Op-Amp Practical Applications: Design, Simulation and Implementation

Prof. Hardik Jeetendra Pandya
Department of Electronic Systems Engineering
Indian Institute of Science, Bangalore

Lecture – 01
Introduction/ Summary on Op-amps

Welcome. This course is an kind of extension to the earlier course; that was on integrated circuits, op-amps, MOSFETs and their applications. So, in that course particularly what we have seen is basics of op-amps basics of MOSFET and we also covered the fabrication part how we can fabricate an integrated circuit. To be precise we understood how to fabricate a MOSFET.

Now once we have a basic idea of all these modules and all these applications, we need to move further and understand its practical applications: how to design, how to simulate and how to implement the things that we have learnt. So, in this particular course, our focus would be on op-amp practical applications and we will be designing several modules based on that.

(Refer Slide Time: 01:44)

Week	Module Name	Assignments Online/Offline
1	Understanding the Datasheet of Op-Amps	Online
2	Introduction to op-amps and discussion on its characteristics by simulation and experiment	Online
3	Understand the basics of Hysteresis and the need of hysteresis in switching circuits	Online
4	Op-Amp Circuits Analog-to-Digital Converter (ADC)	Online
5	Digital-to-Analog Converter (DAC) using Op-Amps	Online
6	To design and build a function generator capable of generating square wave and a triangular wave of a known frequency using simulation and experiment by TI analog system lab kit pro	Online
7	To design and build a voltage-controlled oscillator using simulation and TI analog system lab kit pro	Online
8	To design and build an automatic volume control using simulation and TI analog system lab kit pro	Online
9	To design and build a constant current drive circuit for measuring unknown resistance using simulation and Experiment on bread board	Online
10	To design and build a temperature controlled system using op-amps as ON-OFF controller and Proportional controller by simulation and Experiment on bread board	Online
11	To design and build a signal conditioning circuit for the thermocouple to compensate for temperature correction	Online
12	To design and Implement a speed controller of a DC motor using simulation and experiment	Online
EXTRA	To design and build an op-amp based ECG signal acquisition and BPM measurement	Online

So, if you see the screen, the name of this particular course is Op-Amp Practical Applications Design, Simulation, and Implementation. And to give you idea, what this course consists of: we will cover the data sheet of an op-amp. So, if I give you a data sheet then you should be able to understand; what are the parameters written in the data sheet.

So, we will see; we will understand the data sheet of an op-amp, we will see a little bit of introduction just to brush up our knowledge right, and then we will understand the hysteresis need of hysteresis in switching circuits. Then a very important application of op-amp is in ADC and DAC - Analog to Digital Converter and Digital to Analog Converter. So, we will see both applications of op-amp how can we design ADC, how we can design DAC based on op-amps.

In this particular course we will focus on kit; a kit for professionals from TI Texas instrument and this is called TI analog system lab kit pro. And using this kit, we will design and build a function generator capable of generating square wave and triangular wave. We will also design and build a voltage controlled oscillator, we will also design and build automatic volume control using simulation, further we will understand how to build a constant current drive for measuring unknown resistance. We will take an example of a temperature controlled system and how can we build this kind of system using op-amps as an on off controller and proportional controller .Then we will build a signal conditioning circuit for thermocouple to compensate for temperature correction.

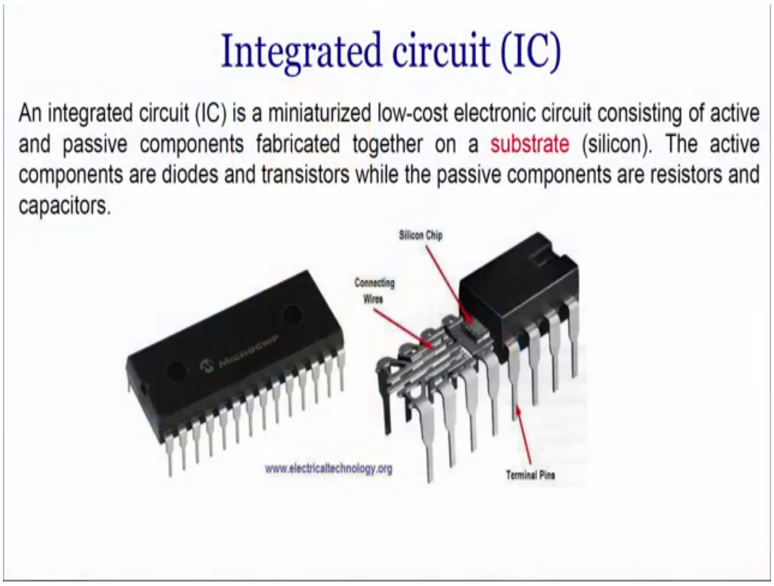
Finally, around week 12th, we will see how to design and implement the speed controller of a dc motor using simulation and experiment. And, we will also see how to build an op-amp based ECG acquisition and BPM measurement. So, they if you see really what we are covering; we are covering all the applications of MOSFET of applications of op-amp. And of course, when you when you talk about op-amp you cannot leave MOSFET behind, you cannot leave transistor behind right.

So, this particular course, we will focus on the things that we have just seen right now. But, to understand this whole session understand everything about op-amps and its application we need to understand and we need to make sure that we have our basics clear. And that is why those who have not taken my earlier course on integrated circuits MOSFETs op-amps and their applications I suggest you to just go through it.

.So, to start this particular course, what we have to do is; I will just take you around to kind of a journey where we studied the basics of op-amp, and then once we finish this, then we will move to actual application of op-amp. So, when you when I talk about the journey; that means, that what we have done in that whole course those people who have not taken it or those people, even who have taken that course it is good for them to refresh that particular course.

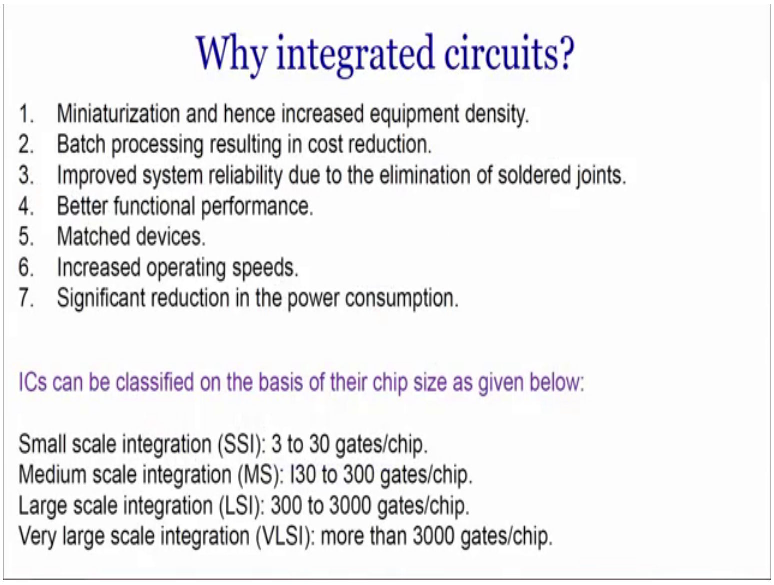
So, this is a kind of summary of that course. And what I feel is that before we start applying the theoretical knowledge into practical applications let us go through once again in case of a summary, right.

(Refer Slide Time: 05:57)



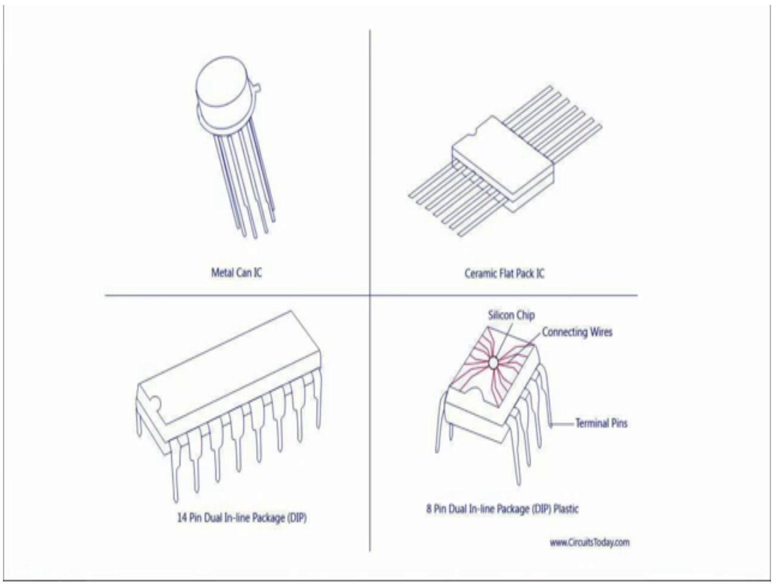
So, if you see, we talked about integrated circuit, and integrated circuit is nothing but miniaturized low cost electronic circuit consisting of active and passive components and it is built on substrate which is silicon. So, when you when you see a IC when you open an IC, you will see a silicon chip within the integrated circuit.

(Refer Slide Time: 06:24)



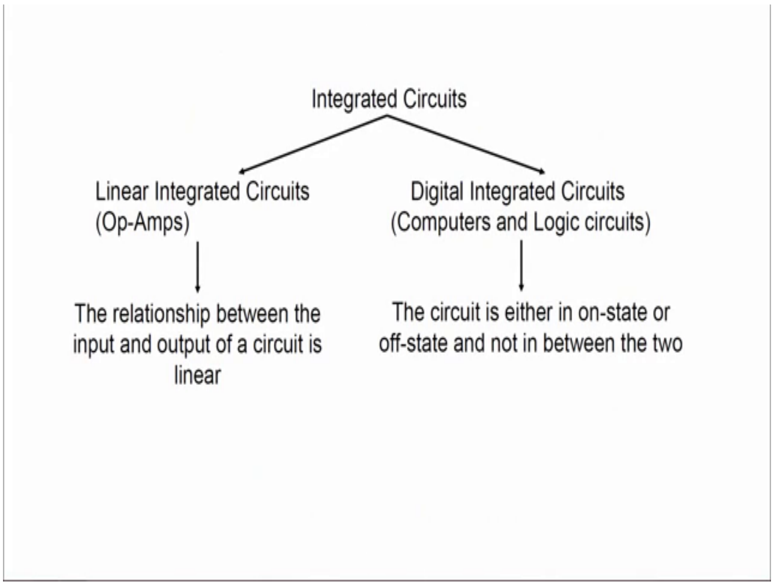
Then we talked about why integrated circuits and we could easily see why. there are several reasons: including miniaturization, batch processing, better function performance, matched devices, increased operating speed, and significant reduction in the power consumption, right. These are all the reasons enough reasons to make sure that we have to use IC instead of discrete components. And then we have also seen that ICs can be can be classified into several categories.

(Refer Slide Time: 07:00)



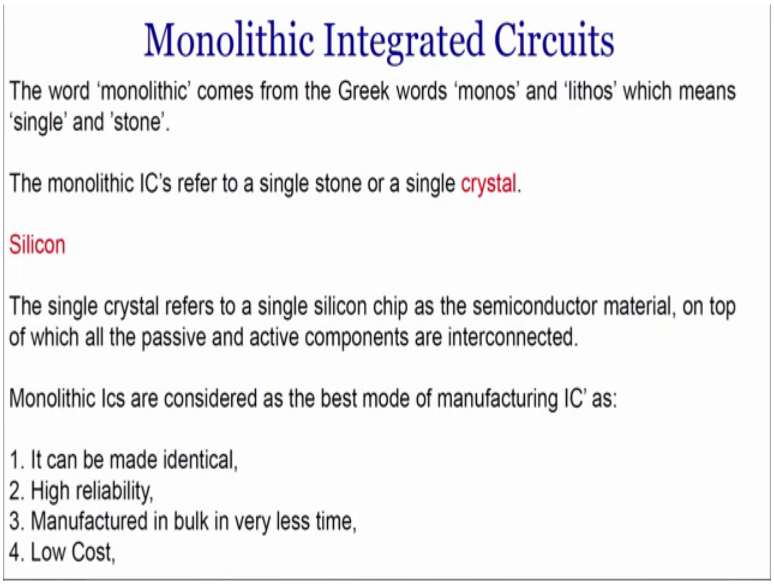
ICs when you look at the IC, it has metal can IC; that the ICs can be divided into few further categories metal can IC, ceramic flat, pack IC, 14 pin dip, 8 pin dip using plastic, right. So, what kind of casing is there based on that also the ICs are classified.

