

Nanoelectronics: Devices and Materials
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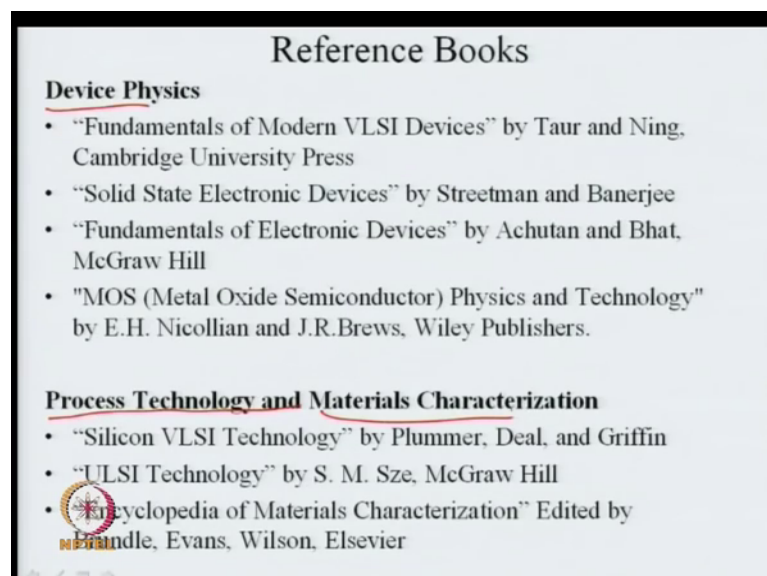
Lecture - 01
Introduction to Nanoelectronics

Welcome to this lecture series on Nanoelectronics, which will include a lot of discussion on devices as well as materials. This course will be taught jointly by 3 faculty members: I am Professor Navakanta Bhat, I will probably cover about one third of these lecture series. And subsequently two other colleagues of mine; Professor Shivashankar and Professor K N Bhat will also cover rest of the course.

We are from centre for nano science and engineering which is a brand new department at the Indian Institute of Science, Bangalore. And you can go to this website which gives a lot more details about the centre and the capabilities of the centre and the vision of the centre and so on and so forth. And the building that you see out here is the new building which is home to the centre for nano science and engineering. It houses state of the art nanofabrication facility and also very extensive nano characterization facility.

So, let us get started with the course just a couple of logistics first. Some of the there is no text book really for this course; however, there are quite a few reference books some of those are listed here and you know these consist of two things.

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Two broad areas that is devices as I mentioned you, know you can go through following series of books depending on which topics that you are interested in fundamentals of modern VLSI devices by Vaun Tour and Ning Cambridge University press; solid state electron devices by Streetman and Banerjee which is a very classic text book on semiconductor devices especially for the basics of devices fundamentals of electron devices which is written by Achutan and Bhat; K N Bhat who is also you know co-instructor on this course that we have then also there is one very important book on MOS technology which is metal oxide semiconductor physics and technology by Nicollian and Brews which is also considered as the bible for MOS technology.

And then you know there is there other set of books on process technologies and materials which include the silicon VLSI technology by Plummer deal and griffin ULSI technology edited by S M Sze McGraw Hill publication and also a very extensive you know topics on material characterization covered in encyclopedia of material characterization published by Elsevier, right. So, as I mentioned in addition to the reference book; books that I have listed during the course we will also point to certain publications which have appeared in the recent conferences and journals that are also very relevant to understand the material that we are going to cover in this course.

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Nanoscience-Nanotechnology-Nanoelectronics

Nanoscience : Phenomenological study at length scale < 100nm

Nanotechnology : Products created with building blocks at length scale < 100nm

- There is tremendous activity in Nanoscience and Nanotechnology the world over
- Nanoelectronics is one of the most mature of the nanotechnologies
- Nanoelectronics is one of the most successful commercial manifestation of nanoscience and nanotechnology
- Nanoelectronics growth in future relies on innovations in new materials and device structures

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So, just put things in perspective when we talk of nanoelectronics right in our nano science of course, is the most fundamental aspect just as the macro counterpart at nano

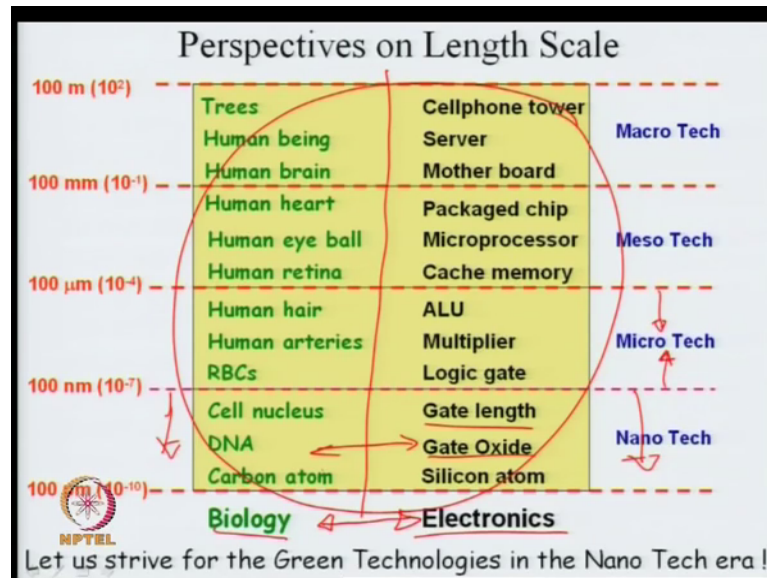
scale the nano science essentially talks about you know studying phenomenon whether it is physical phenomenon chemical phenomenon or biological phenomenon, but most importantly at length scale which are less than 100 nanometer right that is what we broadly classify as nanoscience.

Now when we talk of nanotechnology; what we are saying again just analogous to the macro counterpart based on the understanding that we gather after studying nanoscience we would like to make use of that understanding and create useful products right. That is what technologies all about the distinction here is that the products are created with at least one building block right products will have multiple building blocks in them any product for that matter at least one building block should be at lengths scale which is less than 100 nanometer if that is the case.

Then you know we call that product as a nanotechnology product or nanotechnology enabled product as most of you know there has been a very tremendous activity in nanoscience and nanotechnology in the last few years all over the world and we can certainly say that nanoelectronics which happens to be one of the branches of nanotechnology you see in nanotechnology. We can talk of nanomaterials nanobiotechnology nano electronics nanomechanics and so on and so forth. Out of this I can argue that nanoelectronics is probably the most mature of nanotechnology and in fact, nanoelectronics is the most successful commercial manifestation of nanoscience and nanotechnology right.

So, when we are talking of nanoelectronics, we use nanoelectronics enabled products in our day to day life although we may not really know about that right. And the most important thing to look ahead is that nanoelectronics growth in future relies on innovations in new materials and new device structures only then we can create new nanoelectronics products in the future right. So, this course is essentially trying to address that aspect right a very specific aspect of nanotechnology as I mentioned which is nanoelectronics and to be able to go along the nanoelectronics path in future what do we need to do in terms of materials technology and device technology ok.

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And that is what we you know hope to cover during this course just to get a feel for perspectives on length scale what I have tried to do here is to sort of just supposed to different areas you know one is of course, biology.

