Introduction to Solid State Physics
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Lecture – 73
Charge carrier density in n-type and p-type semiconductors

In the previous lecture, we dealt with acceptor and donor levels in a semiconductor and showed that the difference E c minus E donor or E acceptor minus E v is of the order of 0.1 to 10 meV.

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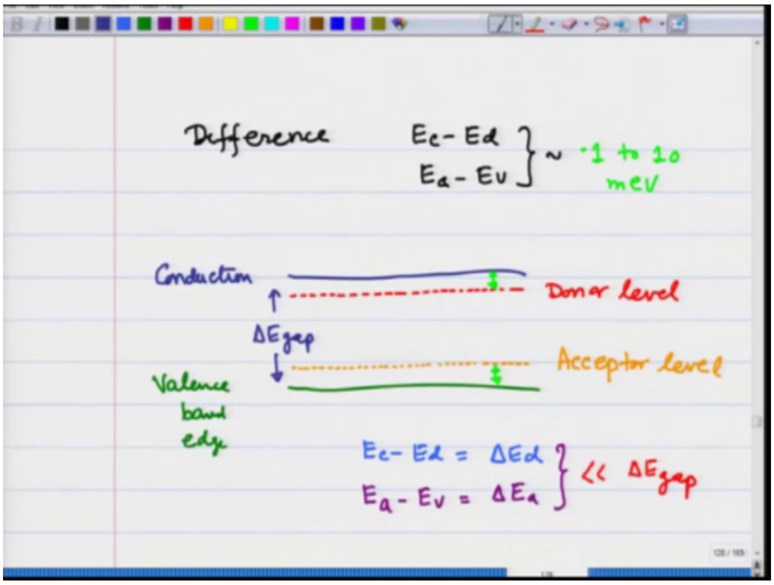

So, let me just show that in picture and I will make the band straight now. So, here is the conduction band edge and here is the valence band edge and the donor level is going to be somewhere here.

And the acceptor level is going to be somewhere here. Of course, this exaggerated, they are even closer. So, this is I am going to call acceptor level and I am going to call this donor level. They are much smaller these gaps out here or out here are much smaller than the intrinsic band gap. So, let me just write that E c minus E donor which I will call delta E d or E acceptor minus E valence which I am going to call delta E acceptor. They are much much less than delta E gap which is out here.

So, at room temperature which is of the order of 25 milli electron volts, main contribution to the charge carriers will come either from donor level or acceptor level if both are not present. So, let us now understand what the behavior of these charge carriers is going to be.

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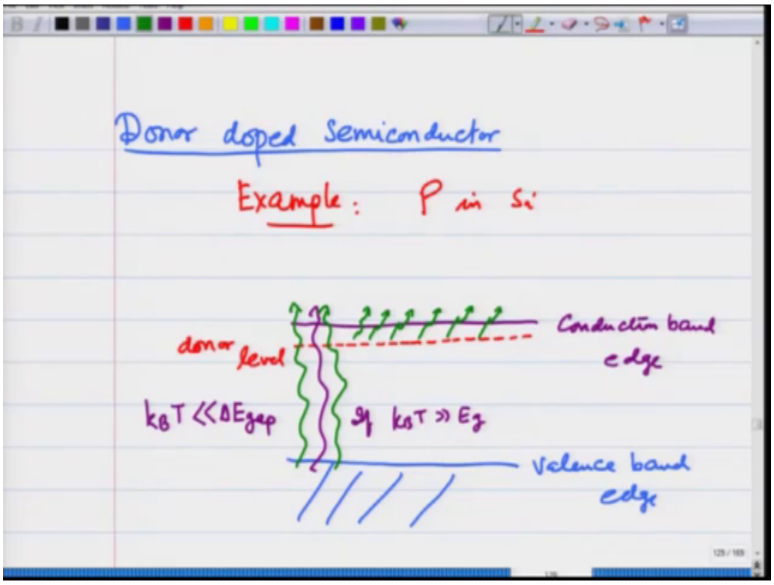

So, let us first understand donor doped semiconductor and the example is going to be phosphorous in silicon. It is just for the example sake. So, if I were to see the levels here is the valence band edge. So, lower side is odd valence band, on top is conduction band edge and here is the donor level, right underneath it. If the temperature is small, so, let us say k B T is much smaller than E gap the only contribution to electrons in the conduction band will then come from the donor level.

