

Op-Amp Practical Applications: Design, Simulation and Implementation
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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.

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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.

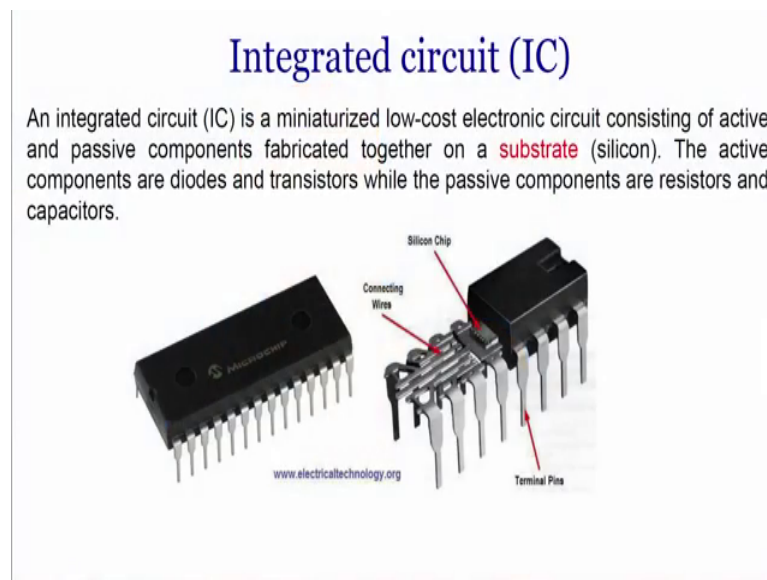
So, this particular course, we will focus on the things that we have just seen right now. But, to understand this whole session understand everything about op-amps and its application we need to understand and we need to make sure that we have our basics clear. And that is why those who have not taken 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.

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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.

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Why integrated circuits?

1. Miniaturization and hence increased equipment density.
2. Batch processing resulting in cost reduction.
3. Improved system reliability due to the elimination of soldered joints.
4. Better functional performance.
5. Matched devices.
6. Increased operating speeds.
7. Significant reduction in the power consumption.

ICs can be classified on the basis of their chip size as given below:

Small scale integration (SSI): 3 to 30 gates/chip.

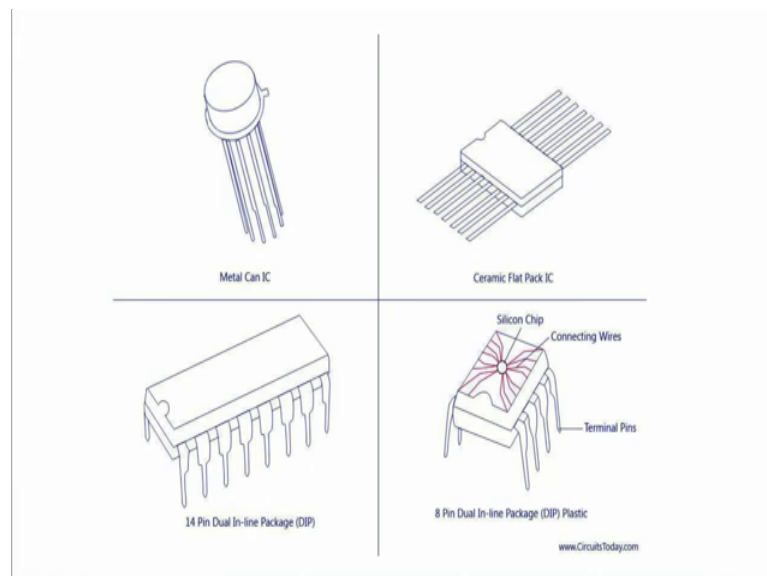
Medium scale integration (MSI): 130 to 300 gates/chip.

Large scale integration (LSI): 300 to 3000 gates/chip.

Very large scale integration (VLSI): more than 3000 gates/chip.

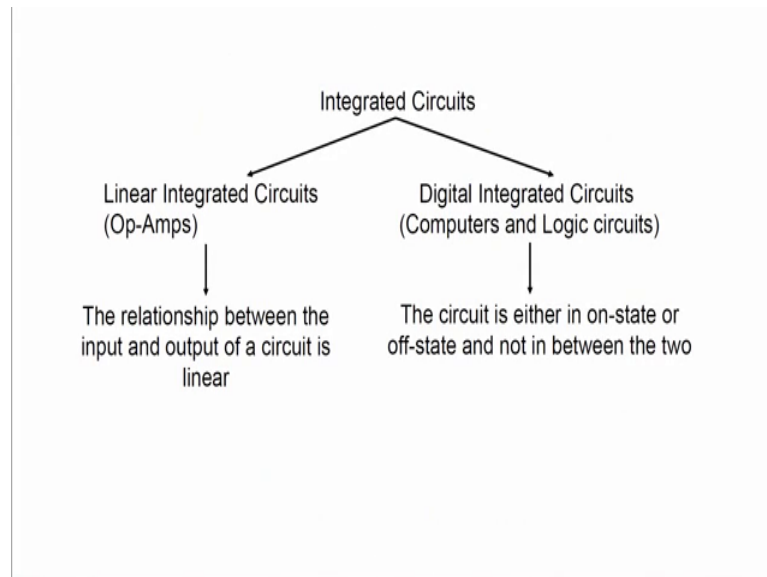
Then we talked about why integrated circuits and we could easily see why. there are several reasons: including miniaturization, batch processing, better function performance, matched devices, increased operating speed, and significant reduction in the power consumption, right. These are all the reasons 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.

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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.

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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.

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Monolithic Integrated Circuits

The word 'monolithic' comes from the Greek words 'monos' and 'lithos' which means 'single' and 'stone'.

The monolithic IC's refer to a single stone or a single **crystal**.

Silicon

The single crystal refers to a single silicon chip as the semiconductor material, on top of which all the passive and active components are interconnected.

Monolithic ICs are considered as the best mode of manufacturing IC' as:

1. It can be made identical,
2. High reliability,
3. Manufactured in bulk in very less time,
4. Low Cost,

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.