(Refer Slide Time: 07:24)



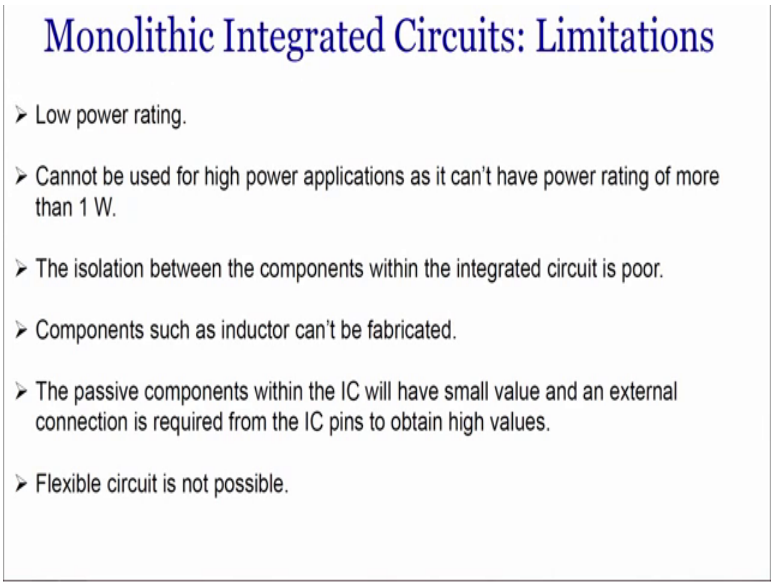
Then if you talk about ICs in further then they can be classified into two parts; one is LIC, one is DIC. So, what is LIC? LIC is nothing, but linear integrated circuits and in this LICs, we are expecting that the relationship between the input and output of a circuit should be linear while in case of DIC, the DICs are computers and logic circuits and circuit is either in on state or off state and not in between the two.

(Refer Slide Time: 08:03)



Then we have seen monolithic integrated circuits, the circuits that are made on a single silicon chip. And the advantages is that it can be made identical is highly reliable, it can be manufactured in bulk and its low cost and in fact, monolithic ICs are the best mode of manufacturing ICs.

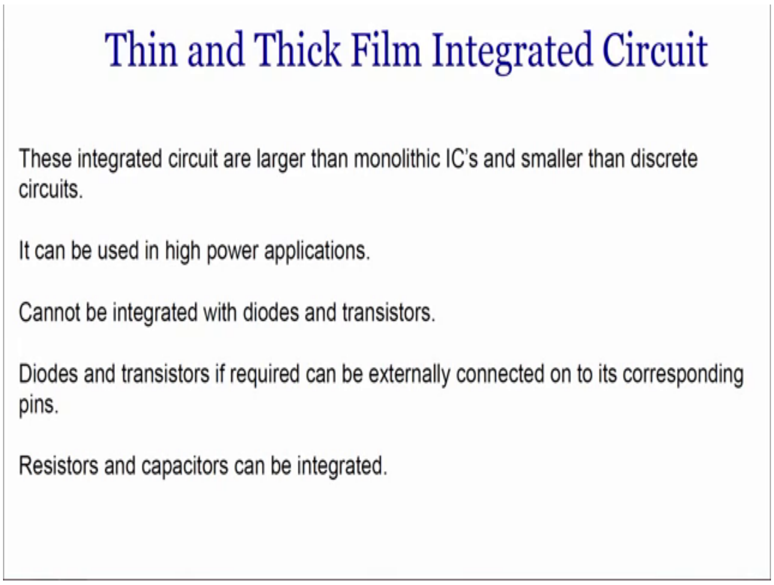
(Refer Slide Time: 08:38)



Then we have seen that what are the limitations and the limitations are lower power rating isolation between components within the integrated circuit is poor components such as inductor cannot be fabricated the passive components within the IC have small value and if you require IC passive components of higher values.

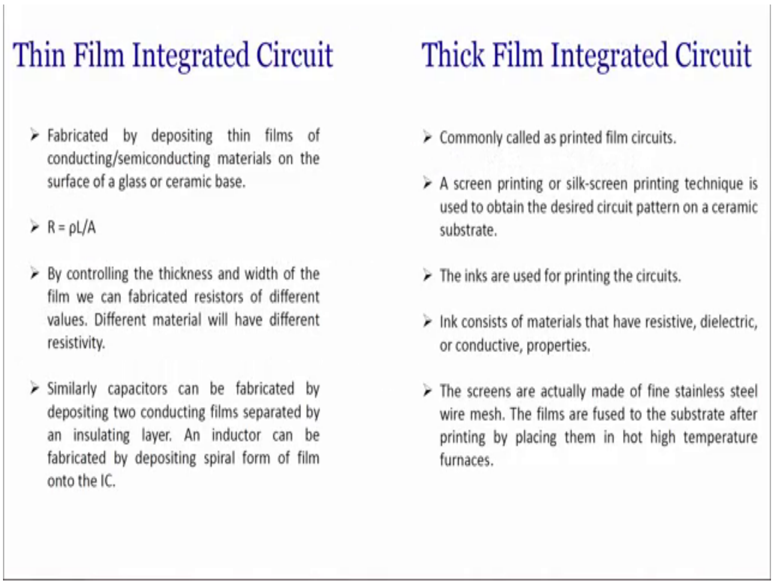
Then an external connection is required from the IC finally, the flexibility is not there in case of monolithic integrated circuit.

(Refer Slide Time: 09:12)



That is why we have to opt for thick and thin film integrated circuits. And here, the advantage is that the resistors and capacitors can be integrated cannot be integrated, it can be used in high power applications, while some limitations are it cannot be integrated with diodes and transistors, while if you want to use diodes and transistor, it can be connected externally on its corresponding pins.

(Refer Slide Time: 09:43)

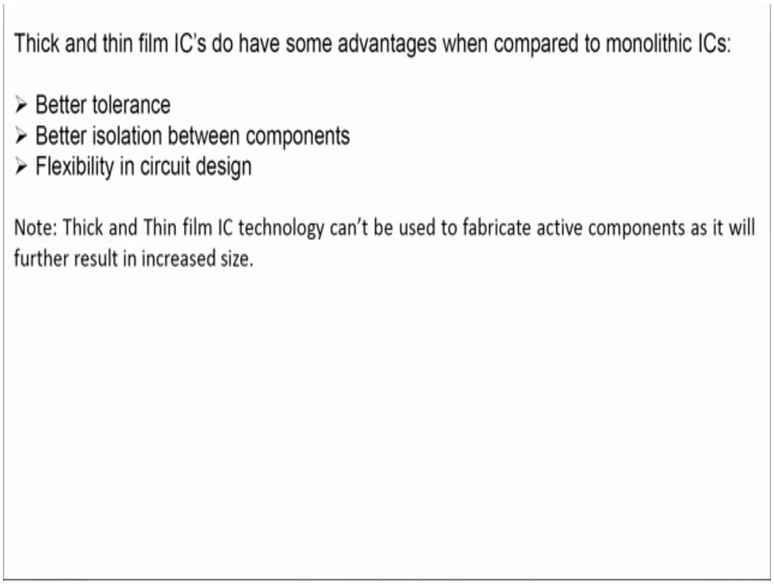


Then what is difference between thin and thick film technology thin film technology using that we can deposit conducting semiconducting materials on the surface of a glass ceramic base or an oxidized silicon.

For example, if you want to fabricate a resistor or fabricator heater then by controlling the thickness and width of the film, we can change the resistance of the heater additionally different materials with different resistivity can be deposited. Same way, we can also fabricate a capacitor. In case of thick film technology, it is commonly called printed film circuits where a screen printing or silk screen printing technique is used to obtain the desired circuit pattern.

Now, the inks are used for printing circuits; that means, the ink can be resistive it can be dielectric or conductive properties, right and screens are generally made of stainless steel with wire mesh we have seen this, right. And the example is of a greeting card or a marriage invitation card; you will see different form of figures sketches printings that is done using thin film using thick film integrated circuit.

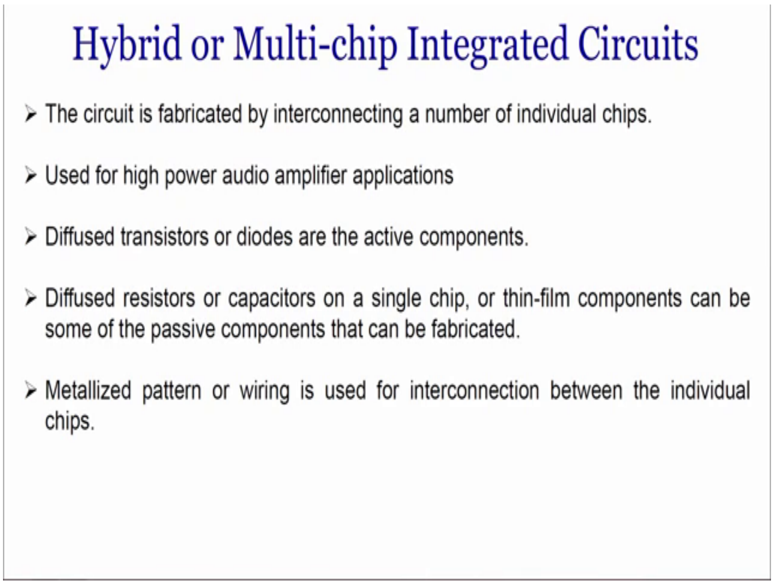
(Refer Slide Time: 11:23)



Some advantages over the monolithic ICs are better tolerance better isolation between components flexibility in circuit design. These are the advantages, you see when we were using monolithic integrated circuits the flexibility was an issue here, we can design the thin and thick film ICs on a flexible substrate that is a advantage.

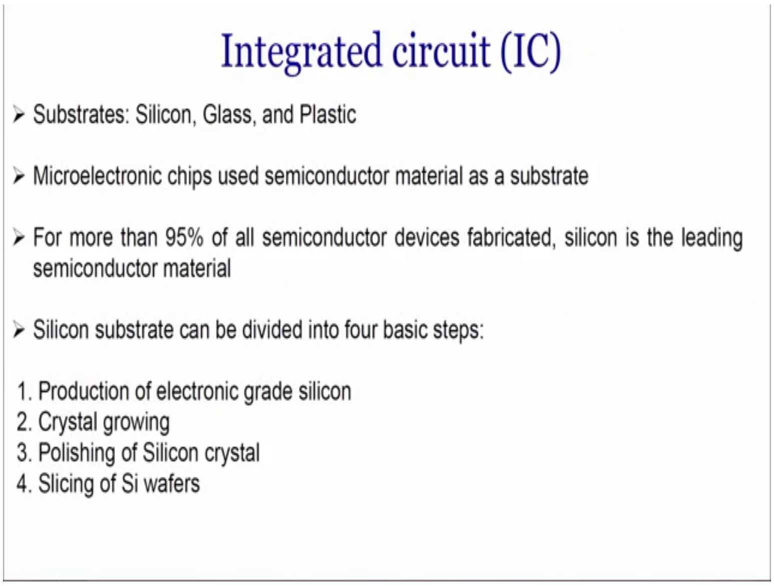
Because, suppose let us say you want to develop a flexible sensor example is a electronic skin, right. So, if you have a touch sensors if you have a ductile sensors if you have a force sensors and you want to wrap it on your skin, right or you want to act those area of sensors and use those area of sensors as a skin electronic skin. Then it should be flexible this flexibility can be obtained using thick and thin film IC technology while in case of monolithic, it is not possible. So, these are the advantages of thin and thick film technology over monolithic ICs.

