Analog ICs

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Lecture - 01
Basic Building Blocks in Analog ICs (Current Mirror)

Analog integrated circuit is what we have to start discussing from today onwards. Let us first consider the most important basic building block in analog ICs. I do not think there is any other basic building block in discrete circuits which can be compared to this particular basic building block that is the current mirror.

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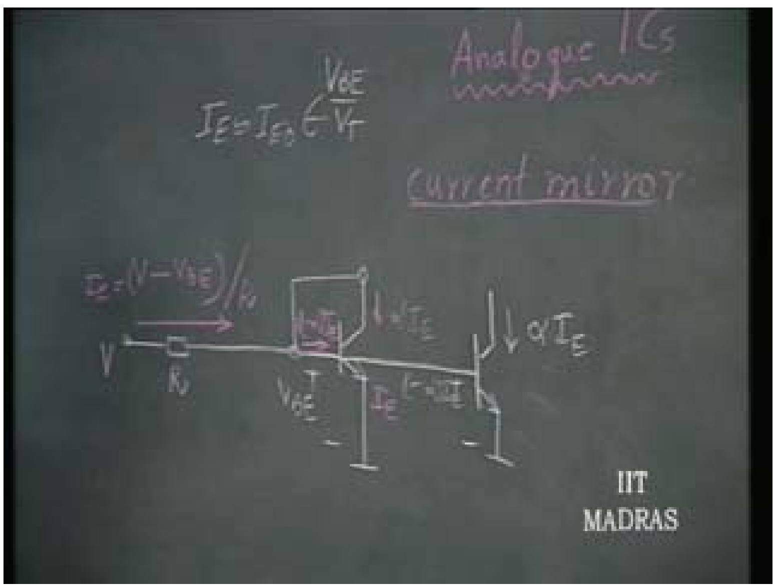

The idea is very simple. As the name itself indicates mirror is something that reflects the image exactly in an identical fashion, Replica of the original stuff of whatever it is. In this case it is a current mirror. It should exactly reproduce the current that is existing originally. So what is it, how is it made?

We have already seen that a transistor connected as a diode with base and collector shorted which is the most popular triode configuration in integrated circuits. It is primarily because we have this transistor even though acting as a diode for the external world within itself it is still acting as a transistor and transistor action still takes place. It is IC is equal to alpha times IE still is perfectly valid because collector base junction has zero bias and base emitter junction can be forward bias so, transistor action takes place in this block but for the outside world it is a two terminal device acting as a diode.

So how do we fix the current in this? One way is to fix the current in this by applying a voltage across this. But we will not know what exactly the current is unless we know something about the transistor characteristics. I_E is equal to I_{E0} exponent VBE by VT approximately. So when I have VBE as a certain value I know there will be certain current IE through this. But this is a very sensitive thing. If VBE changes very slightly IE will change enormously because of the exponential relationship. So this way of fixing the current of the diode is not a stable way of biasing the diode.

The best way of biasing the diode is to force the current into it. How do I force the current? I can forward bias the diode by forcing a current into it by applying a voltage V and the resistance R. So, now the current in the circuit is going to be V minus VBE by R. This is the current through the diode, this current is forced into it. Now VBE should so adjust itself that this current is permitted to flow through the diode.

What does it mean? This is IE, this current is alpha times IE. What is this current then?
If this is IE and this is alpha times IE by Kirchoff's law this is going to be 1 minus alpha times IE. Effectively we have this as still equal to IE. So this current is nothing but IE. We are forcing an emitter current of magnitude is equal to V minus VBE by R.

Automatically transistor action takes place and the ways in which the current required for sustaining that collector current is going to be flowing through this is. This is the way to force through the diode a current of required magnitude V minus VBE by R. If VBE is very small compared to V we know that this is very closely equal to V by R which I can determine according to my choice selecting V and R properly. So, if V is lesser 10V and R is 1K we have a current of 10 milli amperes flowing through this. So I can clearly know that through the diode there is 10 milli ampere current flowing through.

