Analog Integrated Circuit Design
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Lecture - 20
Components available in a CMOS process

Hello and welcome to the lecture 20 of analog integrated circuit design.

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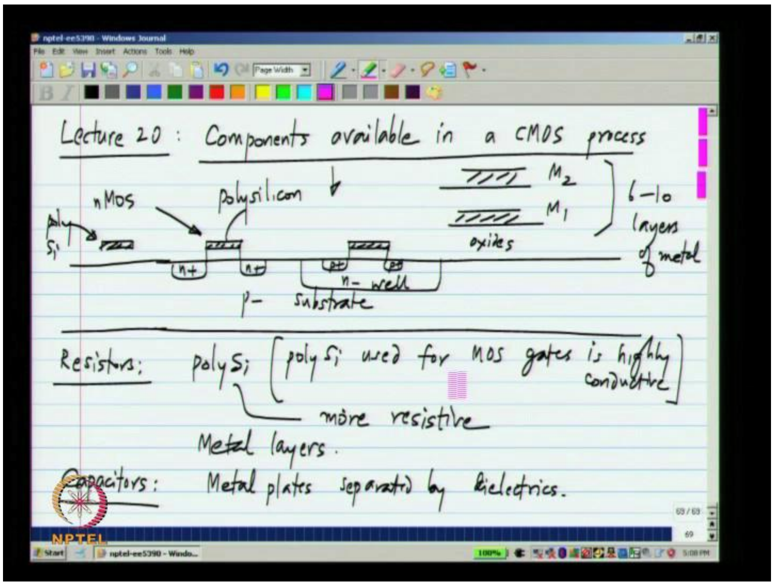

So, far we have discussed a lot of concepts of negative feedback amplifiers the opamps. And, then how to make negative feedback system stable and so on; by looking at the loop an etcetera, etcetera. We also look at how to design the opamps not at the transistor level but at the level of control sources or voltage control current sources that is trans connectors ok.

Now, what we are going to do now is such which clear and look at realize this opamps in a CMOS process. So, as a precursor to that; we will first look at what kind of components are available in a CMOS process; how many of you may be familiar with component that you use in the lab the discrete resistors, capacitors etcetera. Now, the same things are available in I C processes but with some differences in characteristic. And, some things that we need to be aware of before we go ahead and design the opamps. So, this lecture will be devoted to basically the components that are available in a CMOS integrated circuit process.

First of all the I C process are planar; that is a substrate. And, there are many layers on top of this of conducting that is metal layers; and insulating there is oscillate layers and all the components are built up from that. So, as you may be familiar with from your device physics classes we have mosfet made on substrate; typically the starting material is a p type substrate. And, you make the n most transistors directly on the p type substrate.

And, to make a p most transistor you make a n well and put the p most transistor inside. And, you also have basically between the gate and the substrate there will be an oxide layer and you also need to connect many components. So, what happens is we have a number of layers of insulating material called oxides. And, then there will be a metal layer let me called this metal one; and then there will be an another layer of oxide and metal two and so on.

And, in modern processes there could be at least 6 or even more layers of metal; it could have 6 to 10 layers of metal. And, if you look at the process data sheet that will give you the thickness of these metals the resistivity and so on; essentially the one thing to keep in mind is that what you control as an I C designer is not the composition of these materials; all those things will be fixed by the processing people; what you control is the layout of this that is the plan view of this right. Essentially you have 2 dimensions to play with that is looking from the top right; you can draw these gates, you can draw the diffusion regions, you can draw the metals any which you want; you do not have control over this dimension that is the up down dimension on this page ok.

So, it is a planer process and as an I C designer you will be playing around in that plane looking from the top of the chip. Now, what else can do we have here? In addition to the metal layers first of all gate itself is made of polysilicon. And, there may be different flavors of polysilicon available; you do not have to have a mosfet to have a polysilicon, you can have a layer of polysilicon just available for you to make any component that you used to make; will see how it is useful later? Now, what are the components that we need that you are familiar with first of all resistors; and how do you make resistors? You can make them by using polysilicon material; and typically the polysilicon used for the MOS gates is highly conductive; its design to be like that. So, in a given process you could have other variant of polysilicon which are more resistive; so that is available.

And, you can also make resistors using metal layers although obviously metal is highly conductive. And, you can only make very low values of resistance using metal layers. And, you also need to have capacitors; and for capacitors anything we capacitors we have 2 conductor separate by dielectric that is a capacitor. So, using these metal layers I mean using plates of these metal layers which are separated by dielectric; you can form capacitors. And, then you of course have MOS transistors that are available that is why it is a CMOS process; and you can also have an inductors.

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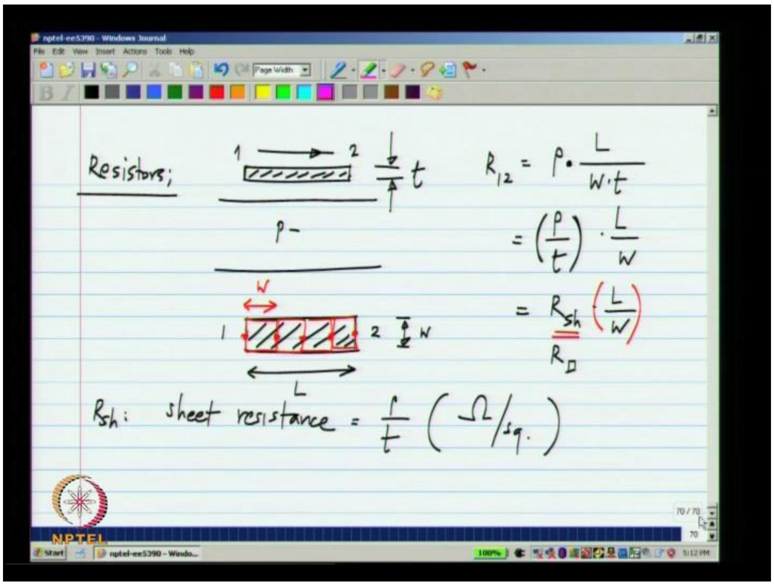

