Basic Electronics
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Lecture - 01
A brief history of electronics

Welcome to Basic Electronics. I am Mahesh Patil, and I have been teaching at IIT Bombay. This course is about basic electronics but before we start with electronics, let us make a few comments about the process of learning. This process involves three components: the first component is the teacher who needs to present the course content in a systematic and logical manner. And we can assign 25 percent weightage to the teacher. Next comes the course material such as video lectures, textbooks and internet resources, we can assign another 25 percent to this part.

We still have 50 percent left and that must be assigned to the effort from the student. The student’s involvement is crucial in the learning process; if the student is learning from a recorded lecture, it is important to realize that it is very different than watching a movie or TV serial. If something is not cleared, you must stop the video, watch that part of the lecture again, work out things yourself with pen and paper and then continue with a recorded lecture. An excellent way to learn is to prepare your own notes based on the recorded lectures and may be other inputs that will surely help in clarifying difficult concepts.

Coming to this specific course, we will cover several useful electronic circuits in this course both in the analog and digital domains. And our emphasis will always be on understanding the fundamental concepts rather than route learning. So, with that introduction, let us gets started. Before we begin with basic electronics, it is a good idea to develop historical prospective of electronics, see how things were evolved and so on. And we should mention before starting that the images that we are going to see have been taken from the internet.

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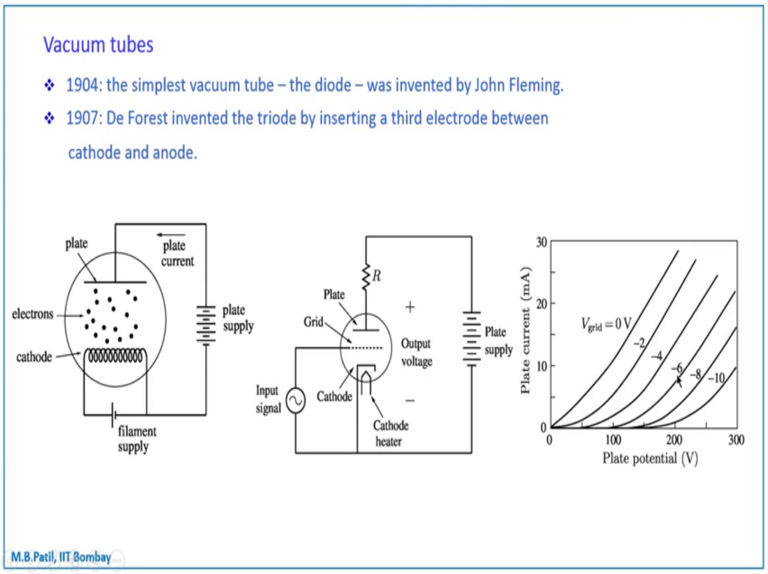

Vacuum tubes

- 1904: the simplest vacuum tube – the diode – was invented by John Fleming.
- 1907: De Forest invented the triode by inserting a third electrode between cathode and anode.

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So, let us get started electronics really started with vacuum tubes because in those days they were know semiconductor devices and the simplest vacuum tube the diode shown here was invented by John Fleming in 1904. So, in this device, there is a cathode which is filament and there is a plate. The plate is biased with a positive potential and the cathode is heated with this filament supply, so that it emits electrons. These electrons get attracted to the plate and that is how the current flows in the external circuit. And if this voltage is made negative then there is virtually no current. So, this device allows current flow in one direction, but blocks current flow in the other direction, so that is how these diode works.

In 1907, De Forest invented the triode by inserting a third electrode between cathode and anode. Here is the schematic diagram and this is the third electrode called grid. The way this device works is that the cathode emits electrons as I did in the diode, and the plate is positively biased. So, the electrons emitted by the cathode get attracted to the plate and that is how we have a plate current. Now, the grid electrode is biased with a negative voltage, and therefore it repulses these electrons, and therefore that causes a reduction in the plate current. Here is the plot of the plate current in milliamps versus plate potential in volts. And observe how high these voltages are 300 volts. Let us take a fixed voltage let us say 200 volts. For V grid is equal to 0, we have that much current for V grid equal to minus 1 the current is smaller; for minus four still smaller and so on. So, this figure clearly shows the control of V grid on the plate current.

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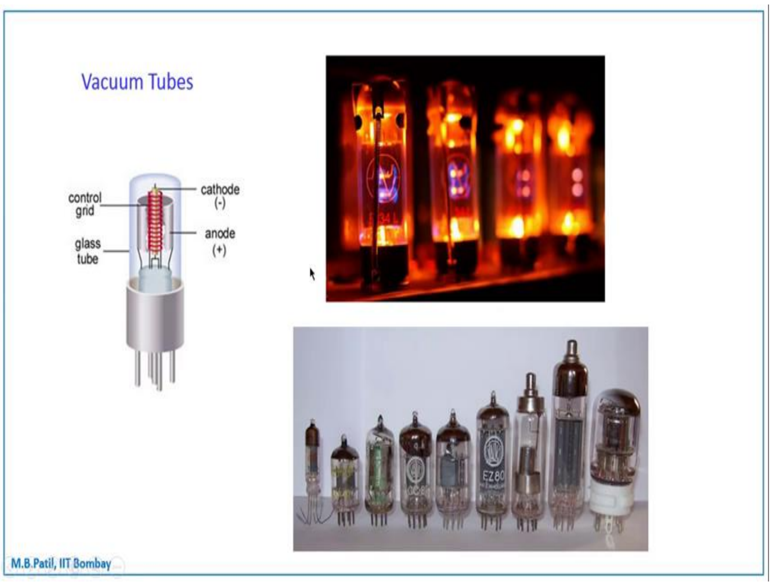

Vacuum Tubes

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Here is what the real structure looks like. We have a glass tube under vacuum this one outer cylinder is the anode; after that, the red structure is the control grid and inside that is the cathode. So, cathode emits electrons which make it to the anode and because of the negative potential on the control grid some of the electrons get repelled that is how the control grid controls the current. And the terminals all of these are brought out like that at the bottom.

