Analog Circuits and Systems through SPICE Simulation

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Lecture – 01
Basic Analog Design Part – I

Hello, and welcome once again to the first part of this course, I am Mrigank. In the introduction session I give you brief overview a hint of what we are going to cover in the first few lectures on analogue design.

So, is going to be from the very essential characteristics of the devices that we are going to use in the circuits, using those devices in building fundamental building blocks of (Refer Time: 00:44) systems, doing the analysis of those circuits including DC, AC, small signal analysis, frequency response, noise analysis, signal swing and linearity to some extent. And then once we are through these basic steps, once we have gone through the device concepts their application in circuits and the tools the basic steps required to analyse those circuits then we can apply those conceptual building essential components of a mix signal design the analogue frontend.

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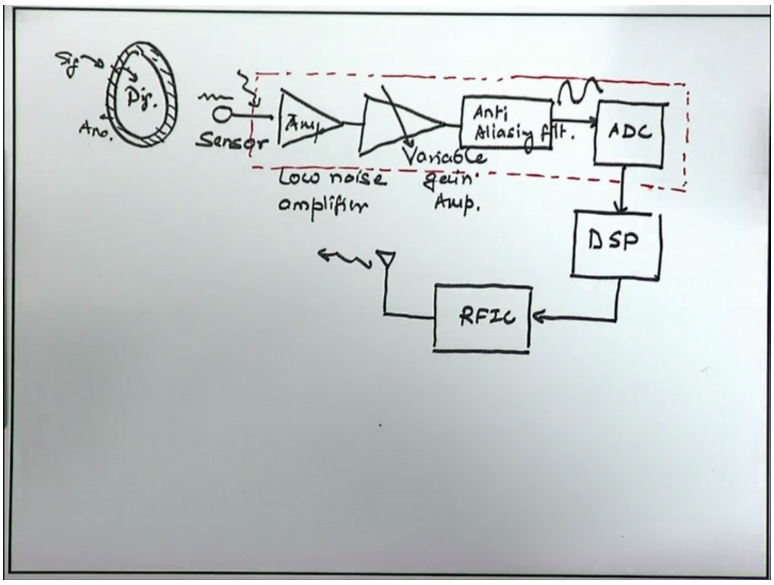

So, if I talk about analogue front end we can look at the whole system; as I said as a shell where the analogue frontend acts like the outer covering or the thin shell which separates the bulky digital engine from the external world. So, the external world is providing us all kinds of analogue signal which has to be processed, conditioned and provided to the digital domain with the help of this thin shell of analogue frontend.

So, we are going to talk about the fundamentals required to understand the design of a practical system interfacing the real world signal to the digital world. So, what are the fundamental blocks that come into such a system? So, if I try to draw generic analogue frontend we may have a sensor which is giving us a real world data. The first stage happens to be amplification of that week signal being provided by the sensor. The sensor itself may be having good amount of noise or there can be additional noise coming from environment. We need to make sure that the first amplifier itself does not have noise or distortion getting introduced into the signal.

So, the first stage must be low noise amplifier. Although this term of low noise amplifier is kind of preserve for RFIC, low noise amplifier or LNA where we have to deal with high frequency operation, matching consideration. But in general in analogue design also whenever we are facing the analogue signal or sensor to the mix signal IC. The first stage happens to be the low noise amplifier where apart from amplifying the signal the amplifier must make sure that is not corrupting the signal by added noise.

So, this amplifiers going to have so many different components is going to have of transistors, resistors, capacitors, transistors and resistors they can contribute to different noises and they can in fact corrupt the signal. So, we must make sure that the noise contributed by the first amplifier stage is significantly lower as compared to the signal over here. The noise level here rms value of the noise should be much weaker as compared to the peak to peak signal that is being received by the sensor.

The next block happens to be a variable gain amplifier, we can denoted with a arrow. It means that the gain of this stage is variable or adjustable. In order to amplify the signals further and also meet the dynamic range of the next processing blocks which may be the filters and the a b c. So, we will discuss that why this requirement of variable gain amplifier is coming into picture when we go into the block level specifications and the designs.

After the variable gain amplifier we may have frequency selective block in the form of a filter. In general the filters perform one of the most essential block that is anti aliasing before the digital mix signal part A D C is sampling the signal and converting into discrete time. Apart from that in many cases they may need to reject noises dominant in certain frequency ranges. So, noise rejection along with that (Refer Time: 05:26) can be an important function of the filter. After the filter we have the A to D converter which is supposed to digitise the condition and the processed (Refer Time: 05:51) being a feed at its input.

