EE40 – Amplifiers

Reading Material:

Chapter 4

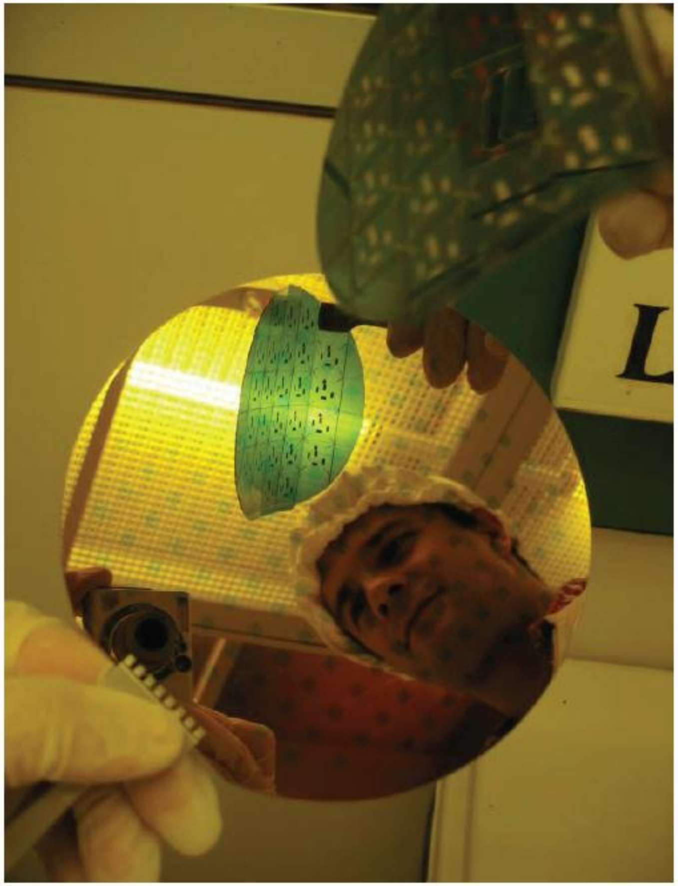
Tech Brief : IC Fabrication

Wafer: Thin slice of semiconductor material with highly polished surface

Processed wafer is cut into many dies or chips.

Lithography: Defining spatial pattern

Photoresist: Polymer material that does not allow etching or deposition of areas underneath it.