We will not discussed them, we will not use them although they are used in high frequency circuits. Because of the limitations of the size; the value of the inductor that you get is very small. And, you can make it by realizing planar spirals of metal on an integrated circuit you can realize inductors as well ok. Now, first let us look at resistors. Now, you know how a resistance is made? Its by using a slab of some resistive material and you know what the resistance of that is; is the resistivity rho times the length of the resistive path divided by cross sectional area of the path. Now, on I see everything is up to you that is it is not that you have given fixed values of resistors; you can adjust these dimensions. So, that you can get the resistance that you want. So, as a designer you do make use of this freedom.

Now, as I mentioned earlier. So, let us say you have the substrate and on that you have some piece of polysilicon that you are using as a resistor. So, let us say this end is 1, that is 2 and resister the current flows from there to there. Now, looking from the top the plan view let say it looks like this; this is 1, that is 2 and this dimension is called the width. And, this is the length; that is why we called this the thickness t. Now, as I mentioned earlier you have control only over W and L; you do not have control over the thickness that is optimized for the process by the processing people and you have to take it as it is. Similarly, you also do not have control over the resistivity of the material ok.

Now, the resistance between one and two is given by the resistivity of the material times the length divided by the cross sectional area which is nothing but this W times the thickness of the material I will write this as rho by t times L by W. Now, because you have control over only W and L; you are not usually given the value of rho and t separately in as a design its more quit common to specify the ratio rho by t as a some unit. And, then you multiply that by L by W to get the resistance that you want.

And, this quantity rho by t is called a sheet resistance; which is either denoted by R s h or sometimes by this times L by W; and what is this? This is nothing but the resistance of one square of material; if the length equals the width the resistance from here to there is this R s h it has dimensions of resistance and times L by W. So, you have as many squares as you want. So, let us say in this case I have 4 squares that is L by W equal 4.

So, then I have the sheet resistance of the resistance times L by W to be the total resistance. And, this is measured in ohms per square it has dimensions of resistance but the ohms per square is expressively given. So, that you understand that it is the resistance of single square from one end to another. And, then you make many squares of it; you multiply that by the number of squares to get the total resistance; L by W after all is the number of squares going from one to two.

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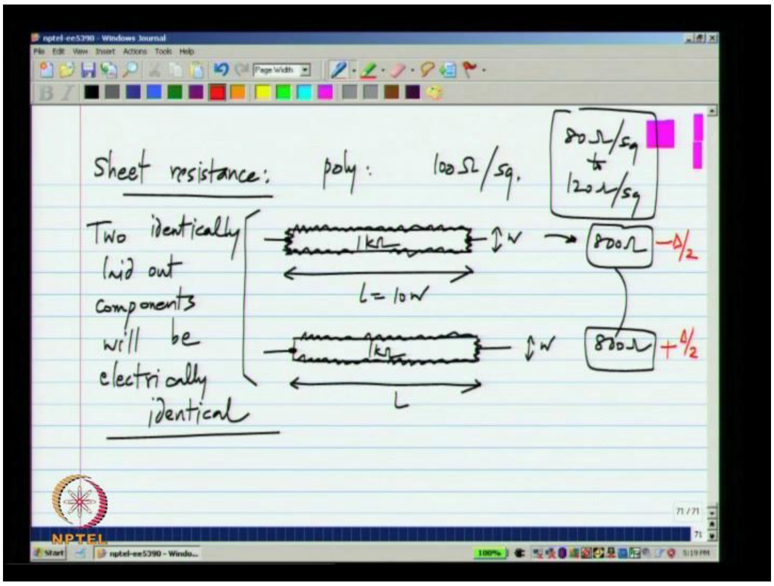

Now, this sheet resistance value is given to you; let us say I mean I will just take some arbitrary example for some polysilicon layer; let us say it is 100 ohms per square. So, that means that if you want 1 kilo ohm resistance you have to use some width and you have to use a length that is 10 time the width. So, that the resistance from this side to that side is 1 kilo ohm L by W is 10; that time 100 ohm square is 1 kilo ohm that is the resistance that you have ok.

Now, the question is how do you decide the absolute value of W and L? Now, you could use W equals 1 microns L equals 10 microns or W equals 10 microns and W of 100 microns. Now, what do you do? First of all obviously if you make W and L smaller the area that you utilize will be smaller and you can pack more resistors. Now, in general there will be a minimum limit on how small you can make any dimension. In fact, this is specified in the process itself you hear terms like 0.18 microns CMOS or 90 nanometer CMOS and so on. So, those the length that is dimension that is mentioned along with the process specify the minimum dimension of some components in the process ok.

So, for instance typically when you say a 90 nanometer CMOS process; what is implied is that minimum gate length is 90 nanometer; sometimes this 90 nanometer refers to the minimum spacing between metal layers. And, the minimum constant of other dimension will be similar; that is the minimum width of the transistor will be limited to if not 90 nanometer but something close to that. So, it is harder and harder to make component smaller and smaller that is why the final technologies are more expensive. But you due do need them as we will see later for getting higher and higher speed circuits.