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Monolithic Integrated Circuits: Limitations

- Low power rating.
- Cannot be used for high power applications as it can't have power rating of more than 1 W.
- The isolation between the components within the integrated circuit is poor.
- Components such as inductor can't be fabricated.
- The passive components within the IC will have small value and an external connection is required from the IC pins to obtain high values.
- Flexible circuit is not possible.

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.

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Thin and Thick Film Integrated Circuit

These integrated circuit are larger than monolithic IC's and smaller than discrete circuits.

It can be used in high power applications.

Cannot be integrated with diodes and transistors.

Diodes and transistors if required can be externally connected on to its corresponding pins.

Resistors and capacitors can be integrated.

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.

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Thin Film Integrated Circuit	Thick Film Integrated Circuit
<ul style="list-style-type: none">➤ Fabricated by depositing thin films of conducting/semiconducting materials on the surface of a glass or ceramic base.➤ $R = \rho L/A$➤ By controlling the thickness and width of the film we can fabricate resistors of different values. Different material will have different resistivity.➤ Similarly capacitors can be fabricated by depositing two conducting films separated by an insulating layer. An inductor can be fabricated by depositing spiral form of film onto the IC.	<ul style="list-style-type: none">➤ Commonly called as printed film circuits.➤ A screen printing or silk-screen printing technique is used to obtain the desired circuit pattern on a ceramic substrate.➤ The inks are used for printing the circuits.➤ Ink consists of materials that have resistive, dielectric, or conductive, properties.➤ The screens are actually made of fine stainless steel wire mesh. The films are fused to the substrate after printing by placing them in hot high temperature furnaces.

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.

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Thick and thin film IC's do have some advantages when compared to monolithic ICs:

- Better tolerance
- Better isolation between components
- Flexibility in circuit design

Note: Thick and Thin film IC technology can't be used to fabricate active components as it will further result in increased size.

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.

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Hybrid or Multi-chip Integrated Circuits

- The circuit is fabricated by interconnecting a number of individual chips.
- Used for high power audio amplifier applications
- Diffused transistors or diodes are the active components.
- Diffused resistors or capacitors on a single chip, or thin-film components can be some of the passive components that can be fabricated.
- Metallized pattern or wiring is used for interconnection between the individual chips.

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.

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Integrated circuit (IC)

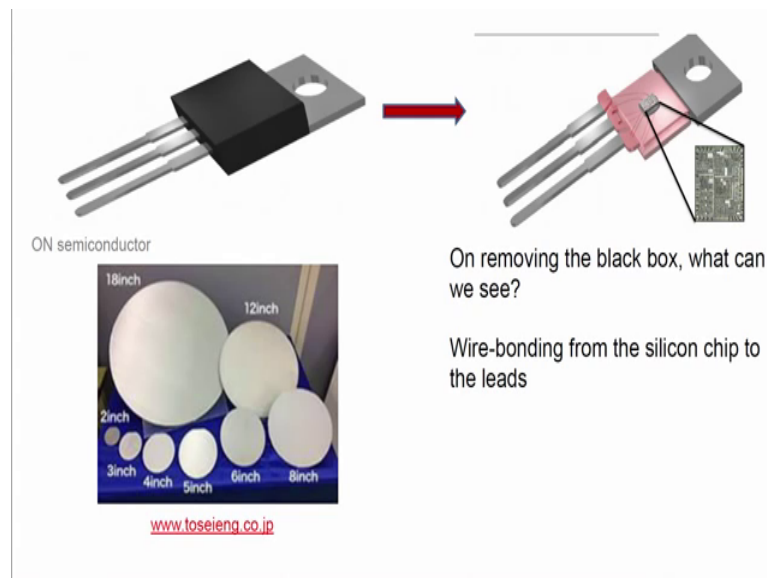
- Substrates: Silicon, Glass, and Plastic
- Microelectronic chips used semiconductor material as a substrate
- For more than 95% of all semiconductor devices fabricated, silicon is the leading semiconductor material
- Silicon substrate can be divided into four basic steps:
 1. Production of electronic grade silicon
 2. Crystal growing
 3. Polishing of Silicon crystal
 4. Slicing of Si wafers

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.

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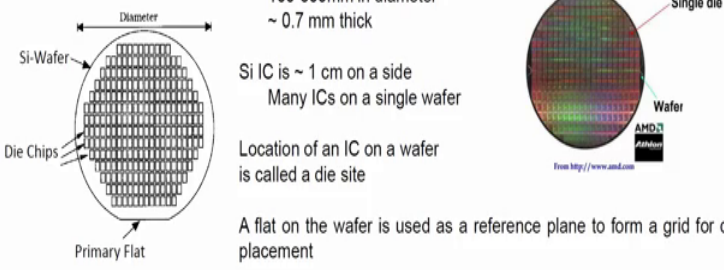


So, when we talk about manufacture of silicon production, of electronic grade silicon, crystal growing polishing of silicon and slicing of silicon wafers. We have seen that we will again seen in this coming slides and we talk about IC, right when we open this case, like I said we will find the chip, 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.

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Silicon Processing - Wafers



Si ICs are created on large circular sheets of Si called wafers
100-300mm in diameter
~ 0.7 mm thick

Si IC is ~ 1 cm on a side
Many ICs on a single wafer

Location of an IC on a wafer is called a die site

A flat on the wafer is used as a reference plane to form a grid for die placement

The number of wafer starts per week indicates the manufacturing capacity of a chip factory

How many fresh wafers are introduced into the fabrication sequence shows the number of wafer starts

Wafers are processed in groups

Typically it takes several weeks for a lot to pass the entire processing line

Labels in diagram: Diameter, Si-Wafer, Die Chips, Primary Flat, Single die, Wafer, AMD, AMD3, AMD4, AMD5, AMD6, AMD7, AMD8, AMD9, AMD10, AMD11, AMD12, AMD13, AMD14, AMD15, AMD16, AMD17, AMD18, AMD19, AMD20, AMD21, AMD22, AMD23, AMD24, AMD25, AMD26, AMD27, AMD28, AMD29, AMD30, AMD31, AMD32, AMD33, AMD34, AMD35, AMD36, AMD37, AMD38, AMD39, AMD40, AMD41, AMD42, AMD43, AMD44, AMD45, AMD46, AMD47, AMD48, AMD49, AMD50, AMD51, AMD52, AMD53, AMD54, AMD55, AMD56, AMD57, AMD58, AMD59, AMD60, AMD61, AMD62, AMD63, AMD64, AMD65, AMD66, AMD67, AMD68, AMD69, AMD70, AMD71, AMD72, AMD73, AMD74, AMD75, AMD76, AMD77, AMD78, AMD79, AMD80, AMD81, AMD82, AMD83, AMD84, AMD85, AMD86, AMD87, AMD88, AMD89, AMD90, AMD91, AMD92, AMD93, AMD94, AMD95, AMD96, AMD97, AMD98, AMD99, AMD100.