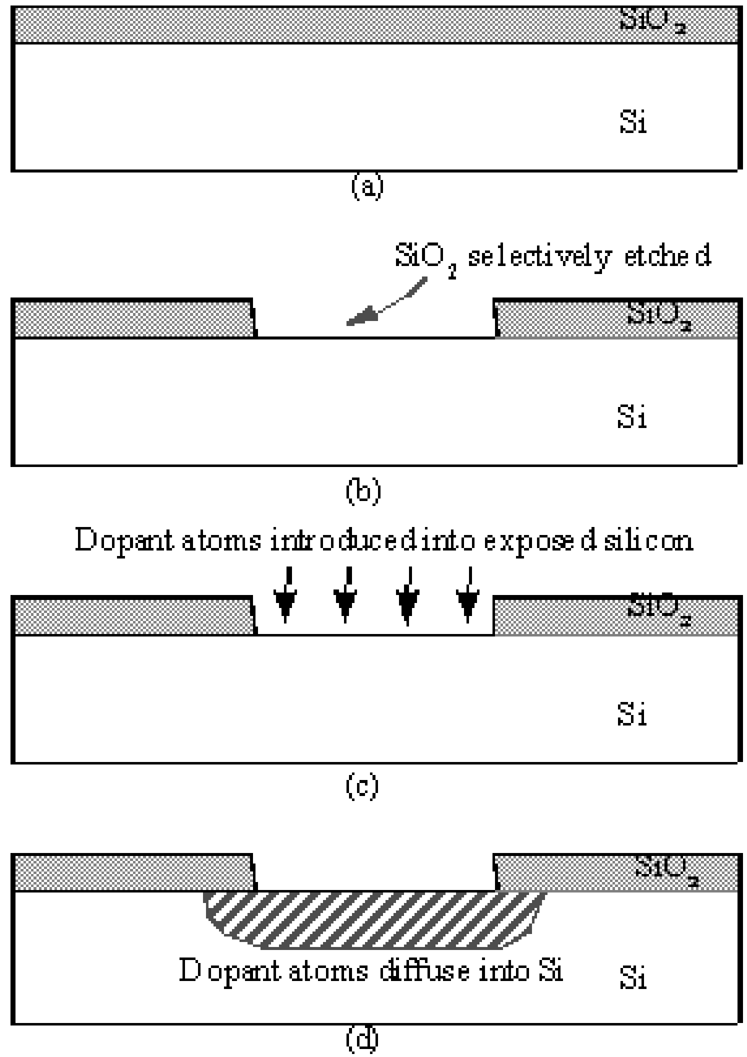
Introduction to Device Fabrication

Oxidation

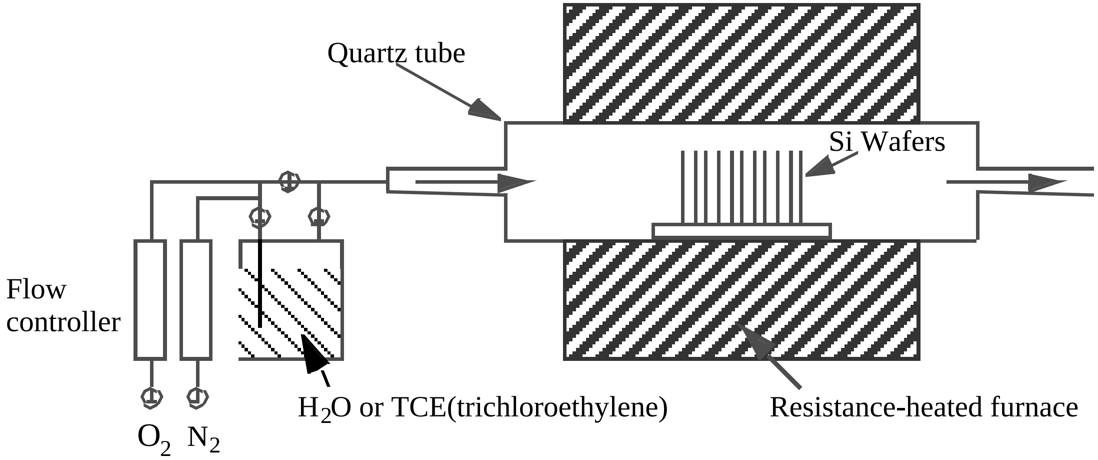
Lithography &
Etching

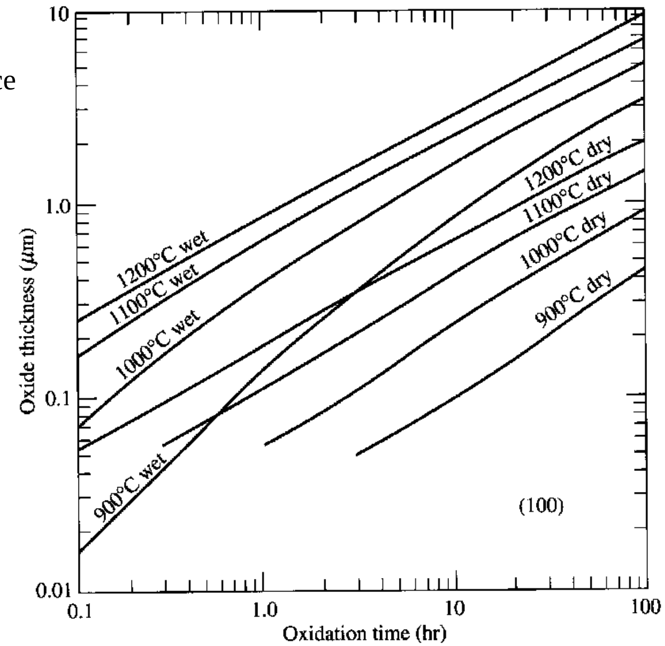
Ion Implantation

Annealing &
Diffusion



Oxidation of Silicon

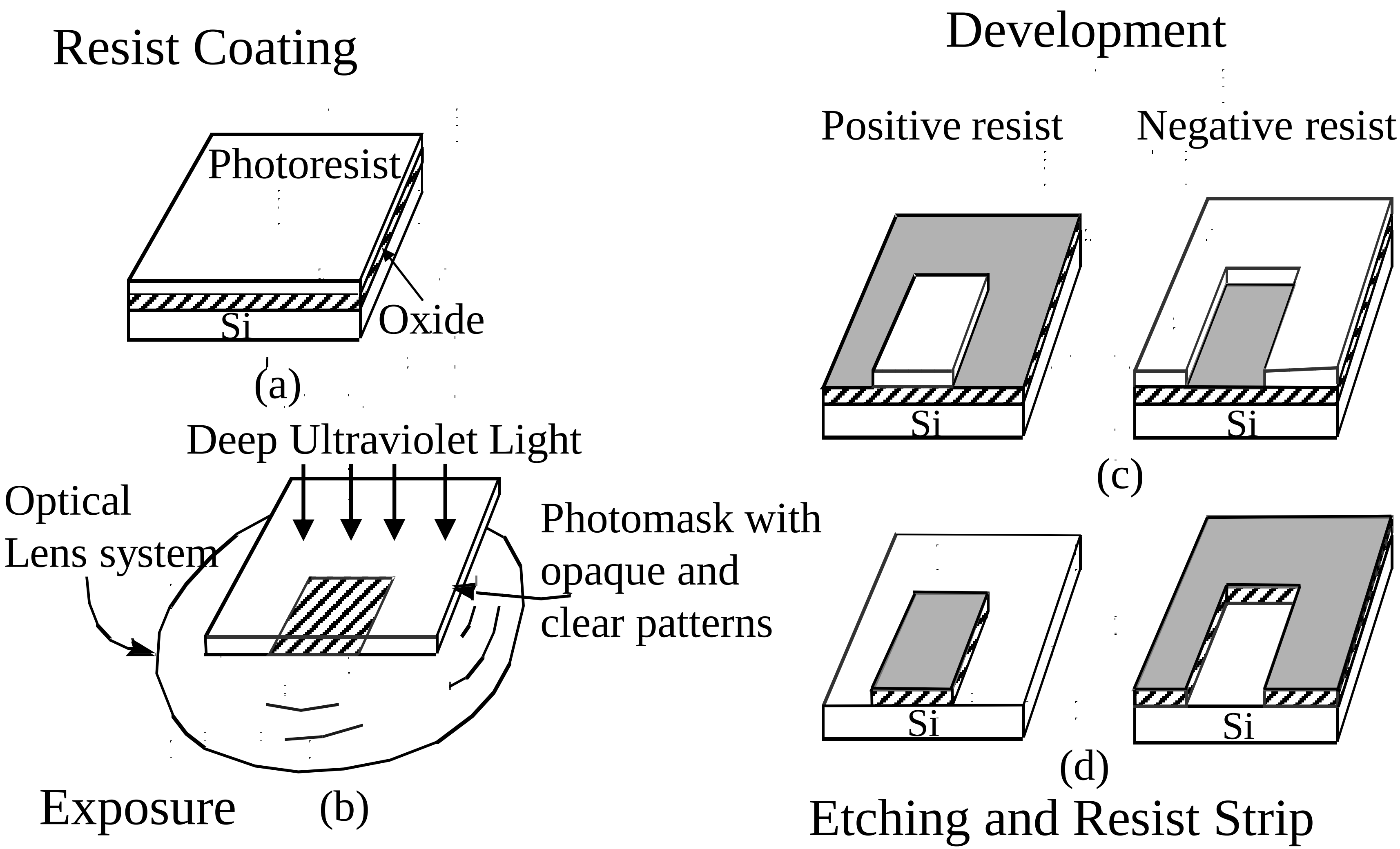




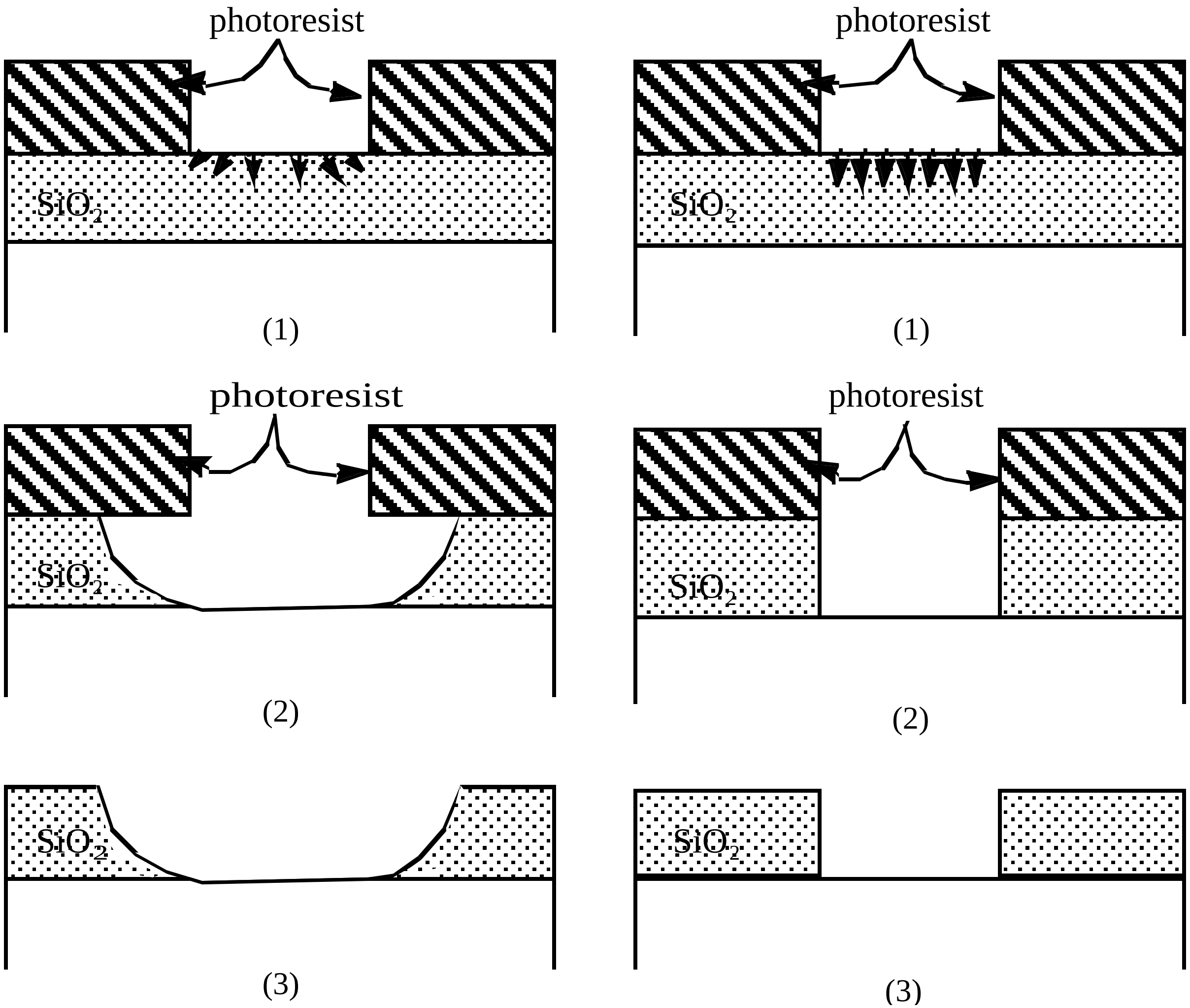
Dry Oxidation : $Si + O_2 \rightarrow SiO_2$

