CMOS Analog VLSI Design
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Lecture - 15
Current Sources

So, here we go. We were talking about the current and voltage references. We were looking for some kind of a current mirrors, and we looked into Wilson current mirror, and then we said it has a good resist output resistance, it has a feedback. So, it stabilizes faster and better. All that we did last time was the Wilson current mirror. So, let us start with the part ahead another current source which is very popular and one of the reason.

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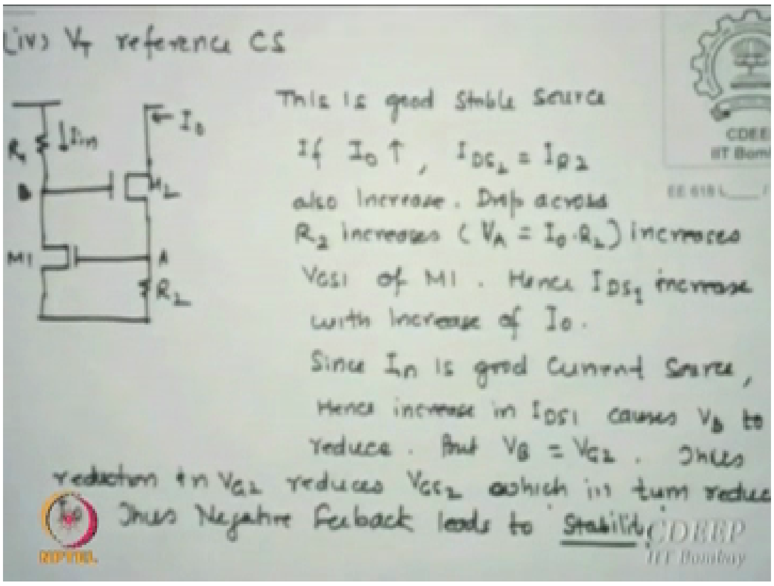

Why we said Wilson. There is a how much voltage across that will get; that is the resistance across. The source is very relevant in many applications. So, we want to see. Now there is another reference available in the book please take it this references, both currents mirrors and current sources, current voltage references are. I am actually teaching it from Li Boyce and Bakers book. So, some data if I am missing here you can go and look at that book

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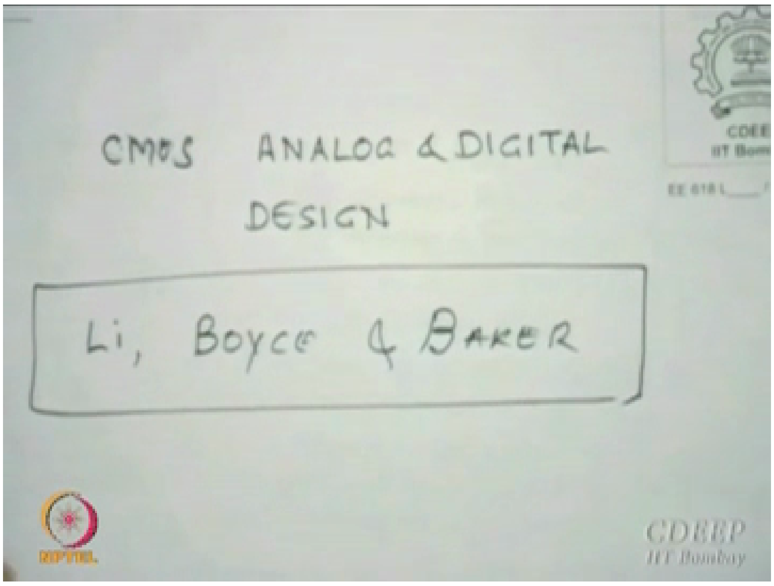

Exact title is not this, but roughly this Li Boyce and is that. So, as I said this is a good chapter. There the values given you essentially for very old technology 5 microns, but that do not matter. Actually the principle behind we can utilize it to any technology we would later. So, I start with the another reference, which is the threshold reference; that is called V T reference current source. The advantage of this is a, its a good stable source, if I 0 increases, we are done already in Wilson if this current increases the drop across this increases.

So, VGS of this increases. So, these current increases, this drop increases. Sorry this drop decreases, because of the saturation core point this reduces the VGS for this, and its feedbacks itself to a constant value as we did earlier. So, this advantage of this is that, it is a called stable source, and typically one has to choose this R 2 values suitably and. So, that the faster recovery is possible, is that ok.

Of course as I said this is only to show you what is the way we had done. This Wilson has done same thing, but its little slightly modified from, this is the Wilson mirror which we had said. There is no R 2. I think here we are given a R 2 drop which is VGS for the next transistor, and that changes the current in the other arm feedbacks to the from here to here, and keeps till that adjust to itself. So, thus it has a stability, because of negative feedbacks as we said is that ok.

This as I said, please do not worried all that, I have written it, because I thought maybe I should not miss what I have said, but other things you can read yourself. Maybe I repeat that the theory is this. Any change here is reflected change here, change here reflect back here and there is a loop going on there. This is the technique behind stabilizing the sources is that [FL]. This you can write which is the final version of output currents.

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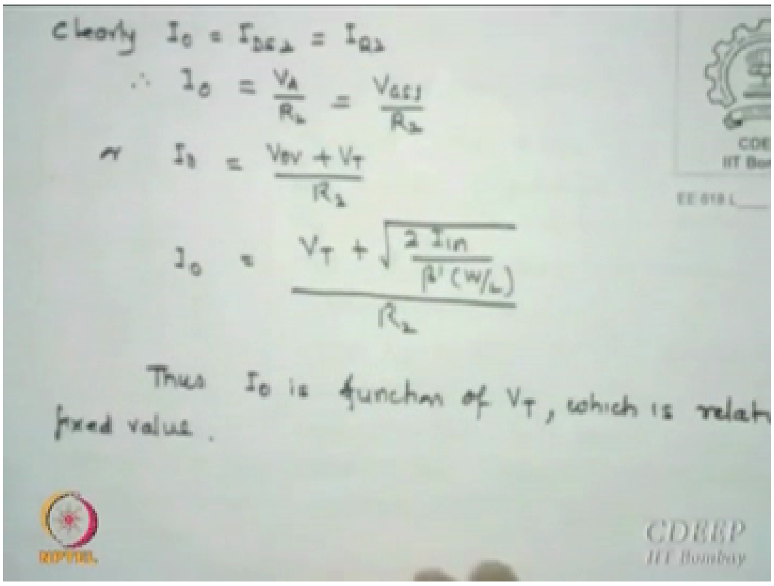

The output current is given by threshold voltage plus under root of 2 I n upon beta. What is this value, essentially; VGS by R is essentially the current is that correct, VGS by R is the current ok. So, that is written in the same form that is nothing very serious I 0 R 2 is VGS and VGS is written in this form. So, I 0 is only a function of V T, V T is normally fixed for a technology 0.8 volt 0.7 volt 0.6 volt whichever value you fix; however, its temperature dependency is not very good and not very bad either, but let us see how much we have done earlier, and we will not do this step for this, because the modified version of this which is the source I shown you is now shown. Have you written down this expression we are not going to use this.

Because it has a V T direct function temperature dependence both for R from beta dash and from thresholds. So, we will like to see. Can we improve the TCf for this source though it is what is the advantage of this source was stable, it is a negative feedback its stable. So, modified version of the same which has been created instead of the resistance, we can replace it by some diode or other, a current a transistor itself which is in active mode that is in saturation mode.

Just let us see anything which you think I have not speech. You please look the book and if there are still varies, I just want to finish this current, because next time I want to start with op amps. So, I am little fast today.

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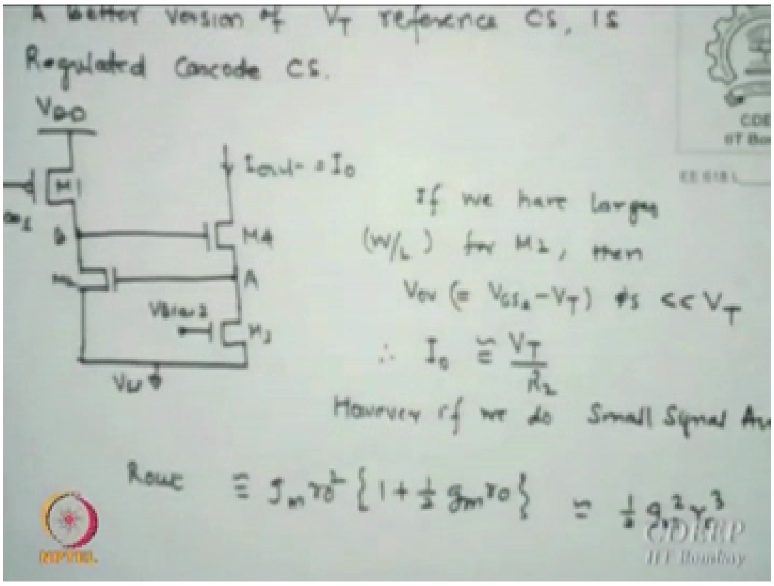

Please note down a better version of V T reference current source is called regulated cascode C S current source. You can see this, this part is same M 2 M 4 M 1. This is same, all that I have replaced is now R by A transistor which is biased by me to my choice which is this, but what will happen to M 4 M 3 combination. This is like a cascade. This is like a, what is the advantage of this circuit.