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.

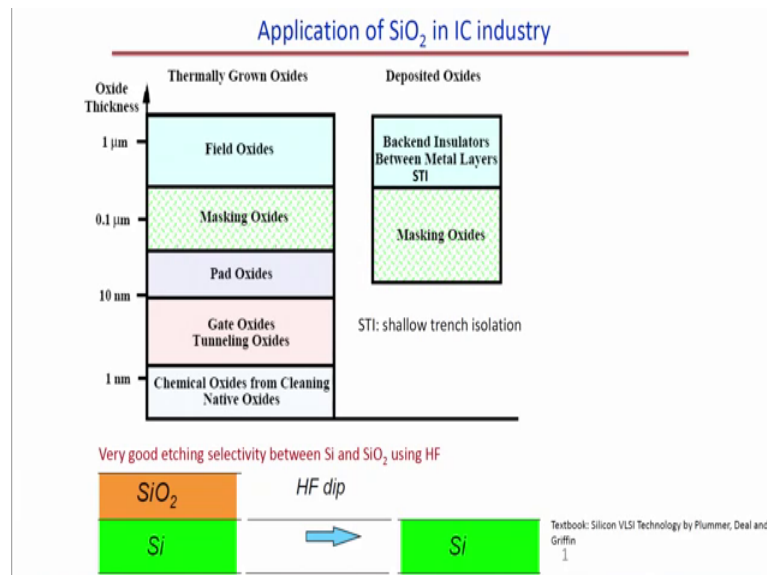
If there is a presence of secondary flat or not and if it the secondary flat was present with respect to primary flat where it is at 45 degree, is it a 9; is it a 90 degree or is it at 180 degree or the secondary flat is not present at all based on that we can identify whether the wafer is n type a or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

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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.

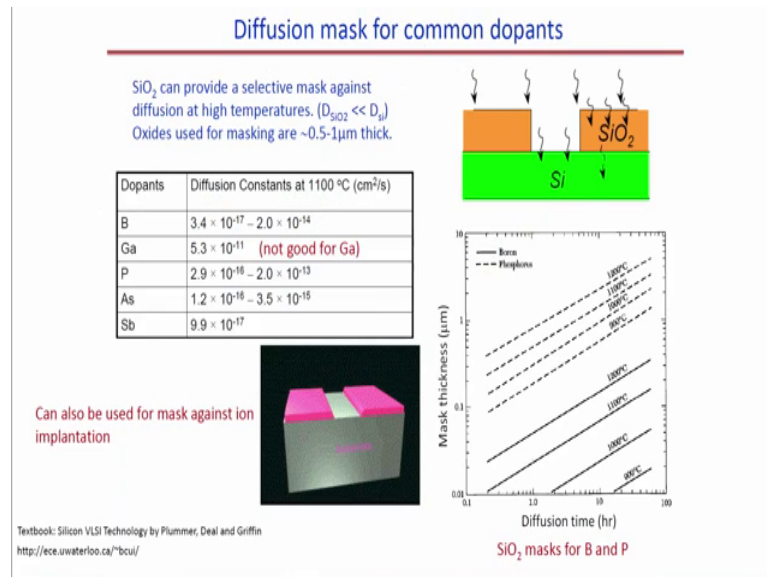
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So, then we have also seen that for a for fabricating any sensor including MOSFETs, right, we need oxides, it can be gate oxide, it can be field oxide, it can be masking oxide and based on what kind of application of the oxide, we are using or based 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.

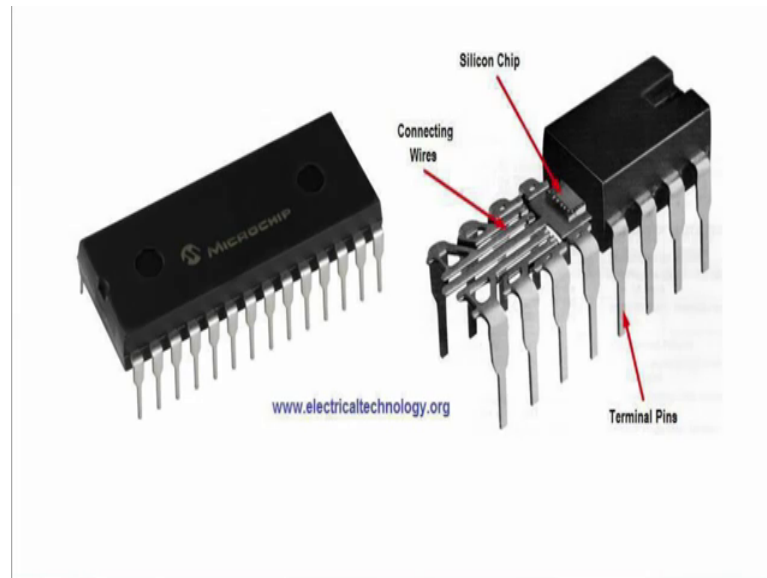
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So, the use of diffusion mask for common dopants; diffusion mask for common dopants is that it will save or it will not allow the dopant to enter through the diffusion mask. And this diffusion mask can be fabricated or can be designed using silicon 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 phosphorus.

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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.