Wet Oxidation : $Si + 2H_2O \rightarrow SiO_2 + 2H_2$

Lithography

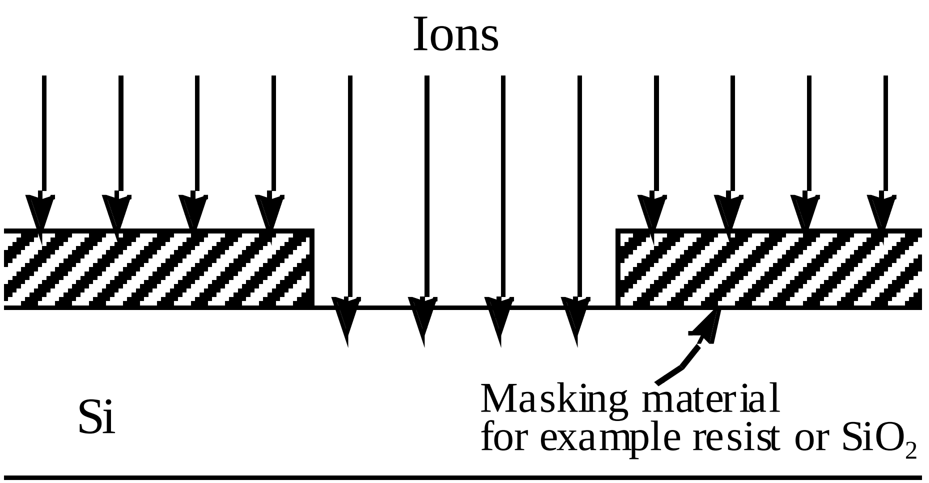


Pattern Transfer–Etching



Isotropic etching **Anisotropic etching**

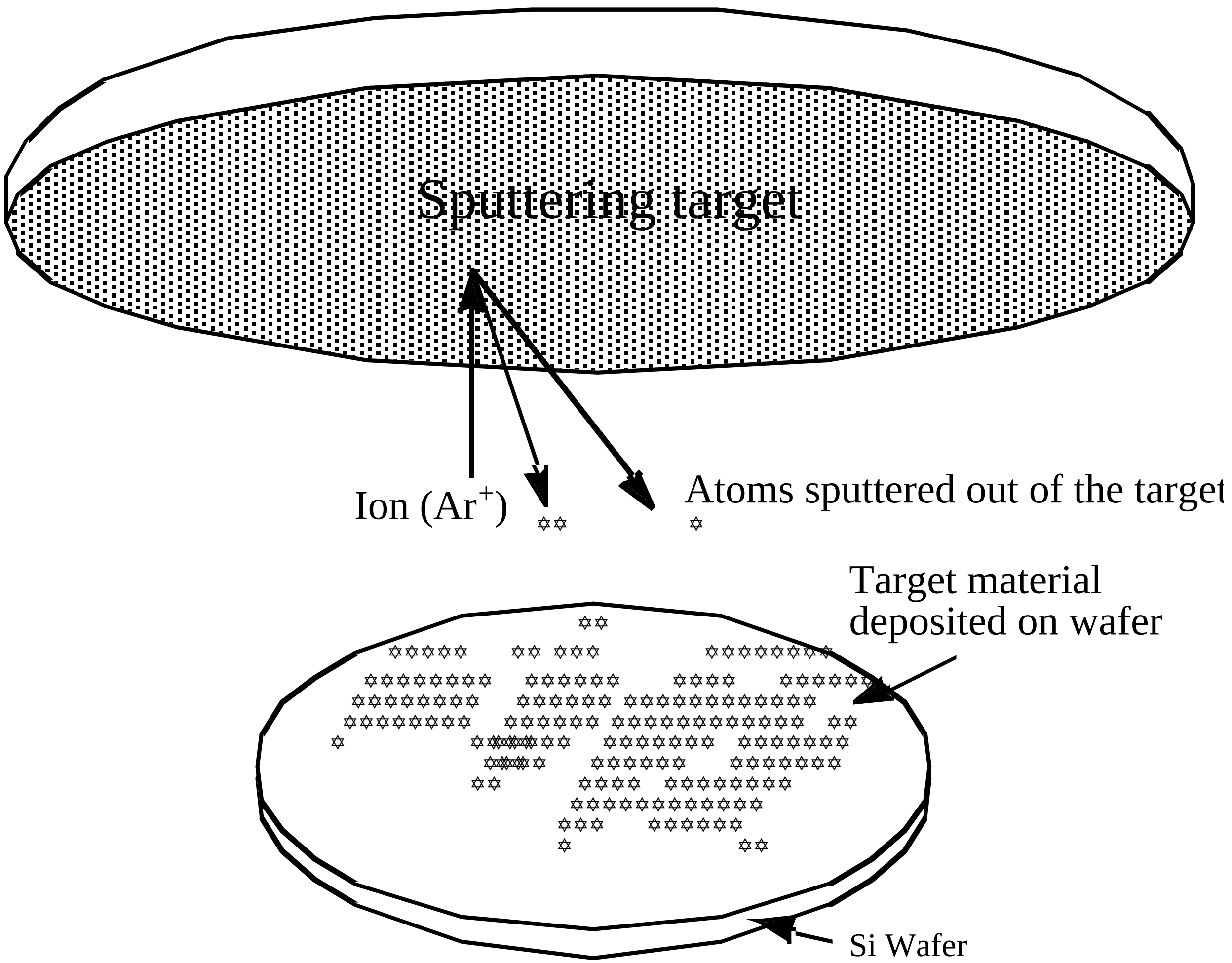
Doping - Ion Implantation



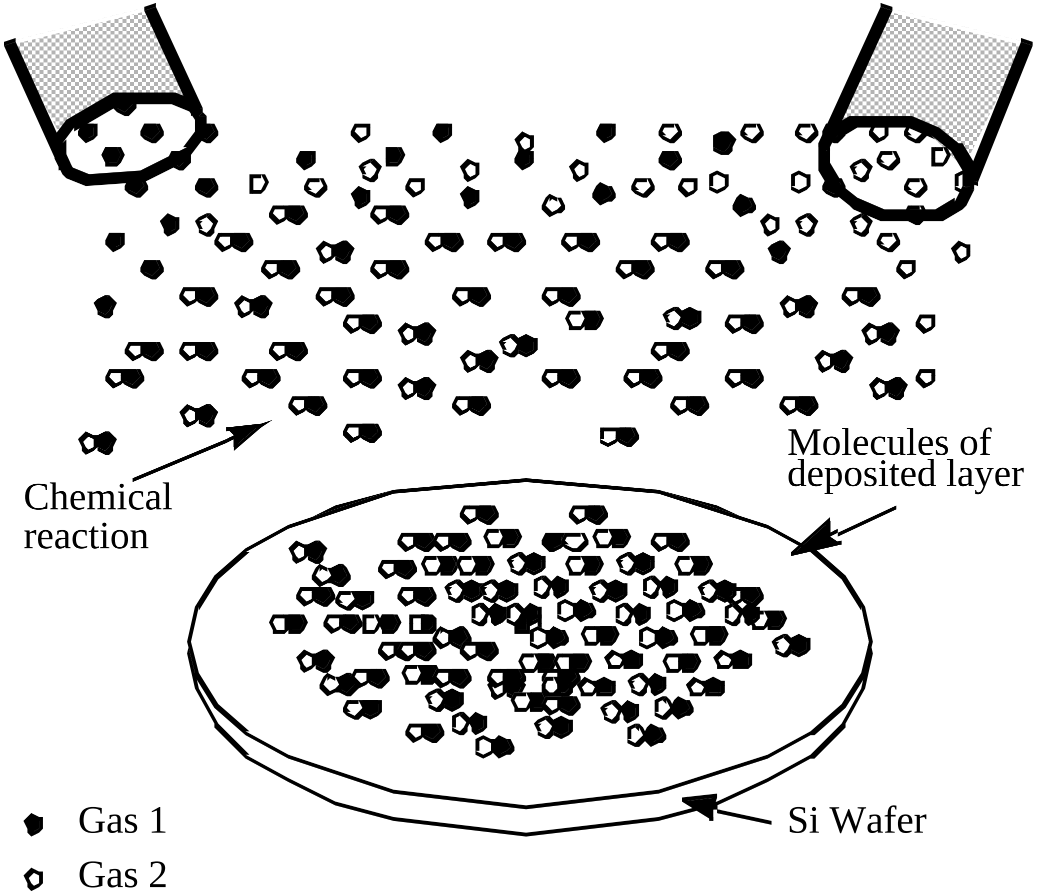
- The dominant doping method
- Excellent control of **dose** (cm^{-2})
- Good control of implant depth with energy (KeV to MeV)
- Crystal damage and need for activation anneal. Requires control of dopant diffusion.

Sputtering

Schematic Illustration of Sputtering Process

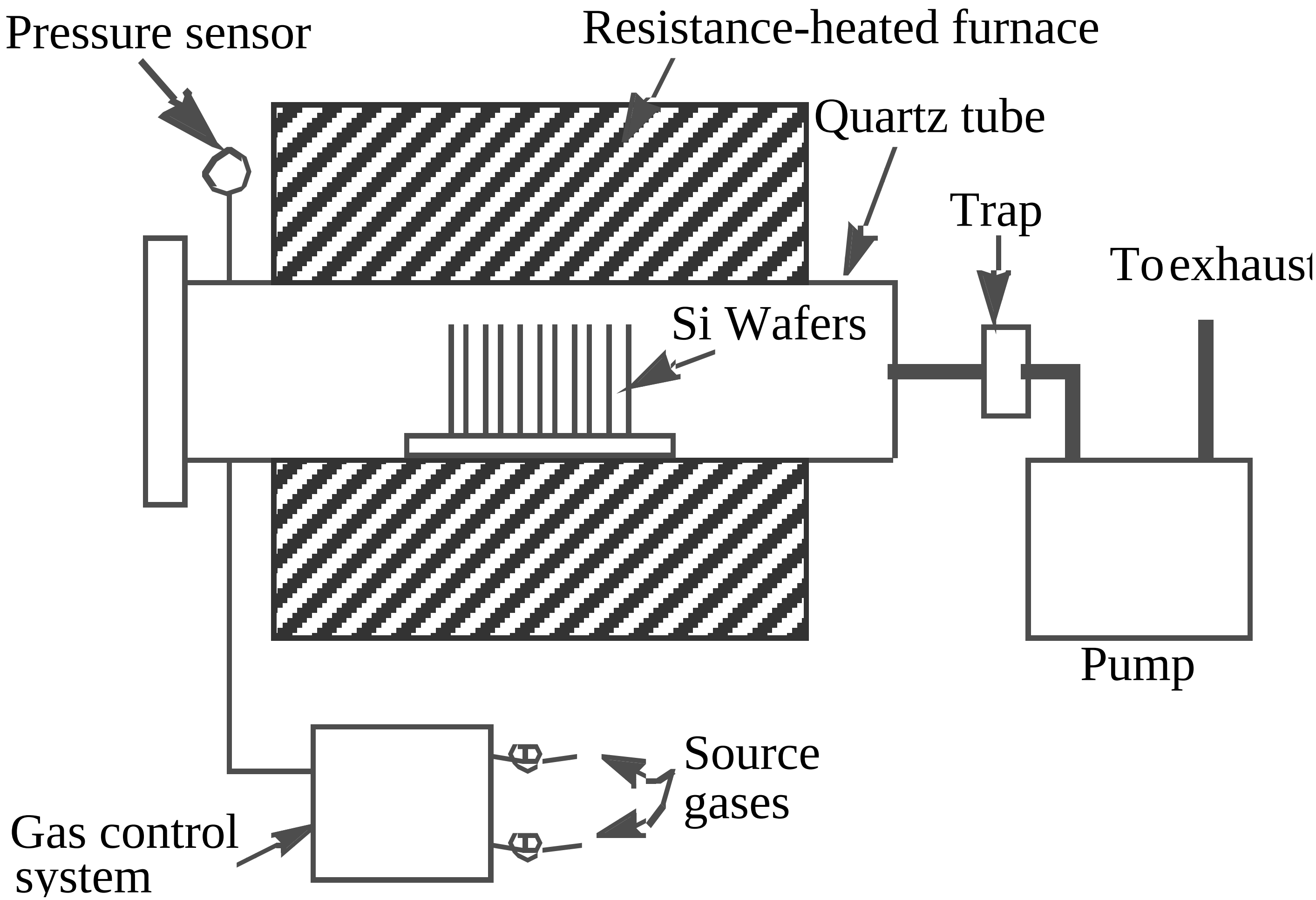


Chemical Vapor Deposition (CVD)



Thin film is formed from gas phase components.

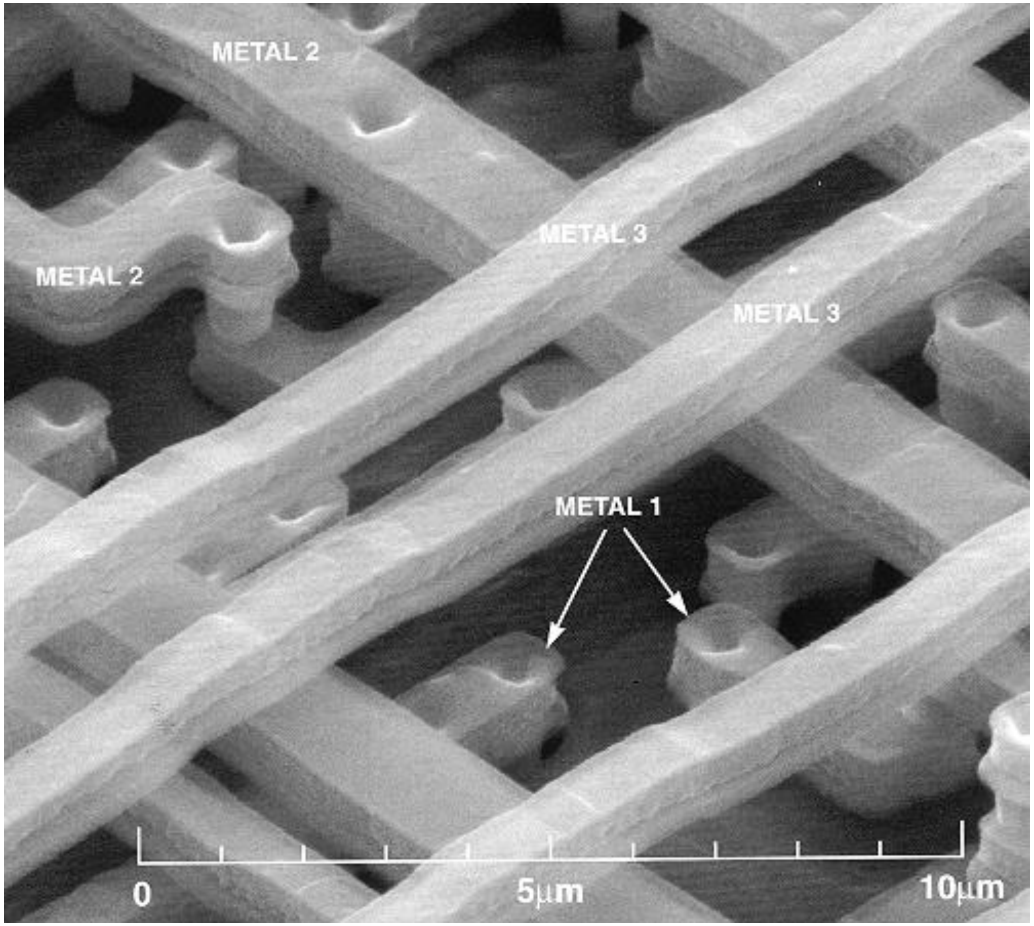
Chemical Vapor Deposition (CVD)



