Solar Photovoltaics: Principles, Technologies and Materials
Prof. Ashish Garg
Department of Material Science & Engineering
Indian Institute of Technology, Kanpur

Lecture – 18
P-N Junction : Effect of Bias

So, welcome again to the new lecture of Solar Photovoltaics Principles Technologies and Materials. We will just recap the last lectures concept ok.

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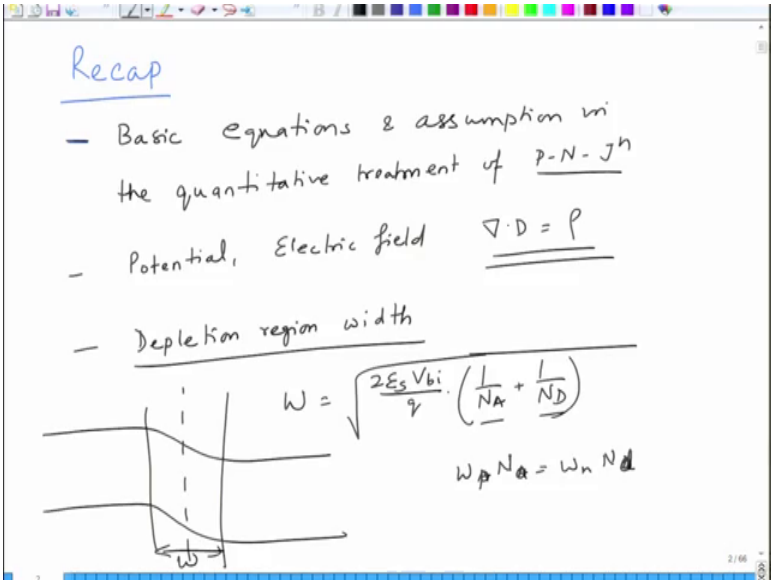

Recap

- Basic equations & assumption in the quantitative treatment of P-N-J^n
- Potential, Electric field $\nabla \cdot D = \rho$
- Depletion region width

$$W = \sqrt{\frac{2\varepsilon_s V_{bi}}{q} \cdot \left(\frac{1}{N_A} + \frac{1}{N_D}\right)}$$

$$W_p N_a = W_n N_d$$

So, we will, so in the recap what we did in the last lecture was we looked at the basic equations and assumptions in the quantitative treatment of P-N junction. So, essentially, we looked at the potential, electric field, how do you calculate them; so how. One thing you have to remember that electrical electric field and potential both are continuous because the bands are continuous. So, they are not discontinuous at the junction at the interfaces. So, and from those and basic Poisson's equations which is basically del D is equal to rho we determine the electric field, then we determine the potential and then we did the estimation of depletion region width ok.

Depletion region width was equal to W was equal to square root of 2 epsilon s V b i divided by q into 1 over N A plus 1 over N D. And this equation tells you very clearly that if your N A or N D go up that wW goes down which means in a P-N junction the depletion region becomes narrow. So, this depletion region becomes at shrink, so, this is

W ok. It shrinks if the semiconductors are heavily doped or it expands when the semiconductors are lightly doped.

It also tells in some sense because we know that W a W p N a is equal to W n N d, N d it also tells that if P side is heavily doped as compared to N side the P side is more narrower or if N side is more heavily doped as compared to P side the N side is narrower as compared to the P side ok. So, this is what the message of previous lecture is.

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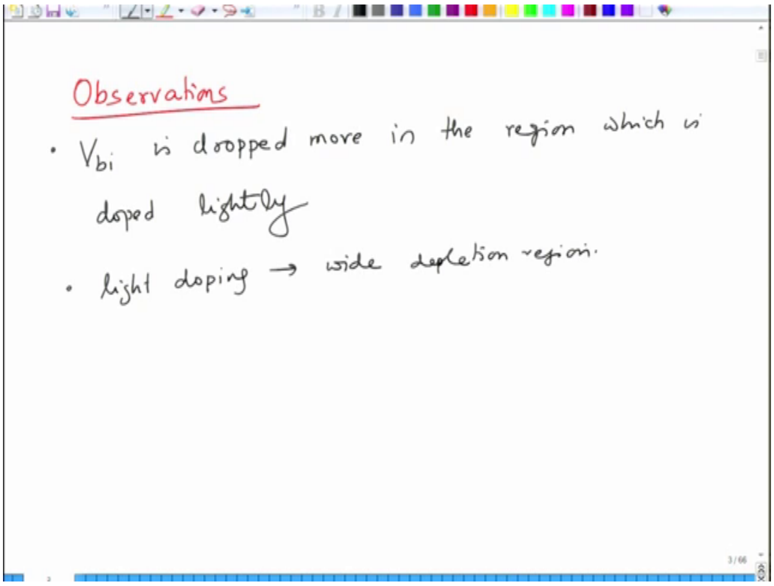

