**Course Name: Engine System and Performance**
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**Lecture – 21**

## Lec 21: Introduction to Transistors

I welcome you all to the session of engine system and performance and in today's lecture we shall discuss about the transistors and then we shall start discussing about the digital circuits. If we try to recall in the last class we have talked about diodes and we have seen that diodes are basically two terminal electrical device and diodes are used to allow current to flow in one direction. So, we have also discussed about forward biased and reverse biased diodes. In continuation of that let us first discuss about diodes and we will see that diodes can be used as rectifiers.

So, draw a schematic of the two terminal electrical devices, then we had seen that this is anode and this is cathode and current flows from anode to cathode. That is what we have discussed in the previous class. And this is basically positive terminal and this is negative terminal.

And we have also discussed that anode is essentially a p-type semiconductor and cathode is n-type semiconductor. So that is what we have discussed. So, this is n-type semiconductor and this is p-type semiconductor. So, we'll see today that these diodes can be used as rectifiers, and these rectifiers have applications in automotive system, essentially to supply DC current for battery charging.

So, let us now consider that if the input is having or waveforms of the input signal, if it is sinusoidal, so this is the input signal, we can see that this input signal is having positive and negative. So, this is positive, this is negative. So, this is input or supply signal in waveforms. And if we use a circuit and, in this circuit, we will be having a power source in the circuit. We have an alternating source of voltage. So, this is alternating source of voltage that is what we can see from this schematic that this input signal has positive and negative halves and then if we use a junction diode if we use a junction diode and if we have a resistor. So, if we have a resistor then say this is $R_L$ and then if we try to draw the output wave forms.

So, this is output signal in the form or in wave forms. So, this is a junction diode and this junction diode has a reverse diode. So, what we have seen from our earlier discussion that reverse bias that means forward bias.

So, if the anode is positive and the cathode is negative, then only it will allow some current to flow. If it is that is forward bias, if the anode is negative and the cathode is positive, then there will be no current flow. So, that is reverse biased, and so the resistance will be high. So, now what we can see from this is, that when you have forward bias.

So, when the resistance is high, when plus voltage is on the cathode, then it is reverse biased. So, we have high voltage. So, in this case, the junction diode is reverse biased. So, when the input signal is positive, then only this will allow current to flow, and when the input signal is the negative half, then no current will flow.

So, essentially, if we try to draw the output signal, then we will get something like this. So, we will get only the positive. So, try to understand that even if we have an alternating source of voltage, using the circuit, that is a rectifier, we can have an output which has only positive components. That means the input signal, which has positive and negative halves, can be converted to only DC, that is positive halves, using this rectifier. So, a DC signal.

So, this is a DC signal, and this signal is getting converted using this rectifier. This particular circuit has applications in automotive systems, especially to supply DC current for battery charging. That is what I told you. So, now let us move to discuss transistors. In our previous class, we discussed that diodes and transistors are two important semiconductor devices, and these two devices have huge applications in modern electronic systems.

And since in engine systems, we need to adhere to the electronic system for better control and operation. We shall require transistors and diodes for collecting signals from different parts of the engine, to convert those signals or to amplify those signals. To the analog unit, essentially, the engine management system or engine control system will receive those analog inputs, and then there will be a digital circuit. So, an analog-to-digital converter (ADC) will be there, and eventually, the engine management system will give some feedback to those systems to make adjustments.

So that the engine can be operated always at an optimum level with better efficiency, lesser emissions, all these things.

So now, let us discuss an important semiconductor device: the junction transistor. So, this junction transistor is a very important device, and these devices have made significant developments in electronic systems, rather, modern electronic systems. So, I should say that this particular semiconductor device has huge potential for the development of small yet complex electronic systems. So, these transistors are essentially semiconductor devices, but these are three-terminal semiconductor or electrical devices. So, these transistors are three-terminal devices; diodes are two-terminal electrical devices.

These transistors have manifold applications, essentially, typically for current amplification. Sometimes these transistors are also used as switches. We will discuss this part. Now, there are several advantages of this particular semiconductor device. What are those? Very small, compact, maintenance is not very stringent, and, of course, efficiency is there.

