Analog Integrated Circuits
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Lecture - 09
Systematic Mismatch

In this lecture we will start looking at mismatch more specifically at a particular type of mismatch called systematic mismatch.

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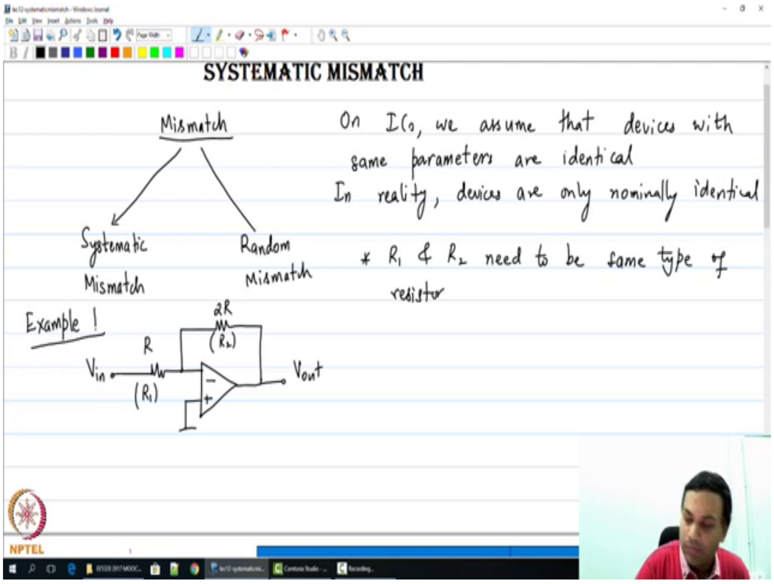

SYSTEMATIC MISMATCH

On ICs, we assume that devices with same parameters are identical

In reality, devices are only nominally identical

* R_1 & R_2 need to be same type of resistor

So, broadly we first need to find out what mismatch means. Now if you look at traditional analogue design, discrete analogue design not an integrated circuits is very rare that you would find people talking about mismatch. Whereas, on integrated circuits pretty much you know almost all the time, you will be interested in what mismatches and how it is going to affect your circle.

The reason is very simple. So, the origin of study of mismatch comes about because on ICs, you assume we assume that devices with the same parameters are identical. What do I mean by this? Suppose I take 2 transistors on an ic, and I make sure they have the same geometric parameter same width and same length, I am automatically going to assume that these 2 devices are going to be identical. In other words I apply a gate source voltage dc gate source voltage on both the devices I should get exactly the same current to as much accuracy as I get to observe.

However having said that what happens in reality is that, these devices are only nominally identical. What do I mean by nominally identical. So, what this means is that these devices will be very close to each other, but there will be some small differences, and a lot of analogue design assumes that you are going to try to make these devices as identical as possible, and hopefully by the end of this course you will be able to appreciate why this is such a strong advantage of IC design. So, the minute you say that if you take 2 devices they are only nominally identical, it means that there is some amount of mismatch between these 2 devices 2 or more devices.

So, therefore, we now identify 2 sources of mismatch, the first type of mismatch is what is called systematic mismatch, that this is the type of mismatch that we will study in this class and in the next class we will study the other type of mismatch which is a called random mismatch. Now let us look at systematic mismatch in a little bit more detail. So, we will actually take an example. So, let us say I am trying to build a resistor why would I want to build a resistor? I may want to build a resistor because I am building an amplifier and to build an amplifier and using the negative feedback circuit, let us say I am trying to build an amplifier of gain minus 2, and I need 2 resistors for this and I need a resistor R and a resistor 2 R to create this amplifier.

The gain of this amplifier of course, is minus 2. Now what do I assume when I do this I assume that I can build the op amp and hopefully by the end of this course you will be able to do this. And you should also be able to decide what type of resistor you need, and what is the size of the resistor value of the resistor etcetera, but let us you know look at that first from a let us look at the resistors for now, because that is an easier thing to understand right now. First of all if you take an integrated circuit there are many different types of resistors. So, now, obviously, these 2 resistors now I will call them R 1 and R 2 I want R 1 and R 2 to be matched first of all and more importantly I am assuming that R 2 is exactly equal to twice of R 1.

So, therefore, the first thing I need to note is that R 1 and R 2 need to be the same type of resistor. What do I mean by this? It turns out on an integrated circuit; you have several different types of resistors made using the different materials available to you. For example, you can take an n plus or a p plus diffusion, which is basically just a piece of dope material and make contacts on either side and that could be your resistor, you could take a piece of polysilicon, you could take a piece of metal etcetera and there are really maybe 4 or 5 or maybe even larger number of resistance.

