CMOS Analog VLSI Design
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Lecture - 14
Current Sources

And we will tell people come in let us see you what we are looking for, we are at the topic of current sources and sinks.

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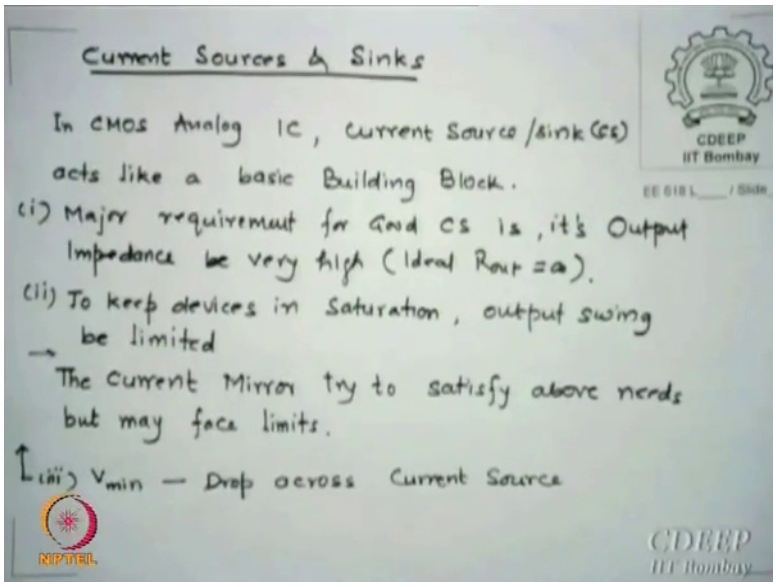

And we have said that in a CMOS analog I C, a current source or sink act like a basic building block. And there are 3 major requirements come from them one of them is that the output impedance should be very high, as high as possible also we must guarantee that the all devices are in saturation and also finally, their mirror should satisfy another limit which is essentially because the both source should have been minimum.

That is dropped across current source should be as small as possible. So, based on these requirements, we already looked into a simple current mirror and we also looked into the variation in parameters a particularly we looked into beta V T and lambda. Generally lambda parameter variations are very small. So, they need not be taken every time, but for the completeness we did take that and based on that we realize that, if I want to reduce the percentage error between the mirror sources and the output source output current then I must somehow manage variations as small as possible, but there are two

times one positive and negative. So, try to compensate them is that point clear what I said. So, really that word what I am saying the expression which we have derived. There is something that day may be I made mistake, but you can check it yourself again.

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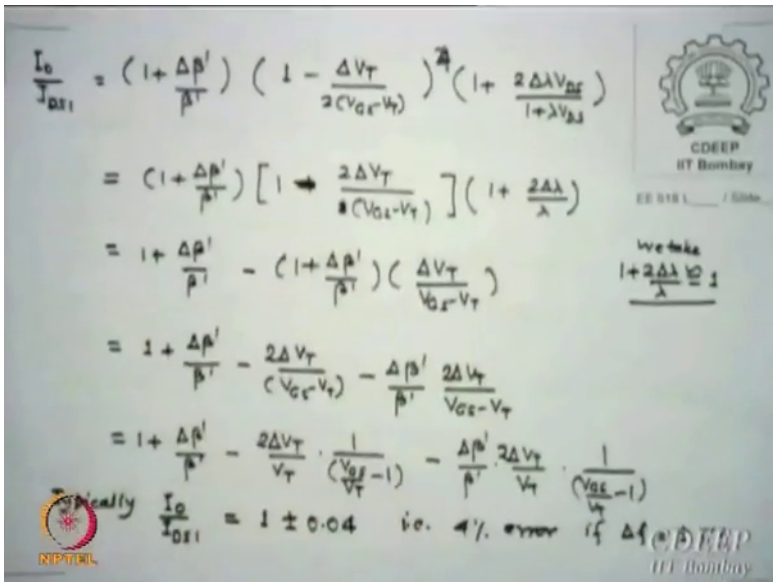

I have a feeling that I think instead of two below the denominator in my expression it is in 2 in numerator. So, this 2 should have something like that some error is do not look this expression look of course, there is a power to the power 4, leaving all higher order terms this is what typically you will get. And I said you that these are the two terms which are essentially governed by delta V T by V T, and there is a term which is delta b dash by b dash. So, if I want to make this as small as possible these two terms must be very close to this term is that clear. So, if that happens only you will tell you can adjust your lengths, widths you can also adjust V G S you can adjust V T possible and then you can minimize the effect of variations.

So, there is in case you need a very strong source with no variations one possibility that we can play with the parameters. So, that that can be minimized, of course 4 percent error is normally acceptable in most cases, but in case it is lower than that you require then you must somehow try to see whether we can minimize that delta.

Student: f

F is a function any of them V T or alpha beta or lambda whatever it is if any of the variation is 5 percent, then we find typically this is 4 percent error appears is that ok. You can see this is getting subtracted. So, it will be less than major error which is coming ok.

Ok so, this is what we did last time. So, today we start with as I say one of the features of good current source for mirror it show high impedance and it should have (Refer Time:03:58)ok. These are the two major features I want to attend and for this, I will start looking into alternative to simple mirrors and here is the first alternative.

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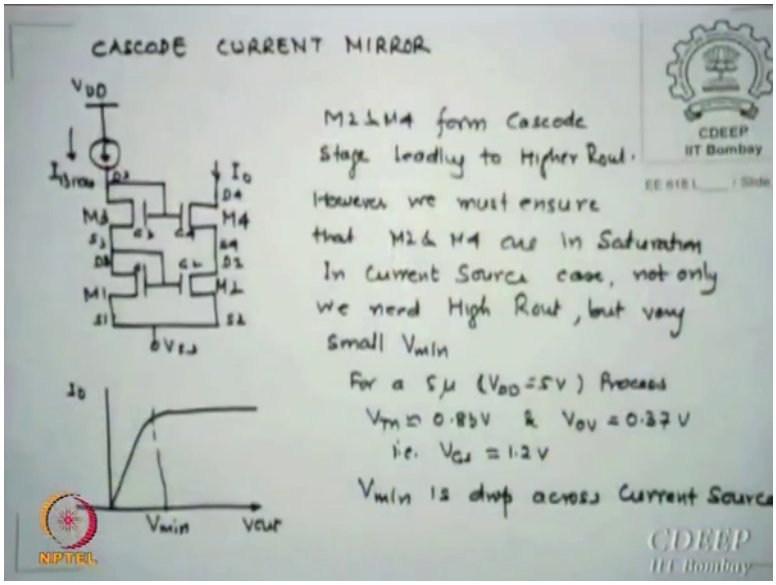

You already know very well that if you use a CASCODE what do you improve the output resistance. So, the one of the feature of a current source was you need a output resistance higher. So, use a CASCODE part there, so automatically all may actually go high or out should go high, we are also looking for minimization of this. So, we will see that how much we V min get, V min means at the output what is V min you are actually going to get somewhere here. And we will figure it out how much is the actually a minimum dropped across the source which is allowed. So, for example, I have said a typical for a 5 micron process which is given in by a bakers book say V T n of .83 volt over voltage of .37 volt.

That gives V G S of 1.2 volt please remember where is V G S minus V T if V T is .83 and if this is .37 V G S has to be 1.2 volt. Now we want to figure out what is the minimum drop across the current source for this data some numbers since we are going

to calculate I thought I should put the numbers this is taken from (Refer Time:05:25) book data. So, please check the numbers if there is something mistake if I have made hopefully not. So, I am trying to now use a CASCODE mirror, in which I have two stages you can see from here M 3 M 4 forms a pseudo mirrors and M 1 M 2 also form a mirror kind of structure and one is sitting over the other, but if you look at M 2 and M 4 and if this potential for AC is 0 this act like a CASCODE to that.

So, this get connected to the driver is that clear. So, we was trying to see that because of M 4 sitting over M 2 at this point the output resistance should be g one times (Refer Time:06:14) plus into I o. So, that little more, but that is the typical value. So, if I can get that value then I have improved my current source requirement R out should higher that possibility exists. Now we can see from here the way it is done this is a current source which you will actually put it through some P channel device later which is called the bias current which is our reference current. So, you see this button D 3 and S 3, V D S 3 you know since I am connecting something like this the gate of this V G S and this V G S is same, since I am connecting something like this V G S and this V G S are also same.