Now how do we use this information?
In an integrated a circuit if base to emitter voltage of this transistor is forced by this current then automatically what happens is based emitter voltage of this can be sustained to be the same for this transistor as well. And then what will be the current in this?

Current in this is automatically going to be alpha times IE. This is going to be always the case, this is what is called mirroring the current. This is the mirror effect. Whatever is flowing through this diode is mirrored through the transistor now because collector you can connect it anywhere you want as long as collector base junction is reverse biased. As long as collector base junction is reverse biased this current is going to be sustained in this. This kind of property is a unique property which is exploited universally in analog IC design. What it this property?

I know that this particular transistor is connected as a diode, what does it mean?

When you connect a transistor as a diode you are giving feed back. It is a three terminal device, the collector current is fed back to the input. Input current minus the collector current is now going to be the new input current to the transistor and from here to here that is a current gain of beta. So this is a current amplifier with full current feed back and the current gain of the current amplifier is beta. So, if there is full current feed back what will be the effective gain of such a current follower? It is beta by beta plus 1.

When there is a voltage feedback in an amplifier with voltage gain of A and when we give full voltage feed back we get a voltage gain of A by 1 plus A. In this case it is going to be beta by 1 plus beta which is nothing but alpha that is what it is. This is really a diode which is treated as a transistor in a feed back mode. And because of the negative feed back the current in the output current is go going to be adjusted automatically exactly equal to the input current where alpha being close to 1, so this is a feed back situation.

Now this feed back information is being utilized to reflect the same current in other transistor. Please make a note of this fact that the property we are trying to utilize is to make the master learn the technique through whatever means, feed back or something etc and make these layers repeat the same thing that the master does.

We can term this theory as, follow the master. This principle is used in many other IC designs simply by making use of the identical property of the transistors. So, this current mirror principle is something unique to IC design. Now once I do this connection, please note that, what will be the current in this now? This is alpha IE so this will be, this is IE and this is also 1 minus alpha IE. So, if I connect one more transistor that will also require a drive of 1 minus alpha times IE.

Suppose I connect n transistors the base currents of all these n transistors will have to be n times 1 minus alpha times IE getting accumulated and that current has to be given by the input current. What happens in such a situation is, V minus VBE by R earlier was simply equal to IE.

Now it is no longer that because this current has to supply not only this alpha IE which is the major portion plus 1 minus alpha times IE which was really IE. Now it is 1 minus alpha times IE into n plus 1 if there are n such stages. That means can we use this principle to arbitrarily reflect the same current in all the n transistors is another question.

How many transistors can I keep on attaching to this so called reference which has been generated by pumping in a current of V minus V gamma by R? How many such current sources can I generate? All the current sources will now have the same current and there is no doubt about it. But will it be the same as what I pump into the original diode? That particular part of it is going to depend upon, here you can see, this is going to be alpha times IE plus 1 minus alpha is actually what? It is IE to n plus 1 by 1plus beta because 1 minus alpha. So actually speaking we want this particular thing to be negligible. It is going to be negligible only when n is very small compared to beta, so n should be much less than beta. Typically beta of IC transistors is going to be around 200 or so.

Therefore typically the number of such current sources that you can get out of a single voltage reference will be of the order of 20 without any problem. That means you can use each one of these current sources anywhere you want in any portion of your circuit later to be designed. That means using a single resistor I am able to simulate n number of current sources. So this is a powerful technique for biasing transistors within an integrated circuit.

Apart from this the same current sources or sinks can also be used as high valued load resistances. So this kind of a technique of current mirror is used for both biasing and amplifier stage as well as dynamic AC resistance of high value. These are the two purposes for which these current mirrors are used in most of the integrated circuit. This same concept is valid even if the transistors used are PNP instead of NPN.

When you use PNP transistors for this purpose then you are simulating what are called as current sources. These are called current sinks, so these are generated by NPN transistors whereas current sources can be generated by PNP. Obviously you can see now, the error in the current depends upon the magnitude of n compared to magnitude of beta.

