

High Speed Devices and Circuits
Prof. K. N. Bhat
Department of Electrical Engineering
Indian of Institute of Technology, Madras

Lecture - 17

Schottky Barrier Diodes
I-V Characteristics and the Non-Idealities -1

We will continue our discussion on the Schottky barrier diodes their I-V characteristics and we will go on with how close are they to the ideal characteristics. I have marked this as 1 because; we will have at least two sessions on this topic because, it is a detailed discussion on this. Before we get along on to that discussion let us just take a look at some of things which you have already seen.

(Refer Slide Time: 01:37)

Schottky Barrier Current Density "J"

$$J = J_0 (e^{V/V_T} - 1)$$

$$J_0 = \frac{4\pi m_n^x q k^2 T^2}{h^3} e^{-\phi_{Bn}/kT}$$

$$J_0 = A^x T^2 e^{-\phi_{Bn}/kT}$$

$A^x =$ Richardson constant

$$A^x = \frac{4\pi m_n^x q k^2}{h^3} = \frac{4\pi m_0 q k^2}{h^3} \frac{m_n^x}{m_0}$$

$$= 120 \left(\frac{m_n^x}{m_0} \right) \text{ Amp / cm}^2 \text{ / K}^2$$

We have shown that the Schottky barrier current density J can be expressed as J_0 just like the diode J_0 into e to power V by V_T minus 1. The only difference is the J_0 comes up by a different mechanism compared to the pn junction. We will have occasion to discuss today the exact difference. What we have discussed here is that the current transport is through the transport of carriers over the barrier. All those electrons which have energy

acting in excess of the barrier height will be able to create or give rise to current. Through that approach we said that, J_0 will be given by this expression and the whole thing here can be put as a constant A^* because that depends on the material because the effective mass comes there and the temperature. The temperature is absorbed here and this A^* is put there which includes the m_n^* and of course it depends on the ϕ_{Bn} . As we have been telling again and again if the ϕ_{Bn} is higher this is smaller. It is better rectifying diode if ϕ_{Bn} is smaller it is a very leaky diode which is closer to ohmic contact. Here what we have seen is A^* , I am pulling out this A^* alone and you can write it because all are constants except that m_n^* is a material dependent quantity. It would vary from silicon gallium arsenide indium phosphide etcetera. All other constants put together it becomes m_n^* star by m_0 . I just discussed this last time, going through it quickly so that we are focused on our discussion today. This thing is 120 into m_n^* star by m_0 amperes centimeter square per Kelvin square. All that is required to evaluate J_0 is this evaluate A^* and this ϕ_{Bn} and temperature.

(Refer Slide Time: 03:51)

Evaluation of J_0 for S.B on GaAs

$$J_0 = A^* T^2 e^{-\phi_{Bn}/kT}$$

$$A^* = 120 \left(\frac{m_n^*}{m_0} \right) \text{ Amp / (cm.K)}^2$$

$$\frac{m_n^*}{m_0} = 0.067; \quad A^* = 8.04;$$

For $\phi_{Bn} = 0.85\text{eV}$ and $T = 300\text{K}$

$$J_0 = 8.04 \times 9 \times 10^4 \times e^{-850/25}$$

$$= 1.24 \times 10^{-9} \text{ Amp / cm}^2$$

Take the case of gallium arsenide evaluation of J_0 for Schottky barrier on gallium arsenide and we are talking of, of course n type substrate because those are the materials which are used for making FETs in gallium arsenide. A^* is 120 m_n^* star by m_0 for gallium arsenide this ratio is actually equal to 0.067. Effective mass is very small in fact

that is one of the reasons the mobility is very high in the case of gallium arsenide. When you substitute for that here you get A star is equal to 8.04 that is the Richardson constant the A star is put to differentiate it from the A. Usually, we call it for area so that you do not confuse between area and this is just put A star. It also indicates you that star, is related to the m_n star effective mass two stars related to each other. That is the A star and not related to area. If the ϕ_{Bn} is barrier height is 0.85, which is usually the value that is obtain for gallium arsenide on n type substrate then you get at temperature T J_0 equal to that A star which is 8.04 multiplied by T square 300 degrees Kelvin square multiplied by e to power of minus ϕ_{Bn} by kT 25 million volts 850 electron milli electron volts. All when you evaluate it is about 10 to power of minus 9 amperes per centimeter square. This is range which we see in the case of gallium arsenide you can see it is excellent in terms of leakage current etcetera.

(Refer Slide Time: 05:48)

Evaluation of J_0 for S.B on Si

$$\frac{m_n^x}{m_0} = 0.6 \text{ for Si}$$

$$A^x = \left(\frac{m_n^x}{m_0}\right)^2 120 = 72 \text{ Amp/cm}^2/\text{K}^2$$

$$\phi_{Bn} = \frac{2}{3} E_g = 0.75 \text{ eV}$$

$$J_0 = 72 \times 9 \times 10^4 \times e^{-750/25}$$

$$= 6 \times 10^7 \text{ Amp/cm}^2$$

Take a look at silicon Schottky barrier there the ratio is about 0.6 m_n star by m_0 . Therefore, the Richardson constant A star turns out to be 0.6 times 120 that is about 72 amperes per centimeter square per Kelvin square. If you want to find out J_0 , we do it at temperature 300. You have got 72 into 300 square into e to power of minus ϕ_{Bn} by kT. That ϕ_{Bn} I have taken as two thirds of E_g which is value that you get when the Fermi level pinning is there. You get close to that point. Notice also that this particular band this

ϕ_{Bn} is smaller than that of gallium arsenide. The moral of the story is you get higher ϕ_{Bn} if the band gap is higher because it is almost related to that E_g . If you want to make Schottky barrier you are better off with materials which have got higher band gap, silicon it is border case because band gap is 1.1. If I want to make Schottky barrier germanium it is a hopeless situation. That is very good point that one should note at higher band gap materials are better suited for Schottky barrier. Therefore, we can imagine or we can estipulate that it is better suited for making JFET or MESFET. For making MESFET metal semiconductor FET's we can make better with wider band gap semiconductor. That is what I want to point out here. Now plug in those values here you will get 10 to power minus 7 into 6 which is almost equal to 10 to power of minus 6. You can see as compared to gallium arsenide Schottky barrier which is 10 to power minus 9 it is higher than that. The leakage currents are more reverse bias currents are more per centimeter square.

(Refer Slide Time: 07:46)

Comparison of I-V characteristics of GaAs and Si Schottky Diodes

GaAs

$$J_0 = 1.24 \times 10^{-9} \text{ A/cm}^2.$$

$$\text{When } J = 1 \text{ A/cm}^2, V = V_T \ln \left(\frac{J}{J_0} \right)$$

$$V = 0.025 \ln \left(\frac{10^9}{1.24} \right) = 0.513 \text{ volt}$$

Comparison of the I-V characteristics of gallium arsenide and silicon Schottky diodes: I am putting them down again here J_0 , we just now estimated is 1.24 into 10 to power minus 9 ampere per centimeter square. If you use that J_0 you can find out the voltage drop using the I-V characteristics.