That we are all made of right and electronics that we create right as you know biology is of course, based on carbon whereas electronics is entirely based on silicon right you know that is underlined distinction out here this is carbon atom which is sort of course, you will have other atoms as well, but carbon is the most fundamental aspect out here. Whereas, here in addition to silicon you will also have various other things, but know silicon is essentially the enabler right. Now when we are talking of atomic scale right we are really talking of the order of 100 picometers right you know on the screen for some reasons these numbers are not coming out properly, but what you have here in terms of these horizontal lines out here this is 100 meters this is 100 millimeter 100 micro meter 100 nanometer and 100 picometer right 3 orders of magnitude decrease in length scale ok.

Now, in this area out here which is less than 100 nanometer right this is the bar that we have you know in biology we have of course, in addition to carbon atom then the building block of life which is n a and cell nucleus all this essentially fall in this domain right. And similarly, in the electronics counterpart you know in addition to the silicon atom you have the gate oxide which falls in this regime and the gate lengths. That we

talk about today are also in this regime right using this fundamental constructs that we have you know we then construct higher level abstractions right in electronics. Of course, we do that, but in biology nature does that right we do not still do not know how to do that right, but you know the idea here is that then we talk of red blood cells human arteries human hair.

You know this is a very classic example that was given when we were talking about microelectronics right just to give the length perspective here as you know less than 100 nanometer I already told you is nanotechnology right if you are less than 100 micrometer, but more than 100 nanometer then you are really in the regime of micro technology in general and if that micro technology applies to electronics then you know we are doing microelectronics right. So, when we started doing microelectronics way back in 50s and 60s the classic example that was given was that we build transistors which are of the size less than diameter of the human hair right diameter of the human hair is about 100 micrometer right then you know between 100 micrometer to 100 millimeter you have MESOS scale technologies right.

You know if you talk about electronics you know if you look at cache memory size or a microprocessor die or even a package chip right that will probably fall in this kind of length scale that we are talking about right then of course, you know using this we build a variety of electronics product right you know. So, this is the big distinction right you know I have also sort of indicated here biology has really figured out how to build the systems which are also you know to the environment meaning that you know once the living organism ceases to live right you know its bio degradable right whereas, you know disposing electronics waste has become one of the biggest challenge today right. Now these are some of the things you know.

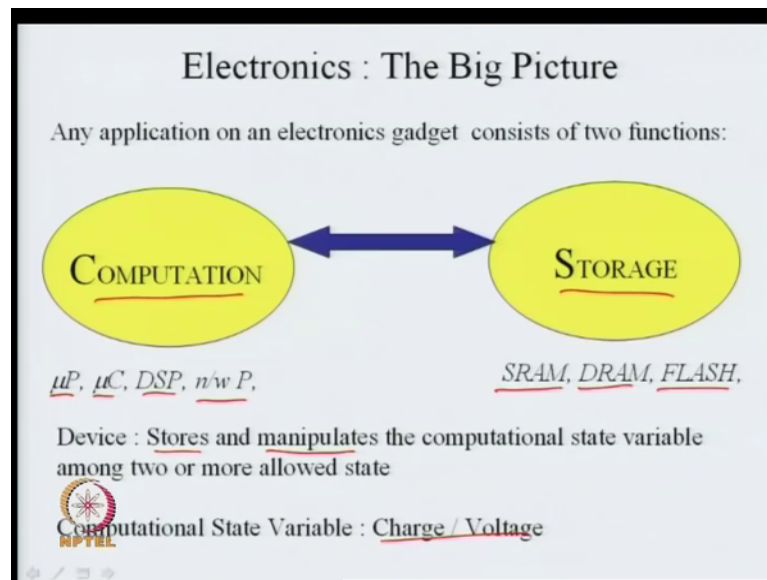
We have still not being able figure how although we have being saying that today we can create a computer which can be as powerful as a human brain which of course, is a very degradable point, right, but none the less we have not being able to do it with the efficiency that biology has been doing, right. So, in other words, the point to also understand here is that there are 2 important messages that I would like to drive home here right in future especially in the era of the nanotechnology right we there is a there is going to be a very strong interaction between biology and electronics. On one hand we would like to build electronics which we would call as bio inspired electronics really

trying to mimic how the brain does computation right I mean the way, we do digital computation is quite different from how biological systems do computation, right.

So, that is one aspect right related to that aspect is also the point of you know self-feeling architectures you know redundancy in electronics and so on and so forth which is to sort of learn from biology right on other hand I think one of the most important you know application area for electronics is really to apply electronics in biology. In the next couple of decades right in terms of really building senses for biological application diagnostic tools you know so called lab on chip devices and so on so forth right. So, although you know when we started the discussion on this slide we said that you know these 2 system seem to be distinct right, but there is going to a lot of synergy going forward among these two. So, seemingly which appear quite different, right?

I think they will have to co-exist and in fact, that is why there is. So, much interest in nanoelectronics and nanotechnology because today we have the capability of building transistors or electronic components which are at the same scale as that of the building blocks of life right and that is where we can actually start interfacing the electronics and biology at their fundamental length scale right. So, you know you need to keep this in mind although in the course we are not going to cover anything on application of electronics in biology or bio inspired electronics and so on and so forth. These are very good research topics to look forward to we will only focus on the silicon CMOS technology and also some other materials which are going to compliment the silicon technology right. So, that is going to be the emphasis of this course right. So, let us move on then.

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So, what is a big picture of electronics right you know electronics is very distinct right I mean you compare electronics industry with any other industry. For example, automobile right what is distinct about electronics as I already pointed out this is the only industry where you can create intelligence you see we create intelligence on silicon right and that is why electronics is really an enabling manufacturing field right. In fact, it is predicted that if you look at a high and automobile today most of the cost I would say easily more than fifty percent of the cost is really in electronics, because it is this electronics which brings intelligence to automobile, right.

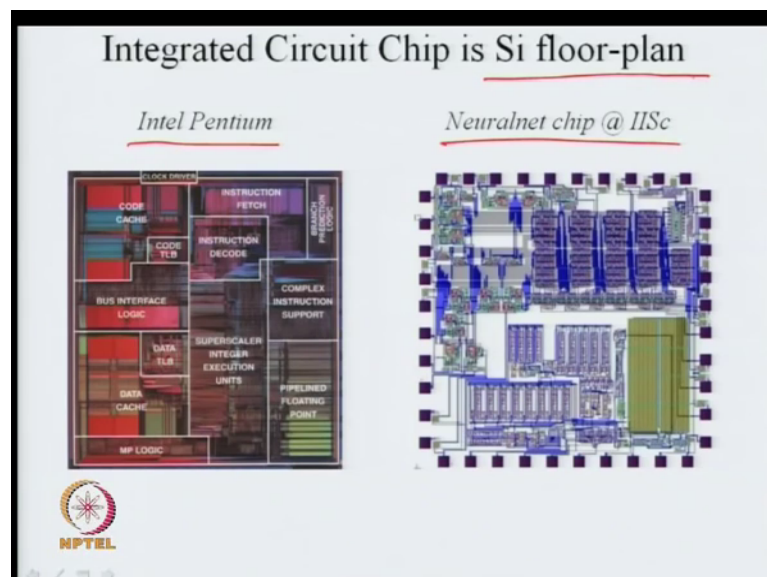
I mean same is true with any other industrial segment in other words electronics industry has a far reaching impact on various other industrial segments that we have right and there is a very interesting survey conducted by body in European union a while ago which said that the electronics industry growth in the last few years was twice as much as world GDP right just imagine that right you know that is the kind of growth that we have in electronics right. So, how is it enabled the big picture of electronics is that we construct these chips which will do either you know computation as is indicated here or storage right you know any field that you would like to look at there is lot of information that you gather.