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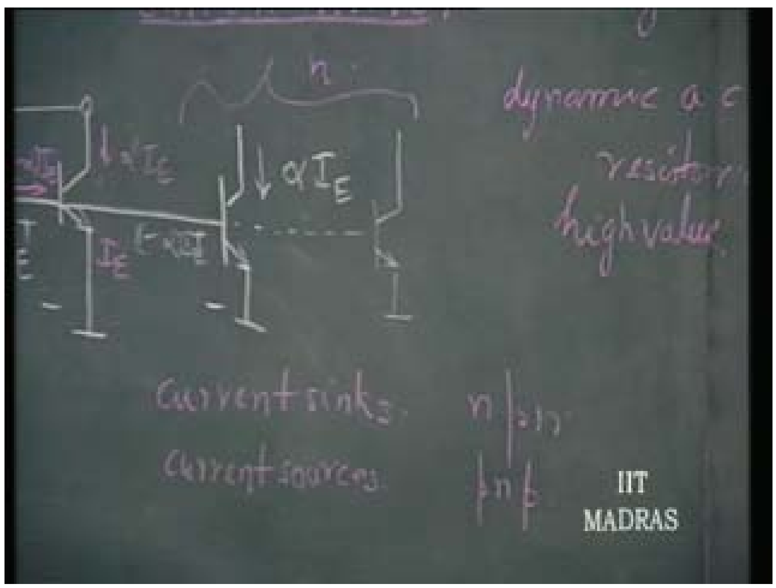

We have already told you in the introductory lecture that beta of an NPN transistor is of the order of 200 or so then the beta of PNP transistor is going to be 10 or 20. If you use a PNP transistor the number of such current sources that it could generate will become smaller. So is there a way of improving the current source? The first improvement you desire is this current reflected should be exactly the same as the current that is going through this resistor. The error should be as small as possible or the current gain factor should be close to 1 that is one requirement.

Another requirement of such current sources is that the output impedance seen from here, what is the impedance seen from here for this current source? You are looking at the current source from the collector, emitter is grounded so what is the output impedance of such a structure? It is 1 by hoe because it is emitter grounded. So, when the emitter is grounded output impedance is typically of the order of 1 by hoe which is of the hundreds of kilo ohms or even mega ohms. In IC transistors it may reach the order of 1 mega ohms. If you want better output impedance than that you have to also adopt some modifications for this current mirror.

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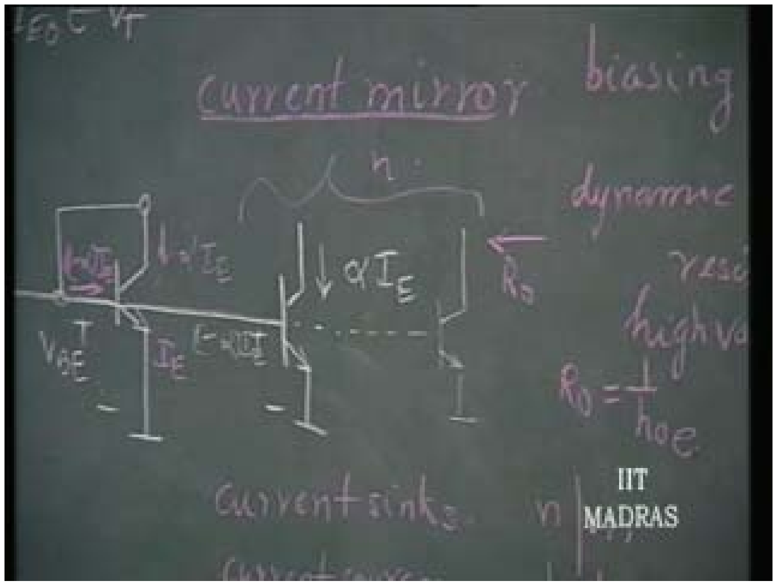

We will now discuss about, what are the other ways of obtaining current mirror with better performance than what is presently given? So far we have been discussing about the simple current mirror. Now let us see how to modify this current mirror so that its performance, parameters associated with this current mirror will be that the current source should have high output impedance and the current reflected should be exact replica of the current which is the reference current that is pumped into the diode. These are the two requirements and how to achieve this.