Is that ok, however please remember some fun part in that, this V G S has something to do with drop from here, but source is not now at ground potential but this source is at drop V D S across this. So, V G S may be same, but this source is not a ground this has to be understood. So, the gate voltage is not exactly at the ground for the upper ones sorry this potential and it is plus something is adding up, but net value of V G S has to be same if the currents are to be same. So, this idea that what will these two to and what will these two do can be figured out from example given to you. This is still a good current source there is nothing much you can do analysis, but what was interesting to me is this g s are only return to prove a very which is gate for 1 and drain for 1.

For example, the source of M 3 is drain of M 1, source of M 4 is drain of M 2 and we are interested in this voltage at the end, why we are interested in D 4 because that is the real minimum. So, we want to know what is that minimum in most cases the source. So, what is grounded and not connected to source they are generally grounded, but there are technologies in which it is connected as well. So, different than V S B effects could be taken care in case this is not connected directly, but through a ground if it is a ground that means, there is a potential to there some V T will move.

So, that part will be there right now I am I am not considering V S B effect, but that they can always be brought into the expressions, may be I will give an example when I have brought that expression is that ok. So, let us see the first thing I am worried about what is the V minimum part because R out I by intuition I know because I have put a CASCODE. I am going to get it higher, but I want to know what is the of course, I will calculate that as well, but first let us see what is the V minimum.

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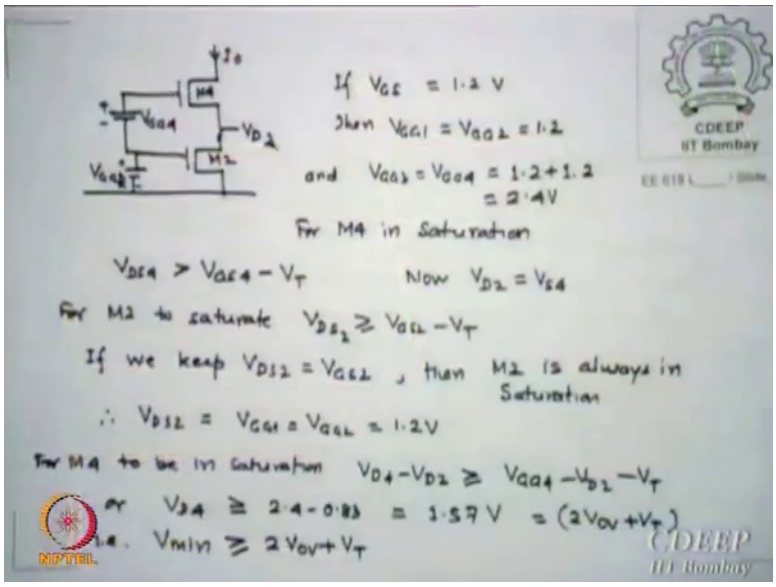

Let us say for the values given by those bias book V G S is 1.2, let say there are two batteries one is biasing this and one is biasing this, we could say there that V G G 1 which is same as V G G 2 this is coming from the mirror side, please remember this value is coming from the actual reference side. So, it is equivalently saying there is a biased to M 2. Please remember V G S 2 is same as V G S 1. So, I am just writing directly there. So, V G G 1 is V G G 2 which is 1.2 volt, because V G S has been given to me 1.2 volt. Similarly V G S, V G G 3 is equal to V G G 4 from the other side I please remember all that I am doing this and this and this ok.

So, this is equivalently saying the supply coming here. So, which is 1.2 here plus 1.2 here for that V G S so it is 2.4 there. So, for M 4 to be in saturation what is the condition M 4 will be always in saturation, the V D S 4 of M 4 should be larger than V G S minus V T for M 4 is that correct that is the condition which it should satisfy if M 4 to remain in saturation. Now we also now V D 2 which is equal to the V S 4 that is the source of M 4

is same as V D 2, let M 2 is saturate the V D S 2 or V D 2 of this should be larger than V G S minus V T of this two transistors should remain saturation. So, that the output resistance will act like a CASCODE structure and you will have mirror transitions in a anyway otherwise because this should be same as the other side current.

So, these are the two conditions and if we keep V D S 2 is and there is a condition we want to force, what is the minimum V D S 2 I should have. If this V D S 2 same as V G S 2. So, V G S 2 minus V T will be always smaller than V D S 2. So, transistor will always remain in saturation if this voltage is same as this voltage as the minimum value of V D 2 which allow transistor to saturate, if this equal to this, is they are equal then transition M 2 will always remain in saturation is that correct V G S minus V T will be always smaller than V D S. This value is going to vary with the difference of currents which I will pass through that this is a function of someone yesterday I was asking I am proving it yeah that may vary, but at the up to up to which I will allow it to vary the max minimum value which I should allow is V G S minus V T should be smaller than V D S will only occur when V G S is same as V T is that correct.

So, if that mean I am calculating what is the minimum I am not saying at a V O V, I am calculating what is the minimum possible available to me. So, M 2 remains saturation with V D S 2 equal to V G S 2. So, V D S 2, V G G 1 equal to V G 2 is 1.2. So, if I keep it 1.2 volt I am guaranteeing M 2 will always remain in saturation. I am actually interested to know what is this value just a minute because I want to see that upper value also should saturate the upper one. So, I am trying to see both together how much I will saturate is that ok. For M 4 to be saturation V D 4 minus V G 2 should be greater than V G G 4 minus V D 2 minus V T, that is V G S which is V D, V G G 4 minus V D 2 is V G S minus V T and this is V D 4 minus V D 2 is V D S for this condition gives me it should be 2.4 minus .83 substitute the values.

So, around .57 so it is 2 V O V plus V T, now this value has now come that unless I have a V O V which is equal to 2 V O V, V T I cannot ensure you now both transition individually V O V sufficient, but together in series I must attend this value. So, that the output of for which I am now calculating both transistor remain in saturation. So, that the minimum now I am now getting is 2 V O V plus V T where it will definitely yeah otherwise you should have to further increase if you want hundred percent guarantee on it, but what is the since V O V is .37 as you said. So, .37 into .74 plus .83. So, it is

roughly 1.57 volt which is required at the output is that correct as the minimum V min so that means, not really doing fantastic job because.

Till 1.57 volt this is not acting like a good current source that is the limit of this, but what is the advantage I got it this I have achieved it I had cleared out that, what is the value I would prefer it should be independent of V O V in such why should I feel it should be independent of V O V because if it is only V T dependent then I am controlling it. So, I will like to have a current source which is only strongly dependent on V D M nothing else no W bias the; if I get that value I am happy. So, I am trying to reach towards that, but if I use CASCODE, I have a larger V D 4 requirements I am coming to keep M 2 M 4 in saturation. Now this is an issue which has to be taken because what is a good current source, in some cases may be then you have a sufficient voltage margins.

So, you can still go ahead and work with it, but in other cases this may not be achieved you will actually prefer point some .8 or .7 volt as V min for you, now this calculations are all this to do how much minimum really I can achieve for you, ok is that now I can do without going into detail but as we already done it.