And, also to pack more and more circuits in to a given area. In fact, that is one of the contributors for this semi conductor revolution; where in a small chip you can have a great deal of functionality of circuitry. So, on the minimum side there is some constraint but like when you let us say you want to design a resistor what really decides further I use 1 micron width or 10 micron width and so on.

So, that will come to soon; that is what we will discussed now. Now, one of the things, one of the features of an I C process is that all these components are manufactured more or less simultaneously; that is all the resistors are manufactured simultaneously, all the resistances on a single chip are doped simultaneously and manufacture simultaneously ok.

So, which means that if you make 2 identical resistor that is why I have another one also which lets say same W as the earlier one. And, the same L on the same material of course it will also have a resistance of 1 kilo ohm. So, that is two identically laid out components will also be electrically identical; these two not only of resistors but also of capacitors and any other component that you can think of like mosfet and inductor and so on. Now, this fact is exploited a great deal in I C design; you use the matching of the components to your benefit in circuit design.

Now, it turns out that the value of the component itself cannot be accurately adjusted; for instance what happens is when your manufacturing the thickness of the poly silicon layer can be quite different from what you expect. And, similarly the amount of semi conductor doping which influences the resistibility can also not be accurately fixed. So, that means that the value of rho and the value of the thickness t can vary. So, that means the rho by t can also vary.

So, the actual value of the sheet resistance where is quite a bit; typically when your half let us say its 100 ohms per square; it really mean it is probably somewhere between 80 ohms per square and 120 ohms per square; sometimes this variation is even larger than this it could be anywhere from 50 ohm per square to 150 ohms per square. So, you have to design your circuits to; so that even with this great deal of variation in the absolute value of components the circuits operate correctly. But one thing you can rely on is that let us say this happens to be in this particular chip the resistivity 80 ohms per square. So, that means that this particular resistance on top is 800 ohms instead of 1 kilo ohm. But this the other resistance will also be 800 ohms that you can more or less guarantee. So, that different component will be identical to each other; although the absolute values will not be very accurately fixed.

So, you do use the fact that they the values match to each other greatly in the design of integrate circuits. Now, will there be match exactly. Now, it turns out that is not the case because of many reasons; first of all the doping will be the same on average in the 2 cases but will not exactly be the same. And, similarly these adjust and so on will have some errors; the definition of the adjust will not be exactly a straight line and there will be some errors there; and doping while it is the same, it is not exactly the same.

So, it turns out that there are some small variations that is these two suppose to be 800 ohms. But there will be let us say one of them is 800 ohms minus some delta by 2 and the other one is 800 ohms plus some delta by 2. So, if you manufacture a large number of identical resistor on integrated circuits; let us say you make a 1000 of them; they will have an average value is 800 ohms. But the exact values will not be 800 ohms and each of them. Now, they will fall in some distribution.

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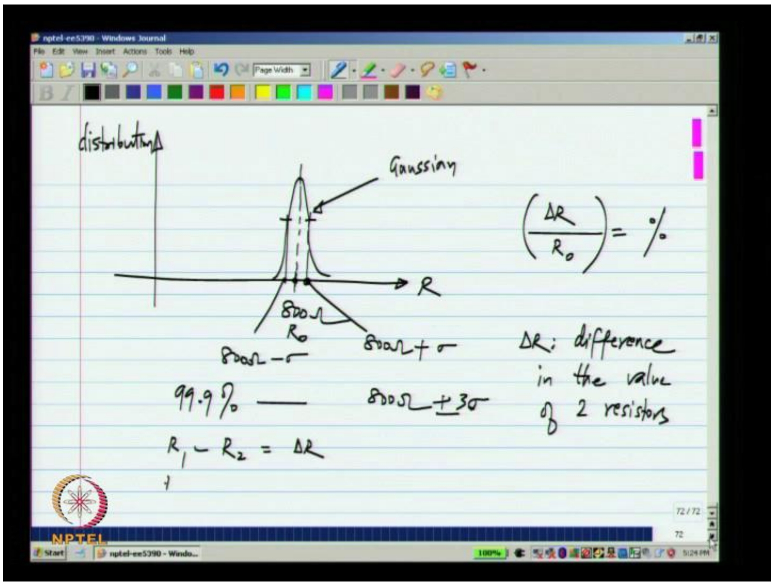

Let us say your manufacture a 1000 resistors of value 800 ohms it turns out there. And, if you plot the distribution and histogram; you will find that it will be of some shape like that. And, like any random quantity influenced by a large number of random parameter this will be a Gaussian; it will have some standard deviation sigma this point is 800 ohms plus sigma; and that point is 800 ohms minus sigma. And, you know that from the knowledge Gaussian distribution that 99.9 percent of the samples will be within 800 ohms plus minus 3 sigma; this means that lets say manufacture like 10800 ohms resistors on a single chip ok.

And there is some sigma value to the distribution. So, 99.9 percent of them that is 9990 of them will have a value within 800 ohms plus or minus 3 sigma. Now, because we rely on matching of these resistors; very simple example is our non inverting amplifier; where the gain depends on the ratio of the resistors. We said that the gain is k; where one of the resistors is k minus 1 R and the other resistor is R.

So, this k minus one is nothing but the ratio of the resistors and again is related to that one. Now, if the ratio is inaccurate the gain will be inaccurate as well; there is a certain amount of inaccuracy that you can tolerate but no more. So, that means that you have to make sure that resistors are not inaccurate by more than some amount ok.

So, basically you need to know the value of this sigma; in order to design your circuit and make sure that there it is sufficiently accurate. Let me call this sigma of the resistance value. Now, it turns out that the nominal resistance let me call it R naught; that will be the average value of large number of resistances which are manufacture like this. And, each one will have a variation from the nominal and this delta R by R naught; where delta R is difference in the value of 2 resistors that is let us say you make a large number of resistors. And, you take them pair wise; let me call them R 1 and R 2 and you take the difference R 1 minus R 2 that is delta R. And, you compare that to the main value of all the resistors this will have also a Gaussian distribution ok.