If T becomes very large right on the other hand if k B T is much larger than E gap then electrons will start coming from the lower level also. And in fact, as I remarked earlier the concentration of donor levels is very small and therefore, at large temperatures is the electrons from the valence band that come to conduction band that will dominate the charge carriers. So, let us identify these regimes.

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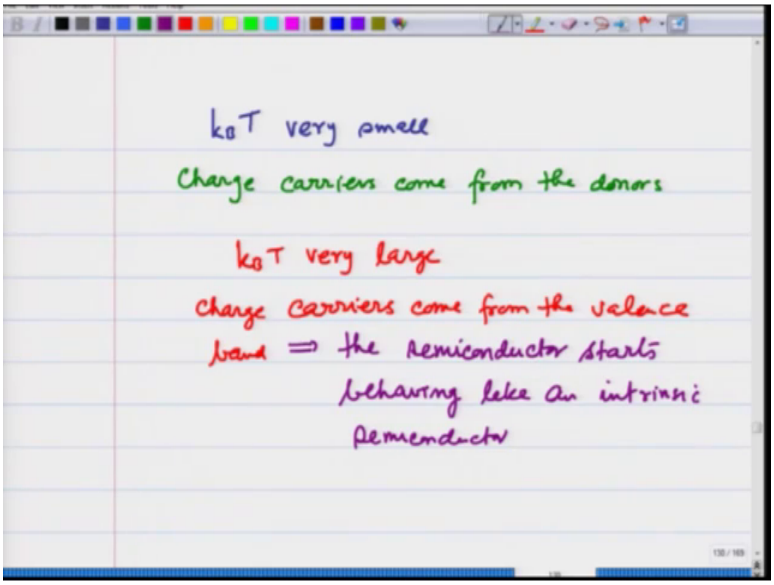

K B T very small and remember these smallness and largeness is with respect to the band gap or the donor level with respect to the conduction band then charge carriers come from the donors and this behavior is going to be different from when I have k B T very large, in that case charge carriers come from the valence band. And therefore, the semiconductor starts behaving like an intrinsic semiconductor. So, let us see how the behavior changes roughly with respect to the temperature.

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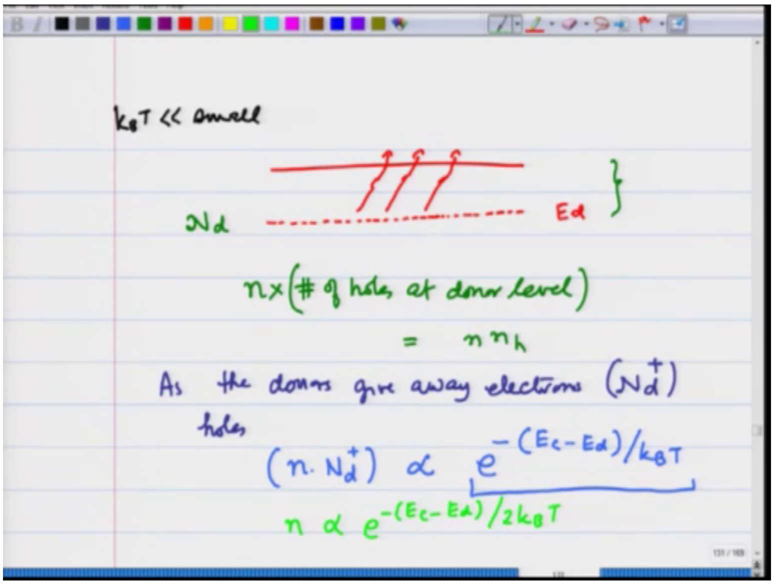

When k B T is very small, then here is the conduction band, here is the donor level mainly carriers are coming from here. So, like we did for intrinsic semiconductors mainly things are coming from the donor levels and let us say the concentration of donor levels is N d.