High performance is the second thing. There are no moving parts and less power consumption—all these things. So, if I try to list down all these things, this three-terminal electrical device is typically used as a current amplifier or as an electronic solid-state switch. So, we will discuss if we need to use a transistor as a current amplifier device or if we need to use this transistor as a solid-state electronic switch. We will discuss this part.

But as I told you, a few distinctive kinds of features, or I should say advantages, are robust construction, no moving parts, contacts needing maintenance. Then we have negligible power consumption, small dimensions, compact size.

Since these devices are of small sizes, lightweight, they are not bulky. So, all these advantages are present in these transistors. Now, let us look into the circuit of this transistor and, at least the operational principle also. So, if we go to the next slide, if we try to draw this schematic, a semiconductor device has three components or one semiconductor device and So, this is N-P-N. This is N, this is P, this is N. This is N-P-N: n-type, p-type, and n-type. So, these are basically material properties. These are semiconductors, typically made from silicon, and the material property is something like that.

I mean, this is n-type doping, p-type doping, and n-type doping again. Now, you have studied all these things in your basic electronics course at the undergraduate level. So, p-type doping means these have a dominance of holes. So, holes are dominant in this p-type, while electrons are the majority in n-type.

So, when this is not that, these three separate units are collected together to form this whole unit. So, this is a single unit itself, but the material property, material characteristics is such that this is n-type doped, this is p-type doped and this is again n-type. So, this p-type semiconductor, basically in this particular case, hole is dominating while in this n-type electron are dominating. So, now, when this n-p-n type is there then electrons will try to migrate from, this junction will form essentially there will be some sort of equilibrium.

Holes will migrate from P to N and electrons will migrate from N to P. So basically, there will be some migration of electrons will be there and an equilibrium condition will reach wherein there will be a band, a barrier and until and unless that equilibrium state is achieved that migration will take place. So, this is basically that is feature of this particular semiconductor device, material property, material characteristics all these things. So, what you have understood that n-type, p-type or n-type basically doped. So, holes are dominating and electrons are dominating.

So, if these two are there then migration of electrons and holes will be there and this migration will continue until and unless an equilibrium situation is or state is achieved. When the equilibrium situation is achieved, that will be characterized by a band having some sort of basically bandwidth or band, kind of resistance. So basically, that equilibrium state is achieved means there will be no sort of migration. So, this is N-P-N.

Now, these transistors, are three-terminal devices. The three terminals are the base, emitter, and collector. This is an N-P-N transistor. Similarly, it is possible to have a P-N-P transistor.

So, we have taken this example. Now, as I said, even if you have this circuit, but externally a power battery. So, this barrier will develop until an equilibrium state is achieved. So, until this equilibrium state is achieved, no barrier will be there, and migration of electrons and holes will occur.

So, now the question is when barrier is developed even if we connect this to base and emitter correct. So, basically as if these three terminals devices can be regarded as two diodes are placed back to back.

Now, let us draw circuit of that. So, two diodes as if two diodes are placed, so this is, P and N. So as if two diodes are placed back to back, so this is the schematic representation of this transistor and we shall discuss all this later on.

As I said you that at the junction of P and N a barrier will develop even if we connect this base and emitter using this circuit some base current will flow and these are basically diodes so this will allow current to flow in one direction. So current will flow from base to emitter because this base is positive with respect to this emitter. So, this is positive, this is negative. So, we know that current will flow from positive to negative. So, base is positive with respect to emitter and current will flow even if we connect this base emitter with this circuit.

So, a small current will flow from base to emitter, but this current will not flow until and unless small voltage, the cut-off voltage that $V_{BE}$ that is 0.7 volt that is provided. So that is the cut-off that we have studied in our basic electronics course. So, this 0.7 $V_{BE}$ is needed that is for the again this is for silicon semiconductor. So, 0.7 Ω is needed to break the barrier to open the gap.