Now, this is a dimension less quantity and this is an easier things to deal with than the dimension quantity. Because the actual sigma will depend on the value of R naught but if we normalize the value of R naught; then that will have some common characteristics; so that the easy to specify. Now, this itself is usually specified as some percentage and then it turns out that.

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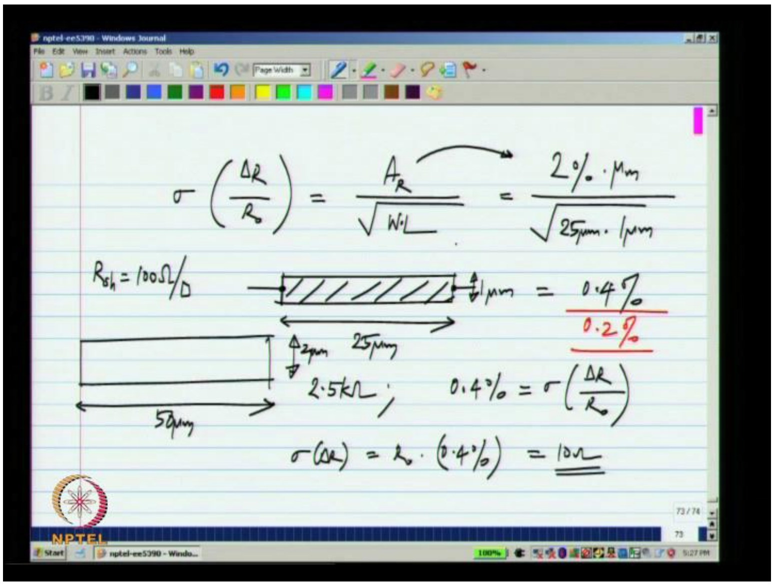

The standard deviation of delta R by R naught depends on the size of the resistor; it is inversely proportional to the square root of the area of the resistor. And, they are in some constant depends on the process; they are defined as they are a specified as percentage micrometer. So, let us say it is given as 2 percent micron and let us say you have resistance of width 1 micron and a length 25 micron ok.

So, the standard deviation of delta R by R naught will be 2 percent micron divided by square root of 25 micron times 1 micron; which is basically 0.4 percent right. And, let us see assume the same material as before; if the sheet resistance is 100 ohms per square this will have a nominal value of 25 times 100 So, it will have a 2.5 kilo nominal value and if you make 2 of these resistors on a chip you expect that there will be variation delta R. And, the standard deviation of that variation will be 0.4 percent; delta R by R naught that is the relative standard deviation ok.

And, from this you can calculate the absolute standard deviation sigma of delta R will be nothing but R naught times 0.4 percent; which you can figure out how much it is 1 percent of 25 kilo ohms 25 ohms times 0.4. So, that is basically 10 ohms. So, that means that if you make a large number of these resistors you can expect 99.9 percent of them to be within 30 ohms of 2.5 kilo ohms. Now, whether the diaphragm is good enough for you or not depends on the application. Now, what do you do if you want to make it more accurate; you have to increase both W and L. So, let us say instead of using 1 micron width I use 2 microns width and 50 micron length what will happen? The standard deviation will change to the denominator will increased by a factor of 2. So, the standard deviation will become 0.2 percent instead ok.

So, similarly you can calculate if you want only 0.1 percent you have to use 4 micron width and 100 micron length and so on; this is the dependence of resistance accuracy on the absolute size and this is what decides the absolute size of resistors. Now, let us say there you have some application in which the accuracy of the resistors is not important. Then, you just use the minimum size because you just you use the minimum area in that case. Now, first of all does this formula make sense? The accuracy seems to be inversely proportional to the square root of area and you can verify that very easily by doing this.

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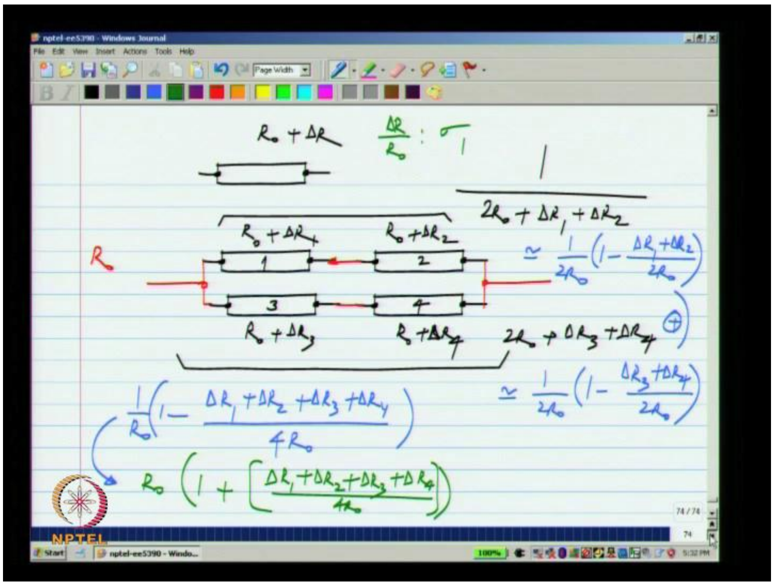

So, let us say I have some resistance R this is a nominal value of R naught. Now, let me take 4 of these and connect it up like that; I will connect these two in series, and these two in series and the two series combination in parallel; what is the nominal value of this; obviously, that is also R naught. Now, let us say this has some deviation delta R. Now, what to happen in this case will have each of these will be delta R; but the important thing is these are random variation which are uncorrelated from each other. So, this is delta R 1, this is delta R 2, this is delta R 3 and this is delta R 4; each resistance will have random variation that is uncorrelated from the variation in all the other resistances. Because each of these variations come from individual distribution of dopants and individual shapes of the layout and jaggedness of the layout and so on.