The signal over here is already processed amplified, filtered noises have been taken care of the amplification over here is such that it is matching with the dynamic range of the A D C. So, in general A D C will have a certain dynamic range it can process input signal from certain maximum value to certain minimum value. So, we have to make sure that the signal reaching at the input of the A D C it is having a range matching with the maximum input range of the A D C so that we can take the maximum advantage of the dynamic range of the A D C.

Now the A D C specification also may heavily depend upon the kind of signal we are using: how many bit precision we need, what is the sampling rate and so on it may depend upon the A D C is signal specifications. After the A D C we may have signal processing going on in digital domain. We can denoted as a D S P block. Where you are trying to do some local processing on the signal acquired through the sensor. We may be learning a lot of complicated signal processing algorithm they are low power implementation in the D S P module.

Towards if we talk about today’s scenario when people are talking about very low power cell sustain sensor knows for example, which are supposed to be operating with very low power battery based operation maybe operative with energy harvesting there the power budget of the entire system is going to be very limited. You are supposed to acquire real time signals from some sensors continuously and make sure that the signal integrity is maintain all the way to A D C while doing the analogue domain processing.

Following that we need to transmit that acquired data through a wireless link to a central unit which has much more competition power memory and resources which is not so much power constrain. So, to do that we may need some digital domain processing before we can send the data out which helps in processing, compressing, extracting certain essential information out of the data coming from the A D C. And once we have the final data ready to be transmitted we may have the RFIC block which is supposed to wirelessly communicate the data to the central unit.

So, in this course of course, we are supposed to cover the three fundamental units. The very first one is of course the analogue signal acquisition chain which I will be covering in my lectures. That constitutes this entire signal chain of frontend amplification, filtering, and analogue to digital conversion. Now, this course of course, is supposed to start from under that level content and based on the feedback that we have received in our earlier sessions it has been recommended that we touch upon the fundamental issues related to devices and the basic building blocks that is a circuit which are going to be applied in building these blocks.

So, we considered it very important to touch upon the fundamentals related with the device characteristics, because the kind of characteristics or kind of information needed from device perspective is going to be very different in case of analogue and is going to be very different in case of a D S P or a digital block. Or the some kind of device parameter that we are so much concerned about while doing the analogue design, they may not be so concern about them in the digital design because they are the device characteristics are different the kind of region the device is operating it is different.

So, it is important to be aware of the device characteristics, the large signal behaviour, a small signal behaviour, noise frequency response and so on. So, that while applying those devices in the circuit we have confident about the circuit operation, we are able to understand its implications in the circuits performance maybe DC, maybe power consumption, frequency response and so many other important aspects.

So, the starting point is going through the fundamentals of the basic buildings blocks. So, let me jot down what are the what are the issues, what are the device level concepts we are going to cover and the discuss.

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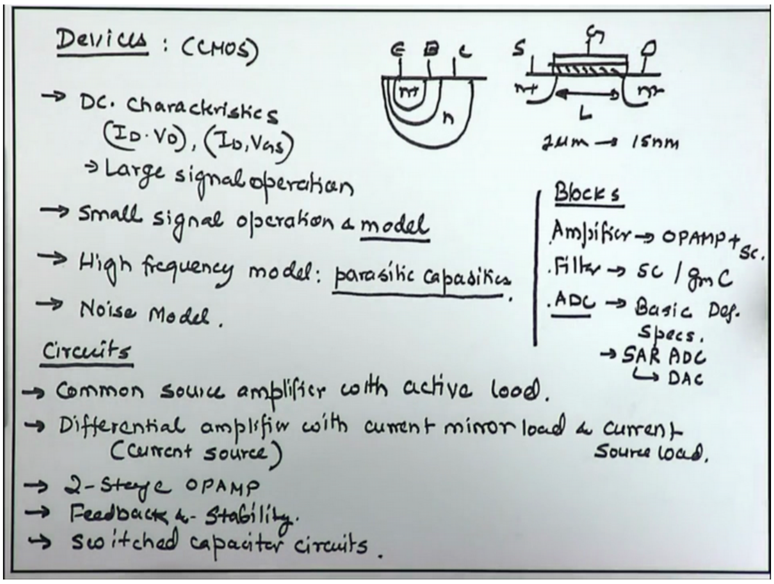

So, if I talk about devices it essentially means the CMOS technology. As we have introduced in the very beginning is CMOS is the key technology which has enabled extensive initialisation, combination of analogue and digital into mix signal IC is where both analogue and digital can be fit in together. And because must fit has facilitated aggressive scaling it has outperformed the previous devices in form of b j t in terms of performance as well earlier technologies b j t used to be choice for analogue frontend or analogue design because that used to offer higher mobility or higher performance.