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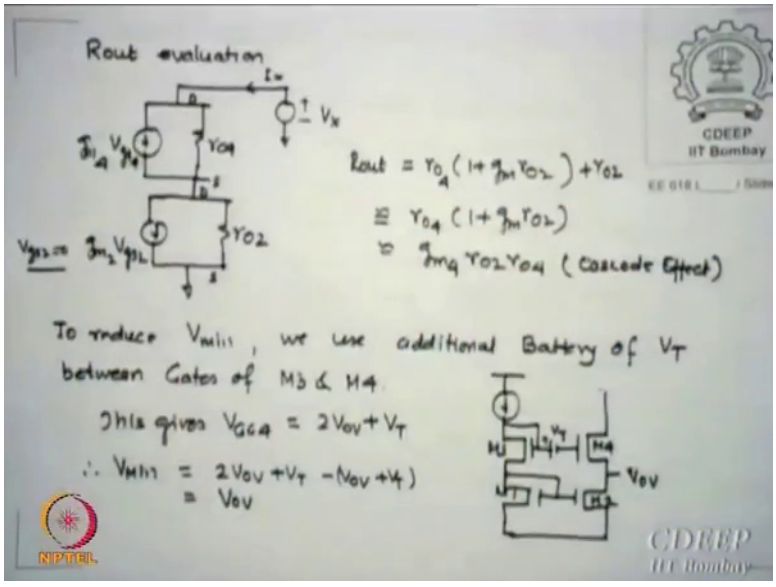

We can do for r o calculation by putting g m v o for this r o 4 parallel g m V G S 2 to both are in as you said you are in saturation. So, these are equivalent circuit I applied V x source pass I x current, why V G S 2 is 0 I said because the source is coming from reference and that I must actually create it to 0 no current in the reference all sources

current sources be opened and voltage sources should be shorted. So, the other side of circuit is not necessary because they are I am forcing V G S 2 to go to 0, now if I do this you can see g m V G S is also will go away.

So, if I calculate this value g m V G S 4 multiplied by parallel combination this. So, R out will come which we did earlier is g m 4 r o 2 r o 4 which is essentially gain times the r o. If r o s are equal then you can say g m r o square is that correct; what is the output resistance of a CASCODE g m r o square. So, we will achieve higher output resistance by simply cascoding at what cost I did this. I had to have 1.57 V min for this current source to operate as a good current source is that clear. So, the conditions which I thought we can achieve by just cascoding was not sufficient is that point clear. I have improved r o, but I also saw it has improved increase the V min which I as I said my first characteristics.

Ideally I want V min to be close to 0, or very sharp rise very small V min then it is a good current source.0, I am trying to reach that. So, why are we looking into this to reach there will one by one go step bias. So, I said first we went for simple then we say it is let us CASCODE. So, I brought r o out higher and now I want to keep this output stay similar because I do not want to reduce my arrow, if possible I may want to increase it further, but I want to now reduce V min. So, what should I do so that I can reduce V min?

Now, what we do is we can reduce the V min by very funny circuit is done, this is called magic battery solution this solution is named as magic battery solution. The rest part is similar except that please do not worry too much circuit is same as what it was.

Except that between the gates of M 3 and M 4 I have applied a small battery of V T. And that is why it was called of course; there are number of variations on this I am giving you the simplest on them there are four such circuits which can do similar things one of them we will see. So, what is now happening is we have this 2 V O V by V T which we have got in minus V O V V T because this additional V T we are supplying now which will get subtracted. So, now, we are getting V O V as your V min. So, we have reduced from 2 V O V plus V T to only V O V which is what you say smaller. So, I putting a battery to compensate I will be able to reduce my V min, but no cost at output because I CASCODE stage is not change by me is that correct now may be you look into the book.

There are variety of course, this name is not given by baker, but this is an interesting name I read somewhere it is called magic battery solutions. How to create this V T is what the solutions are, different way you can create V T s and then you can see that you can compensate for please remember this is opposite sign that is why it is deducting actually this technique of readjusting the V minimum by adjusting additional batteries you can have multiple there are multiple systems. So, maybe you look in to book this is just give an idea how V min can further be reduced, normally batteries are not put like this. So, some other method will use to put V minimum V T there equivalent source equivalent reference. So, I need a voltage reference there. So, now, we must look for voltage reference because I have I need that somewhere here to get it, but as far as theory is concern if I can put some value there I can minimize this value is that this.

Student: (Refer Time: 20:02).

If you change the V G S corresponding the; this voltage plus this voltage this 2 V O V minus this if you subtract, then the V D S will be this to this will be this try yourself substitute the values. For every node the method I will suggest you every node you calculate voltages and find voltage here and find voltage there V D S of M 2, but that additional that will be same V D S because that that I cannot minimize because that will decide by my current which I will push, but at least here it was V O V plus V T that V T I have actually cancelled where point is sorry I think you are also right, this value which I have reduced here it was V O V plus V T that I have actually reduced by 1 V T by putting a battery is that correct. So, overall 1 V T reduction I had done this is just you can see 1 V T only I am reducing out of it that V G S I had subtracted 1 V T. I can readjust this value to some further reductions, but the problems is I reduce this too much this transistor may not remain in saturation.

Student: (Refer Time: 21:11).

So, how much V T to adjust I have how much battery to adjust is force by me M 2 to remain in saturation. So, this is what I thought that this is good enough and that is the minimum I should start with. So, at least 1 V T, V minimum I have gone down is that sorry I should not have said, this is not be this is what we have said is correct this is at V D S 2 is the value which I got you are really good. The another thing which is worrying me on any current source and current mirrors is something which is you know in real life

no parameter remains constant is that we have seen variability issue. So, how do you monitor variability what is the method of finding variability.

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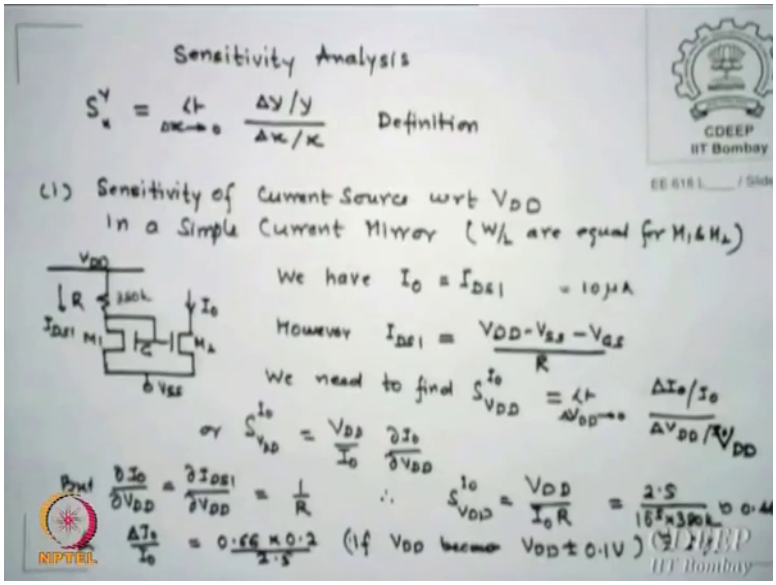

So, one method is called sensitivity analysis is that clear what is sensitivity here is a definition of sensitivity. I want to find variation of y with reference to variation in x is that I want to find sensitivity of y with reference to variation in x. So, it is defined as limit of x to 0 delta y by y upon delta h by x this is the definition of sensitivity of y.

Student: (Refer Time: 22:33).

If this is my sensitivity for more details please read Boyce and Baker's book if I have missed something you actually look further circuits there. Because now I do not want to spend all the; my time in only current sources I have limited time. So, I only showed you the method what they are trying and that is what we are looking for. So, let us look for this sensitivity of current source with respect to which parameter is the first parameter I should look into the power supply, because power supply is never a constant quantity it is externally connected from the pad and that can vary because of a variety of reasons particularly opamp, we actually look for that variation in what term we call they are power supply rejection ratio if there is a variation of V D D what happens. Here there is no p s r, but we just want to know what is it let us say for a simple mirror I calculate my sensitivity. So, it is I D S 1 is equal to I D S 2 w bias are equal then I 0 is I D S 2 which is equal to I D S 1, but how much is ids one we have calculated V D minus V S S minus

V G S please remember where drop across this, plus drop across this plus V S S is essentially met V D D.

Is that correct R R plus V G S plus V S S is V D D. So, I can evaluate I D S 1 from that V D D minus V S S of course, this is minus of minus, so it will add minus V G S upon R. Now we want to find the sensitivity of I 0 because that is my output with reference to variation in power supply voltage. So, I define it is limit of V D D tends to 0 is a small value delta I 0 by I 0 delta V D D sorry yeah sorry. I made a mistake everywhere please check it you are a very good. So, this if I rewrite this is equal to V D D by I 0 partial derivative of I 0 to V D D. So, it is this is my S I 0 V D D is V D D by I 0 delta I 0 by V D D.