So, you need to store information and you need to process information right the electronic chips enable us to do that when we talk of computation it could be a

microprocessor or a micro controller or a DSP chip or a network processors and so on and so forth right all these essentially take in digital inputs and digit bits and manipulate this bits right do lot of computation on this bits having done that you need to store the result right. I mean then you need storage elements the storage elements could be a static random access memory or a dynamic random access memory flash memory and so on and so forth, right.

So, when we talk of a device the device essentially stores and manipulates the computational state variable today most of the time we are essentially talking of digital electronics right. So, essentially it is a binary digital logic that we built till today. So, you know computational variable has 2 states and we manipulate this computational state variable computational state variable can take one of several forms, but today it essentially takes the form of voltage which comes about, because we store charge on the circuit nodes that we have in CMOS circuits right and you know this is how we build electronics right. So, any electronics chip that you have no matter what chip it is fundamentally it either does computation or it does storage.

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Now, if you go and put an electronic chip under a microscope under an optical microscope this is what you will see you will see a regular pattern on an electron I mean on optical microscope as is indicated here, if it is a chip in this example I have taken intel Pentium chip, you will have you may not know that unless you are a designer, but the one person

who has designed, it would know that there is a data cashier you know there is a floating point unit here and so on and so forth, right. So, this is what you will see when you look at the plan view or a top view and it does not matter which chip you look at you know.

This is another example of one of the chip that we have designed at I s e which was a neural net chip again you see some regular arrangement of some building blocks right and in other words integrated circuit chip is really silicon floor planning just as when you build a house you do floor planning right to begin with right. Similarly you need to decide how many blocks should be there on your silicon chip where should a blocks should be placed and so on and so forth. This is the task that is done by a chip designer as far as the subject matter of this course is concerned, we are not going to talk about chip design instead what we will do is really to ask the question what is inside the chip.

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The slide features a title "What is in a 'Chip'?" with a handwritten note "1cm" and "1000x" in red. Below the title is the text "A large ensemble of transistors connected 'appropriately' through multilevel metal interconnection lines...". The slide is divided into two main images: on the left, a scanning electron microscope (SEM) image labeled "SEM (After Sidewall-Cut)" showing a cross-section of a transistor with labels for "Sidewall Cut", "GATE", "150 nm Ti-Al sputted sidewall", "SOURCE", "DRAIN", and "IBM Lab FIELD". On the right, a top-down view of a chip with the "IBM" logo. At the bottom left is the NPTEL logo, and at the bottom right is a photo of a man in a white shirt looking at a laptop. A quote by Albert Einstein is at the bottom: "Every thing should be made as simple but no simpler! - Albert Einstein".

I mean you got that dye; dye is essentially a piece of silicon on which you have made the chip right you have put it under a op optical microscope, but if you take a cross section now you cut this silicon piece and take a side view; what will you see right what you will see is essentially a very large ensemble of transistors which are connected appropriately right this is a key depending on how you connect them how you interconnect them you get a particular function, right you may get a memory function, you may get a microprocessor function and so on and so forth right. And in order to do that you will also have large number of metal interconnection lines.

So, when you do the cross section at a very top right you probably will see a multilevel metal interconnects today state of the art chip can easily have more than 10 layers of metal lines right; for example, this is the top metal line and underneath, there will be you know another metal line and so on and so forth and eventually you will reach silicon on silicon you have a transistor and this is what is your transistor right and today, we are only talking about MOS transistor when we talk of CMOS its complementary metal oxide semiconductor transistor if you look at any electronics today more than ninety percent of the electronics that is built today is based on CMOS technology a very very small fraction may be less than 5 percent is by bipolar junction technology either on silicon or mesprits on gallium arsenide and so on so forth, right.

So, majority of the silicon electronics that you see is CMOS and hence the entire focus of this course is going to be on CMOS and this is what you will see at the very bottom on silicon right you will have constructed a silicon MOS transistor which will have you know a source terminal inside silicon a drain terminal inside silicon and a gate oxide we will see a blown up version a little later and a gate electrode right. It is essentially a three terminal device well strictly speaking, it is a 4 terminal device there is also a body terminal, but we will ignore that for the time being right.

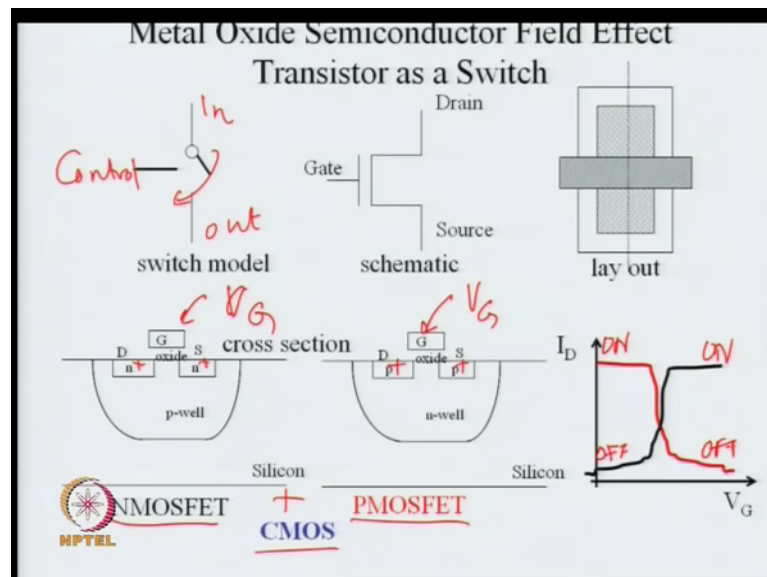
So, today's modern chip will have close to billion such transistors on a very small silicon area silicon area could be 1 centimeter by 1 centimeter in other words you will have you know a square silicon die about 1 centimeter by 1 centimeter and inside this you would have put close to billion transistors just amazing population density of the transistors right on silicon if you have billion transistor on such a tiny area they need to be interconnected right and that is why we need multilevel interconnects right otherwise I cannot pack them in 1 centimeter by 1 centimeter if I am given only 3 layers of metal interconnect maybe this chip will have to be 5 centimeter by 5 centimeter or whatever that is right.

So, that is why over the generation of the silicon technology we have also increased the number of metal interconnects and you know this is what you see. In fact, you know if you have an artistic view you know. In fact, somebody had remarked that today we are building cities on silicon right these look a flyovers that you see in modern cities today. So, this is a kind of things that you will see inside a silicon right and the entire focus of

this course is only on transistor we will not even talk about interconnects right. So, that is how focused this course will be right.

The next 45 lectures or so maybe we will you know have a brief reference to interconnects in one of the lecture, but that is not going to be a theme right the reason simply is that you see in silicon chips transistor is the active element interconnects are passive elements, right it is active element which is doing all the functions right it does not mean that the passive elements are not important, but you know it is very important to design the active element right.

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And that is why you know we will only focus on the transistor right. So, as I mentioned metal oxide semiconductor field affect transistor, right.

This is what we are going to look at right a very simple model for a transistor is you know you can abstract it as a switch right. So, there is a controller input that you have in a switch right and a signal will pass from input to the output if the control input has the right condition then the switch could be closed. And then you have input signal propagating to the output otherwise switch is open you know it is a very very abstraction when we talk of doing circuit, we come up with what is called a schematic abstraction of a transistor, right.