And here is a real photograph showing various types of tubes. There are tubes with more than three electrodes, and they get quite complicated, but roughly we can see that there is a glass tube, and we also notice that they are large, these dimension could be something like 5 centimeters for example. So, this size is one column with vacuum tubes, they tend to be very large compare to the moderns in a semiconductor devises for sure. The other problem can be seen in this picture. And these vacuum tubes when they conduct they glow like a light bulb and we can see that in this picture and that is the other problem with vacuum tubes they consume very too much power.

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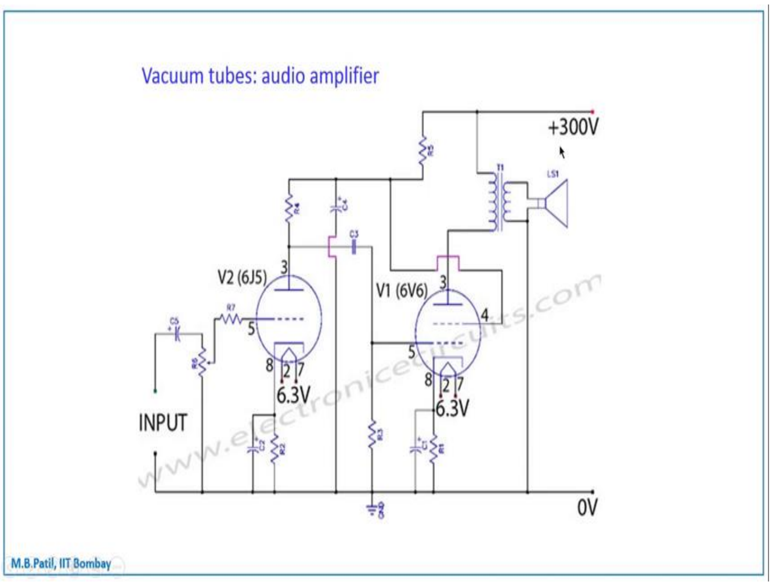
Vacuum tubes: audio amplifier

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Here is a circuit diagram of an audio amplifier made with vacuum tubes. These are the tubes here that are the speaker that is the transformer there. And what should we really notice in this circuit diagram is this part here 300 volts that is a very high voltage; and in modern electronics we simply do not have these kinds of large voltages, we probably have 10 volts or 15 volts, but certainly not 100 of volts.

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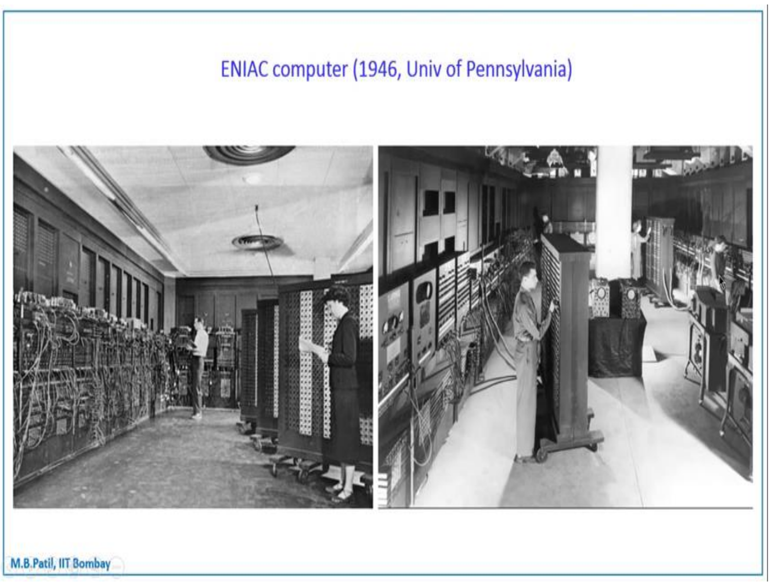
ENIAC computer (1946, Univ of Pennsylvania)

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Here are some pictures of another first computer called the ENIAC computer built with vacuum tubes; we are talking about 1946, so they were no semiconductor devices at that time. The vacuum tubes are not seen in this picture, but they may be behind these panels here. This entire room is one single computer, and this is another view of the same computer. And these people we see here they are probably computer engineers or computer programmers of those times.