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Brief History

- First patent for Vacuum Tube Op-Amp (1946)
- First Commercial Op-Amp available (1953)
- First discrete IC Op-Amps (1961)
- First commercially successful Monolithic Op-Amps (1965)

Operational Amplifiers

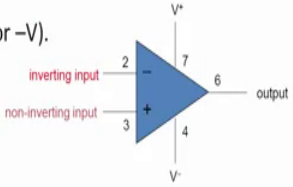
The slide includes a circuit diagram of a vacuum tube op-amp and a pinout diagram for the Fairchild $\mu A741$ op-amp. The pinout diagram shows an 8-pin package with the following connections: Pin 1 (Offset Null), Pin 2 (Inverting (-)), Pin 3 (Non-Inverting (+)), Pin 4 (Power V^-), Pin 5 (Offset Null), Pin 6 (Output), Pin 7 (V^+ (Power)), and Pin 8 (Not Connected (NC)).

- Leading to the advent of the modern IC which is still used even today (1967 – present)

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 741, right.

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- Operational Amplifiers have atleast following five terminals:
 - The positive supply voltage terminal (V_{cc} or $+V$).
 - The negative supply voltage terminal ($-V_{cc}$ or $-V_{EE}$ or $-V$).
 - The output terminal.
 - The inverting input terminal.
 - The non-inverting input terminal.



- The input at inverting terminal results in opposite polarity (antiphase) output.
- While the input at noninverting terminal results in the same polarity (phase) output.
- The op-amp is fabricated on a tiny silicon chip and packaged in a suitable case. Fine gauge wires are used to connect the chip to the external leads.

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.

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- Op-AMP is a very high gain amplifier fabricated on Integrated Circuit (IC)
- Combination of many transistors, FETs, Resistors in a pin head space
- Finds application in:
 - Audio amplifier
 - Signal generator
 - Signal filters
 - Biomedical Instrumentation
 - And numerous other applications

Advantages of OPAMP over transistor amplifier:

- ✓ Less power consumption
- ✓ Costs less
- ✓ More compact
- ✓ More reliable
- ✓ Higher gain can be obtained
- ✓ Easy design

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.

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Ideal Operational Amplifiers

Infinite voltage gain
a voltage difference at the two inputs is magnified infinitely
in truth, very high (~250000)
means difference between inverting terminal and non-terminal is amplified by 250,000.

Infinite input impedance
no current flows into inputs
in truth, about $10^{12} \Omega$ for Field Effect Transistor input op-amps

Zero output impedance
rock-solid independent of load
True up to current maximum (usually 5-25 mA)

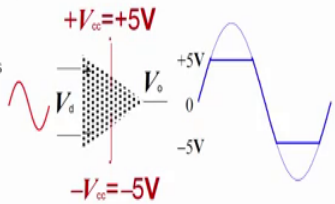
Infinite fast (infinite bandwidth)
Practically limited to few MHz range
slew rate limited to 0.5-20 V/ μ s

The output voltage never exceeds the DC voltage supply of the Op-Amp

Op-Amp "Golden Rules"

When an op-amp is configured in any negative-feedback arrangement, it will obey the following two rules:

- The inputs to the op-amp draw no current (true whether negative feedback or not)
- The op-amp output will do whatever it can (within its limitations) to make the voltage difference between the two inputs zero



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.

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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)	∞	$10^6 - 10^{12} \Omega$
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.

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+V = +15V
-V = -15V
Balanced

+V = +15V
-V = -12V
Unbalanced

Power Supply

Single ended output

Double ended output

- Op-amp works on a dual power supply.
- $\pm 9V, \pm 12V, \pm 15V, \pm 22V$.
- Output is taken between the output terminal and ground is called single ended, unbalanced output.
- The output taken between the two terminals and not with respect to the ground is called double ended, balanced output. As none of the terminals is grounded, it is also called floating output.

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 supply 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.

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Feedback in op-amps

negative feedback loop

The internal op-amp formula is:

$$V_{out} = \text{gain} \times (V_+ - V_-)$$

So if V_+ is greater than V_- , the output goes positive

If V_- is greater than V_+ , the output goes negative

A gain of 200,000 makes this device (as illustrated here) practically useless

Infinite gain would be useless except in the self-regulated negative feedback regime

negative feedback seems bad, and positive good—but in electronics positive feedback means runaway or oscillation, and negative feedback leads to stability

Imagine hooking the output to the inverting terminal:

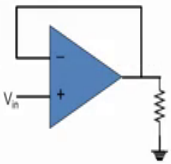
If the output is less than V_{in} , it shoots positive
If the output is greater than V_{in} , it shoots negative
result is that output quickly forces itself to be exactly V_{in}

Then we move further and we see that the internal op-amp formula is nothing, but V_{out} equals to gain into V_{in} plus minus V_{in} 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.

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Even if we load the output (which as pictured wants to drag the output to ground)

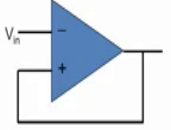
- The op-amp will do everything it can within its current limitations to drive the output until the inverting input reaches V_{in} .
- A negative feedback makes it self-correcting in this case, the op-amp drives (or pulls, if V_{in} is negative) a current through the load until the output equals V_{in} so what we have here is a buffer: can apply V_{in} to a load without burdening the source of V_{in} with *any* current!
- **Note:** op-amp output terminal sources/sinks current at will: not like inputs that have no current flow



Positive Feedback

- In the configuration below, if the + input is even a smidge higher than V_{in} , the output goes way positive
- This makes the + terminal even *more* positive than V_{in} , making the situation worse

This system will immediately "rail" at the supply voltage. It could rail either direction, depending on initial offset



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

(Refer Slide Time: 24:42)

- Four stages can be identified from the internal block diagram of op-amp:
 1. Input stage or differential amplifier stage can amplify difference between two input signals; Input resistance is very high; Draws zero current from the input sources
 2. Intermediate stage (or stages) use direct coupling; provide very high gain
 3. Level shifter stage shifts the dc level of output voltage to zero (can be adjusted manually using two additional terminals)
 4. Output stage is a power amplifier stage; has very small output resistance; so output voltage is the same, no matter what is the value of load resistance connected to the output terminal

- The essential building block of modern IC op-amp is a differential amplifier.
- It amplifies the difference between the two input signals and has excellent stability, high versatility, immune to noise and interference signals and hence used in most of the analog circuits, ranging from DC to high frequency applications.