(Refer Slide Time: 08:22)

$$J = J_0 (e^{V/V_T} - 1)$$

↓

$$1 \text{ A/cm}^2 \quad V = ?$$
$$J = J_0 e^{V/V_T}$$

The clarification on what I have written there what we use is J equals $J_0 e$ to the power of V by V_T minus 1 that is the forward characteristics. What we are trying to find out is when this is 1 ampere per centimeter square how much is V ? Given that as J_0 , you should also note that this is what you are trying to find out just by using this. Also notice we can neglect that term very comfortably e to power of 4 if you take even if 100 milli volts 100 by 25 e to power of 4 is large compared with 1. When you go to 200 milli volts etcetera it is totally negligible, we are just taking J is almost equal to $J_0 e$ to power V by V_T . We are using that to find voltage for 1 ampere, gallium arsenide; we know that actually J_0 is equal to 10 to power minus 9 into 1.24. So, that the number we substitute here find V there; that is what we are trying to do when you have used this particular term here. J is equal to $J_0 e$ to power V by V_T V is equal to V_T logarithm of that, substitute for all that 10 to power 9 this is 1 this is 1.24 into 10 to power minus 9. That goes up there V is equal to 0.513 volts. This is actually not bad it is slightly lower than what you get for pn junction diode is silicon but getting closer to that of the pn junction characteristics. Let us see what we get in the case of silicon Schottky barrier.

(Refer Slide Time: 10:13)

Si

$$J_0 = 6 \times 10^{-7} \text{ A/cm}^2$$
$$\text{When } J = 1 \text{ A/cm}^2, V = V_T \ln\left(\frac{J}{J_0}\right)$$
$$V = 0.025 \ln\left(\frac{10^7}{6}\right) = 0.358 \text{ volt}$$

For the same value of "J", Voltage "V" is higher in M-n GaAs than in M-n Si

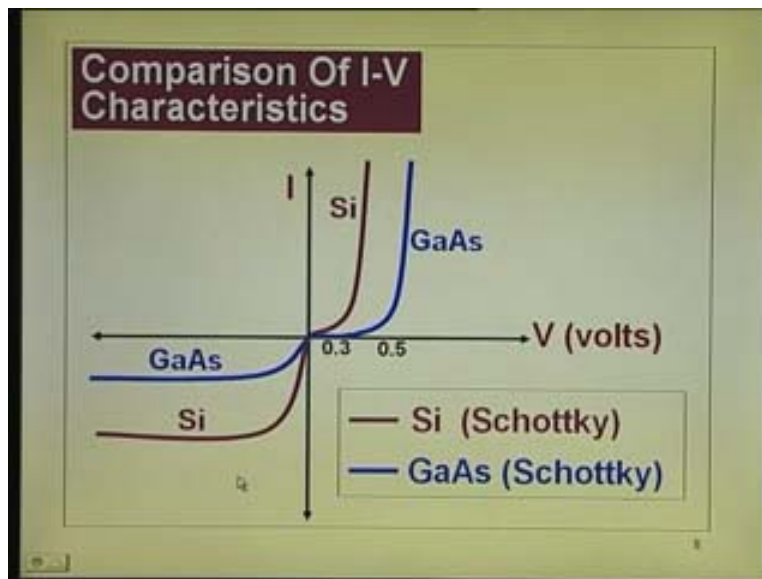
J_0 , we estimated it to be 6 into 10 to power of minus 7. Same formula V is equal to V_T logarithm of J by J_0 substitute here 6 into 10 to power minus 7. 7 gone up there 10 to power 7 by 6 you get 0.358 volts. You can see the problem with or the differences between the silicon Schottky and gallium arsenide Schottky.

(Refer Slide Time: 10:39)

Parameter	GaAs	Si
Φ_{Bn}	0.85	0.75
A^x	8.04	72.0
J_0 Amp/cm ²	1.24×10^{-9}	6×10^{-7}
Forward Bias Voltage at $J=1\text{A/cm}^2$	0.513V	0.358V

The sum of all those results in the table, we have seen ϕ_{Bn} is 0.85 you have got higher band gap, higher ϕ_{Bn} because closer to two thirds here 0.75. That makes the J_0 smaller here compared to this silicon also A star because of smaller effective mass 0.067 compared to 0.6 in silicon this is 8 and this is 72. All of them make the leakage current here is large compared to that J_0 of gallium arsenide Schottky barrier. When we use that we found out it is 0.513. There is no sanctity about 0.513 etcetera. You can say about 0.5 0.54 in that range depending upon how much is the barrier height will vary say about 0.5 this about 0.358 volts. That is the forward drop for one ampere current. This will go through all the range of the current.

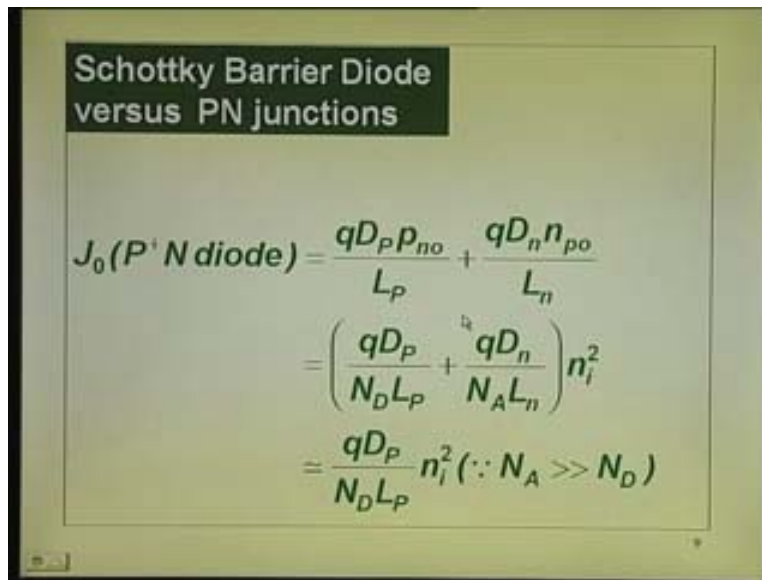
(Refer Slide Time: 11:40)



Now see the I-V characteristics of the silicon Schottky barrier this color. This colors here the silicon like that gallium arsenide smaller J_0 larger J_0 this one voltage drop is smaller in silicon compared to voltage drop in gallium arsenide. In other words in a language of circuit engineering you can say the cutting voltage of silicon Schottky is much smaller compared to cutting voltage of a gallium arsenide Schottky barrier. The cutting voltage of silicon Schottky is almost getting closer and closer to that of cutting voltage of germanium pn junction. Germanium pn junctions all of us know that cutting voltage is about 0.2 volts because of small band gap barrier are small there. The difference is

mainly because of the barrier and the A star that is the point here. You have got I-V characteristics approaching to that of pn junction of silicon, we will see that now.

(Refer Slide Time: 12:47)



**Schottky Barrier Diode
versus PN junctions**

$$J_0(P+N \text{ diode}) = \frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n}$$

$$= \left(\frac{qD_p}{N_D L_p} + \frac{qD_n}{N_A L_n} \right) n_i^2$$

$$= \frac{qD_p}{N_D L_p} n_i^2 (\because N_A \gg N_D)$$

Let us see through the pn junction look to recall what we already know about pn junction I take p plus n junction. The total formula for this J_0 of pn junction diode is this. These are actually the carriers which are generated in diffusion in one depletion length diffusion length on either side of depletion layer diffusing into that. When you substitute this is the minority carrier concentration in the n type region thermal equilibrium. This is the minority carrier electron concentration is the p type region thermal equilibrium. You know that product of majority and minority carrier is equal to n_i square majority carrier concentration equal to doping concentration when you do that p_{n0} is n_i square divided by doping. Similarly, n_{p0} is n_i square divide by doping N_A . That is all what we done there this is a very standard formula. Let me not get in to that we have discussed it in many forums. Between these two terms both will be almost comparable if the doping concentrations are same. But, when you talk of p plus n diode acceptor doping concentration is large compared to the donor doping concentration. This term in the denominator is much large compared to the doping on the N_D . This term actually goes off very small four or five order of magnitude larger here denominator that means this term will be four or but five order magnitude smaller compared to that. We put that

approximately $qD_P N_D L_P$. I just put this formula that you can substitute on that for yourself and see I have done that work for you.