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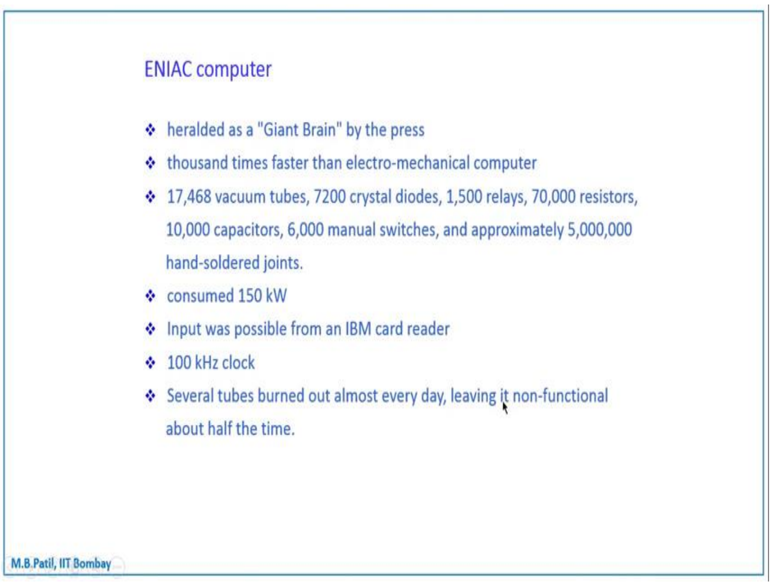

ENIAC computer

- heralded as a "Giant Brain" by the press
- thousand times faster than electro-mechanical computer
- 17,468 vacuum tubes, 7200 crystal diodes, 1,500 relays, 70,000 resistors, 10,000 capacitors, 6,000 manual switches, and approximately 5,000,000 hand-soldered joints.
- consumed 150 kW
- Input was possible from an IBM card reader
- 100 kHz clock
- Several tubes burned out almost every day, leaving it non-functional about half the time.

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Let us now look at some facts and figures about the ENIAC computer. And there is a lot of information on this topic on the internet, and you should really look it up. Here we will just look at some other points. It was heralded as Giant Brain by the press. And Giant Brain, it was compared to the electro-mechanical computers of those days. This computer was a thousand times faster. It had some 17,000 vacuum tubes, some 6,000 manual switches and approximately 5 million hand-soldered joints.

This of course, was bad news, because with each hand soldered joint the reliability of the entire computer goes down. It consumed 150 kilo watts that are a huge amount of power. Input was possible from an IBM card reader and each card was one statement of a program; its clock frequency was 100 kilohertz. And for comparison our modern computers have a clock frequency of 2 gigahertz or 3 gigahertz. So, you can find out how many times faster today’s computers are.

Several tubes burned out almost every day, and also these soldering joints keep problems; leaving the computer non-functional about half the time. So the computer could not be used continuously because of this reason.

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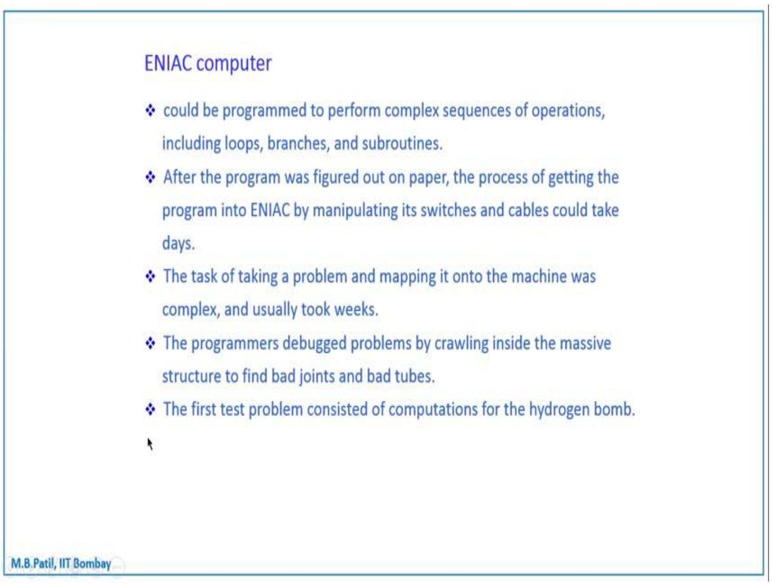

ENIAC computer

- could be programmed to perform complex sequences of operations, including loops, branches, and subroutines.
- After the program was figured out on paper, the process of getting the program into ENIAC by manipulating its switches and cables could take days.
- The task of taking a problem and mapping it onto the machine was complex, and usually took weeks.
- The programmers debugged problems by crawling inside the massive structure to find bad joints and bad tubes.
- The first test problem consisted of computations for the hydrogen bomb.

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And what did the computer do, it could be programmed to perform complex sequences of operations including loops, branches and subroutines. After the program was figure out on paper, the process of getting the program into ENIAC by manipulating its switches and cables could take days. Today once we have a program, we can just key it in with our keyboard, but in those days that was not possible. The task of taking a problem and mapping it onto the machine was complex and usually took weeks which are a very long time.

This point is very interesting the programmers debugged problems by crawling inside the massive structure to find bad joints and bad tubes. There was really no other the choice, so they have to do that. The first test problem consisted of computations for the hydrogen bomb. So, here or some of the facts and figures about this computer, but you should really look up the internet and there is lot of other information over there.

