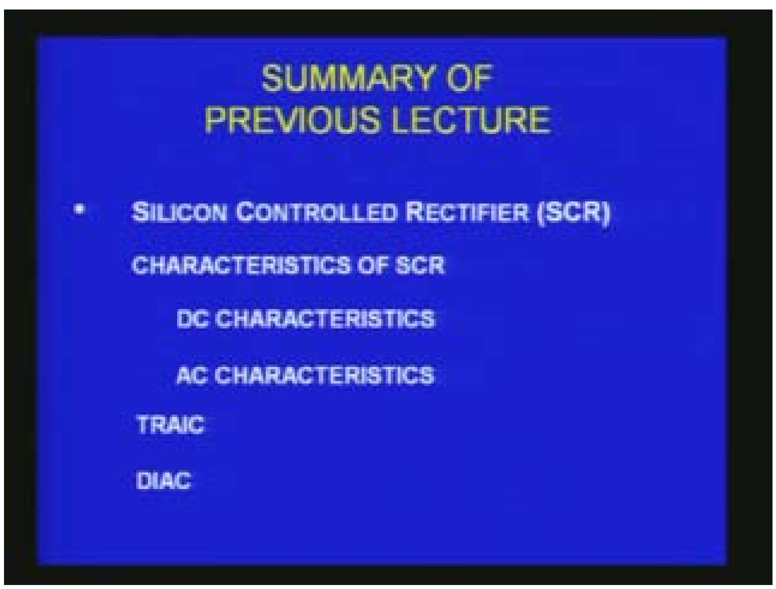
Basic Electronics
Learning by doing

Prof. T.S. Natarajan
Department of Physics
Indian Institute of Technology, Madras

Lecture – 40
(Field Effect Transistor (FET)
(Types, JFET, MOSFET, Complementary MOSFET)

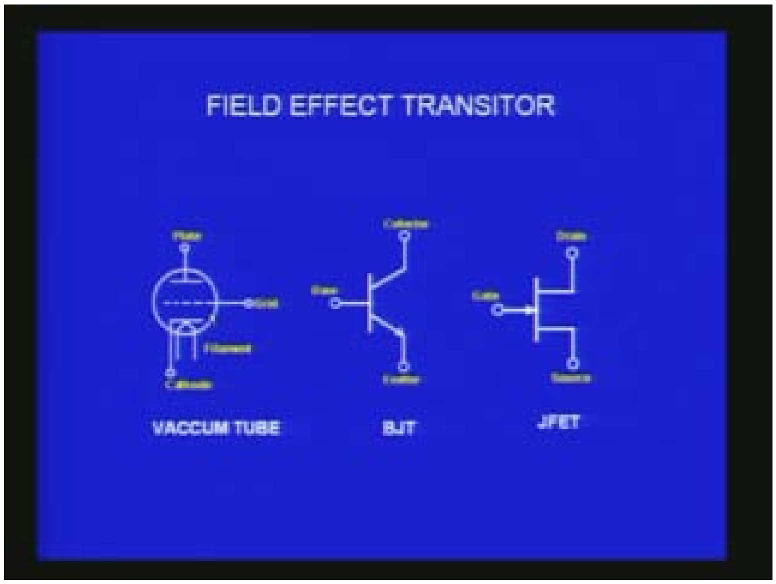
Hello everybody! In our series of lectures on basic electronics learning by doing let us move on to the next. Before we do that we will as usual quickly recapitulate what we discussed in our previous lecture. You might recall in our previous lecture we were discussing about some new devices like uni junction transistor and silicon controlled rectifier or the thyristor.

(Refer Slide Time: 1:53)



In the last lecture we discussed about the thyristor, the silicon controlled rectifier which is also called the SCR for short form. We saw the characteristics of the SCR. How the SCR can be triggered by a gate pulse and how it can be used for power control both in the dc as well as in the ac mode and the dc and the ac characteristics was discussed and at the end I also showed a demonstration how in a simple scheme the SCR can be used to control the intensity of a light lamp. The same idea can be extended to control the power delivered to a fan or any other type of electrical device. Before I concluded I also gave a very brief idea about the other two variations of the SCR namely the TRIAC and the DIAC. Now in this lecture I want to again present you another new device, very important device which I have so far not discussed that is namely the field effect transistor. The field effect transistor is a very, very important development in the history of electronics and it is important that in a course on basic electronics we should at least have some discussion about the field effect transistor. If you look at the history of the electronics we started with vacuum tubes. This is actually a vacuum tube triode.

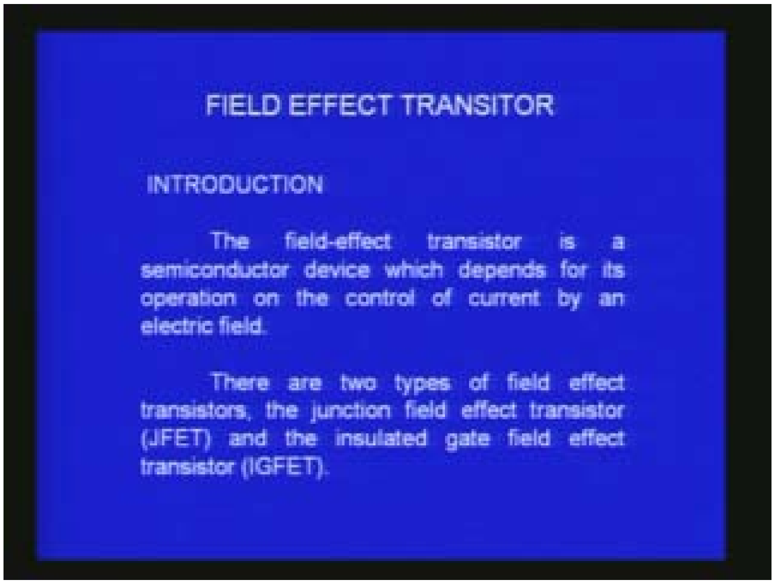
(Refer Slide Time: 3:36)



You have plate, grid and the cathode; the filament is anyway a constant factor, for generating the thermionic electrons. Then came the solid state device that we have already seen; the transistors. But it is one form of the transistor which is called the bipolar junction transistor the npn or the pnp type of transistor with the collector, base and the emitter. Now what we are going to look or discuss in this lecture is going to be the JFET, the junction field effect transistor whose symbol is shown here (Refer Slide Time: 4:13). It is a three terminal device; the drain, the gate and the source. In all the three devices there are certain common features. There is current which is flowing from plate to the cathode or the collector to the emitter or the drain to the source. The third terminal, the middle terminal, the gate or the grid or the base, as the case may be, is used to control the flow of current between the drain and the source or collector and emitter or plate and cathode. That way the basic characteristic of the device is the same in all the three cases. That is there is a large current flowing between two terminals and the voltage or the current on the third terminal is used to control the flow of the main current flowing through the two terminals that we talked about. That is the basic principle. That is why it is called as vacuum tube valve or in this case transistor which is an amplifying device an active device. What is a field effect transistor?

The filed effect transistor is basically again a semiconductor device, solid state device which depends for its operation on the control of current using electric field that is applied between the gate and the source.

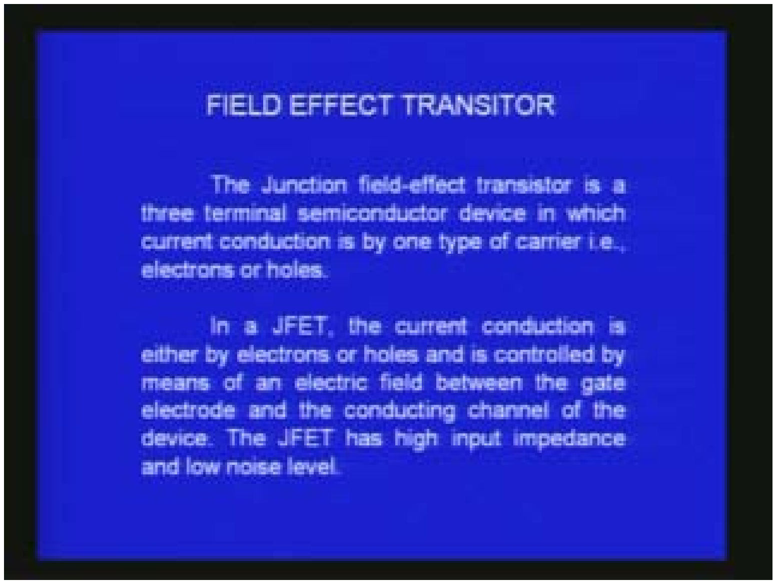
(Refer Slide Time: 5:38)



You have three terminals drain, source and the gate. By controlling the voltage between the gate and the source you will be able to control the current between the drain and the source. That is what the basic function of FET is. There are two types of field effect transistors that we normally come across. One is called the junction field effect transistor which is almost rarely used these days in the laboratory more for basic understanding and the other one is the most popular version which is called the insulated gate field effect transistor, the IGFET. The IGFET is basically a FET which is a modification of the junction field effect transistor but this IGFET is the one which is responsible for other things that you have already come across like the MOS, the metal oxide semiconductor field effect transistor, the MOSFET or the CMOS, the complementary symmetry metal oxide semiconductor field effect transistor. These are the variations of the IGFET insulated gate FET and they are the ones which basically revolutionized the field of electronics. These field effect transistors and the metal oxide semiconductor transistors can be fabricated on planar technology on one single plane of a semiconductor silicon wafer and you can put more density of those active devices per square inch and that brought in the revolution that you see all around in electronics, basically in the integrated circuit electronics.