But if I see delta I 0 by V D D from this term which is delta ids one by delta V D D, if I differentiate this equation of I D S 1, I get one upon R is that correct. So, if I get 1 upon r because these are constants. So, I leave them delta I 0 by I 0 if you are look at it I substitute some values, but first let us look at this is V D D 0 by I 0 R and the expect value which I last time used value is this R is 380 k for a 5 4 supply, 5 4 means 2.5 V D D and 2 minus 2.5 V S S is net 5 is that clear 2.5 V D D and minus 2.5 V S S. So, sum total is, but here only V D D I am looking V S S I am still keeping constant. So, 2.5 point 10 to the power minus 5 into 380 I 0 is let us say 10 micro amp current.

Assumption is I 0 in our case example is 10 micro amp current that is what we solved the problem. So, this is what it is. So, this gives me a sensitivity of .66. If I want to know the change in current of I 0 then .66 .2 about 2.5 which means if V D D has change a .1 volt plus minus .1 volt this is the kind of percentage variations you can get in I 0 is that clear. So, this is the sensitivity, but I 0 will change if V D D changes is that correct, this is essentially why we are looking this because we constantly say I want constant current source now this constant what is how many how much constant. So, what should be the idea here whether this sensitivity should be larger or smaller as small as possible because I do not want current to change with change in V D D.

Or very small change in R 0 with reference to large change in V D D that happen I say I have closer to my constancy of current, at least from the power supply side. If that influences directly I change 1 percent either 1 percent 10 percent also then I will worry. So, at least it should not be it is less than 1 any way. So, at least you have (Refer Time:

27:22) by this kind of sourcing you did. So, this is one parameter which is the other parameter we should worry about in variations, one is power supply value what else when the circuit is working somewhere what is it changes because current is flowing.

Student: temperature.

Temperature, so the next value is temperature variation is that sudip, the first is power supply voltage variation the other is temperature variation and temperature variation is many times much stronger. In fact, because device is normally operate from where to where. In many operation as much as minus 25 to 150 or 125 or minus 40 to some 105 degrees, this is new standard, military standards. So, device may even ambience may vary in it is own temperatures or device during working I square R last will keep hitting the device unless you dissipated properly. So, if the temperature variation is a crucial fact for us to figure out whether R 0 will change at different temperature. What do we expect should not change that is what I ideally will like.

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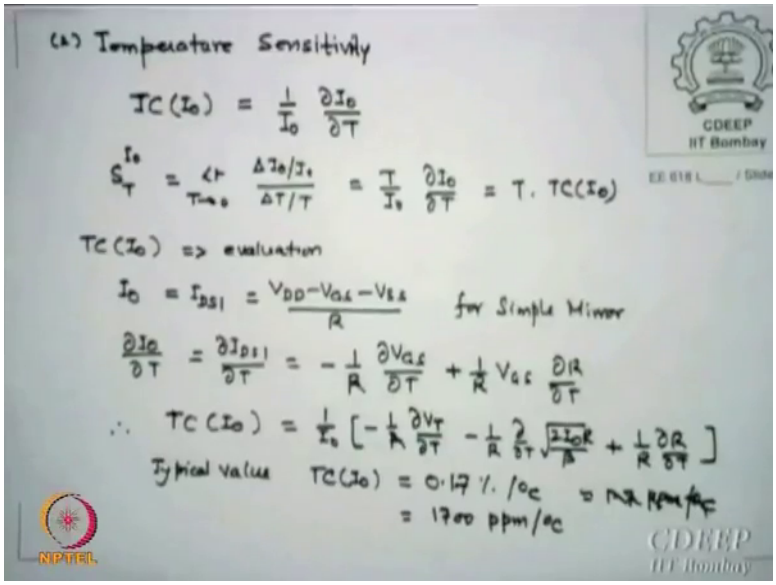

The temperature variation sensitivity is expressed as temperature coefficient is different defined as temperature coefficient ok, sometimes they write like this some may be I will write like this ok.

Student: (Refer Time: 28:49)

T C is capital f is subscript. So, T C f temperature coefficient of I 0 is defined as one upon I 0, delta I 0 by delta t this is how temperature coefficient of I 0 will be defined. We already have written sensitivity of I 0 to temperature if we can find out. So, it will be I same this take again limit of delta T tends to 0, delta I 0 by I 0 delta T by T I T by I 0 delta I 0 by T. So, you can see from here there is a relationship between sensitivity and T C f is that clear this part one upon I 0 delta I 0 by d t is nothing, but T C f of I 0 you look at it T C f of I 0 is one upon I 0 d I 0 by d t, in differential this I get one upon I 0 d y by 0 multiply to T. So, T times the temperature coefficient if I put f of I 0 is sensitivity.

So, if we have been given sensitivity and temperature of operation and actually specifying temperature coefficients is that clear all vice versa. So, again same thing data is given in some cases in S form some cases in T shape form, but both are anyway interrelated, let us calculate T C f what is I 0 I just we wrote it will be is it. So, far so good I 0 is ids one which is V D D minus V G S minus V S S by R for the simple mirror I differentiate. So, it is delta I D S 1 by delta T and I differentiate this term with reference to temperature now which are the terms which are functions or temperature, we assume V D D and V S S do not change with temperature ok this is also not very valid statement every time.

But assume it right now, but mostly yeah we can assume that, but which is the strongest function of this temperature the resistance which are the direct change in resistance occurs with the temperature, but V G also changes because V G S has something to with V T S which we have V O V plus V T so obviously, I must look for V G S variation with temperature and I must look for resistance variation with temperature. So, I differentiate this two terms. So, one upon R d V G S by d t plus 1 upon R d V G S d R by d t, if I do this then I get R to be 1 upon minus 1 oh minus 2 [FL] you are right differentiate [FL]. So, I have done substitute this 1 upon I 0 T C I 0 and if I whatever just they verify properly 1 upon d v by d T minus this T r.

So, now I substitute V G S is that correct what is V G S, V G S is equal to V T under a 2 beta I oh sorry I by beta, if I do that then I can actually look for this expression. Similarly this just check you know may be I have I say in adding I might have done some issue, but just check it well. So, basically what is T C or T C f if we keep calling same name everywhere, if you substitute for both values are simple mirror 380 k and 1.2 volt V G S V T upon .38 volts, we can substitute those value and we figure it out this is .17 percent

per degree centigrade typical, but normally all T C S are expressed in what numbers not in number they always expressed in part per million 1 into 10 to power 6, that is the unit they normally use.

So, if it if you convert this into part per million, It is 1700 part per million per degree centigrade is the temperature coefficient of I 0 by the way 1700 is not a large value compared to other value which may be 3000 or sometime 2400. So, this value is not largest among the values which are used in my analysis resistance. In fact, you calculate this is typically around 3000 for the actually resistance I make in chip. So, it is largest variation come from resistance further this comes from V T variations. So, we will see how much variation temperature depend each has how much ppm they have, but this is to give an idea typically the source currents are 1000 to 1500 to 2000 ppm per degree centigrade rise is always seen with the temperature.

So, now you think of it if I increases it by some amount of temperature the current will correspondingly change proportionately and are you really accepting that much change if that is acceptable to you for your device circuit further is no problems, if you do not want that then think of it to adjust these values what should I do you can see if I can sum how these two terms equal plus and minus I can bring down that value; that means, I design it something, but we design this if I change my W value or V G S are anything or V T then what will I change whether that M 2 M 4 will remain in saturation I am not guaranteed. So, I must first go look to verify every time there because my R 0 guarantee I am I must ensure that R 0 is higher. So, by doing this I must see that my other factors are not terribly disturbed and that is where the design starts at how much T C f you can have to adjust what best R o we can get.

At what V minimum you can get designed whichever is possible that is the source for you is that correct, but in simple mirror R o is not very high. So, we any way going to do CASCODE of that with battery magic battery there. So, that further reductions in V min I can attain and also I have higher R o, but with that I am not done this with that I must calculate now T C f I 0 and figure out whether it is lower or higher than 1700 for those simple mirror, if that is much higher how much tolerance you have, verify yourself with that happens fine otherwise go back any design everything is that issue clear to you, parameters I am worried about it is saturation of M 2 M 4 to get my R 0 higher, I learn V minimum.