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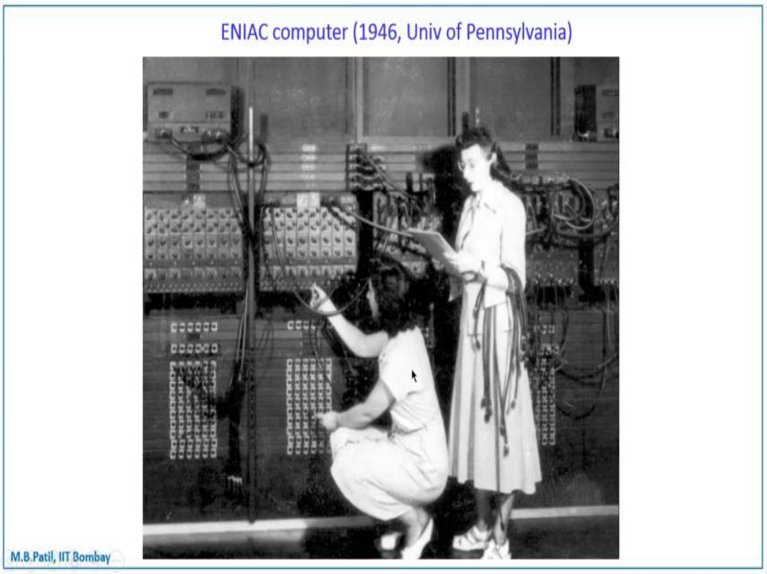

ENIAC computer (1946, Univ of Pennsylvania)

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Another interesting picture about the ENIAC computer; these ladies are probably computer operators, she is carrying a program listing in her hand, she is also carrying some cables to give this other person. Now, this person who is sitting is actually changing the position of the switches and making connections with cables that she receives from this standing lady.

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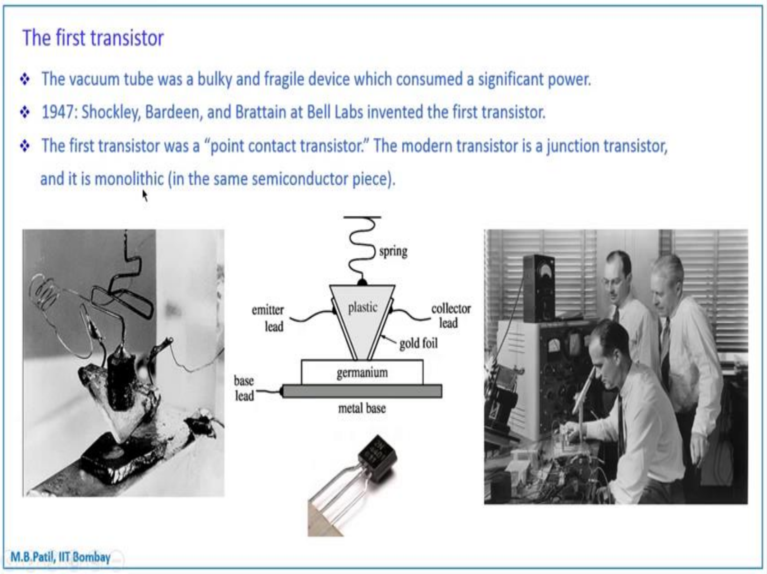

The first transistor

- The vacuum tube was a bulky and fragile device which consumed a significant power.
- 1947: Shockley, Bardeen, and Brattain at Bell Labs invented the first transistor.
- The first transistor was a "point contact transistor." The modern transistor is a junction transistor, and it is monolithic (in the same semiconductor piece).

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So, let us now talk about the first transistor. And why was it required in the first place, the vacuum tube was a bulky and fragile device which consumed a significant power. So, the US government particularly the department of defense was looking for a solid state alternative for the vacuum tube. And this job was given to Doctor Shockley at bell laboratories, this person sitting here. In 1947, Shockley, Bardeen and Brattain, this is Shockley, this is Bardeen that is Brattain at Bell laboratories invented the first transistor. This is the picture of the first transistor, and this shows its schematic diagram. So, this triangle that we see over here is actually a piece of plastic, and on both sides we have a gold foil, one is the emitter and the other one is the collector. And this whole structure is pressed on this semiconductor in those days it was germanium, and this way a point contact was made between this emitter and the germanium and also between this collector and this germanium.

This semiconductor was called the base and that is how, we have this emitter, base collector transistor structure. The modern transistor looks very different. Here is a packaged device and inside there is a single semiconductor piece which has all three emitter, base and collector. So, the emitter-base and base-collector junctions are all in the same semiconductor and that is called monolithic.

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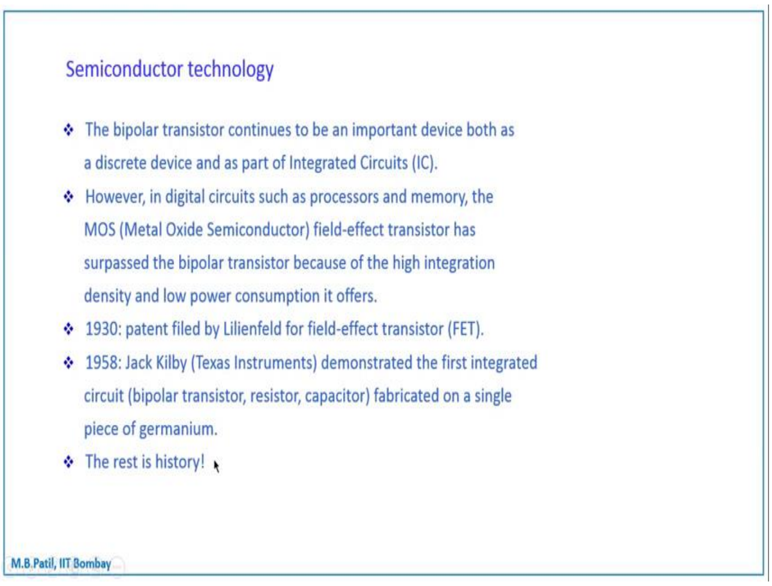

Semiconductor technology

- The bipolar transistor continues to be an important device both as a discrete device and as part of Integrated Circuits (IC).
- However, in digital circuits such as processors and memory, the MOS (Metal Oxide Semiconductor) field-effect transistor has surpassed the bipolar transistor because of the high integration density and low power consumption it offers.
- 1930: patent filed by Lilienfeld for field-effect transistor (FET).
- 1958: Jack Kilby (Texas Instruments) demonstrated the first integrated circuit (bipolar transistor, resistor, capacitor) fabricated on a single piece of germanium.
- The rest is history!