First let us see a very simple technique. One way is the usual negative feed back technique. All of you know that when you want to improve the performance of a structure in terms of reaching its ideality, if it is a current source it should become an ideal current source, what does it mean? By giving proper negative feedback I can make the original current source become a better current source. And therefore let us see how a negative feedback concept can be utilized in making the particular current source a better current source than original

What is the kind of feedback we have to give in order to make this output current become a better current source? First of all we want the current to be same in all and that is easily achieved. Current is same in all because VBE will be the same for all, the current is the same. The reference current should be the same as the current reflected that is what we have to have.

The second one is, when we are connecting it to something the output current source should act as a true current source, that is, its output impedance should be infinity. These are the two requirements. That means if you vary the voltage between the collector and emitter the output current should not change. So this is the second requirement. How do we do this? Obviously it is by using negative feedback.

What kind of negative feedback should we adopt in order to make the current source a better current source? It is the current feedback. Now whether it is shunt or series is of no consequence because we are not bothered about what happens at the input. It is current shunt or current series it could be current feedback. So we have to select the output current and feed it back as a current or select the output current and feed it back as a voltage. These are the two techniques that can be made use of in order to improve the output impedance of a current source.

So how do we do it?
I have a current in the output as Io. Do we have something which tells us that the current in the output is as same as the current at the other side? The emitter current is very nearly same as output current. So I can sense the current here and how do I sense the current here?

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I now connect here a diode because we know that the diode now will have the current which is the same as the output current, a transistor. And I want to generate a current that can be fed back. And how do I do it is use a current mirror. That means the same idea that I have been using now can be used in the reverse. That if I now use just kind of structure this current which is same as the output current very nearly is getting reflected at this point.

What do I do? I have to feed it back to the input. Feeding back a current is very easy, Kirchoff's law itself does it because this was the original input and this input was going into the base. Now the fed back current is going to be opposing to original input current and the difference in current goes into the base. So this is the current, that is current which is sensed is fed back as current. This is a famous current mirror called Wilson current mirror due to this.

Obviously now you can see that in order to improve the performance of the current mirror I have used three transistors in place of two transistors which was originally there. Now base to collector voltage is made 0 here, this has V gamma here, so what is the reverse bias voltage of this transistor, which is V gamma because this is V gamma, there is V gamma here. Therefore, this potential and this potential that the difference is V gamma but in order to reflect the current better, what does it mean?

In order to prevent early effect from making the current reflected different here I should make the collector base potential of that transistor also equal to, this collector base potential is 0 so this collector base potential also must be maintained at 0 if it is possible, how do I do it? There is a current going into this, so if I put a diode here that is it, so I simply put a diode here which is nothing but again a transistor connected as a diode.

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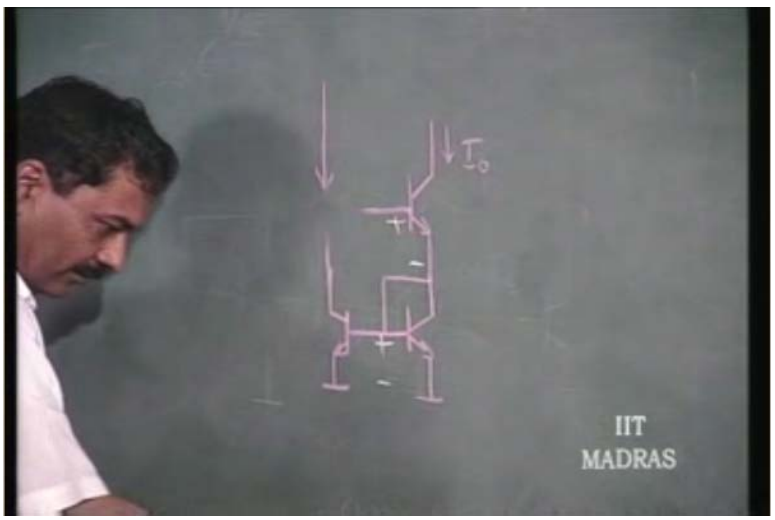

The difference now is, this is simply a diode brought in so as to make this current get reflected here more exactly otherwise what would happen is, this collector base potential of this would have been different from the collector base potential of this there will be some difference. So this four transistor configuration is even better than the earlier. Obviously what will be the output impedance now? It should go towards its ideal value. The best that a single transistor can give as output impedance corresponds to in the common emitter which is 1 by hoe.