(Refer Slide Time: 12:34)



Then we have seen hybrid or multi chip integrated circuits right and what we have seen in this particular case that the circuit is fabricated by interconnecting a number of individual chips, right. And here the diffused transistor or diodes are the active components. It can be used for high power audio amplifier application. And finally, metalized pattern or wiring is used for interconnection between the individual chips.

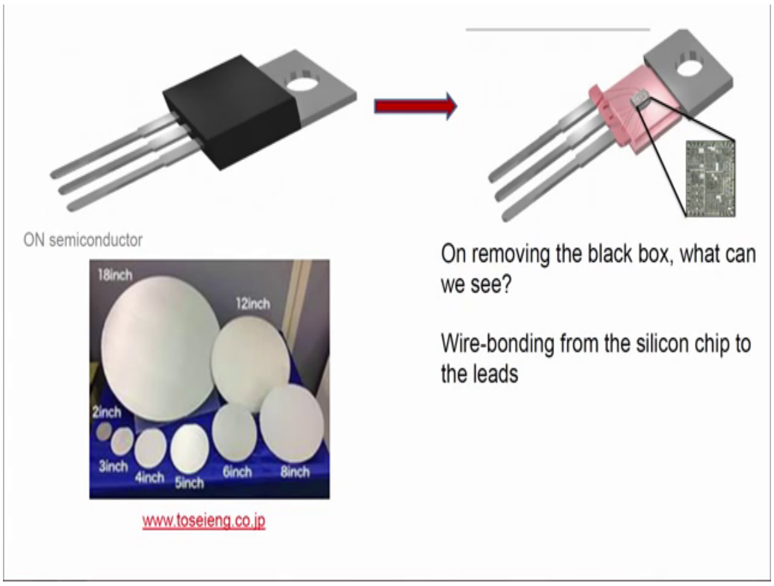
(Refer Slide Time: 13:09)



So, after we saw a introduction of ICs, right we also saw that the ICs can be fabricated on different substrates. We just discussed right flexible substrate, we can we can fabricate an IC on silicon we can fabricate an IC on glass, we can fabricate an IC on plastic right or at least we can fabricate sensors on this kind of substrates right. So, polymer we can deposit and we can fabricate. So, we can deposit performer ethography and fabricate a sensor on variety of substrates right. Thus, substrate is very important substrate is what it is a base on which we are going to fabricate the whole circuit or whole sensor. So, it is a base.

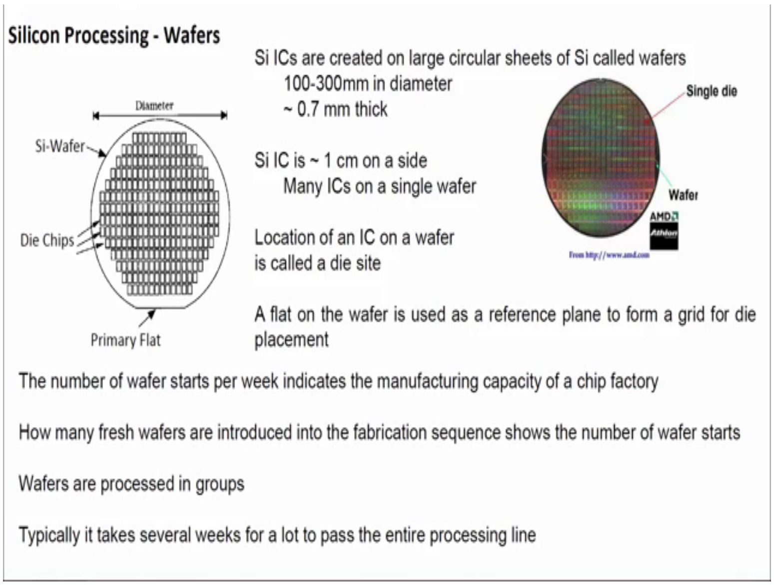
Now, in case of integrated circuits particularly when we talk about op-amps right or we talked about MOSFETs, then the substrate 95 percent is silicon a silicon. And then we have seen that how we can manufacture the silicon. So, for manufacturing of the silicon what we have seen, we have seen that there are several processes.

(Refer Slide Time: 14:23)



So, when we talk about manufacture of silicon production, of electronic grade silicon, crystal growing polishing of silicon and slicing of silicon wafers. We have seen that we will again seen in this coming slides and we talk about IC, right when we open this case, like I said we will find the chip, this is silicon chip. And within the silicon chip on your right side of the screen top, right, what you see is that there are lots of circuits integrated on this silicon chip right. And the wire bonding is used to take to bond the contexts from the silicon chip to the leads. Then we have also seen that there are several kind of silicon wafers when I say several kind of silicon wafer is based on size, right from 2 inch wafer to 18 inch wafer, right, then there is a single side polished wafer and there is a double side polished wafer, right.

(Refer Slide Time: 15:33)



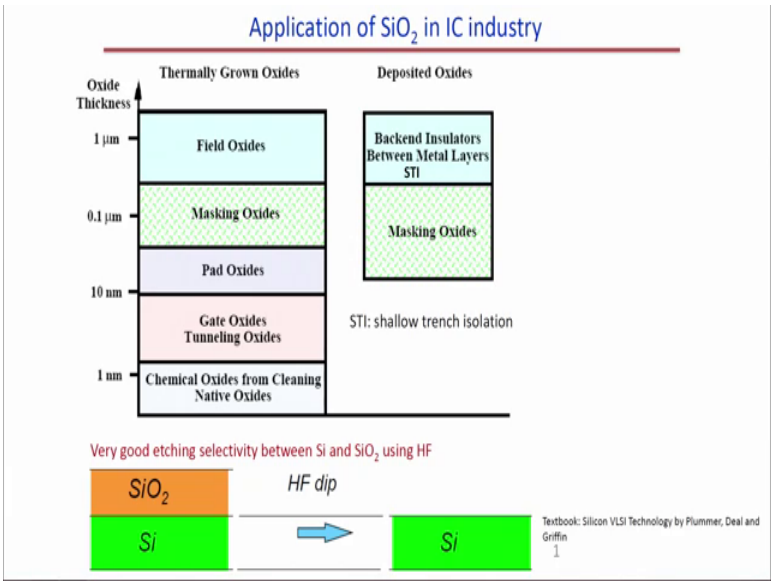
So, we will see that we have seen silicon wafer processing. So, silicon when you talk about processing of silicon and in terms of wafer on wafer. Then we have individual chips at the end of the fabrication process and each chip is called a die right each chip is called a die. And then we also seen that there is a primary flat, and this primary flat is for a purpose what is the purpose of primary flat to understand with respect to secondary flat.

If there is a presence of secondary flat or not and if it the secondary flat was present with respect to primary flat where it is at 45 degree, is it a 9; is it a 90 degree or is it at 180 degree or the secondary flat is not present at all based on that we can identify whether the wafer is n type a or p type or the orientation of the wafer 1 0 0 or 1 1 1, right.

(Refer Slide Time: 16:32)

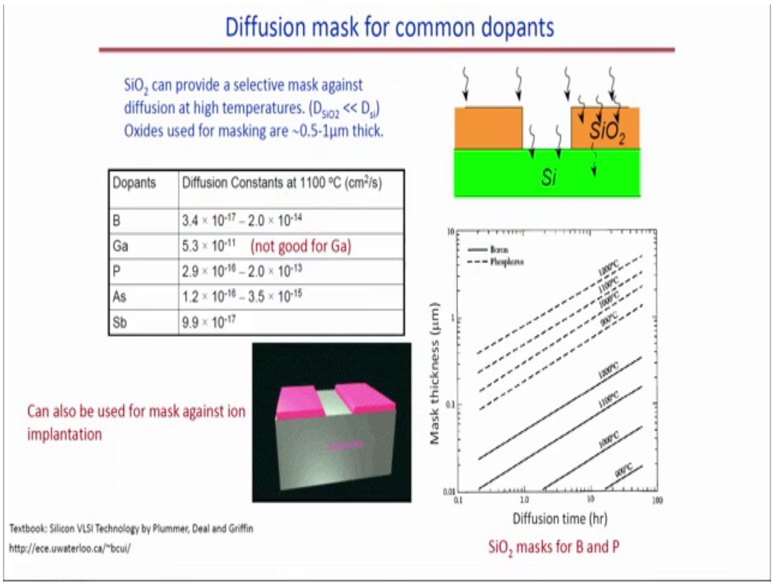
Then about the silicon right silicon is manufactured in a clean room in a clean room, what you can see in the right side is a Boule of silicon, right. And wafers are cut from this and polished to form the final wafers silicon is cut from this particular Boule to form final wafers, right.

(Refer Slide Time: 17:03)



So, then we have also seen that for a for fabricating any sensor including MOSFETs, right, we need oxides, it can be gate oxide, it can be field oxide, it can be masking oxide and based on what kind of application of the oxide, we are using or based on the application we can use; we can use different thickness of oxide. Generally, when it is gate oxide is around 10 Nano meter masking oxide 0.1; 0.1 micron where field oxide is around one micro meter and we all know that the silicon dioxide is HF.

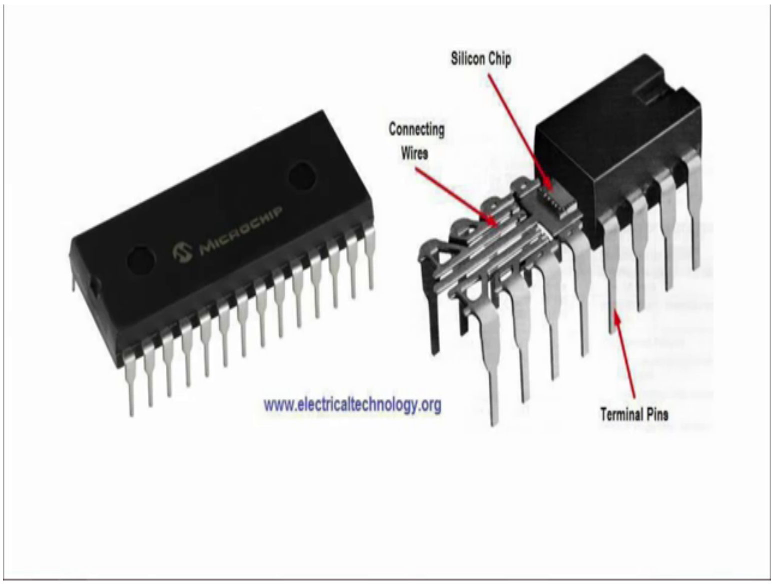
(Refer Slide Time: 17:51)



So, the use of diffusion mask for common dopants; diffusion mask for common dopants is that it will save or it will not allow the dopant to enter through the diffusion mask. And this diffusion mask can be fabricated or can be designed using silicon dioxide as you see on the figure. So, silicon dioxide over silicon substrate right, this silicon dioxide here, right, this is grown on silicon. And it is patterned sorry it is patterned on silicon such that the window is created in the centre and silicon dioxide is protected on both the sides of this window. Thus this silicon dioxide will act as a mask when we are doping the silicon.