Observations

- V_{bi} is dropped more in the region which is doped lightly
- light doping → wide depletion region.

So, essentially and so you can say the observations are one built in field potential is dropped more in the region which is doped lightly and light doping will mean a wide depletion region ok. So, let me see what we make out of it.

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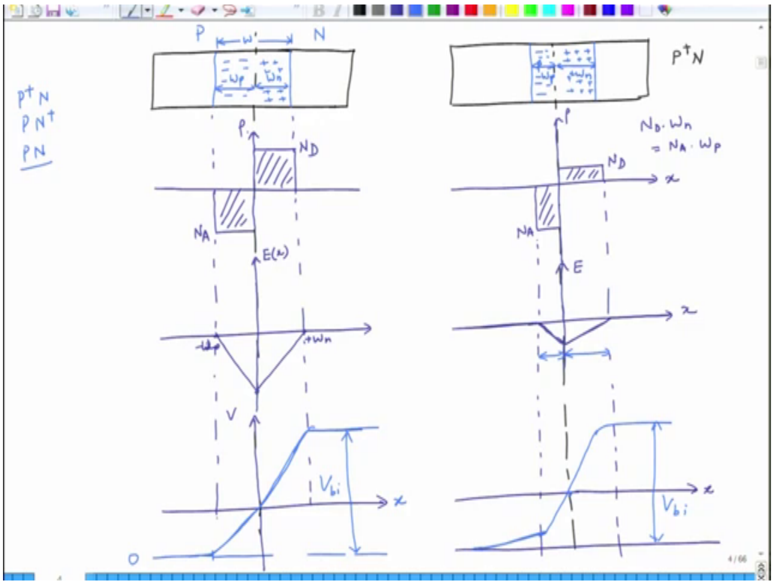

So, if you have a picture like this, let us say, so this is the P-N junction let us say somewhere here we have the depletion region. So, this is P this is N this is the interface. So, this is basically you can say capital w, all right. This is minus w p and this is plus w n ok.

Now, here we are saying that doping of P is similar to N ok. So, they are not generally if one is heavily doped we write it as P plus N if N is heavily doped we write as P-N plus if both are lightly doped we will write them as P-N ok. So, if you now plot let us say we want to plot electric first we want to plot the carrier density. So, when you plot the carrier density; the carrier density of this side is. So, this is N D and this is N A ok. If you want to plot now electric field, so this is carrier density.

Now, we want to plot electric field ok. E x the electric field is 0 at interface and it is also 0 here, it changes the curvature at this point the bands change the curvature at this point. So, as a result a electric field is 0 at that point, the variation is like this the electric field varies the rate of change of electric field is vary its same in both the regions. So, this is minus x p this is sorry minus w p this is plus w n ok. So, essentially both the regions have same width as a result the slope of electric field is also similar in both the regions.

If you look at the potential, now let us look at the potential the V and let us say I can use slightly different colour. Let us say we start from 0 here, this is 0, it achieves a value V b i in this region ok. It has a 0 value here it goes through a change like this in the and this value being V b i ok.

Now, it depends upon the reference, all right. So, if reference is slightly above, if reference is closer to the to the central axis, so, this is x ok. It depends upon basically what is the reference for the energy levels because V is nothing but minus e by q ok. So, you have certain level, then it goes increases a potential increases at the at minus w p it starts increasing until you reach plus w n going through the I mean there is no origin of this, there is no meaning of this origin, but it is just the interface ok.