LPCVD Systems

Interconnection–The Back-end Process

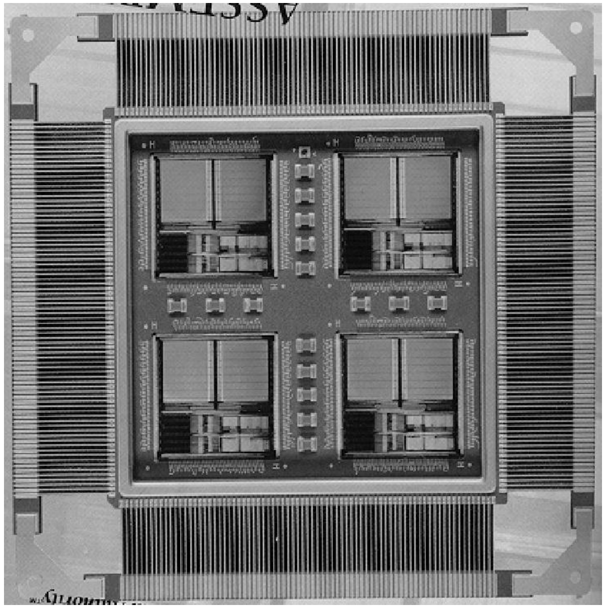
Multi-Level Metallization



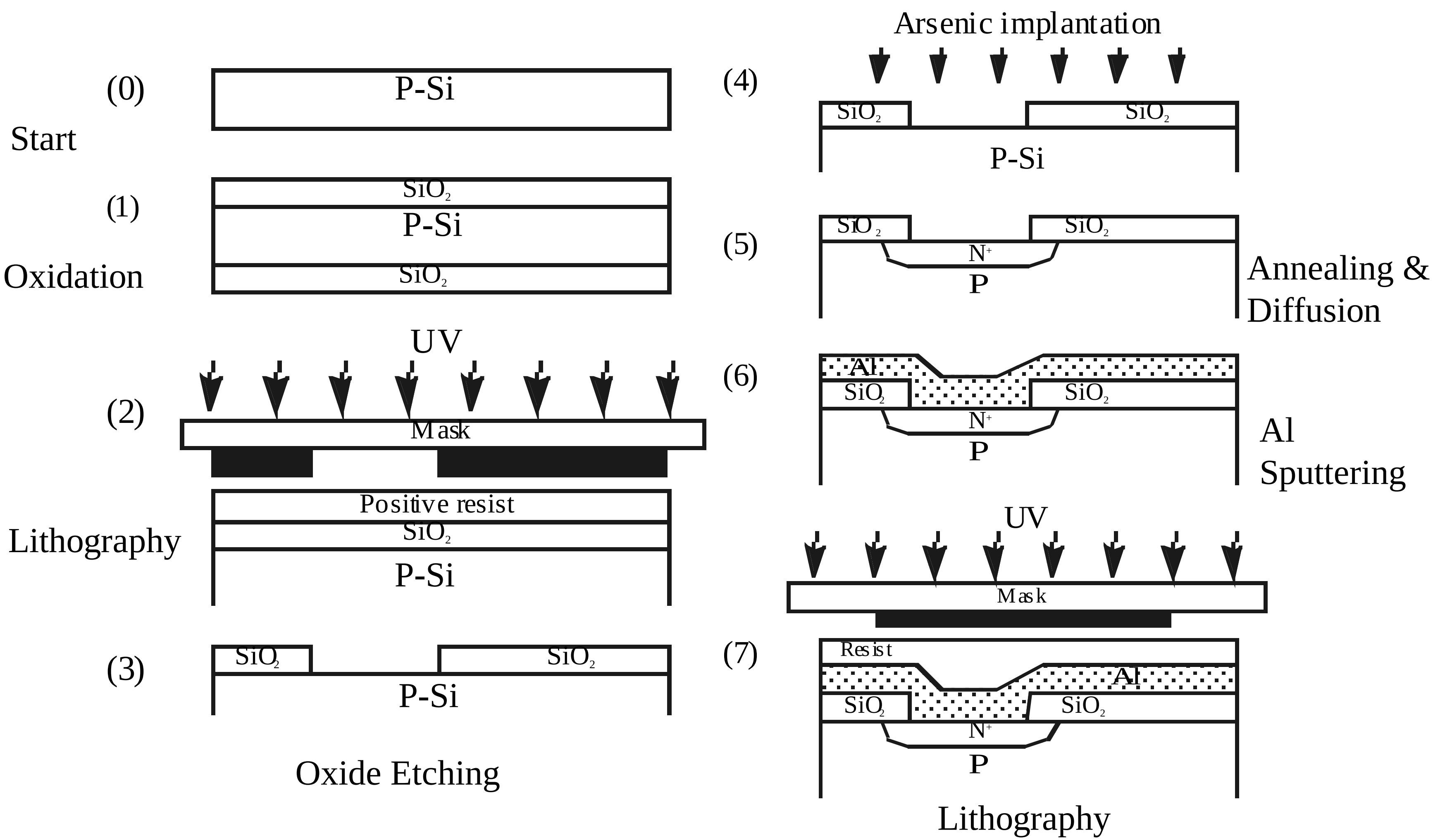
Sun Microsystems Ultra Sparc Microprocessor

Testing, Assembly, and Qualification

- Wafer acceptance test
- Die sorting
- Wafer sawing or cutting
- Packaging
- Flip-chip solder bump technology
- Multi-chip modules
- Burn-in
- Final test
- Qualification

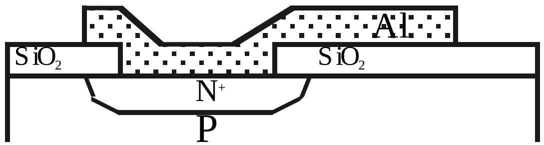


A Device Fabrication Example

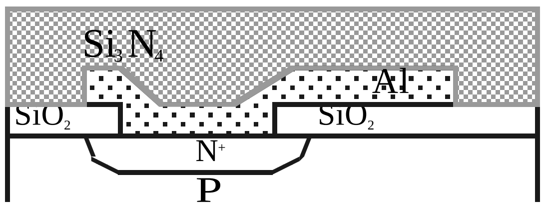


A Device Fabrication Example

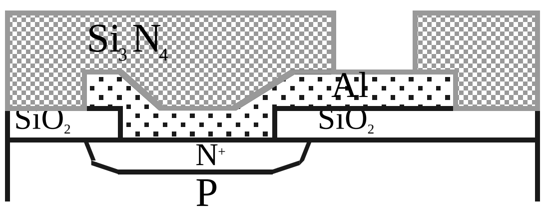
Metal etching (8)



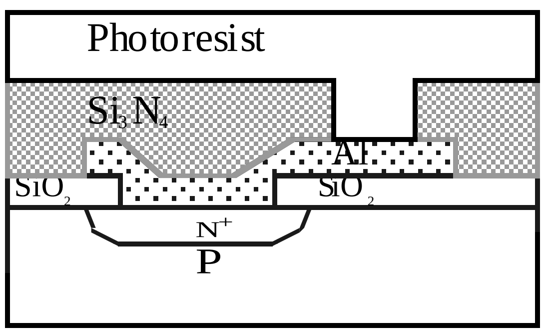
CVD nitride deposition (9)



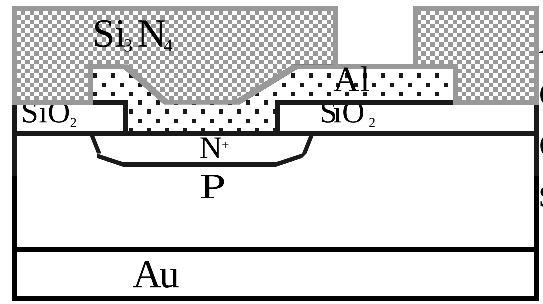
(10) Lithography and bonding window etching



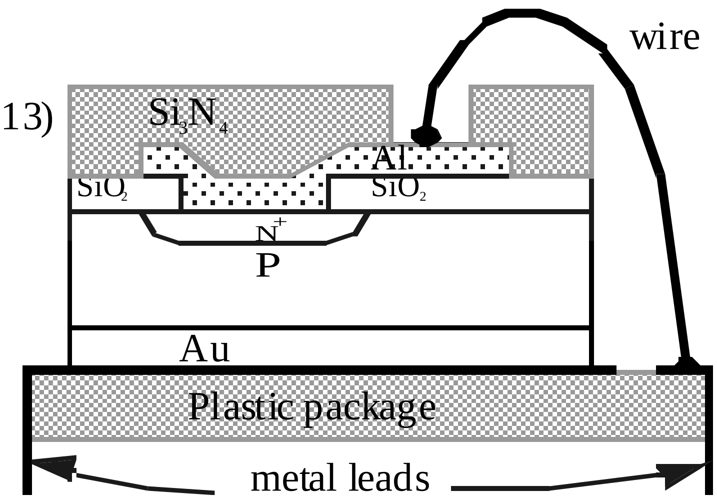
(11) Back Side milling



(12) Au deposition on the back side

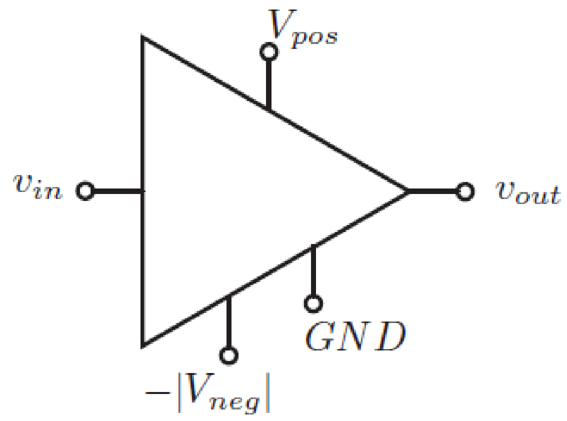


(13)



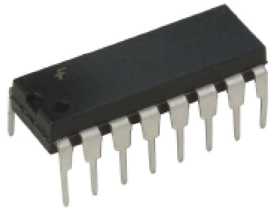
Dicing, wire bonding, and packaging

Amplifiers

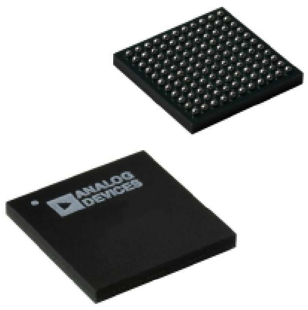


- An amplifier is a multi-terminal element. It usually has an input terminal, an output terminal, both referenced to a common reference (ground), which is supplied through another terminal, labeled V_{ref}, GND.
- There is also a positive supply terminal, labeled V_{pos}, V_{supply}, or V_{CC}, or V_{DD}. In some cases, the amplifier has a negative supply terminal, labeled as V_{neg}, V_{SS} or V_{EE}. The supplies are also known as the rails of an amplifier.
- Inside, the amplifier is constructed with various devices such as resistors, capacitors, and transistors. Sometimes inductors and transformers also appear inside, especially in high frequency amplifiers.

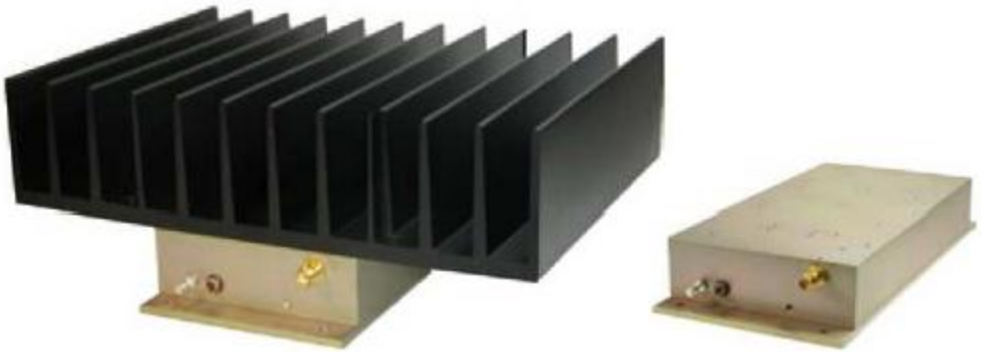
Amplifier Packaging



- Depending on the frequency of operation, different packaging options are available for the amplifier. Often a DIP (dual in-line package) is used to package integrated circuit amplifiers. Inside the package an integrated circuit die is wire-bonded to the package leads.
- For larger number of pins, pin grid array (PGA) or plastic quad flat packages (PQFP) are used. Ball grid array (BGA) can be surface mounted using solder balls.