Then what I am going to have is that the number of electrons in the conduction band times the number of holes at donor level is going to be equal to that n n h and I am going to repeat this calculation taking only these two levels. If I do that what I should have is as the donors give away electrons I am left with N d plus the donors that have ionized holes. So, I am going to have the number of electrons times the number of holes proportional to E raise to minus now the energy gap that I am going to have is E conduction minus E d over k B T.

So, the temperature dependence will come mainly from this term and exactly like we did for the intrinsic semiconductors and then is going to be proportional to E raise to minus E c minus E d divided by 2 k B T. So, this is the temperature dependence when k B T is very small and main contribution to the charge carriers in the conduction band comes from the donor levels alone.

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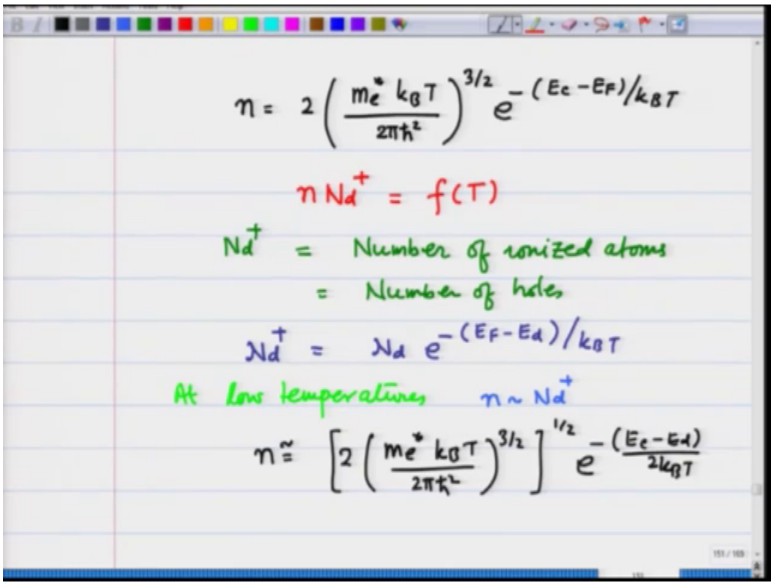

If you want to get the prefix also then I am going to have n equals 2 m e star k B T over 2 pi h cross square raise to 3 by 2 e raise to minus E c minus E F over k B T. This is the number of electrons and we are going to have n times Nd plus equals a function of temperature alone by the law of mass action where Nd plus is equal to the number of ionized atoms which is equal to the number of holes.

Now, I am going to calculate later that we are going to have Nd plus is equal to Nd where Nd is the number of donor atoms E raised to minus E F minus E donor divided by k B T. Now, using the law of mass action and multiplying n Nd plus we can get the number of electrons in the conduction band. Notice that at low temperatures all the electrons are coming from the donor levels. So, I can say that n is roughly equal to Nd plus and then using all this I am going to get n equals 2 m e star k B T over 2 pi h cross square raise to 3 by 2 this whole thing raise to one half E raise to minus E c minus E d divided by 2 k B T.

And I am going to put a an approximate sign here because we have made certain assumptions along the way. Let us now fill in the details of this calculation.

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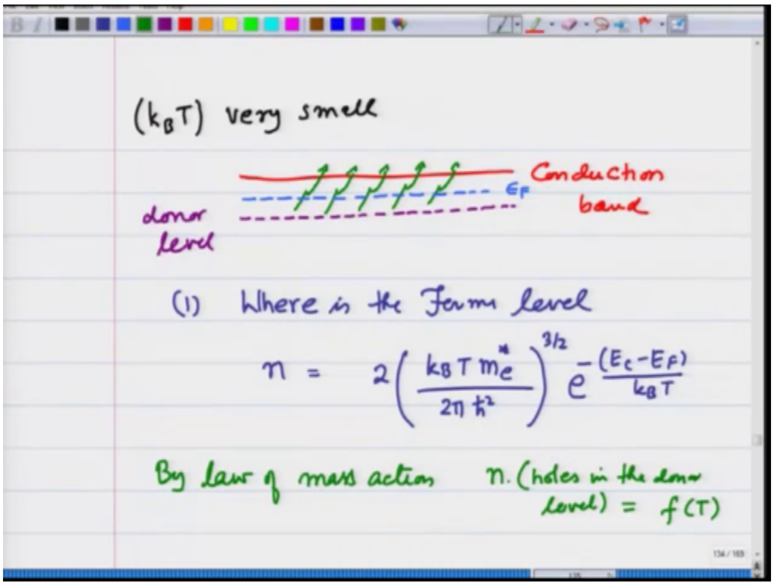

So, let us work on finding out the number of careers when k B T is very small and that is when I say smallest relative to the band gap of the intrinsic semiconductor. So, in that case what we had argued is that this is the conduction band edge this is where it starts from and I have the donor level right here and the electrons are going to come mainly from here.