So, a barrier will develop when equilibrium condition will be reached and then to break that barrier we need 0.7 volt then only a small current $I_B$ will flow from base to emitter right. So, this is $I_B$ is the base current. And as I said you this 0.7 volt is needed and that is also known as knee voltage, so that is threshold 0.7 volt, so that is, this voltage is needed. Now when this 0.7 volt that is the minimum, so that is the cut-off, this is also known as knee voltage.

Now, the moment when a small current will flow from base to emitter if this is the transistor circuit. Then in this transistor circuit what we can see now that immediately this is collector current this is collector $C$, so a small current the moment when small current will flow from base to emitter that means if we have 0.7 volt that is the cut-off a voltage or new voltage that voltage will break the barrier and it will create a gateway and then only a small current will flow from base to emitter. This small current will allow a significant amount of collector current to flow, if this circuit is of a significant amount of collector current to flow from collector to emitter until and unless because this is basically these two diodes are placed back to back. So, current will flow from this base to emitter but current cannot flow from base to collector because this terminal is negative with respect to this collector terminal from you can see this particular battery arrangement so a few batteries are connected, so though you can see that the *B* is negative but this *B* is positive.

We can see, but this *B* is negative with respect to the collective. If you look at this particular part, that is *B*. So, if you do not look at this part, then as if *B* is having a positive terminal, but now *B* is having negative, *B* is negative with respect to the collector terminal. And the moment when a small current $I_B$ flows from base to emitter, a small gap, a small opening area will be there, and that 0.7 volt will break the barrier. And during that, immediately, a significant amount of collector current will flow from collector to emitter. In that case, *B* is having negative with respect to the *C* terminal. *C* is positive.

So, current cannot flow from *B* to *C*. That is why the current will flow from collector to emitter. That is the concept. Now, what we can see from this particular circuit is that, under normal operating conditions, current flows forward from the base to the emitter but does not flow in the reverse direction. So, current cannot flow from negative to positive. So, under normal conditions, from base to emitter, a small current will flow if the voltage is 0.7 volts or more.

Then only, when the small gap is there—a small opening area is there—that is the moment we break the barrier. A significant amount of collector current will flow from collector to emitter because this way it is not possible, as this will be negative with respect to the collector. Now, what you can understand is very important. So, we are getting a significant amount of collector current, for a given or small amount of base current, and this is known as gain and indicated by $\beta$. So, $\beta$ is gain.

So, try to understand if we have a small voltage which is equal to or more than 0.7 volts, then we are getting a significant amount of collector current compared to the small amount of base current, and this is known as $\beta$ or gain, which is typically around 100. So, we can see that the collector current, we will get is 100 times the base current. So, we can amplify the current using this semiconductor device. So, as I said, this semiconductor device can be used as a current amplifier or signal amplifier.

Sometimes it is also used as a solid-state electronic switch, but in most cases, typically, these transistors are used to amplify the signal, which is very important. Now, the question is, why do we need to study this particular solid-state device or, circuit?

Electronic system in the context of this course. Try to understand: we have discussed that in the context of the engine system, we have an engine management system or electronic control unit. This ECU or EMS will receive signals from several sensors.

Now, the signal that will be received by the sensors is very small electrical voltage, so very small voltage, 0.05 volts like this, so we need to amplify that, and to amplify that signal, we need this circuit so that the ECU or engine management system will receive very clear and proper information about what to do next, what information to provide to other systems so that the engine can be operated always at its optimum condition. So, this is gain. Now, if we try to draw the equivalent circuit for this, just for example, then it will help us.

So, if we try to draw this schematically, so this is emitter and this is collector and this is base. So, this is $I_B$. So, this is $V_B$ and this is base. So, this entire is basically is grounded.

So, this is basically the schematic depiction of N-P-N type transistor. So, this you can see is the base then emitter then collector. So, initially when this $V_B$ equal to 0.7 volt then this $I_B$ will flow and then we will be getting $I_E$ that is emitter current right and when this 0.7 volt is breaking the barrier then we will be getting significant amount of collector current $I_C$ to flow.