JFET and field effect transistor in general is a very, very important step in the development of electronics. It is again a three terminal semiconductor device in which current conduction is by one type of carrier that is it is either by electrons or by holes. It is a unipolar device. That is what we call it. You should compare it with BJT, the bipolar junction transistor. In a bipolar junction transistor during the operation there will always be two types of carriers at any time, the majority carriers and the minority carriers. The majority and the minority carriers can be the electrons or the holes. It depends on whether the device is npn transistor or a pnp transistor. You can have two types of charge carriers contributing to the current, total current whereas in the field effect transistor it is a unipolar device that means the current that is ….. or being controlled is basically due to either electrons or holes. How is it? We will discuss in a moment.

(Refer Slide Time: 8:19)

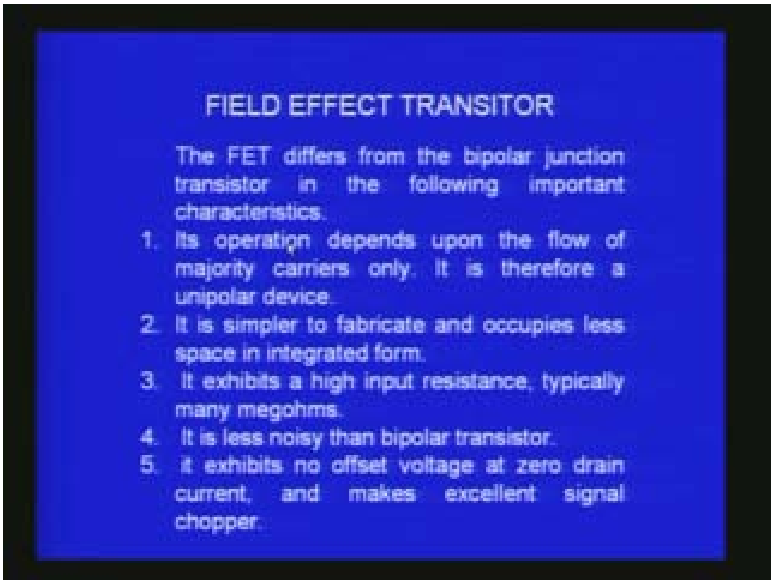


This movement of the current is controlled in this case by the electric field between the gate, electrode and the channel or the source. This is a field effect. What is electric field? Electric field is electric voltage divided by the distance. I have something like a capacitor plate. If I apply a large voltage the electric field is the voltage divided by the separation distance d between the two electrodes. Here also it is the field which is responsible in controlling the flow of current. You should again compare this with the BJT, bipolar junction transistor which is basically a current operated device, current controlled device. Junction field effect transistor is a voltage controlled device and it is very similar in that sense to a vacuum tube triode. In a vacuum tube triode also it is vacuum inside. You have a plate and you have a cathode. In between you have a grid which is normally positioned very close to the cathode. When the electrons are emitted from the cathode by using a filament by thermionic emission they will start going towards the plate when the plate is more positive.

To control the flow of electrons you apply a voltage on the grid, small voltage. Because the gird is very close to the cathode, the field due to this voltage will be very large compared to the field due to the voltage kept on the plate. Because the grid is very close to the cathode the distance is very small; distance comes in the denominator for the field. F is equal to V by d and the field corresponding to the grid will be very, very high and so it will be able to control the flow of electrons between the cathode and the plate very conveniently and that is also a field controlled device or a voltage controlled device similar to the junction field effect transistor where again the control of current is by electric field rather than the current. In the case of BJT, bipolar junction transistor it is the base current which is basically controlling the emitter current or the collector current in the common emitter mode and it is basically a current controlled device and the JFET is a voltage controlled device. That is a bipolar device this is a unipolar device. There are lot of advantages and disadvantages of the devices. One has to choose the proper device for a particular application.

This is what I have actually listed here in this slide. The FET differs from the bipolar junction transistor in the following important characteristics.

(Refer Slide Time: 11:07)

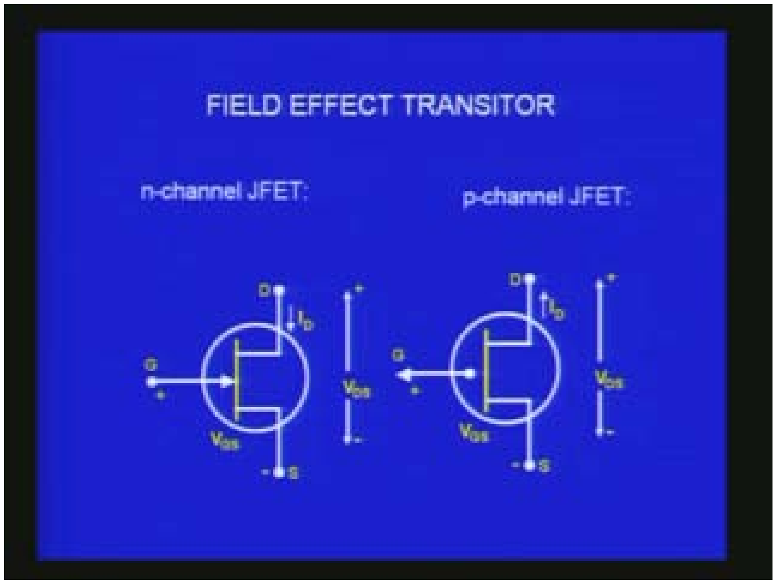


The operation depends upon the flow of only majority carriers. It is a unipolar device. It is simpler to fabricate and occupies less space in integrated form. This is a very, very important form technologically and it provided the giant leap we required in the field of integrated electronics, IC electronics. The most other important characteristic of the JFET is that the input junction is reverse biased. In the case of transistors the base emitter junction will have to be forward biased for the transistor to conduct and the amplifiers that we design using these transistors will always try to forward bias the base emitter junction. In the forward biased base emitter junction input resistance will be low and it is a low resistance at the amplifier input as against what ideally you would require for a good voltage amplifier which will be high input impendence.

Transistors are not really very good for voltage amplification in that sense. Whereas if you take the JFET the input junction is to be reverse biased between the gate and the source. Because it is reverse biased the input impedance of an amplifier made out of the JFET is also very high and that characteristic also is very, very important in the design of different circuits. There are many operational amplifiers that we talked about. You would find there will be FET input operational amplifiers. In the differential amplifier at the input stage you try to include a JFET rather than a BJT so that you will have very large input impedance and that is a very important characteristic that will bring down the input bias current and improve several other good characteristics of the operational amplifier. Using JFET will be prompted by large input impedance that it provides at the input stage.

It is less noisy than bipolar transistors and it exhibits no off set voltage at zero drain current and makes excellent signal chopper. These are the more advanced applications but let us try to see the circuit symbol of the JFET.

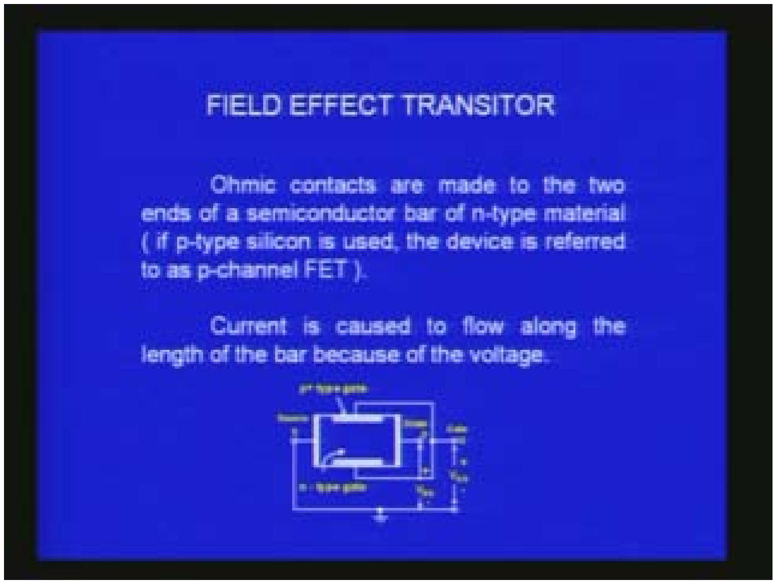
(Refer Slide Time: 13:37)



There are two types again. Just as you have in BJT npn transistor or a pnp transistor in the same way you can have two transistors here. One is called the n-channel field effect transistor. The other is called p-channel field effect transistor. The circuit symbol the difference is only in terms of arrow just as you have in the case of transistor. Even in the case of BJT bipolar junction transistor the emitter will have an arrow which will be in opposite direction for the pnp and the npn. Similarly here the n-channel and the p-channel will be shown by the direction of the arrow that you see on the screen. You must also compare it with the symbol of an UJT, uni junction transistor. In the case of uni junction transistor the base, the gate, the terminal will have a break here. It will have a slant here. In the circuit that you see here there will be a slant here. If the same arrow is bent here then it becomes the UJT (Refer Slide Time: 14:42). If it is straight then it becomes a FET. So you should remember the difference in the circuit symbol of these devices.

