Analog Electronic Circuits
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Lecture - 59
The Bandgap Reference - Part 1

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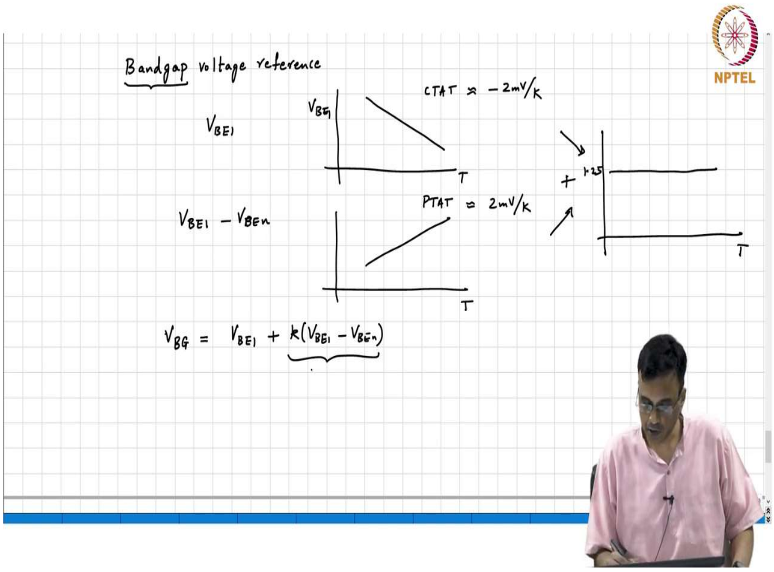

In the last class, we were looking at the basic idea behind the Bandgap voltage Reference. I will tell you why it is called the bandgap. So, the basic idea as you saw was to take a diode drop which we called V_{BE1} whose temperature coefficient is CTAT and roughly - 2 mV/K, right. And somehow generate a PTAT. If you generate +2 mV/K, if you add these 2, you get something which is independent of temperature, right.

So, what is the rough value that we get and how do we get the PTAT? You take the voltage difference between V_1 - V_{BEn}, ok. And so, roughly, this voltage will be roughly about 1.25 volts. So, why is it called the? So, it is a voltage reference, alright. The question is why is it called a bandgap voltage reference? If you go and write out all the device equations for V_{BE1} and V_{BE1} - V_{BEn} and manipulate through, you know that all of this will contain expressions for the saturation current I_s, ok.

So, if you go and work out all the math there, it will turn out that you can actually trace it to the bandgap of silicon which is about 1.2 volts, right. So, this is why these are called bandgap voltage references. And you can get something, anything proportional to, once you have 1.2 volts, you know you can get a fraction of it or multiple of it by appropriate multiplication.

So, as far as we are concerned, we said that we need to add. So, that reference here is called V_{BG}, right? V_{BG} stands for bandgap and that is basically nothing but V_{BE1} + V_{BE1} - V_{BEn} some k and this whole thing will turn out to be, how many V_T did we have to add? This is approximately 24 V_T.

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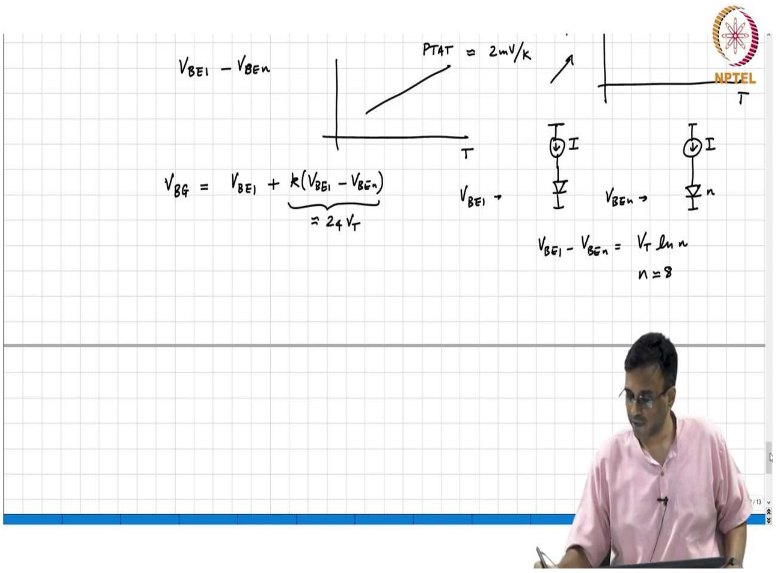