So, then we will be getting $I_C$. So,

$$I_E = I_B + I_C$$

So eventually this is not kind of a schematic depiction but these two terminals are also connected. So essentially a small $I_B + I_C$ is giving that is will be getting current base to emitter and collector to emitter. So base to emitter that is $I_{BE}$ collector to emitter this is $I_{CE}$ that is the total emitter to collector current.

So, this is the emitter, $I_C$ plus $I_B$. So, $I_{CE}$. So, the total current—essentially, our objective is to have current amplification. So, the total current eventually will be base-to-emitter current plus collector-to-emitter current. So, in fact, you can—it is confusing.

So, just write that. Total current will flow from base to emitter and collector to emitter. So, this emitter is equal to base plus collector. So current will flow to the emitter. So, it will come from base to emitter and collector to emitter. So that is

$$I_E = I_B + I_C$$

Now, we have already defined

$$\beta = I_C / I_B$$

So, if we write here that

$$I_E = I_B + \beta I_B = I_B(1 + \beta)$$

So, that means $\beta$ is the gain, which is typically 10 to 100 even. So, if it is 100, then we can have a small base-to-emitter current that can be amplified using this transistor circuit. So, now the question is, these transistors are operated, or these transistors can be operated in three different modes. One is known as cut-off, the second is known as saturation, and the third is known as active or linear. So, you can see that $I_C$ equals $\beta I_B$. So, this is a linear relation. So, the total current that we will get is $I_C$ equals $\beta I_B$. So, this is linear. So, as I said, transistors can be operated under three modes.

These are the three modes. Number one is the active or linear regime, number two is cut-off, and number three is saturation. Let me discuss all these things. Cut-off and saturation—if we try to operate the transistor as an electronic solid-state switch, then certainly we need to operate the transistor in these two regions, and these two zones are responsible for switching, and this is the current amplifier. So now, let me quickly discuss what this is?

Either we can use a transistor as an electronic solid-state switch, in which case we need to operate the transistor in these two regimes: cut-off, which is off, and saturation, which is on. If we need to use a transistor for the amplification of current or signal, then we need to operate the transistor in the linear regime, and that is what we have discussed. Now, what is cut-off and what is saturation? So, let me tell you one thing: if $V_B$ is less than 0.7, then it is not possible to break the barrier that is already there between the p and n-type junction. So, this is a P and N junction.

So, in this junction, the barrier that will develop for the migration will attain a saturation state, if the voltage is less than 0.7, then it is not possible to break. So, this is totally off. The circuit is totally off. That is cut-off.

If it is 0.7, then a small current will flow from base to emitter, and that small current will allow a large collector current to flow from collector to emitter. Because the collector terminal is positive with respect to the base terminal, current will flow from collector to emitter, and that is basically the active or linear region, where $I_C$ is equal to beta times $I_B$.

So, when this linear or active region is there, even if we try to, so there will be a limit; even if we try to increase $I_B$, the base current, a small increment in $I_B$ will, rather beyond a certain value of $I_B$, the increase in $I_C$ will be very small. So, that is called saturation.

So, even if we try to increase $I_B$, increase in $I_C$ will be very small or negligibly small and that is the saturation that is on as if the transistor is between off and on. When on that means saturation. Saturation state has reached. So, if we try to increase this voltage then current will increase.

$I_B$ will increase that is base current, base to emitter current will increase. If base current reaches a threshold then a threshold value of base current increases. collector current will not increase significantly that is the saturation that is on when base current is zero that is voltage across this base emitter junction is less than 0.7 volt, no current will flow, no base current, no collector current, that is off that is switch on and off but when base current is 0.7 beyond the threshold value of that base current that is the current which will start flowing for 0.7 volt until that threshold value of base current which is responsible for a small increase in conduction collector current that regime is the active or linearism. So, these transistors can be used as current amplification for signal amplification and in that case, we can use transistor as an amplifier, we also can use transistor as an electronic solid-state switch in that case transistor should run in these two regimes that is cut-off and saturation.

So, with this I stop my discussion today and we shall continue our discussion in the next class.

Thank you.