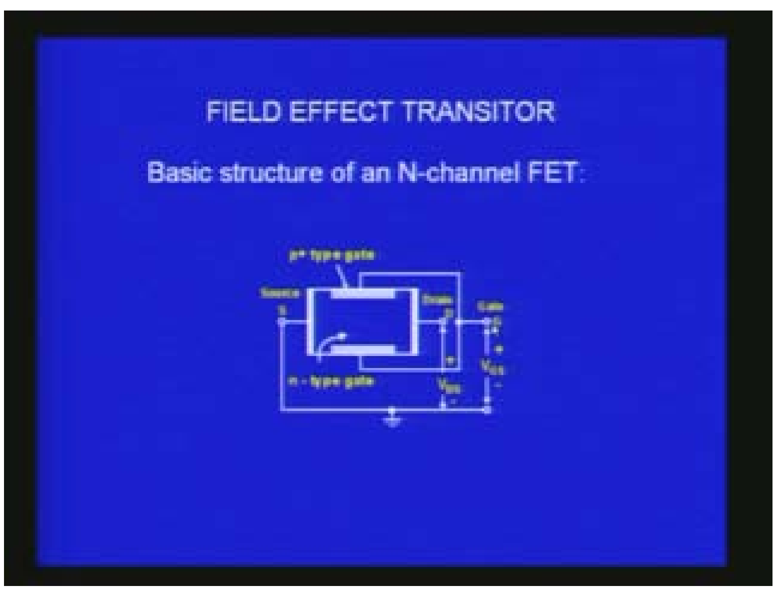
Basically what is the field effect transistor? It is nothing but a simple silicon block you see here on the screen. You have a silicon block here and this is n-type or a p-type. Let us assume that this is n-type. If it is n-type then there are two regions here which are called p plus type gate. p plus means heavily doped p type. So the difference between this and UJT again is in the UJT the p-type region is a very, very small region almost near the middle of this n-channel. Whereas in this case it will be reasonably over a region and more importantly this p-type will be all through like a belt around the silicon block that I considered. So you will have all around a p region and that provides the gate region.

(Refer Slide Time: 15:46)



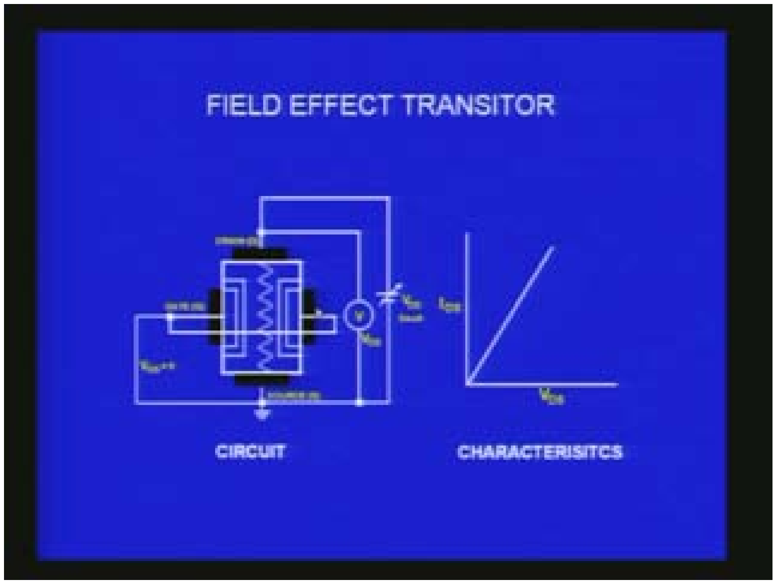
That is what is shown in this picture. The two white shaded area I have connected together and I call that as the gate. That is the gate terminal and one end of the block is called the drain. The other end is called the source between which I will have to apply a large voltage which is called the drain source voltage. You have three terminals the drain, the other end is the source of the n-type block and you have in between the belt region which is called the gate region.

(Refer Slide Time: 16:19)



What is going to happen? Let us understand the basic characteristics of the field effect transistor. I have shown here the same in the circuit. You have a block of n-type semiconductor let us assume and you have the two gate regions on either side.

(Refer Slide Time: 16:39)

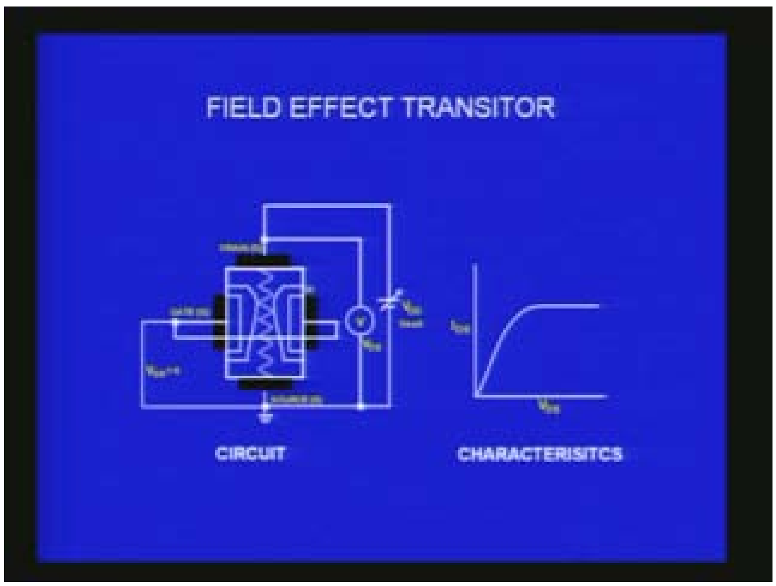


These black things are the electrodes, metal electrodes for contact. The drain is connected to a power supply which is variable V_{DD} and the source is grounded. The voltage supply is between the drain and the source and you also have a voltmeter connected between the drain and the source and here there is also a connection between the gate and the source. It is actually shorted. There is no voltage here. So the V_{GS}, the voltage between the gate and the source is equal to zero. The V_{DS} is variable with this battery here that we have. You can measure the voltage and the source is common and that is grounded. This is the configuration. If I keep increasing this voltage and if I put a current meter here and measure the current. What will happen? Because this is just a simple n-type semi conductor it can be equated to a simple resistor for all practical purposes. When I increase the voltage for some limits the current will keep increasing because it is just simply …..

If I draw a graph between V_{DS} and I_{DS}, V_{DS} is the voltage between the drain and the source I_{DS} is the current that is generated between the drain and the source. If I monitor that you will have a beautiful straight line which is nothing but simple Ohm's law. But this straight line will come up to certain value of the voltage. Beyond that what is going to happen? This resistor if you measure the voltage at the drain point it will be the applied voltage. If you measure at this point it is the zero because it is the source. In between you have a resistor. So if you measure at any point in between, the voltage at that point will be a fraction of the total. It becomes a potential divider; the region on the top and the region at the bottom become the R_1 and R_2. At the center you will have a fraction of the total voltage applied only. At various points along the channel the voltage is different. At this point it is high. It is slightly less, still less, still less and still less. It keeps on coming down and what is the effect of that? Because this is connected to the ground, the gate is connected to the ground the drain is connected to plus of the battery. On the n side there is a plus voltage on the p side there is zero. n side is more positive than the p side, the gate and there is a reverse bias. But more importantly this reverse bias is not a constant. It has got some value very close to the top. It has got a higher value because the voltage there is more and as I come down there is a drop along the channel because the channel is something like a resistor and at different points along the channel the voltage is different, less and less and reverse bias between the gate and the channel is also different at different points. It is maximum at the top and minimum at the bottom.

What is the effect of this? The effect of this is as I keep increasing the V_{DS} voltage the depletion region produced on the n-type will no more be perfect rectangle. It will have a wedge shape.

(Refer Slide Time: 20:14)

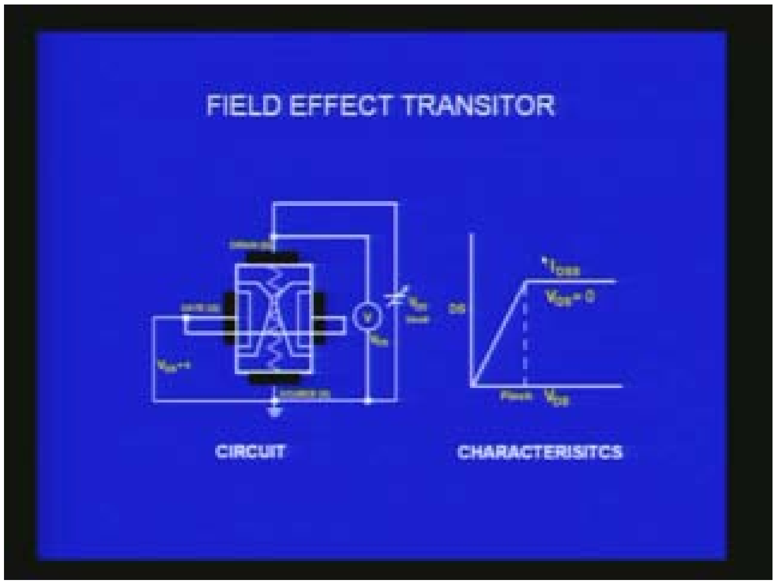


The depletion region will be proportional to the reverse voltage. It will be more on this side. The thickness of the depletion region will be more at this point and it will be less at the bottom. Slowly at the top, the region available for conduction of the electrons, the resistance that will be much less compared to the bottom. There is a wedge shape. Because of this the current will be constricted while it is flowing through this channel and the characteristics will show a bend.