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Output resistance is boosted up. So, one of the major advantage of, major requirement of a good. Last time someone was asking what is good current source. The question asked was that whether it is temperature dependent, how small is temperature dependence, how small is the, or how large is the R out, and how much is depending on VDD variations. A good current source should have lower VDD variation. This lower VDD temperature variation and larger R 0s, those are called good current sources.

The current sources given to you an exam both are bad; because they are strongly depend on temperature as well as VDD. So, they were not good current sources. If someone has written good and forget, not then he is getting 0 on that [FL]. So, please take it these are the trivials, but that is how choices are made in real life ok. If you have seen this, I already calculated r 0 for a cascade, and if the ac output impedance is around g m square r 0 cube, assuming all transistors are same W by same lambdas. And if you look at the current, now it is VT divided by R 2, because the maximum voltage across this will be V T, and this R 2 essentially is coming from. Sorry the R 2 has been ok.

It is essentially trying to say whatever resistance offered here, is divided by V T by. This is the one, which will give you the current, which is equal to I 0. Now this analysis which we have done earlier, which all that it shows that it is stable, because its a feedback. Now it is only a function of threshold voltage whatever is given to you, only one temperature dependence and this is opposite polarity.

Because, please remember one interesting feature you should all remember resistances. Normally if you have learned earlier I hope. So, some of you have, it has a positive temperature coefficient; that is resistance increases with temperature, but all semiconductor resistors have negative temperature coefficients is that correct, mu is proportionality T to the power minus 3 by 2 is that clear. And therefore, the semiconductor resistances have minus TCf s, typically 2000 3000 ppm per degree centigrade

Like n plus transistor source for. If I use it is around 3000, if you use a poly resistor, poly doped resistor, it can be 2000. So, is that point clear. So, the resistor in semiconductors are my negative temperature coefficient, and that sometimes advantages, sometimes disadvantage, because both minus may add the other quantities plus it may actually subtract ok.

So, in that case semiconductor resistors are preferred over external resistance. You can always put in a board separate resistor. After all a chip is there, you can always put a resistor at the board, but that is never done is that correct. That is never done, because that will give you positive temperature coefficient. Its a carbon resistor. Carbon shows positive temperature coefficients. So, the same source slightly modified gives you better

VOV. VOV is VGS minus VT which is less than this. So, typically you can say I 0 is threshold by resistance, which you can calculate.

And you can see its R 0 is very high. R 0 is R out is very high. So, this is closer to what you are looking for, good current source is that. Read more about it. Now let us start with, this was the part which I should finished last time. So, I just now start with the real one, which I am now looking for, there I spend time.

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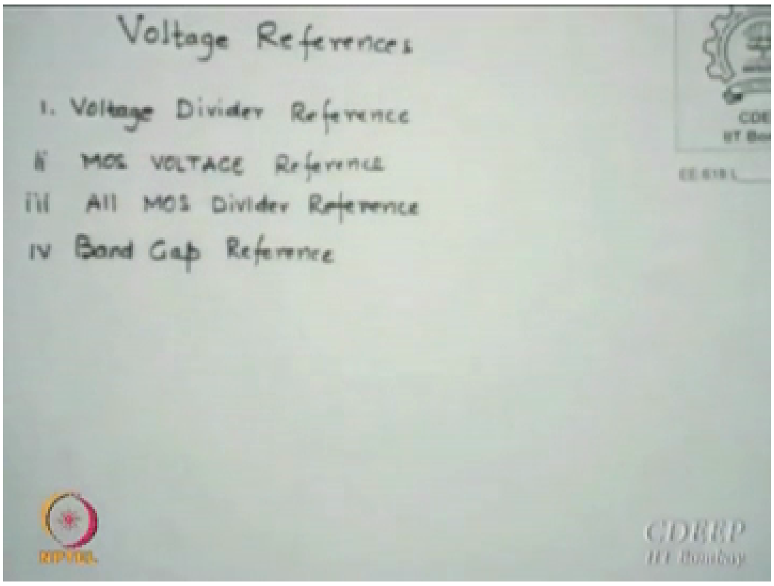

The other requirement other than the current source is the voltage reference, what is the, why it is called reference again. Because this voltage otherwise you take a power supply directly that also is a voltage reference, but what is the problem with those power supply voltages, because they will change it, all kinds of things by the load, by the VDD, whatever the inside transformers, all currents, everything will shift to. Though we may stabilize it, though normally most power supplies are stabilized power supply, but there is still a ripple on it, you cannot reduce it to 0.

So, a good reference DC source, because we are requiring now a DC output, which is strongly, which is very strong in the sense, that it does not change very much with temperatures, and it also is independent of each. Of course, the easiest reference how can you create by using resistors easiest. The first one voltage divider take 2 resistors take a tap out of it and that can still do the job which you are looking. So, this is a question for those who have, want to work with analogue later in future. These days all mixed signal circuits have analogue power supply as well as digital power supply, unit is created there. This is management, power management units, all chips have, they require 1 volt 1.5 volt, 2 volt, 5 volts kind of supplies they need.

And they use what they call as dc to dc converters. Questions to all of you, why DC to DC I mean if dc is available, just put a divider and take any amount of tax on it, but why do we create DC to DC converters on check to

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[FL] we will come back to it later. He has a point, but that has a cost on it, its not free, is it visible.

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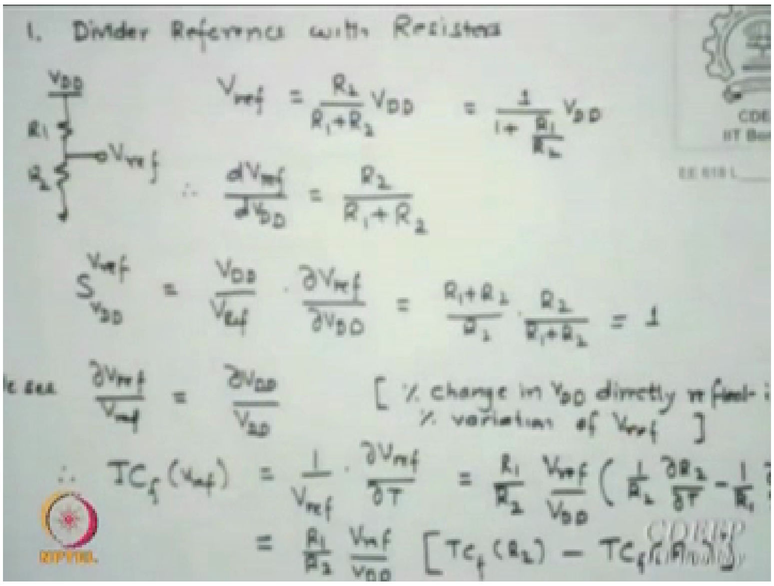

Yes, I have take care that, I remain inside, but you know its only my thinking. I am doing it the easiest reference. As I say its can be created by two resistance network, or what we call divider which is R 2 upon R 1 plus R 2. If I take d V reference by VDD then it becomes R 2 upon R 1 plus R 2 and if you take the sensitivity of V reference with VDD.

This is VDD by V reference, V reference which is unity. So, the sensitivity of reference voltage is VDD is 1, which essentially means every change, there is transparent to the V reference, which is obvious. You can see if I change this output is proportionately changing. So, there is nothing I can do about, because you are just using the divider part there.

If I do this dv reference by v reference; that is change in this percentage, this is same as this is. So, if we calculate the temperature coefficient of v reference. I differentiate this with temperatures equations. Then I get 1 upon V reference d V reference by d T is equal to R 1 by R 2 V reference by VDD, and this function, this is TCf R 2 minus TCf R 1. If you are making the same material resistance, the difference will be smaller, because this 1 upon R term is going to still come d R by d T may be same, but 1 upon R values are different.

So, these are not equals is that point clear. Other than sometimes you may feel why I am putting it, because 1 upon R d R by d T for will be for the same material, but 1 upon R s different. So, these two values may have difference. So, one of the criteria is this R 2 should be closer to R 1, but what does; that means, 50 percent shifts, nothing more. I cannot do 0.2 VDD or point. I have to do only half VDD kind which is not every time you may require. So, its a good to have simple divider, if you are only using VDD by 2, but it is a very strong function of change in VDD temperature vise, it may not be that strong function if you keep closer, but it still has a problem of VDD sensitivity is very strong with that ok.