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)

Op-Amp characteristics

Open loop gain:
It is the voltage gain of the op-amp when no feedback is applied. Practically it is several thousands.

Input impedance:
It is finite and typically greater than 1 M Ω . But using FETs for the input stage, it can be increased upto several hundred M Ω .

Output impedance
It is typically few hundred ohms. With the help of negative feedback, it can be reduced to a very small value like 1 or 2 Ω .

Bandwidth:
The bandwidth of practical op-amp in open loop configuration is very small. By application of negative feedback, it can be increased to the desired value.

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)

Op-Amp characteristics

Input offset voltage:

When both the input terminals are grounded, ideally, the output voltage should be zero. However, in case of the practical op-amp, a non-zero output voltage is present. To make output voltage zero, a small voltage in mV is required to be applied to one of the input terminals. This d.c. voltage is called as input offset voltage denoted as V_{ios} .

Input bias current:

For ideal op-amp, no current flows into the input terminals. For the practical op-amps the input currents are very small, of the order of 10^{-6} A to 10^{-14} A. Most of the op-amps use differential amplifier as the input voltage. The two transistors of the differential amplifier must be biased correctly. But, practically, it is not possible to get exact matching of the two transistors. Thus, the input terminals which are the base terminals of the two transistors, do conduct the small d.c. current. These small base currents of the transistors are nothing but bias currents denoted as I_{b1} and I_{b2} .

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^{-6} to 10^{-14} ampere right. So, the input terminals which are the base terminals of two transistors do not conduct small dc current, this small base current of transistors are nothing, but the bias currents denoted by I_{b1} and I_{b2} . 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_{b1} and I_{b2} .

(Refer Slide Time: 27:28)

Input bias current: contd...

Thus, input bias current can be defined as the current flowing into each of the two input terminals when they are biased to the same voltage level i.e. when the op-amp is balanced.

The two bias currents are never same hence the manufacturers specify the average input bias current I_b , which found by adding the magnitudes of I_{b1} and I_{b2} and dividing the sum by 2.

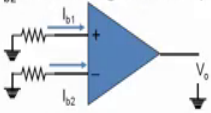
$$I_b = \frac{|I_{b1}| + |I_{b2}|}{2}$$

Input offset current:

The difference in magnitudes of I_{b1} and I_{b2} is called as input offset current and is denoted as I_{ios} . Thus, Input offset current $I_{ios} = |I_{b1} - I_{b2}|$. The magnitude of this current is very small, of the order of 20 to 60 nA. It is measured under the condition that input voltage to op-amp is zero.

If we apply equal d.c. currents to the two inputs, output voltage must be zero. But practically, there exists some voltage at the output. To make it zero, the two input currents are made to differ by small amount. This difference is nothing but the input offset current.

[Both input bias and offset current depend on the temperature.](#)



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_{b1} plus mod of I_{b2} by 2 where you talk about input offset current. It is the difference in the magnitudes of input bias currents right I_{b1} and I_{b2} is called input offset currents and is donated by I_{ios} I_{ios} equals to mod of I_{b1} minus I_{b2} , right. One very important point that you have to remember here is that both input bias and offset current depends on the temperature.

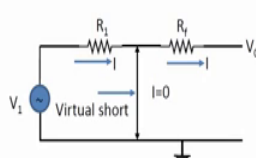
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<i>Zero Input Current:</i>	<i>Realistic Simplifying Assumptions</i>
<p>The current drawn by either of the input terminals (inverting or noninverting) is zero. In reality, the current drawn by the input terminals is very small, of the order of μA or nA. Hence the assumption of zero input current is realistic.</p>	
<p>Virtual Ground:</p> <p>This means the differential input voltage V_d between the non-inverting and inverting input terminals is essentially zero. This is obvious because even if input voltage is few volts, due to large open loop gain of op-amp, the difference voltage V_d at the input terminals is almost zero.</p>	
<p>Example: If o/p voltage is 10 V and the A_{OL} i.e. the open loop gain is 10^4 then</p>	
	$V_o = V_d A_{OL}$
	$V_d = V_o / A_{OL}$
	$V_d = 10 / 10^4 = 1 \text{ mV}$
<p>Hence V_d is very small. As $A_{OL} \rightarrow \infty$, the difference voltage $V_d \rightarrow 0$ and realistically assumed to be zero for analyzing the circuits.</p>	
	$V_d = V_o / A_{OL} \rightarrow (V_1 - V_2) = V_o / \infty = 0$
	<p>Therefore, $V_1 = V_2$</p>

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)



Thus we can say that under linear range of operation there is virtually short circuit between the two input terminals, in the sense that their voltages are same. No current flows from the input terminals to the ground.

The double arrowed line indicated virtual short circuit between the input terminals.

Now if the non-inverting terminal is grounded, by the concept of virtual short, the inverting terminal is also at ground potential, though there is no physical connection between the inverting and the ground. This is the principle of **virtual ground**.

Thus we can realistically assume that the voltage at the non-inverting terminal of the op-amp is equal to inverting terminal.

Concept of Virtual Ground in op-amp

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.

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Operational Amplifiers Characteristics

- **Differential mode gain A_d**
 - It is the factor by which the difference between the two input signals is amplified by the op-amp
 - $V_o = A_d (V_1 - V_2)$

A_d = Gain with which Differential Amplifier amplifies the difference between two input signals. Hence it is also called Differential gain.
- **Common mode gain A_{cm}**
 - It is the factor by which the common mode input voltage is amplified by the op-amp
 - What does it mean?

If we apply two input voltages which are equal in all the respects to the differential amplifier i.e. $V_1 = V_2$ then ideally the output voltage $V_o = A_d (V_1 - V_2)$, must be zero.