So, I will used some other circuit part is V minimum and then all that with that W bias I will use I figure out my T C f is too high and I want to re change everything, that is where the design starts given this value how much tolerance I have because designers do anything at the end of chip it should follow you. So, what it will give you will have to model it back and say oh I have did not take care of T C f therefore, this values are gone out. So, this such a situation you must take in designs ok.

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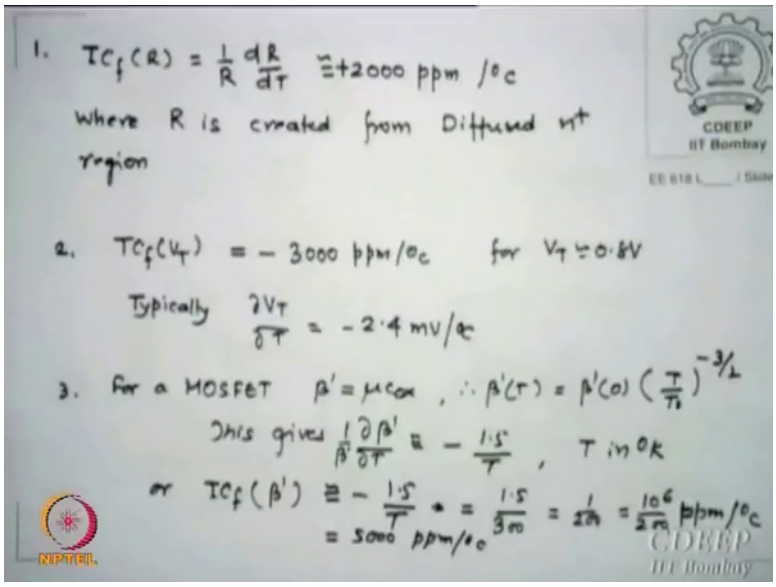

Search for the (Refer Time: 36:30) of it I will just give some values for you to values to see what they gives typically a resistance which is used in diffusion n plus region of source in whatever you used in a mass transistor, if I make a resistor out of n plus region how do I make a resistance of n plus region anyone may be I will show you quickly.

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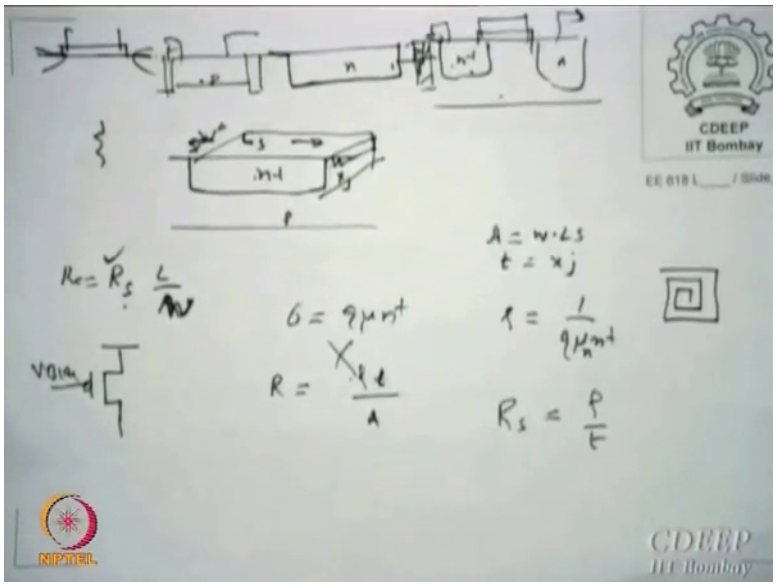

This is my n plus area, this is my junction depth in p, ok this is the source drain lengths what we call L s or L d whatever it is and if you see it another dimension which is w this is my w. So, the area is w into L s thickness is x j and the resistivity of this sigma is q mu n plus. So, I know rho which is one upon q mu and n plus, mu n is known n plus is known, R is rho that is rho l A by A t of course, rho t by A So, I can calculate the length of this source region though you source has source in the transistor as used another say for example, the resistors are make something like this is your transistor for example, plus another n plus region is created here ok.

And the resistor is built in that that is how I C s are made, whichever component you want you should put another region for that what is the problem with such putting there what is the criteria I should have, this is n plus this is n plus this is n plus, but this is p isolate now how to isolate the two areas, this either put an oxide down here which is a s t r or this n p n transistor should have a gain of less than 1, is that clear or put even higher doping here. So, that the gain goes down it is called guard ring. So, put either a guard ring or put isolating diode oxides below trench it down and separate the two areas ok, that is the basic requirement to make any other component. So, every component in this circuit has to be isolated from the others by either of these techniques and that cost hell of money.

Student: sir.

Yes.

Student: (Refer Time: 39:07) for the resistance.

This is a resistance know [FL] bar of semiconductor has length, width and thickness. So, l by A so I have just only lengths and width is given by w which is given to us. So, I have a longer l and l n region or this decides my resistance typically even this is not done because n plus is not a constant quantity. So, it is actually given by R is equal to R S l by a sorry l by W, R S is called the sheet resistance of the n plus region which is typically may be 10 on percent square or 15 ohm square or sometimes even 1 ohm per square in some areas.

So, R S is known to me from technology, W is generally used as the standard widths and the lengths are only adjusted to get your sheet resistance or proportional that are you I need want is that this is how all resistances are made, which is the higher resistance if I want to what should I use which area I should use, n plus in a very low resistance because n plus is a higher doped regions. So, conductivity is higher. So, what should I which area I should use P region. So, I actually I have another this reference and this P region I have another P created in the P which is the dope sheet resistance of my choice and then make a contact here to make a higher resistances is that clear. I have P region created in the P value itself and make two contacts separated length L to be my sheet resistance into L by W values.

Why I said P will have a higher resistivity and therefore, higher sheet resistance how can we I increase or decrease sheet resistance other than the this what is sheet resistance I have defined anyone rho by T thickness I can adjust even thickness, but normally I cannot separately implant something here and separately implant if I already doing implant I will open a window and implant write there, but the higher resistance are I will have to implant anyway. So, for a more resistance the source area that is area whatever n plus I am doping same I use it for low resistance values, I will only adjust this lengths for them and width of course, standards. So, I will get mention resistance of that, but if I want to higher I can even do better I can deposit anyway I am going to have a poly here. So, I can have a poly layer of course, it has to be also protected by oxide and I can make a contact to poly.

Because poly has a very high resistance relative to everyone else ok is that clear another mass please remember what is the orient technology everything I do individually I required every other area to be must do process there [FL] [FL]. So, now do we really wish to do that because how many means many is money how money I have [FL]. So, everything is not. How do I capacitors in this technology I have a M O S [FL] mass capacitors sitting there, but there are other capacity methods also and I also have a transistor and ground it both side, this is the good capacitor if connect gate to the source I will make a diode out of it I showed you earlier diode connections.

So, I do not make any additional device in the I C I only convert my M O S technology areas into variety of component, what I cannot do then resistor I did capacitor I did diode I did inductance is nothing I can do for about, all that I can do a print a spiral on the top of this and that is very difficult gain you know and it should you some it takes. So, much area make a small inductance mainly .1 nano and there is a still require some 20 tons or 18 tons and that area if you see a R S circuit ninety percent of R S circuit area is because of the inductances. In analog chip except for V C O where they will actually go to inductance will never use inductance anywhere even in filters which we will do possibly I replaced L by something ok.

Student: (Refer Time: 44:02).

By using switch capacitor I use I c a as combination and every l I will replace at by c. So, I will never use the inductances as far as possible in analog I will only use capacitors, I will use resistors also out of the same and I will use mass transistor and nothing more than nothing less that is how the integration is possible. So, please do not think that I any even if I show you this essentially what I am going to do is the following, a P device properly biased it acts like a resistor. So, I am not actually going to use any time a resistance anywhere is that clear to you. So, please take it that in real life on a chip only mass transistors are preferred everywhere convert as much as you can it is [FL], but that is all that I will give you ok.