So, let us look at it if this is not very good what should I do. I replace at least one of the resistor by a transistor is that everyone. This is trivial, all that I am going to. I was trying to say that its look to be simple, a problem it creates is only close to 50 percent VDD shifts only are possible, but even than its proportional to VDD as a variation, that has temperature wise you may probably minimize it ok.

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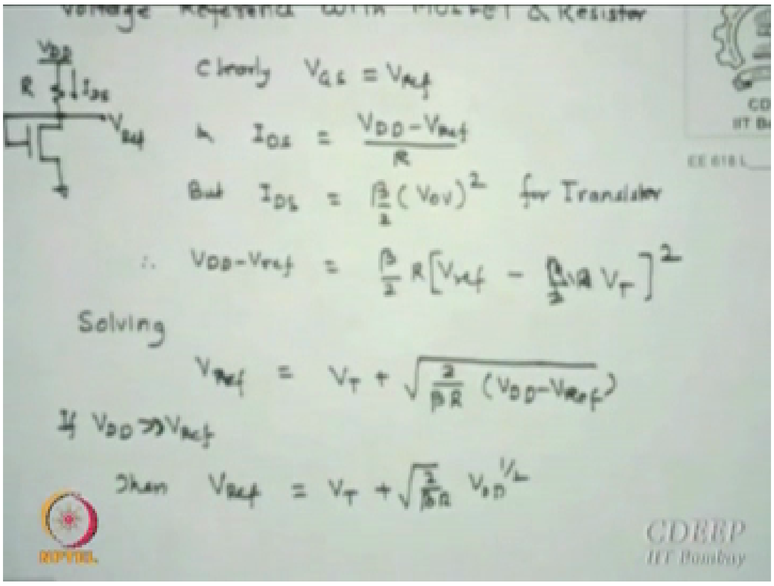

So, the next stage we replace the R 2 by a mass transistor in saturation, and we know in saturation transistor has larger resistor, but its value can be modified by VGS itself right have a slope. So, one can adjust and W by L s. So, here is, we have make the reference voltage is across the diode across. Of course, this is a diode connection. So, VGS is v reference, the current in the transistor is should be current in the resistor.

So, VDD minus V reference by R, but we know ids is beta by 2 VOV square for the transistor, assuming lambda to be very small. So, VDD minus v reference is something like this. So, I will, we get V reference as VT plus 2 beta R VDD minus V reference, still this V reference is there. So, let us assume VDD is very large compared to V reference. Then I can leave this V reference here, and I can directly write v reference is V T plus 2 by root beta R VDD by 2.

What you say this will be a good. You can directly say its a function of VDD, is that correct. It has a function of temperature. It is also a function of temperature through beta dash. So, as far as this dependency is concerned, does not seem to be a great, this divider. I mean great voltage reference for the sake of my, I have not solved it as I said I have taken it this from the Boyce, this of course, I have solved, but the next two formulas I have just copied I hope. So, I have done some rough calculation, I thought they are done correct, I hope. So, is that everyone wrote.

The function V reference is VT plus 2 root beta R VDD to the power half is the reference. So, how do adjust V reference value. Therefore, by adjusting the value of W by L, by adjusting the value of R, and of course, the supply which is given to you that will decide your reference volt. Please remember VDD is not in your hand, why technology will say 1.2 volt 1.5 volt 2.1 volt, whatever they say that is the voltage you have. So, we are no gain on VDD, but we can always look for beta, which has size R which is we are actually.

Can you know what this R could also be, instead of this another transistor, but which one you will prefer. There a P channel device is much easierly preferred, and then the ratio of W by L will give you these voltage output at this is that clear. Just replace the P channel device and gate connected to drain as usual, and then; that means, the same gate goes to these. So, it looks like more like a CMOS, but the input is connected to the output,because they are two diodes is that clear.

So, this essentially gives me this formula, and as I repeat, I have taken it from the book

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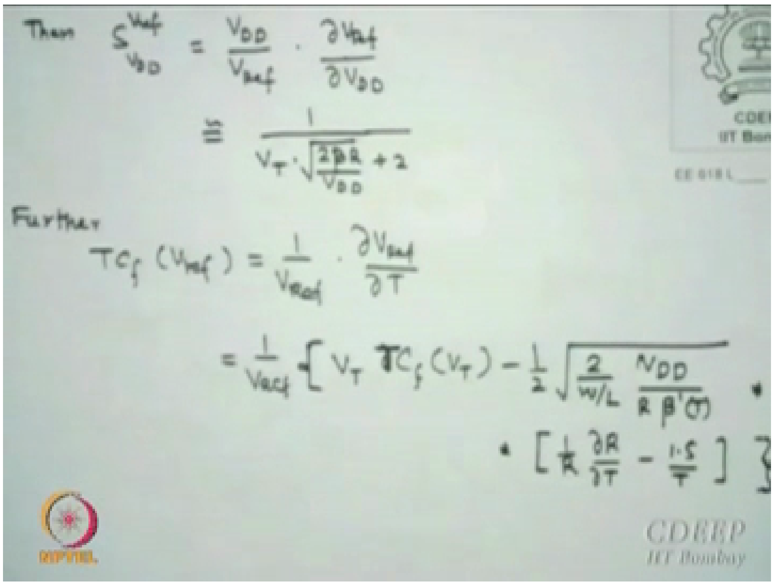

So I am not saying they are wrong, but the owners of right or wrong, with mister baker, not with me. So, it says that as V reference. Though I have done it, but in an hurry I did not know exactly, whether I roughly got same, but I just copied at the end (Refer Time:19:10) just differentiate very 1 upon this. There is nothing great we are doing VDD upon V reference D reference this.

And this comes to be VT times 2 beta R by VDD plus 2. And if you look at the temperature coefficient, this gives me a long expression VT times TCf VT minus half, but 2 by W by L VDD upon R beta dash T into 1 upon R d R by d T minus 1.5 by T is that correct. This 1.5 by T is coming from where, D beta dash by beta dash that last time we did in a class also, I forgot. So, I remember while going to main building that I am not given that detail to you ok.

Please remember one catch is which I said in the class. Also T is here in Kelvins. All other things are expressed in pared per million per degree centigrade, but when you divide 1.5 by TTS in kelvin. So, how if I divided by 300, how much it will be roughly, 5000 ppm per degree centigrade is that clear. 5000 I think, yeah 1 upon 1.5, yeah 5000 ppm per degree centigrade.

So, this remember that this number looks to be small, but that is giving you a huge value for you. So, do not think that it is neglected, 1.5 by T is equal to 5000 ppm per degree centigrade, which is huge number is that clear. And actually that is the one which observes most of it that is the grate one of this part. So, this also reference has, you can see though I have not done.

I may next time I show you a problem or maybe I will post it on the web, few problems on this. This still has 3000 ppm to 1000 to 2000 or 4000 ppm per degree centigrade TCf s, which is not contest less than 1000 or 1000 is acceptable or anything more than 1000 is not very good TCf.

If you can get along thousand or lower what is the ideal one. I want 0, I want 0. Now I try to see this word I say 0, can I really get 0, how can I get 0. If two terms one is plus and one is minus and I adjust the values of either or one at least. So, that the two terms has same value in opposite sign, then TCf can go to 0, and that is exactly what the last part of this todays. This will be what we call band gap reference ok.

And we will show you a TCf could be close to 0, it can met 0 also, but that W bias will be. So, odd, you cannot put it on the check, and therefore, you may probably not getting exactly 0, but close to 0. So, let us see. So, this is at voltage reference, no grate problems with this, making it is easiest of it, because anyway CMOS there is sitting, there just connect the gate to the output, and we have divider and adjust W by L to get the ratio you want.

So, it is the easiest divider this and digital circuit. This is very often used. Where do you think we use this. This divider is extremely useful in digital circuits, its also called voltage translator. The reason is, let us say [FL], but you are using a by CMOS chips also with. I mean by CMOS means Bipolar, and CMOS they are new technologies, rather old one which is re circuiting.

Now, therefore, called new by CMOS started in 1987-88 was given to be at 90s useless (Refer Time: 23:06) let us look at it. So, it has come back. So, in by CMOS, these issues may come that bipolar requires. For example, noise merge or shift point is around 1.2 volt from 0 to 2.4. For a supply of this, it may require 0.6 1.2 supply. So, you may have to actually get half of that equal to half of the other, is that clear. CMOS half should be equal to half of the Bipolar sink, which may not be same whatever we do. So, you need translators.