But the output voltage of the practical differential amplifier not only depends on the difference voltage but also depends on the average common level of the two inputs. Such an average level of the two input signals is called common mode signal denoted as V_c .

$$V_c = (V_1 + V_2) / 2$$

Practically, the differential amplifier produces the output voltage proportional to such common mode signal also. The gain with which it amplifies the common mode signal to produce the output is called as common mode gain of the differential amplifier denoted as A_{cm} .

 - Total output of a differential amplifier can be expressed as $V_o = A_d V_d + A_{cm} V_c$

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_{cm} . And this V_{cm} can be found by formula V_{cm} 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_{cm} into V_{cm} , 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.

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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 A_d is large and A_{cm} is small hence the value of CMRR is also very large.

Many a times, CMRR is also expressed in dB, as:

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

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

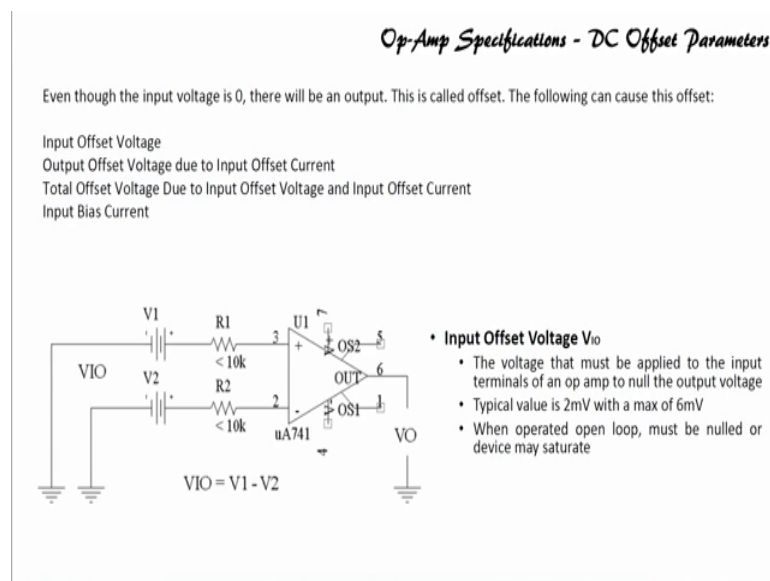
$$= A_d V_d [1 + A_{cm} V_c / A_d V_d]$$

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

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.

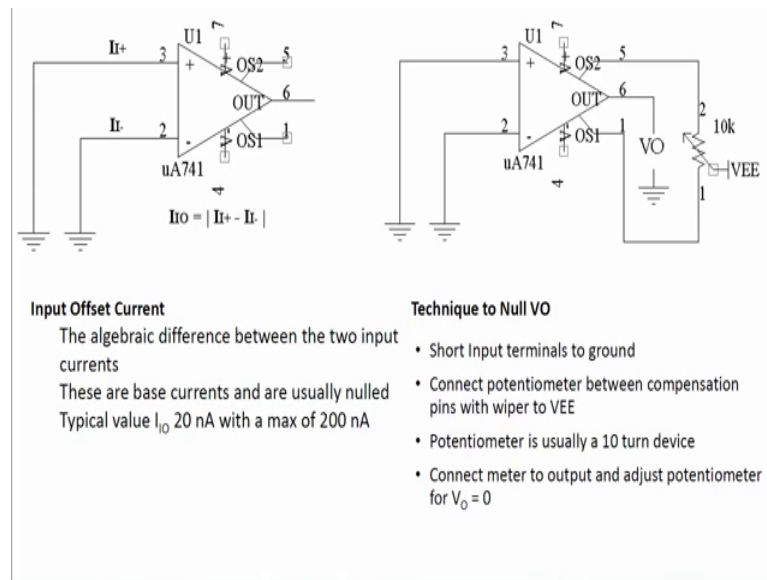
Then we have seen common mode rejection ratio. So, what exactly common mode rejection ratio means right common mode rejection ratio is the ratio of differential gain to common mode gain ideally the common mode voltage gain is 0, right, because we do not want common mode gain we want only differential 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_{cm} is small and CMRR is also very large and many times, you will also see that CMRR is expressed in decibels.

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Now, input offset voltage we already discussed, right.

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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.

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Op-Amp: Datasheet Parameters

How do input bias currents I_{B1} and I_{B2} affect amplifier operation?

- Ideally we know that the input impedance of an op-amp is infinite that is no current entered the input pins of the op-amp
- But in the real world some current does enter the inputs. The amount of current that flows into the input pins of an op-amp to bias the transistors are called **input bias current** (Typically the it is about 80 nA in case of 741). Note: Some FET op-amps have input bias currents well below 1pA
- The op-amp datasheet usually specifies the input bias current as the average value of the input bias current I_{B1} at the non inverting terminal and the input bias current I_{B2} at the inverting terminal

$$IB = (IB1 + IB2) / 2$$

To understand the affect of bias current on the op-amp let us consider an inverting configurations as shown in the Figure

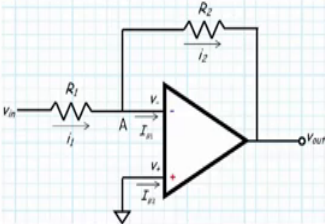
Let us apply KCL at node A,

$$i_i = i_2 + I_{B1}$$

Apply virtual ground concept where

$$V_- = V_+ = 0$$

Therefore, from KVL and Ohm's Law:

$$i_1 = \frac{V_{in} - V_-}{R_1} = \frac{V_{in}}{R_1} \text{ and } i_2 = \frac{V_- - V_{out}}{R_2} = -\frac{V_{out}}{R_2}$$


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_{B1} and I_{B2} affect the operation, right.