Obviously the characteristics of these 2 resistors will be highly variable. One type of resistor may have a completely different temperature coefficient from the others from the other one; it may have different linearity behaviour and so on and so forth. And therefore, it is extremely important that you make R 1 and R 2 be the same type of resistor. Now this is like the zeroth order of mismatch understanding we need to have before we start looking at this in a little bit more detail. Now let us say we choose the diffusion resistor let us go to the next page.

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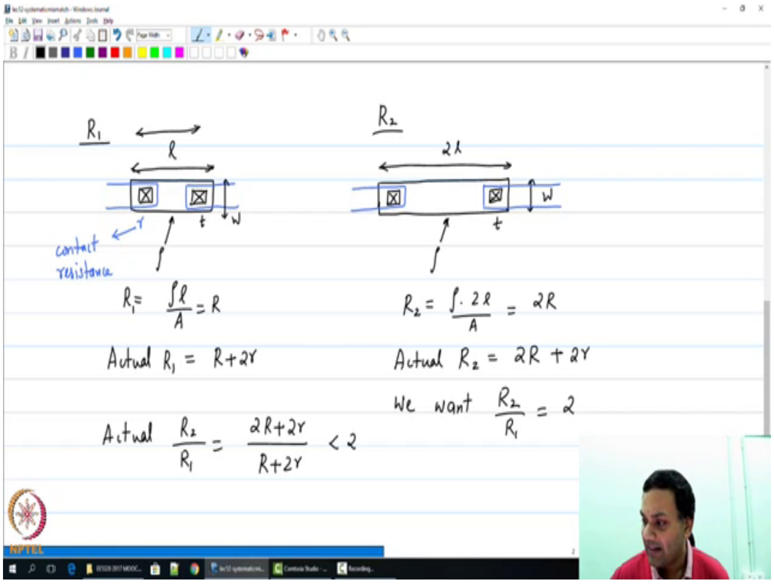

$R_1 = \frac{\rho l}{A} = R$

$R_2 = \frac{\rho \cdot 2l}{A} = 2R$

Actual $R_1 = R + 2r$

Actual $R_2 = 2R + 2r$

We want $\frac{R_2}{R_1} = 2$

Actual $\frac{R_2}{R_1} = \frac{2R+2r}{R+2r} < 2$

So, let us say I am going to build R 1, I am going to take a piece of diffusion right and some a let us say n plus diffusion, and now I need to make a contact I need to connect this resistor to the rest of the circuit.

So, I am going to put in what is called a contact, which allows you to connect a metal wire or a metal layer to this particular resistor. Let us say I am going to show that using the blue colour. So, this blue colour is the metal wire that I am using to connect the resistor to the rest of the circuit. Now how would I built R 2. So, now, first I need to note that this diffusion is going to have some conductivity right and it has a certain lengths and a certain widths right, and knowing the conductivity and the sorry knowing the resistivity the and w I can say that the resistance is going to be rho l by the cross sectional area A, I should note that if current flows there is some cross there is some thickness t for this for this particular diffusion when the current is flowing in this direction.

Now I want to make a resistance of value 2 r. So, of course, the first thing that I would try to do is to build a piece of diffusion that is twice as long. So, 2 l, I would use the same width and of course, the same thickness which you normally do not have control over and use the same type of material. So, that you have the same rho and this is R 1 this is R, R 2 should ideally be rho into 2 l by A and this should be 2 R. This is the nominal value that you will get, now unfortunately it turns out that there are some other aspects to take care of.

So, first of all the resistors that you connect to the rest of the circuit you need the metal wire and the contact. So, let us assume that the metal wire is ideal for this purpose, in reality that may also affect your design. Let us say it is the contact that has some resistance small r. So, the contact has a resistance small r and I am going to call that the contact resistance. So, the actual value of value of R 1 is actually equal to R plus 2 small r. Now let us look at the 2 R resistor which is R 2, now that will also have 2 contacts and it is going to be connected using the same metal wire in blue, what is the actual value of R 2.

It turns out the actual value of R 2 is not just 2 R, it is 2 R plus 2 small r. Now remember what do we actually want. We are not specifically in this particular application we do not care about the value of the exact value R 1 even if it varies by little bit it may not affect your amplifier in a very big way, but the ratio of R 2 to R 1 matters in a very big way. So, what we want is we want R 2 by R 1 should to be equal to 2 exactly. It turns out in this case actual R 2 by R 1 is 2 R plus 2 r by R plus 2 r this of course, is going to be slightly less than 2 clearly.