So, now if you do a comparison with another semiconductor junction which is let us say P plus N in this case, so this is the interface, all right. So, what will happen in this case is your depletion region will shrink on this side, it will remain wide on this side. So, this will be, so sorry minus w p this would be plus w n.

So, this would be basically the negative carriers, negative fixed charges, this will be positive fixed charges, similarly here we did not draw them ok. Now, if you plot the charge density here the charge density in this region is lower, but for longer distance in this case its higher, but for shorter distance. So, this is N D and this is N A and basically we are saying here is the product of N D into w n is equal to product of N a into w p. So, you can see that if N A and N D are not equal, w p and w n will also not be equal. If I plot the electric field in this case, the electric field goes like this its continuous it is like this. This is what is I can say is the electric field ok.

Now, if I look at the potential, this is x, the potential goes as this is some level 0, different colour. So, it goes as goes as something like this. So, this whole value is V b i, but it goes through a few changes here. So, the region which is lightly doped the potential is generally dropped. So, it does not go through 0 here so, the region which is lightly doped the potential gets dropped a little bit more as compared to in the region which is heavily doped and the profile changes a little bit in terms of because of changes in the carrier density in the two regions. So, it is always continuous, it is never discontinuous but the profile changes to something like that.

So, you can see that the electric field it goes from 0 to some value in the heavily doped region whereas, it goes from, so it goes over a shorter distance then it goes in this region. So, you can see that the drop in the electric field is more in the region which is heavily doped, right, as compared to the region which is lightly doped, because within that small distance you have large charge density and suddenly you go to 0 charge density here. So, so you come from 0 to large charge density which means you have larger gradient in the electric field as compared to in the region where you have a smaller charge density over long distance and correspondingly you have variation in the potential. So, this is how the variation of potential and electric field is going to happen.

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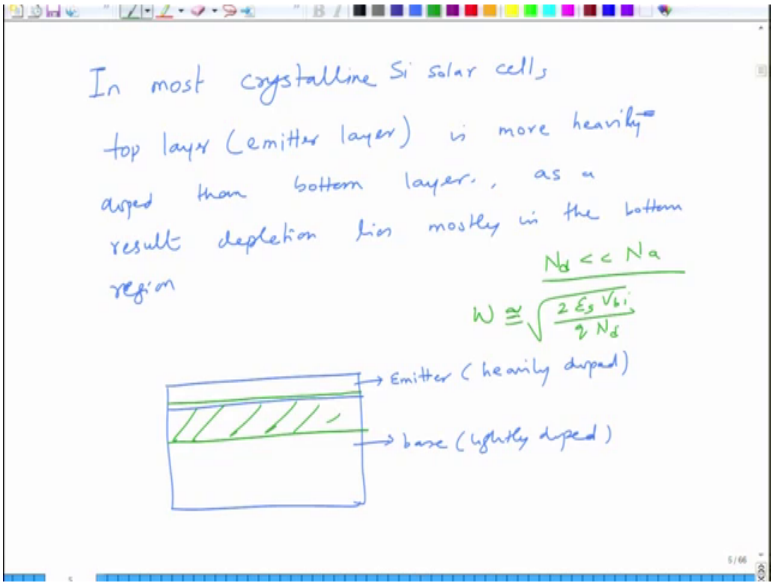

In most crystalline Si solar cells top layer (emitter layer) is more heavily doped than bottom layer., as a result depletion lies mostly in the bottom region

$N_d << N_a$

$$W \cong \sqrt{\frac{2 \varepsilon_s V_{bi}}{q N_d}}$$

Now, in most solar cells how is it relevant to solar cells is, in most solar cells at least crystalline silicon solar cells the top layer which is called as emitter layer is more heavily doped than the bottom layer as a result depletion region lies mostly in the lie in the bottom region.

So, this is how, so you have a solar cell like this is emitter and this is base ok. This is heavily doped and this is lightly doped right. So, the depletion region basically extends up to a large distance here, but up to a very tiny distance in this region. So, most of the depletion region lies in the base layer than the top layer ok. And emitter layer is also very thin at we will discuss the reasons of that later why is that in this fashion in the solar cells when we come to crystalline silicon solar cells, but this is how it is that depletion region in the.