But why must it took over because it is lateral structure as compared to b j t which is relatively having a vertical structure with three terminals which is more relatively more difficult to scale. As compared to that MOSFET is a lateral or a relatively 2Dstructure which have been much more convenient to scale. And industry has been very diligently following the Moose law and have been able to scale the channel length of the MOSFET. MOSFET starting from earlier days of one micrometre going down all the way to 15 nanometre and it today they are progressing towards ten and seven nanometre.

So, because of this aggressive scaling provided by the MOSFET technology it has in many ways outperformed the MOSFET in terms of performance also. Therefore, the focus shift it completely towards MOSFET and trying to integrate MOSFET based analogue as well as digital design together in form of a mix signal (Refer Time: 12:33) has became the main focus of the industry.

So, when we talk about devises it will be mostly about the MOSFET device characteristics which are essential to understand in order to apply them in analogue mixed signal circuit design. So, while covering devices the very first thing that we have to be clear about is the DC characteristics of the MOSFET the I D V D characteristics I D V GS characteristics., understanding the large signal behaviour. Now when we are talking about analogue when we are talking about processing those minute analogue signals acquire from external world we are essentially talking about small signal operations.

So, we need to understand the physical characteristics of the device which enable that small signal operation, while we are doing digital operation they are the MOSFET have been used as switches. So, either it is in on condition or in off condition. So, they we are not so much concerned about the physics of the device about the physical characteristics of the device. They are not exploiting the physical characteristics of the device in doing the processing or the computation.

But when it comes to another processing it is all about using the physical characteristics of the devices to enable small signal operation; to enable amplification, to enable signal processing, to enable filtering, to enable the frequency characteristics of the devices, to allow as certain frequency domain characteristics; likewise suppressing the noise characteristic for the devices, making sure that it is not corrupting the analogue signal.

So, the course physics of the device we come a lot more important while dealing with analogue circuits. And therefore, understanding the device, understanding the MOSFET from the point of view of analogue design becomes very crucial before we take up any complicated comprehensive block level or system level design like low noise amplifier or filters or A D C.

And the same holds to for the RFIC. They are some more conceptual that is to higher frequency operation comes into picture, high some additional parasitic need to be taken care of some additional device modification make to be incorporated, and the device may be meaning to be optimised for RFIC operation in a slightly different way. But the fundamentals remain same for applying MOSFETs for in analogue design or RF design is very important that we are aware of the device characteristics which enable that analogue or RF operation.

Next comes is your small signal operation and model. How do these DC characteristics from the devices enable small signal operation? Once again as we said we have to look into the small signal behaviour how does the small signal model can be constructed out of the DC characteristics of the devices, how does it make sense, what do we mean by trans conductance, what do we mean by the small signal output resistance of the MOSFET, what do we mean by channel length modulation, what do we you know mean by the noise component in the MOSFET, how do the parasitic capacitance is coming to picture, how with the depend upon the device dimension. If you are increasing the device dimension how does the parasitic capacitances change, how do the small signal parameters like gm ro change. If you change the DC bias condition how do these small signal parameters change?

So, that is very important to understand because when you are talking about IC deign we have some parameters in our hand that we can adjust. So, while dealing with an IC design, while dealing with our real world mix signal design we have certain parameters at our disposal. And it is important to understand how to decide about the choice of these parameters so that we can get to design our circuits meeting the require specs and get the best performance out of it.

So, towards that end the first point is understanding the small signal operation; not just the definition, not just the formula, but the origin of that small signal parameter; how they are coming into picture and making real sense of it. So, the purpose should not be just remaining the formula and solving some numerical problems, it is very important very crucial to have the physical intuition of the overall process.

It is very important to see how the gm is coming, it is very important to see how the small signal resistance of the MOSFET is coming, why does the drain give us high impedance, why does the source give wards low impedance and so on. So, if you are having that physical characteristic of the device in our mind we can very well understand and appreciate the application of those devices in analogue circuits, because it does require having a very good grasp of the real physical operation of the device, large signal as well as small signal to deal with the circuits efficiently.