Now, how do we fix this problem? Of course, if the actual error depends on the relative values of a capital R and small r, but you can imagine that there will be cases where this difference this error will matter. So, now, the best way of fixing this problem is to first figure out what we want.

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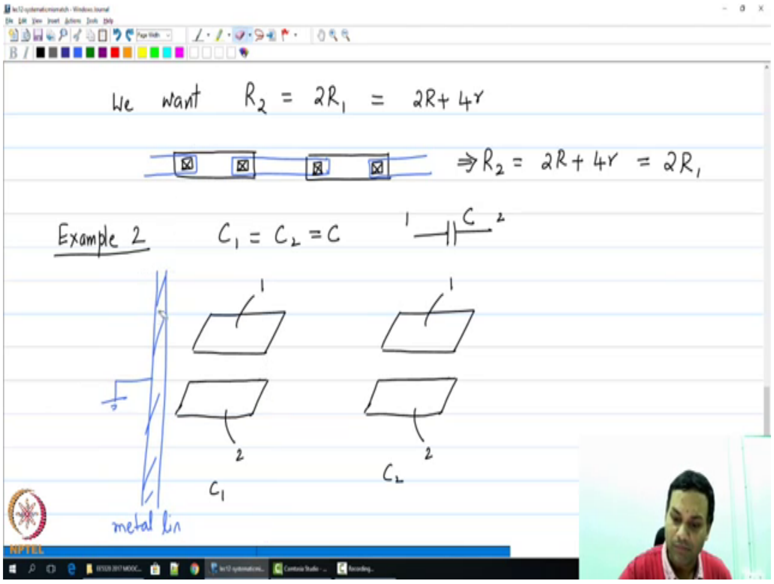

We want $R_2 = 2R_1 = 2R + 4r$

$\Rightarrow R_2 = 2R + 4r = 2R_1$

Example 2 $C_1 = C_2 = C$

Let us assume that we cannot do we cannot remove the contact resistance completely. So, what we actually want is R 2 should be equal to 2 R we want R 2 to be 2 R 1 which is actually 2 R plus 4 small r. In other words the way we should build R 2 is not just one single large piece of wire, but a single large piece of diffusion, we actually need to put in 2 pieces of R 1 2 pieces that are identical to R 1.

And in this reminder that in this particular case we are assuming that the metal has no resistance, and if you build R 2 in this manner, then the value of in this case R 2 will be equal to 2 R plus 4 small r, and this will give you exactly twice of R 1. This is actually a very simple almost trivial example for people experienced in analogue design, but I just kind of wanted to show you how small changes in the way you use build and use these kind of components, can make big differences in your actual circuit design. Obviously, now you can extend you can imagine that such small changes can be extended for other types of resistors for other types of components and so on.

Let us look at one more example, let us say you are trying to build some circuit where you need 2 capacitors to be identical. So, in other words this was a case where you wanted 1 resistor to be twice the other, let us say this is example number one. So, this is example number 1 and my next circuit is going to be example number 2. I want to create capacitors C 1 and C 2 that are exactly equal to C.

So, the way you build the capacitor is probably using 2 parallel plate capacitances. Let us say I have these 2 parallel plates and on a different metal layer I draw out 2 metal layer, 2 plates and I get my 2 capacitors I get a capacitance between these 2 plates. So, this is note 1 and note 2 now I can make a copy of this and call that C 2. So, let us say I make a copy of this and I call it C 2. So, this is C 1 and this is C 1 and this is C 2.

But now let us assume that next to one of the capacitors there is actually a metal line running on the same metal layer, and I am going to show that this is some metal line let us say this was at ground potential. What is going to happen is that, this capacitance this metal layers in. In fact, I should actually show you the top view before you can understand this. So, maybe I will move to the top view on the next page.