So, what is the total resistance that we have here? The resistance of this segment is 2 R naught plus delta R 1 plus delta R 2. And, this will be 2 R naught plus delta R 3 plus delta R 4 and calculate the parallel combination we need to add up the conductance. If I calculate the conductance of this; what will I get? I will use the approximation delta R and much smaller than 2 R naught.

So, this is approximately equal to 1 over 2 R naught 1 minus delta R 1 plus delta R 2 divided by 2 R naught 1 by 1 plus x is approximately 1 minus x; that is what I have used here. And, similarly this is 1 over 2 R naught 1 minus delta R 3 plus delta R 4 divided by 2 R when I add up the conductance what am I going to get the total conductance will be 1 by R naught I am just summing these 2; 1 by R naught minus delta R 1 plus delta R 2 plus delta R 3plus delta R 4 divided by 2 R naught sorry divided by 4 R naught.

So, that is what I will have I mean I have 4 R naught square in the denominator here I will also have 4 R naught square in the denominator over here. And, I will calculate the resistance again from this; I have to take the reciprocal I will again use 1by 1 minus x approximately equal to 1 plus x the resistance turns out to be. Now, let us say delta R by R naught as a certain sigma I will call it sigma 1. Now, my new resistance has a delta R by R naught which is equal to this number.

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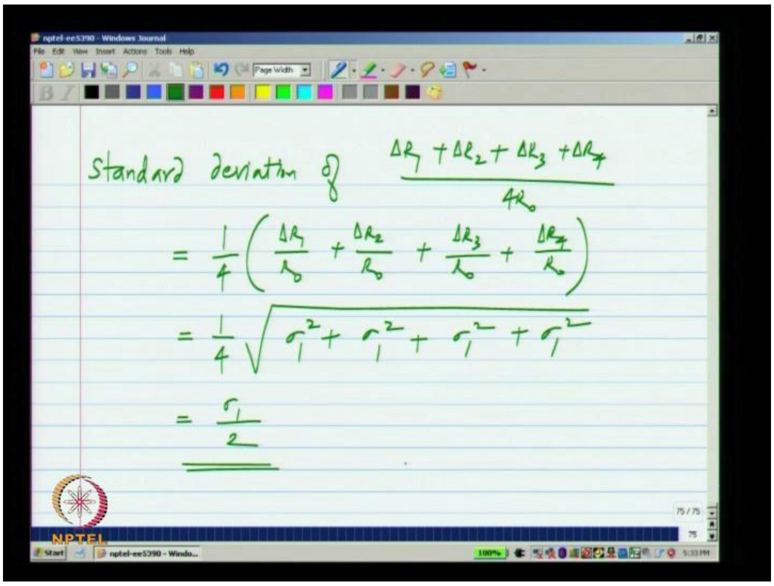

So, I have to find out what the standard deviation of delta R 1 plus delta R 2 plus delta R 3 plus delta R 4 divided by 4 R naught is. Now, each of these is identical to the other. So, if the standard deviation of delta R by R naught is sigma 1; then what I have here is 1 by 4 delta R 1 by R naught plus delta R 2 by R naught plus delta R 3 by R naught plus delta R 4 by R naught. Now, each of these has a standard deviation of sigma 1. But because I am adding uncorrelated quantities; the total standard deviation will be the square root of sum of squares and which is nothing but sigma 1 divided by 2 right.

So, what I will do we took a resistor we look 4 of those and connected in series parallel combination. So, that the resistance value itself as the same as before. Now, the variation in each of these 4 parts is uncorrelated from each other. And, finally when you calculate the standard deviation of the relative error; that is standard deviation of the delta R by R naught what do we get? We get standard deviation to be on half of what was before. Now, you can consider these 4 resistances; let say I put the next to each other; this is one, that is the other one, this is the other one, this is the other one.

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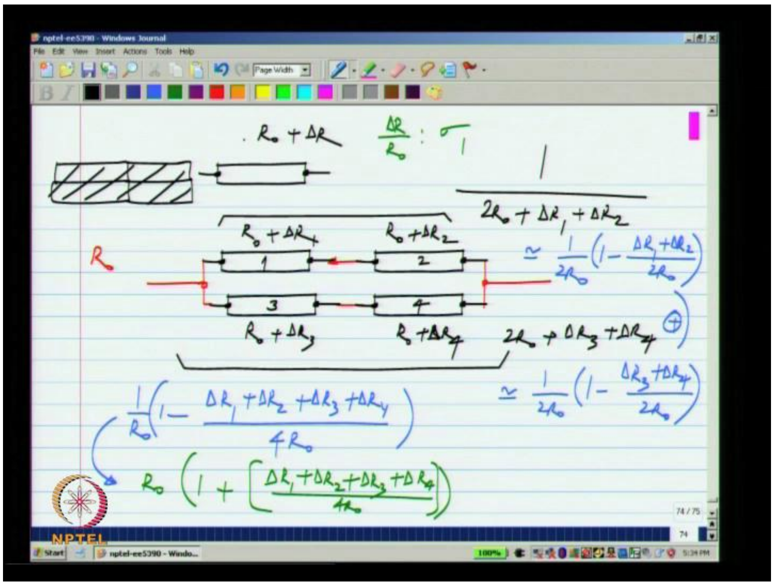

So, you simply think of it is a single resistor with twice the width and twice the length. So, this is just to show you that if you increase both the dimension by the same factor the standard deviation also reduces by the same factor; this is consistent with the formula that we have where the relative error in a resistor the standard deviation of that is given by some constant area divided by the square root of W L ok.