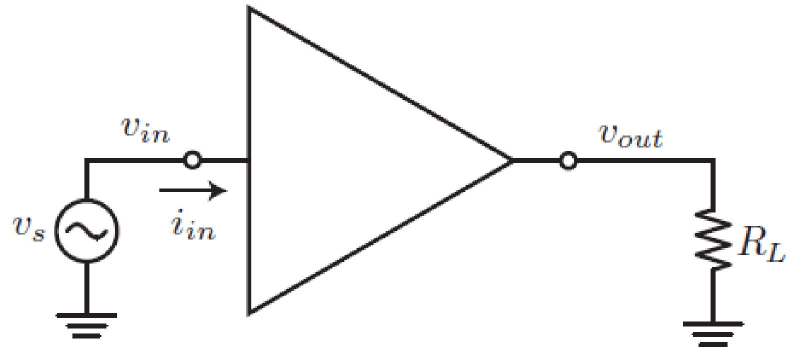


Amplifier Modules



- High frequency amplifiers and precision amplifiers are often packaged using a metal housing to limit the amount of interference in the package.
- Often co-axial cables are used to deliver the input and output signals. Coaxial cables use a ground shield that is effective against noise pickup.
- High power amplifiers have heat sinks to keep the temperature cool.

Real Voltage Amplifier



- A real voltage amplifier has three important imperfections. First, the input current is non-zero, which means it has finite power gain. This input current also leads to a loading effect, because the input of the amplifier is now smaller than the source voltage is the source has any resistance.
- Likewise, the output of the amplifier will vary if the loading at the output varies. This means that the output can only faithfully amplify a range of load resistances.
- The output voltage is also limited in range. Typically it cannot exceed the positive/negative supply rails.

Input Resistance

- The input current can be modeled by an input resistance. A test source is connected to the input terminals and the current flow at the input terminal is modeled by a Thevenin equivalent resistance

$$R_{in} = \frac{v_{in}}{i_{in}}$$

- When a voltage supply with source resistance R_s is connected at the input, the actual input voltage is reduced by the voltage divider formula

$$v_{in} = \frac{R_{in}}{R_{in} + R_s} v_s$$

- which means the performance is the most ideal with $R_{in} \to \infty \Omega$ or in practice, $R_{in} \gg R_s$.

Output Resistance

- Since the output voltage varies depending on the load connected at the output, the output terminal have an equivalent Thevenin resistance at the output terminals.
- To find this resistance, we can take the ratio of the open circuit voltage to the short circuit current, or connect a voltage (current) source and monitor the output current (voltage)

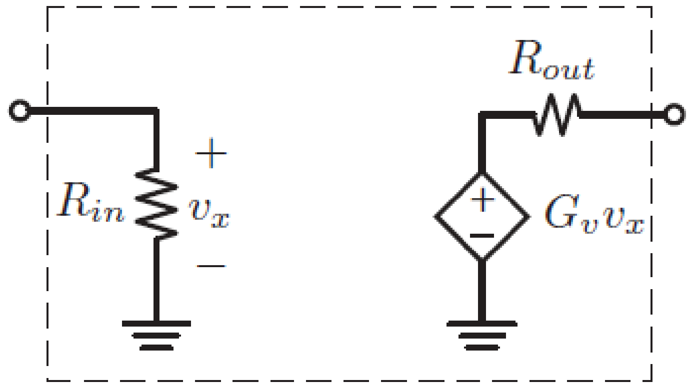
$$R_{out} = \frac{v_{out}}{i_{out}}$$

- When a load is connected to the output, the actual load voltage is reduced by the "loading" effect

$$v_L = \frac{R_L}{R_L + R_{out}} v_{th}$$

- Do we desire a high or low output resistance? Why?

Equivalent Circuit Model

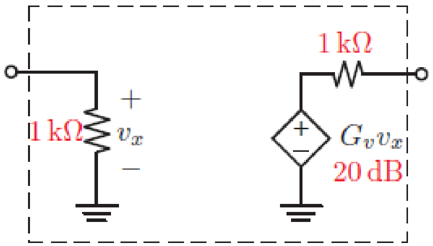


- The complete equivalent circuit model for a voltage amplifier is shown above. The input and output resistance model the fact that the amplifier is subject to gain reduction due to the loading effects of a source/load resistance.
- The dependent source models the gain from the input to the output, but it's ideal because a real amplifier can only provide gain over a limited range (determined by the power supply voltages).

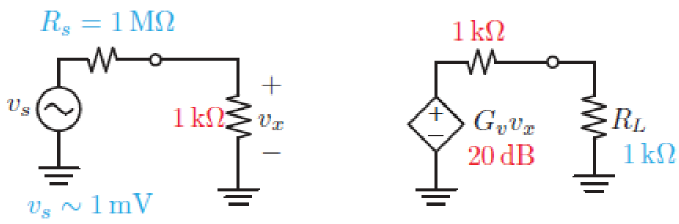
Example: Amplifying weak signals

- Suppose that we wish to amplify a weak signal, on the order of 1mV, to a range appropriate for digitization. Suppose the signal originates from a sensor (such as an ECG electrode) with higher source resistance, say $1\,\mathrm{M}\Omega$.
- The digitizer is an analog-to-digital converter (ADC), which takes an analog input voltage and produces a digital representation of the voltage, which can be stored using digital memory.
- The ADC usually can only amplify signals larger than a certain range. In this examples, the range of the ADC is given by $1\,\mathrm{mV} < V_{in} < 1\,\mathrm{V}$. Also, the ADC has an input resistance of $1\,\mathrm{k}\Omega$.
- We select the following amplifier to perform this job

$$A_v = 20\,\mathrm{dB}, R_{in} = 1\,\mathrm{k}\Omega, R_{out} = 1\,\mathrm{k}\Omega$$



Example: Amplifying weak signals



- Because of the loading effects, the actual gain of the amplifier is going to be lower. By how much?

$$A_{eff} = \frac{R_{in}}{R_{in} + R_s} A_v \frac{R_{out}}{R_{out} + R_L}$$

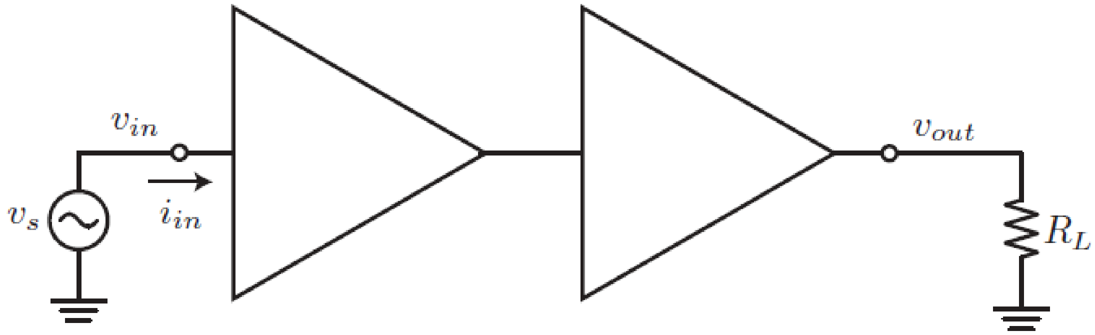
- In this example, R_s is much larger than the input resistance R_{in} of the amplifier, which results in significant loading

$$A_{eff} = \frac{10^3}{10^6 + 10^3} \cdot 10 \cdot \frac{10^3}{10^3 + 10^3}$$

$$\approx \frac{10^3}{10^6} \cdot 10 \cdot \frac{1}{2} = 5 \times 10^{-3}$$

- The gain is now in less than 1, which is exactly opposite of what we're trying to do. To solve this problem, we need a buffer (next lecture) or an amplifier with a higher input resistance.

Example: Amplifying weak signals



- When several ideal amplifiers are placed in cascade, the gain increases, as you might expect

$$A_v = A_{v,1} \cdot A_{v,2} \cdots$$

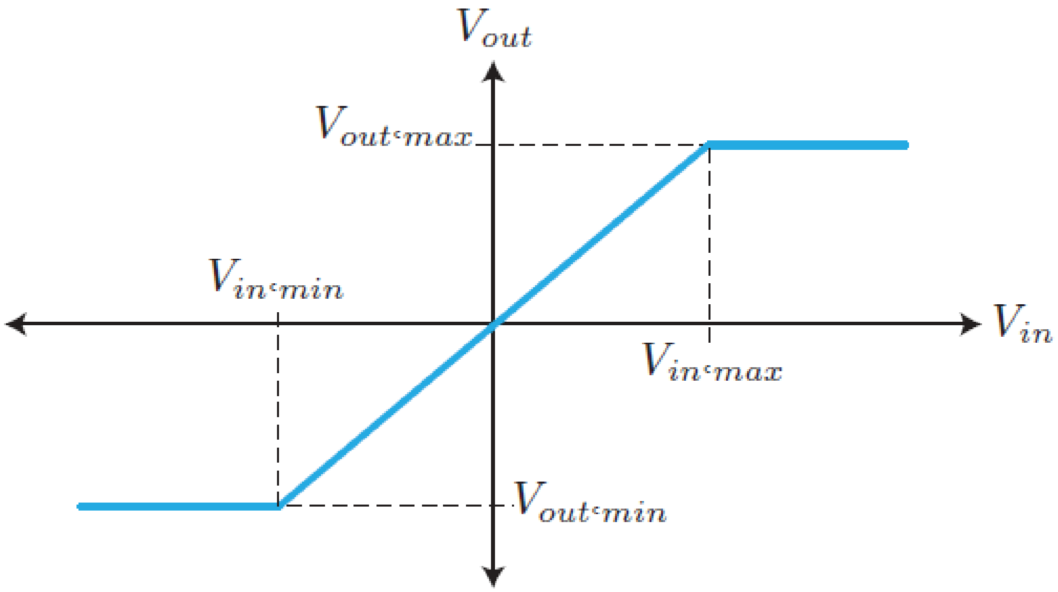
- When real amplifiers are cascaded, we have to take loading effects into account. For instance, for the cascade of the two amplifiers from the previous example, we can derive a new amplifier equivalent circuit model

$$R_{in} = R_{out} = 1\,\mathrm{k}\Omega$$

but

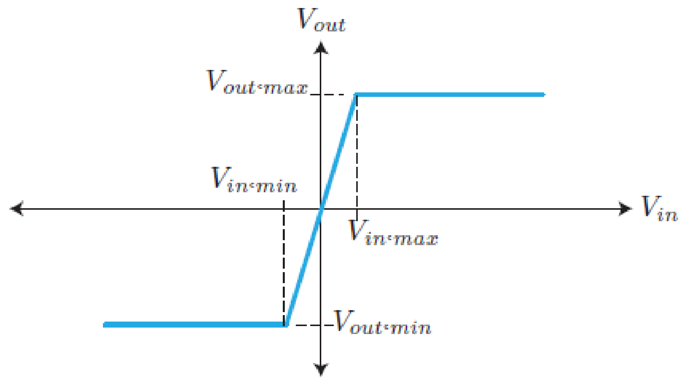
$$A_v = \frac{1}{2} A_{v,1} A_{v,2} = 50$$

Dynamic Range



- Because of the limited output range of the amplifier, the input-output curves saturate (usually at a voltage lower or equal to the supply rails).
- This means that the input voltage cannot exceed a certain range before the amplifier behavior becomes non-linear.