(Refer Slide Time: 14:36)

J_0 in silicon P⁺N junctions

For $N_D=10^{16}/\text{cm}^3$ and $\tau_p=3 \times 10^{-6}$ sec,
 $D_p=12 \text{cm}^2/\text{sec}$, $n_i=1.5 \times 10^{10}/\text{cm}^3$

We get $J_0 = 7.2 \times 10^{-12} \text{ A/cm}^2$

When $J = 1 \text{ A/cm}^2$, $V = V_T \ln(10^{12}/7.2)$
 $= 0.641 \text{ V}$

For a Si (SB), $J_0 = 6 \times 10^{-7}$ and we have
 seen that $V = 0.358 \text{ V}$ when $J=1 \text{ Amp/cm}^2$

For a given J , $V(\text{PN junction}) > V(\text{SB})$

p plus n junction in silicon I take doping of 10 to power of 16 centimeters cube per centimeter cube life time. Life time of holes in n region is about three microseconds typically. This is only order of magnitude to get an idea. I am putting these numbers. Do not say this is the number say this is a number which generally will be varying depending upon the doping and life time characteristics. D_P is 12 that is for silicon you say and n_i is 1.5 10 to power of 10 per centimeter cube at room temperature. We are calculating J_0 at room temperature. When J is 1 ampere for this case this also has got J equal to $J_0 e$ to power of V by V_T . But, J_0 we are calculating is a different formula. This is V equal to V_T logarithm of J by J_0 J is one ampere J_0 is this quantity that is why you get 10 to power 12 divided by 7.2. We are using the same formula.

(Refer Slide Time: 15:55)

$$J = J_0 e^{V/V_T}$$

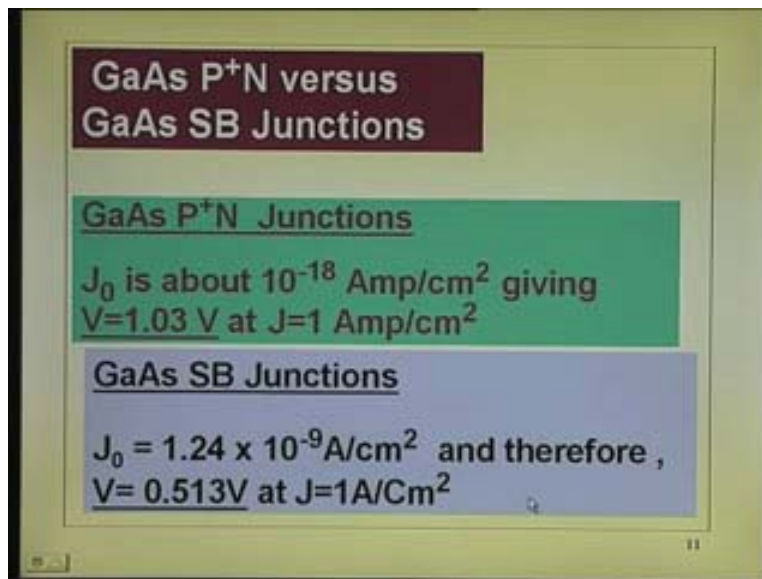
↓

$$7.2 \times 10^{-12}$$

You are using the same formula: J is equal to $J_0 e$ to the power of V by V_T this J_0 is something like about 10 to power of minus 12 into 7.2 . This is very small compared to this in the case of Schottky barrier. That is why for a given current 1 ampere you will get a larger voltage drop. In the case of Schottky barrier the silicon Schottky barrier we got it as 0.35 volts. Here, when you substitute for J_0 and this is 1 this is 1 and this is 7.2 into 10 to power minus 12 amperes per centimeter square. You get a value of V which actually is much larger than that what you get for the Schottky barrier. What we have to see here is when you plug in those numbers you get the voltage drop across the diode for 1 ampere per centimeter square it is 0.64 . You are used to here in number cutting voltage of silicon pn junction is about 0.6 or 0.65 . That is the implication of that. About that current range you get that voltage drop. It does not mean that the diodes starts conducting at 0.6 it conducts even better. Otherwise if you go to 0.1 amperes per centimeter square you will get that voltage much smaller than that. It is conductive but when you using that at particular range you get 0.64 . When you say cutting voltage that is the meaning of that. If you actually spun the I-V characteristics on the lower range you will get small voltage. Do not be perturbed if somebody comes and tells I get a voltage at a diode is conducting at 0.4 voltages, it will, but very low current density that is the meaning of that.

Cutting voltage is a concept which is used by circuit engineers for convenience because, in the normal range of operation that is the voltage across the diode that is about 0.6 volts that is implication. People who are cautious will say 0.6 to 0.7 that is about the range. Silicon Schottky barrier J_0 is that and we have 0.358 volts as the drop that is the range. What we say now is the voltage drop across the pn junction for a given current density is more than that of a Schottky barrier diode. That is finally the thing. That is what we said here V for a given J the voltage V across the pn junction is greater than the voltage across the Schottky barrier.

(Refer Slide Time: 18:29)



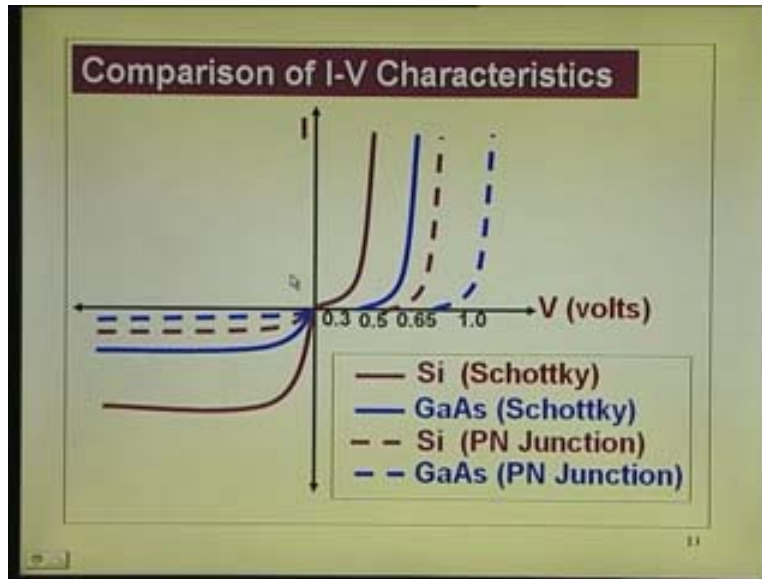
Quickly go through the numbers for gallium arsenide Schottky barrier we have seen it is about 10 to power of minus 9 into 1.29 and 0.513 volts voltage dropped across that Schottky barrier. p plus n diode used the same formula that we used for silicon it is about that very low (18:49) and very lower than that ampere per centimeter per square because n_i is 10 to power 6 as compared to 10 to power of 10 in the case of silicon that low number makes it very very small. n_i square is 6 orders of magnitude smaller that is why it is low. When we use that for 1 ampere current density same $V_T \log J$ by J_0 you get about 1 volt.