What is the configuration in which the output impedance is the highest, single transistor configuration? It is the common base, it will go towards common base output emission which is 1 by hob.

Here is a problem to be solved:

Show that the output impedance of this is going towards what 1 by hob from 1 by hoe because of this feed back this is what happens. Now you have improved the output impedance by an order of, how much? What is the difference between 1 by hob and 1 by hoe? It is beta plus 1. So, the order of improvement in output impedance is of the order of beta which is two hundred times. This is commonly used wherever you think the output impedance of the current mirror is what matters in the performance of a structure amplifier or otherwise.

The Wilson current mirror is used where output impedance of a current source has to be very high, this is one technique. Another technique is the other kind of feedback. First is to show that the output impedance is 1 by hoe and another thing is because of negative feed back I_i should be closer to I_0 than before. In the earlier situation what was the case? I_0 is equal to 1 by 1 plus 1 by beta. If you say the original single diode and transistor current mirror you see that I_0 is going to be Ii by 1 plus 1 by beta.

In this particular case you can show that I_0 is going to be Ii into 1 plus 2 by beta by 1 plus 2 by beta plus 1 by beta power 2 which are closer to 1 than before. Show that I_0 by I_i is this in this case and therefore I_0 is closer to Ii that means even if beta is lower I_0 is going to become close to I_i in this case.

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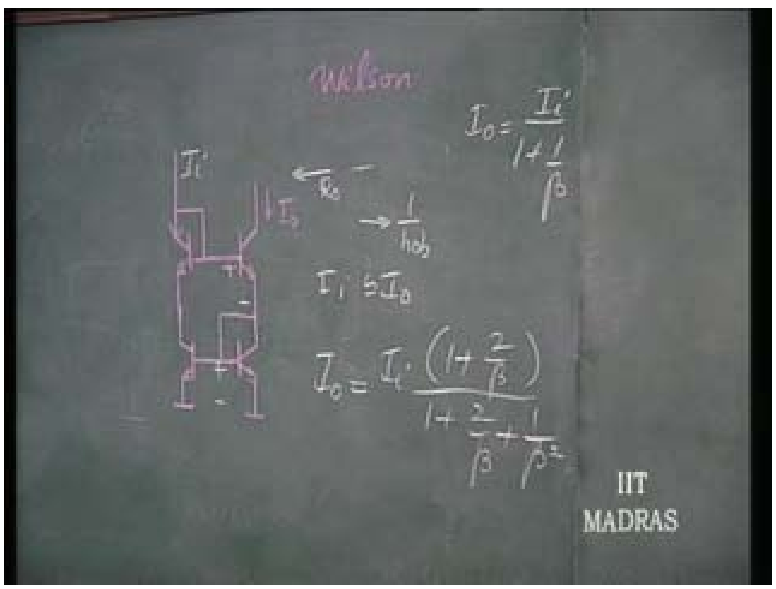

That means this kind of concept can be therefore straight away used in PNP configurations where beta value is known to be lower. Now let us see the other negative feedback concept that we can utilize.