So, this has to be understood that in I c technology the reason is size w by l I want to see smaller any other way I go it will be larger. So, I will it will not be as good. So, what is the problem, the sheet resistance I am sort the T C f of this and T C f of this is different in sign and that is the problem starts, then should we not really put a resistor to

compensate. So, that is what band gap reference people do they actually put a resistance to compensate, they do not put mass device or any other device to compensate they actually use a resistor because it has a opposite sign of T C f oh you want to subtract. So, please remember different components have different way of looking of it in a given circuit this is some additional examples I gave you.

So, for the given n plus region coming back to our analogs T C f R is 1 upon d R by d T which typically for n plus region in 2000 part per million per million degree centigrade, T C f for threshold I think this value you must be aware of those who have done second year course it is del change in threshold voltage with temperature is typically 2.4 millivolt per degree of centigrade with a minus sign that is decrees into that point. So, for the typical point at 3 value of this T C f becomes roughly minus 3000 ppm per degree centigrade typical as I have said please remember in T C f 1 upon V T is the value coming for. So, this value will be function of V T itself which V T you are using is that ok, what is T C f of V T, 1 upon V T delta V T by delta T. So, 1 upon V T has the value which you have to at different V T this will be large.

So, smaller V T what will happen T C f will be even larger is that clear minus larger then this is around .8 volt V T s this 3000 to 3500 is typically a ppm per degree centigrade is T C f, for a mass fact how much is this in the dipolar (Refer Time: 47:19) the delta V B by delta T, there we calculate how much base emitter voltage changes with temperature.

Student: 23 millivolt.

23 millivolt to 2.3 millivolt per degree centigrade similar numbers not exactly same number [FL]That is the way similar thing that there for a mass fact beta dash is mu c ox. So, if I see mobility variation in this it can be written as beta dash 0 T by T 0 to the power minus 3 by 2 this is temperature dependence of mobility, this gives one upon beta dash delta base roughly equal to minus 1.5 by T where T here is in Kelvins.

So, typically T C f for beta dash for the values which I have used could be around 5000 part per million very large T C f for these device beta dash. So, I have seen as yesterday we are saying na beta dash is the very strong temperature dependence, please remember this is for the Boyce Baker's books zeta based on that calculations I have been done for different values we will have to figure out actual values there. So, do not say sir [FL] expression remains same data you substitute of course, 5000 will not become 25000 [FL]

it may become 5500 4500, but it may not be a 5000 for all cases to we handle now we have seen sensitivity due to power supply and sensitivity due to this.

So, now when I am when I am designing a current source all these areas are in my mind, how much current I want how minimum voltage I want how much R o I want and how much is the sensitivity of say both for V D D and V T temperature I have based on that only my design will be a good current source is that clear ok. We will have another current source which slightly improve some of them not necessary all of them we know the variation occurs how do you get rid of variations in a normal circuits, world is not I mean you are right work compensation, but what do we really do feedback negative feedback stabilizer everything. So, one technique of improving this is to actually use negative feedback [FL].

That is what the negative feedback do. So, based on negative feedback and a simple current mirror value we can improve some of the sensitivity issues and to such most popular current mirror which are available one is called Wilson mirror other is called regulated CASCODE both uses negative feedback in their sockets.

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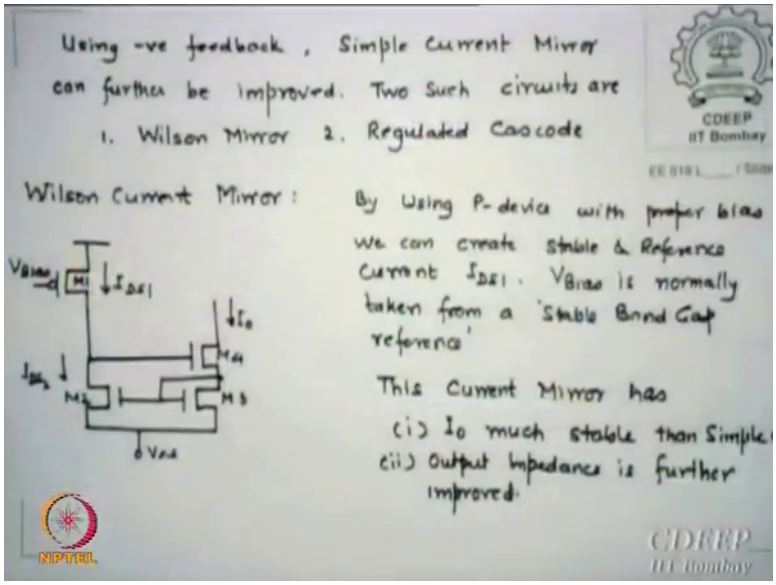

Just now I said it and now here that circuit this R has been replaced by a P channel device, now the question which we should ask what is this V bias this value we know that M 1 must remain in saturation so that resistance is constant. So, how do we fix V

bias? So, we need where voltage reference which is be constant actually use connect their; I repeat what I say I need a constant voltage source which I can connect here.

So, I will also be after the current source I will also try to see; what is voltage references available and how to constancy I see their sensitivity temperature in specific and value with the power supply variations. So, if device constant I can connect them here, that value will push a fixed amount of resistance have for this and flow a current of my choice through a M 1 and therefore, M 2 is that. So, V bias as of now I say it is constant how do I get that constant is also a gain. So, we will see of course, there are another way of doing it instead of actually doing it you can use a feedback also to keep V bias constant. So, it will give some tricks there also [FL] and then it does not work itself.

So, we will see that now [FL] here is Wilson mirror one mirror what resistance did where the CASCODE area. He did not change anything on the simple reference side, however he has a CASCODE on the output side because r o you do not want to reduce I kept this series like this, but what I did is the output of the first this stage or into drain I connected to the gate of M 4 now let us see how it feedbacks please first you do not write think only first here just draw this circuit and let us discuss first. So, start looking I right now assume because of my fixed bias this current which need not be call I D S 1 may be call I reference whichever book something said is constant is that clear, I D S 1 is that constant current generated because V bias is fixed by me, I know variations are I have taken care of all of it as a this current is constant is that clear. Now let us say first for some reason R 0 increases if you say this current increases what will happen.

Student: (Refer Time: 53:35).

That means this voltage drop will increase, which means this current will increase. If this current increases what will increase, this current will increase because say mirror part of that, if this current increase then this is constant this voltage must go down ok because you are pushing it top and now you are asking it to increase.

So, this voltage must goes down if this voltage goes down V G S 4 goes down. So, R 0 reduces if it goes too low the opposite will occur this will push till both side match. So, this is what essentially negative feedback does is that clear and since negative feedback allows you to stabilize, which is the standards of stabilizing anything you can use a partially CASCODE mirror using Wilson current mirrors, Wilson connections and say

that it will see much better than normal CASCODE sources is that clear to you did not get it I D S 1 is constant, but by force you are trying to change your I D S 2 is current from mirror from M 3 side [FL] what was saying is how can it happen no it will not if that is what feedback gives how feedback will push that same current is what I am telling is that point clear to you your idea is in a circuit two currents cannot go that is exactly I am also saying is that clear to you because two currents cannot flow, but now I am forcing this to increase which means this voltage must go down because I add drop will go down.

So, then this V G S falls. So, this current will reduce them is that correct because we say I D S 1 has to be I D S 2 is that clear. So, how the feedback will force that issue that ids one only current will flow down, if one there is a variation in I 0 is what I said and therefore, I 0 will become constant independent of anything; this is called Wilson's feedback system. These are simple statements nothing very wait current there has I 0 must stable than the simple mirrors output impendence is further improved because of the CASCODE connections ok.

I already said for those I made a statement the V bias is normally taken from the stable band gap reference which will look into can you think why there also it is a constant must be there also should be feedback because other way it cannot create a constant value. So, a band gap reference must have some comparisons it must find errors and feed it back. So, that it reaches to a constant value. So, we will see that later is that everyone this is V G S 2 this is V G S 3 ok.