As I keep increasing the voltage beyond certain critical voltage, threshold voltage it will slowly bend and finally when this becomes very large, when the reverse bias becomes very large when the two depletion layers almost come together there will only be very small region for the electrons to flow and you cannot push the electrons still further. Because the electrons are negatively charged they repel each other. There is a repulsive force from inside the electrons flowing in the channel and there is a crowding effect due to the channel depletion layer increasing in width. There will be equilibrium at some stage. Due to the external pressure and the internal pressure there will be equilibrium.

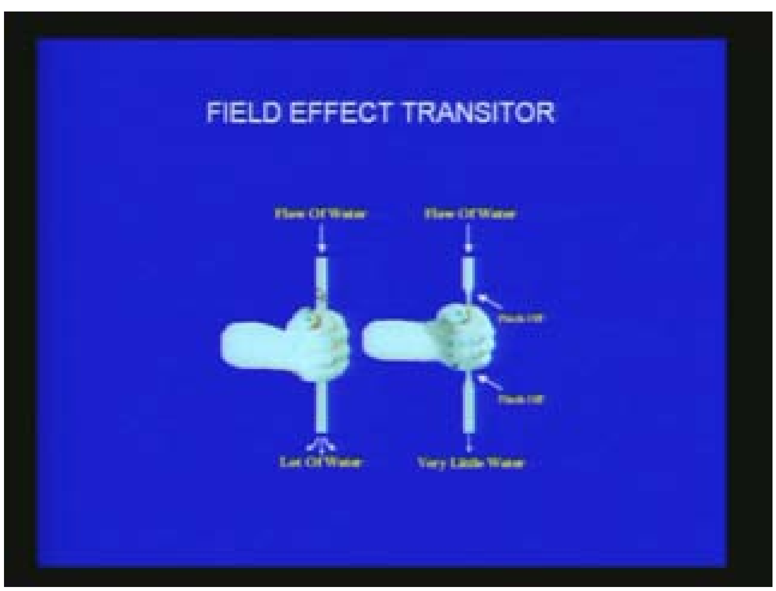
Once the equilibrium is reached no effect of the voltage will be felt and the current will become a constant. You cannot increase it or decrease it. It will come to saturation. This point is what we call a pinch off voltage. I have shown it in the next picture where almost we are at the pinch off. Then the current becomes almost constant.

(Refer Slide Time: 21:54)



This current we call I_{DSS}. When the gate source voltage is zero what is the maximum current, saturation current that I achieve between the drain and source is what I call I_{DSS} and this is corresponding to a condition called the pinch off. I have shown the pinch off condition by equating it to a normal rubber tube in a garden.

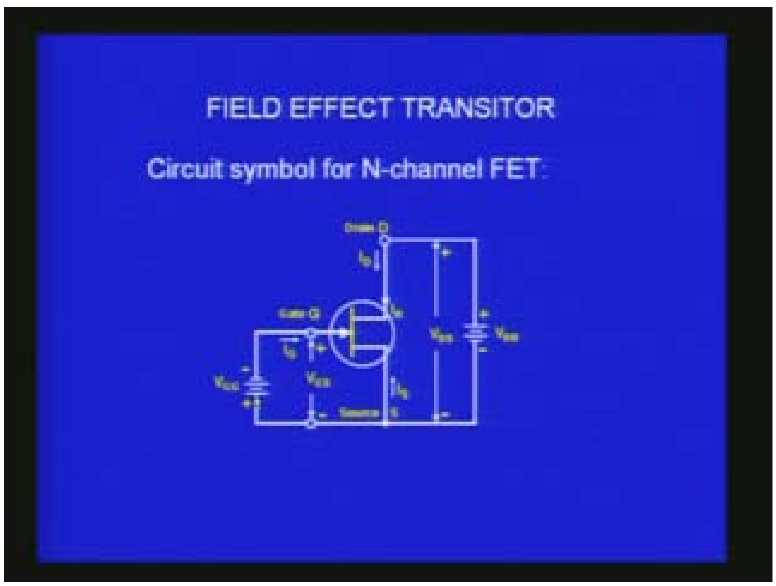
(Refer Slide Time: 22:17)



When you water the plants in the garden you have a hose, a pipe through which water will be flowing and if I now start squeezing the rubber tube from all sides I can never make the flow completely zero. Small amount of water will still be coming but it will be a steady flow. That is the maximum pressure that you can apply on the rubber tube. You get very small flow but it is a very, very constant flow. That is why it is called pinch off. The same thing happens in this case. As the depletion layer keeps growing on both sides the channel available for the flow of electrons will become smaller and smaller in area and ultimately there will be a constant area below which you cannot change anything and current also at that time becomes constant which we call I_{DSS} or the pinch off current.

Having seen that we will go back to the circuit and then we can also connect a power supply between the gate and the source. We have a power supply between the drain and the source which I call V_{DD}. You can also have a power supply between the gate and source which is V_{GG}.

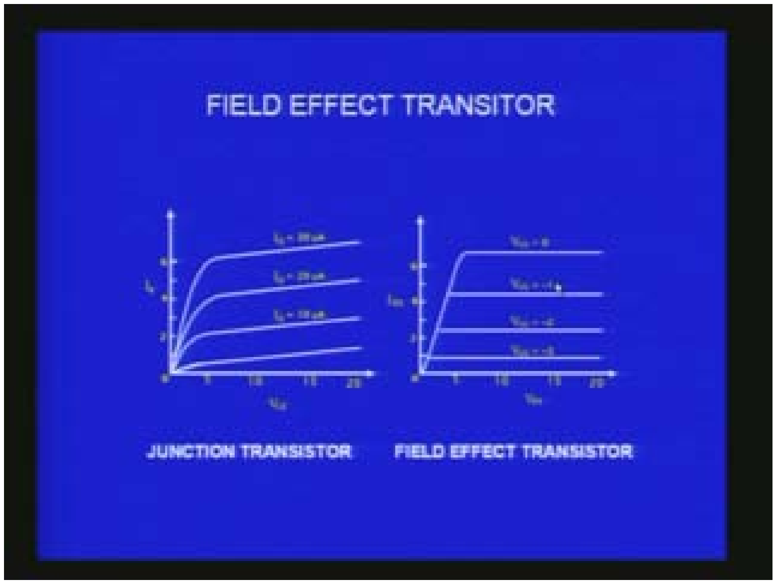
(Refer Slide Time: 23:40)



In the case where I just discussed I made V_{GG} zero. Then when I keep on increasing V_{DD} from a small value to large value initially it goes like an Ohm's law in a straight line and then it bends and once the pinch off is reached it becomes constant saturation current. I have some voltage on the gate with reference to the source and more importantly look at the polarity of the battery. The gate is connected to the negative terminal and the source is connected to the plus. That means it is reverse biased. This is the p-type this is the n-type. p-type is connected to the negative terminal and the n-type source is connected to the positive and the gate source junction is reverse biased and if I now put let us say -1 volts or -2 volts here and then go through again from zero to a large value for V_{DD} what will happen?

When V_{GS} is -1 volt the saturation will be reached even before because there is already some negative voltage available on the gate and I have to go to a much lower voltage on the V_{DD} supply before I can reach the pinch off condition and that pinch off or the saturation voltage or the saturation current comes much lower to the I_{DSS} when V_{GS} is equal to -2.

