know what a high-pass filter is!
- One which rejects high and low frequencies but passes only a certain range of frequencies is called a band-pass filter. Now you know what a band-stop filter is!
- Consider the case of a low-pass filter. How low frequencies will it pass, and how high frequencies will it reject? The answer is through a parameter called the **cut-off frequency**.
- Let us see a simple example.

A Simple Low-pass Filter

Consider the simple circuit shown below. V_S is an AC source with variable frequency.



The resistance of R does not vary with frequency. However, the reactance X_C of the capacitor does vary as

$$X_C = \frac{1}{2\pi fC}$$

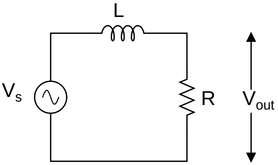
This means that as the frequency increases, the reactance X_C decreases, hence providing a low-resistance path to ground. Thus, the voltage drop across the capacitor decreases as frequency increases. This is a low-pass filter. The cut-off frequency is found using the time constant of the circuit, as

$$f_c = \frac{1}{2\pi RC}$$

A Quick Quiz- and an Exercise!

Based on our knowledge of signals and filters, try to answer the following questions.

1. Is the circuit shown below a high- or a low-pass filter?



2. Let's go back to the above circuit. Interchange the positions of R and L. How will the circuit behaviour change?
3. Consider a signal $x(t) = A_1 \cos(2\pi f_1 t) + A_2 \cos(2\pi f_2 t)$. Draw its frequency domain diagram. Sketch $x(t)$ as a function of time.

Exercise: An R-L-C circuit can act as a band-pass or a band-stop filter. Convince yourself.

Things You Should Know

There are some useful theorems you should be familiar of, before venturing into complex electronic circuits.

- Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL)
- Superposition Principle
- Thevenin's and Norton's Theorem

In addition, you should know certain tools and techniques to handle complex electronic circuits to make them simple.

- Star-Delta transforms
- Source transformation
- And many more........

Some Good References

For circuit/network theorems

- Engineering Circuit Analysis by William Hayt, McGraw Hill
- Several good online resources

For electronic devices (not just diode and BJT!)

- Electronic Circuit Analysis and Design by Donald A. Neamen, Tata McGraw Hill
- Microelectronic Circuits by Sedra and Smith, Oxford

For electronics as a general overview, The Art of Electronics by Horowitz and Hill is a good read.

References

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- http://electronics-for-beginners.com
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- http://www.electronics-tutorials.ws/diode/
- Donald A. Neamen, Electronic Circuits Analysis and Design, Third Edition, Tata McGraw Hill