So, you can say if you are for example, if your N d is much smaller than N a, then you can say that w is approximately equal to square root of 2 epsilon s V b i divided by q into

N d, it is only governed by N d. So, if there is a to order of magnitude difference in N a and N d then; obviously, one is going to be ineffective. So, as a result N d is the more dominating factor over N a in determining the.

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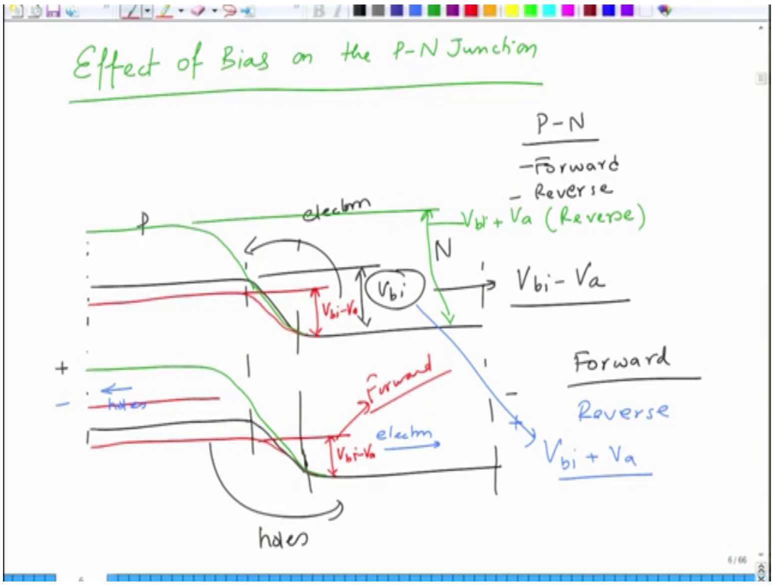

Effect of Bias on the P-N Junction

So, now if you now we want to look at the effect of bias, effect of bias means effect of applied field ok. So, what you do here is, essentially what you do is that if this is your P-N junction little bit, all right and we said that this is V b i. What do you mean by work bias here? So, bias in semiconductor P-N junction it is called as either forward bias or reverse bias.

What does it mean? It means that you have a P-N junction here, the P side is, so forward bias means your p side is made more positive it is connected to positive terminal and N side is connected to a negative terminal this is called as forward bias. What will happen in this case? In this case what will happen is that since you are applying negative bias, so this terminal, the N terminal the electrons in this N side will feel a force to go to N side P side. Similarly, when you positively bias the P side the holes from the P side will be repelled towards the, so they will be forced to go towards the junction to the N side. So, you have electron migration from here to here and you have holes migrating from here to here.

What essentially it means is that the energy barrier on this side is lowered. So, when you apply a positive bias the energy barrier gets modified to V b i minus V a this is forward bias. And you will have large junction current the electrons hopping from this side holes going from this side there is large current that flows across the junction as a result you have large current.

What happens in reverse bias on the other hand is in the reverse bias if I, so if I depict reverse as blue. So, reverse will mean you are connecting P side to a negative terminal and N side to a positive terminal which means the holes are going to go to, so the holes will go to this side and electrons will go to this side which means they are drawn away from the junction. Which means, there is no junction current which is going to flow, the electrons and holes going to go through and we are going to recombines at some point and in the in the circuit there is no current that is going flowing from the through the junction. So, junction current is very small in the reverse bias.

So, in the reverse bias essentially what it means that this barrier increases essentially it becomes V b i plus V b a, V a. So, essentially when you, so, if I if I want to depict it if this is at V is equal to 0, in the forward bias case it will become like this sorry, it will become like this ok. So, the junction height has reduced in the forward bias case ok, so, this is V b i minus V a, all right. In case of reverse bias what will happen is it will become more like this.

So, essentially your junction has become V b i plus V a, so, this is reverse bias, and this is you can say is forward bias, all right.