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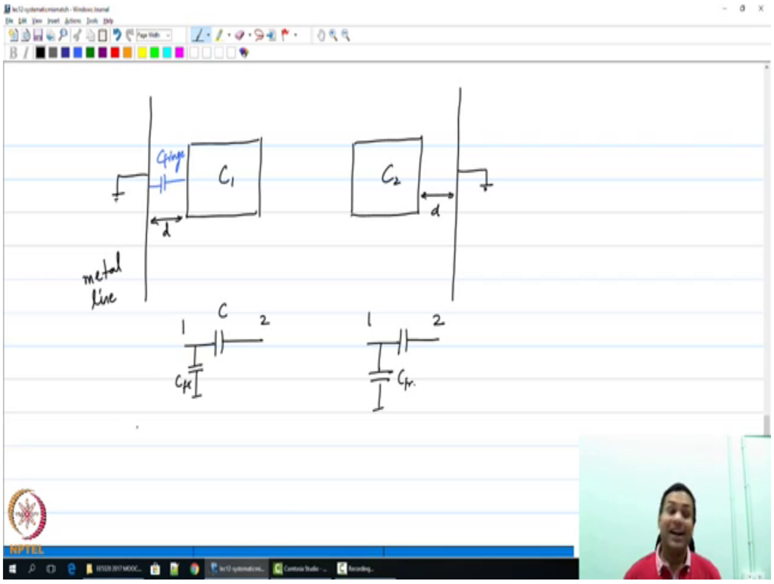

So, let us say this is the top view of the 2 capacitors, and let us say I have a metal line running next to one of them which is grounded. So, I will just show it is a single line and this line happens to be grounded.

What is going to happen is that there is going to be some fringing cap between C 1 and this metal line. So, if you actually look at this the equivalent circuit of C 1 between nodes 1 and 2, you are going to have a capacitance C, but you are also going to have a capacitance C fringe between node 1 and ground whereas, C 2 is going to look exactly like this. Now let us assume that between nodes 1 and 2 you want C 1 and C 2 to be completely identical, what you should be going in and doing is to put in a grounded metal line next to C 2 also at the same distance d.

So, that C 2 also has a C fringe between its 1 nodes 1. And ground this will make sure that C 1 inside 2 C 2 are identical in all respects. So, now, you can see I can now extended to all different kinds of structures.

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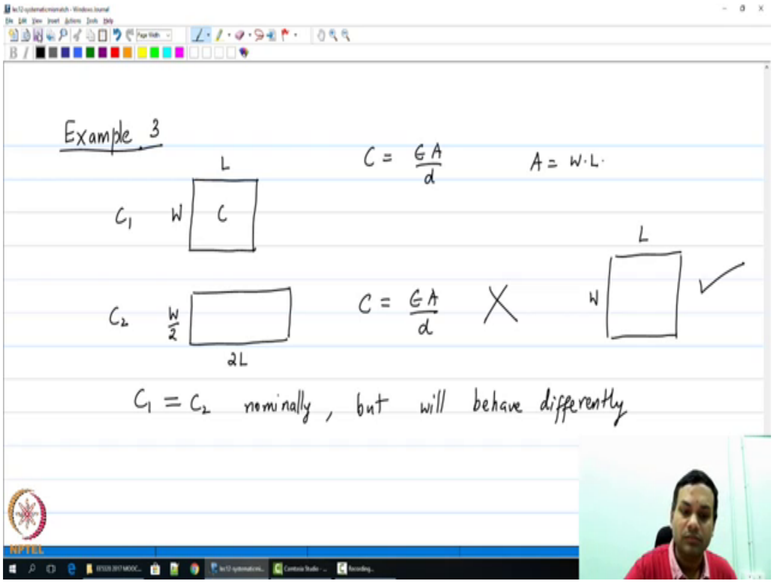

Example 3

$C = \frac{\epsilon A}{d}$ $A = W \cdot L \cdot$

$C = \frac{\epsilon A}{d}$ ✗

$C_1 = C_2$ nominally, but will behave differently

Let us take a third example, I am going to take a third example, let us say I want to build the same capacitor I used width W and a length L for the plates. Remember that the capacitance is epsilon A by the distance between the plates where A is W times L. Just a reminder that we are still dealing with the top view of the capacitor, now this is C 1 let us say somebody decides to build C 2 in this manner.

Let us say somebody decides to build C 2 in this manner, now nominally it will look like the capacitance is epsilon A by d, but first of all any capacitor that you build will always have fringing capacitances to any ground line; however, far away it is and what you will find if you take into account all the non ideal effects, you will find that C 1 is equal to C 2 nominally, but these capacitors will behave very differently with respect to very differently when there used in a circuit.

Now, so, you should always build these kinds of circuits such that the (Refer Time: 19:36). So, you should always build the circuit such that you have the same aspect ratio.

So, you should not be building C 2 like this. So, you should build a C 2 such that you have the same width and length, and this is the correct way of building this capacitor. I can go on with other examples. So, maybe we will take one more example before we summarize our understandings.