So, V_{BE1} is the voltage developed across a single diode when a current I is pumped through it. And V_{BEn} sorry, is the same current. The important thing is basically to have the same current pumped through a diode which is n larger, instead of drawing n diodes, I just draw one diode and put n by the side and it means the same. The important thing is that both of them must have the same kind. Alright? So, evidently we need (V_{BE1} - V_{Ben}), right? (V_{BE1} - V_{Ben}) is nothing but V_T ln(n), ok. And if we choose a reasonable value of n, a typical value for n, a good value to choose is 8, I will tell you why that 8 makes sense. But at this point, anyway you know, if 8 is just a choice as good as any other, right. You only get, you know, ln 8 is roughly about maybe 2 or so, right? So, 2 you only get 2 V_T, but we need 24 V_T. So, what should we do?

We want to, we need to amplify this, this 2 V_T to about 24 V_T. So, how do we amplify a voltage? We always, in whatever we do gain, voltage gain is always obtained by taking, converting voltage into a current.

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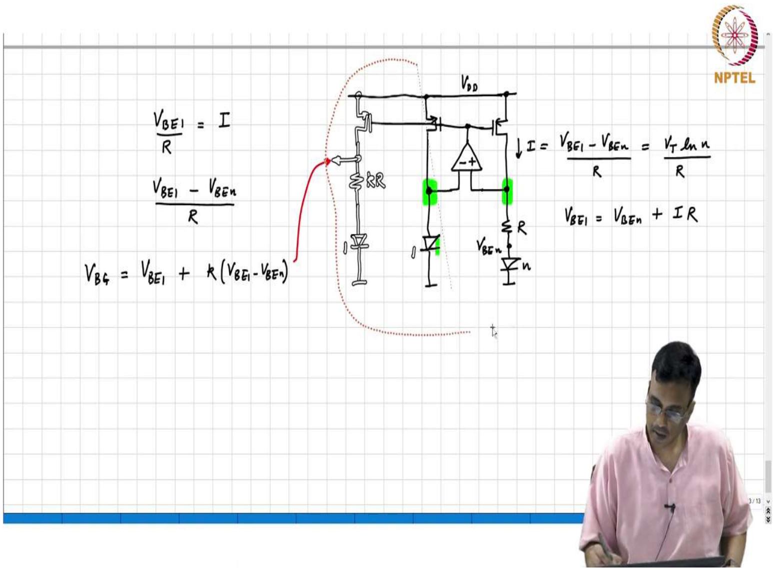

And then taking that current, pushing it to a larger resistor, right. Whichever amplifier you have seen, basically that is what is happening. So, the first job is to convert, you know, V_{BE1} - V_{BEn} into a current, alright. And before that, we said, we start off with converting V_{BE1} into a current, then we will figure out how to convert V_{BE1} - V_{BEn}.

So, how do we convert, we want V_{BE1}/R, you want this current and how do we do this? Well, you know, we have seen this over and over again. If we had, if you want, if you basically had a variable current source, which is modelled by a PMOS transistor with a variable gate voltage there, then by varying the gate potential up and down, you can change the current flowing through the resistor.

So, what you need to do is compare this voltage with, with IR, this is I and this is V_{BE1}, ok. And go and hit the gate. So, if IR < V_{BE1}, it means that the current I is too low, which basically means the gate voltage is too high. So, if this voltage on the right side is low, the gate must be pulled down. Is that clear? So, what should be the signs of the Op-Amp + to the right side - here, ok. So, this is where we were last time, ok. So, this is V_{BE1} by, we have converted V_{BE1} to what you call a current, ok. Now, it is straightforward to take this current if you want n V_{BE1}, what can we do?

If you want to amplify, there is no big deal you can create as many copies of this current as you want, right. And for instance, if you want to do this, this gives you. What is the voltage there? This is n V_{BE1}. Is this clear? Ok, anyway. So, that is not my main point though, alright.

So, we have converted V_{BE1} into a current. The point I am trying to make is that once you have a current, you can mirror it because the current basically, in this case, is just simply coming from a transistor with appropriate source gate voltage. So, you can mirror it and make as many copies of your current you want and therefore, you can accomplish gain, So, but what we need is not V_{BE1}/R, what we need is $(V_{BE1} - V_{BEn})/R$, ok. So, any suggestions on how I can use how I can get $(V_{BE1} - V_{BEn})/R$? So, as we discussed the last time around, basically if you had a battery of V_{BEn}, you would connect it like this, correct. And so, here in this case, therefore, we will connect a diode of size n, alright. So, this is V_{BEn}, correct. So, what am I? $(V_{BE1} - V_{BEn})/R$, ok, alright. And what is V_{BE} and how do we generate V_{BE1}?