So, they are in all digital by CMOS circuits. A translator is essential, and this the simplest translator uses a CMOS divider. So, please check it why they are using it, because they are not really looking so much temperature sensitivity, because they feel volume 0 has enough margin for me, as long as four corner design I made, thank you very much kind of thing analogue goes heavy wire. So, we are worried there is that ok.

So, please remember these circuits which I show. Sometimes you may not feel they are relevant, but they are relevant somewhere else, and therefore, I thought I should show you. Now I show you another voltage reference, here is a better reference which is called boot strap.

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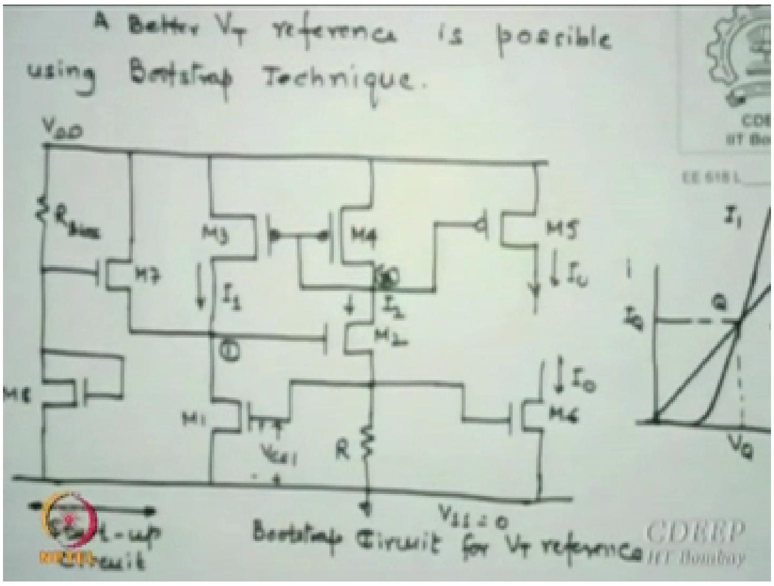

What is a boot strap, where is the word boot strap came from. So, when voltage levels are actually pulled up; that is why it is called boot strap [FL] one can see, it is not very different from threshold reference which we are done, all that is there. See M 3 and M 4 are identical ok.

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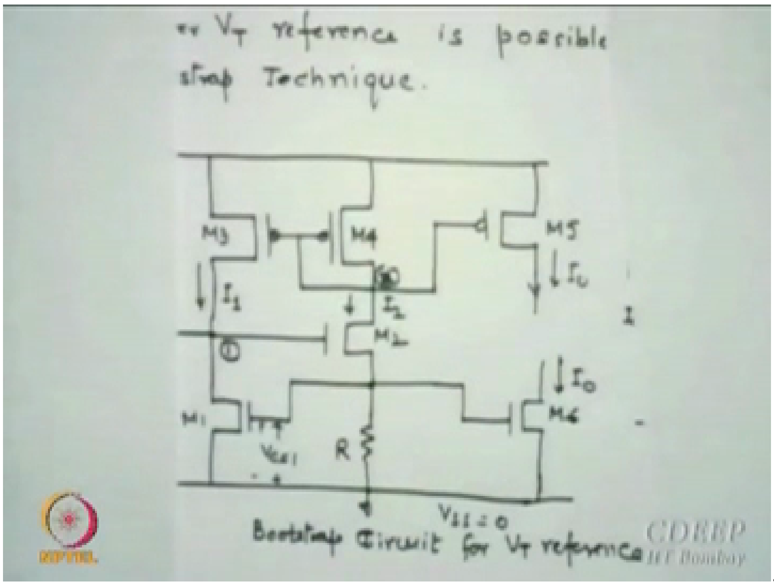

And they are connected in diode form here. So, what does that mean M 3 mirrors M 4 currents M 3 mirrors and if these are sizes are same current in M 3 is same as current in M 4. So, I have written current I 1 and I 2. In fact, I 1 and I 2 will be equal provided M 3 and M 4 are same W by L s same thresholds and connected in this fashion is the end therefore, it will mirror this current into this. So, then also I will put I 1 equal to I 2, but right now I show in two separate currents. Now this there is an other transistor, this is like a feedback circuit which we did just now is that correct. At VT reference this is same circuit. So, this current goes through R these are all gates. So, no current can go either side, this all I 2 will go through R ok.

So, it will create a voltage drop here, which is the voltage drop here [FL] and. So, now, you can see the current here is, because of VGS 1, and this is coming from here. So, they will again do a feedback, and adjust I 1 equal to I 2 at the end is that point clear. So, how much is the current I 2 VGS 1 by R is equal to I both, I 1 and I 2 is that correct. This is what we want to, we did earlier just that is repeated. Only difference here is, this is coming from P channel sources down, is that if problem starts what is the problem.

Now, if you see still you forget this. And these are outputs; one is current source, other is current. Since this is N channel, this is P channel, just connect it here. I have connected from here, you can also extend this here, because they are the same terminals. Now sometimes I showed direct line, sometimes this. So, I just thought. Now let us see, is that. This currents are this currents, and they are transferred to M 5 and M 6, and right now they are W by L s are same as this, is same as this, and this is same as this, and therefore, same current is flowing in N channel, as well as in P channel.

Please remember I can make that difference if I need. What do I do. I increase the size and I have the other currents possible, but normally I may suggest you as an example, if I want two I 0 current, I never duplicate double base transistor, what do I do. I take another n and put it double think of it. Why this itself is not doubled, but we have another gate. You put another transistor there sinking with 2 W by L s, why preference is given to separations, this is thinking.

Now, let us say is that figure. So, I will start looking here, I already said, let us say I 1 and I 2 are mirror. So, equal I 1 flows through VDD to VSS and M 5 and M 1 I 2 flows M 4 to M 2, which is what I am saying, this going here, this is going here. So, VGS 1 is I 2 R.

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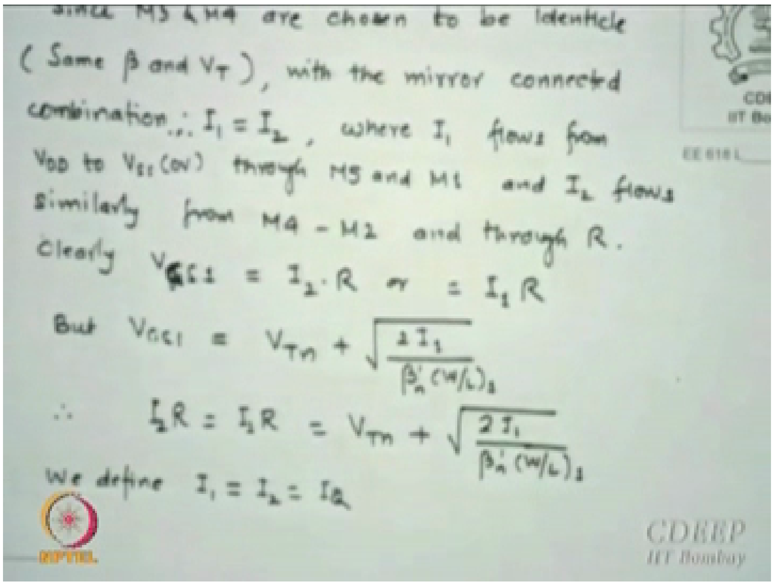

Which is same as I 1 R, same as I I R. You can say that I Q R, let us define a current I 1 equal to I 2 as I quiescent. Why I started using Q word now, because this is DC current. I am going to bias next circuit for your choice is that correct. So, it is called coercion currents. So, I 1 is equal to I 2 into I Q, and if I write this expression for VGS 1, which is V T n 2 I 1 upon this and if I 1 I 2 this I 1 can be replaced by I Q. So, I 1 R drop is V T n plus 2 I I 1 or I 2 right, which is upon beta and W by L dash upon 1 ok.

So, I now have an equation which can be derived simply by VGS equivalence equal to I R drop, is that from VGS 1 is same as I R of the drop across the resistance. I repeat those who have not, the drop across this is the voltage here. So, there is nothing seriously we done so far. So, I got this expression that I R drop is equal to V T n plus 2 I upon beta and W dash l. And once I get this expression, then I am going to write, figure it out. Please remember I is here, I is here. So, what is it means, when I calculate such things it may lead to a, what is called, which kind of equation leads to quadratic or essentially, its called transcendental. So, what is the problem in cardinal? There is a non-linearity, and since there is a non-linearity quadratic always you can solve because, this is first order non-linearity.

So, its much easier to solve, but in second order, third order, you can only do in numerically. And there is no other technique, very simple Newton Rapshon to many techniques are available to solve this transcendental equations is that drawn everyone. So, I write; therefore, I 1 I 2 is equal to I Q.