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Let us now talk about semiconductor technology and see how it is evolve a time. The bipolar transistor, which was the first transistor to be invented vacuum 1947; continues to be an important device both as discrete device and as part of integrated circuits that is ICs, so such op-amps. However, in digital circuits such as processors and memory, the

MOS that is metal oxide semiconductor field-effect transistor has surpassed the bipolar transistor by several miles actually. Because of the high integration density and low power consumption that the MOS technology offers. It is interesting to note that the idea behind the MOS transistors actually it dispatch to 1930 that is before the bipolar transistor was invented in 1947 as we saw. And in 1930, Lilienfeld filed a patent for field-effect transistor which forms the basis for MOS transistor.

But the MOS technology took several years to mature, and therefore, ICs with bipolar technology came first to the market followed soon by ICs in MOS technology. The first MOS IC was in 1964 and it was a shift resistor. In 1958, Jack Kilby at Texas Instrument demonstrated the first integrated circuit consisting of a bipolar transistor and resistors and capacitors fabricated on a single piece of germanium. So, this was a big break through. And around a same time Robot Noise of fair child was also perusing this idea of integrating certain things on the same semiconductor piece; and he also came up with some improvements especially related to metallization.

So, this work was done more or less in parallel. And the rest is history and we will see a part of that.

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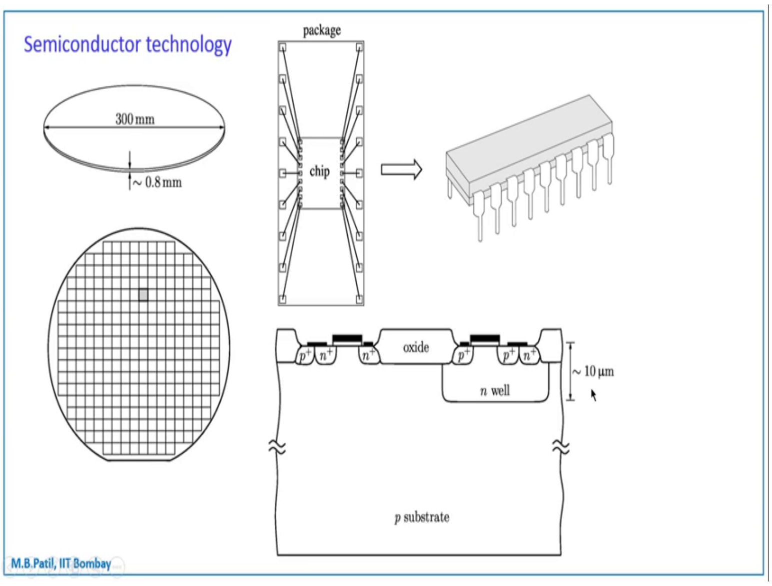

Semiconductor technology

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In the next few slides, we will try to get a glimpse of semiconductor technology. These of course are a vast subject and people have courses one semester long courses on this topic, but we will only take a quick look to get an idea. The starting point is a silicon wafer and its diameter is something like 30 centimeters or 1 foot, which is pretty large and it is relatively thin; its thickness is less than 1 millimeter. And after going through a series of processing steps using very sophisticated equipment, this is what the wafer looks like this is the top view. It has got some pattern on it; and each one of these rectangles for example, this one is one chip. Now, the chip could be as simple as a single diode or a single transistor or it could be as complex as a microprocessor with 10 million transistors or 100 million transistors.

The chips are separated from each other and each chip is mounted in a package like this one, this package is called the dip package, but today we have very sophisticated packages with how much larger number of pins as well. Now, this chip has got these little squares here, which are called the metal pads, and those are internally connected to the devices, the transistors or whatever on the chip. From this metal pad, we have a metal wire bonded to the pins of the IC, which looks like this. As the end user this package is what we see, but you should remember that huge amount of effort, time and of course, money goes into the design and fabrication of this chip.

This is what the cross section of this wafer looks like after all the processing steps are over. And be see several small regions here we have n-type doping here we have p-type doping and so on. And we will take a look at part of this how it is done and an important thing to note is that this entire structure the so called active devices is confined only to a very small region on top of the wafer that is only 10 microns may be in thickness. And the rest of the wafer is simply there to support this entire top layer.