What is V_{BE1}? It is voltage across a diode of size 1, provided the same current must be flowing through V_{BE1}. Then only will be $V_{BE1} - V_{BEn}$ be PTAT, correct. So, how do you suggest that I get the same current I am through? What do we do? So, you add another PMOS transistor which mirrors or which copies this current, ok. So, if the Op-Amp is ideal, the two voltages at its inputs are the same. So, the current is $(V_{BE1} - V_{BEn})/R$ which is nothing but $V_T \ln(n)/R$, ok. Now, if you want. So, now, what must we do? What all so, we have a current which is PTAT. So, what we want to do is we want $V_{BE1} + k\,(V_{BE1} - V_{Ben})$. So, how do we get this now? Any suggestions? There are multiple ways of doing it, anyone is good enough, very good, ok.

Diode of size 1. Alright, so this is kR, ok. So, what is this voltage? So, this is basically simply that guy $V_{BE1} + k(V_{BE1} - V_{Ben})$. Of course if you are looking at the circuit for the very first time and trying to analyze it that is easy enough, what do you do? Well you know the Op-Amp is ideal. So, these two voltages are the same, ok. And therefore, V_{BE1}, both of them carry the same current.

So, V_{BE1} must be equal to $V_{BEn} + V_{BEn} + IR$, right. So, $V_{BE1} - V_{BEn}$ is IR which basically means $I_s\, V_T \ln(n)$. Now can somebody think of a way in which you can avoid one extra diode? Stare at these two branches and see if there is something that we can do. So, an alternative thing to do is that is V_{BG} is $V_{BE1} + k\, V_T \ln(n)$, right.

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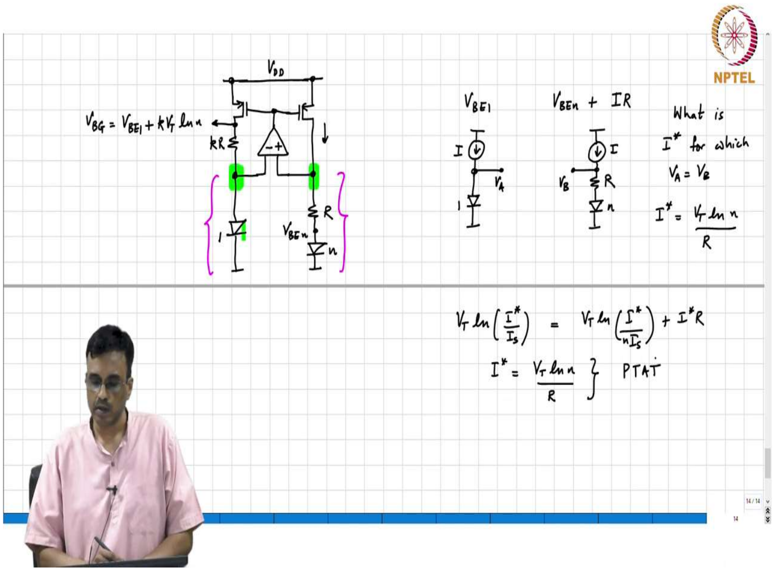

So, basically there is, this is one way of interpreting or deriving the band gap. There are many other ways of doing it, right? Let me just say for completeness do a couple more. One way of interpreting this result is to think of it as the following. So, let me ask you the question, let us say you take a diode and pump it through it. Let us say I take a diode of size n and size 1, look at these two potentials, ok. Now, the question is, for an arbitrary value of I is, what comment can we make about V_A and V_B? Will it be the same or will it be different? There is no reason for the two to be the same.

However, if for one magic value of I which is I*, what is that magic value of I* for which V_A will be equal to V_B? Ok, 0 is one answer, alright? Is there any other value of I for which VA is equal to V_B and both of them are not 0? What is V_A? Ok, what is V_B? Ok. So, when will both of them be the same? That is what it means when they say, the two of them are the same. Same equals are the same. So, for what magic value of I* Will the two voltages be the same? I made a mistake, yeah, this is R_o in. So, I mean the answer is staring at it, now the left side it's exactly the same thing, correct. On the left side what is the Op-Amp doing? The two voltages are the, what comment can you make about the voltage across the two branches? Why?