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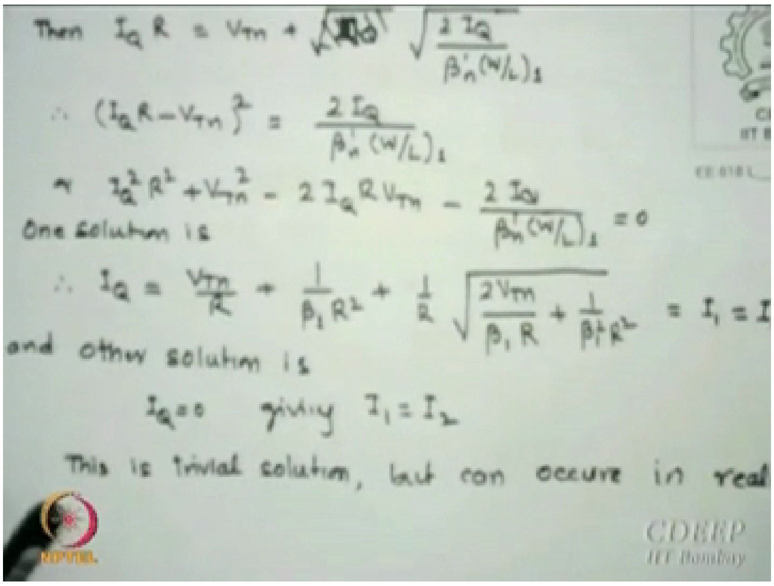

I Q just I substitute I 1 equal to I 2 equal to I Q. So, it is I Q R is VTn plus 2 I Q upon beta dash W as 1 I expand this square root, and this I get this kind of so called first order non-linear equation, or a quadratic term. And if I have a quadratic equation, I can always solve this equation by simple quadratic nature. So, the first solution is minus V under root plus minus under drop plus minus B squared minus 4 AC by 2 a same solution [FL] 1 V T by R.

One upon beta 1 R square plus 1 upon R under root of 2 V T n beta 1 R plus 1 upon beta 1 square R square, but the other solution also existed to this. What is that solution. I Q equal to 0, also has I 1 equal to I 2, but that solution we call it as trivial, but this trivial word is good for mathematics, but in real life circuit may actually enter trivial point, and there is no way, once those voltage is in feedback, you have put it and both are 0. Nothing can be done, circuit will remain switched off, even if power supply is on everything is on. So, you may land in this situation at the start. Sometimes not necessarily, but you may start is that clear, in case it is there. So, how do we start the current source then, or how to create a reference then ok.

So, I must actually noise come out of that 0 situation is that clear. So, essentially I 1 equal to I 2 equation, what I wrote. You write down this, and I will come back the figure again. So, it will be very clear to you is that figure or expression drawn. So, we come back. Basically what was they trying, this VGS 1 we wrote getting equal to I R is that correct. So, if I only draw this line I versus V and I draw this line straight line I 2 which is V is equal to I R. So, a straight line V is equal to I R is a straight line, and if I see a current through this VGS, because of VGS 1, it has a square law. So, this current is because of the transistor, which is giving me VGS 1 and when they are equal.

What do you mean by equal? These two intersect; when they are equal they two intersect. So, this is the point where the VGS 1, and this are matching, and therefore, Q is the bias point which you are getting corresponding to this V Q and this I Q, but I just now said I 1 equal to I 2 can be attend at this point one is this, one is this. If that happens then the circuit will never start, because it does not have any voltage to show in the voltage, because why it does not change, because there is a feedback. There is no feedback open loop, it will. It is trying to adjust whatever value we have got it. It wants to retain those values; that is the problem with feedback that stable. So, it makes this point as much stable as this point. So, we are closer here, we will sit here is that correct. This feedback word is good for staminatity fair enough.

The situation is here. We are now landing in a stable point here, and no way, unless you physically change the value. This can move from here to here, and the circuit which does this, is called the startup is that correct is the word clear; startup. A startup means if you are peruse here, then it should change the voltage. So, that I 1 I 2 start flowing, but no current is flowing; obviously, it is VGS. There is nothing the voltage have such that everything is 0. So, this potential is also 0 is that clear. No current open arm is [FL]. Now if this is our 0 when the startup starts the way of startup circuit is, this is R bias, this also can be replaced by what.

I can always replace this like this. Its a diode, essentially I am making a diode drop VDD minus diode drop. So, there is some potential, which is larger than. I mean smaller than VDD, but I am adjusting that. So, that this one diode drop gets VGS here. This potential is 0. Now is that, then everything is 0 this potentially at 0, this potentially that positive value. So, what is it creating a VGS for M 7, which is larger than threshold VGS for 7. So, will be VGS for 7 is larger than VT. So, what it will start doing M 7 starts conducting.

As soon as M 7 starts conducting, the I 1 starts flowing down, because this current has no path here, no path here. So, it starts conducting through M 1 is that correct. As soon as M 1 starts conducting, what will happen to VGS. It will appear. Now VGS by R will appear in I 2 other side, once this sets are some this, now there is a feedback and this voltage will start rising as the VDS starts increasing is that clear. As this voltage starts increasing this potential is less 1 VT, not 1 VT above node 1 voltage is that correct; that means, M 7 will switch off is that correct.

Once M 7 switches off. Now I 1 and I 2 where feedback paths are taken care, and whenever they will be become equal, you will reach stable point of this. So, is that correct. Yes, let us us say initially this was at 0, when both currents at 0, this is ground or ground. So, this is 0. So, there is a VGS sufficiently have, because only one diode drop was taken out of it. So, VGS was larger than VT for M 7 is that correct.

So, M 7 conducts means, it pushes the current in M 1, whenever current goes into transistor. What it shows VGS; otherwise I cannot have current inversely, saying apply VGS to the current, force the current so it create VGS. If VGS will increases, because I 7 is going through this drop increases VGS by R current flows, but this current is essentially taken from this arm current, cannot be in hanging, is that correct.

So, I 2 starts flowing now I 2. Whenever I 2 this drop and this feedback will keep pushing VDS of this transistor. So, that these two currents are equal a way. This values are adjusted, that at the point, where you reach here VGS minus VT should VGS, should be slightly lower than VT. So, that M 7 switches off, and switches off, where, at this point, is that clear. Now we say once M 7 switches off, it does not participate why, because ones the circuit is on, this remains off, for say, because of some reasons of fluctuations comes, other it start change in currents, then it will start pushing the current from here, and again bring it to I Q, is that correct.

So, you achieve a stable bias point by putting a startup. And once startup occurs, it does not participate in the remainder current source behavior, is that correct. So, this is the feature of a, why it is called boot strap. Can you think I am pulling this voltage up boot strap [FL] whenever I need a V, I am supplying a VDD, but I need two VDD surface. What do I do? I must hold somewhere earlier VDD on a capacitor, and the lower transistor should switch of them becomes to VDD ok.

So, boot strap can actually pushes the voltages like a doubler kind of thing to more than VDD. Where do you think, you need double more than VDD, you need for a short time transience, which will some other time. So, this point is stable now, and therefore, you have a good stable I Q V Q situation. And one can say now that this circuit only participates till I N I 2 becomes equal, and reaches this value. And once that happens M 7 switches off, and therefore, the startup circuit does not participate afterwards; is that clear.

So, this is only as long as the circuits are, we are not here otherwise its. So, we are not bothered about, you know it continue to hold their what it will not. It will automatically switch it off itself, but pursue any environmental situation it goes, it will start to pull up again. So, its some kind of a feedback, second feedback. If there to make output reference as much constant as possible, is that correct; and that is something what this boots strap circuit is famous for.

There is another reference which is very interesting and I thought it is for similar forms, but very interesting.

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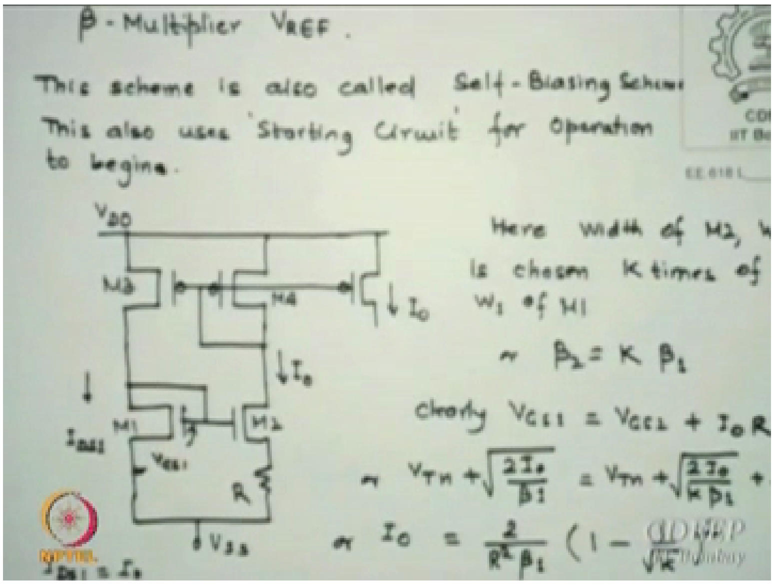

This is called beta multiplier v reference. What is beta multiplier means? So, something to do with increase of betas and some word is shown here. The kind of circuit I have shown here also requires startup, will not shown. It is identical similar circuit. So, it will also requires startup. This node does not become as it should. So, right now I am not showing the startup, the startup does have exists on the left.