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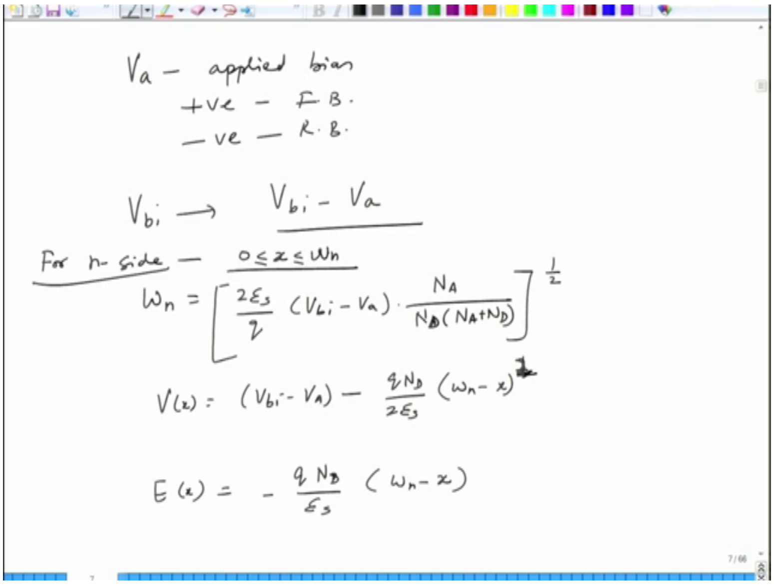

V_a – applied bias
+ve – F.B.
–ve – R.B.

$V_{bi} \longrightarrow \underline{V_{bi} - V_a}$

For n-side – $\underline{0 \le x \le W_n}$

$$W_n = \left[\frac{2\varepsilon_s}{q} (V_{bi} - V_a) \cdot \frac{N_A}{N_D(N_A+N_D)} \right]^{\frac{1}{2}}$$

$$V(x) = (V_{bi} - V_A) - \frac{qN_D}{2\varepsilon_s} (W_n - x)^2$$

$$E(x) = -\frac{q N_D}{\varepsilon_s} (W_n - x)$$

So, essentially let us say we have applied potential V a, V a is the applied bias. So, V a value is positive when its forward bias and its negative when its reverse bias ok. So, let us say if this happens then we replace V b i by V b i minus V a ok. So, depending upon the sign of V a it will become plus or minus ok.

So, for N depletion region this will become, so w n will become for N side for x smaller than w n between 0 and w n w n will become 2 epsilon s divided by q into V b i minus V a into N A divided by N A into N A plus N D sorry it should be N D to the power half. V x will be V b i minus V a into minus of q N D divided by 2 epsilon s into w n minus x to the power to the power 2 ok. And E x will be, so we are just replacing this, ok so this will be q N D divided by epsilon s into w n minus x ok. Electric field remain the same it is only the bias just changed ok.

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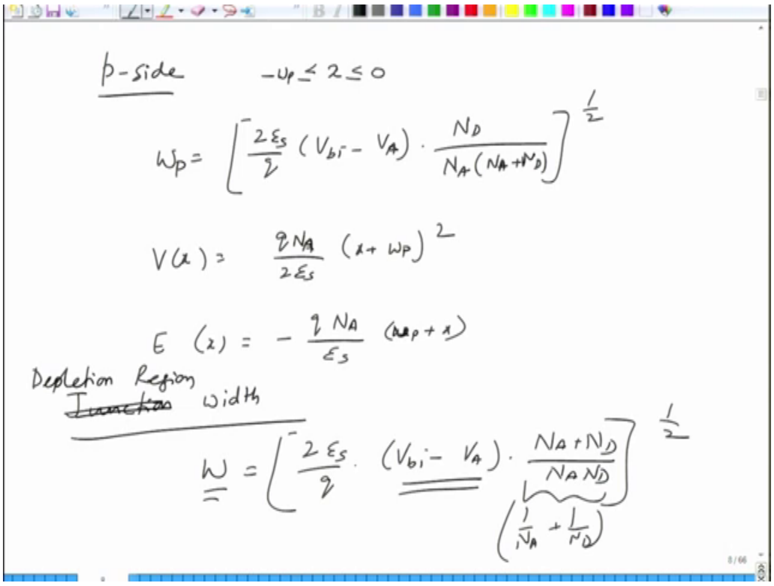