So, first question I ask is where is the Fermi level? And you can see that the Fermi level again arguing like we did for the intrinsic semiconductors is going to be somewhere in the middle of the donor levels and the conduction band edge. And the number of electrons is going to be equal to; remember the way we did the calculation for the intrinsic semiconductors, number of electrons is going to be proportional to you know 2 k B T m e star over 2 pi h cross square raise to 3 by 2 e raise to minus E c minus E F over k B T.

Now, this is the number of electrons in the conduction band; E F I do not know yet and by law of mass action that we discussed earlier I am going to have n times the holes in the donor level is equal to a function of temperature. So, using this I can find the number of electrons n the conduction band due to ionization from the donor level.

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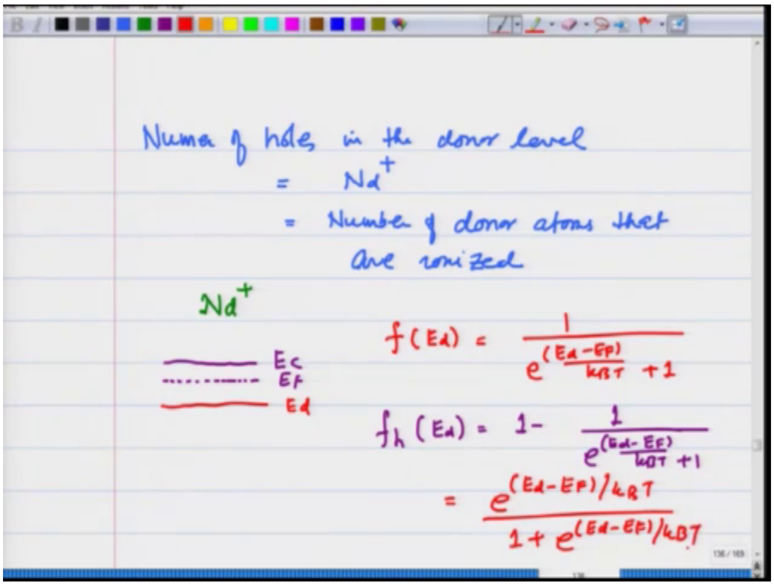

Now, let us see the number of holes in the donor level is going to be equal to Nd plus by Nd plus I mean the number of donor atoms that are ionized. So, to calculate Nd plus I am again going to use the same trick I use for the intrinsic semiconductors and let us see what we did there. Here is my conduction band edge, here is the Fermi level E F which I have already argued is somewhere in the middle of E donor and E F.

Now, the probability of occupation of E d is going to be equal to 1 over e raise to E d minus E F over k B T plus 1. So, probability of having a hole f h here if not being occupied at E d is going to be equal to 1 minus 1 upon e raised to E d minus E F over k B

T plus 1. So, this is equal to e raise to E d minus E F over k B T over 1 plus e raise to E d minus E F over k B T.