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Op-Amp: Datasheet Parameters

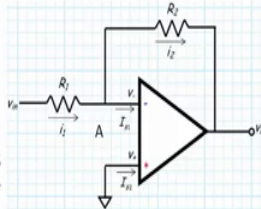
Combining these results,

$$\frac{V_{in}}{R_1} = \frac{-V_{out}}{R_2} + I_{B1}$$

Therefore, the output voltage is thus:

$$V_{out} = -\left(\frac{R_2}{R_1}\right) V_{in} + R_2 I_{B1}$$

- Note that if $I_{B1} = 0$, the result reduces to the expected inverting amplifier equation and the second term in the above expression $I_{B1}R_2$ represents **output offset voltage**
- It can be analysed that if the input is not connected ($V_{in} = 0$), ideally $V_{out} = 0$. But because of input bias current it results in an output voltage even with zero input
- A typical bias current of an op-amp is 80 nA. It results that when no input is applied ($V_{in} = 0$) and op-amp has a feedback resistance of 1 MΩ, the op-amp would produce an output voltage of $V_{out} = 80 \text{ nA} \cdot 1 \text{ M}\Omega = 80 \text{ mV}$ and the value may be too high for many circuits
- In application where the signal levels are measured in mV, this is totally unacceptable. This can be compensated
- For example if we use an opamp for designing a signal conditioning circuit for a sensor and even when no stimulus exists it may results in an output voltage (i.e. the system may understand that the stimulus exists). Generally, the sensitivity of the sensor is very poor and hence it affects the accuracy of the system



So, we will just skip this you can just look at my earlier course right and look how exactly the input bias currents I_{B1} and I_{B2} affects the operational amplifier or amplifier operation then.

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Op-Amp: Datasheet Parameters

How to Compensate for the effect due to Bias current?

- It can be seen from the output voltage expression that, one way to decrease the output offset voltage is by minimising the feedback resistance (R2). But decreasing the feedback resistance the required gain cannot be achieved
- One way to compensate for the effect due to bias current is by using a resistance at the non-inverting terminal to the ground of an op-amp

What resistance to be used?

- To know what resistance is to be used let us consider the figure shown below. Where input is also grounded and the non-inverting terminal is connected with R3 resistor

Let us apply KCL at node A,

$$i_1 = i_2 + I_{B-}$$

Apply virtual ground concept where because of R3

$$I_{B-} = (0 - V_+)/R3 \Rightarrow V_+ = V_- = -I_{B-} * R3$$

Therefore, from KVL and Ohm's Law:

$$i_1 = \frac{V_{in} - V_-}{R_1} = \frac{0 - (-I_{B-} * R_3)}{R_1} = I_{B-} * \frac{R_3}{R_1}$$

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)

Op-Amp: Datasheet Parameters

How does Input offset voltage affect the amplifier operation?

- Another practical concern for op-amp performance is **voltage offset**
- Even though the effect due to offset current and bias currents are compensated the output of the op-amp may not be still zero. This is due to unavoidable imbalances inside the op-amp. That is, effect of having the output voltage something other than zero volts when the two input terminals are shorted together
- Remember that operational amplifiers are differential amplifiers: they're supposed to amplify the difference in voltage between the two input connections and nothing more. When that input voltage difference is exactly zero volts, we would (ideally) expect to have exactly zero volts present on the output. However, in the real world this rarely happens. Even if the op-amp in question has zero common-mode gain (infinite CMRR), the output voltage may not be at zero when both inputs are shorted together. This deviation from zero is called **offset**
- A perfect op-amp would output exactly zero volts with both its inputs shorted together and grounded. However, most op-amps off the shelf will drive their outputs to a saturated level, either negative or positive
- In the example shown in the Figure, the output voltage is saturated at a value of positive 14.7 volts, just a bit less than +V (+15 volts) due to the positive saturation limit of this particular op-amp
- This is because the offset in this op-amp is driving the output to a completely saturated point, and it is very difficult to estimate the amount of offset voltage present at the output

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.

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Op-Amp: Datasheet Parameters

Thermal Drift

- Being semiconductor devices, op-amps are subject to slight changes in behaviour with changes in operating temperature
- A circuit nulled at 25 °C may not remain so when the temperature rises to 35 °C. This is called **drift**. Bias current, offset current and offset voltage change with temperature
- Drift parameters can be specified for bias currents, offset voltage, and the like. The manufacturer's data sheet specifies the quantity of any particular op-amp
- It tells about the amount of input offset changes with each degree of celsius change in temperature
- For the LM741A the worst case drift is 15 $\mu\text{V}/^\circ\text{C}$. So, if the circuit had to operate from 0-60 °C the input offset could change by $15 \mu\text{V}/^\circ\text{C} * 60 ^\circ\text{C} = 0.9 \text{ mV}$ over the 60 °C temperature range

Example:

A non-inverting amplifier with a gain of 100 is nulled at 25 °C. What will happen to the output voltage if the temperature rises to 50 °C for an offset voltage drift of 0.15 mV/°C

Solution:

Input offset voltage due to temperature rise = $0.15 \text{ mV}/^\circ\text{C} * (50 ^\circ\text{C} - 25 ^\circ\text{C}) = 3.75 \text{ mV}$.

Since this is an input change, the output voltage will change by

$$V_o = V_{os} * A_{CL} = 3.75 \text{ mV} * 100 = 375 \text{ mV}$$

This could represent a very major shift in the output voltage

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.

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Op-Amp: Datasheet Parameters

How does input offset current affect amplifier operation?

- The input offset current I_{io} is the difference between the currents into inverting and non-inverting terminals of a balanced amplifier.

$$I_{io} = | I_{B1} - I_{B2} |$$

- The I_{io} for the typical 741C is 200 nA maximum. As the matching between two input terminals is improved, the difference between I_{B1} and I_{B2} becomes smaller, i.e. the I_{io} value decreases further. For a precision OPAMP 741C, I_{io} is 6 nA
- To understand the affect of offset current on the op-amp let us consider an inverting configurations as shown in the Figure

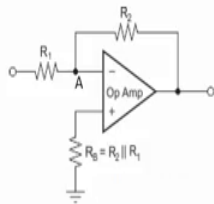
Let us apply KCL at node A,

$$i_1 = i_2 + I_{B1}$$

Apply virtual ground concept where

$$V_- = V_+ = - I_{B+} * R_3$$

Therefore, from KVL and Ohm's Law:

$$i_1 = I_{B+} * \frac{R_3}{R_1} \text{ and } i_2 = \frac{-I_{B+} * R_3 - V_o}{R_2}$$