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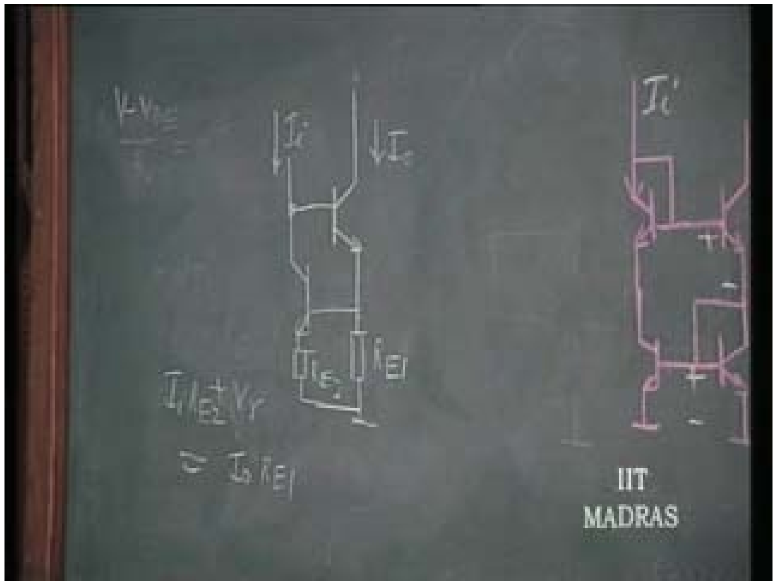

This is one where we have sensed the output current and we are feeding it back as current. Now let us see how we can sense the output current and feed it back as a voltage. Again this is the output current, how you convert a current into a voltage, put a resistor. We put a resistor here which will convert this output current same as this current so it will convert this as a voltage and then I can feed it back as a current or a voltage. I have sensed this and then I am feeding it back as a current or a voltage, it does not really matter. This voltage is sensed, this is dependent upon the current here and this is getting converted into another current, let us call it R_{E1}, this is R_{E2}.

Even here the output impedance should go towards, what is the value to which output impedance should reach? It is 1 by hoe. Therefore hoe to 1 by hob and the same effect takes place even here. The effect that happens at this particular point is that once again you can see this is the input current and that is the output current. You can see here that input current is same as collector current. This input current is going to flow through this as Ii into R_{E2} plus V gamma is equal to I0 into R_{E1} approximately.

I can now see to it that a current ratio can be anything that I desire as long as V gamma is negligibly small I can see to it that the current ratio can be anything I desire by appropriately selecting R_{E1} and R_{E2}. This is another technique of improving the performance of the current mirror. Only thing is this property of current ratio becoming closer to 1 is no any longer valid because I am not feeding back the total current at the output as input current. This is not getting valid here and there is some amount of error because of all these, conversion from voltage to current etc.

Now there are other techniques where feedback is not at all necessary for improving the performance of the current mirror.

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The current feedback that we have talked about is not necessary at all instead let us say I drive this ……. current, how do I do it?
If I put a resistant in the emitter or if I put a current source in the emitter itself the collector current has to be the same as emitter current. So I can put a current source at the emitter of this so this current being fixed by the principle that we have just now studied that this can be a current mirror. The fact that this is V gamma and this is V gamma and this is 0, in order to make this it also has V gamma here so I can put another diode here so as to force this voltage also to be collector base voltage to be 0.

Now this is not a feed back circuit. This is reflecting a current here and this current is coming here. But only thing that happens is, because it is emitter being driven by a current this is nothing but a common base circuit because base is at a low potential AC wise compared to emitter. Emitter is being driven by means of a current. This is a straight forward common base configuration.

How this is appearing as a common base? This is because base AC wise it is at ground potential and emitter is connected to a current source and therefore output impedance of this should be straight away 1 by hob. There is no feedback here. Only thing is it is not necessary that I0 here and Ii here are going to be pretty close to 1 and that aspect is destroyed. Not only that, in all these current mirrors, Wilson current mirror and the other modified Wilson current mirror as well as this you would have noticed that I have sacrificed something.

Now, when I pump in a current using the same V and R the current in this becomes V minus 2V gamma by R that is also a danger because I would like V to be much greater than 2V gamma now instead of becoming much greater than V gammas so that the current is independent of the transistor. V gamma varies with current and temperature. So I do not want that variation to be reflected in the current that I am generating. So this becomes 2 here, same is the case with the Wilson current mirror, there also you have the reference current is equal to V minus 2V gamma by R, that is the only disadvantage of this. All these simple configurations of current mirrors can be straight away used in biasing integrated circuits.