(Refer Slide Time: 19:25)

Comparison of J_0 , J and V n-Substrate $N_D = 10^{16}/\text{cm}^3$				
Parameter	Schottky Barrier On		P ⁺ N Junction On	
	Si	GaAs	Si	GaAs
J_0 Amp/cm ²	6×10^{-7}	1.2×10^{-9}	7.2×10^{-12}	10^{-18}
Forward Bias Voltage at $J=1\text{A}/\text{cm}^2$	0.358	0.513	0.641	1.036

The entire result is shown here in this table, Schottky barrier silicon Schottky barrier gallium arsenide; we have seen it 0.358 is the voltage dropped cutting voltage about 0.3 and 0.5 cutting voltage for gallium arsenide Schottky barrier. Go to silicon PN junction here on silicon PN junction P plus N junction J_0 is much smaller compared to Schottky here and then correspondingly voltage is you can see 0.358 for Schottky barrier 0.64 for PN junction gallium arsenide. Gallium arsenide PN junction voltage drop is about 1 volt compared to Schottky barrier of 0.5 volts forward difference.

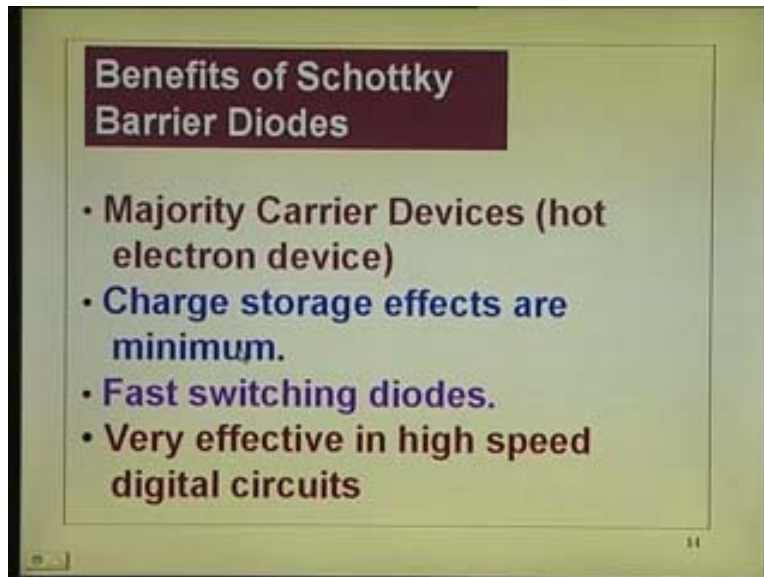
(Refer Slide Time: 20:18)



Take a look at the total I-V characteristics of all the things. I have put the Schottky barrier of silicon. I have put the Schottky barrier of gallium arsenide. I have also shown the PN junction of silicon P plus N junction also PN junction of gallium arsenide. Moving from left-hand side to right hand side, the dotted lines are the junctions the solid lines are the Schottky. On the forward conduction region here, we can say now minimum voltage drop 0.35 volts or 0.3volts. I put here as cutting voltage about 0.3 for silicon Schottky barrier. For gallium arsenide Schottky barrier about 0.5 cutting voltage and you can see here I have put 0.65 for silicon PN junction all the curves extend to the right and if I see the gallium arsenide PN junction, 1 volt. Some information related to this. This property of higher cutting voltage of gallium arsenide makes it useful for solar cells with the higher open circuit voltage. When you shine light if you take a junction you will see there is a voltage developed. If the solar spectrum falls on the PN junction and if you just measure put a multimeter there across that or a voltmeter you will see there is a voltage developed. If you take silicon we will get something like about it will be less than the cutting voltage, less than the built-in potential. It will be about 0.55 0.6 if you get you will hit the roof with joy. You do not get 0.6 after 0.55 volts it becomes tougher and tougher; whereas, in gallium arsenide pn junction solar cells will get close to 1 volt higher open circuit voltage. We will see if we have occasion to discuss this later on much later some aspects of these things.

This is what I want you to note. Also you see the current starting from this dotted line higher voltage lower is J_0 . This is the curve from here to here (Refer Slide Time: 22:50) and this one silicon junction that dotted line with second dotted line. Here, you move from this side to this side and here you move from below like that. Smaller forward voltage larger leakage and if the leakage becomes largest that is the ohmic contact. If this curve keeps on shifting towards left side this keeps moving down and you will have ohmic contact close to the ohmic contact. You can see that silicon Schottky barrier is not so good rectifying. It is not as good gallium arsenide it does the rectifying job no doubt with a band gap of about 0.75 or so. You do get rectifying contact. It is not very encouraging like in case of gallium arsenide the gallium arsenide is almost, see the characteristics close to pn junction of silicon here also.

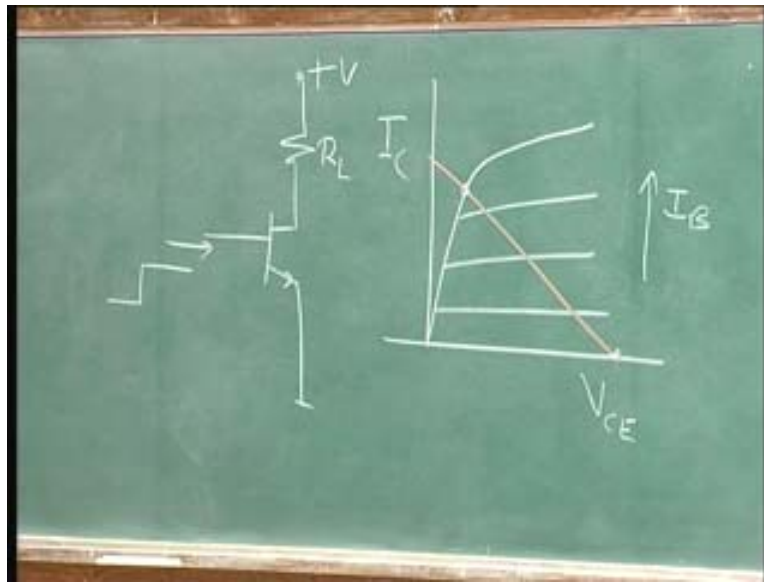
(Refer Slide Time: 23:43)



Let us go further down, benefits of Schottky barrier diode. Before going into that few things I want to discuss keeping this diagram in mind here, we will discuss one or two things. One thing is the application of the Schottky barrier diode even in silicon technology the Schottky barrier diode is used. It is not the proprietary of the gallium arsenide technology Schottky barrier diode; you see that it is conducting at lower voltages 0.3 volts. You can see if there is a junction in parallel with this as diode and Schottky barrier diode and a pn junction in parallel, this will be dominating. The current

will pass through Schottky barrier diode. That property is made use of in fast switching TTL transistor, transistor logic circuits if you see you have the transistor. In the TTL logic circuits it is slow compared to emitter coupled logic easier. The reason is in the TTL the device goes into saturation. I will go through that particular thing now.