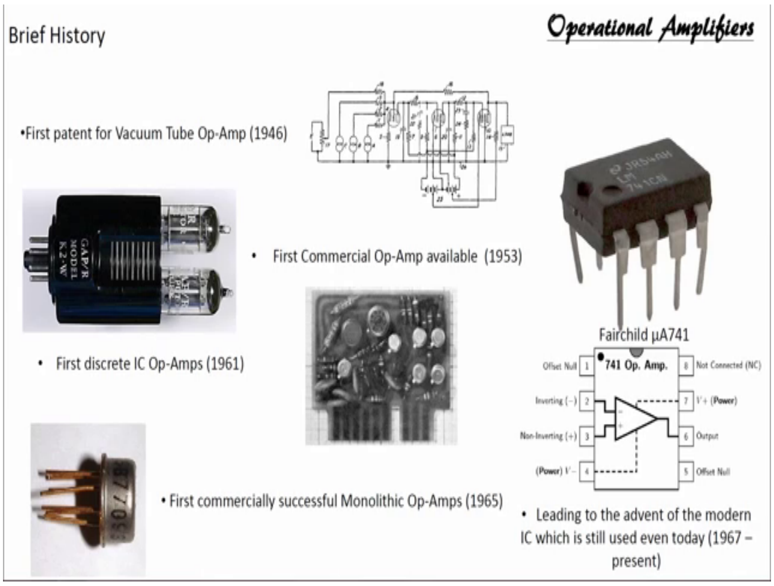
And this doping can be done either using an implantation or diffusion, right that we have seen and the most common dopants are boron and phosphor.

(Refer Slide Time: 19:19)



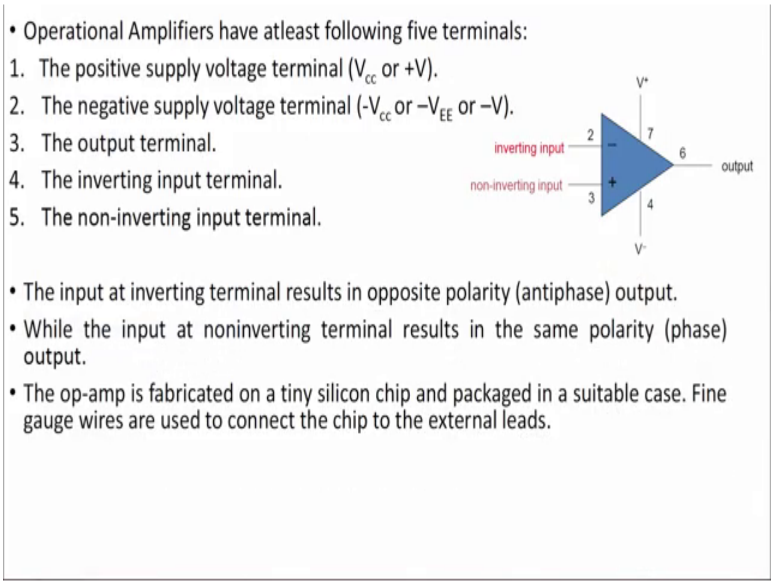
So, after this we moved to op-amps and silicon chip when we see the silicon chip, right this is this entire IC can be an operation operational amplifier.

(Refer Slide Time: 19:24)



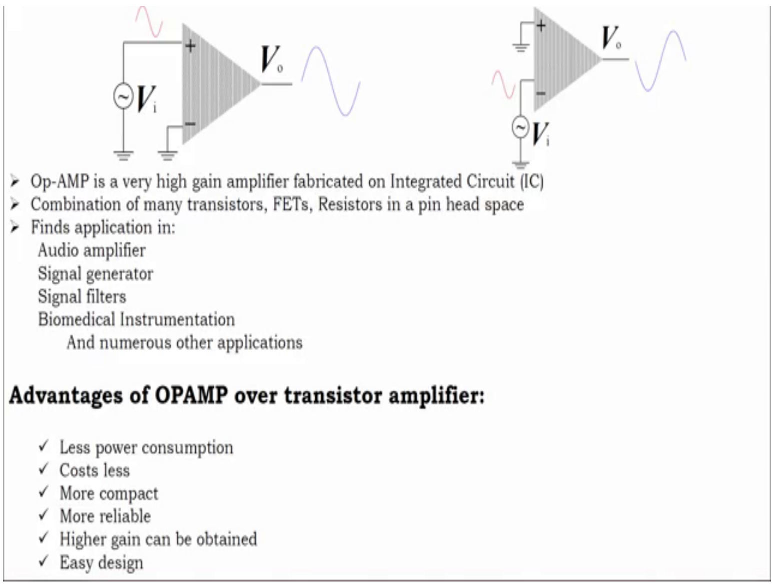
And like I said earlier within the IC, there is the silicon chip and within the silicon chip, there is there are billions of transistors, right. So, we have seen the brief history of the op-amps, right from 1946, right till 1965 from monolithic op-amp was first designed and commercially available right. Then Fairchild mu a 741 from 1967 till present, we are using it mu a 7 4 1, right.

(Refer Slide Time: 20:01)



And then when we talk about op-amp, generally, we will see a five terminals actually this is this op-amp is 8 a terminal device, but most of the time. We talked about 5 main terminals positive and negative supply voltage output terminal inverting and non inverting terminals, right, 1 and 5 pin; 1 and 5 which you cannot see here is used for offset while pin 8 is not connected, right. Then we are seeing how the inverting and non inverting inputs are used for right. We apply a signal at inverting the output would be antiphase, if we apply this signal at non inverting the output would be in same polarity same phase.

(Refer Slide Time: 20:46)

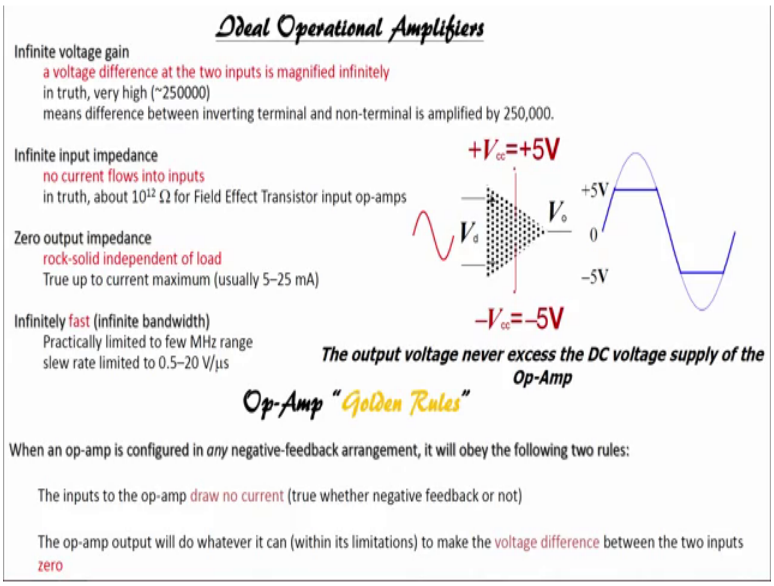


Then we saw; what are the advantages of op-amps over transistor amplifier. So, there are several advantages that are listed over here right which are less power consumption, it cost less.

It can be manufactured in bulk more reliable easy operation easy design, right. So, these are the advantages of operational amplifier over transistor amplifier that is why this course is designed to use the op-amp. And use this op-amp for several applications right not transistor based amplifier for several applications. So, you should understand that why we are using op-amp right. And in fact is some of the applications of op-amp are right now listed in front of you; audio amplifier signal generator signal filters biomedical instrumentation and numerous other applications, right. So, op-amps are used in signal conditioning circuits they are used in amplifier they are used in different that we have seen in the last class, last course particularly we have seen op-amp is an integrator, right, we have seen op-amp as a adder, then we have seen the functionality of op-amp as an application for different circuits, right.

And then we have also seen how we can design several circuits not only design, but also simulate those circuits using simulane. So, simulane then breadboard here, we will do something different, all right. We will now use the TI kit and we will see how we can implement several application of op-amps or op-amps in several applications and try to understand how it operates or how it works.

(Refer Slide Time: 22:25)

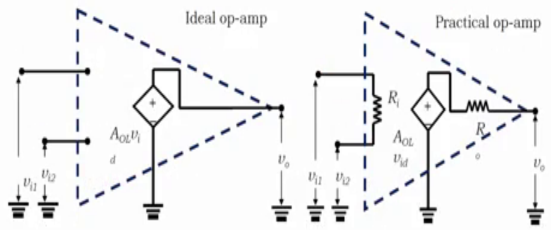


So, then we have seen ideal op-amp an ideal op-amp has few characteristics such as infinite voltage gain infinite input impedance, 0 output impedance infinitely fast of course, op-amp has 2 golden rules. We had discussed those golden rules first is that the input to the op-amp draws no current, and second is the output will do whatever, it can to make the voltage difference between 2 inputs 0 these are the 2 golden rules.

(Refer Slide Time: 22:53)

Ideal Operational Amplifier versus Actual Operational Amplifier

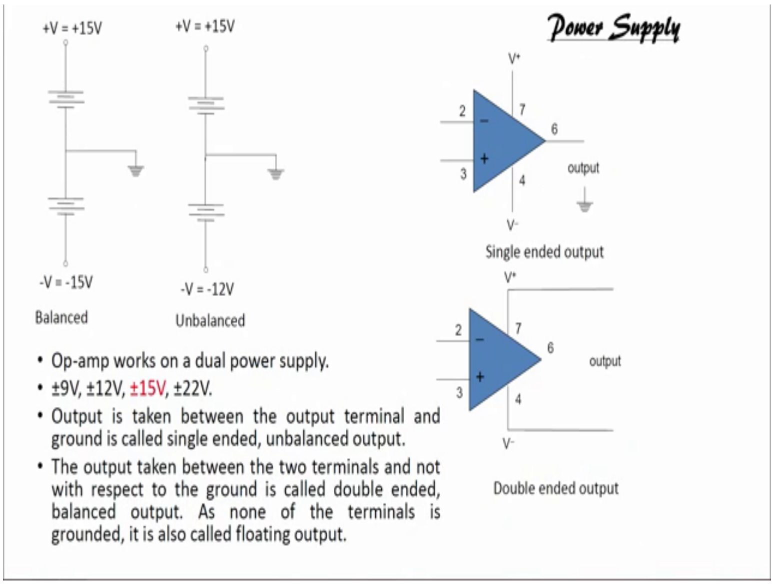
Parameter	Ideal Op-Amp	Real Op-Amp
Differential Voltage Gain	∞	10^5 - 10^9
Gain Bandwidth Product (Hz)	∞	1-20 MHz
Input Resistance (R)	∞	10^6 - 10^{12} Ω
Output Resistance (R)	0	100 - 1000 Ω



We have seen the ideal versus real op-amp, right real is nothing, but actual or practical op-amps.

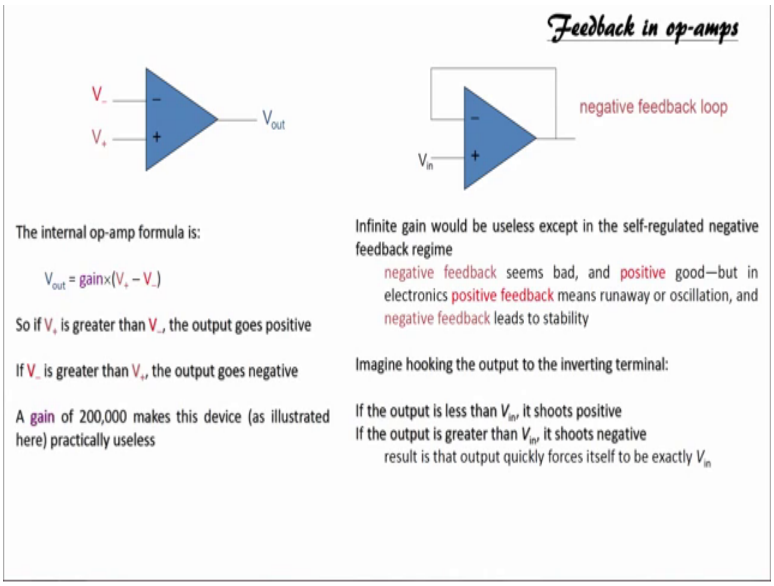
And we see that there is a difference in terms of the character parameters where we say voltage gain is infinite actually it is about 10 raised to 5 to 10 raised to 9 when we talk about gain bandwidth product is infinite, it is about 1 to 20 mega hertz input resistance infinite. And actual case, it is 10 raised to 6; 10 raised to 12 ohms while output resistance is zero in actual or real case, it is about 100 to 1000 ohms.