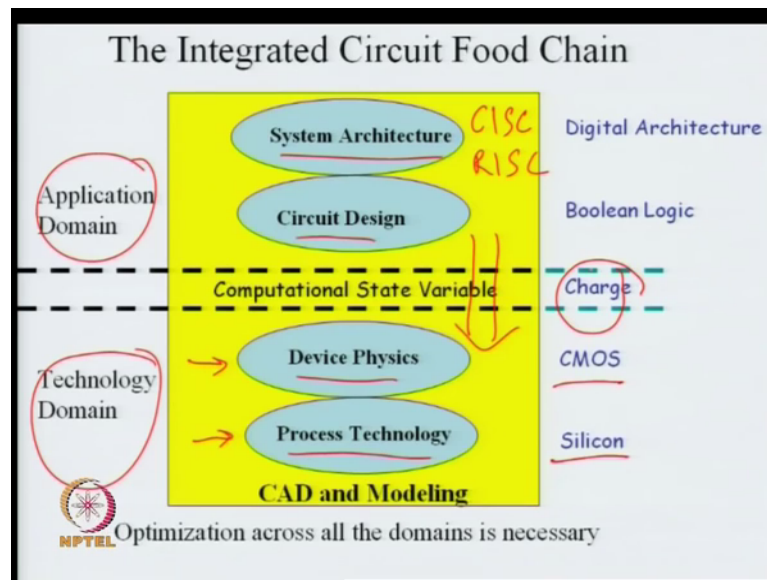
So, this is how you will represent a schematic of a N channel MOS transistor it will have a gate terminal it will have a drain terminal which will drain the carriers it will have a source terminal which will source the carriers right the carriers could be electrons and holes and accordingly you will have 2 flavors of transistors we will see in a minute look at the top view as I mentioned already this is what you see you know some regular arrangement of rectangles or you know some structures right this is what you see, but what we are really interested is cross section. So, as I mentioned you will have N channel transistor or N MOSFET and P channel transistor and if you build chips combining N and P channel transistor and that is your complementary metal oxide semiconductor technology right and.

You know your N channel transistor will be built in a P well which will have N plus drain and plus source and a gate insulator which is what we call oxide and a gate terminal and similarly you have a complement of this and that is why the name complementary metal oxide semiconductor wherever you have you P N you have replaced that with P you have P plus. In fact, these will typically be represented as N plus N plus which means they are very heavily doped N region N plus does not mean that you know N is of course, electrons are majority carriers electrons do not have positive charge right electrons have negative charge plus here indicates the doping concentration very heavily doped N plus regions out here and here you have very heavily doped P regions right a source and drain region and insulator is same N well they a built on N well and a gate insulator and.

You know they have complementary characteristics right with respect to the voltage that you apply to the gate this is what we call gate voltage right v_g you will have the transistor conducting very very little current ideally zero current when it is off, but it is never the case as becomes as it becomes clear later on in the course it will have very small non zero current and if you apply the appropriate voltage you know N channel transistor will turn on, right. So, this is off state for N channel transistor and this is on state for an N channel transistor, but P is exactly complement of this right when N is off P will be on and that is why it is conducting large current out there and when N is on P will be off correct.

So, this is how we build you know a circuits based on the transistors right. So, in other words, if you look at the integrated circuit hierarchy, right.

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We can classify broadly that there is a technology domain which enables the construction of the building blocks of chips transistors and interconnects that is where you need to have very good knowledge of device physics only if you know device physics you can come up with very innovative designs of transistors and having gotten that design you need to build that that is where you need appropriate process technology you need to use appropriate materials and sequence of processes to build that transistor this is what we call a technology domain.

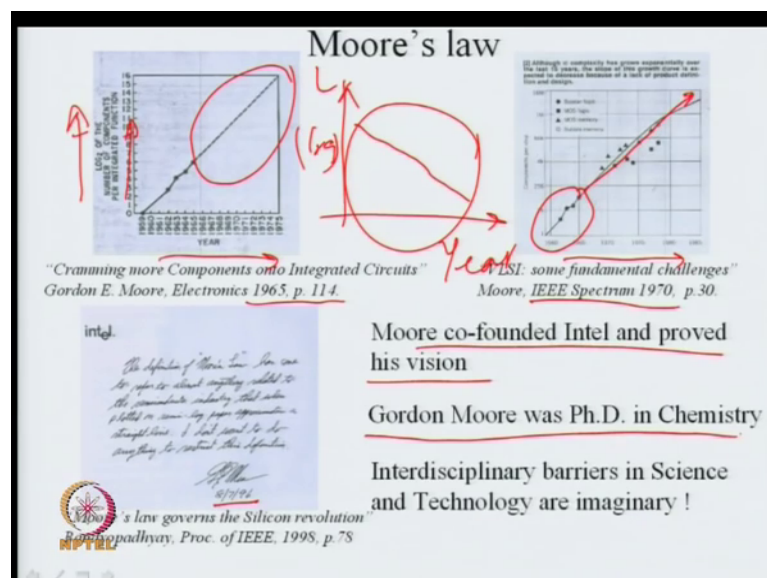
If you look at any foundries silicon foundries that is not mechanical foundries they essentially do this they do silicon chip fabrication they focus on device physics and process technology whereas, when we talk of application domain this is where the designers system designers and chip designers are working on they talk about what kind of system architecture they want to build for example, if it is a microprocessor you know you know what kind of architecture you know should it be CISC architecture or a RISC architecture things like that if you are building an ADC what kind of an ADC analog to digital convertor that you want to build successive approximation or flash a to d convertor.

So, this kind of system architecting happens here and once you do the system architecting you do circuit design right at the fundamental building block which is transistor you need to architect the circuit design the circuit and do the lay out only when

you do the layout you complete your design then pass the design onto the foundry then a foundry can the design run through all the processes and build your chip right. So, this is really an interdisciplinary area you see you need lot of understanding of materials chemistry out here good understanding of physics good understanding of circuits computer science or whatever that application domain is. And of course mathematics to develop models computed design is key here right we do lot of cad both in the technology domain as well as you know circuit domain right.

So, today as I mentioned our process technology is based on silicon our devices are CMOS complementary metal oxide semiconductor and our computational variable as I said charge and hence we are not going to talk anything about for example, using spin as logic variable right. So, called the area of spintronics right that is not at all going to be discussed in this course right and of course, we build circuits today based on Boolean logic digital architecture. This is where the point I mentioned earlier that bio inspired circuits could be quite different from you know digital architecture and Boolean logic right. But again we will not really discuss too much about that we need to really do optimization across all these domains only, then we can get a very high performance integrated circuit right that is the key otherwise we will not be able to do that.

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Any discussion on you know scaling and nanoelectronics is incomplete in my opinion without reference to Moore's law you you might have heard about this Moore's law, but

let me just walk you through that Gordon Moore published a paper way back in 1975; 1965, I am sorry this was also published in a trade journal called electronics the paper was titled cramming more components onto integrated circuit that was the title of the paper, it is a very interesting paper easy to read you know you just google it you will certainly get this paper on the internet right; what he did there are lot of things that he discusses, but there is one very interesting the thing that he did right he constructed a graph right which is shown out here what he did in this graph on x axis he put the year time line is on x axis on y axis he put the number of components per integrated function essentially what it meant means is that by the way this graph first of all is plotted on a semi log sheet ok.

So, this is log scale here y axis is a log scale and x axis is a linear scale all he did was he took integrated circuit chip introduced in any given year and counted how many transistors where integrated on that chip on that given year right. So, number of transistor is plotted on y axis and year on the x axis and he did not have too many data points you see the first integrated circuit was invented way back in 1958, if you may recall the first I C was invented by Jack Kilby at Texas instruments that was in 1958 right the first semiconductor transistor itself was way back in 1947 right which was a bipolar junction transistor not a MOS transistor.