So, in connection with the small signal module once again we are going to have a discussion on high frequency model, where we are going to talk about the parasitic capacitances, they are origin, how do they influence, the circuit operation and so on. So, once again understanding the origin of parasitic capacitances is important not just looking at the pictorial model of the parasitic capacitances some parasitic connected between drain and grain wet and source, but it is also important to appreciate what is their origin. So, we are going to look into parasitic capacitances.

And finally, one of the very important issues then we are dealing with practical design is the noise model. So, because of the current flowing these kind of nano scale macro scale devices we have several sources of noise. We will try to understand the origin of noise in the device, how to model it, how to include that affect in the small signal characteristics so that we can apply that complete model including small signal low frequency components, the high frequency parasitic capacitances along with the equivalent noise sources in doing the analysis for the circuit; complete analysis for the circuit.

Now, once we are gone through these device characteristics we will be in a good position to look at the circuits and apply those device concepts in building our circuits. Next comes the topic which we are going to cover while describing circuits. So, first is going to be a common source amplifier with active load. This is the very fundamental block, because once we are comfortable with the common source amplifier and the design steps associated with that the signal analysis DC characteristics, small signal analysis, frequency response and noise analysis associated with the common source amplifier we will be in a good position to go towards more complicated circuits; like differential amplifier, 2-stage amplifier, opamp and so on which are going to be essentially our building blocks for building larger functional units like the low noise amplifier, filters A D C, and so on.

So, this is the very first stage, talking about the common source amplifier; how does the functionality depend upon the choice of load and being comfortable with the fundamental steps in analyzing those circuits: DC, small signal, high frequency, and the noise model.

The next step is going to be differential amplifier with current mirror load and current source load. Now once again these two topologies of different amplifiers are very fundamental and maybe very crucial in designing different blocks that you are going to use in our low noise amplifier design. So, understanding these two basic topologies of the differential amplifier with current mirror load and current source load, how they are different how do they are DC biasing frequency response small signal differ. And while using them in a circuit what are the practical design consideration that we need to make; it is very important to understand while proceeding towards our larger functional blocks.

So, spend some time or understanding the differential amplifier. And this is also incorporate some discussion on current source current source; that is related to the biasing scheme how do we operate differential amplifier, what is the basic principle of differential amplifier operation and its connection with the next higher level that is a 2-stage amplifier or an opamp Now, this 2-stage opamp is going to be our building blocks for the first day; that is our low noise amplifier as well as the variable gain amplifier.

So, there once again we will need to understand the basic characteristics. The four basic analysis: DC, small signal. high frequency. and the noise model in our to be able to appreciate the design issues associated with the very first stage of our mix signal frontend; analogue frontend that is the low noise amplifier and the variable gain amplifier. So, we will talk about many practical considerations. We will pick up and example a particular case where we are building and analogue frontend for a biomedical signal. And try to study the characteristics of the signal and based on that signal we will be trying to determine what is the specs of the entire analogue signal acquisition chain.

From those peaks we will try to figured out what is going to be the specs for the frontend amplifier and the frontend amplifiers specs we will tell us something about the specification of this 2-stage amplifier which is going to be used in building that of low noise amplifier. So, this is the top down approach; highest level we are having the signal known that we are going to process, acquiring process that gives a some specification about the system about the entire signal acquisition chain. It is some way also linked with the digital processing.

So, the D S P person may tell me that in order to process this algorithm he required certain resolution in the digital domain without that resolution he was not able to you know get accurate results in whatever signal processing is trying to do. So, there is definitely some feedback from the digital domain I need to talk to the digital person, I need to talk to the D S P engineer who is telling me who is giving me the specification of the bit resolution required for extracting more sophisticated more hidden information from the signal. And I have to address that need and that in a way you know has of feedback and tells me something about the specifications.

So, first set of specifications come from the signal itself: what is the frequency content of the signal, what is the noise content of the signal, what is the amplitude of the signal, whether the signal is stationary, whether it is having some dynamic off set, whether the baseline is fluctuating, all those considerations design my frontend design specs.

But equally important is the feedback from: the person doing the digital signal processing which has, because he is going to tell me how much resolution, how much linearity, how much precision and accuracy, the analogue block should pres preserve so that the digital block can do more extensive competition in digital processing and extract the required information. So, there is always the feedback from the digital people also to design this or determine the specs of the entire analogue signal acquisition chain.