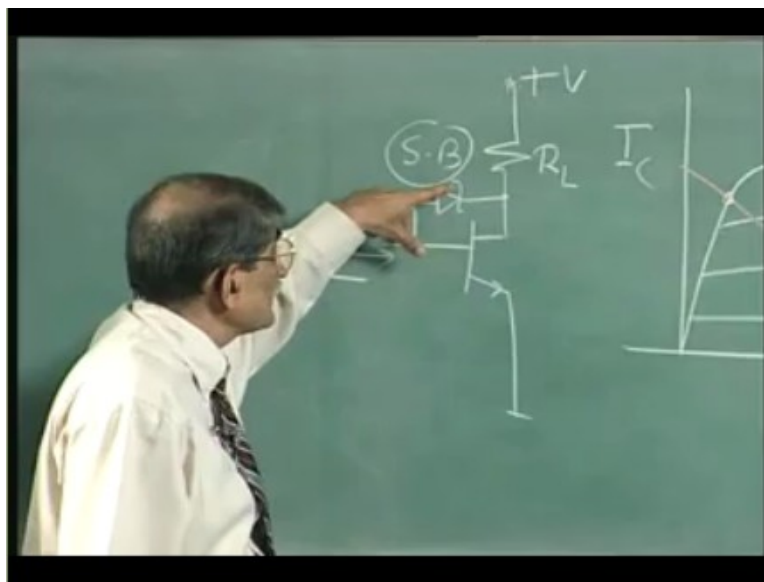
(Refer Slide Time: 25:34)



I have a simple example: you show this inverter like this, I will put that plus there and pumping in current I am not sure in the biasing circuit etcetera. If you see when I have the input actually going like this 0 to 1, what way it goes? In fact, I_C versus V_{CE} if you take, you just recapitulate your memory on these particular switches when the bipolar transistor is used. I have the characteristics which go like that with different I_B . I have that characteristic now you can draw a load line on that, that R_L which is the load line. We can draw that load line so when the device goes from 0 here it is off and when it is 1 it is totally on that is you are driving base current with 0 that is here you are moving on to that curve. That means, you are moving from here (Refer Slide Time: 27:05) to that point. The transistor is driven from the cut off to saturation the transistor goes into saturation here when the transistor goes into saturation you know that there are charges stored in the region base region collector region everywhere. If you want to come back from here to turn it off, the charges stored in transistor various regions will have to be removed that is what makes it slower. If you want to prevent the transistor to go into saturation, what is

done in the TTL is this I am showing one inverter only of some portion of that TTL where some inverter comes in we will have and rest are here, is a different story. But I am showing the principle finally. I do not want to this to go to this thing. What you do is you prevent the transistor, you know when this goes into this portion. What is the state of voltage across the emitter base and collector base? When the transistor goes into saturation emitter base junction is forward biased collector base junction is also forward biased. When it goes deep into saturation collector base junction voltage will be almost equal to 0.6 volts. If the junction is going to saturation that is conducting may be somewhere (Refer Slide Time: 28:31) here. I do not want the transistor go into deep saturation when you say deep saturation, lot of forward voltage across the transistor collector based junction is large almost close to the emitter base junction voltage is 0.7. This may be 0.7 this may be 0.6 when it goes to that unless it is less there would not be current flow. Both of them are equal current will become 0 that never happens. What you do you is put a Schottky barrier diode here. I think we can put it like this; this is the Schottky barrier diode.

(Refer Slide Time: 29:11)

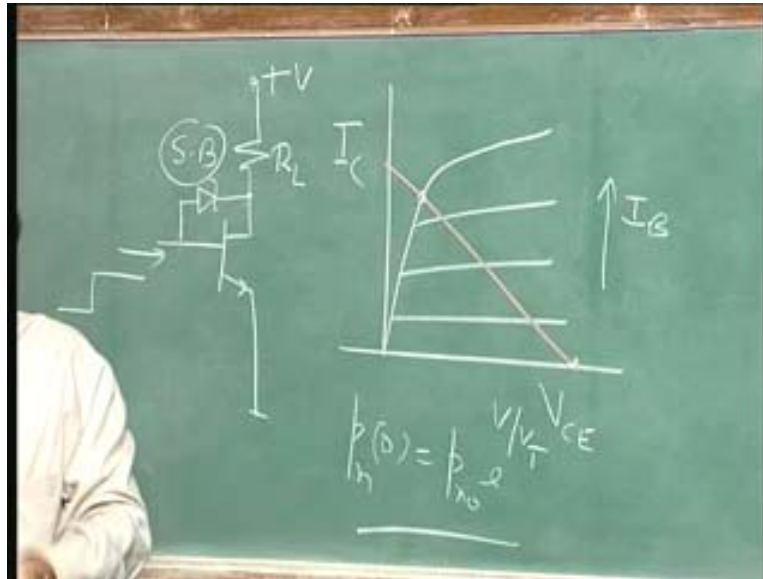


Connect a Schottky barrier diode. In fact you can actually integrate along with the transistor between the base and the collector. Integrate a Schottky barrier diode or you can put it separately make it diode connect them within the surface connect internally.

The way they do it I am not getting to that technology right now. The way they do is this is done by putting a metal over the base region and the collector region you make the Schottky with the n region collector. You put a metal on n region it becomes the Schottky barrier and allow that metal to go over to the base region that becomes ohmic. We get an ohmic contact here p type region any metal on p type becomes ohmic because of low barrier height and Fermi level pinning. Metal on the collector n region become rectifying very easily without showing that diagram you can feel that this a single device with just a metal layer put between the collector and base. That is the technology that is done there. This is the TTL Schottky TTL STTL. Here, when this goes into this region (Refer Slide Time: 30:27) here, when the device goes into the saturation this voltage across will never become 0.6. Why? There is a diode connected across that Schottky barrier which will divert all the current instead of going through that it is divert diverted through that with a smaller voltage. There is certain current flowing through that current will flow through this device. The current instead of going through this it will go through that, that voltage dropped across that is limited by the voltage drop across the device.

Now, we can see this diagram instead of 0.6 volts here pn junction across when it goes in saturation (Refer Slide Time: 31:15) you have put a Schottky here this one this dotted and this one first one. That voltage drop across is 0.3 volts. The voltage drop across the collector base junction which is forward biased is now 0.3 volts. It has not gone much into deep saturation now when a diode here in the junction is forward biased you have got carrier concentration raised as e to power of V by V_T . When a forward bias junction is there carrier concentration is raised as e to power of V by V_T .

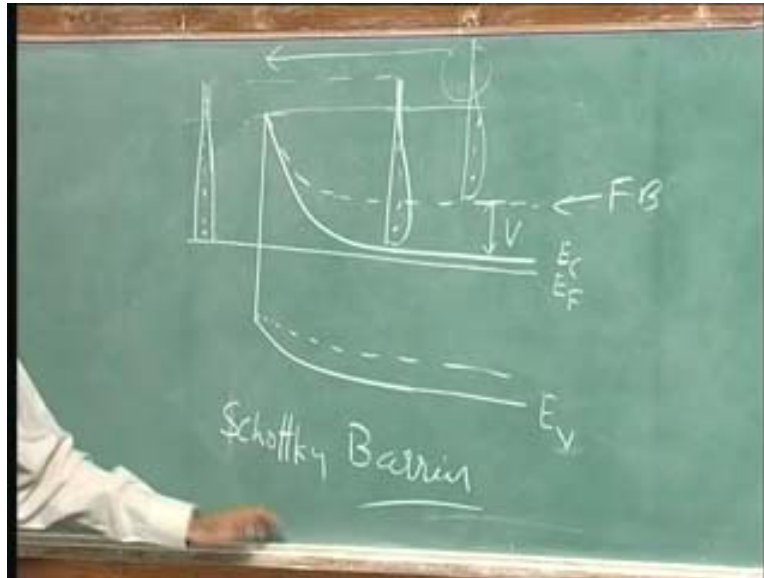
(Refer Slide Time: 31:57)