Dynamic Range



- The maximum input signal that we can apply to the amplifier is thus related to the supply voltage and the gain of the amplifier

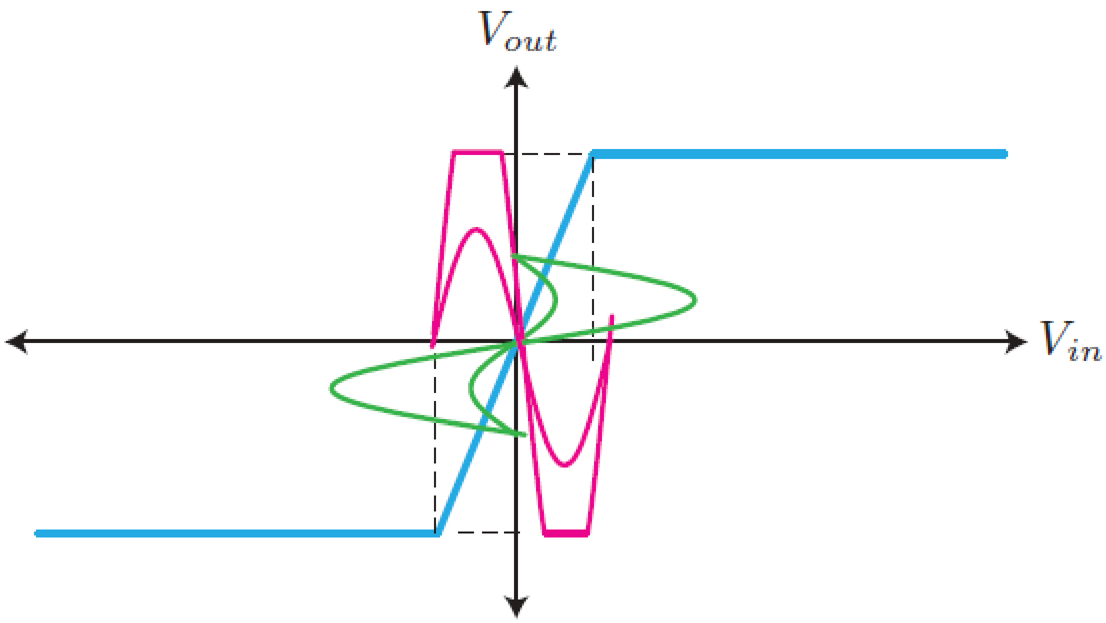
$$v_{in,max} \leq \frac{V_{sup}}{G_v}$$

- Similarly, the smallest input has to be larger than

$$v_{in,min} \geq \frac{-V_{sup}}{G_v}$$

- For a high gain amplifier, this is a very limited input range. Unless the supply voltage can be increased (limited by technology), the output dynamic range is fixed.

Clipping



- When the input signal goes beyond the linear range, the output can exhibit clipping, which is very non-linear.

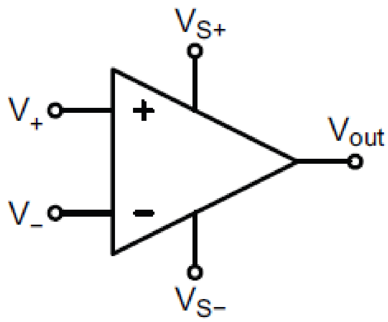
Distortion

- When the input range even approaches the linear input range, the amplifier behavior becomes much more non-linear. All real amplifiers are non-linear and the input / output relationship can be modeled by a Taylor series (for small signals)

$$v_{out} = a_1 v_i n + a_2 v_{in}^2 + \cdots$$

- This non-linearity produces *distortion* int he signal, which can change the signal enough to make the system operation poor or unacceptable. Audio applications are a commonly known example.

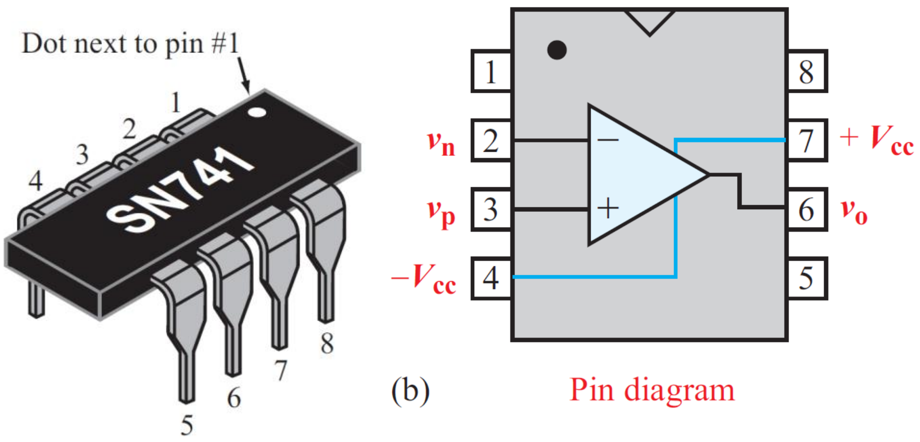
Operational Amplifiers

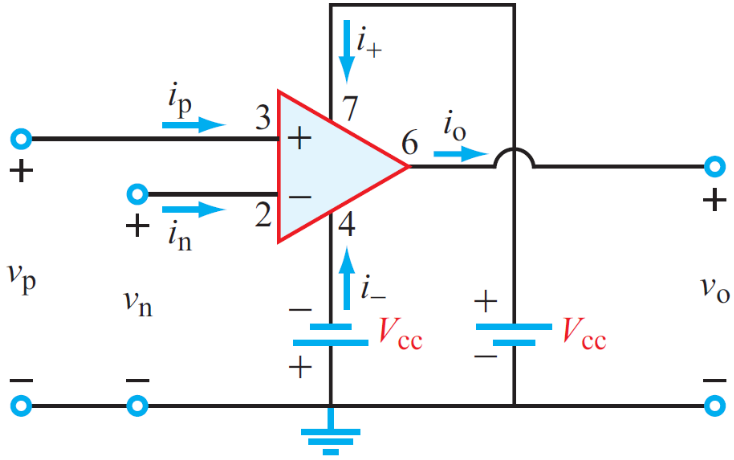


- Invented in 1941by Bell Labs engineer Karl D. Swartzel Jr. using vacuum tubes. It found wide application in WW-II.
- First monolithic IC op-amp was designed by Bob Widlar at Fairchild Semiconductor.
- The 741 op-amp is perhaps the best known op-amp in the world. Many other op-amps use the same pin configuration as the 741.
- Commonly known as the op-amp, is a high gain amplifier with *differential input*.
- The output voltage is usually millions of times larger than the voltage presented at the inputs. The amplifier responds to a voltage difference between its input terminals, hence the term *differential*.
- Op-amps are ubiquitous low cost components used in countless applications for analog signal processing (gain, filtering, signal conditioning).

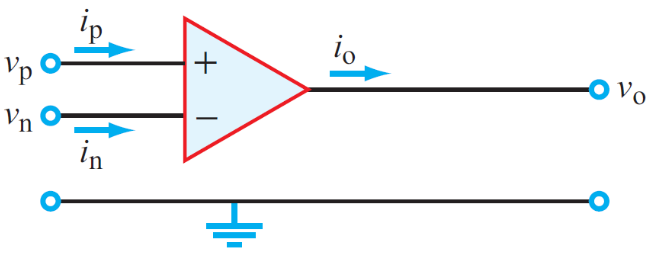
Operational Amplifier "Op Amp"

- Two input terminals, positive (non- inverting) and negative (inverting)
- One output
- Power supply $+V_{cc}$ and $-V_{cc}$

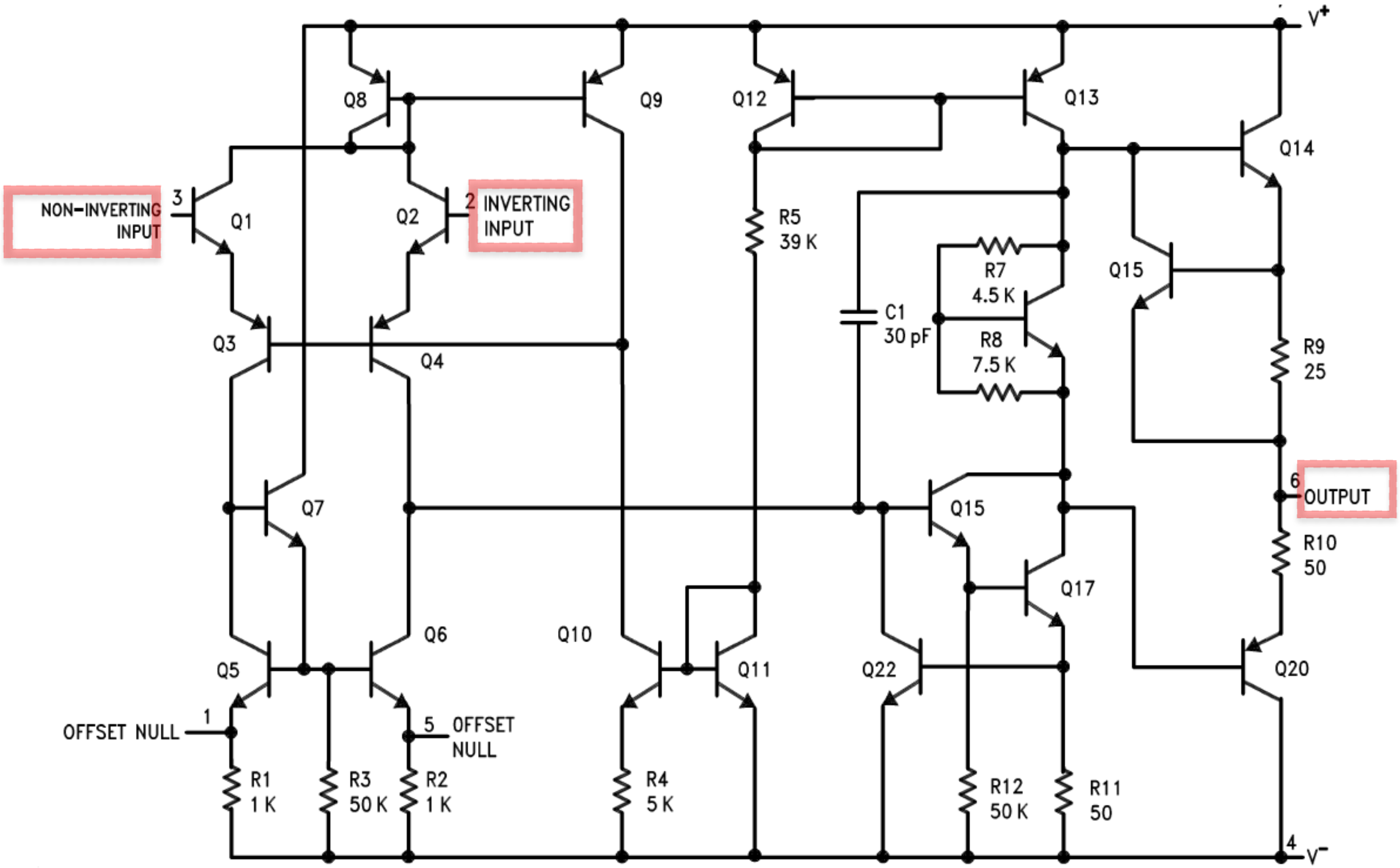




Op Amp with power supply not shown (which is how we usually display op amp circuits)