(Refer Slide Time: 23:28)



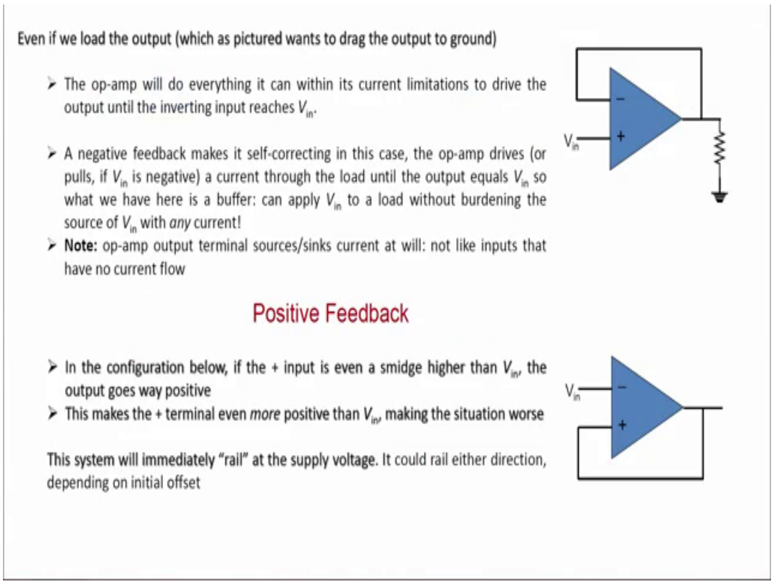
Then we have seen balanced unbalanced power supplies, right. And we have seen single ended output and double ended output, I will just keep this fast just to make sure that the balanced and unbalanced power supplies are used in a 7 applications most applications. You will see balanced power supply while some applications also used unbalanced power apply same way single ended output is with respect to ground double ended output, it is not with respect to ground that is why it is also called floating output.

(Refer Slide Time: 23:58)



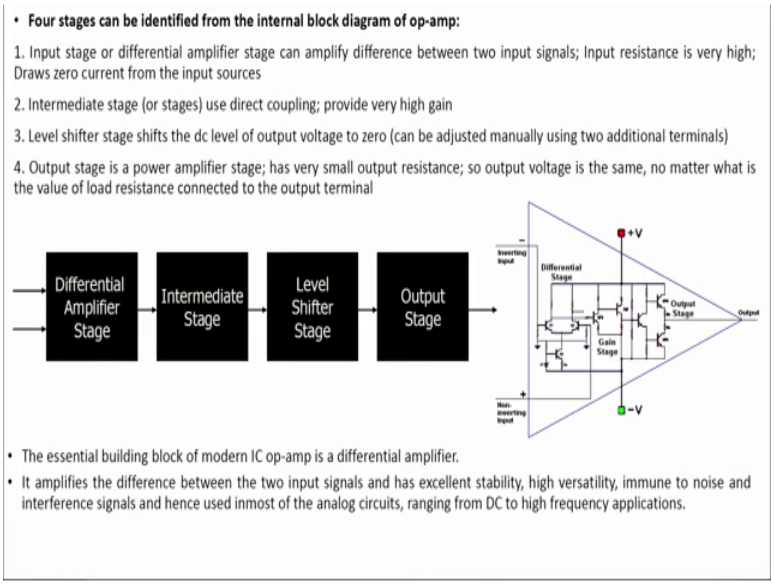
Then we move further and we see that the internal op-amp formula is nothing, but V out equals to gain into V plus minus V minus is inverting minus non-inverting or non-inverting minus inverting whatever is great like whatever is higher the signal at inverting is higher, right compared to non inverting. Then our output will be negative if the signal at non inverting terminal is higher compared to inverting our output will be positive right. Then we have seen feedback negative feedback a negative feedback is used for amplifiers while positive feedback is used for oscillators, right.

(Refer Slide Time: 24:33)



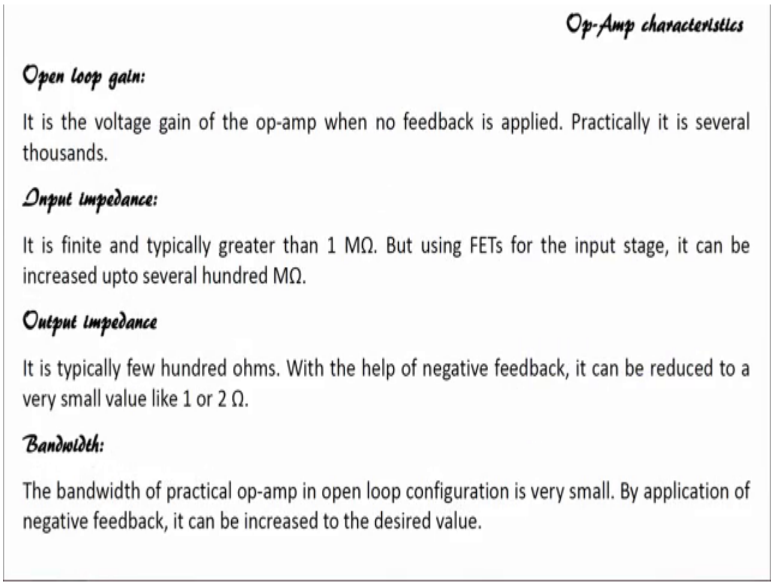
So, we have seen that; what are negative feedbacks what are positive feedback, right.

(Refer Slide Time: 24:42)



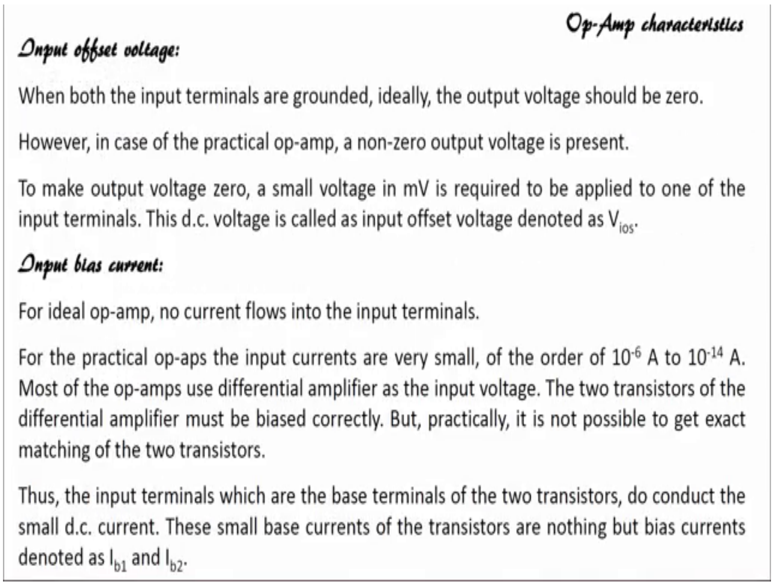
Then we have seen the internal stages of operational amplifier it consists of differential amplifier intermediate state level shifter, state output state. And most of the op-amps are now replaced by MOSFETs internal circuit that you see here BJT most of the cases. Now we are using MOSFETs, alright.

(Refer Slide Time: 25:00)



Then these are very important parameters or characteristics of the operational amplifier starting with open loop gain right, what is open loop gain, it is a voltage gain of operational amplifier when no feedback is applied. So, practically it should be or it is several thousand second is input impedance it is finite and typically greater than one mega ohm, but for FETs for the input stage. It can be increased to several 100 mega ohms output impedance around 1 to 2 ohm bandwidth of practical op-amp in open loop is very small, but by using negative feedback. We can increase the bandwidth to desired value input offset voltage when both input terminals are grounded the output should be 0.

(Refer Slide Time: 25:42)

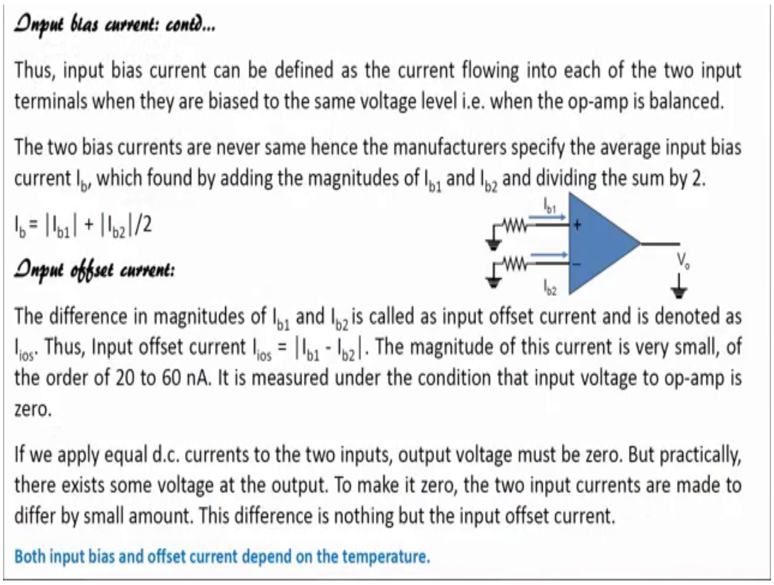


But when you do that like I said in the last course that when you ground both the input terminals of the operational amplifier, you will not find that output voltage is 0, right; and to make that output voltage 0 a small voltage is required to apply to one of the input terminals and that small voltage is nothing, but your dc offset voltage is called input offset voltage.

Same way if you talk about input bias current what is input bias current, if you come back on the screen for ideal operational amplifier no current flows into the input terminals right. But for practical op-amps you will see that the input currents are very small around 10 raised to minus 6 to 10 raised to minus fourteen ampere right. So, the input terminals which are the base terminals of two transistors do not conducts small dc current, this small base current of transistors are nothing, but the bias currents denoted by I b 1 and I b 2. You see why this happens, because the two transistors of the differential amplifier. So, when we have seen most of the op-amps are used as a differential amplifier right. Differential amplifier for the input voltage the two transistor of the differential amplifier must be biased correctly.

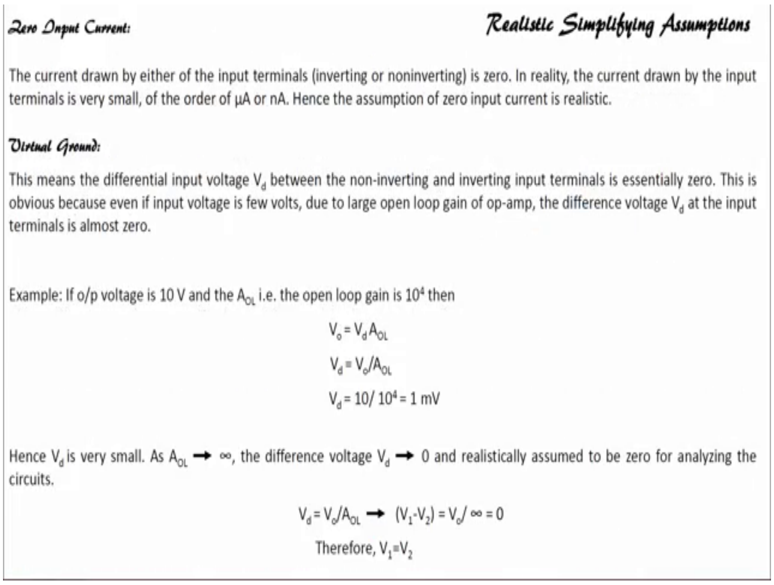
But practically it is impossible or it is not possible to get exact matching of two transistors right. This mismatch of the two transistors will allow a small base current to flow a small dc current to flow to the input of the transistor, right. This small base current of the transistors are nothing, but input bias currents right bias currents denoted by I b 1 and I b 2.