Now there can be a question. How many resistors are therefore needed for biasing here? Only one resistor is needed to convert the voltage into current. Now the question is, can you bias an IC without using resistors. There is only one configuration which will give you current straight away as a current source without using resistor. What was that? It was the depletion type of MOSFET or equivalently JFET. These are the only two configurations JFET or depletion type of MOSFET. How do you do it here? Just connect base VGs is equal to 0 this is a simple current source where VGs is equal to 0 and the current in this is equal to IDSS and the output impedance R_0 is going to be rds.

Here there is no need for any resistance at all. This is a configuration where you can obtain a current source with fairly reasonable high output impedance without using resistance. It is commonly used where you are not so much bothered about the value of the current because the value of the current is dependent upon the parameter of the FET. You just want some current, where do you have such a situation?

Suppose you would like to bias a zener diode you want some current which is higher than the knee current. You are not bothered about what value of that current is used. So in such a situation we go for this kind of current sources. You will see such current sources normally used in biasing the zener diode without using resistor. So, similar configuration is also valid for the JFET.

So far we have discussed about current mirrors and how one can obtain a variety of current mirrors. There is a very nice principle in this current mirror concept. That can also be written in a manner slightly differently. Let us therefore see that quickly. Let us talk only in terms of this.

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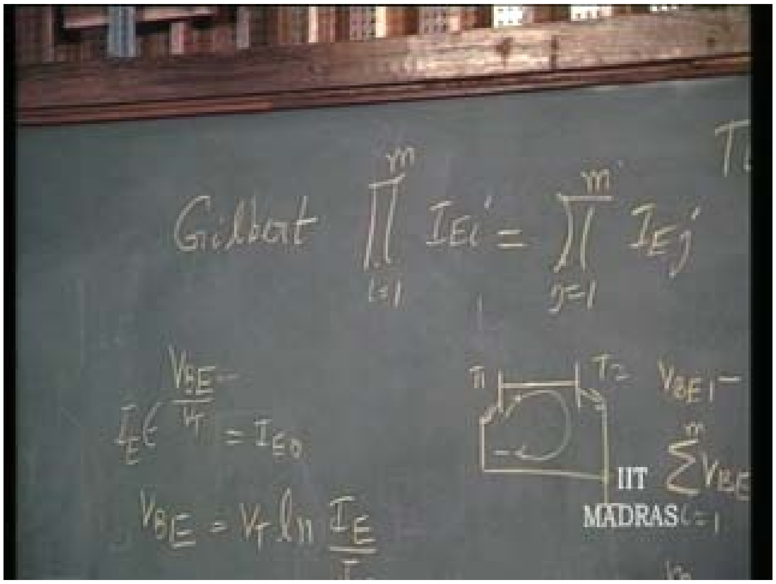

There is a loop here and the Kirchoff voltage law says total voltage inside the loop should be zero. So the voltage here is, let us say this is T_1 and this is T_2, V_{BE1} is equal to V_{BE2} or V_{BE1} minus V_{BE2} is equal to 0. You can put any number of such diodes. All diodes which have plus minus voltage like this will add V_{BE1} plus V_{BE2} up to V_{BE} L and then another set of diodes with opposing polarity like V_{BE} dash1 V_{BE} dash2 of the same number. The total voltage should be 0 or you can just say sigma of V_{BE1}i where i is equal to 1 to m should be equal to sigma of V_{BE}j where j is equal to 1 to m. So m diodes in clockwise direction are getting forward bias, and m diodes in anticlockwise direction, this is a simple thing. If these voltages sum up like this let us look at the current.

What is the current of how is it related, V_{BE} by exponent V_{BE} by VT IE is equal to I_{E0} so what is V_{BE} for any transistor? It is VT log IE by I_{E0}. Is this point on the step?
Now do you make something out of this relationship? It is a beautiful relationship. Why is it beautiful? It is because sigma of all voltages here will mean sigma of i is equal to 1 to m VT log I_{Ei} by I_{E0} is equal to sigma of j is equal to 1 to m VT log I_{Ej} by I_{E0}. What happens now? VT gets cancelled.