The both voltages would be the same, right. So, you can see that both voltages here are the same because of the negative feedback of the Op-Amp and both currents are the same, right. And so that is obviously, the, I mean. So, if you could see that and say straight away that I* must be equal to V_T ln(n)/R, that is very good. If you are not able to see it, then you simply we write V_T, V_A is nothing but V_T ln I*/I_S and V_B is nothing but V_T ln (I*/n I_S)+ I* R, if these two have to be equal, right. Then I* must be equal to V_T ln(n)/R, correct, alright. So, this is the magic value of I for which the two voltages are equal. And what comment can you make about that magic value of current? The voltage across the two branches is the same only if the current is V_T ln(n)/R and that magic value of current is PTAT, right.

It is proportional to absolute temperature. Why? Because ln(n) does not change your temperature R does not change your temperature and V_T is k T/q alright? Does it make sense to people? Now, so, how do we know if we are at the magic current or not? Let us say so again. Let me draw the picture again.

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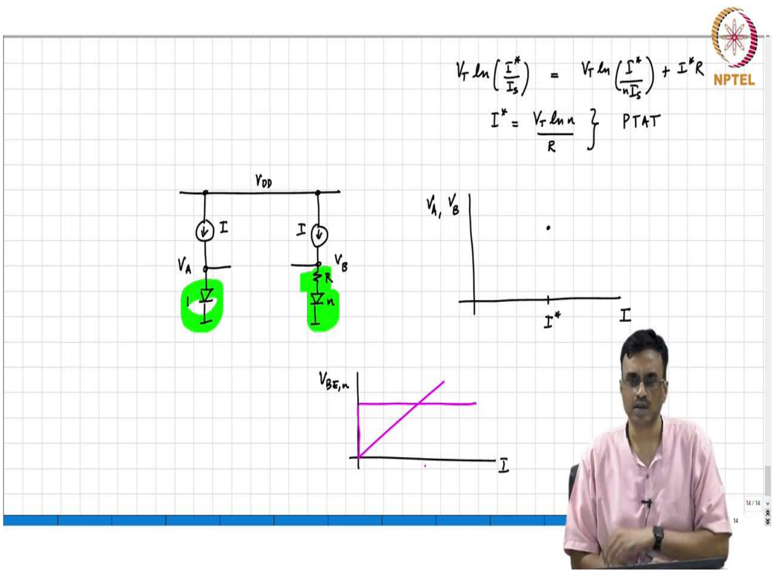

So, let us say we have pumped in some current I. So, this is V_A, this is R, this is V_B. So, let us say you are in the lab and you pump some value of current I. You are asked to find the, you are in the lab, you are given this thing two identical current sources which can be varied. You are asked to find this I star. What will we do? How will we figure this out?

This some magic value I* V_A and V_B will both be identical, correct. Now, below I* below the magic value for currents which are way smaller than I start, how will be which will be larger V_A or V_B? Why? This graph is not with respect to temperature. For very small I right, which will by the way for the same I which of these diodes or one diode which of them will have a larger voltage? The one diode will always have a larger voltage. Now, V_B is the small voltage.

The small voltage in diode voltage + I R. For voltages which are very for currents which are very very small compared to I* Which one can you neglect the voltage across the resistor or the voltage across the n diode? Do you understand the question I am asking? The voltage V_B is the sum of the diode drop of the n size diode + I R. For very small values of I which one can you neglect which drop can you neglect, which will contribute the most to V_B? So, what does the log look like? What is the model for the diode drop for what is the idealized model for the diode drop? Ok. So, if I plot voltage across the diode versus current what is the idealized model it's open? Ok. So, in forward bias what so, if I plot only the forward bias region and what will be the voltage drop?

Ok. So, the idealized model is something like this, correct. In reality what will it be something like that right, there is a logarithmic not exponential. But I mean if you look at your head 90 degrees then it's exponential, ok, alright. Now, what is IR, how does I R look? Linear. So, for small values of I which will dominate? Why did you say before? Why? I mean what is the logarithm? Even when the input changes by an order of magnitude the logarithm only changes by a small amount, correct? So, when the current is very small, which term will dominate, which term will dominate? You have convinced or you are not convinced? Right.