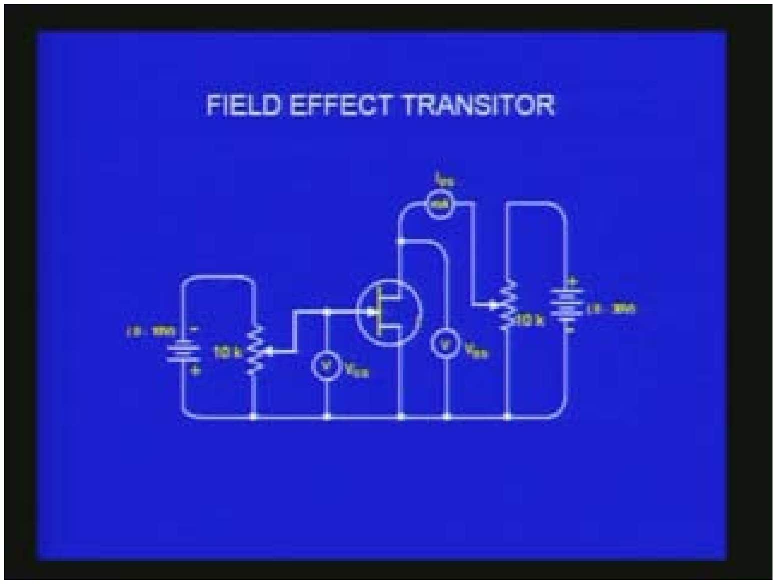
(Refer Slide Time: 25:11)



When I make it -2 V_{GS} is equal to -2 or -3. These things will become much less as shown in this graph. This is the graph corresponding to field effect transistor and I have put the other graph also here which is corresponding the BJT, junction transistor. I am sure we have seen this graph earlier in our lectures. It is the graph between collector emitter voltage V_{CE} to the I_c, the collector current. This is output characteristics as we call. You can see the similarity between the two graphs. But the change is here. It is for different I_B. Because it is a current controlled device I_B is equal to 30, I_B is equal to 20, I_B is equal to 10, etc you have here. Here it is a voltage controlled device. You have V_{GS} is equal to 0, V_{GS} is equal to -1, V_{GS} is equal to -2, etc. Otherwise they look almost very similar. But there is a very important difference in that and that is the saturation current here is much more flat, almost horizontal constant; whereas in the case of transistor there is a finite slope. This is due to the base width modulation as we normally call. It is not completely perfectly horizontal you have got a finite slope and this is a very important change in the case of field effect transistor and junction transistor.

Having seen that now I think it is time for us to go and try the characteristics of the field effect transistor on the work table. The same circuit I have used where I have used the filed effect transistor.

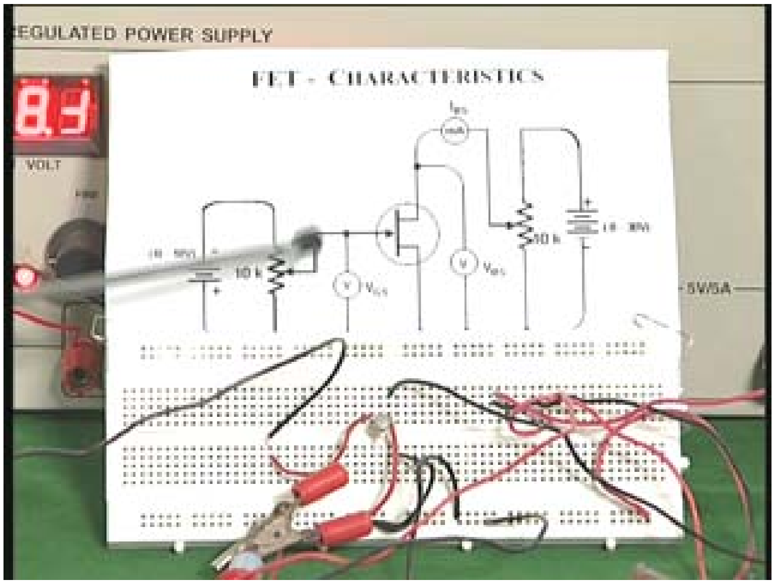
(Refer Slide Time: 26:58)



This is BFW 10 which is a standard junction field effect transistor available in the market. You have this voltmeter which measures the voltage between the drain and the source V_{DS} and you have a current meter which is I_{DS} and this is about zero to 10 milli amperes. You have a variable power supply which is obtained from a fixed power supply and on this side, on the gate side you have a variable power supply and a voltmeter V_{GS}. There is no current meter here because the current is going to be very, very small. It is a reverse biased junction. The current through the gate will be very, very small and we require only three things; the drain source current, the drain source voltage and the gate source voltage. These are the three parameters that we will try to vary and see how the characteristics come. You should also remember the graph that I showed you with reference to the characteristics.

See this circuit. This is the FET characteristics circuit. You have the FET, the same circuit I showed you sometime back on the slide. You have the variable power supply here. You also have another variable power supply and you have the voltmeter and the current meter and voltmeter all the three here.

(Refer Slide Time: 28:16)



Now I have used the millivolt source here as the voltage that is to be applied across the gate and the source. This source is used for the gate source supply and I have here in voltage range. If I change it 1, 2, 3, 4, etc it will be -1, -2, -3, etc because the terminals are properly inverted when I connect it to the FET. This FET is BFW 10. It is a very standard FET available in the market. It has got 4 leads. Normally transistors have got 3 leads. Here we have 4 leads the drain, source, gate and shield. The shield is actually one terminal which is connected to the top can. We normally ground it. We don't use it. Then this power supply at the back which is 9 volt approximately is what I am using as the V_{DD} the drain source voltage and we have got a potentiometer here which I will use to vary the V_{DD} from zero to high value and that voltage V_{DD} will be measured by this voltmeter that you see here. This blue voltmeter is going to measure the V_{DD} voltage; V_{DS} to be precise and this current meter is the one which is going to measure the I_{DS}, the drain source current for different gate source voltages. No other current meter is required because we are going to only vary the gate voltage and measure.

Gate source voltage is kept in zero position and concentrate on the voltmeter and the current meter as I change the V_{DD}, drain source voltage. I am going to change the voltage. The voltage is increasing and it is about 0.1 volt and correspondingly the current also is increasing. It is about 1 milli ampere.

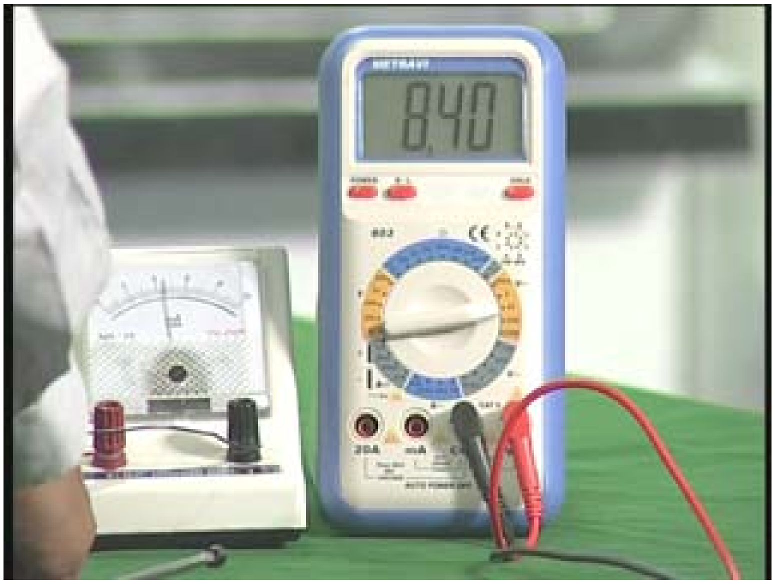
(Refer Slide Time: 30:22)

Now it is 2 milli amperes and as I keep on increasing it is 4 milli amperes, 5 milli amperes and it keeps on increasing and it goes beyond 10 milli amperes. That means I_{DSS} is going to be larger than 10 milli amperes. That is what I see here. If I use much larger may be 15 milli amperes I may be able to get about 12 or 15 milli amperes as the I_{DSS}. Now what I am going to do is I am going to change the gate source voltage to -1 volt. Now I have kept it as -1 volt. I will again go through the V_{DSS}. The voltage and the drain source I am going to increase now. See the meters. As I increase the current also is increasing slowly. You can see the current is increasing. I keep on increasing the voltage. It is about 4 milli amperes; now 8. Almost I have come to 8 milli amperes.

(Refer Slide Time: 31:28)

I still increase the voltage but nothing happens. So the current is constant at 8 milli amperes. Previously when V_{GS} was zero it was going beyond 10 milli amperes. It is usually around 11 or 12. When I go with -1 volt between the gate and source the current is saturating at 8 milli amperes. Now I will bring it back to zero and change the gate source voltage to another value say -2 volts. I keep it at -2 volts. Again I go through the characteristics and you observe the two meters. As I increase the voltage the current also increases slowly much slower than previously and almost I have come to 1 volt. It is about 3 milli amperes. If I still go further I am not going beyond 4.5 milli amps. I have almost come to 9 volts in the voltmeter, around 8.4 volts but then the current is only 4.5.

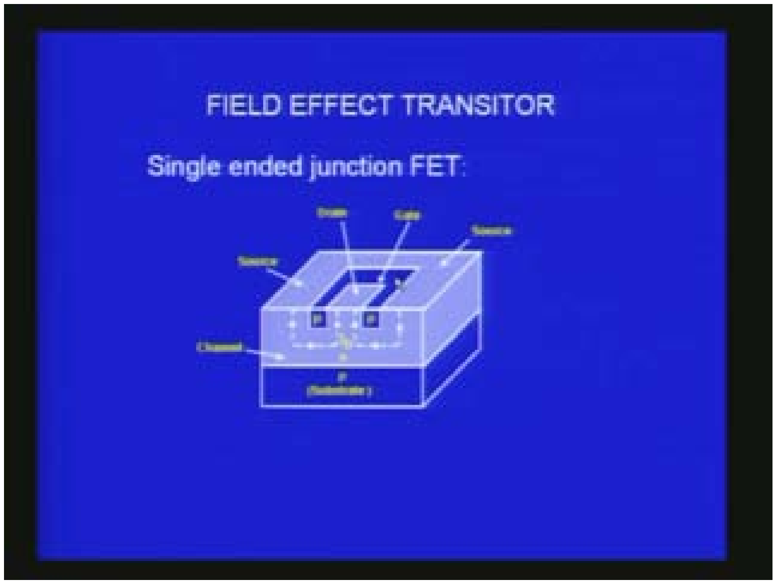
(Refer Slide Time: 32:40)



The current is now saturating much earlier than what it was for -1 volts or for zero volts between the gate and source. If I keep on doing it I will be able to get all the different characteristics corresponding to different values of V_{GS}, the voltage between the gate and source. We saw the characteristics of the field effect transistor, junction field effect transistor; how for different gate source voltages the saturation current is different. If I increase the gate source voltage to -1, -2 the saturation current comes at lower values. You have seen that. But one of the greatest advantage of the junction field effect transistor is the capability to make the junction field effect transistor on the same side of the silicon wafer.