(Refer Slide Time: 27:28)



So, how input bias current is measured the input bias current is measured by using this formula that I b equals to mod of I b 1 plus mod of I b 2 by 2 where you talk about input offset current. It is the difference in the magnitudes of input bias currents right I b 1 and b 2 is called input offset currents and is donated by ios I ios equals to mod of I b 1 minus I b 2, right. One very important point that you have to remember here is that both input bias and offset current depends on the temperature.

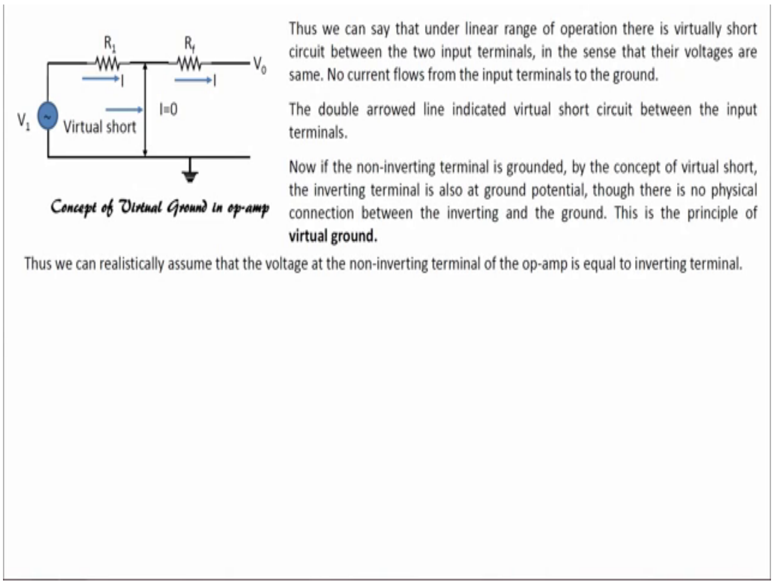
(Refer Slide Time: 28:10)



If you change the temperature, you will find that the input bias and offset current also changes zero input current, right. What is that? The current drawn by either of the input terminals is 0, right. In reality the current drawn by the input terminal is very small of order of microampere or nanoampere, hence assumption of zero current is realistic these are all realistic simplifying assumptions, right. So, actually ideally what will happen that the current drawn by input terminal should be 0, but practically when we when we measure it. It is about microampere to nanoampere which is close to 0. Hence, 0 assumption is realistic second is virtual ground very important in case of operational amplifier. So, this means the differential voltage V d between the non-inverting and inverting terminals is essentially 0, correct.

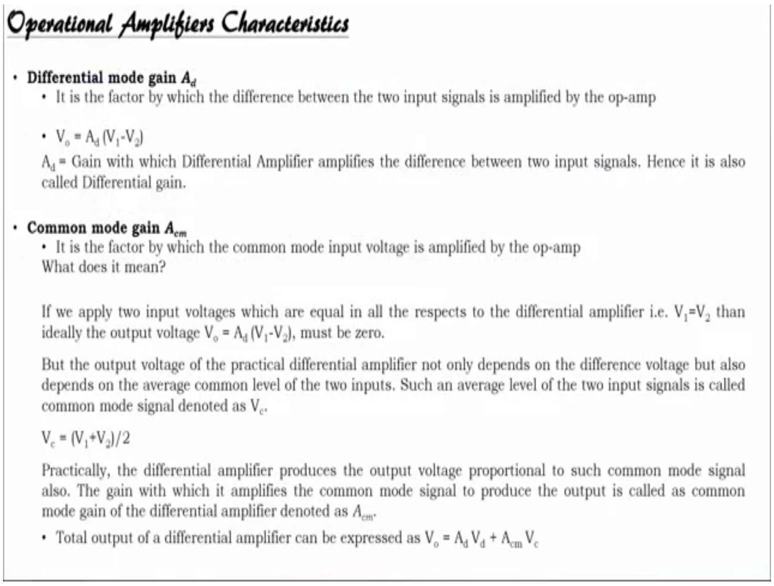
Essentially, 0 this is obvious because even if the input voltage is few volts due to large of loop gain open loop gain of the operational amplifier the difference voltage at the input terminal is almost 0, we have seen that right.

(Refer Slide Time: 29:23)



So, let us move forward we have seen the concept of virtual ground, right. So, even if one of the terminal is grounded the second terminal is also considered as a ground. And that is a concept of virtual ground.

(Refer Slide Time: 29:35)



Then we have seen differential mode gain differential mode gain is nothing, but V o or output voltage equals to differential gain into difference of input voltages V 1 minus V 2 right. So, A d is nothing, but gain with which differential amplifiers amplifies the difference between two input signals. Hence it is also called differential gain because it amplifies the difference between two input signals right; common mode gain, what does common mode gain means?

So, it is a factor by which common mode input voltage is amplified by operational amplifier. So, what exactly common mode gain means if we apply two input voltage which are equal in all respect to differential amplifier right. That means, that say the voltage at the inverting terminal we consider V 1 voltage at non inverting terminal of the op-amp we consider V 2 and if V 1 equals to V 2. Then ideally what should be the output voltage should be V o equals to differential gain into V 1 minus V 2 V 1 is equal to V 2. So, output voltage should be 0 output voltage should be 0, but in practical op-amp practical differential amplifier right. It does not only depends on different voltage, but also depends on the average common level of two inputs.

And such an average level of two input signal is called common mode signal denoted by V c or V c m. And this V c m can be found by formula V c m equals to V 1 plus V 2 by 2 right, thus we cannot just say that V o equals to A d into V 1 minus V 2, but the output voltage of the operational amplifier depends on A d V 1 minus V 2 or A d into V d V 1 minus V 2 is what V d right differential voltage. So, A d into V d plus A c m into V c m, right. So, the output voltage depends not only on the differential mode gain, but also on common mode gain and common mode voltage as well as differential mode voltage so.

(Refer Slide Time: 31:58)

Common mode rejection ratio *CMRR*

The ability with of a differential amplifier to reject common mode signal is expressed by a ratio called CMRR.

CMRR = $|A_d / A_{cm}|$

Ideally the common mode voltage gain is zero, hence the ideal value of CMRR is infinite.

For practical differential amplifier Ad is large and ACM is small hence the value of CMRR is also very large.
Many a times, CMRR is also expressed in dB, as:

CMRR = $20 \log|A_d / A_{cm}|$

$V_o = A_d V_d + A_{cm} V_c$

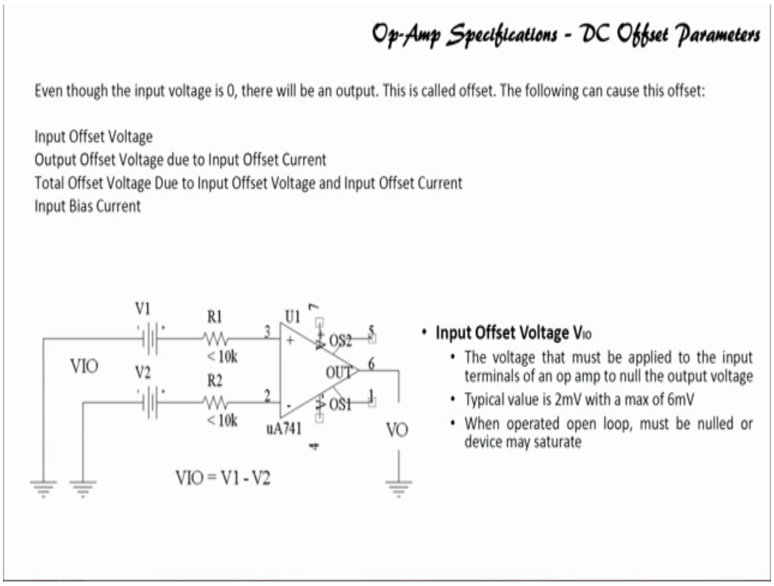
$= A_d V_d [1 + A_{cm} V_c / A_d V_d]$

$= A_d V_d [1 + 1 / (A_d/A_{cm}) * (V_c/V_d)]$

This equation explains that as CMRR is practically very large, though both V_c and V_d components are present, the output is mostly proportional to the difference signal only. The common mode component is greatly rejected.

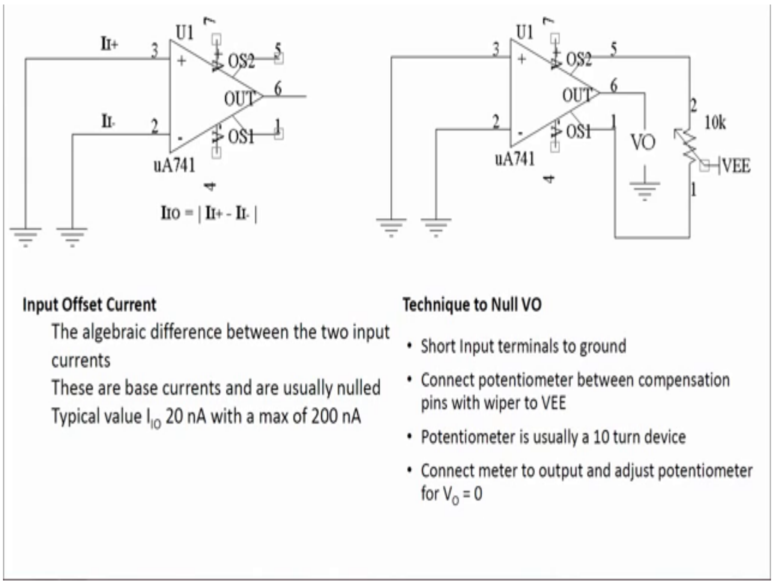
Then we have seen common mode rejection ratio. So, what exactly common mode rejection ratio means right common mode rejection ratio is the ratio of differential gain to common mode gain ideally the common mode voltage gain is 0, right, because we do not want common mode gain we want only differential gain, but. So, ideally in ideal situation if we say that common mode gain is 0, then what will be CMRR; CMRR would be A d by 0 which will be equal to infinite, right. The CMRR ideally should be infinite, but practically you will see that A d is large and A c m is small and CMRR is also very large and many times, you will also see that CMRR is expressed in decibels.

(Refer Slide Time: 32:54)



Now, input offset voltage we already discussed, right.

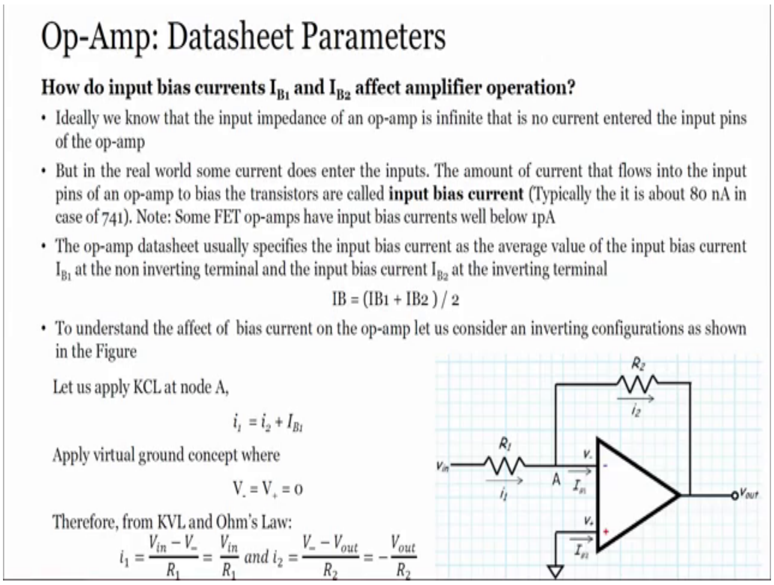
(Refer Slide Time: 32:58)



Input offset current right the algebraic difference. So, what is the technique to null the output voltage technique to null the output voltage you see when we short the input terminals 2 and 3 to ground, right. Practically should be 0 output voltage will be 0, right so, but it is not 0. So, we have to make it 0 that is called nulling output voltage.