We will see that this law holds for all components; this simply is dependent on each component being made up of smaller pieces which are identical and uncorrelated to each other. So, which of the pieces uncorrelated to each other; that is the key assumption here. So, this tells you something about resistors; the absolute value is not fixed very well you will have to live with wide variation sometimes like what you think is 100 ohms could be 50 ohms or 150 ohms. But you can rely on the ratio of the resistors to be accurate but the accuracy has to be quantified and that is given by this number sigma (R). And, what does that measured that simply gives you the distribution of difference between 2 resistors divided by the nominal value of the resistor. And, that depends on the absolute size of the resistance itself.

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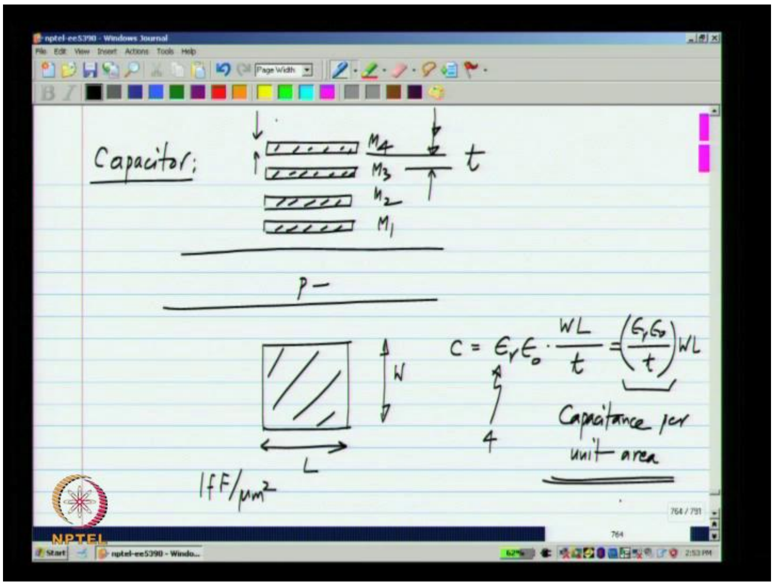

Now, moving on to the next component; let us say like capacitor. So, again we have this up straight and we have many metal layers like I said we have up to even 10 metal layers in some process; I will just show 4 of them these are not to scale drawing; you can refer to process documents for drawings to scale. And, you can make capacitors let us say between M 1 and M 2 and like before you have control over only the plan of this one; that is the top you of this one; the thickness of this metals and also the spacing between these metals is fixed. Now, let us say the spacing between these two metals is t and I make a capacitor by forming a plate of metal 4 and metal 3. Let us say the width is W and the length is L. And, we know that the capacitance between these 2 will have, the capacitance between these 2 plates is given by the formula epsilon r which is the relative form activity time, epsilon naught which is the formatively of vacuum times the area of the plates W L divided by the spacing between the plates t ok.

Now, typically for the oxide material that is used in integrated circuit the relative form activity is 4. And, you know the value epsilon naught and this t because it is not fixed as before epsilon r epsilon naught by t is specified as a constant times W L. And, this is nothing but the capacitance per unit area and this very much depends on the spacing between the plates.

And, there are technologies in which specifically for making capacitors there will be 2 layers of metal which are separated by a small gap. Now, these metals cannot be used for anything else except for making capacitors. So, in addition to the normal metal layers which we used as wires for interconnecting everything; there will be 2 layers which are very closely space specifically for making capacitors ok. But even then the amount of capacitance that you can get on a chip is very small; a typical value of this capacitance per unit area is 1 femto farad per micron square.

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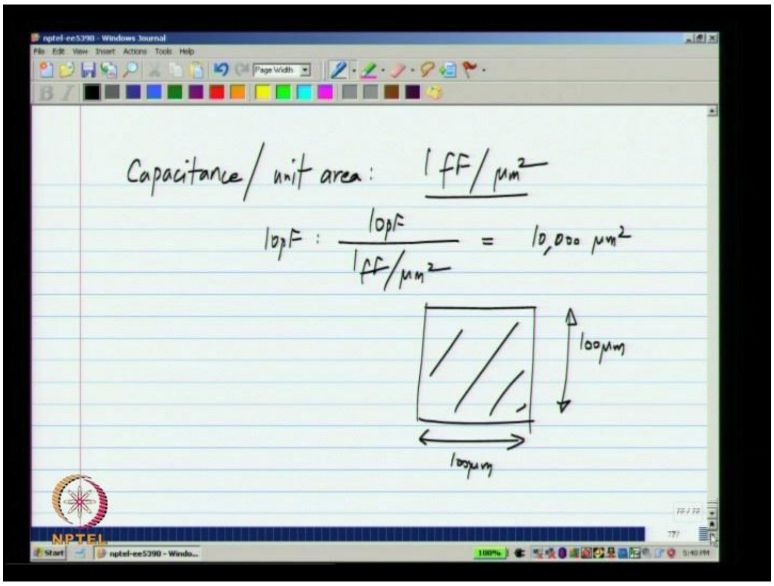

So, this means that let us say you wanted 10 Pico farad capacitance; in a 10 Pico farad divided by 1 femto farad per micron square; it basically gives you 10000 micron square. So, you need to use a metal plate that is 100 microns for 100 microns to realize this capacitance right. Now, this is a very large area you may not be able to appreciate this right now. But this kind of area you probably hold a opamps or some complicated digital circuitry; which can perform significant signal processing functions ok.