Now, this is very simple one p channel mirror and one n channel mirror connected with it, Wilson like resistor sitting here. So, why are we? So, keen about this, we are interested to find this circuit is used, what is called as self biasing circuit; that is used in biasing R 0 is created from this circuit. What is the requirement of a good circuit reference.

It should not change with temperature in specific. Of course, should not change in VDD. It should not change with temperature very much. Any good word means the variation should be small, whatever variation you are looking, thermal is the strongest of them. So, that people more worried on thermal part, because why thermal part is worrisome, because chips starts getting heated. So, the thermal variations are immediately (Refer Time: 42:27) ok.

In analogue, even it is worst, why I s are higher than digital. So, I square R is even stronger. So, more temperature likely to rise in analogue parts than in digital. So, there is why we say look in to constantly temperature worry, worries all that we did here. If you are drawn the figure, this is now output current, this is my current in this arm, and if there M 3 and M 4 are identical I 0 will also flow as you know M 1 arm.

Please remember M 3 and M 4 are identical in every respect VT and W by L s both are P channel device. So, they sources current I 0; however, M 1 and M 2 they are not 100 percent identical. The only difference is VT. Of course, is same, but the size of this is some K times size of M 1; that is the why I never say W by L. What should I say really, because lengths have normally never change, unless you need specifically; otherwise only widths are change. So, widths of M 2 is some numbers K greater than 1. Now you can say always say 0.8 [FL], but I my assumption K is greater than 1 ok.

Now, you can see from here this voltage VGS 1 is VGS 2 plus drop across resistor, the way diodes are connected, or way M 1 M 2 are connected. So, I say VGS 1 is equal to VGS 2 plus this drop, is that correct. So, VGS 1 is VGS 2 plus I 0 R this, but we know VGS 1, I can write as VTn plus 2 I 0 by beta 1 VGS 2, I can write VTn plus 2 I 0 by K times beta 1, because now size is double K times W 1. So, why I do not have to write beta 2 I write K beta 1, and then I 0 R collect the terms of I 0 by quadratic equations, and roughly maybe I should say to great extent this may come.

But roughly 2 upon R square beta 1 1 minus 1 upon 2 K is that I 0 is 2 upon R square beta 1 into 1 minus 1 upon root K to the power square, this VTn cancels [FL] exactly. So, what should I calculate. Now for this current this source, the TCf, I like to see temperature dependence of this current source, [FL] the VGS 1 is essentially referred. This is taken out, and that should remain constant with temperature, is that correct; V VG O was one is the reference voltage, is that clear; VGS 1 is the reference voltage ok.

So, let us start. So, which resistor I should use madam. If I want larger R which material I should use; n plus is the smallest resistor I can create, because doping higher means conductivity is higher, resistance is smaller. If I want larger R, then what should I use; poly silicon I do not know whether you are reached poly silicon in mos silicon gate technology in your technology course, but do look at there the gate is automatically will diffuse, same as source and gain, and N channel device, it will become N plus in P channel, it will become P plus. Of course, it can engineer that also can be made N plus if needed ok.

So, this expression now I come back and show you on this, let us say I am using poly silicon layer doped to N plus, if I want higher resistor. So, what should I do? Two ways I can create higher resistance in poly or any region [FL]. Please remember resistance is created [FL].

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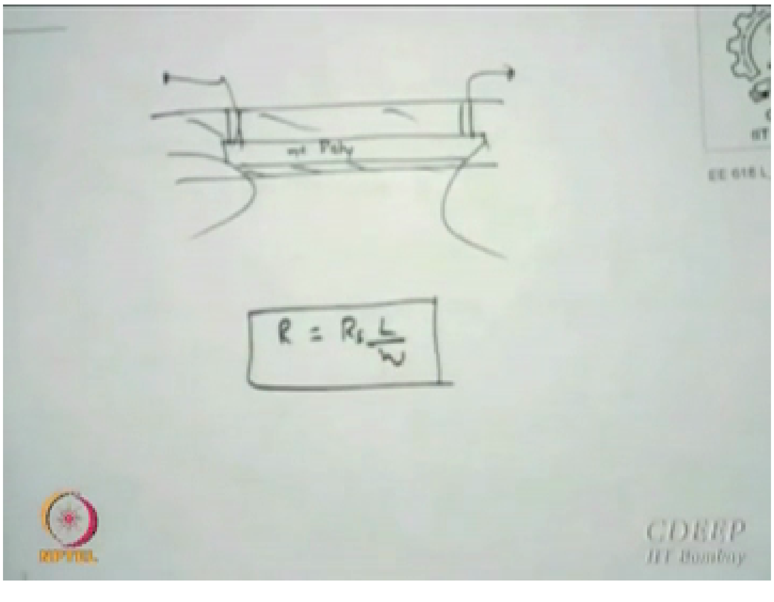

This is how resistors are made. So, in a, this is poly N plus are in it. I can separately dope poly, what will happen then. What is the extra thing that I have to another mass, because only for these polys R, I will have to open and rest, I have to close in a lithography. So, additional mass few million dollars [FL], generally even if its, we want exactly resistance have value. We can always create poly has a heat resistance of 10 to power 8 ohm per square which is very huge ok.

So, I can create mega ohms of resistance in fact, but if I do that, I have an issue; that I need another mass to create different resistors, different kinds of resistance, different mask. Means [FL] R is equal to R s L by W R s is are enough length to width ratio. I want to keep small so that the area is small. So, that is how heat resistance is R s is decided by the doping in the poly. So, R s known to us for that dope poly. Then you can adjust length width, get your exact resistance values, you note directly with R s. You only play with length and width ok.

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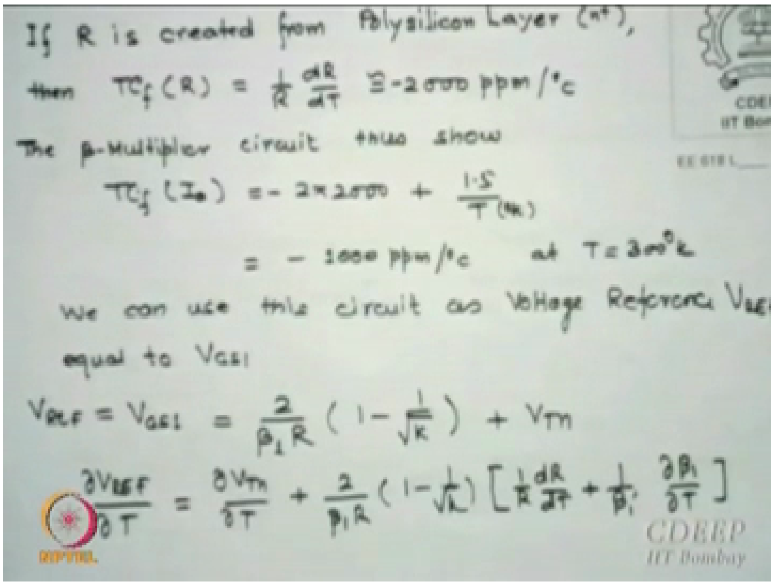

So, this part which poly silicon layer TCf R is 1 upon this. Typically it is minus 2000, this is for n plus poly in the CMOS, that gives minus 2000 ppm per degree centigrade, as its TCf for the beta f multiplier, beta multiplier circuit, just shown for that I 0, which I wrote. I can get TCf of I 0 is two times the TCf of this plus 1.5 by T [FL]. So, it gives you T into TCf of R or 2 upon R d R by dT plus 1.5 by T. So, now, this is 2000. So, it is minus 4000.

This is 1.5 T is around 5000. So, sorry this will be plus. I am sorry 5000 minus 4000. So, you have 1000 ppm per degree centigrade as TCf for I 0 at 300 degree kelvin. Now very interesting thing I am going to, how you, why with term multiplier became very popular, also how much is TCf, around thousand; that means, reasonably within your limit. Not it preferably I want how much 0, but at least it is not 0, but not very bad.