Now, V is the forward bias you have reduced that V from 0.6 to 0.3. So, e to the power of 600 by $V/25$ that is the by V by V_T . This is 600 by 25 originally carrier concentration. If you just recall, I just write that here below. If I take the n region pn boundary condition is $p_{n0} e$ to power of V by V_T . This is the charge which we have injected into n region when a forward bias collector base junction is there. V by V_T if V is 600 this 600 by 25 this is about 24 e to power of 24 that may be something 10 to power 14 or of that order very high. Instead of V to power 24 now by connecting this is what you have done is you have reduced that to e to power of 300 by 25 that is 12. The fact of e to 10 to power of 12, huge reduction in stored charge split up is tremendous that is why you get split up thing as Schottky barrier diodes. Schottky barrier diodes are very important device for high speed circuits. That is calling with the theme of our discussions in this high speed circuits. High speed devices are made in silicon with Schottky barrier connected across collector base junction integrated like that. May be later on we may have time to recall but this is the key to the thing. I want to discuss why that difference between J_0 between the pn junction and the metal semiconductor contact. You do not see this explicitly discussed but, you very closely examine the mechanism of current transport, you can easily figure out what is happening. If you take metal semiconductor contact, how is the current transport taking place? Take a look at how the current transport is taking place in the case of p plus n junction. What is the difference? If you see, why J_0 is smaller in pn

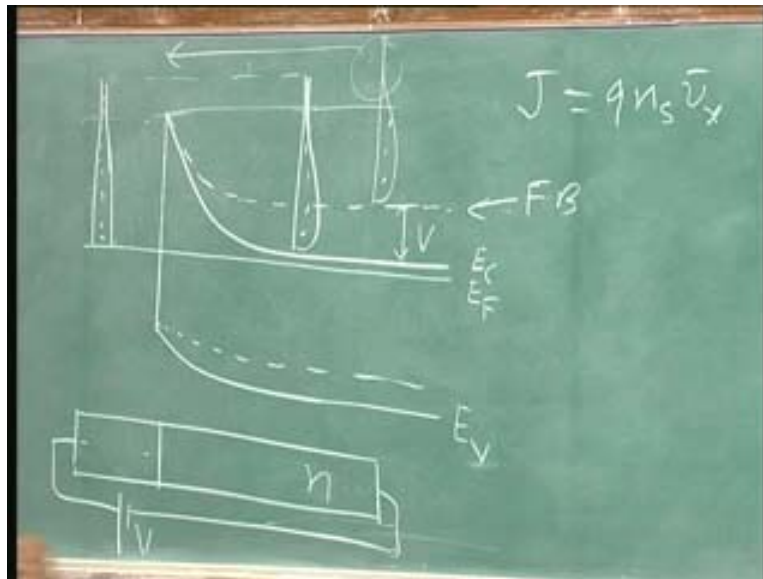
junction compared to or why the currents for a given voltage, for a given voltage see for a given current the voltage is larger in a pn junction compared to the metal semiconductor contact. Or putting in other way for a given voltage current is smaller in pn junction. Why? We will take a look at that. Now, this is a very important concept that one should see actually.

(Refer Slide Time: 34:53)



Let us draw the energy band diagram which we have been drawing is for Schottky and we draw the Fermi level there E_C E_F E_V . Recall, we have drawn this sort of diagram in fact it is a very powerful diagram to visualize what is happening. Those are the electrons which have energy above that which are able to cross that is the one which gives us J_0 . This is the ϕ_{Bn} metal semiconductor. This is the metal or Schottky barrier. People like to call this more as Schottky barrier than the metal semiconductor. I called it because when you say metal semiconductor it can be Schottky barrier, rectifier or ohmic general term.

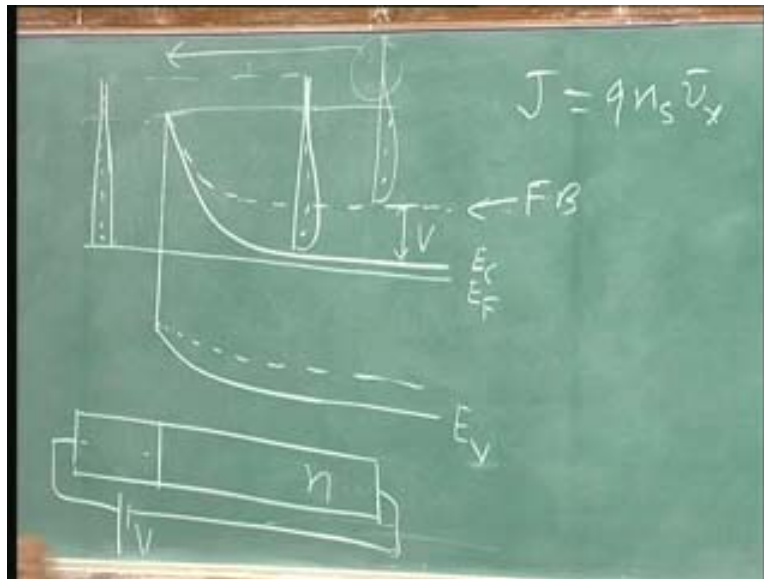
(Refer Slide Time: 36:03)



Now this is thermal equilibrium when you forward bias or here you have got similar distribution here. I am redrawing the diagram which you have been drawing and this is balanced by that. These electrons have energy more than this barrier these electrons have more than the barrier that is balancing. When you forward bias this is forward bias, this is forward bias situation the conduction band valence band will also go up similarly. By the same amount equal to V forward bias voltage now this distribution goes up and you have many more electrons which are able to cross. I am discussing this deliberately because we have to see the difference between pn junction and this. These extra electrons have energy above this. We have computed this electron concentration there if you remember what have we computed. We computed q and whatever electrons are there above that because they are the electrons which are actually here impinging on the boundary into the mean velocity. That is all we have done current density. The same thing happens in the pn junction also absolutely no difference. The difference is what happens beyond these points. Let us take a look at what happens beyond these points. These electrons whatever have energy above that of course there some part of it is compensated by this. Let me talk of only total quantity now they are impinging reaching here now they are here. The quantity n_s equal to $n_{n0} e^{-V/V_T}$ all those numbers are able to cross that barrier. Now, how much is the current depends upon what is the fate of this carrier after they cross the barriers. What is the number that is reaching that metal? How much is the

number compared to the total number available in the metal. That is the key to the whole thing. In the case of Schottky barrier in the metal you have got 10^{22} to 10^{23} of that order number of electrons per centimeter cube. What number of electrons which are crossing this barrier (Refer Slide Time: 38:48) here? How much are they? If this is 10^{16} much smaller quantity compared to that n_{n0} e^{-} to power of minus V by V_T n_{n0} into e^{-} to power of minus V by V_T that quantity. In fact minus V_{Bi} minus V if you look back it is related especially the voltage. You have actually that number much smaller than equilibrium concentration. If you have 10^{16} as the equilibrium concentration the crossing number is much smaller. May be 10^{11} to 10^{10} . It is like putting a drop of water into ocean it disappears immediately. In the sense it is not disturbing thermal equilibrium here when the carrier concentration is so large from here to the contact.