So, this is how we are going to you know detail the discussion among 2-stage opamp. And in order to do that we are going to require some additional concepts, like feedback and stability which is going to be very important while dealing with the design of a 2-stage amplifier operating in feedback mode. So, we will have some discussion on feedback and stability which is again linked to frequency response in tight manner.

Another topic that may be essential to cover at circuit level before we go towards the blocks is going to be switched capacitor circuits, which basically deal with some special kinds of circuit techniques which can be very useful while dealing with practical analogue frontend design. We will basically involves combination of must the switches and capacitors integrated along with operational amplifiers to give us some interesting functionality; for amplification purpose, for filtering purpose, A to D conversion and so on.

So, the switched capacitor circuits are also going to be very fundamental in you know coming up to the higher level. They are going to be very much essential they are going to act like an link between the what was circuit level components we discussed. And their application in building the functional units namely the amplifiers filters and the A D C. So, we will have some discussion on the switch capacitor circuit concepts as well.

So, once we are done with the basic circuit analysis then we are ready to go on towards the building blocks of our frontend system; that is the low noise amplifier, frontend amplifier, filter, and the A D C. So, amplifier part as we have already said we will be using the operation amplifier in conjunction with some switch capacitor units to arrive at the amplifier design, there will be some additional concepts required to you know address some practical issues so that they will recovering as we go on.

Filters: once again we are talking about not just some bed board circuits where we have large resistances and capacitances at our disposal that we can use to get desired frequency response. While designing filters for integrate circuits we have faced which certain stringent constrains, you cannot have any arbitrary value of r and c. For example, on bed board circuits on P C B design we can have arbitrary large c millifarad farrar, microfarad, nanofarad you know very wide range of c and r through which we can design appropriate filters. But when you are talking about choosing on chip components the value of c and r that we can use to get a desired frequency characteristic is going to be very limited. A single millimetre square area chip cannot a four more than say a nanofarad of capacitor.

So, total capacitance some together in the entire 1 millimetre die can be limited to 1 nanofarad. And in general individual capacitances used in the circuits; for example in 180 nanometre technology may be well within 10 picofarad. There may be very few which are around that range most of them will be few peak of farad or smaller. So, likewise for in resisters also we need to take care of the practical consideration the constraints provided by the IC design environment. And appropriately choose the r and c component to meet our filter characteristics.

Many other issues, like the component variations, mismatches are going to play important role or it is going to be necessary to considered those while trying to arrive at a desired frequency characteristics of the filter. And that tells us about the kind of topology we are going to require to meet our specifications. A simple opamp with r and c feedback may not be the best topology to use, because we do not have those r and c value the available. So, once again we may have to go for switch capacitor filters or gm c filters where we are going to use active blocks trans conductance blocks, similar to differential amplifier, similar to operational trans conductance amplifiers and opamp that we are looking at and the earlier sections.

So, we are going to look at two popular topologies, two popular scheme formulating on chip integrate filters for the kind of signal we are using here for biomedical signals. And we will see what are the advantages and disadvantages of these two schemes and what are the circuit issues how we can make a delicious choice between the two schemes and then go towards the component and transistor level implementation of these two schemes.

Finally, the A D C which deals with the p processing, the digitisation of the p processed analogue signal and interfaces the analogue process analogue signal with the digital world; that is I am gain another very broad topic. Many different topologies many different kinds of A D C is exist. Within a single topology you may have many different variants many different proposals for implementing that topology.

So, as I said the A D C itself can be of full one semester course and still we may not be able to cover enough it is a very broad topic. Likewise of course, the same holds true for amplifiers and filters you can have full semester courses just dealing with filters and amplifiers. But the objective of this course is to give your taste. Pick up an example, pick up a case study in this case we are talking about biomedical signal we have a certain frequency range of interest, we have a certain signal amplitude signal characteristics in our mind. And we are going to choose than A D C topology which is suitable for that particular signal.

So, we will talk about the basic definitions or specifications related to the A D C. To begin with, basic definitions and specs of the A D C. And then we will choose a particular topology suitable for a biomedical signal processing device. This may be a SAR, A D C successive approximation A D C which is inherently also having the DAC involved. So, there is a good point about it because we can also very briefly have a discussion on the DAC part.