So, P reference is taken from VGS 1, which is 2 upon root beta R 1 by K plus VTn and differentiate,-+ this with temperature V reference value. So, I get T VTn by dT 2 beta I M R [FL] that expression anyway I have written to some extent 1 upon V reference time [FL]. Now one can see from here if I want this term to be 0, what do you see from here [FL] 1 upon V reference d V reference by dT is TCf, is that correct, but I if I want TCf to be small as 0, I want v reference differentiate with temperature should be 0. Now we have two terms, the threshold voltage goes how much, what is the way I said how many millivolt per degree centigrade 2.3 millivolt per degree centigrade minus is the threshold variation with temperature. So, you know this, you see the values put here.

And yeah we have another term which is R and K two parameters in your hand R. Of course, is decided, deciding your VGS 1 also that is reference value, but for this two together we are. Now we can fix this value and fix this value to its minimum preferably 0, is that correct. If you do that we say TCf of V reference will be small R 0. So, is that point clear.

Why we choose this one, because we figured it out that these terms I can correspondingly adjust; such that V reference can dv reference by dT could be smaller is that point clear. This is the feature of beta multiplier circuit in which TCf could be minimized, even better control of this, is what the next circuit, and which is the most popular circuit in the case. What is that reference voltage circuit, which is most popular for analogue people any name.

Student: Band gap.

Band gap reference why this word band gap has come [FL] 1.2 normal [FL] since the reference voltage you get, is typically around 1.2 we call it band gap reference. It is not directly function to some extent, it can be brought from N I square term, as well E to the power minus e g by K [FL], but basically the idea was that the value you get, is very close to the band gap of silicon, and therefore, we say it is band gap reference, what should be the advantage of band gap reference.

It should be seen from this formulas, it should have lower temperature coefficient preferably 0. No variation is VDD and 0 variation with temperature, if that happens you say you have created a good voltage reference. Why do we need a good voltage reference raj [FL] what kind of biasing. So, far we are showing for you only by current biasing [FL] you need a constant voltage which is generated VDD is not good this. So, I want a good reference which is constant. So, reference voltage is an essential part of any analogue chip it is separately created used is that correct and that is called band gap reference. So, let us look at it.

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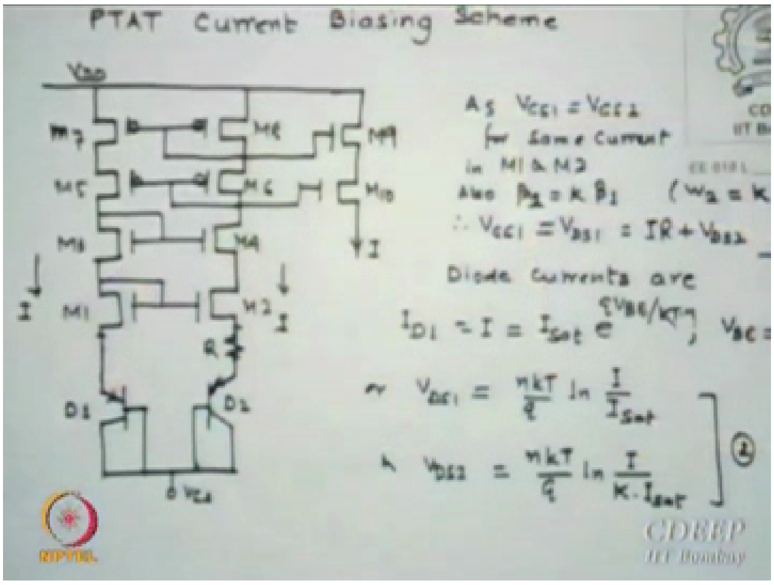

What is P tat. P stands for proportional. Yes T to 2 proportional to A stand for absolute, T stand temperature, P tat proportional to absolute temperature; that is whatever value is V reference is directly proportional to T. So, its called P tat, this is going to be the part of my band gap reference. So, I thought, first let me show you the P tat itself. This itself can be used as bias current refer biasing, you can see here. I can use this itself as a current biasing circuit.

Student: (Refer Time: 55:49).

Your point is well taken I said this is a part of this circuit, which I am going to use in the band gap reference ok.

This does not have good TCf anyway, is that. Though it is not very bad idea as you are thinking you calculate that proportionality, is much better than analyze. Now look at it this is how many? Whatever these four looking for you, two P channel current sources and two N channel current sinks two P channel two N channel, is that correct. Then this M T below M 2 is again K times as we did earlier. M 2 is K times M 1 as far as widths go. There is a resistor R here [FL] thus its R can be check something else. We put two diodes, we put. Why do I show you this kind of diodes?

Because in technology there is always a parasitic transistors sitting N P N P N P [FL] if you see a CMOS process, there are always transistor sitting there. The problem there is they should not turn on. So, we take care that they never have a beta of more than one, less than one, it should be, but there is a transistor sitting there. So, if I connect base collector, then I get a diode which is base emitter junction [FL]. This I can recollect base emitter direct. I can have base collect base emitter and open collect or short it. There are three possibilities which I can do is, base collector junction a collector [FL] when I want higher voltage break down systems, I use base collector junction, base doping in a collector, when I want a smaller base, I use base emitter junction.

So, I need a smaller values. So, I use base emitter junction as the diode here anyway, as I said this is your choice, but I am just trying to show this is how one dugs. So, these are two diodes; D 1 and D 2. So, now, you can say again VGS 1 is this drop plus this drop [FL] is that clear. Please remember [FL] I remember, I must tell you this potential is VGS which is same as VDS, this voltage plus this, whatever is the drop here must be equal to this voltage.

Plus this drop plus this voltage, but these diodes are taken identical. So, for practical purposes, this must be equal to this plus this, is that clear. So, I wrote it, but i; obviously, I has not clear. So, I repeat this potential is this or this equal to this potential plus this, because drop here and drop here is same. So, reference [FL] they are equal. So, what is the diode current. Now here is that diode [FL], a diode current is I saturation Q to the power V V by N K T, and if I say V B for this is nothing, but VDS for the other one, which is same as just now I said.

So, I calculate VDS 1 and VDS 2 from this diode currents. Please remember why I am make it K here, because M 2 has a size of VGS 2 has a K times beta, one has the value of beta 2. So, now, I calculate drop here, I calculate drop here in terms of saturation currents. What is M ideality factor, how much is the ideality factor. Normally I should be used for silicon diodes [FL] one, why one, because we are in diffusion current limited situation. You are neither in high current site or nor in generation site. So, in between E to the power V B by K T only N is 1. There if you are in a very high injection stage, it becomes 1 upon 2 K T.

If you are in a very low current state which is generation state, and again Q V by 2 K T ok otherwise most cases N A is 1 percent silicon. So, if I substitute 2 in 1 then I get n K T L N R S are equal to n K T by Q L n R by K I set plus R R n K T [FL].

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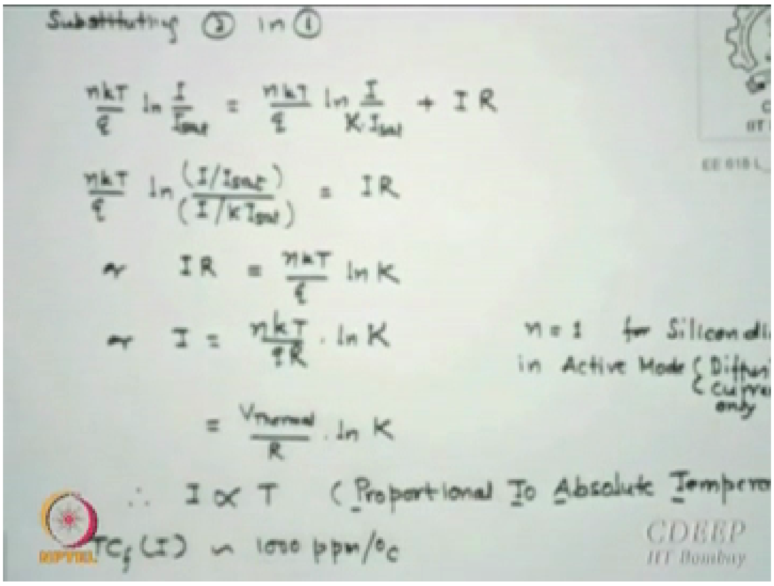

So, I get I is equal to n K T by Q R L n K k T [FL]. Many books write V T like bias writes for n channel P channel, he puts V T M n V T P T to separate from this V T, but mangier time I do not do that. So, I have wrote full name V Thermal K T by Q. So, I get, now the current in the P tat circuit output current is V Thermal by R L n K ok.

V thermal is K T by Q. So, R is proportional to temperature directly proportional to temperature. So, this current source is called proportional to absolute temperatures, [FL] what is, that is advantages using this, where do you think use this sensor, thermal sensor [FL] is that clear. So, this is not useful as a current source, but it is useful as a same temperature sensor, is that correct; that is why the word came proportional to absolute temperatures, is that clear, is that. So, do not ask me [FL].