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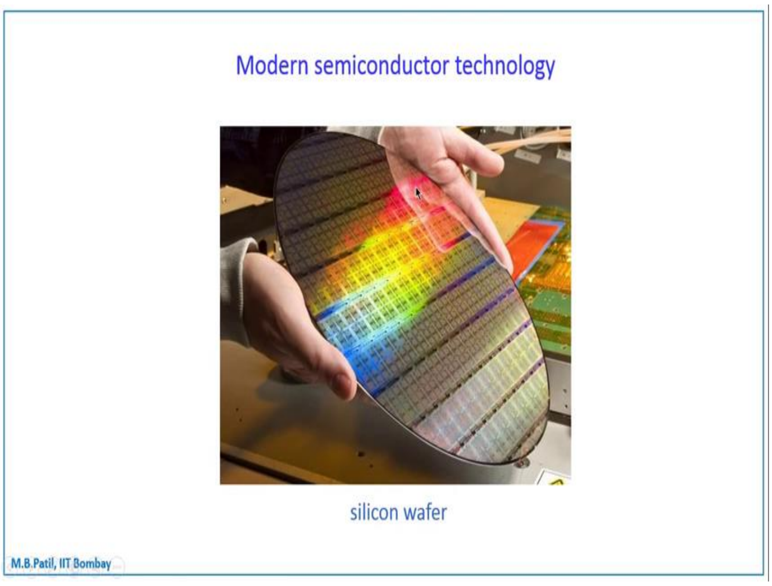

Modern semiconductor technology

silicon wafer

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Here is the picture of the silicon wafer after the processing steps are over. And we can see these rectangles here; each one of those is going to be one chip. And notice how shiny it is, we can see the reflection of this persons hand over here, and that is because it requires to be polished to a very smooth finish, so that processing can be accomplished.

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Modern semiconductor technology

Diffusion furnace

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As we mentioned, the wafer goes through a series of processing steps there is one important process called diffusion in which the wafer is heated to very high temperature such as 900 degrees or 1,000 degrees. And a gas is passed over the surface of the wafer to dope it, either p-type or n-type. So, here is a diffusion furnace, they are this controls here to control the temperature as well as the duration of that processing step, and the wafers are start over here. So, this whole contraption comes out, we start the wafers and push it in. And here is a close up. So, these are the wafers, there will be pushed into the furnace the furnace will be locked up for whatever number of minutes and that is how this diffusion process takes place.

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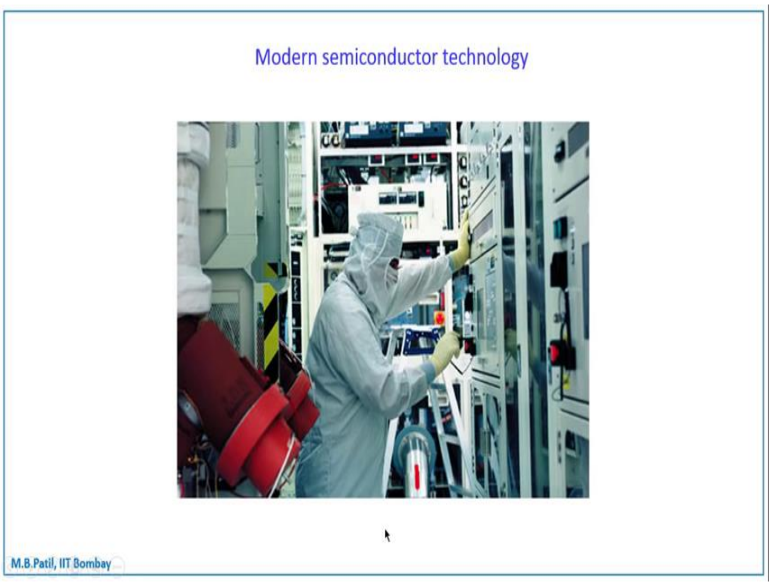

Modern semiconductor technology

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Let us look at some more pictures of the fabrication process. And notice that we do not see any semiconductor wafers anywhere, those are inside this equipment somewhere. Here is an operator who looks more like a surgeon in an operation theater. And this kind of extreme cleanliness is really required in the fabrication process, because any contamination is absolutely disasters for over devices that we are trying to fabricate. For example, our body goes on shedding dead skin cells continuously without our knowledge, and if any of those cells lands up on the semiconductor wafer, there is going to kill several transistors, and the chip is simply not going to work as we wanted to.

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Another picture this person is taking these wafers from one equipment to another. In each equipment, a different processing step takes place; and at the end of all of that, we have the final product.

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Another picture here is photo silicon wafer looks like and you can see once again that it is very smooth we can see the reflection of this persons face over here.

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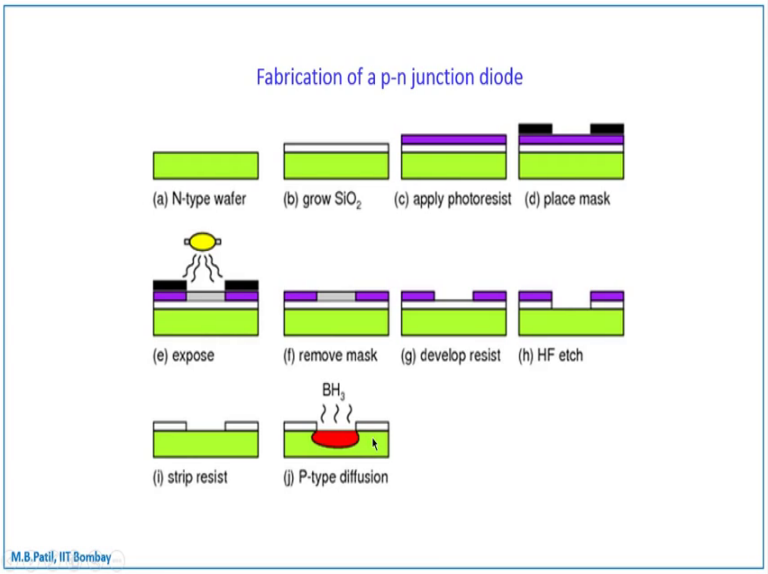
Fabrication of a p-n junction diode

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Let us go through a very simple fabrication process, namely fabrication of a p-n junction diode here is the cross section of an n-type wafer that means, it is a silicon wafer with n-type doping such as phosphorous. If first grow silicon dioxide on that shown there; after that we apply photo resist shown with this purple layer here. Now, this photo resist is a material, which is sensitive to light. After that we place the mask on top of the photo resist shown here in black color, then we expose this whole thing to ultra violet light.