Although in this course we only talk about MOS transistor that is an irony right the first semiconductor transistor was indeed bipolar junction transistor although you know the scientists at bell labs were really trying to make a MOS transistor, but making a MOS transistor was. So, difficult they ended up doing a bipolar junction transistor right, but that apart the data points are only from 1958 till the year 1965 when wrote this particular paper right. So, you know he has about 5 data points here he notice that it fits a straight line, right. In other words because it is a semi log sheet it indicated that the number of transistors that were put on the chips were increasing exponentially over the time in particular at least during that period, the number of components or transistor was doubling every year, but the lot of credit is given to Moore, because of this dotted line that he has in this paper you see.

You know this is not based on any data point you see this was written in 1965; obviously, no chip was done in subsequent years at that time the point he made here was that this will continue to happen in the years to come that was a very very bold prediction at least

what he said was that he does not see any fundamental impediments from science it is only the limitations of technology if any we are not able to construct that, but otherwise we should be able to increase the number of transistors exponentially over the years right and indeed subsequently there was a paper published in I triple E spectrum in 1970 right again it is a very interesting paper you can go back and read that and.

What is done here is that now there are few more data points on x axis because this was you know published the subsequently right and what you see is that these are the original data points which were published in the Moore's paper and you see that all subsequent data points are also on the same line right it has continued to happen. In fact, Moore wrote in his handwriting out here on you know sometime in 1996 a very interesting he says the definition of the Moore's law has come to refer to almost anything related to the semiconductor industry make a note of it almost anything related to semiconductor industry, right that when plotted in a semi log paper is a straight line right. So, you see Moore's law is not a fundamental science law, it is not a law in physics; for example, you know it is a; it is a very very bold prediction that was made by Moore you take feature size or the dimension of the transistor plot it as a function of year meaning this is year and.

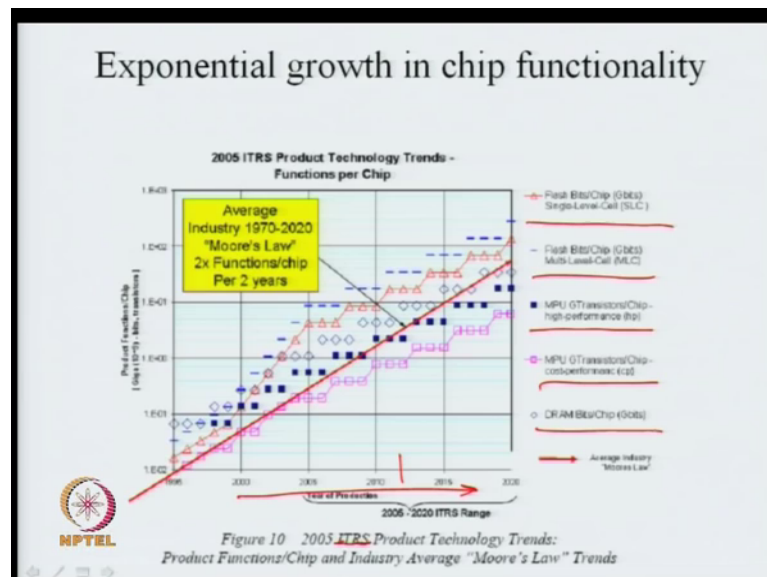
This is the transistors size let us say length of the transistor if this is log scale we see that over the years the length of the transistor has decreased exponentially any anything that in semiconductor industry you know goes according to this law right, but you see the key here is really this because we are able to miniaturize the transistors, because we are able to miniaturize this this will happen if you had not done this there is no way we can cram more components on to integrated circuit right this key here the message here is scaling we need to scale technology. In fact, we will have more discussion in one of the future lecture why do we need to scale in the first place apart from putting more transistor in a given real estate of silicon.

There are various other advantages of scaling as well we will discuss a lot more of that in one of the future lectures of course, Moore not only did this prediction, but he also proved his vision you see; Moore co-founded intel one of the technological giants in electronics, right, Gordon Moore and Robert Noyce co-founded intel way back and of course, you know because microprocessor happened. Then of course, you know there was an explosive growth of electronics right before that we had only memories memory

chips were there of course, right. But memory chips were only for storage the real intelligence comes that is information processing comes because of microprocessor or any of these logic chips and very interesting point I always tell my students is that you know Gordon Moore actually had a degree in chemistry although he went on to lead a technological giant in electronics industry right.

So, there is really no barriers in science and technology right if you have you know real liking for any field you know pick up that at point in time of course, you need to have perseverance and interest and you should really want it right, only then you can get it.

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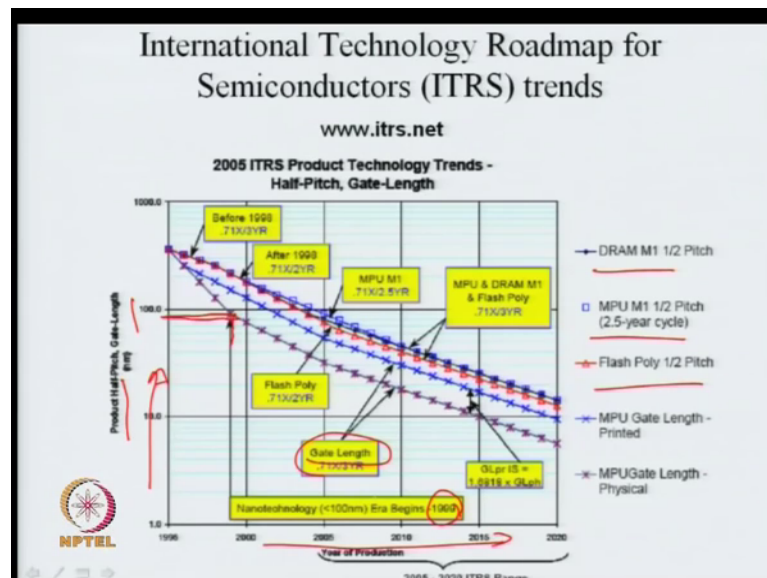
So, this is a just a same data just to sort of highlight in from what is called international technology road map for semiconductor this is an authoritative body ITRS as is indicated here again you know you can Google; ITRS, you get lot of information right at least I would recommend everybody who is interested in nanoelectronics to really to take a look at ITRS website it has lot of interesting technical information out there what ITRS does is to look at the history and make prediction for future make prediction.

For future based on not only historical trends, but also based on a fairly good understanding of current capabilities and where is science heading in future right it is not like kite flying future prediction right; the future prediction are done very consistently, but more importantly ITRS revises its technology road map every year right you go to ITRS website and you can take a look at all the previous technology road maps right

only by having that yearly revision and upgrade you know you can have these road maps correct right, but what is plotted here again on x axis is year of production going from 1995 the prediction is of course, all the way to 2020. Today we are somewhere around 2012 what is plotted on y axis are multiple things a product functions per chip is what it broadly indicates, but what is plotted is flash memory number of bits that you can make on a chip and if it is a single level cell in flash memory.

You can also build what is called a multilevel cell, if it is a multilevel cell chip, how many bits can you put in a chip, if it is a microprocessor unit right then how many transistors that you can put on a chip and again there are different kinds of microprocessor called high performance microprocessor low power microprocessor different flavors this is also a different flavor of a microprocessor, if it is a DRAM how many bits can you put can I make 16 GB DRAM, 32 GB DRAM and so on and so forth. So, this line right essentially says that all this products their capabilities are increasing exponentially over the years and this is happening because of miniaturization right that is the key otherwise you know we would not be able to do this.