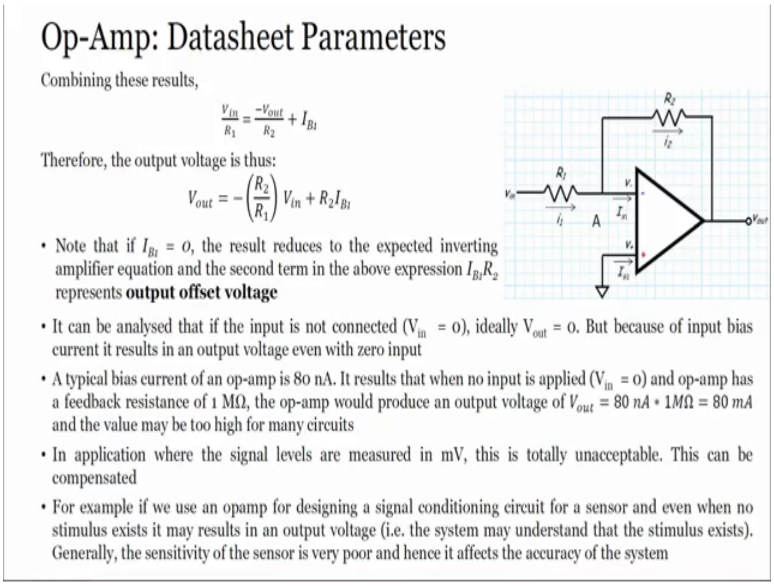
So, we have to connect a potentiometer between compensation pins right one and five I told you earlier 1 and 5 are the compensation pins right. And with a wiper to V e e. So, potentiometer with the help of potentiometer we can adjust the output voltage V o to be 0, right. So, we change we turn the potentiometer, such that we apply a small amount of voltage is called offset voltage to make our output voltage 0 or to nullify.

(Refer Slide Time: 34:03)



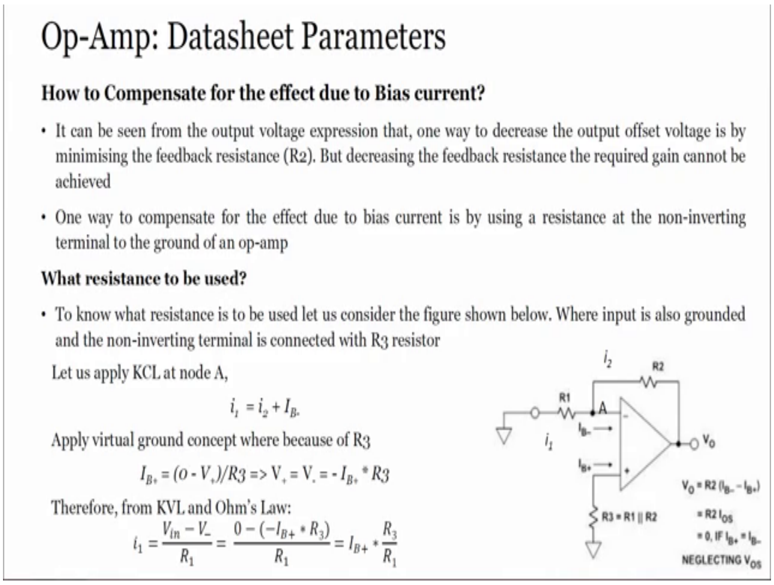
The output voltage now we then found that the input bias currents affect the amplifier operation, right. And we took an example of how the input bias current I b 1 and I b 2 affect the operation, right.

(Refer Slide Time: 34:28)



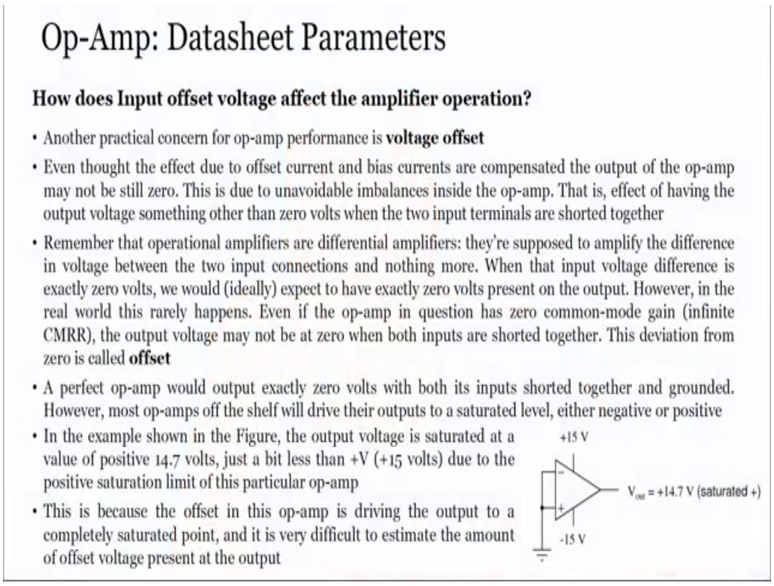
So, we will just skip this you can just look at my earlier course right and look how exactly the input bias currents I b 1 and I b 2 affects the operational amplifier or amplifier operation then.

(Refer Slide Time: 34:47)



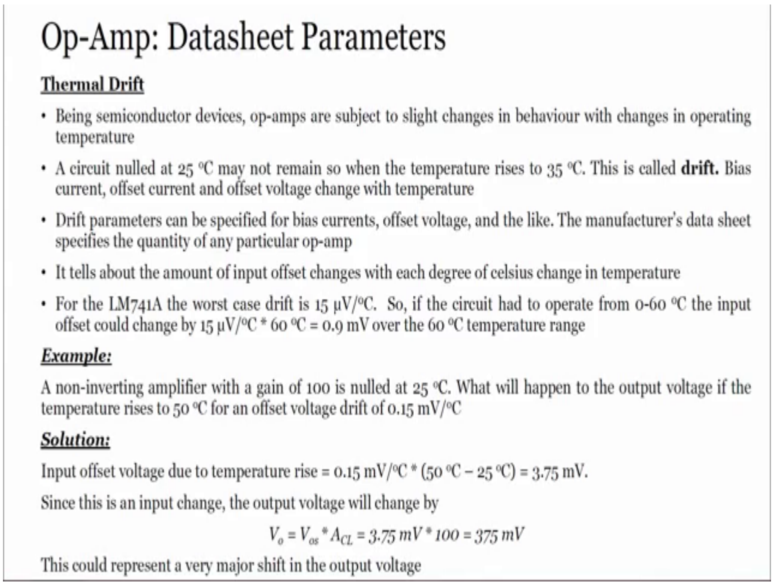
Then we also saw how we can compensate the effect due to the bias currents right and what resistance can be used to compensate the effect of bias currents right. So, again you see the videos. That already available and when you see that you see those videos you will understand how we can compensate or how we can exactly compensate the effect of the bias currents then if you come back to the screen what we see.

(Refer Slide Time: 35:21)



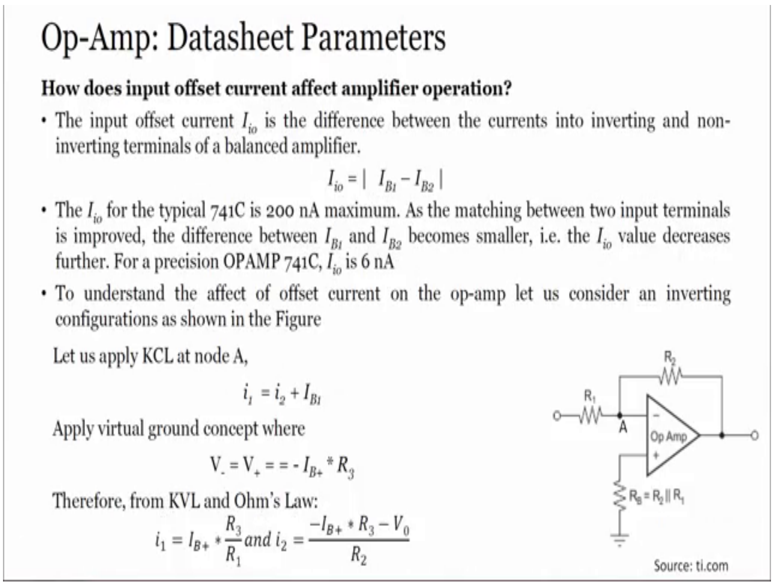
Another question is how does input offset voltage or how does input offset voltage affect the amplifier operation right. Earlier, it was input bias current here, it is input offset voltage right. So, this also we have seen. So, just look at the videos please, right.

(Refer Slide Time: 35:44)



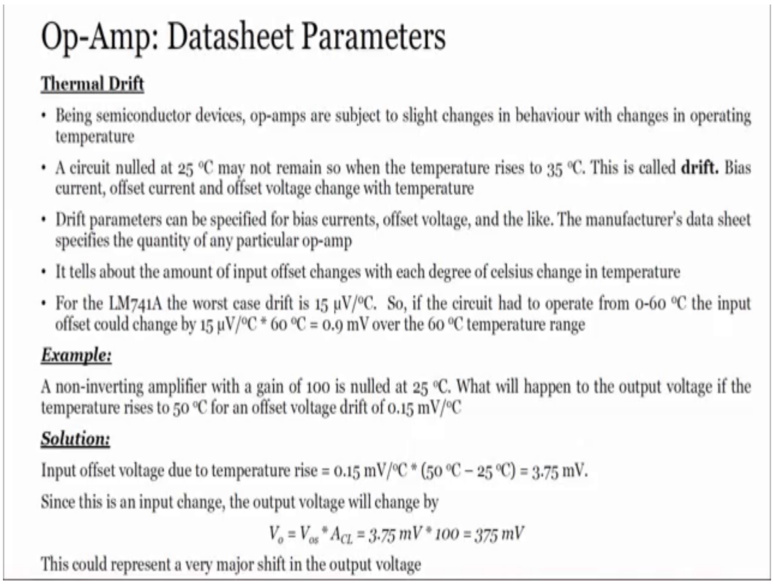
Then the next example is thermal drift thermal drift, right. These are all datasheet parameters by the way these are all datasheet parameter right datasheet parameters.

(Refer Slide Time: 35:54)



So, when you see input offset current input bias current input offset voltage you know CMRR, these are all datasheet parameters. So, just look at it thermal drift, right.