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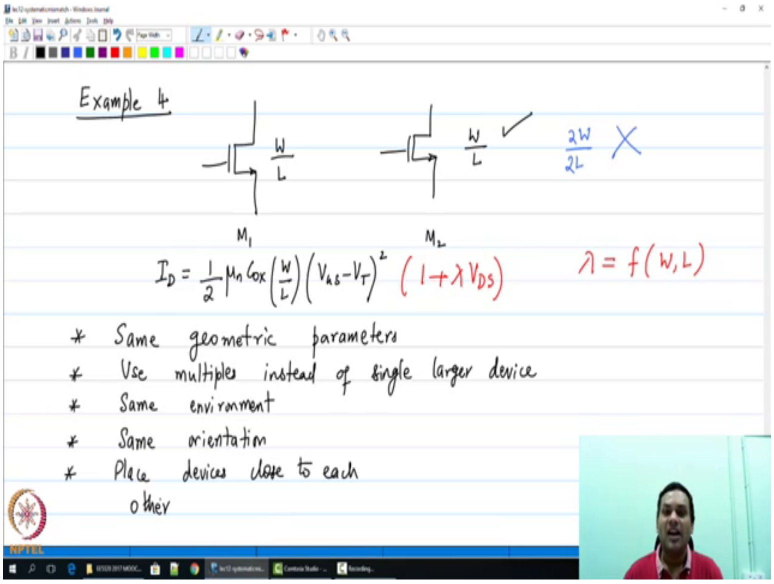

Example 4

M_1 $\frac{W}{L}$ M_2 $\frac{W}{L}$ ✓ $\frac{2W}{2L}$ ✗

$$I_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS}-V_T)^2\,(1+\lambda V_{DS}) \qquad \lambda = f(W,L)$$

* Same geometric parameters
* Use multiples instead of single larger device
* Same environment
* Same orientation
* Place devices close to each other

So, let us take a Mosfet and I am no going to draw the layout, but the schematic I mean the circuit just drawing a Mosfet symbol itself and drawing out the parameters, will be good enough to for you to appreciate this difference.

So, suppose I want to take 2 Mosfet's and make sure that they are identical. So, this is M 1 this is M 2. Let us say that you want them you apply a certain bias voltage you want them to have the same bias current. Let us say that this Mosfet has a width L width W and a length L. You of course, you want to make sure that this transistor also has the same width and length; we know that if you just look at the bias current in the saturation region, we know that the dependence of the current on the voltage is quadratic. Now clearly this equation does tells you that the current is proportional to the ratio of the width and length.

So, you may think that this is exactly the same as using twice the width and twice the length or half the width and half the length, but is that is, but that is completely incorrect. You will find that you should be using the same width and the same length for these types of transistors, that is because there are always second order dependencies of the current on other parameters, which will depend on the actual values of width and length. For example, we are ignoring the dependence on drain source voltage due to channel length modulation.

It turns out that lambda itself is a function of the width and length, but in different ways, which means if you use a device with twice the length and twice the width its lambda would be completely different from the original device. So, let us now summarize our understanding. So, if you need to have 2 devices or 2 or more devices that need to be perfectly match, the way you would summarize these findings is that they need to have the same geometric parameters. So, when I see the same geometric parameters, what I mean is if they have a certain width, a certain length, a certain thickness, certain distances etcetera all of those should be kept identical across the multiple devices that you want to be very well matched.

And if I want a larger or smaller multiplication, I need to make sure that I use multiples instead of single large device. So, that example that particular point is covered by example the first resistor example that we took. We first tried a single larger device where we wanted R 2 by R 1 of 2, but then we found that what actually works is 2 devices which are identical to the first one which are connected together.

So, use multiples instead of one single larger device, and the same can will hold through even if you want to build a current mirror for example, using Mosfet's. And you need to ensure that both devices have the same environment, what do I mean by in environment? We saw the exa in example 2 where you could have fringing capacitance because 1 device has a line a metal line next to it where the other one does not. You need to maintain the environment around the device to be identical.

Finally you need to ensure that these devices have the same orientation, this is because you really do not know when building the device whether there is some gradient in thinks like temperature in the foundry doping concentrations etcetera. So, that is extremely important. And now this fifth one because there maybe gradients across the IC, you want to place these devices close to each other. What I mean is that if you build the same circuit on one end of the dye compared to the other end of the dye, you could have completely different values of doping concentrations, mobility is thickness, metal thicknesses etcetera. So, this is following these conditions is extremely important.

Now, if you follow all of this, you will find that your systematic mismatch is reduced to a very large extent. In other words you can think of systematic mismatch has something that is almost completely under the control of the designer, and there are some very simple techniques that you will routinely follow to take care of systematic mismatch.