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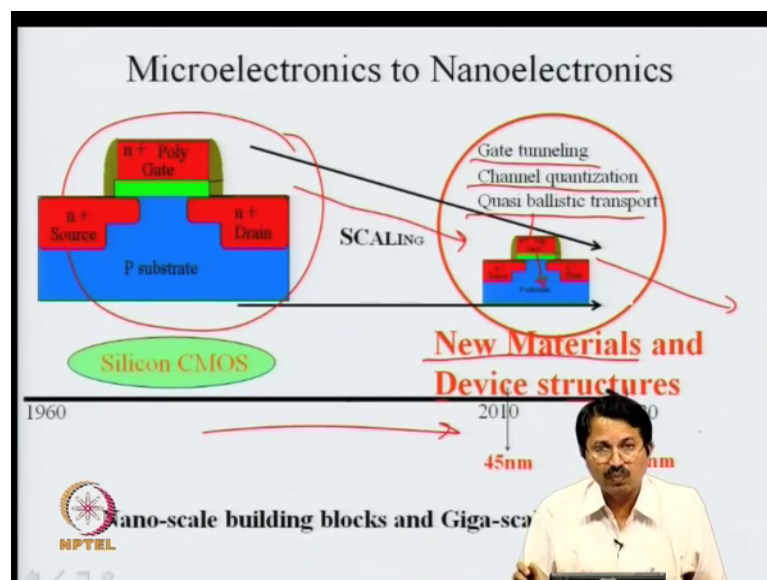


Yes, this is the point right now the previous comes about because of this again on the x axis, I have the years and on the y axis you know what we call as a feature size there are multiple things that are plotted here called product half pitch gate length and so on and so forth again for multiple products for DRAM for microprocessor for flash and so on

and so forth all of them have the same trend the feature size is decreasing over the calendar year of course, the graph that you have at the at the very bottom is essentially the gate length you see this is the gate length the gate length of the transistor that is the lowest dimension using this you build other constructs right pitch will be half pitch will be little more than the gate length and so on and so forth; we will talk more about that later now.

This point here is an important point I want you to look at and. In fact, that is where it says nanotechnology era begins in electronics when did it begin it began in 1999; not today, it began in 1999 which is almost thirteen years ago today we are talking of 2012 right although you know there was not much fanfare right because electronics for electronics it was just a evolution you know you are doing little more than a 100 nano meter you cross that 100 nano meter barrier right. So, what is the big deal kind of right? So, there was not much fanfare about saying oh I have a nanotechnology product right, but on the fact that now we have so much hype on nanotechnology, it is not just hype you see we have been using nanotechnology product at least nano the building nanometer have been used in chips since 1990 and of course, we are continuing to scale this and very soon of course, we will also cross the 10 nanometer barrier ok.

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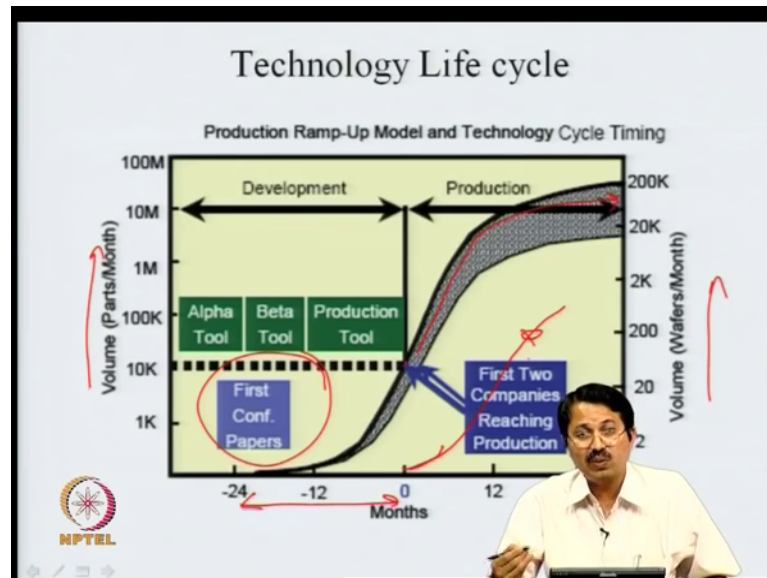
That is how small we will be building the transistor. So, in other words what have it done we have taken a MOS transistor which is the building block remember that source drain

a well or a substrate a gate insulator and a gate electrode and made it smaller and smaller and smaller over the years this is all silicon CMOS right as I mentioned the first transistor was not CMOS BJT and first few years right in 50s, it we were essentially building chips based on bipolar junction transistor the MOS transistor was actually invented although concept was very well known way back in 30s and 20s, it was actually made possible only in 1964. And then of course, in 1960s once we made MOS transistors the technology was just silicon CMOS, it just displaced bipolar junction technology, but we took the fundamental building block and just made it smaller and smaller that is how we have been doing the business in the last a few years.

But today, we are facing some very fundamental challenges in making this transistor smaller in future because we are really hitting some fundamental limit there is lot of gate tunneling current w use to say that the insulated gate MOS transistor has an insulated gate, if I apply voltage on the gate no current flows through the gate terminal because there is an insulator that is no longer true now this causes lot of problems, we need to overcome that problem there is lot of issues with channel quantization the channel here between source and drain is so small that the quantization effects cannot be neglected and the transport itself is no longer drift diffusion based transport right, it is becoming quasi ballistic transport right.

So, if we have to scale in the future miniaturize the transistor in the future we can do that only if you have new materials and new structures otherwise you know there is no way we can go down to 15 nanometer kind of dimensions right.

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Now, there is one important point that I want to bring up here is something called technology life cycle right this also gives you a feel the place of electronics right you know at least from the point of view of using electronics products right you see the best way to best time to buy electronics product is always tomorrow right if you want to buy a cell phone you wait till tomorrow, because you get a better cell phone with better features for a lower cost right, you will buy a cell phone today and your friend will buy one 6 months down the line and you will curse yourself why did I buy this right six months ago right you know technology is becoming obsolete so fast right.

If you look at the history the way things are happening is that a new technology cycles start emerging at time line this. Let us say reference zero is reference x axis is month it takes about 2 years develop a new technology during this period you know you are working on your equipments you are working on your processes you are working on your device structures and so on and so forth. But there is no product in the market really; however, you will be seeing lot of papers published in the conference leading conferences and journals right and very quickly you figure out; how to make a product using this.

Because making a single transistor is one thing making billion transistor all of which are working properly and interconnect them appropriately is a marvelous feat right that is where you need to you know have lot of learning right that comes about and you actually

start making the products right you start selling chips what is plotted here is volume parts per month and here parts here is chips per month and here wafers per month right you know twenty wafers can give you 10000 chips right this is 10 k here this is 2200 and so on and so forth. The scales are different because each wafer can support a large number of chips you see, ok.

So, then of course, the production ramps up and you really have large number of chips porting to a new technology at the same time in the r and d there will be a new wave that will start right you start working on a new generation of the technology you know; it is sort of ongoing right and that is why you have continuous miniaturization introduction of new technology nodes and so on and so forth, right. And that is a very unique thing about electronics unparalleled compared to any other industrial segments.