I have shown a picture here on the screen. I have a p substrate and a n-type semiconductor grown on the p substrate and you again have one more layer of p here in the way shown on the graph or picture?

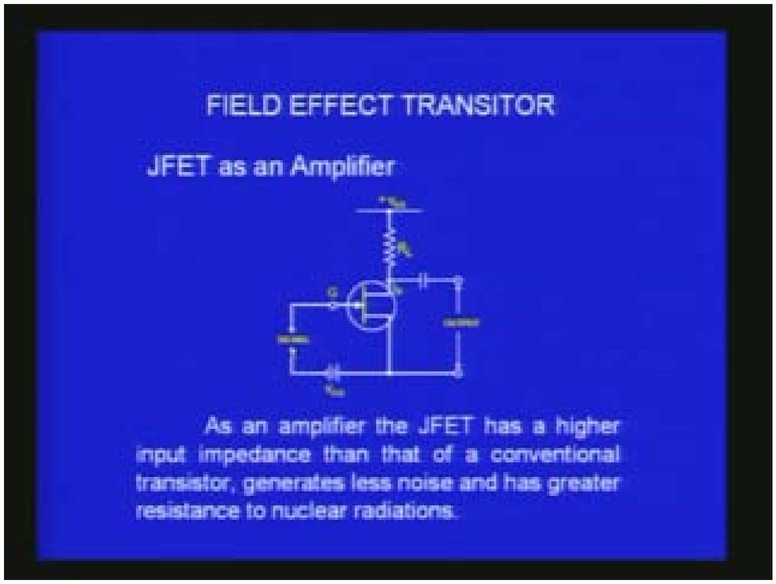
(Refer Slide Time: 33:56)



Then what happens on either side of the p region here and here it becomes a source and the drain. This becomes the drain. This becomes the source and this is the gate. Similarly on this side I have the drain, I have the source and in between I have the gate. I have got two JFET’s connected together. At this source a common drain is there but the source and the gate are different. On the same side I have got two FET’s side by side. Like that I can develop number of integrated circuits especially the field effect transistors in very small regions on the wafer and if I try to do also the interconnections and the resistances using n-type or p-type semiconductor then in principle on the same side of the silicon wafer I can generate all the parameters the resistors, the capacitors. Capacitors are very rare but you can generate capacitors because it is again the diode reverse bias diode which is the usual capacitor that we have. So you have resistors, you have transistors and in the interconnections you can have metal regions and the whole circuit can be fabricated within very small regions of few microns in area on the same side of the silicon. That is what we call integrated circuits. The whole revolution in the electronics due to integrated circuits became possible because of this capability to generate different devices on the same side of the silicon chip.

Let me show you the importance of the other variations of the junction field effect transistors. Junction field effect transistors can be used also as an amplifying device. Just as the bipolar junction transistors can be used as an amplifier the JFET can also be used as an amplifier. I have shown a very simple circuit here where it is very similar to a triode amplifier. You have a load resistor R_L and you have a coupling capacitor and there is a bias here V_{GS}; V_{gg} we call it, power supply and if I give an input signal here this signal will sit on top of this V_{gg}.

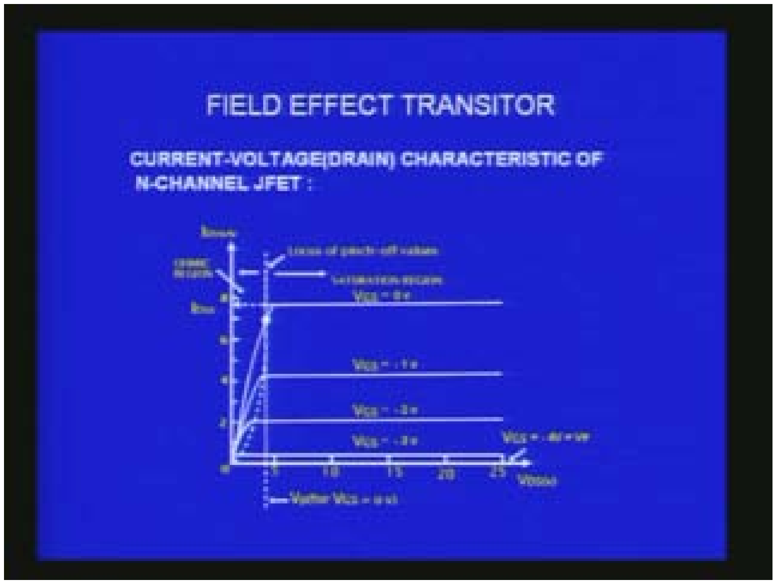
(Refer Slide Time: 36:18)



Depending upon the amplitude of the signal the V_{gg} will be modulated. It may be higher when the sine wave is going higher and it will be lower when the sine wave is going down, negative and depending upon that this current between the drain source will also vary according to this signal. Because this current is varying that current flowing through the R_L will make a voltage develop across this which will also be varying in exactly the same way as the variation in the signal here and the output when I now connect to a loud speaker I will get an amplified signal at the output. The basic junction field effect transistor can in principle be used to amplify small signals which are in the order of few millivolts. Because the field produced by the millivolts is very large it will control large current flowing between the drain and source and it will produce large voltage variation after the capacitor at the output. That is the basic principle of the amplifier. I will not be going into too many details of these devices. Normally they can be discussed at length; the variations of various devices and the characteristics, the biasing mechanisms and the different configurations of amplifiers that can be constructed using all those things. But due to want of time I am not discussing. Because basically this is a lecture on basic electronics I don’t want to complicate too much by having too many data, too many information.

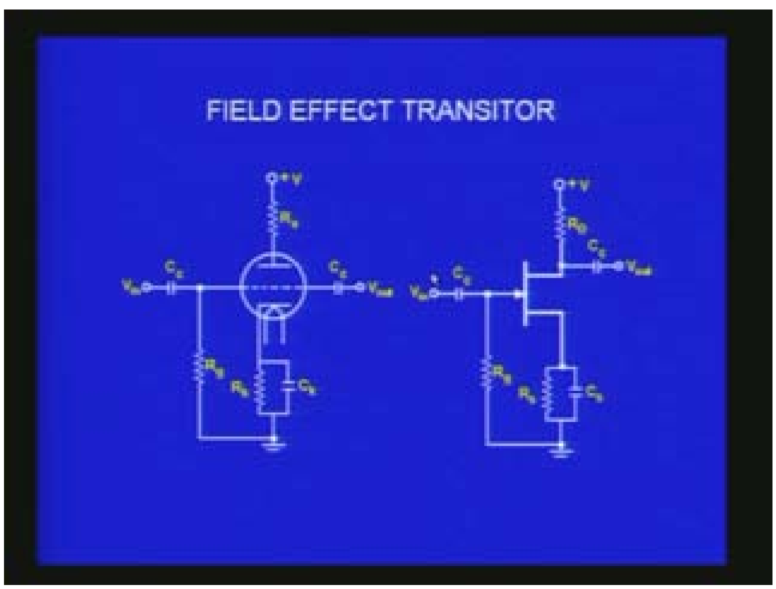
This is the basic configuration of the junction field effect transistor. You see almost horizontal lines corresponding to the saturation. In principle this can also be used as a current source. Junction field effect transistors can be used as a current source and if you find the slope of this it will be very, very high. That means it is a high impedance device and a current source is characterized by large input impedance.

(Refer Slide Time: 38:25)



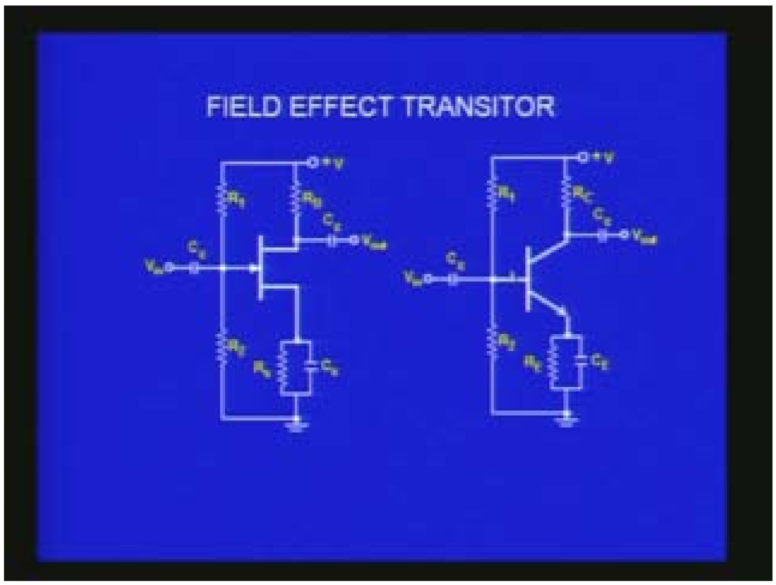
The current is going to be constant and dependent only on the voltage you applied between the drain and the source as well as the gate and source. I want to show very interesting thing with reference to the amplifier configuration. Here I have shown two circuits.