Summation of log is product. Product of all currents of those diodes having voltage in clockwise direction will be equal to product to all currents flowing through those diodes which are connected in the anticlockwise direction. This is what is now becoming famous as Trans linear principle. And a minor example of this Trans linear principle is the simple current mirror.

What does it say? Again product of I_{Ei} i is equal to 1 to m is equal to product of I_{Ej} j is equal to 1 to m. This is the most powerful concept ever to be found out in integrated circuit. And I would say the father of this concept is a famous person in electrical engineering by name Gilbert. He has done a lot of work. And you can readily see for this trivial case of this particular structure V_{BE1} minus V_{BE2} is equal to 0 which means I_{E1} is equal to I_{E2}.

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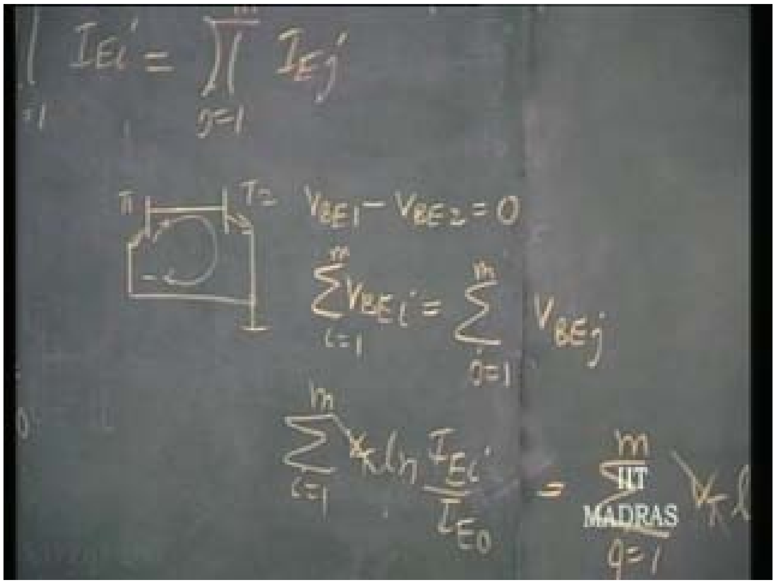

And exploiting this principle we have been able to design precise multipliers, logarithmic amplifiers, square rooters, squares, two enamors indicators and all signal processing activity using just the bipolar transistor or mass transistor working in the sub threshold region. Mass transistor working in the sub threshold region has a current voltage relationship which is exactly similar to that of bipolar transistor.

So making use of this concept we have what are called as the signal processing circuits becoming popular now-a-days in what are called as neural networks. These are nothing but neural networks which will simply do highly complicated non linear signal processing with just few devices which otherwise requires host of computers. These can be done straight away at the device level itself, the signal processing can be done straight away at the device level itself without necessarily converting it into digital and then using an fast algorithm and then converting back to whatever you want.

So the neural networks make use of these basic blocks in order to realize lot of signal processors. That is what is done in the human brain also. Most of the signal processing is done at the transducer level, eye, ear, skin etc. Signal processing is not postponed to the brain. Lot of signal processing is done at the transducer level and what is absolutely necessary to be transmitted to compare and contrast are the only ones transmitted to the brain and then the information is fed back as to what to do.

Otherwise most of the signal processing activity in the brain is sort of distributed all over the transducers themselves eye, ear, skin etc. So the present attempt is to replicate the brain in terms of first getting some basic performances of eye, ear, skin, and nose, the smell. So, can these things be done by the transducer itself in which case the transistor itself can act as a transducer and then do the processing and decide whether to send the signal to the brain or not.

We will learn more about what are called as Translinear networks in the next class. We will also learn what are the various analog signal processing block that can be formulated very simply using test bipolar transistors or mass transistors working in the sub threshold region.