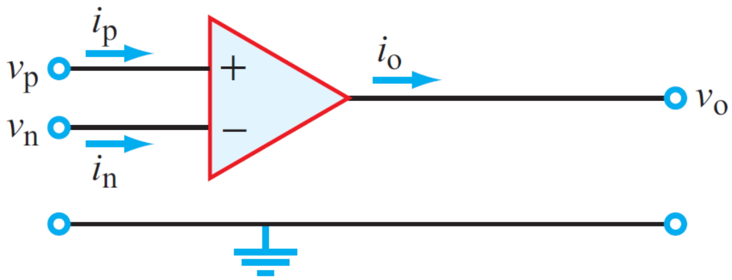
Inside The Op-Amp (741)

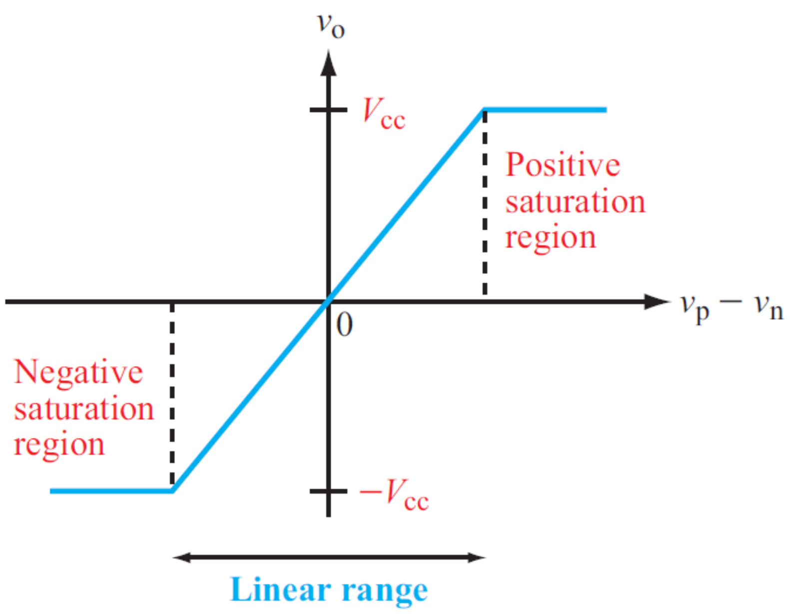


Gain of an Op Amp

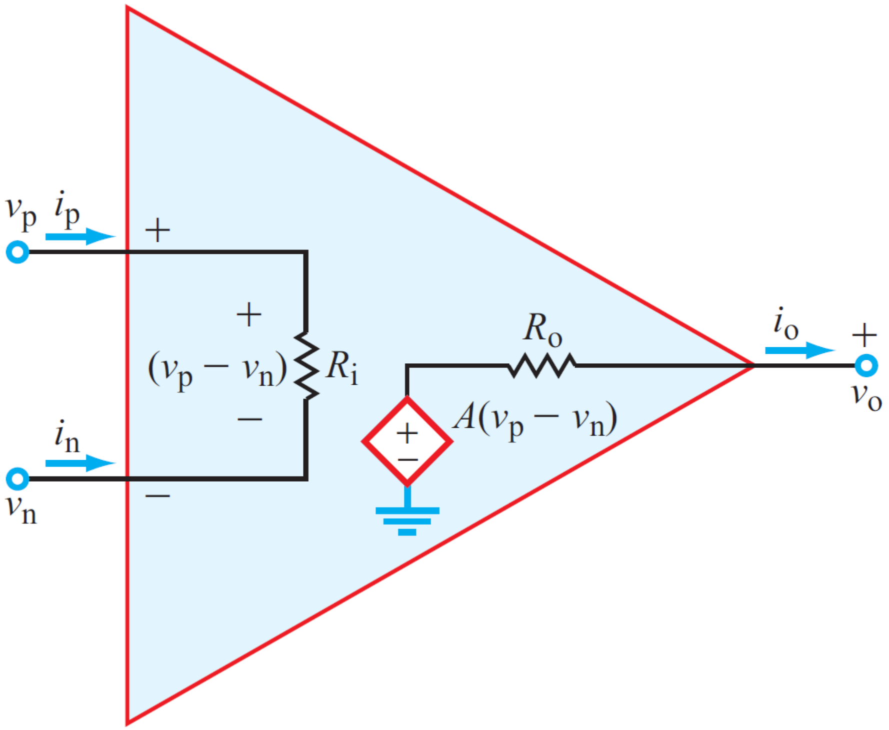
- Key important aspect of op amp: high voltage gain
- Output , A is op-amp gain (or open-loop gain) – different from circuit gain *G*
- Linear response

$$v_o = A(v_p - v_n)$$



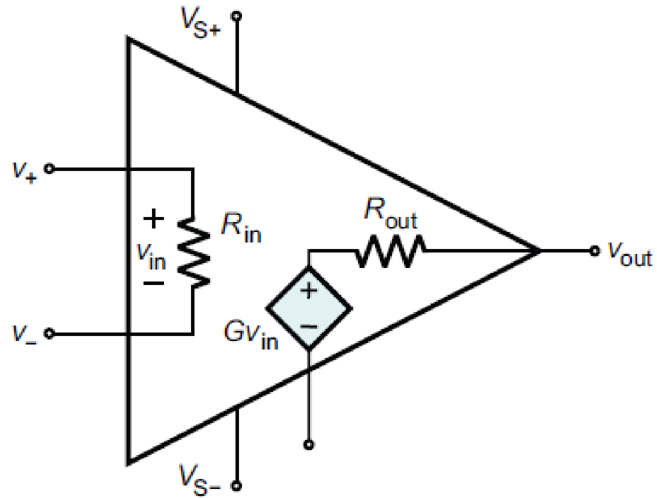


Equivalent Circuit



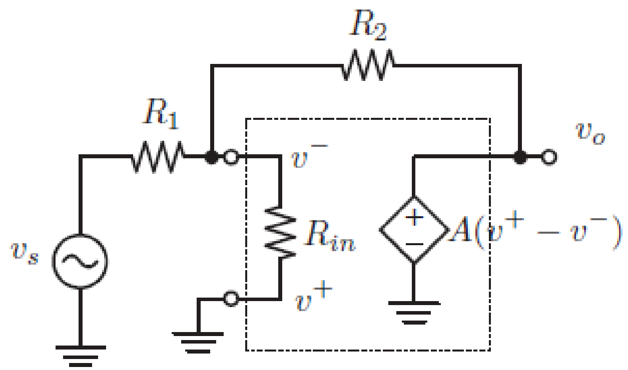
Op-Amp Characteristics	Parameter	Typical Range	Ideal Op Amp
• Linear input–output response	Open-loop gain A	10^4 to 10^8 (V/V)	∞
• High input resistance	Input resistance R_i	10^6 to 10^{13} Ω	∞ Ω
• Low output resistance	Output resistance R_o	1 to 100 Ω	0 Ω
• Very high gain	Supply voltage V_{cc}	5 to 24 V	As specified by manufacturer

But how should we use an Op Amp?



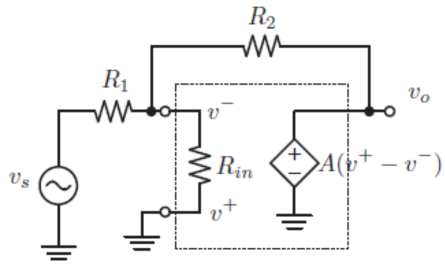
- We model the complex op-amp by using the simple equivalent circuit shown above. The most salient features are the high gain G (tyipcally a million or more), very high input resistance R_{in}, and low output resistance R_{out}.
- Because of the large gain, only a few microvolts of input signal is required to saturate the op-amp output. Thus the amplifier is very impractical if used without *feedback*. In fact, the gain of the op-amp is a very poorly controlled parameter, often varying wildly with temperature or from part-to-part. How do you design with such an imperfect component? *Feedback*.

Example: Feedback



- The above example shows a typical op-amp configuration where the output signal is fed-back to the negative input terminals. This is called negative feedback.
- This seems strange at first because we are subtracting the output from the input, but as we shall see, this is a self-regulation mechanism that results in a very precise amplifier.
- Write KCL at the input node of the amplifier

$$(v^- - v_o)G_2 + v^- G_{in} + (v^- - v_s)G_1 = 0$$



Example: Feedback

- But the output voltage in this case is simply given by $v_o = -Av^-$, where A is very large, which means that $v^- = -v_o/A$ is a very small voltage

$$\left(\frac{-v_o}{A} - v_o\right)G_2 + \frac{-v_o}{A}G_{in} + \left(\frac{-v_o}{A} - v_s\right)G_1 = 0$$

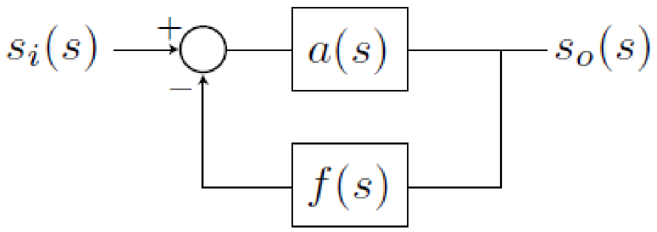
- which allows us to write the complete expression for gain

$$\frac{v_o}{v_s} = \frac{-AG_1}{G_2(A+1) + G_{in} + G_1}$$

- Assuming that the op-amp has a very large gain, the above equation simplifies

$$\frac{v_o}{v_s} \approx \frac{-AG_1}{G_2(A+1)} \approx \frac{-G_1}{G_2} = \frac{-R_2}{R_1}$$

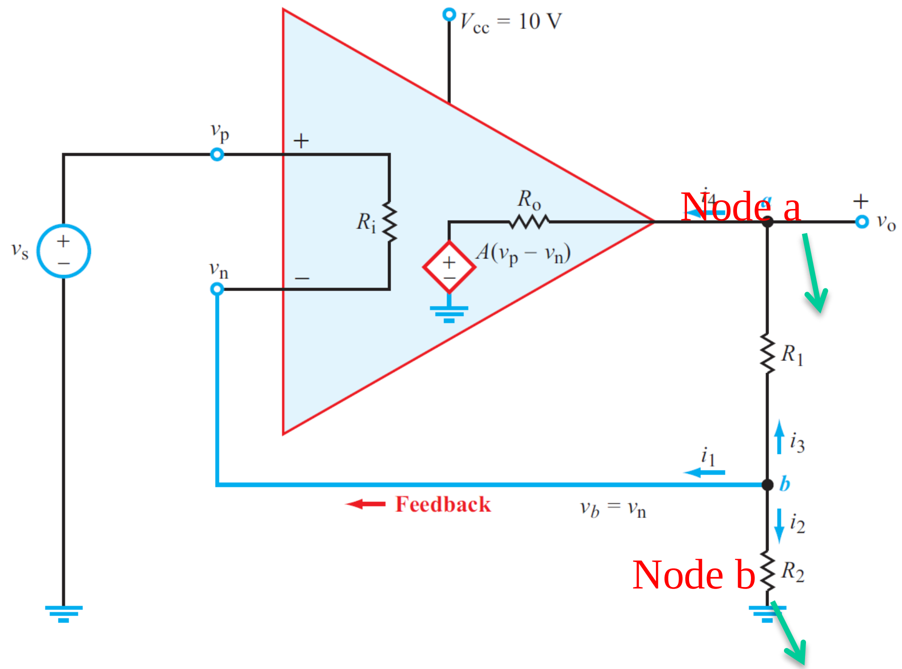
Advantages of feedback



- In the last result we have a nice result that the voltage gain of the overall circuit is just set by the ratio of two resistors, which can be made very precise and can track temperature.
- The internal gain of the amplifier A does not appear in the final expression, which means if it varies due to temperature or from part to part, it plays a negligible role in setting the gain.
- So we sacrificed gain to arrive at a solution that is much more robust. This is the concept of negative feedback and it is used widely in biological systems.
- The idea is to sample a fraction of the output and compare it to the input. By forcing equality between the sample and the fraction of the output, the gain is determined by the fraction rather than by the raw gain of the amplifier.
- Note that positive feedback is not used, since it has a saturating (rather than regulating) characteristic.