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ITRS Projections

Year of Production	2007	2010	2013	2016	2019	2022
Technology Node (nm)	65	45	32	22	16	11
Transistor Gate Length in Microprocessors circuits (nm)	25	18	13	9	6.3	4.5
Wafer diameter (inch)	12	12	18	18	18	18
Number of masks required for fabrication of Microprocessor	33	35	37	37	39	39
Number of Transistors in Microprocessor (billion)	1.1	2.2	4.4	8.8	17.7	17.7
Number of interconnect wiring levels in the Microprocessor	15	16	17	17	18	18
Number pins for packaged Microprocessor chip	1088	1450	1930	2568	3418	3760
Operating voltage (V)	1.1	1.0	0.9	0.8	0.7	0.7
Microprocessor frequency, GHz	9.3	15.1	23	39.7	62.4	73.1
Chip power dissipation (Watts)	189	198	198	198	198	198

This is the only industrial segment where the cost of your product is decreasing every year with more functionality right. So, what is the projections for the next few years right this is taken from ITRS road map as I mentioned you should go and look at the ITRS road map. You know today we have something like a 45 and 32 nanometer technology in volume production, you know in future we will of course, go down to something like eleven nanometer technology node there are multiple matrix here technology node is quite different there is also something called transistor gate length right when I am

building a chips on so called 45 nanometer technology the transistor dimension may actually be much less than that.

You know I may be making transistor whose gate length is as small as twenty nanometer right there is a big difference between the so called technology label which is derived based on a definition of half pitch as the actual very much smaller right when you have the gate dimension and spacing equivalent then the gate length becomes equal to half pitch, whereas if the gate length is much smaller and di spacing is much larger than half pitch is more than gate length you see there is a distinction between the technology node definition which is derived from the half pitch that is you have one transistor here you have another transistor here. So, this is the pitch right how closely you can pack the transistors and if the spacing and dimensions were to be identical half pitch and gate length would be identical, but that is not the case right, we miniaturize the gate length more aggressively we can pack the transistors together.

So, that is why there is a difference out here wafer diameters today we are building silicon chips on twelve inch wafer diameter right these are like you know big dinner place that you have twelve inch wafer diameter reason being that if you have twelve inch wafer you can populate large number of chips right that is how you know you can reduce the cost of chip you will have so many chips from a single wafer and of course, in order to do that you have to go through a very complex process steps; you will probably go through at least 35 photolithography steps in a nanofab facility.

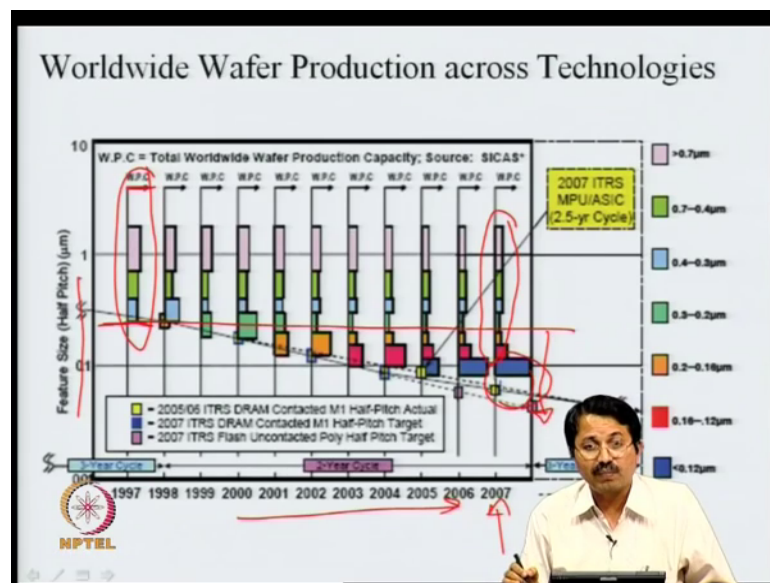
The number of transistor that you are talking about is about 2 billion transistors that you would integrate and you know number of interconnects as I mentioned you know something like more than 10 that I already mentioned because you have. So, many transistor you need to be able to interconnect them right that is why you need large number of interconnects right. And of course, toady we are talking of ultra-low voltage operation right about 1 volt is what the supply voltage for all these chips they are no longer you know your 5 volt chips you know at if you apply 5 volt the transistor will dry instantaneously.

So, the supply voltage has to be very very low of 1 volt and of course, you know very large number of I packaged a pins right you can never remember the pin out of the chip right 1450 package pins right very interestingly out of this 1450 at least for

microprocessor kind of chip at least two-thirds of the these pins are only VDD and ground pins right that is required to bring in supply into the chip from multiple a regions. So, that you can minimize the noise because your chip is working only at 1 volt right; you need to make sure that you do not have much noise margin here you need to make sure that you minimize the noise right and.

That how that is why you need to be able to distribute your so called power network very efficiently and of course, because we do that we get very high performance we talk of frequencies upwards of 10 gigahertz and of course, we also consume very large power today you know state of the art microprocessor is consuming more than 100 watt this is also becoming a serious issue; it is as if you have a 100 watt light bulb sitting in your CPU box, right.

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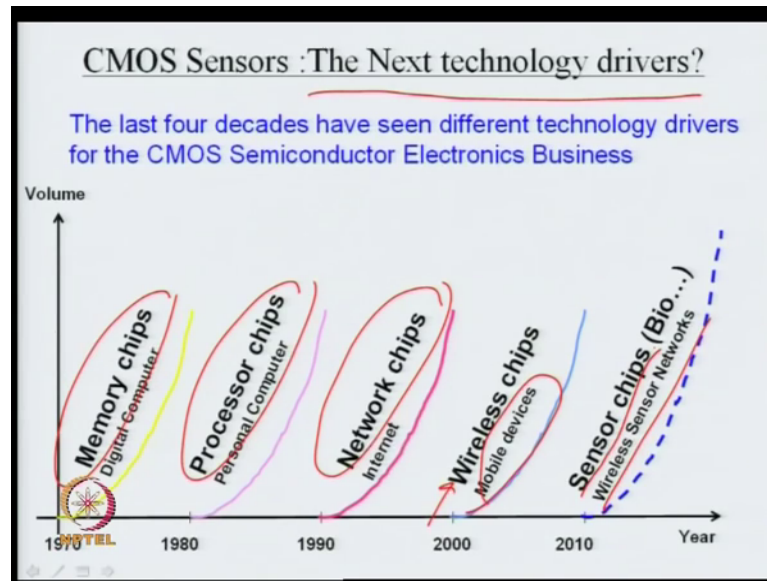
You know that is the kind of power dissipation that we have in this chips another important point I wanted to bring about is that just because we have a newer and newer technology introduced almost every 2 years, it does not mean that all older generation technologies are obsolete each technology has its relevance size the fit all it means is that the highest performance the so called leading and bleeding edge chip such as microprocessor very high performance flash DRAM and what have you that will immediately go on to the new technology node what.

This is a very interesting plot again x axis is year time line, but y axis is a very interesting plot out here you know this essentially is a worldwide wafer production across technologies if you look at 1997. Along this 1997 you have actually created another x y graph on out here w p c refers to wafer production and here this refers to the feature size way back in 1997, we had only technologies going up to point 5 micron that is why along this horizontal line you do not have any data points coming down here the technology the best technology that you had stopped there you had lot of products out here, but at that time one micron technology which was state of the art maybe in 1990 continued to stay there for niche application.

So, there was wafer production to make one micron chips as well and as you go along the years you see along this line there are new rectangles that are being added you see right all. That means, is that today you know if I look at 2 thousand seven it is not today of course, 5 years ago; you see in addition to this there are new rectangles added which corresponds to different generations of the technology right going all the way to ninety nanometer technology back, then if I construct this plot today it will go all the way down to 45 nanometer, but the point to note here is that of course, the highest performance chip will immediately go to the latest current technology, but even then you still have worldwide wafer production happening on 0.5 micron technology point seven one micron and so on and so forth.