p-side $\quad -w_p \le x \le 0$

$$w_p = \left[\frac{2\varepsilon_s}{q}(V_{bi} - V_A) \cdot \frac{N_D}{N_A(N_A + N_D)}\right]^{\frac{1}{2}}$$

$$V(x) = \frac{qN_A}{2\varepsilon_s}(x + w_p)^2$$

$$E(x) = -\frac{qN_A}{\varepsilon_s}(w_p + x)$$

Depletion Region ~~Junction~~ width

$$\underline{\underline{W}} = \left[\frac{2\varepsilon_s}{q} \cdot \underline{\underline{(V_{bi} - V_A)}} \cdot \underbrace{\frac{N_A + N_D}{N_A N_D}}_{\left(\frac{1}{N_A} + \frac{1}{N_D}\right)}\right]^{\frac{1}{2}}$$

Similarly, if you write the same equations for P side for x less than 0 to minus w p, your w p will become equal to 2 epsilon s by q sorry then I have factor of half into V b i minus V a into N D divided by N A into N A plus N D raise to the power half. And V x will become q N A divided by 2 epsilon s into x plus w p square and E x will become minus of q N A divided by epsilon s into x p plus w p plus x ok.

And the junction width will become w will become 2 epsilon s divided by q into V b i minus V A into N A plus N D divided by N A N D and this whole to the power half. You can write this as 1 over N A plus 1 over N D also ok. So, this is what the change in the bias so, you can see that as you increase, as increase your applied bias junction width also what will happen; when you when you are when you are in forward bias the junction width the depletion region width. So, this is the my junction a should be depletion region width, actually to be up to be correct.

So, the depletion region width will become narrower when you apply a forward bias and when you apply a negative bias then this value will become larger as a result the junction width will become or depletion region width will become larger as you apply more and more bias.

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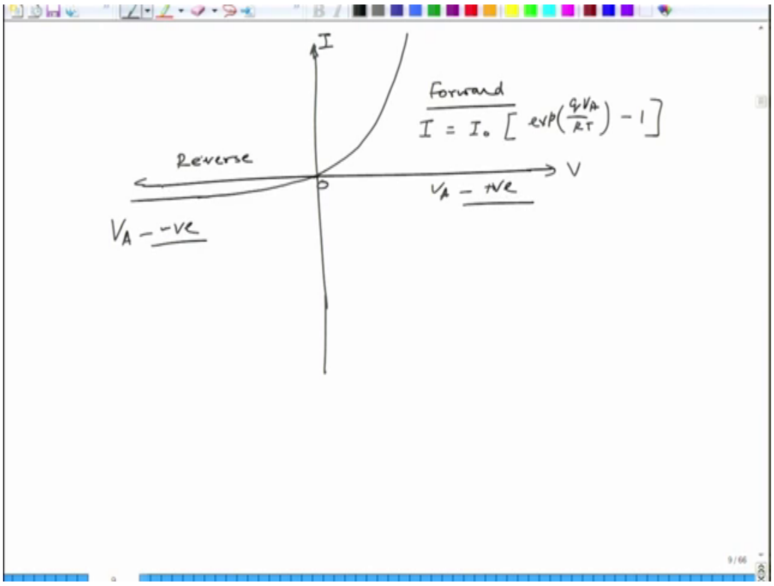

And what happens here is then, so the effect that it has on the characteristics, I V characteristics is that is like this which we will derive. So, when you draw the I V characteristics essentially no current flows across the junction. It is a very small reverse current in the reverse bias. So, this is reverse bias, so this is 0 ok. So, when V is less than 0 its reverse bias very small current flows across the junction as a result what you have is very little current flowing.

This is reverse bias and then in the forward bias because a large current flows through the junction by electrons pushing across from N to P side and holes pushing across from P to N side, where there is a very large junction current and this current is essentially the forward current, so, this is forward current.

And mathematically speaking this current is basically I is equal to I naught, exponential of q V A divided by k T minus 1 and this current and that in the reverse bias it is basically I is equal to I naught exponential. So, you can see that this will be positive in this region and this will become negative in this region. So, in a sense sorry, I do not have to write this, but this V A will become V A is negative in this region and V A is positive in this region. And this current is essentially equal to we will continue this in the next lecture to work out the electrical characteristics of P-N junction ok.

Thank you.