(Refer Slide Time: 38:43)



The circuit on the left is basically making use of a vacuum tube triode of the olden days. You have the coupling capacitors, you have the bleeding resistors R_{gl} as it is called and you have the cathode bias. R_k and C_k form the cathode bias for providing a bias for the triode and you have the R_p load resistor. This is a simple amplifier configuration using triode and by the side of it you see another device which is the modern field effect transistor and you see the exact replica of the circuit except that the device is different. Here it is vacuum tube. Here it is field effect transistor and the other important thing is this voltage that is applied at the plate will be around 200, 250 volts whereas here it is about 20 volts. So the voltages have come down. It is a solid state device. The size has become very, very small. There is no need for any filament. That means there is no need for a separate power supply and the circuit has become very simple, small in dimension and the voltages are also very, very low. The comparison is very interesting to see. Similarly I now take another configuration. Here what I have is the transistor amplifier.

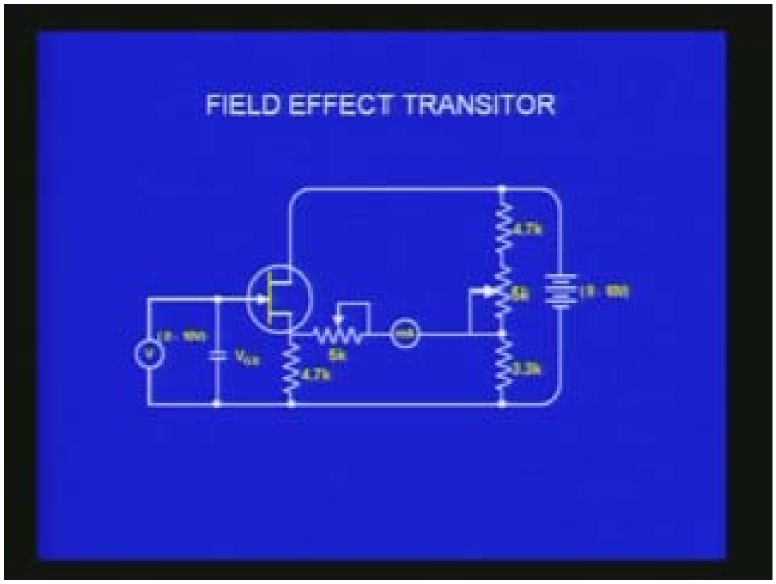
(Refer Slide Time: 40:08)



This is again familiar to most of you. This is a voltage divider bias with R_1 and R_2. You have the collector resistance R_c. You take the output between the collector and the V_{cc}. The input is given at the base through the capacitor. This is called emitter bias, the R_{ece} value. This is an amplifier constructed using transistor and on the left side you have the same amplifier constructed using a field effect transistor except that I removed the BJT and introduced the FET. Other than that the circuit looks exactly identical and the design of new circuits becomes rather very simple. If you have a triode circuit all that you do is take out the triode, reduce all the voltages, remove the filament supply, put the field effect transistors effectively. It should in principle work. It is not as simple as that but in most of the cases it will be reasonably good to try a design like that.

In the case of transistor you still can have a whole circuit retained, remove the bipolar junction transistor and replace with an appropriate field effect transistor. In principle you should get your things going without any major problem. This is a very great advantage with reference to design of circuits using field effect transistor. There are lot of related materials which I have not discussed reasonably but then I want to show you at least one important application of field effect transistor. The field effect transistor is very important because the input junction is reverse biased.

(Refer Slide Time: 41:50)

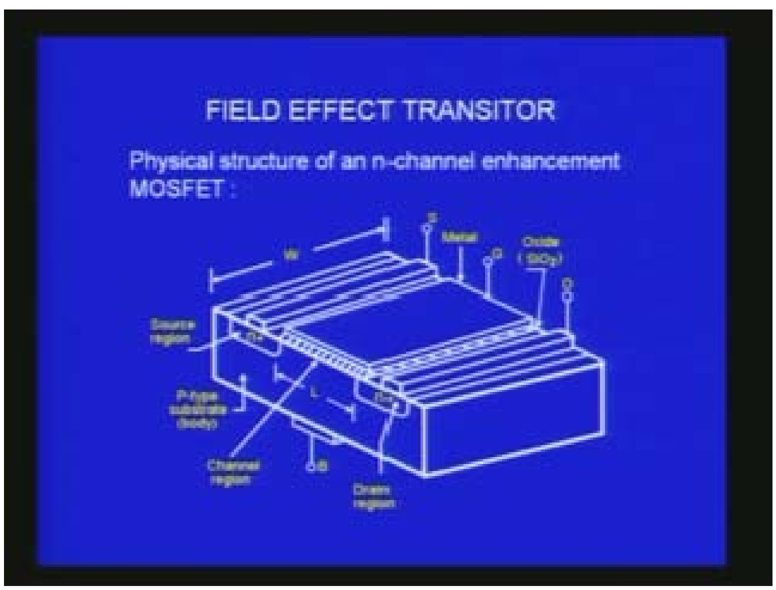


That means the amplifier made out of field effect transistor will have much larger input impedance. I want to exploit that concept and build very useful application circuits which you can quickly try in the lab and learn the importance of the field effect transistor. I have given you a circuit here which is actually a field effect transistor voltmeter, FET voltmeter. What is that I have here? I have a field effect transistor and I have a set of resistor. If you look at it, it is something like a bridge Wheatstone's bridge. One arm of the bridge is having the drain source resistance of the field effect transistor. The other arm has got 4.7K and 5K variable 5K in series. The third arm is having 4.7K, the fourth arm is having 3.3K and I apply a power supply here and between the middle terminals I have a current meter and a variable resistance in series. At the base of this FET I have the input voltage. What is going to happen?

The drain source current will be controlled by the voltage on the gate or in another way I can say the resistance between the drain source is going to be controlled by the voltage applied here. When this resistance is going to change due to the voltage applied at the gate, the balance of the bridge will be disturbed and there will be some finite voltage developed across these two points and that will drive current through milli ammeter. There will be a deflection in milli ammeter proportional to the voltage here. So this becomes a very convenient way of measuring the external voltage. Because it is reverse biased I can apply a voltage here and correspondingly there will be a current variation here which can be measured by us and this becomes a very inexpensive FET voltmeter. An ideal voltmeter should have very large input impedance. You all would have studied how to convert a galvanometer into a voltmeter. One of the simplest methods to convert a galvanometer into a voltmeter is to connect a very large resistance in series and the whole thing will be used in parallel as a voltmeter in measurement. A good voltmeter is characterized by large input impedance. Keeping the input impedance of the voltmeter high is a very important consideration in the design of the voltmeter. If I use transistors for designing my voltmeter then the input impedance of the transistor, because it is a forward biased junction, is very low. Whereas if I use in place of the BJT, the field effect transistor the input junction will be a reverse biased junction and the resistance automatically will be very high and it will be much better voltmeter than I design with transistors, BJT’s and one of the good examples of the application of the field effect transistor is a very simple voltmeter made out of FET amplifier. That is what I have been showing you.

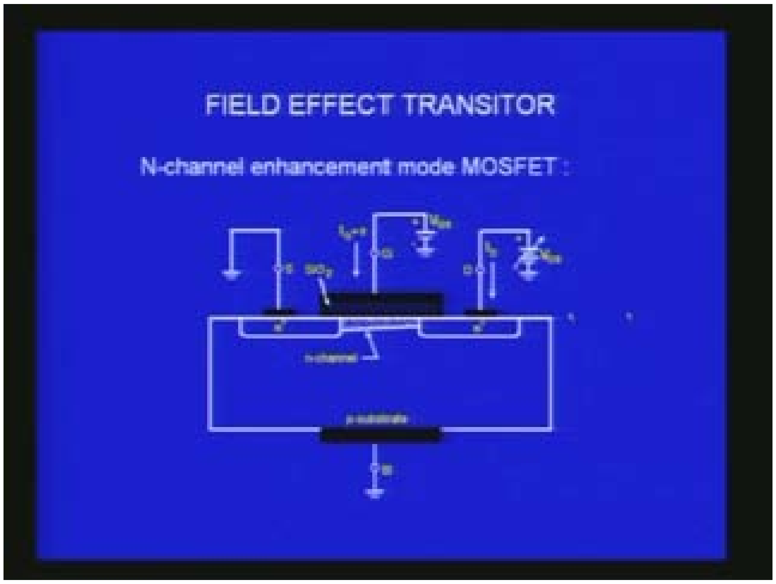
I have a potentiometer here. This potentiometer is actually used for controlling the zero of the milli ammeter. You can adjust the zero so that the current in this wing is adjusted to make it zero and this is also used for adjusting the balance of the bridge and now you apply any external voltage. For whatever basic thing that you have you adjust the two potentiometers and make it zero and then you apply external voltage here. When I apply, this voltage is going to be applied as a reverse bias here. 1 volt, 2 volt if I apply here correspondingly the variation in the resistance will change the balance of the bridge and there will be a current flow and if the bridge is properly balanced the current can become proportional to the voltage. Then I have a very nice electronic voltmeter. Normal galvanometer or current meter is converted into electronic voltmeter by having a very simple field effect transistor amplifier in the configuration that I have shown here. This is what I want to show you. I will show you demo of this and then I will also discuss some of the important aspects of the field effect transistor which is in this case metal oxide semiconductor field effect transistor or the IGFET which is another variation of the field effect transistor.