Just to give an example if you want to make a very high power chip you want to drive several watts you know into you know your audio amplifier or what have you right then I cannot do that with 1 volt right I need to maybe use 5 volt or 10 volt then the only way I can construct is using one micron bigger transistors, because if I go to you know smaller transistors the transistors will just die as I said they will break down. So, each technology has its relevance, but the point is that the leading edge technology will occupy most of the business because most of the business really comes from the very high end chips like microprocessors and you know a very high capacity memories and so on and so forth.

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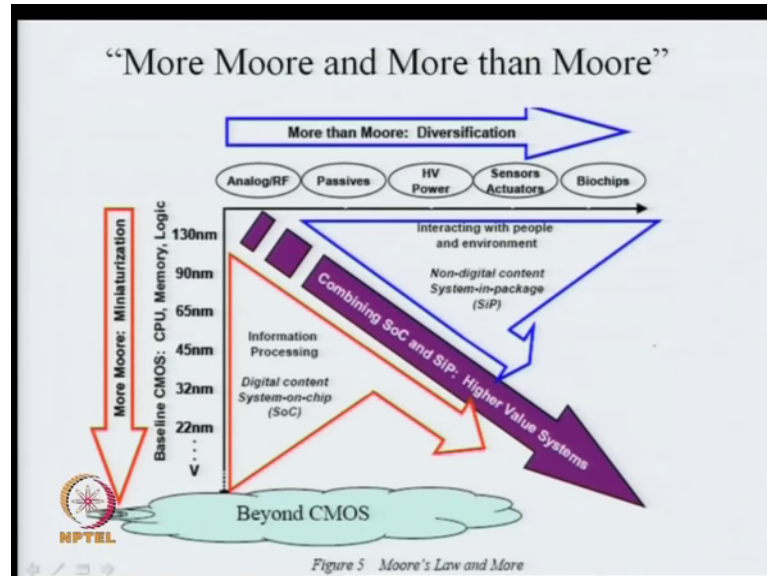
In addition to this there is something interesting happening for last few years and that is something called building sensors on silicon so called CMOS sensors presumably these will become next technology drivers in other words if you see last few decades in every decade there was a technology driver right way back you know in 1970s until microprocessor happened. We had only memory chips well of course, you had microprocessor chips that microprocessor was invented and 1990s was really internet era right internet was invented and you had lot of new chips the so called network chips which enable networking came about it does not mean that we did not fabricate processor.

We did not fabricate memory we continued to do that, but there is a vector that has emerged in the last decade you know it is really an explosion of hand held devices right and accordingly, we had large number of chips which enabled you know your cellphone PD as digital cameras and so on and so forth. I think next couple of decades really is going to be you in terms of systems we will really be building so called wireless sensor network based system right.

So, called ambient intelligence right we need to be able to have very low cost sensors spread all around which will collect lot of information in real time and you know makes sense out of it right in order to do that we should really enable a large number of sensor chips right. So, this is also that is happening although in this course we will not really

talk about sensor right, but when we talk of nanoelectronics this is also a very very important aspects.

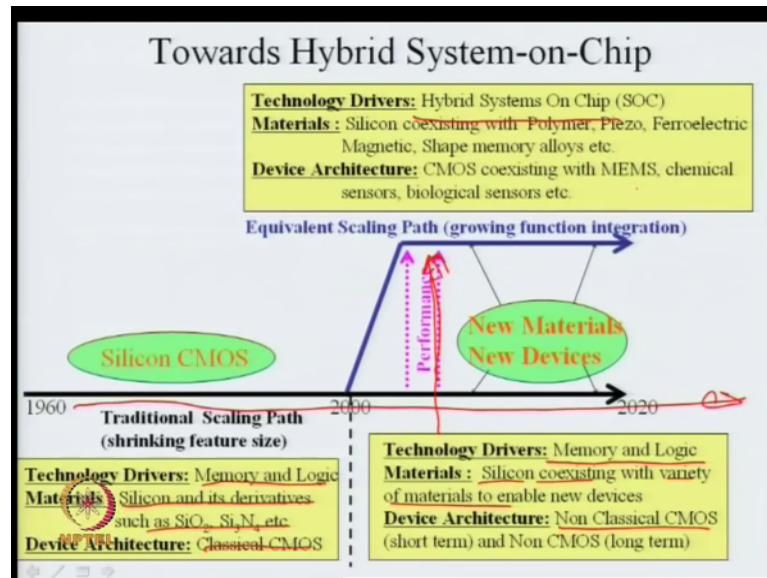
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In other words, we talk of what is called more Moore and more than Moore what we mean by more Moore is essentially this is conventional electronics, we are building computational units such as CPU logic and storage unit such as memories right all that we are doing is miniaturization and this is what is happening as per the Moore's law, we are miniaturizing scaling and so on and so forth; more than Moore is essentially along with electronics trying to embed something different right to begin with along with digital you may say I want to embed analog and RF function then I want to embed passives such as inductors capacitors on the same chip.

Then also I want embed high voltage high power transistors on the same chip which has low voltage low power transistors then taking it further sensors and actuators and biochips and so on and so forth right. This is that we will not really talk about.

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So, we will restrict ourselves only to what we call traditional scaling right what I call traditional scaling is essentially shrinking feature size, we take the building block which is transistor we are only looking at electrical domain make the transistor smaller and smaller the technology drivers have been memory and logic the technology drivers will continue to be memory, and logic along that traditional scaling part the material and devices are silicon and its derivative classical CMOS is what we had going forward silicon will coexist with a variety of materials that will be the focus of this course.

We will talk quite a bit not only on silicon on germanium on compound semiconductors and so on and so forth right in addition to that device architecture not only CMOS, we will also talk about non classical CMOS that will also form a significant chunk of the course that we have whereas, this equivalent scaling path is really staying at the same dimension not necessarily miniaturizing, but doing functional integration add more functions to the chip not just compute and storage, but add you know sensing and actuation this is what we call hybrid systems on chip or S o C s silicon will coexist with variety of functional materials polymer plezo ferroelectric magnetic so on and so forth. In terms of devices not only CMOS, but mems chemical sensor biological sensors everything will be sort of integrated on a single chip ok.

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New materials are essential ...

The periodic table of the elements

	1A	2A	3A	4A	5A	6A	7A	8	1B	2B	3B	4B	5B	6B	7B	0		
1	H															He		
2	Li	Be									B	C	N	O	F	Ne		
3	Na	Mg									Al	Si	P	S	Cl	Ar		
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	L	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	A															
			L	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			A	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Legend:

- Metals (orange)
- Metalloids (green)
- Non-metals (cyan)
- Transition Metals (yellow)
- Gases (pink)

NPTEL

So, we would need new materials also to be able to do that this as I said is going to be the emphasis of this course new materials and new device structure right. So, you know what I will do at this time you know is just flash this periodic table for you to go back and think about you know of course, you know silicon is out here in column 4 which a semiconductor and our entire electronics is based on silicon right in addition to silicon there are lot of other materials we will see in the next lecture that what it used to be until 10 years ago we will recognize.

That we had only handful of material if you were to ask what is the ingredient of the chip you will see only about five or six material that you could list, but today its quite different. We will see why that is the case and we will also talk about the device structure right. So, we will save it for the next lecture and you know with that we will conclude the lecture for the day.