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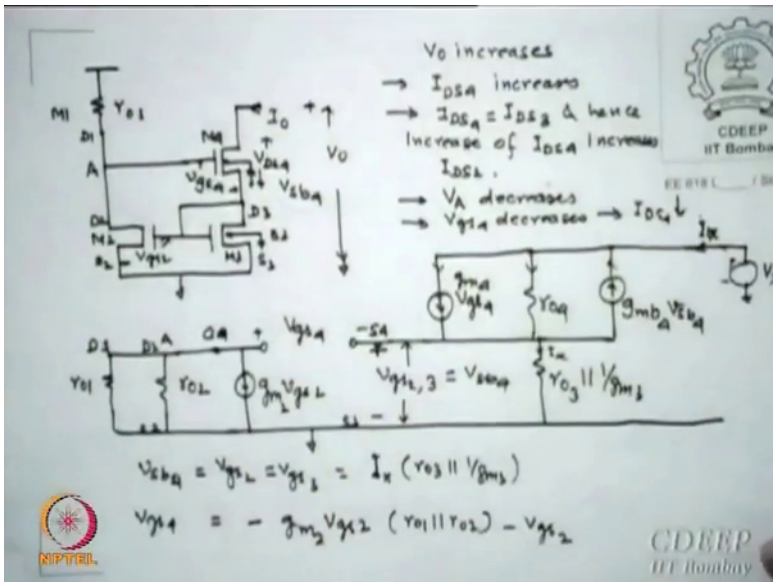

Now, we see this is V G S 4 this is V D S 4 this is what we said as far as the P channel device is concerned it is now only acting like a current source with a resistance of R o 1 and that is a constant current source because we say V bias is fixed. So, we do in I C we do not consider that that is a fixed source, but this r o one will appear for that because there is a output resistance of that P channel device ok.

So, as far as I am concerned for the first transistor only R o 1 from gain to source is available. So, I have plotted it here for the D 2 for this V G S 2 by the way what I am calculating I am calculating I am doing a V x here and finding V x by I x to get R out I am not doing anything, I already shown you here I am trying to find R out from substituting putting a V x source and finding R x there, on the transistor D 2 it is R o 2 shunted by g m 2 V G S 2, but this D 2 is create of M 4 is that clear, please check it D 2 or D 1 is g 4 [FL]. So, this D 1 D 2 g 4 are same connections.

D 1 D 2 g 4 are same connections is that this terminal this terminal and this terminal are same. So, this is that line three of them D 1 D 2 g 4 now you see what is the V g is coming here which is same as A voltage minus the source voltage of M 4 is the V G S 4 is that correct. So, the S of this transistor M 4 and the voltage here subtraction is V G S 4. So, this is my gate this is my source the gap voltage drop between gate and source for 4 is V G S 4 sign please check it this has to be plus because this is an n channel device. So, this is plus and this is minus for S 4 is that ok.

So, this V G S 4 why I have drawn this circuit is this you should also see that the way I see a circuit I can make an equivalent right there and then I will say they shunt have an [FL], but basic idea is just to substitute whatever you are looking for making an equivalent, my suggestion to you is this method is always correct. Because we are only following node and from there whatever you are seeing you are substituting there the S 2 and S 3 are same which I ground it S 2 S 3 source of M 2 M 3 are connected and grounded S 2 S 3 are connected and grounded.

Now I have to see drain of 4 this. So, this is my where I am actually going to push the V x I x currents V x force and I x this, which is my I 0 which I am looking for say this term step what is the current source g m 4 V G S 4 shunted by R o 4 just wait for this if I say and just now someone was asking if the source is crack bulk is grounded between source and this there is a voltage now V s b is that correct; however, the rho V S B I can see V S B 4 is nothing, but the signs I am putting plus minus for the source which is essentially equal to V G S 2 and V G S 3, V G S 1 where V G S 2 V G S 3 because they are connected with this is same as this potential.

So, I say V S B 4 is nothing but V G S 2 or V G S 3 is that correct. So, this voltage so this is my S 3 this is my S 4 this is V G S 2 which is equal to V S B 4 and since please remember this is V S B opposite polarity current pushes up g m b 4 V S B 4. Now this is the equivalent for this for n 3 is g n term will appear there because this is a diode connection. So, in the R o 3 parallel g n 3 I kept it R o 3 you can even neglect R o 3 because g n 3 will always larger than 1 upon R o therefore, that, but right now I kept I always say I related because I do not know what currency we are going to use. So, I want to retain them in case they are compatible make it parallel.

Now this is very big circuit looking, but there is nothing big part in that. So, first thing I calculate is V S B 4, V S B 4 is V G S 2 same put same node V a V G S 3 now look at the current which is passing through this drop is V S B 4 is that correct, drop across R o 3 and g m 3 and what is the current flowing sum total of these three what are current in this is essentially net current. So, current coming out is also I x [FL] no current. So, all this I s current flow through R o 3 parallel 1 upon g n 3 is that current that is your V S B four.

So, I get V S B 4 is V G S 2 equal to V G S 3 is I x times R o 3 parallel this, now I want to calculate V G S 4 how much is V G S 4 we find where this voltage and if I find this

voltage is that point clear how does I calculate V G S 4 this voltage minus this voltage is that correct that is my V G S 4. So, I write how much is this voltage g m 2 V G S 2 parallel combination of R o 1 and R o 2 is that correct. So, this is my voltage here is that should be clear the voltage drop across parallel combination of R o 1, R o 2 is nothing but the voltage across this that is V G S 4 how much is V G S 4 the V G S 2 just now we wrote that please remember this voltage is this voltage so you subtract this is that clear.

So, we get V G S 4 is minus g m 2 we get this minus V G S 2 is your V S B 4, but what is V G S 4 now why I am interested in V G S 4 because I want to find drop across because of this. So, I want this current source is that ok, everyone please write down this circuit is as I said you can simplify circuit by parts and can directly write many things please do not write, because this gives you a actually features what is happening there is that correct not only for this circuit for any circuit if you have more than one transistor on the top please put three layers of them actually match the nodes correctly that will never make any mistake in evaluations at the end. So, this is I am not saying this is the method, but this is much simpler method of doing things.

And I am saying this from my experience, but you can do much better you can simplify circuits much equivalent of what is the other method, for each stage find equivalent familiar source and in terminal resistor you place there they are keep doing that also is a equally good method, but doing that essentially you are partly doing the same thing which I am doing I am doing all together that is it Is that correct. So, my method is no different from the other methods given in the books it is same I am only trying to see visualize what this circuit is dong. So, I actually show you what is the equivalent of that from there please do not think it this is diode technique or something before we quite let us finish this today.

V S B 4 is the between the source because please remember there is a drop here which is the source voltage for D 4, M 4 since subtract is grounded there is a V S B 4 is that correct, but I know this V S B 4 is same as because this is the same terminal source here must be same as this and this V S B 4 this is plus and this is ground is that sign correct, source is that higher potential than the ground. So, that is the way that is why say the way I had drawn I am only keeping signs accordingly what will have and that is why actually I change this sign also upwards ok is that now clear to all ok.

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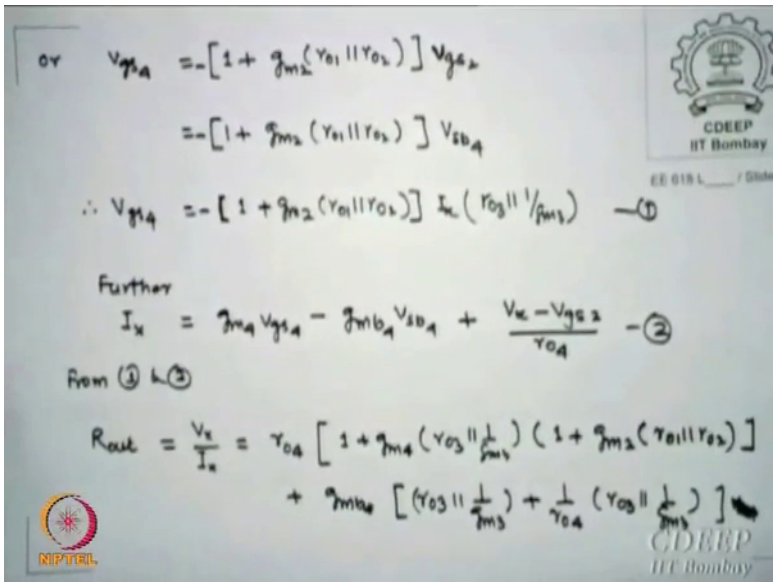

So, V G S 4 is that there for equal to minus I will take sign 1 plus g m to R 1 parallel into V G S just combine nothing very serious, but V G S 2 is V S B 4 I just wrote. So, I replace V G S 2 by V S B 4, but V S B 4 I already calculated I x parallel multiplied by R o 3 parallel 1 upon g n 3. So, I substitute that here. So, I get V G S 4 is equal to minus 1 plus g n 2 R o 1 R parallel R o 2 into I x R o 3 parallel 1 upon g m 3 is that. So, one equation I figured out in which V G S 4 is related to this if you look at this circuit once again please wrote write down this we will come back to circuit again. Only up to equation one you check and then I will draw this circuit is that everyone wrote down this equation see this circuit, this I x is divided into three currents is that correct g m V G S 4 minus g m d V S B 4 plus V x divided by V x minus V G S 2 or V S B 4 by R 0.