[FL] we are not using this as a good disk. So, now, this circuit is a part of my band gap reference, is that, should be is that point clear. Why I shown you this, because this is going to be a part of the next circuit and the advantage here, I keep saying is I is proportional to T, any scale you create. If its portion is much easier to draw and figure it out extrapolation is the easiest thing to happen. So, therefore, these are used as thermal sensors. Now here is the band gap reference which is most important.

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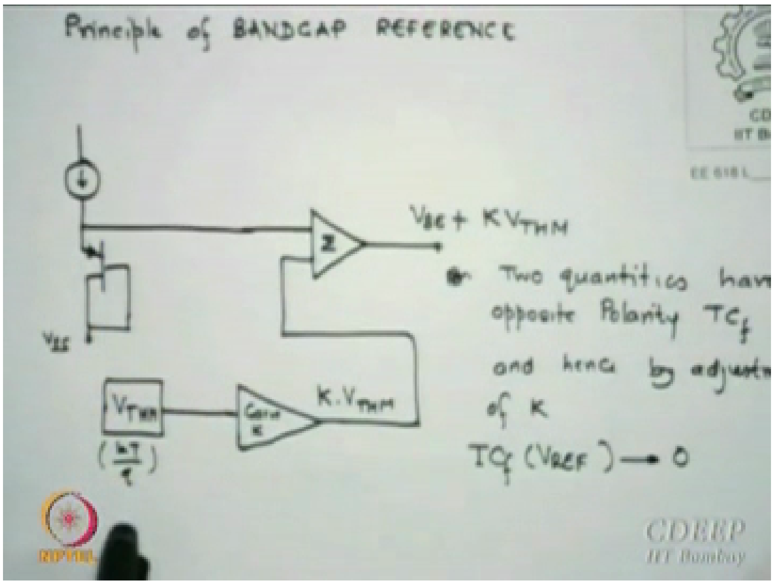

This is some K T by Q source V T H M you multiply a gain factor. So, it becomes K times V T M pass through an adder.

So, V B plus K V T M [FL] is that clear. This is the principle of band gap reference. Now the way it will happen the two quantities have opposite TCf in polarity. I repeat this and this have opposite in polarity as their TCf values, this is a function of K, is that correct. So, I can always adjust this one value. This may not be adjusted, but this value so that its exactly becomes equal to the other for its coefficient, is that clear to you. If that happens what will happen. TCf of this reference will be 0. So, ideal reference can be created, is that clear, is the principle clear.

Not that, this is how I actually I am doing it the principle is shown here, whatever V B is added with K times, the thermal voltage both have different polarity of TCf. This values TCf can be changed by K. And since I can change the TCf by K and value by K, I can adjust the value; such that the difference of TCf is 0; that is the trick in making a band gap reference [FL] is that task clear. Why I showed P tat, because I am going to use that P tat here in. Now for this thermal, I will create, from there is that all of you two parts have different polarities of TCf values, can be adjusted through K, and the sub difference can be made as close to 0. As is possible is it all of you. Now here is that circuit [FL].

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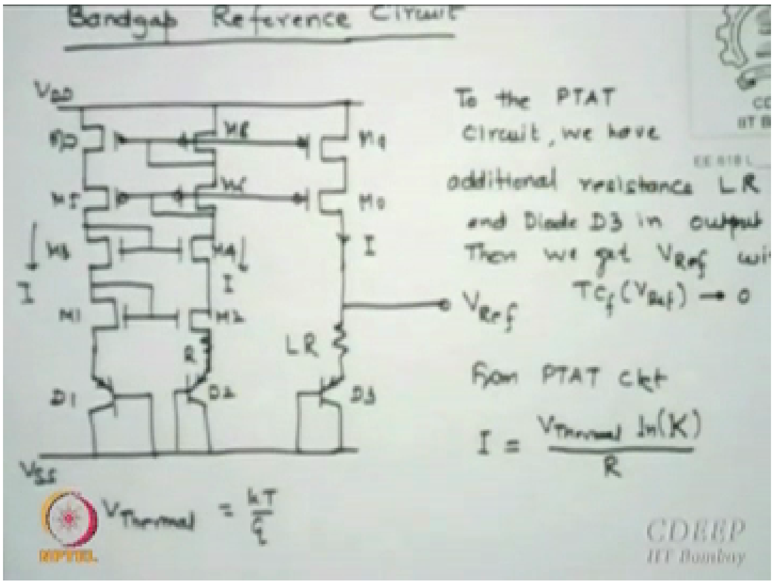

Already I now did in the output circuit, I put another resistance which is L times this resistance R this M 2 has a K times the width of M 1, but this resistance, is as it some number more than one of this, and there is another equivalent diode same diode D 1 D 2 D 3 which is kept here, is that correct. This is P tat and I added this much additionally.

See if I do this for a P tat, we just calculated I is equal to V Thermal l n K by R; that is the current in P tat. Just now we derived, where the V reference voltage I am now taking what is the V reference I am using, whether you can, right now show P tat only and put this, this we do not have to redraw all of it is that that P tat [FL]. So, to P tat circuit I additional diode D 3 and L R resistor series could there, and output is taken across. So, what is the output in V reference here drop across D 3 plus drop across L R is the reference voltage. Please do not draw this again [FL] or two diodes then plus this two.

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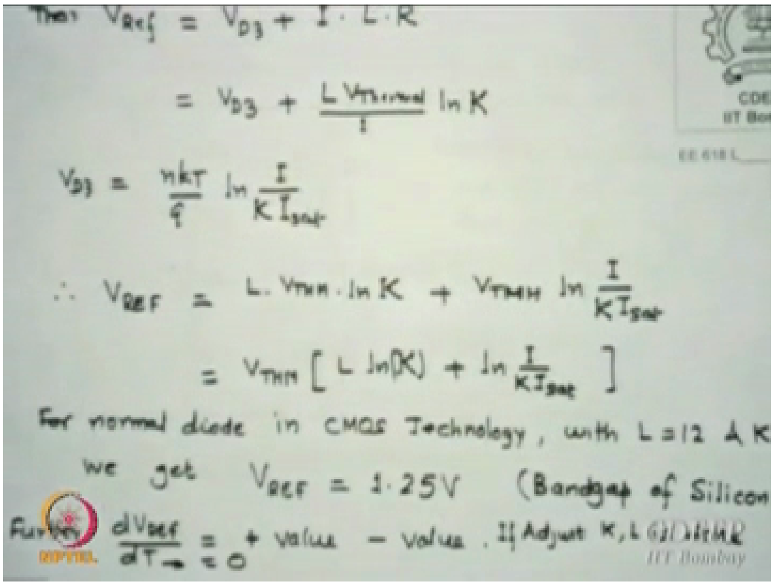

Then is it all of you. So, v reference is nothing, but the diode drop V D 3 plus I times L R the drop across the resistor V D 3 [FL] that R cancels R into R is R cancels. So, I get v reference is L times P thermal into l n K plus V Thermal l n R by K sat K I sat [FL] minus 2 millivolt to 2.3 millivolt per degree centigrade [FL].

[FL] change with temperature is minus the right side term is all positive. So, its thermal its proportional to temperature. If you have adjust l n K such that whatever is V D 3 coefficient, coefficient for l n K values becomes exactly same with the opposite sign, because this is minus, this is plus. So, TCf can be made 0, is that correct. So, what are the choices for us choice of l n K, if I use this reference value shown here, I have for a given normal CMOS technology. I normally use L f 12 K of 8 saturation is current of the order of 10 to the power minus 12 picoamps typical, I are used in micro amps, few micro amps, 10 micro amps, 20 micro amps.

I is typical of the order of 10 to 20 micro amps. Saturation currents is typically form tens of nanoamps to. Sorry 0.1 nanoamps to hundreds of nanoamps or not 100.100 of picoamps to hundreds of picoamps or 0.1 nanosecond nanoamps, K is typically around 4 to 8 L is typically between 12 to 16 and if I try to adjust.

Please remember if I adjust these values that TCf may not become 0 too much, because same values will decide by reference. So, please check it that reference voltage, how much accuracy you want. It maybe 1.2 or 1.25, anyway you need to a fix value. So, you better try for TCf to be smaller, as the first criteria of making this, because of large small 12 to 16 or 4 to 8, this value will not change other than the second or third decimal. So, its not very bad for anyway. Typical reference value which you get for, these is of the order of 1.2 volt, which is the band gap of silicon there for this is called band gap reference. What is the TCf value, as small as you think you can may be 0 in best case

Student: (Refer Time: 71:29).

[FL].

Student: (Refer Time: 71:37).

[FL] ok

Student: (Refer Time: 71:42).

[FL]

Thank you very much.