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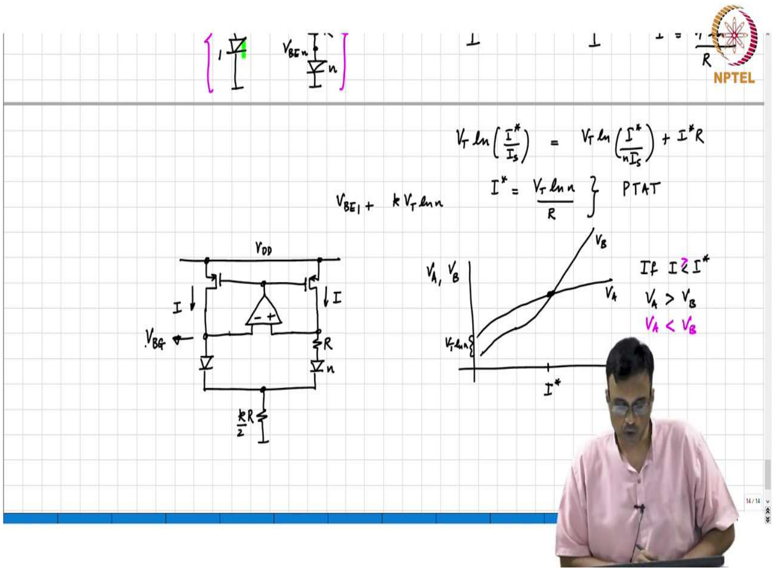

So, for very small values of I which will be greater I mean which will be greater V_A or V_B? V_A. So, V_A will look like something like this V_B, for very small I will be this difference. For very small I will be V_T ln(n) because the drop across the resistor is very small. As you keep increasing I for large values of I which will dominate? The linear term will dominate. So, basically the curve will eventually do something like, right. So, if I is less than I* V_A is, this is V_A, this is V_B. V_A is greater than for and for I greater than I* V_A is less than V, correct? Alright. So, now if you are in the lab what will you do? You put a voltmeter like what Roy suggests then what will you do?

So, if V_A is greater than V_A will you put the voltmeter between A and B. So, basically if V_A is greater than V_B. It means that I am too low. I must increase I and vice versa, right. So, So, if V_A is greater than and how do you make two identical current sources which are variable of what with what transistor? PMOS transistors. So, alright. So, if V_A is greater than V_B we must increase I, correct. If you have to increase I what comment can you make about the gate voltage? Must be reduced.

So, if V_A is greater than V_B. So, you compare V_A and V_B. So, the voltage control gate voltage is controlled by the difference between V_A and V_B. And therefore, what kind of controlled source is this? Voltage control voltage source. How much must be the gain ideally infinity. So, even if there is a small difference you can go and keep the current in the right direction. Now, what is the direction? If V_A is greater than V_B the gate voltage must be pushed down.

So, that must be what must be this is negative this is positive, alright. So, this is basically just another way of deriving the same circuit, alright. This is the P TAT. Once you have the P TAT you can basically add V_{BE1} + P TAT in multiple ways, right. Yet another way is the following. What should I do if I want to generate $V_{BE1} + k\ V_T \ln(n)$? What should be the value of this resistor R x and where is my bandgap voltage? What is this current? $V_T \ln(n)/R$, ok. So, what is the current flowing through R_x?

Student: $2V_T \ln(n)/R$.

So, what should I make R_x? I should make it k R/2, ok. And where is your bandgap voltage? You can take it either there or that this is also a bandgap, ok. So, it is something you know you can come up with. Now, there are so many ways of adding the P TAT to the C TAT, right. So, you know this is basically saying I mean the approach here is basically telling you that one way of thinking about that P TAT current is pump the same current through a branch which contains a diode of size 1 and another branch which contains a diode of size n and a resistor R, right. In general the voltages across these two branches will not be the same.

In general the voltages across these two branches will not be the same, right. However, there is one magic value of I*, which will make the voltages the same and that magic value is? Is V_T ln(n) which is the P TAT current that we need, right. Finally, if you want P TAT V_{BE1} must be equal to V_{BEn} + I R. We want (V_{BE1} - V_{BEn})/R which is equivalent to saying that V_{BE1} must be equal to V_{BEn} + I R, ok. If you put an arbitrary value of I that volt that equation will not be satisfied. It will only be satisfied when that current I* that I is V_T ln(n)/R, correct.

So, the key point to observe is that at the P TAT point or if you want the current to be P TAT the voltage across this branch is the same as the voltage across this branch and the currents through these two branches are also the same. Does it make sense? Ok. So, one way to do this as we just did was to pump the same current and find when the two voltages are the same, ok. What can somebody think of an alternative way of doing the same thing?