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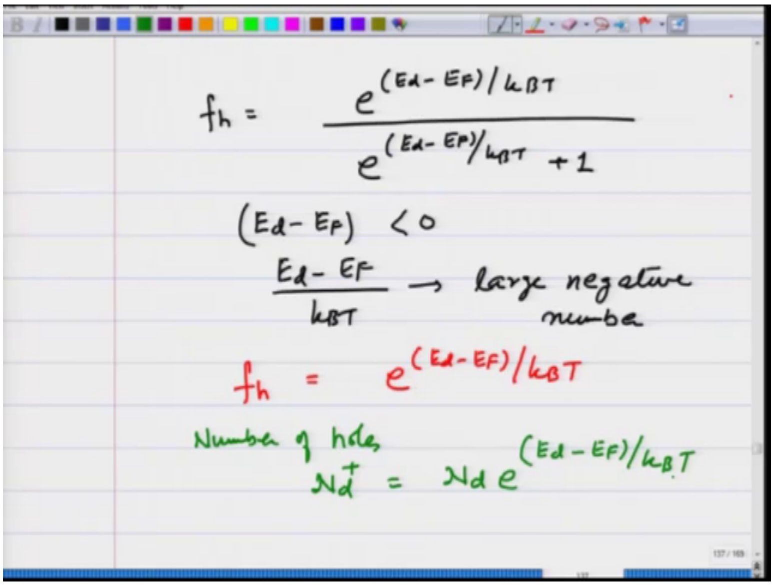

So, I get f h which is e raised to E d minus E F over k B T over e raised to E d minus E F over k B T plus 1. Now, we already said k B T is very small and E d minus E F is negative and E d minus E F over k B T is going to be large negative number. So, I can write f h is equal to E raised to E d minus E F over k B T roughly. And therefore, the number of holes at the donor level Nd plus is going to be equal to Nd times e raise to E d minus E F over k B T.

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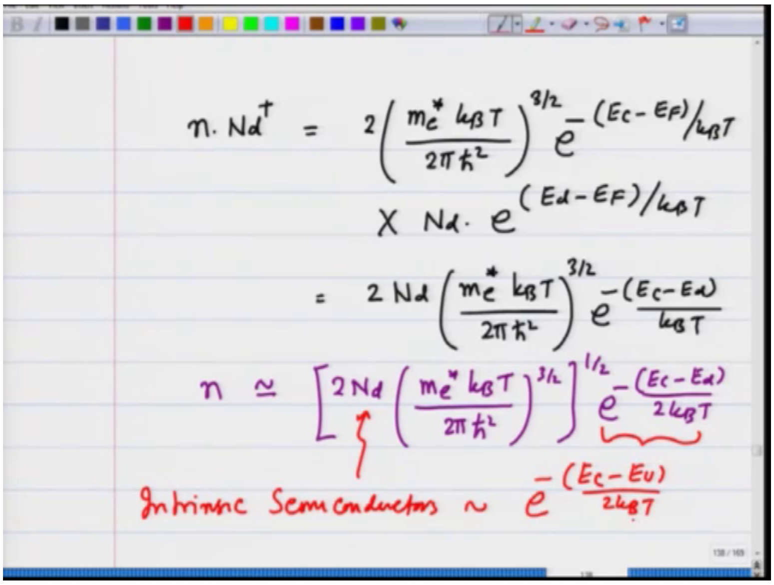

This gives me Nd plus is equal to 2 m e star k B T over 2 pi h cross square 3 by 2 times e raise to minus E c minus E F over k B T times Nd times e raise to E d minus E F over k B T which is nothing, but 2 Nd m e star k B T over 2 pi h cross square raise to 3 by 2 e raise to minus E c minus E d divided by k B T.

Since the particles are coming mainly the electrons are coming mainly from the donor levels I can therefore, then say that n is therefore, is proportional to or roughly equal to 2 Nd m e star k B T over 2 pi h cross square raise to 3 by 2 this whole thing raise to 1 by 2 E raise to minus E c minus E d over 2 k B T. You see this calculation exactly like what we did for intrinsic semiconductors, except now I get this factor of Nd here rather than there it was the expression for the hole because all the holes are coming from the donor level.

And this is the proportionality term for the temperature which in the case of intrinsic semiconductors was e raise to minus E c minus E v over to k B T. So, that E v has been now replaced by E donor.