Source: ti.com

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)

Op-Amp: Datasheet Parameters

Thermal Drift

- Being semiconductor devices, op-amps are subject to slight changes in behaviour with changes in operating temperature
- A circuit nulled at 25 °C may not remain so when the temperature rises to 35 °C. This is called **drift**. Bias current, offset current and offset voltage change with temperature
- Drift parameters can be specified for bias currents, offset voltage, and the like. The manufacturer's data sheet specifies the quantity of any particular op-amp
- It tells about the amount of input offset changes with each degree of celsius change in temperature
- For the LM741A the worst case drift is 15 µV/°C. So, if the circuit had to operate from 0-60 °C the input offset could change by 15 µV/°C * 60 °C = 0.9 mV over the 60 °C temperature range

Example:

A non-inverting amplifier with a gain of 100 is nulled at 25 °C. What will happen to the output voltage if the temperature rises to 50 °C for an offset voltage drift of 0.15 mV/°C

Solution:

Input offset voltage due to temperature rise = 0.15 mV/°C * (50 °C - 25 °C) = 3.75 mV.

Since this is an input change, the output voltage will change by

$$V_o = V_{in} * A_{CL} = 3.75 \text{ mV} * 100 = 375 \text{ mV}$$

This could represent a very major shift in the output voltage

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.

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Op-Amp: Datasheet Parameters

Input Resistance:

- The impedance seen looking into the input pins. The LM741A has a minimum input impedance of 2 M Ω . Note: This is considered low. Many op-amps have input impedances over 1 G

Input Voltage Range:

- How high or low the voltage at the input pins can be applied before the op-amp doesn't function properly (or gets damaged). In this case (assuming +/-15 V supplies) the inputs should stay below +/-13 V. Note: In general

Large Signal Voltage Gain:

- The gain of the op-amp at DC (i.e. low frequency). Earlier we stated that the gain was infinite. In the real world it's large but not infinite. The typical gain is listed as 200 V/mV (200,000). Note: Many op-amps have gains over 10^6

Output Voltage Swing:

- The output can't swing all the way to the power supply rails. The max output voltage also depends on the load current. With a smaller load (i.e. a big load resistor drawing little current) the output can go higher than with a large load (i.e. a small load resistor requiring more current). Most op-amps can swing the output to within a few volts of the power supply rails. Note: There are special op-amps called "Rail-to-Rail" op-amps that can swing the output to within 100mV of the supply rails. These special op-amps are often used in battery-operated products where the power supply may be 6 V or less

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 10^6 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 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.

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Op-Amp: Datasheet Parameters

Output Short Circuit Current:

- How much current the op-amp can source or sink from the output pin. Note: The output voltage could drop near zero volts when delivering the maximum current. Typically the op-amp can't deliver more than 25 mA

Common - Mode Rejection Ratio (CMRR):

- The ratio of the difference gain to the common mode gain. Op-amps are only supposed to amplify the difference between the input pins. In reality, if there is a common voltage (say 1 VDC on both pins) there will be a small gain even though the inputs are the same. The CMRR tells you how good the op-amp is at minimizing this common gain. The LM741 has a worst-case CMRR of 70 dB and typically it 90 dB (i.e. 30,000). Note: Some instrumentation and difference amplifiers can have a CMRR over 110db (300,000)

Power Supply Voltage Rejection Ratio (PSRR):

- This tells about how well the op-amp filters out the noise coming through the power pins. Ex: Using a 12 V supply with 100 mV of ripple at 120 Hz. How will this affect the op-amp circuit? With a PSRR of 96 dB ($\text{inv_log}(96/20) = 63,000$) the ripple seen by the input will be reduced by a factor of 63,000. So, with a 100 mV ripple and a PSRR of 96 dB the op-amp inputs would see a ripple of 1.6 μV . For a gain of 100 the output will have a ripple of 160 μV even when there is no input to the op-amp. This is why it is required to filter the power supply well and to have a good PSRR. Note: The PSRR isn't constant with frequency. It's usually specified at 120 Hz but drops off at higher frequencies

Transient Response:

- This gives you an idea of how fast the op-amp will respond to pulse input (rise time may be the time it takes for the signal to go from 10% to 90% of its final value)

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 milliamperes. 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_{cm} and CMRR should be extremely high CMRR should be extremely high. So, if you talk about 741 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.

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Op-Amp: Datasheet Parameters

Slew Rate:

- How fast the output can change (measured in V/μs). This gives you an idea of the maximum frequency and amplitude signal the output can handle without distortion. The LM741 output typically can only slew at 0.5 V/μs. If you have a 10 KHz, 10 Vpeak sine wave on the output the fastest point at which the voltage changes is at the zero crossing. The rate of change dv/dt is $(10\sin(2\pi \cdot 10,000t)) = 0.63V/\mu s$. Since 0.63 V/μs is above the typical 0.5 V/μs spec there is a good chance that the 10 Vpeak, 10 KHz sine wave will have distortion at the zero crossings. To operate without distortion the way is to lower the voltage or lower the frequency. Again, the LM741 is considered a slow op-amp. You can get op-amps with slew rates in excess of 1000 V/μs (1 V/ns)

Bandwidth (or gain bandwidth product, GBW):

- The gain as a function of frequency for smaller signals (i.e. the output isn't limited by the slew rate). The LM741 has a GBW around 1 MHz (but not listed in the datasheet). This means that with a 1 MHz input the max gain is one (the gain drops off as frequency increases). Actually the gain is less than one because GBW is defined as the 3dB point (i.e. where the voltage drops to 0.707 of its original value). If the input signal was 100 KHz the max gain would be 10, with a 10 KHz input the max gain would be 100, and so on. Note: The LM741 is considered a slow op-amp. There are op-amps available with a GBW over 1 GHz

Supply Current:

- The current drawn from the power supply when no load on the op-amp. Note: There are low power op-amps available that run on less than 10 uA. Usually the faster the op-amp the more power it requires

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, $10 \sin 2 \pi$ 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 \times 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.