So, possibly whatever we discuss in the switch capacitor circuits, and to some extent in the earlier sections on differential amplifiers and opamp that is again going to be very useful while talking about the SAR A D C. So, all the design concept that we talk about at the block level are going to depend heavily upon the fundamental that we built; starting from the device characteristics their application is circuits analyzing those circuits and then finally applying those circuits in building this blocks to meet our specs.

So, to cover all this in a total of I think I would say six classes that is just 9 to 10 hours is a is a challenging task definitely while making sure that people having very weak previous link with analogue there also compatible with the material covered. So, please see free to you know post your comments, if at any point to feel that we are taking a jump and we are skipping certain things that you are not aware of are you would like to stop at a particular point and ask me to emphasis on certain aspects which have not been covered- feel free to do that you can post your comments online and I will be happy to respond to those especially the broader comments which are you know being posted by lot of people.

So, it may be difficult for me to respond to all comments because are there so many of us attending this session together, but definitely the broad and the more relatively repeated comments and demands I will try to (Refer Time: 33:55) them definitely. So, this is the you know broad outline of what we are going to do in the analogue frontend part. And let me once again talk about different kinds of applications that we can have in mind. So, for this course we have just chosen biomedical signal processing as an application.

Likewise and we are talking about today is industries interest in IOT internet of things sensor nodes where people are imagining all kinds of low power devices which can operate with battery without even replacing the battery for very long hours, they can be devices which can be fitted over bridge and buildings, they can sense the environmental conditions, they can sense the structural stability vibrations coming in those buildings. Likewise you can have devices which you are wearing on your body.

So, in future we may see variable devices where some of those chips can be implanted in your variables, in your clothes which are acquiring your biophysical signal and transmitting it to your handheld device like a cell phone. Even more exciting it can be implantable devices which can go inside our body, they can go inside our brain and you know acquire some very critical health signals and transmitted outside. We can have devices which can acquire signal important signal from the brain and let us manipulate those signals or take help of those things to do some interesting thing outside.

So, biomedical engineering or application of these analogue mixed signal designs in biomedical engineering is a very exciting feel with lot of interesting research opportunities available worldwide. And therefore, just at a high level have chosen this particular topic signal characteristics align with biomedical application to present this course.

And of course, as a part of our research, as a part of our projects we do work on all these different applications with very bright very dedicated students. And I am probably towards the end we can give you some example of such applications at high level. So, this is with very first slide that I showed you it was regarding a generic frontend. What is the basic compounds in the frontend? So, we may say that may this is the basic frontend and at the max what we have to do is adjust the specification. So, why do we need to invest so much time in learning analogue once the design is made, once the low noise amplifier or the variable gain amplifier filters and A D C is known, why do we need to keep re designing it. Technology nodes about the districts we are not so eager to go for technology is lower than fitting nanometre. In fact, for biomedical applications people are working with 180 nanometre technology because they are the speed or the scaling may not have so much advantage.

So, why we still you know may be interested; why do we think that this field is still exciting, if this is a standard frontend available and already design on available understood. If we will try to address those issues may what are the challenges what are the different aspects that we need to address while dealing with different applications? So, first thing is signal characteristics. In this particular application we are dealing with biomedical signal there are many different kinds of biomedical signals which can be a quiet with you know different kinds of sensors.

So, there itself the characteristics of the frontend the kind of analogue signal processing you can do, the kind of frontend amplifier filter A D C we are going to have is going to be very different. It may not be as simple analogue chain like this. You can have many different functionalities embedded into the analogue change itself. You can have some interaction between the D S P part and the analogue part; the digital part may need to take this sum instruction to the analogue part to tune it, to calibrate it, program it or configured it allowing along according to the desired input signal.

So, there is a tight interaction between the analogue part and the digital part. In today's edge it is not very practical to confine ourselves only with analogue or only with digital part, because these two things are getting so tightly link there is always some help of the digital part in calibrating or assisting the analogue part. Likewise in many cases the analogue part may come in to the rescue or the digital part. So, we will take certain examples there that kind of interface between the analogue and digital is being used. Digital part is assisting analogue in a certain fashion so that is performance, characteristics, specs can be improved.

So, with that we would like to start with the basic core content, starting from the devices and going all the way to circuits and the blocks.