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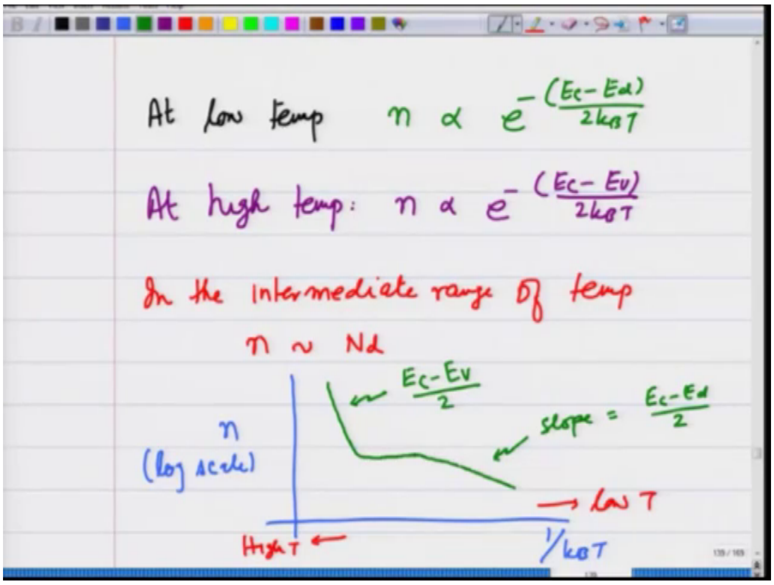

So, at low temperatures n goes as e raise to minus E c minus E donor divided by 2 k B T and at high temperatures, I had already argued that now that high temperatures the domination is going to be from the carriers coming from valence band and therefore, n is going to be proportional to e raise to minus E c minus E v over 2 k B T.

And in the intermediate range of temperature the n would be roughly equal to Nd because all the donors would have been ionized. So, if I were to plot the carriers on a log scale versus 1 over k B T. So, that this is high temperature this is low T, I am going to get a curve which is slope E c minus E v by 2 in the beginning then there will be a saturation because intermediate range all the ions are ionized and then there will be a less slope which will be proportional to E c minus E d. So, here slope is E c minus E d divided by 2. Here the slope will be E c minus E v divided by 2.

So, you see how over a range of temperature, the carriers n the conduction band are varying at high temperature they the change is very fast depending on the band gap of the intrinsic semiconductor, at low temperatures it is slow; it is E c minus E d divided by 2 and in between the range remains constant and this is how the conductivity of the system is also going to be affected. And you can see from the kind of range I gave you earlier for E c minus E d at room temperature it is the careers coming from the donor or acceptor level that are going to be dominating the conductivity and things those properties transport properties.

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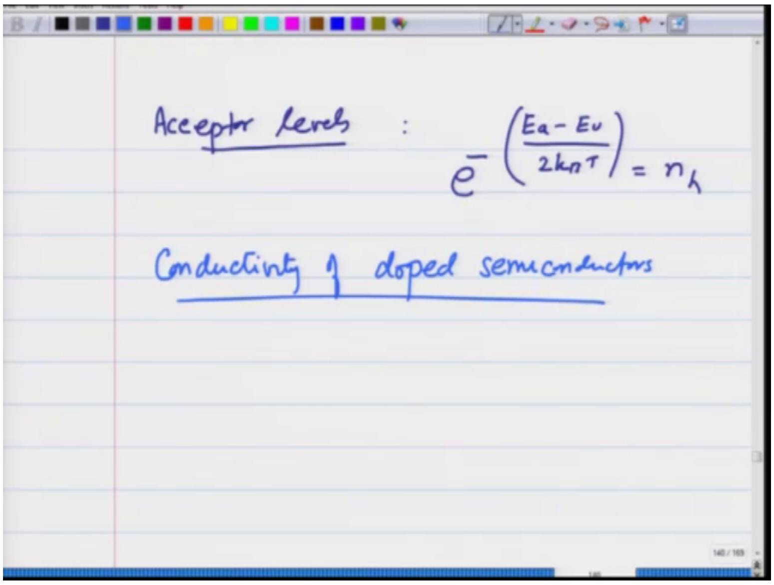

Exactly the same calculation would also be acceptable for acceptor levels. In acceptor levels I am going to get E a minus E v over k B T as a proportionality constant for number of holes, so, that I will leave for you. So, the conductivity of doped semiconductors is going to give you two different slopes depending on what temperature range are you at.

So, we will derive in the next lecture the expressions for the conductivity and also other transport property like hall coefficient for a semiconductor and show their usefulness that will complete our lectures on semiconductors.

Thank you.