This voltage minus this voltage divided by R 4 this current source and opposite current source, this is the net current which is I x is that three parts each is this I x is sum total of these three because you can see below I x is coming. So, all three must be summed up proper signs. So, in some book sum g m 4 V G S 4 minus g n d V S G 4 plus V x minus V G S 2 is that correct V G S 2 divided by a R o 4 is the second equation, then I use this two equation and evaluate it V x by wherever the V G S 4 is there I substitute it all of it here. Collected the terms for I x collected terms for V x and then divide V x by I x. So, just check this is R o. So, this is.

Student: (Refer Time: 69:12).

R o I do not know which one, but just check some R o must appear there.

Student: [FL].

[FL] [FL] So, check it all that I say what I did in the paper I actually substituted V x V G S 4 here V S B 4 in terms of I x again and then I collected V x and I x terms and divided this is what I did. So, this is what I got [FL] please check it sorry for my mistake I should do that anyway I am really tomorrow I will actually show you correct expression which I got.

In normal cases g m 3 will be same as g m 4 because I keep M 3 M 4 identical thresholds are same R o 3 parallel 1 upon g m 3 I will replace it by 1 upon g m 3, because I know R o s are larger and g m 3 is equal to g m 4. So, I will say R o 3 parallel 1 upon g n 3 is 1 upon g m 3 or 1 upon g m 4 and call them g m itself pensive I can use that I will also say a one is equal to R o 2 equal to R o all this mirrors are same. So, all R o s are A.

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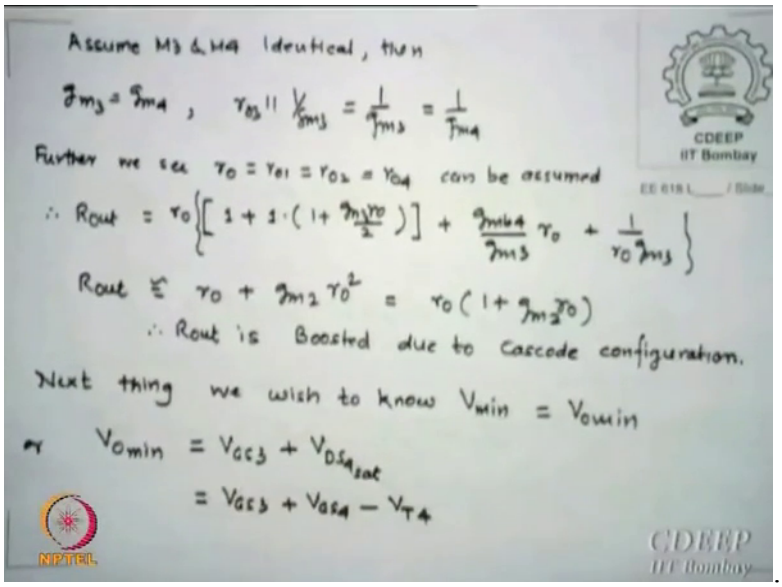

If I do all this at the end of the day and let us say g m 2 and g m 4 are only one these are this can be adjusted we say roughly R out will come R o plus g m 2 R o square or roughly g m 2 R o square do CASCODE. So, nothing grate all that I did after all this huge calculations I arrived at saying. That it is g m r o square no grate this, but just to say at the circuit is larger things do not change very large all that you have to keep evaluating expression wise longer expression. So, do not get fear of that so obviously, we knew it is

the CASCODE and therefore, it has to boost R o now V o minimum is the next thing we will we must want to know man you just write this final expression which is of relevance to you can do whatever you did R out is R o plus g m 2 R o square by cascode the output impedance has boosted gain times R o g m R o is the gain. So, times r o there is the boosting of that further boosting; how can we do you can use CASCODE with the gain. So, you can further boost R o in case you need further R out higher.

Some other penalty of power and area you may give what is V o minimum V D 4 at the end what I wrote is otherwise I also prove I did not bother to see of I say it should be R o plus g m R o square equivalently, if you see this figure this voltage is this voltage plus V G S. I repeat this is V G S you have come here plus V D S is that correct I repeat again this voltage is same as you reach here this plus V D S of this is by V D 4 is that. So, V G S 3 plus V D S 4 is the output voltage V 0. So, V o is V 0 3 plus V d sat V D S 4 sat the transistor must remain in saturation.

So, we say it is what is age of saturation minimum [FL] V G S minus V T. So, you substitute V G S 4 minus V T 4, I can rewrite now V G S how do I write V G S in what terms V T plus under root 2 by beta plus have you written down this.

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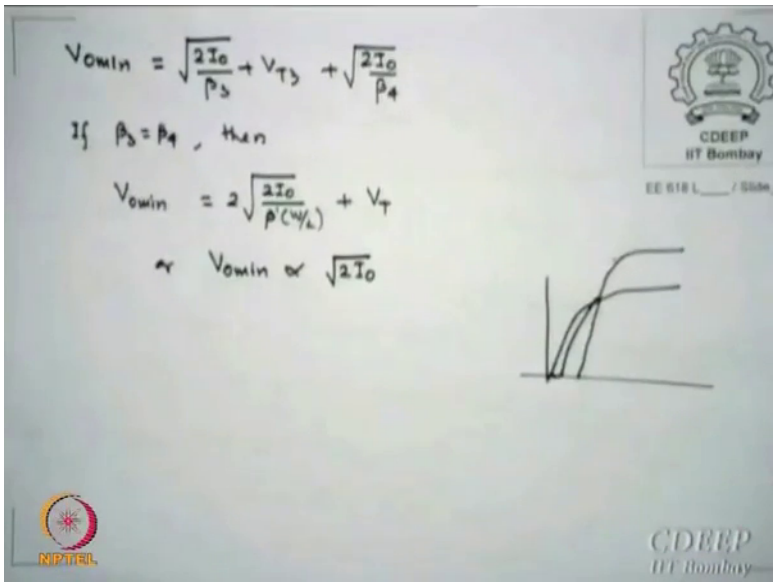

So, we write V minimum is under root 2 I 0 by beta 3 plus V T 3 plus 2 I 0 by V T [FL] a beta here also equal which you can then [FL] 2 into 2 I 0 beta V T w by l plus V T. So, now, V O V minimum is proportional to 2 I 0 under root of 2 I 0. So, larger the current

source you are getting by definition or by theory your V o min will increase is that clear this is now you cannot do much, essentially I am saying V 1 is looks V o minimum whatever you are getting if this is your this if you want higher currents you will have to sorry yeah you will have to do only this, there is no other way of pushing higher currents if you push higher currents drops will also increase essentially what I am saying [FL] there is nothing I can do only thing is it is not linear like ohms law it is under root of I 0 which is it proportional to it because of the square law term I am getting. So, I can evaluate V o min how to minimize this I cannot change the I 0 because that is what I am looking for all that I exist is w by L s, but if I adjust w by l what will happen the more current then reference current may not be same.

So, I will have to figure out what reference I should keep. So, that with this w by l I get the I 0 of my choice that you can always think is that clear because the ratio may not be same than then it will transfer in a ratio. So, initial current must be boosted to come to this value if w by l change on the other side figure it out what should be reference current that is how you will be able to define specifically this we will come next time what is we called V T reference current source.