Now, there is a window in the mask over here. So, the light goes through and this part gets exposed, and this part does not get exposed, because we have the mask blocking the light over there. Next, the mask is removed and now we have the photo resist; some part of the photo resist has been exposed to UV light and the rest has not been exposed to UV light. Now, we develop the resist that means we dipped that in a chemical the part that has been exposed to UV light gets dissolved and goes away leaving behind the unexposed part of the photo resist.

That is followed by an etching step in which the silicon wafer is immersed in hydrofluoric acid HF. Now, this part of the oxide which is exposed gets dissolved and this part which is protected by the photo resist (Refer Time: 23:12). So, at the end of this step, what we do is strip the resist that means, we dip the wafer in some other chemical which removes this photo resist, and that is followed by a p-type diffusion step that means, the wafer is heated to a high temperature like we have seen some time ago in a diffusion furnace. And the boron gas BH 3 passes over the wafer, and because of this oxide nothing happens if in these regions, but where there is no oxide, the boron atoms get inside and that makes it p-type. So, now, we have p-type semiconductor here, and our original sample was n-type. So, we have a p-n junction. After this metallization is carried on that means, one contact is made to this region, and another contact is made to this region, so that is how we have a p-n junction diode.

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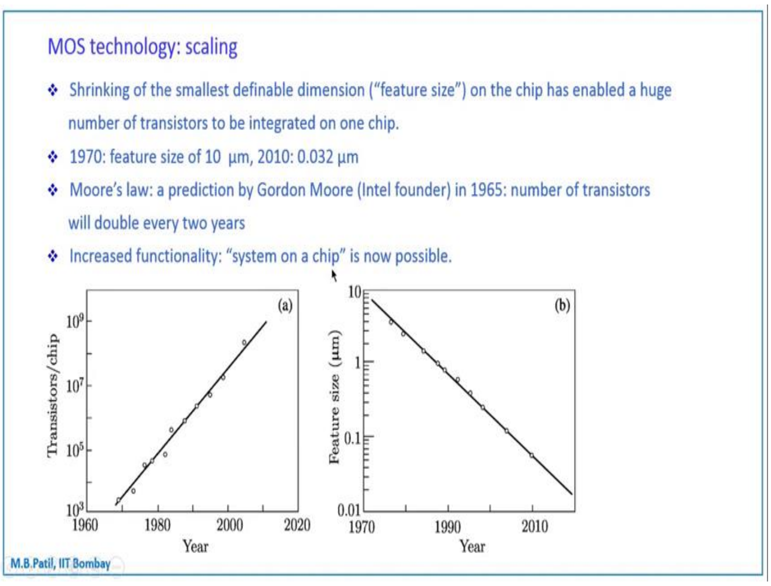

MOS technology: scaling

- Shrinking of the smallest definable dimension ("feature size") on the chip has enabled a huge number of transistors to be integrated on one chip.
- 1970: feature size of 10 µm, 2010: 0.032 µm
- Moore's law: a prediction by Gordon Moore (Intel founder) in 1965: number of transistors will double every two years
- Increased functionality: "system on a chip" is now possible.

Let us now talk about scaling of MOS technology which has been happening over the years. Shrinking of the smallest definable dimension also called the feature size on the chip has enabled a huge number of transistors to be integrated on one chip. As this size per transistor reduces, what it means is we can pack how much larger number of transistors in the same area and that is how this number of transistors per chip has been going up. Here have some figures in 1970, the feature size was 10 micron; in 2010, it was 0.032 micron, so much smaller. And here is a plot of the feature size versus year and note that this is a logarithmic scale.

So, in the 70s, we were talking about feature sizes of a few microns; and in 2010 ten it is less than 0.1 micron. And as a result of the study reduction in the feature size over the years, the number of transistors per chip has been going up correspondingly, and here is a plot this is the number of transistors per chip and that is the year. And note that this scale is also logarithmic. This is thousand transistors per chip, this is ten thousand, and this is hundred thousand, one million, ten million and so on.

In the 1970s we were talking about a few thousand transistors per chip. And now around 2010 year we are talking about a much larger number something like hundred million transistors per chip. So, this increase is really very dramatic. Now Gordon Moore of Intel predicted this kind of trend in 1965 and his prediction was that the numbers of transistors will double every two years; and this prediction as turned out to be more or less accurate over several decades in fact. And it has become known as Moore's law. Now, what is a practical implication of all these developments in the semiconductor industry? In the 1970s, we were talking about probably a few hundred gates per chip; and now they have much increased functionality possible.

And we can talk about system on a chip which is much more complex than what we use to have in the seventies.