(Refer Slide Time: 46:50)



This is a very important device again. Almost all of integrated circuits make use of this configuration where the junction is formed in the normal junction field effect transistor whereas here what we do is we actually use like this.

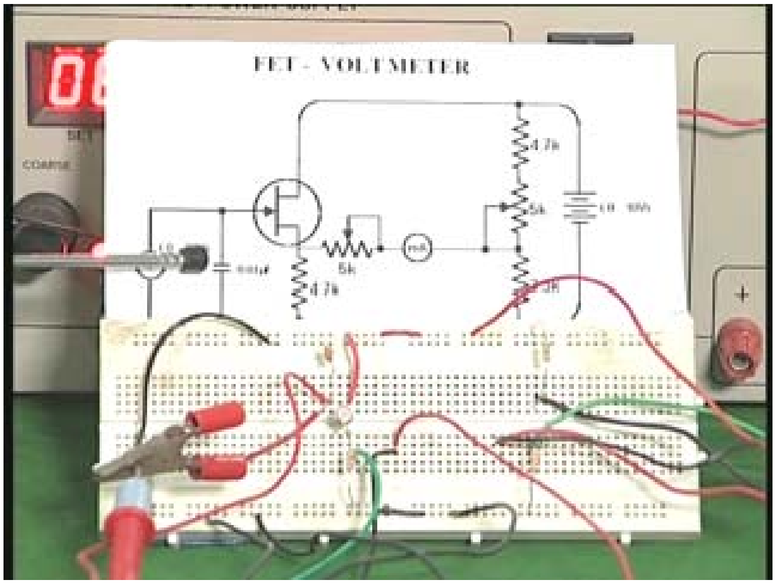
(Refer Slide Time: 47:06)



You have a n channel, you have a p substrate on which you make two regions of n with the gap in between. Over this gap you put silicon dioxide, an insulator. Silicon dioxide is an insulator and over that you put a metal. You have a metal insulator and a p substrate that forms a capacitor sort of a thing here. This n will become the source and this will become the drain. I have a V_{dss} here and all are on the same side of the silicon wafer and I have insulation here. The gate becomes insulated from the channel and it is called insulated gate field effect transistor and whatever voltage I apply here for example if I apply plus voltage here then the electrons will be attracted towards this positive electrode. Whatever minority carriers that I have in the p substrate they will start accumulating here and so I get a channel of n produced between these two. Then there could be a current flow and so you get a corresponding field effect transistor brought into operation. This is the metal oxide semiconductor field effect transistor and there is another variation of that. This is called the enhancement mode. There is another method which is called depletion mode and these two find very wide applications in different areas of electronics especially in modern electronics. I will complete the discussion by showing an actual demo of the FET voltmeter about which I explained to you.

You can see the circuit diagram here. It is exactly the same as the one which you have just now seen. You have the field effect transistor in the form of a bridge, Wheatstone's bridge and this is the current meter connected between these two ends and this potentiometer and this potentiometer are the ones for adjusting the zeros and you apply the input voltage between the gate and the source of this field effect transistor for operation.

(Refer Slide Time: 49:17)



I am using this voltage source which is a familiar voltage source. We have been using all along in these lectures and this is a millivolt source that is used as the external supply, external voltage. I am going to vary the voltage here 1, 2, 3, 4, etc and see how the deflection is changing in the ammeter that I have here in the circuit. On this side I have a voltmeter and I also have a current meter. This current meter is the one which I have in the circuit and this voltmeter is to measure the voltage that is produced at the input. Now there is no current in the current meter. The potentiometer has been adjusted to become zero. Now I am going to apply 1 volt from this power supply. This is 1 volt which is applied between the gate and source and correspondingly see what happens at the current meter. You look at the current meter. There is a deflection here.

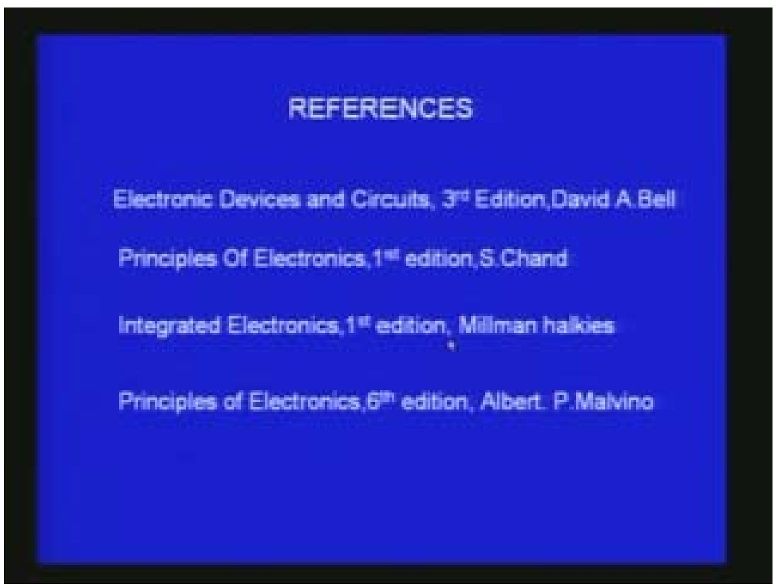
(Refer Slide Time: 50:28)

This is for 1. If I now reduce it comes down. If I increase it, it comes for 1 volt. Now I go to the next position -2 volts. See what happens? The current increases to much larger value. If I keep increasing why is it changing? It is because the gate source voltage is now varied and the resistance is changing and in the bridge there is an imbalance and there is a current flowing through that. This is what is being made use of as the voltmeter. Instead of applying 1 volt I can put a potentiometer here and make it up to zero to 1 volt. I can reduce this voltage that I apply here to 1 volt when I apply 10 volts. That means I can have 10 is to 1 reduction here. That means this voltmeter will read from 0 to 10 volts. If I make a reduction from 100 to 1 by having number of resistors here then I can have this current meter read up to 100 volts. That is what is normally done in a multimeter. You have different ranges because you have different input attenuators which will proportionally reduce the voltage and this basic voltmeter will be good for 1 volt or 2 volts, for full scale deflection. But by introducing the dividers here I can make it measure higher magnitude of voltages. That is how I get the multimeter. In principle multiple voltages can be selected and then the whole voltmeter can be designed. This will be a very interesting exercise to try, to make this work for 0 to 10 volts, 0 to 100 volts and 0 to 1 volts for full scale deflection just by adjusting the resistors in the bridge and you can achieve this easily. It becomes high impedance, almost ideal voltmeter because I am using a field effect transistor which requires reverse bias at the input and this is a very good example of an application circuit of the field effect transistor.

In the past few of the lectures you would have seen the whole area of basic concepts in electronics have been explained in a very practical way. Wherever this is necessary we also showed an actual demonstration of the different circuits and then the focus is more on applications of operational amplifiers even though we discussed some aspects of basic diode transistors, BJT, uni junction transistor, silicon controlled rectifier and other related devices. But the main focus of these lectures have been on integrated circuit operational amplifiers because they are much easier to buy and use and they are much more closer to an ideal device and much easier to understand in various applications and it is also very modern.

The lectures will not be complete unless I also tell you some good books for reference. If you are interested in reading more important materials or higher level of electronics you can read. It is important that you try and get very good books written on this topic. There are enormous numbers of good books that are available in the market. Apart from that in the internet there are enormous numbers of resources available for learning electronics on your own from the basic level. But I would like to list few of the important books that I have also been following and I hope you will also have occasion to follow. These are electronic devices and circuits by David A Bell. This is a third edition by David A Bell. This is a very lucid and nice book and then Principles of Electronics by S. Chand and Integrated Electronics by Millman and Halkies.

(Refer Slide Time: 54:31)



This is a very, very exhaustive book, well written book and a wonderful text book and then the best book I would say is Principles of Electronics by Albert. P. Malvino. It is almost like a novel. You can read it and understand very easily the very difficult concepts in electronics. With lot of simple examples he would have explained the various concepts of the diodes, the transistors, the integrated circuits, etc. What I have not discussed in these lectures is the principles of the digital electronics which by itself is a very important area and that is the one which is responsible for the modern day computers. They are also not very difficult. They can very easily be understood and if there is an opportunity we will discuss about the basic digital circuits and fundamentals. Thank you very much.