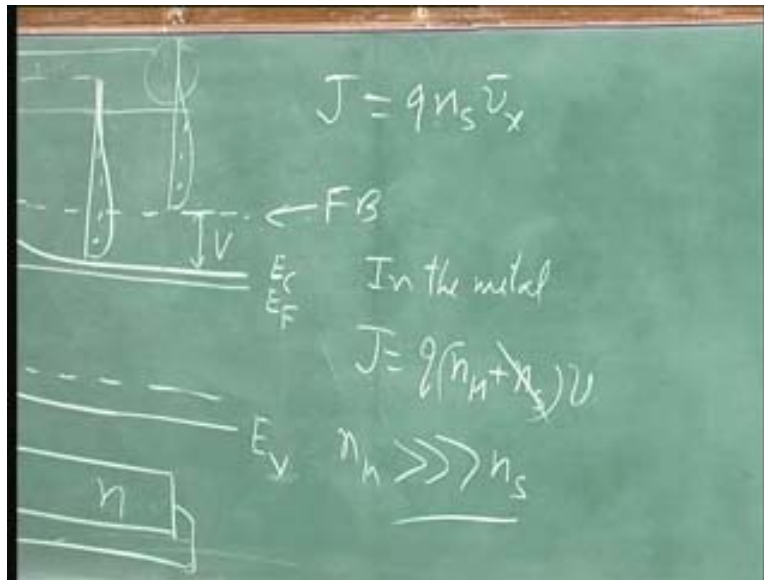
(Refer Slide Time: 39:49)



If I have metal like this and a semiconductor I am applying a voltage V this is n type what we are talking of is these electrons which are crossing here. Now, you have got small even the smallest field that is appearing is there will be able to take away those electrons because the total electron concentration is very large 10^{22} if you have. Even a very small field will help to remove those charges which have injected give rise to current. It is again here you calculate it as $J = n_s$ into V J is equal to $q n_s$ into V_x that

is when it is here. Once it goes into metal, what is the current? Same current should flow if all of them are flowing out. This is across the barrier.

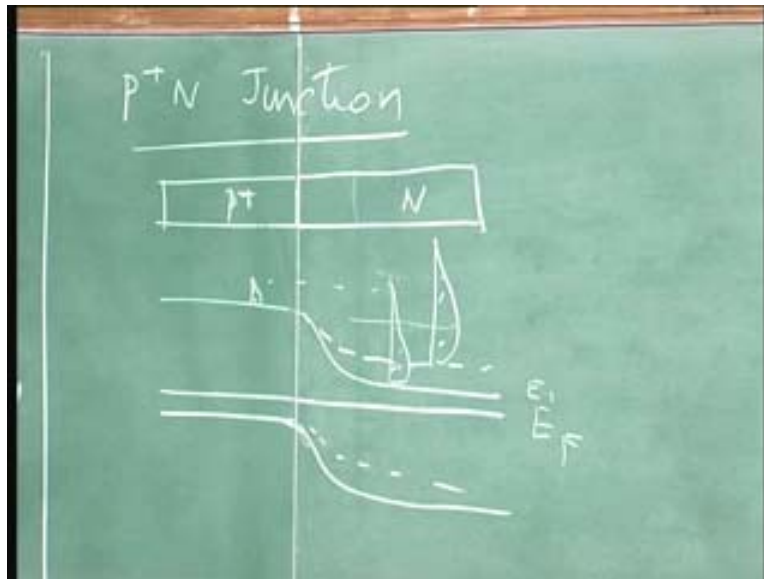
(Refer Slide Time: 40:58)



In the metal J will be what q into n in the metal plus whatever n_s is injected that is negligible. Let me write rewrite that in the metal J is equal to $q n$ in the metal plus n_s which has been injected there into velocity in the metal. This is actually small compared to that n_m is very large compared to n_s which would mean this is very large compared to that this is the mean thermal velocity. Whole thing is given by transported because of this higher velocity because this is hardest of magnitude larger than that. What will be that quantity? This current continuity is there. Whole thing limitation comes up. How much can go across the thing? All other will be transported with a very low velocity here; very low velocity means u is equal to V is equal to μ into T . There is mobility of electrons is there in a metal. V can be very small that means very small electric field will take away give rise to this current in the metal. Very small electric field in the metal will be able to handle this amount of charges which are injected to remove them away because, it is not this that is flowing through that because the amount that is the voltage across the metal the current transport to not merely due to that it is due to whole of the things. We are not dealing with that injected electron alone when you apply voltage total number.

Total number is what existed originally. That is possibly with very low velocity which would mean that is possible very low field there that means very smallest milli volts drop across (Refer Slide Time: 43:11) this will be enabling to allow the current flow. What I trying to point out is in a Schottky barrier diode the current transport the extent of current that is flowing through the junction is totally controlled by that component. This component is not limiting it with very small field that will take away all the current because n_m is very large there metal. n_m electron concentration in the metal is very large compared to the electron concentration on the surface of the semiconductor. n_m is the electron concentration in the metal that is the one which is very large therefore, this is not limiting that. They just swept away whatever is injected total current is limited by this. That is the way, we have estimated the current. Now, in the case of pn junction also, let us see what happens.

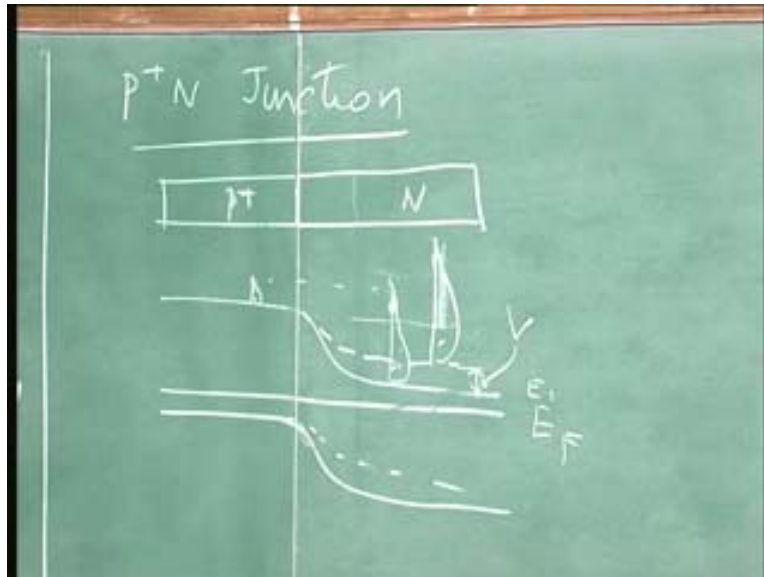
(Refer Slide Time: 44:20)



I will just retain this here I will go to this side pn junction. I will say p plus n junction. I will switch over from there I will retain that there in case, we want that for discussion. We will focus here now. In the case of the pn junction the diagram is p plus n. The story is totally different what is energy band diagram? Take a look at this in the same light as the Schottky barrier diode E_F thermal equilibrium. This is p type material I will put that as a junction and you will have depletion layer there. From there onwards due to the built

in potential and here that is E_C . p type material n type I have not shown the Fermi level not too much difference but if that is p plus it will be closer to that pn junction or even if you do not put p plus it is okay our discussion holds good for that. What will be the distribution here? Exactly, we can put same diagram that we drew for metal semiconductor junction. This goes like that that is the electron distribution. When the Fermi level has equalized what happened is these have some energy, this is the barrier. What you saw in the case of Schottky barrier that same type of barrier is there for electrons. Here electron concentration very small. This is actually like this (Refer Slide Time: 46:32). Now, look at the fate of electrons which are injected from here to here when I forward bias that dotted line becomes like that. I can actually compute the total number of electrons which have energy to cross this exactly the way you have computed the electron concentration at this surface here. You can compute electron concentration on surface $n_{n0} e^{-\frac{V_{Bi} - V}{V_T}}$ of course or $n_{n0} e^{-\frac{V_{Bi} - V}{V_T}}$ that will be concentration here. That is what you are doing computing how many have got the energy above that. All of them are capable of crossing this barrier that extra, previously this was equal to that thermal equilibrium when you forward bias.