(Refer Slide Time: 36:11)



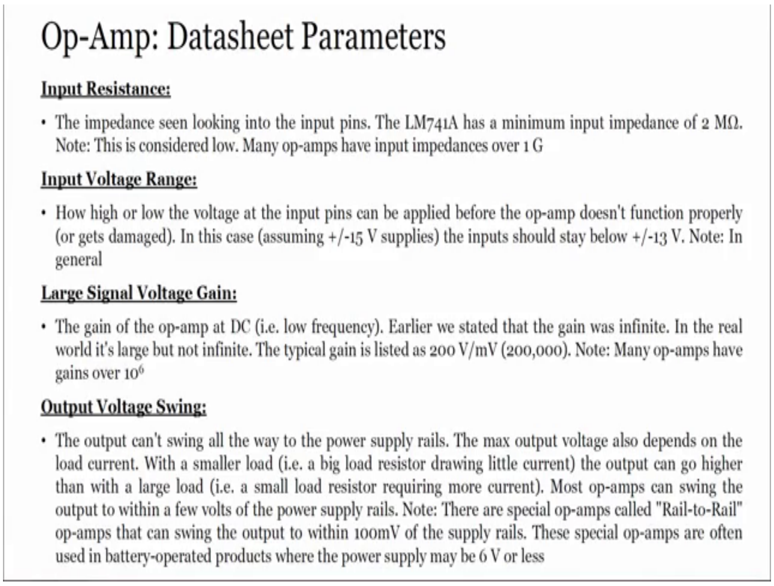
Being semiconductor devices op-amps are subject to slight changes in behavior with change in operation of the temperature or with change in operating temperature, see if the temperature changes because its semiconductors, right. The op-amps are subject to slight changes what behavior changes are there a circuit nulled at 25 degree may not remain. So, when temperature is raised when temperature rises to 35 degree. So, if there is a temperature difference of 10 degree, then you will see there is a drift and this is called of course, this called a drift and bias current offset current and offset voltage change with temperature, right. So, thermal drift is very important parameter we do we need to understand thermal drift parameters can be specified for bias currents offset voltage.

The manufacturers data sheet specifies the quantity of any particular op-amp it tells about the amount of input offset changes with each degree Celsius change in temperature. So, for example, if you take LM 741; a the worst case drift is 15 microvolts per degree centigrade. So, if the circuit has to operate from 0 to 60 degree the input offset voltage right or input offset could change by 15 microvolts per degree centigrade into 60 degree which is 0.9 millivolts over 60 degree temperature change which is really huge change right 0.9 millivolts.

So, let us take the example and let us see a non inverting amplifier with a gain of 100 is nulled at 25 degree ok, what will happen to output voltage if the temperature rises to 50 degree centigrade. So, from 25, we go to 50 degree centigrade and for an offset voltage drift of 0.15 millivolts per degree centigrade.

So, in this case its very simple we can write that input offset voltage due to temperature rise is nothing, but 0.15 millivolts per degree centigrade right into 50 minus 25; 25 is equal to 3.75 millivolts, since, this is an input change the output voltage will change by V o equals to V o s into A c l or 3.75 into 100 gain of 100, right 375 millivolts, right, 375 millivolts, this is a huge change or major shift in the output voltage. Thus it is very important to understand the thermal drift and based on the thermal drift based at different temperature, you have to nullify your op-amp or you should understand the temperature compensation circuits.

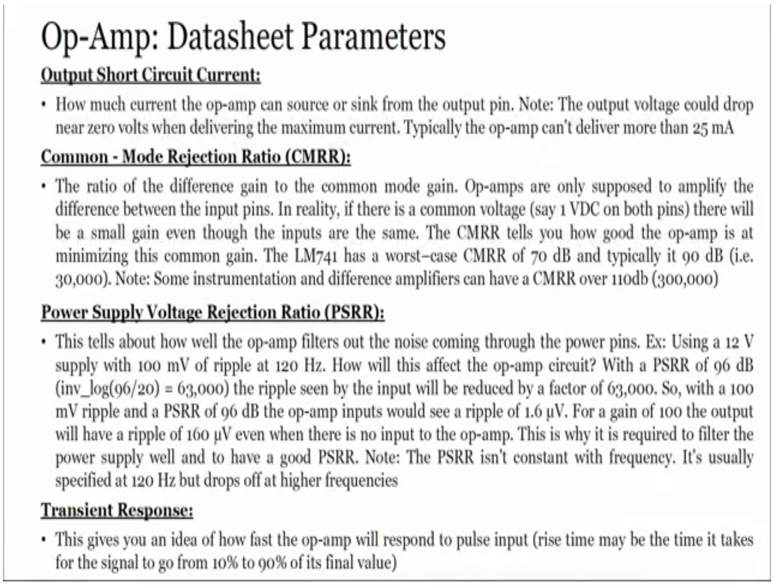
(Refer Slide Time: 38:51)



So, other parameters input resistance input voltage range large signal voltage gain output voltage swing, right. These are the parameters you will see in the datasheet hm. So, impedance in looking into input in input pins LM 741 as a minimum input impedance of 2 mega ohms many op-amps have input impedance of or over 1 gig ohms right; input voltage range how high or low voltage at the input pins can be applied before op-amps does not function properly practically, we know that if there is plus minus 15 volts supplies input should stay below plus minus 13 volt large signal voltage gain. What is that the gain of op-amp at dc that is low frequency right earlier we stated that the gain was infinite we always see that gain is infinite right, but in real situation is large, but not infinite the typical gain is about 200 volts per millivolt or 200,000 right many op-amps have gain of greater than 10 raised to 6 output voltage swing.

What is that the output cannot swing all the way to power rails right cannot go all the way to plus minus 15, but the maximum output voltage also depends on the load current with a smaller load the output can go higher than with a larger load this obvious, right. Most op-amps can swing to the output to within a few volts of power rails, right, these are the special op-amps called rail to rail op-amps that can swing the output to within 100 millivolts of the supply rails, it goes as close as to 100 millivolts of the supply volts; so if it is plus minus 15 volt, it can go 14.9 volts, alright. So, these special op-amps use battery products which power supply maybe 6 volts or less.

(Refer Slide Time: 40:57)



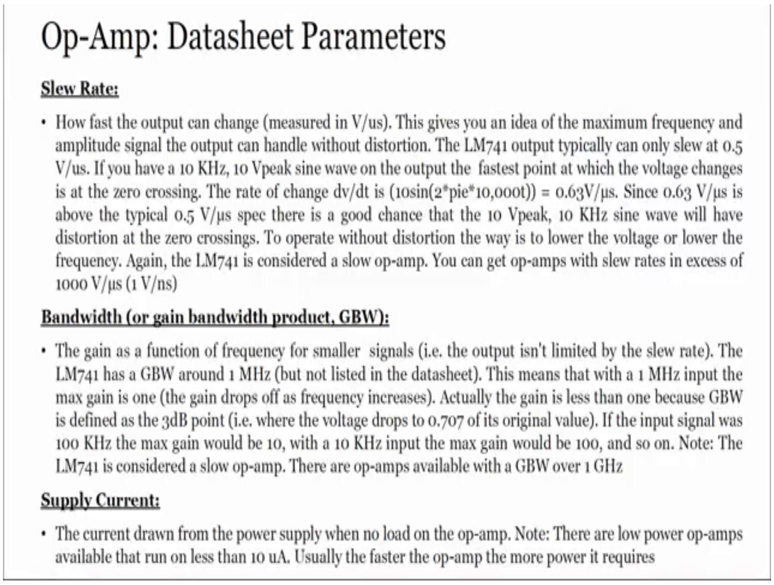
So, we have to see which how much voltage we are applying, then there is output. Short circuit current; what is that how much current the output can source or sink from the output pin is the output short circuit current right. Output voltage could drop near 0 volts when delivering the maximum current typically the op-amp cannot deliver more than 25 milliampere. Then we have seen common mode rejection ratio that is another parameter in the datasheet what is this parameter the ratio of the difference gain to the common mode gain, we have seen that right; A d by A c m and CMRR should be extremely high CMRR should be extremely high. So, if you talk about 7 4 1 that is LM741 the worst case scenario for CMRR in LM741 is 7 dB while and typically about 90 dB, right some instrumentation and differential amplifier can have a CMRR over 110 dB.

That is about 300,000 very high CMRR excellent for the operational amplifier to be used as an amplifying circuit power supply voltage rejection ratio PSRR, this is another parameter, then when you open a datasheet, you will see PSRR. So, what is that this tells about how well the op-amp filters out the noise coming from the power pins, right? So, noise can be generated from the power pins how well it can be filtered out. So, using a 12 volt supply with 100 millivolts of ripple of at 120 hertz, how will this affect the op-amp circuit? Let us taken an example where we are using a 12 volt supply, right. And there is a 100 millivolt of ripple at 120 hertz. In this case with PSRR 96 dB the ripple seen by the input will reduced by factor of 63000. So, with the 100 millivolt ripple and PSRR of 96 dB, the op-amp inputs would see a ripple of 1.6 micro volt.

For a gain of hundred the output will have a ripple of 160 microvolts even when there is no input to the op-amp, this is it is required to filter the power supply and to have a good PSRR, you understand. See, if we have this example where 12 volt power supply is there and about 100 millivolt of ripple is there at 120 hertz, right, then with the PSRR of 96 dB right, PSRR of 96 dB. If you consider the output; output would see about 160 microvolt of ripple voltage and that is not good right. That is why we should use a we should use a filter, right for the power supply right to have a good PSRR. Now transient response what exactly transient response means this gives you an idea of how fast.

The op-amp will respond to pulse input right. So, rise time maybe the time, it takes from signal from 10 percent to 90 percent how fast the op-amp is transient response.

(Refer Slide Time: 44:12)



Then we talked about slew rate what is slew rate slew rate is how fast the output can change right, when you apply input signal how fast the output can change with respect to input signal. This gives, you an idea of the maximum frequency and amplitude signal that op-amp can handle without any distortion right and then we have taken an example. And from the example, what we found is that to operate without distortion the ways to lower the voltage or lower the frequency, right. So, how does it work how does it work either we can lower the voltage or we can lower the frequency. So, let us say let us say.

Let us see the example let us is the LM 741 output typically can only slew at point five volt per microseconds if you have perform the experiment slew rate experiments you will know that it is around 0.5 volt per microseconds. If you have 10 kilo hertz 10 volt peak sine wave on the output the fastest point at which the voltage change is at 0 crossing the rate of change is dv by dt. So, 10 sine 2 pie into 10,000, right 10,000 is a kilo hertz. So, 10,000 t equals to 0.63 volts per micro second since 0.63 volts per micro second is above point five there is a good chance that the 10 volt peak 10 kilo hertz sine wave will have a distortion at 0 crossing, right. So, if you want to avoid these distortion what we can do? We can either we can either lower the voltage.

So, that it comes around 0.5 volt per micro second or below it or we can we can lower the frequency right by lowering the voltage or frequency, we will see that the rate of change dv by dt would be less than 0.5 volt per microsecond right. So, again LM 47 is considered as a slow op amp; however, you can get up op-amps with the slew rate in excess of 1000 volt per microsecond or one volt per nanosecond. So, fast right slew rate can be very fast then we move to next parameter and this parameter is also mentioned in the datasheet that is called bandwidth or gain bandwidth product the gain is as a function of frequency for a smaller signals this means that with the 1 mega hertz input the maximum gain is one.

Actually the gain is less than one because gain bandwidth products is defined as 3 dB point right, we have seen by 3 dB where the voltage drops around 0.707 of its original value if the signal input signal was 100 kilo hertz the maximum gain would be 10 with the 10 kilo hertz input the maximum gain would be 100 and so on, right. So, this is how the gain bandwidth product is defined and the LM471 is considered again as a slow op-amp right. There are op-amps available with gain V product of or gain bandwidth product around and over 1 gigahertz. So, what is another parameter supply current the current drawn from the power supply when no load on the op-amp, right. So, there are low power op-amps available that runs on the less than 10 micro ampere.

This one is a faster op-amp the power it requires is more faster op-amp more power slower op-amp small less power ok. So, this is all about your datasheet of the op amp. So, in this particular module what we have seen we have seen that we are just quickly summarized about ICs, we are quickly summarized about the substrate. And we have seen characteristics of op-amp as well as some realistic parameters and some characteristics of parameters that are listed in datasheet right.

In the next module we will see some applications of op-amp. And then we will move to actually implementing the circuits right using not only simulation, but like I said and I mentioned we will use kits to perform the experiment right. So, just go through this particular module and understand and make your concepts clear because these concepts would be used in the following classes, right. Till then take care. Bye.