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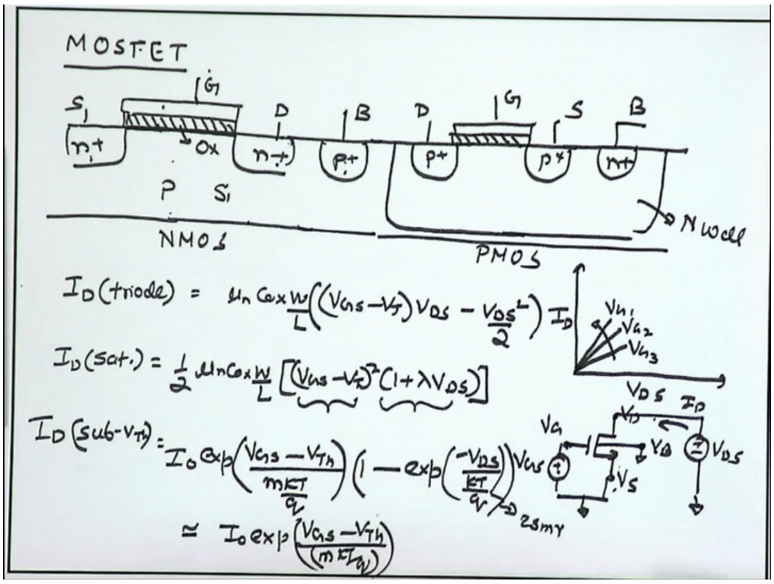

So, as we said the fundamental device which has facilitated preparation of this technology is the MOSFET- Metal Oxide Semiconductor Field Effect Transistor. And we are all familiar with the basic current equations, of course we cannot go to deep into physics you have just going to start from the current equations and from there go towards the large signal and power signal characteristics.

This is the basic structure of a MOSFET. For N MOSFET you may have a P type substrate that you start with. On the top of that you are having a thin gate oxide created. So, you have an oxide layer S i o 2. The reason why silicon has been so popular and not germanium is because S i has enmity oxide dock side which is very well matched with the silicon. The interface between the S i o 2 and the silicon happens to be of high quality there is one of the reason why silicon has been the winner despite germanium having higher mobility. Because the moment you have poor oxide interface with the silicon it can degrade the transistor characteristics it can make it more noisy.

So, it is very important to have this interface between dockside in the silicon high quality. And then on the top of that you can have a metal or a poly silicon gate which is forming the gate terminal. Performing a source and drain we have highly dobbed N plus regions. And once again in order to have contact with the body terminal we can have P plus contact over here, highly dobbed P plus region which is needed to lower the contact resistance associated with the body contact. So, this P plus acts like the body terminal. So, here I can name it has the P or the body terminal for the MOSFET.

For an N value technology we know what is the condition. We have this entire silicon wafer dobbed P type. So, this entire silicon wafer to begin with is dobbed P type. And the NMOS transistors they are directly fabricated on the top of that silicon wafer. You have the N plus region and the gate forming the NMOS transistor directly on the P type substrate.

In order to fabricate PMOS on the other hand we need N substrate and p channel right. So, in order to get an N substrate we create a well an N type well within the P type dobbed substrate where you have larger N doping. So, we are making this well region N type and within this N type well we can create our t mos that. So, we can have the P plus regions for the source and the drain of the MOSFET, you can have the gate terminal, and likewise the source and the drain terminal. And once again in order to have the contact with the substrate of the N well that is the body of the PMOS we may need N plus contact over here. So, this is the body of the PMOS.

So, this is the N well technology where the substrate is P type, you are having all the NMOS transistor sharing the same substrate, because this p substrate to begin is common to all the NMOS that your directly fabricating on the t type substrate. Whereas, for NMOS we can have isolated wells, so these are isolated regions which means that essentially different PMOS transistors they can have different bulk contacts. So, each PMOS transistor can have a separate well or you can have a larger well combining lot of PMOS transistors used in a particular circuit.

So, we need to be aware of this N well process which one of the most popular ones. They are many different pays you can have P well process, we can have a dual well, triple well process you can have silicon on insulator where you can have PMOS as well as NMOS in separate wells sitting on insulator and so on.

So, that different tastes but commonly use very popular one is N well technology. And we should be care full or we sold be aware of the terminal characteristics of the substrate required for NMOS and PMOS. So, that while talking about the real circuit design we are aware of the body terminal how to connect it what is the effect. If you are having different voltages at the body terminal so that also becomes important while looking at the circuits.