So, unless you really need it you do not go around wasting area like this. So, of course there are analog circuits in which you need many ((Refer Time: 36:39)) Pico farads of capacitance. But clearly you can see that to have very large capacitors like Nano farad is quite impossible on an integrated circuit simply because of area constant; typically the capacitance is limited to a few Pico farads to sometimes even 100 peak farad is made.

So, that is only in personal conditions and then also you cannot use many of them because they will use a lot of area. So, whatever you have to do in a integrated circuits you have to do it with either no capacitors or the minimum value of capacitors that is possible ok; unlike resistors once you decide on the value of the capacitor; there is no ambiguity you have to have a certain size. Now, you can choose to either make it square or ((Refer Time: 37:17)) square but beyond that you would not have any freedom. But just like resistors there will be mismatched between capacitor.

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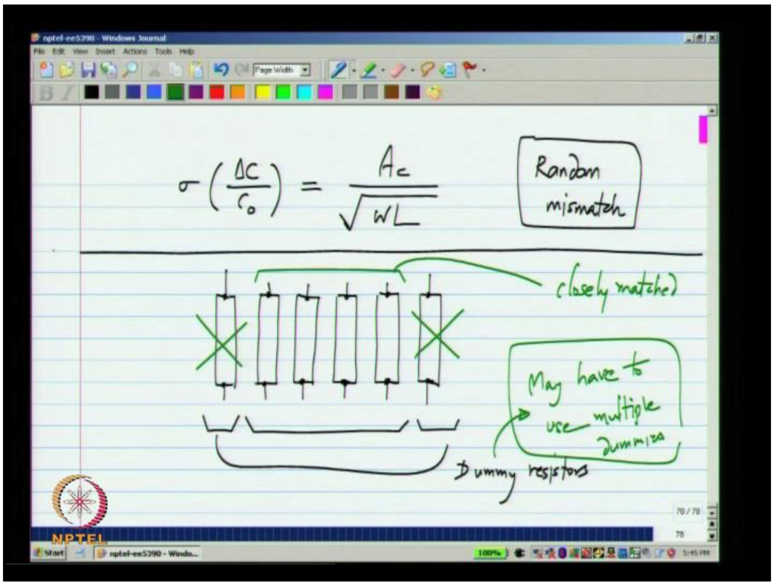

And, the standard deviation of the relative mismatch delta C by C naught is given by some constant A C divided by square root of W L. Now, this is again similar to what we had in resistor; let us say you take a integrated circuit and you make a 1000 capacitors on it. And, you take them pair wise and measure the difference in capacitance between them; there will be some difference; the ratio of that difference to the nominal value of the capacitors C naught is this number which is A C by square root of W L. So, the larger the capacitor you make the more they will be match to each other; the more closely they will be match to each other, right.

So, if you have circuit in which matching between capacitors are important; you will be forced to use larger capacitors this is similar to resistors. Now, it turns out that the matching between capacitors is usually somewhat better than the matching between the resistors. So, this is something to do with what are all the things that can vary in I C fabrication process; just turns out that the capacitors typically match better than resistors.

Now, before we go to other things; we can also look at what are the factors that influence matching beyond this what is known as random mismatch; the kind of mismatch I discussed so far is known as random mismatch. Now, besides this there will be other kind of mismatch; which are due to systematic causes right I said that you make let us say 2 identical resistors; they will match to each other.

Now, you cannot laid this things out arbitrary; first of all if you have this resistors very close to each other they will match to each other very well. But if you have them very far from each other or in arbitrary orientation. So, let us say one of them is like this; and the other one is in that direction they will not match to each other very well. Although they have the same dimensions; this is because of some directional dependence during fabrication and so on.

So, in general to get the best matching you must have components aligned in the same direction and also in the same environmental condition; what do I mean by that? So, let us say I have 4 resistors like this; and they all have the same W and L right. So, these are the terminals of the resistors. Now, as you can see these 2 resistors have 2 neighbors; neighbors on both sides whereas the resistors of the ends have neighbors only one side. So, it turns out that these resistors will be different from whatever is inside; if you have an array of resistors once outer most will have slightly different values from the once inside. Now, if you are really interested in matching these 4 resistors; what you must do is to place additional resistors on either side; these are known as dummy resistors.

Now, you can see that this one has 2 neighbors, this has 2 neighbors and this has 2 neighbors all of them. And, these resistors are not useable; because these are placed only to make the environment similar for the other resistors. Now, these 4 resistors will be closely matched to each other. Now, it is not guaranteed that whereas with single dummy resistors you will have close matching; sometimes you may also have to use multiple dummy on either side. So, I will use one on each side but you may have to use 2 or 3. Now, this is a very important thing and this comes in to picture when you start doing the layout of your analog circuit; you want 2 resistors to be match and this is how you have to do it.

Now, exactly the same principle hold for capacitors; if you have multiple capacitors you will have to make sure that each one of them sees the same neighborhood. So, to speak; so that there will be identical to each other. Now, another common issue is what I showed earlier is if you want 2 identical resistors how to arrange it. So, that they will be as close to being identical as possible.