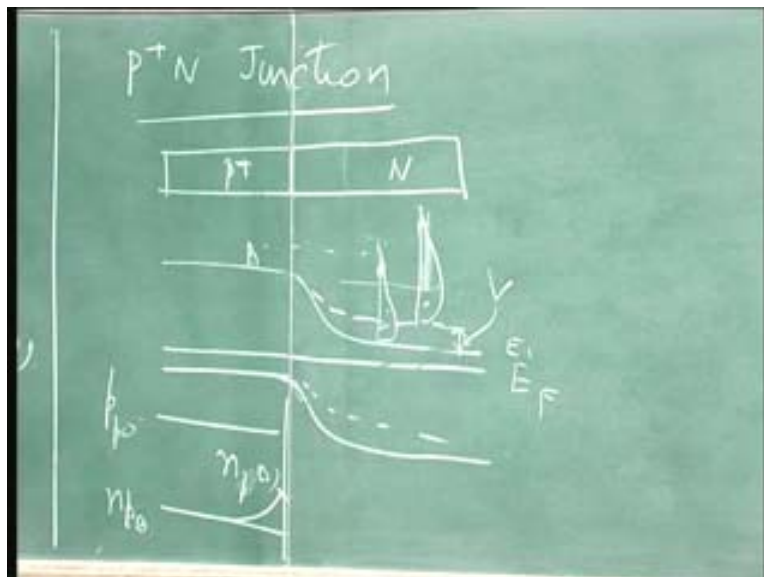
(Refer Slide Time: 47:46)



When you forward bias this V , when you do the forward biasing this whole thing gets lifted up more of the carriers are there. If you give a chance to those electrons to be

removed away once it is injected to the p region the same way that is done in the case of the metal. The current will be exactly equal to that. Supposing this barrier height is the same as that ϕ_{Bn} that you have got in the Schottky barrier you would have got the same current. But, if this barrier height which is the built in potential is the same 0.75 volts, the current that you get will be much smaller than that or same voltage. Reason is these electrons which are impinging on the surface with the same equation $q n_s$ is actually this quantity $q n_s$ into V of x they are striking the surface and are able to cross the barrier. But, having crossed the barrier they find that they are minority there. Once they are minority it is actually now the current depends upon which of them is larger. In the case of Schottky barrier you are impinging the current is transported across the barrier with $q n_s$ into V of x and from that point onwards there is no limiting because carrier concentrations are very large. $q n$ into V $q n_m$ into V very small V or very small drift field will take away those electrons. Whereas, here n is minority carrier this may be what you have the electron concentration here may be 10 to power 10 or 10 to power 11 . What you have here will be 10 to power 2 10 to power 3 . Now, what happens is if you want to remove them at the same rate you must have a large velocity. For large velocity there should be electric field coming up. Alternately, the carriers are not removed as fast as you require because, there is no field available there. They get piled up here the minority electrons which are injected here be piled up here.

(Refer Slide Time: 50:09)



Now you take a look at the boundary condition here p_{p0} is a hole concentration. I am sorry this is the p_{p0} and n_{n0} is the electron concentration there. You are pumping in electrons at a very fast rate here governed by that equation, n_s into V of x . But, it is not able to take it away because, there is no field there. Immediately when you inject at a fast rate what happens you are dumping electrons at a fast rate from the boundary. Therefore their concentration goes up there and there is no concentration there, from that point onwards it is carried away by very familiar side. The concentration builds up there because it is not being taken away fast that is because it is the minority carrier and it will be very large field to take it away. There is no large field there only small fields are not sufficient. Carriers get piled up there that is why this builds up. This is slightly different concept that we usually see but the fact is that. I think we can put it as n_p . Hole concentration is p type material hole electron concentration is p type material and then you have got n_{p0} that goes up. The mechanism by which the current is transported now through that p layer is by diffusion, because of this concentration gradient, once it crosses the barrier the transport is by diffusion. The diffusion is actually slow process this is slow compared to the transport from here to here where equilibrium is hit so that the rate at which is removed controls the total current. The difference in the Schottky barrier and the metal semiconductor contact for a given voltage in the Schottky barrier the current is controlled by rate at which you are able to transport across the barrier. From there it is taken away fast because large number of electrons is available in the metal. In the case of pn junction the current is controlled by rate at which we are taking it away from that. One is the rate at which is coming here other one is rate at which taken away current is controlled by a slower process which ever is slow is controlling. In a pn junction this process is slow diffusion driving force is concentration gradient.

This process is faster this is the one, two of them in series. The slower one control the current flow slower one is the diffusion and that magnitude is much smaller than what is crossing there. This is smaller compared to what is crossing there and this is the total current which is actually given by q_d and n_{p0} by I_p . Whereas, that current would have been(Refer Slide Time: 53:33) if you have able to take it away completely that will be that A star d square into power ϕ_{Bn} by V_T ; whereas, this turns out to be q_d and p_{n0} n_{p0} into e to power of V by V_T . This is small. Going back to sum up what I said about these

two currents now take a look at this particular thing. This portion is able to carry the current fast so total current is controlled by is the amount coming through this which is much larger compared to what is been taken away here. This is very small when compared. In both the cases the rate at which it comes up here for the same barrier height will be same. But, mechanism by which it is taken away the other region that controls. Here it is taken away by drift in the presence of large quantity of electrons that why it is fast and in other case it is taken away by diffusion. Notice you have got this charge storage effect. This is the charge that is stored here similarly on other side you can talk of whatever holes then same thing you can talk of here. Holes are hitting the surface at fast rate but they are taken away by small rate because, hole concentration in n region is very small. These are the two subtle differences between the two. For the given voltage the current there is smaller because the current has ultimately decided by diffusion.

That is the reason why physically this current in a pn junction (Refer Slide Time: 55:14) is smaller compared to this current which has gone up all the way up there. Or for a given current you can drive a particular current with a smaller voltage Schottky barrier compared to that. That is actually the key thing for that. In fact, I just went around going through this because this particular point is not clear this whole thing becomes clear only when you look at it this way. The electrons having distributed there how many electrons can cross that and once they are injected beyond that point what happens. I think that is about the main thing that I wanted to point out to you. One of them is Schottky barrier used in TTL because, lower voltage other one is the mechanism. Also I have pointed out to you today that this charge storage here is there because, minority carriers are stored. What about such charge storage here? Absolutely no charge stored because, whatever injected is very small no charge storage effect here (Refer Slide Time: 56:20) either here or here. Whenever there is no charge storage effect whenever it is absent, we can say the device is faster. In high speed circuits it is become very effective to use a device which has no charge storage that is the Schottky barrier diode. In pn junction always you will have charge storage effect and that will be slower than the Schottky barrier. You will see in a logic circuits with gallium arsenide gives you Schottky barrier diode. With that I will conclude the discussion today. We will continue on some aspects of this in the next lecture.