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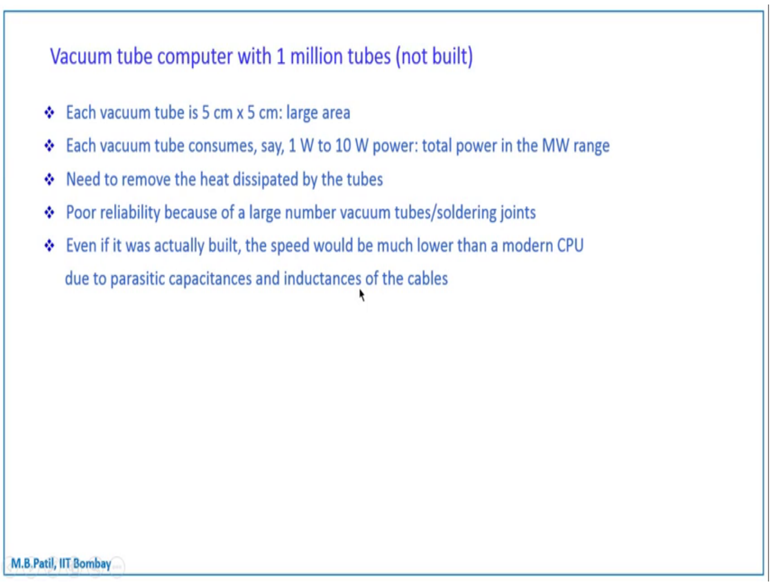

Vacuum tube computer with 1 million tubes (not built)

- Each vacuum tube is 5 cm x 5 cm: large area
- Each vacuum tube consumes, say, 1 W to 10 W power: total power in the MW range
- Need to remove the heat dissipated by the tubes
- Poor reliability because of a large number vacuum tubes/soldering joints
- Even if it was actually built, the speed would be much lower than a modern CPU due to parasitic capacitances and inductances of the cables

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Let us consider vacuum tube computer built with 1 million tubes. And we should emphasis that such a computer has not been built we only want to know what it would look like. We find that there are several difficulties, and let us see what those are. First each vacuum tube would occupy an area of 5 centimeters by 5 centimeters roughly. And when you multiply that by one million that area of course, turns out to be very large, it is like a football field. Second - each vacuum tube consumes let say something like 1 watt to 10 watts of power, and therefore when we multiply that by 1 million we are talking about a total power in the range of mega watts very large power. Now, this power which is in the mega watts range very large power turns into heat and that has to be removed; if you do not remove the heat then the computer temperature will keep raising and finally, things will melt smoke will come out and so on which of course, we do not want.

The next issue is reliability these kind of computer will have very poor reliability, because it has a very large number of vacuum tubes and soldering joints. And what it means is that this computer is going to require very frequent maintenance because every half an hour or one hour some tube or soldering joint is going to go bad and that will need to be fixed. And finally, even if it was actually built the speed would be much lower than a modern CPU, because of parasitic capacitances and inductances of the cables that we are going to use for the connections.

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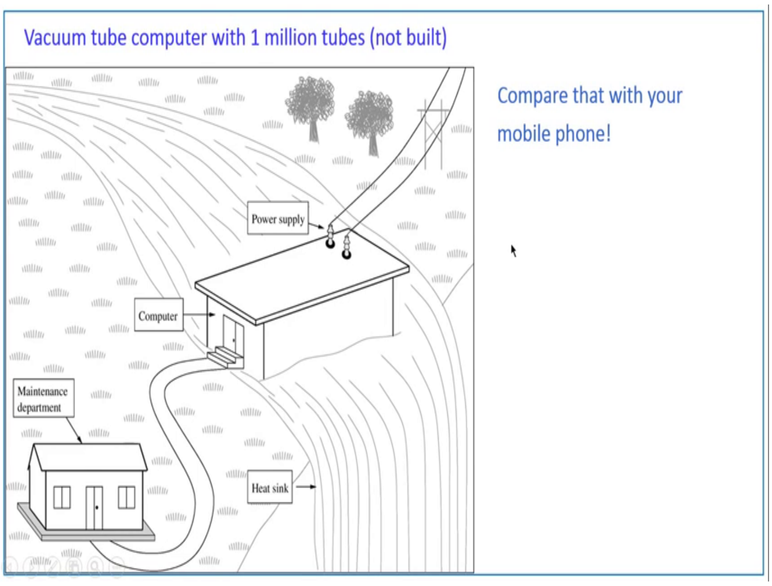

Vacuum tube computer with 1 million tubes (not built)

Compare that with your mobile phone!

So, here is what the computer would look like and we must emphasis once again that it has never happened nobody has really built such a computer. It will be large and it will below to be housed in a building of this kind - one; second - it is going to consume a huge amount of power and therefore, will need to get a separate connection from the state electricity board coming like that so that is our power supply. Third such a computer is going to required a massive heat sink, and the only practical way of removing such a large amount of heat is to immerse the whole computer in a water fall.

So, that the water keeps taking the heat away on continues basis. And finally, we are going to require a maintenance department to be located on the same premises because some tube or soldering joint is going to keep failing and we need somebody to attempt to that. So, we require a 24 by 7 service for this computer and the best way to do that is to have somebody write on the location. And now compare that computer with the mobile phone that you carry in your pocket or your purse.

So, that was the short revive of how electronics has progressed so far and now it is time to get down to the basics and understand how things work. So, see you in the next class.