Now, if I talk about the current equations. So, most of us are familiar with the MOSFET current equations for different region of operation. For triode region we can write down the current as V GS minus V T times V DS minus V DS square by 2. This is the triode region or linear region operation where the dependency on the drain to source voltage is very strong. If the drain to source voltage is small the current will be small. So, in this region we have a very strong dependency on V DS.

If I plot I D versus V DS characteristics for this region has the as the V DS increases the current strongly increases with the applied voltage and their curve for different values of V G. So, we are plotting for different values of V G the curves will be you know going high. So, this called the linear region or triode region operation of the trans I because, here the device is having three terminal operation or strong three terminal operation is acting like a triode. So, the name is borrowed from a diode where you have essentially two terminal operations right in a diode we have two terminals you can control the voltage across those two terminals and that is going to control the current flows across that two terminal device. So, that is a diode.

In the triode region the current flow through this MOSFET assuming that the body terminal you know is fixed or it is at a particular potential. So, we are going to fix the body terminal for the time being and mainly concentrate on the other three terminals: that is the gate, drain and the source. So, assuming that body terminal is at a fixed point. Here in the try would region if you are applying a certain gate to source voltage call it V GS and then applying a particular drain to source voltage called V DS the resulting drink current strongly dependent upon both the voltages gate to source as well as drink to source. Therefore, the current through the must it is being controlled by three terminals in, therefore we can say it is a triode region operation of the device.

And you will see why this operation is not commonly used for amplification purposes, for building analogue circuits, we need sub saturation region operation. So, we will see how to use saturation region operation, why saturation region operation is necessary and how to imply that in you know building our circuits. So, what is the fundamental region why we are going for saturation in operation?

So, for saturation region we know what is the overall current equation. The first term these are the square dependency of current on the gate to source voltage V GS minus V T square. And the second term gives us dependency on the drain to source voltage; the proportionality factor being lambda. We will briefly discuss this concept of lambda and how does we channel length modulation occurred, and what is its role in analogue circuits. This is a very important role in analogue circuits, channel in modulation or lambda its crucial to understand how what is it interpretations on the last signal and small signal operation of the MOSFET, and how do we exploit it in building high gain amplifiers.

So, this is the very important factor which we may not worry about while designing and digital circuits, because in digital circuits most of the time transistors maybe in this region in deep triode region. We are not much concerned about the channel modulation we are not so much concerned about lambda. So, here we do need to understand the effect of lambda its DC characteristics as well as the its effect on the small signal characteristics and the small signal model.

We may at some point need the sub threshold sub V T or sub threshold characteristics of the MOSFET, which is having an exponential relationship or exponential dependency on the gate to source as well drain to source voltages. Generally, when we are talking about very low power circuits sub threshold operation is critical where to save powers we are loading down the supply voltages. So, the concept of power dissipation comes in a big way that we are talking about analogue design or digital design mixed signal design for power constrain environment say sensor node or biomedical application, where the overall power budget may very limited. And those conditions they would like to aggressively scale down the supply voltages and it can be even lower than or close to the threshold voltage of the device.

And in that case definitely the transistors are operating in deep sub threshold regime, we cannot apply the square law of the MOSFET directly and from there derived the small single parameters rather we need to use the sub V T equations of the MOSFET. Which for again can be derived regressively through you know device suffix, but we are going to definitely avoid those parts we are going to use the equations. And try to see how does the same small signal parameter that we are arriving at using the saturation region operation gets modified when we use the sub threshold region operation having exponential dependency on the terminal characteristics terminal voltages.

So, for sub threshold operation or the MOSFET we have exponential dependency on the gate to source voltage and there is a non-ideality factor m over here, V T h is the threshold voltage. And also there is a week dependency on drain to source voltage K is the Boltzmann constant k t by q k t at room temperature is around 25 millivolt. So, if V DS is sufficiently larger than k t by q that is around 25 millevolt at room temperature we can approximate this current as just the first term and in ignore the second term. Because for larger V DS more positive V DS the second term almost becomes negligible as compare to 1, so we can drop it and we can just use the first term over here to find out the small single parameter.

So, this becomes our DC current equation and from here we can try to find out the small single parameters or the MOSFET. Once again here to find out the concept of output impedance, we may again need to take care of the second term so that is going to come into picture at some point. So, towards the end when we are talking about low power frontend amplifier design; we may just revise it this concept of sub threshold operation and define our parameters parallelly in terms of the threshold operation so that in case some of you in future are working on very low power circuits sub threshold circuits, or teaching these similar topics we can explain this operation mode as well.

Thanks a lot.