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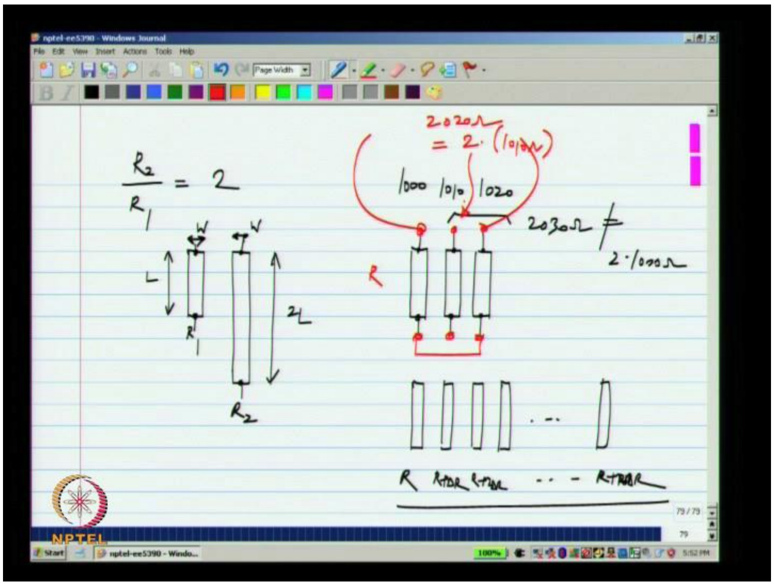

Now let us say you want the ratio R 2 by R 1 equals to that is you want 2 resistors; one of which has twice the resistance of the other one; how do you realize these resistors on a chip? So, the immediate possibility that comes to mind is something like this let us say I use the same width. But twice the length for this and some unit length for that one. So, let us say this is R 1, R 2. Now, it turns out that if you do measure these things these 2 resistors the ratio will not be exactly 2; this happens because the total resistance is a sum of the resistance contributed by the body and the contacts and so on. And, near the ends what happens is the current is not uniformly distributed across the cross section of the resistor; remember the formula for resistance rho times the length divided by area is obtained assuming uniform current electricity through the resistance.

Now, if the current electricity is not uniform then the resistance will not be given by that formula. So, that is why if you simply make one of the resistances twice as long as other; the resistance will not be exactly larger by a factor of two. So, what do you have to do; to realize this properly you have to make 3 resistors and connect 2 of them in series. Now, because each of these has exactly the same width and length; the ratio of whatever is contributed by the ends of the resistors where the current density is not uniform to the middle will be the same. So, whatever these resistances this will be the same as that and that will be the same as that. And, between these 2 you will have some resistance R which is R 1 and between those two you will have resistance R 2 which is equal to 2 times R 1.

So, this is what you will have to do in order to make accurate ratios of resistors. And, just as before this has only 1 neighbor whereas this one has 2 neighbors. So, you also have to use dummy devices on either sides. So, this means that you can only realize the resistance ratios which are integers accurately. So, if you have some arbitrary ratio then it is more difficult; what you have to do is to try and reduce it to some integer plus something.

So, the integer part realize the accurately and the fractional part it may be slightly inaccurate. But that is the best you can do you can also represent; the ratio that you want the ratio of integer. But if the numbers become very large that is say you have 243 divided by 356 you will have to make that many unit resistors and that also is very expensive in terms of area. So, you try to do it such you get this integer ratio as much as possible plus the fraction part which may be realize somewhat in accurately. If you do integer ratio if you do all of these things that I mentioned earlier; you use the dummy devices. And, you also lay out everything else multiples of identical units. If you want 2 to resistance ratio you never make one of them twice as long as other one; you make 3 resistors you connect 2 of them in series. So, that will give you twice the resistance of the single resistor.

Now, in addition to this the one more aspect that can come in to picture; that is let us say you have a number of resistors in a line. Now, what happens is that can be systematic gradient. And, this could be a systematic gradient because of either the thickness or the doping of the resistors. So, what happens is this is let us say some R; this could be R plus delta R this is R plus 2 delta R and so on and this is R plus n delta R. Now, delta is different from the random mismatch I discussed earlier; this is because of systematic variation as you go from one side to the other side of the chip it could be that the thickness of the resistive material is slightly different or the doping is slightly different and so on.

Now, let us say this is the case. Now, we will still wanted this 2 to 1 ratio now what happens is this resistance is slightly different from this and that is slightly different that one. Now, just let me just take some specific numbers let us say this is 1 kilo ohm and the next one is 1 kilo ohm plus 10 ohms and the next one is 1 kilo ohm plus 20 ohms; these numbers are slightly exaggerated to show you the effect. Now, clearly if you put 2of these in series what happens is the sum of these two is 2030 ohms and this is not to same as 2 times 1000 ohms. But what can you do to rectify the situation; it turns out that there is a very simple remedy what I do is I do not connect these 2 in series; I connect those 2 in series.

So, what happens is between these 2 terminals I get two 2020 ohms and that is exactly equal to 2 times 1010 ohms which is the resistance of the middle resistor. So, this is known as the common centroid technique; the single resistor has the same centroid as the series combination of the 2 resistors. So, accuracy is really really important to you and you suspect that this linear gradients on the chip are playing a significant role; you do this common centroid layout where if you have let us say pair of resistors. The pair of resistors should have the same centroid; that is the same average position; the average position of these 2 is in the middle as well which is the position of the middle resistor.

And, exactly the same principle holds for capacitors this makes the inter connect complicated. So, you use it only when need it but you use this for laying out resistors and capacitors and so on. So, what we have discussed so far are resistors and capacitors on chip; and how to match them very well? Because matching is extremely important in a integrate circuit design; you need to use this principle. Now, later we will also exploit matching between MOS transistors. And, even there when you want 2 devices to match exactly; these are the principles that you use; that is when you want to multiplicity you use multiple devices and connect them together instead of making dimensions larger or smaller see you in the next lecture.