Example: Op Amp Amplifier

For $V_{cc} = 10$ V, $A = 10^6$, $R_i = 10^7$ Ω, $R_o = 10$ Ω, $R_1 = 80$ kΩ, and $R_2 = 20$ kΩ,

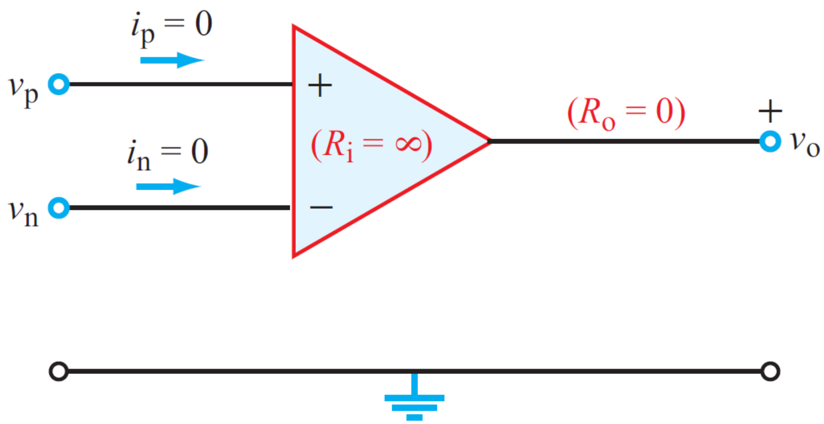


KCL at Node a:

KCL at Node b:

For infinite A:

Circuit Analysis With Ideal Op Amps

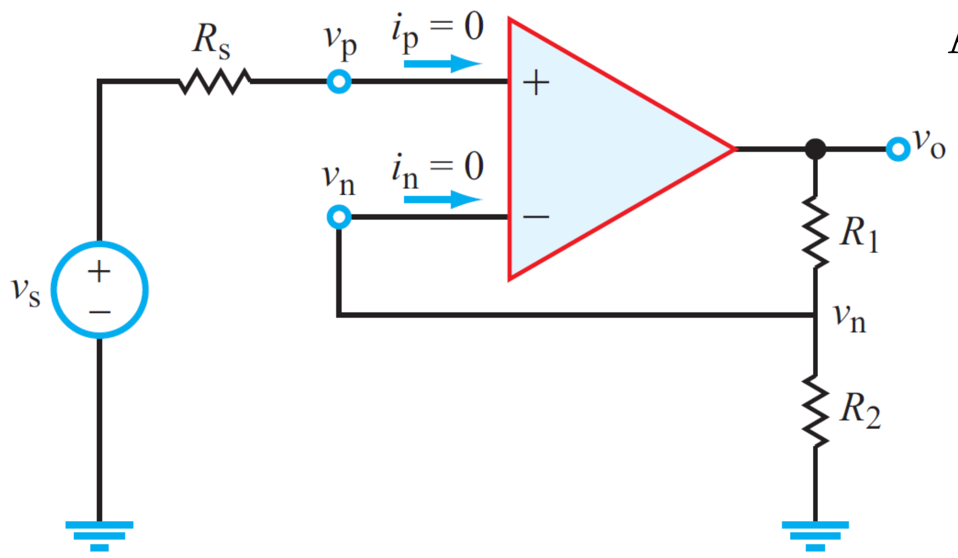


Ideal Op Amp

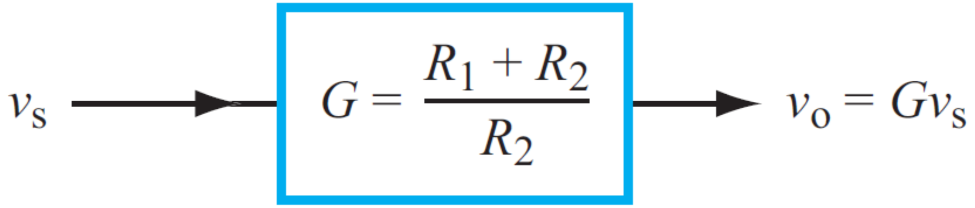
- Current constraint $i_p = i_n = 0$
- Voltage constraint $v_p = v_n$
- $A = \infty \quad R_i = \infty \quad R_o = 0$

- Use nodal analysis as before, but with "golden rules"
- $v_p = v_n$ (Ideal op-amp model). Both inputs are at the same voltage
- $i_p = i_n = 0$ (Ideal op-amp model). No current into op amp
- Do not apply KCL at op amp output

Non-inverting Amplifier

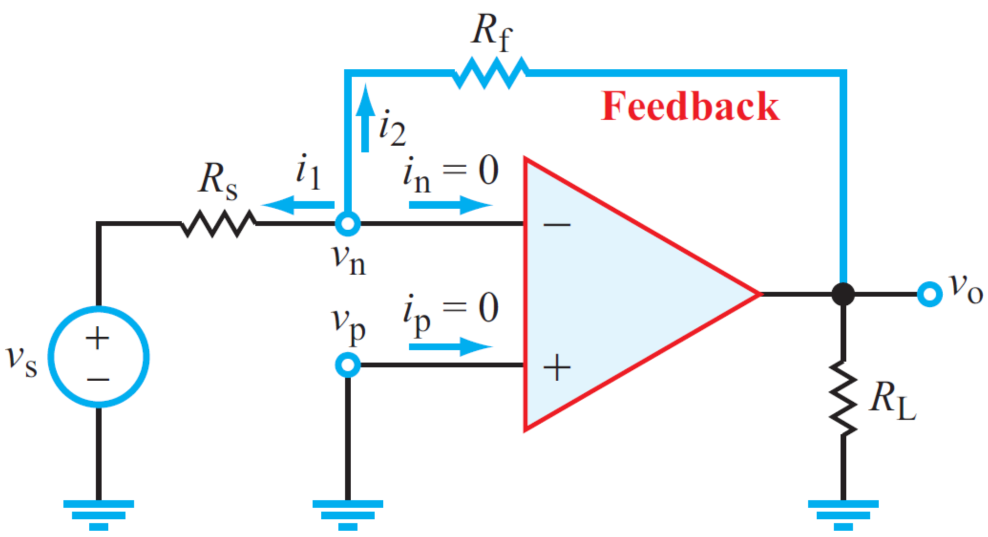


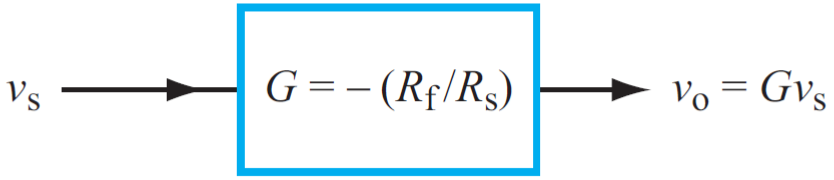
At node v_n



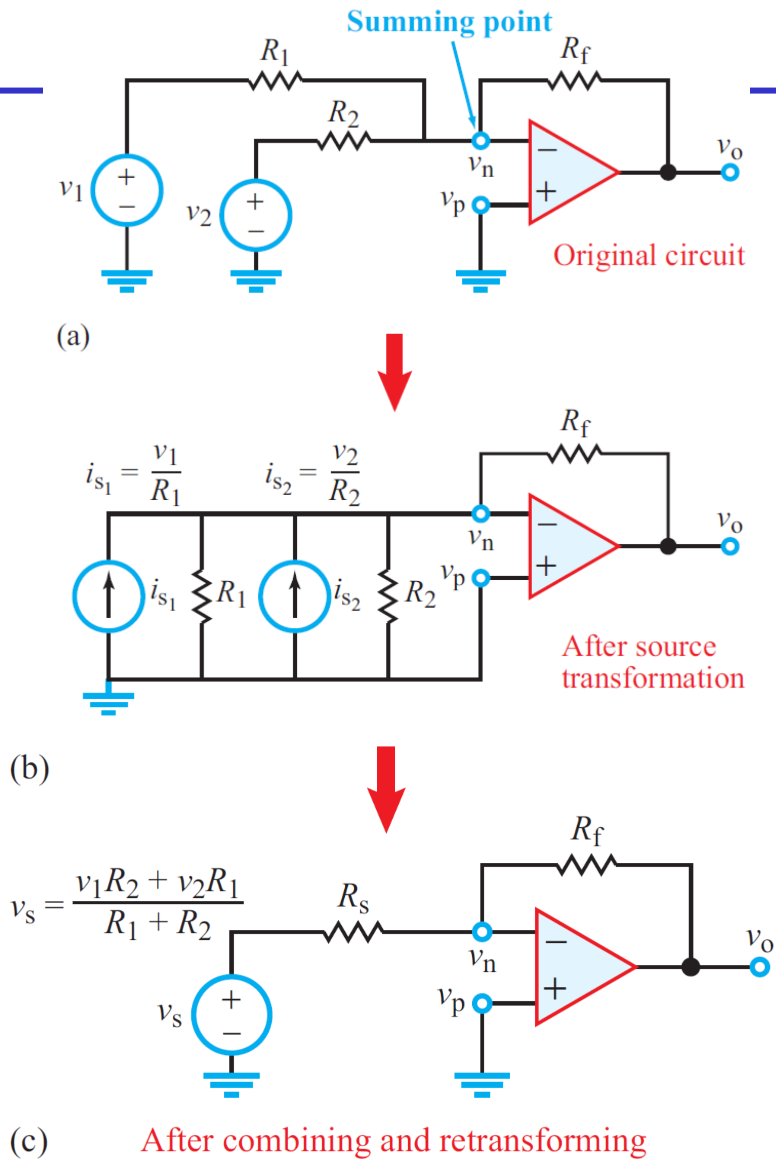
Inverting Amplifier

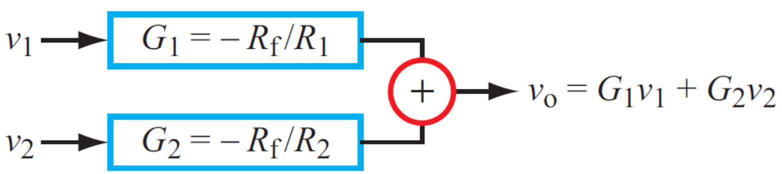
At node v_n



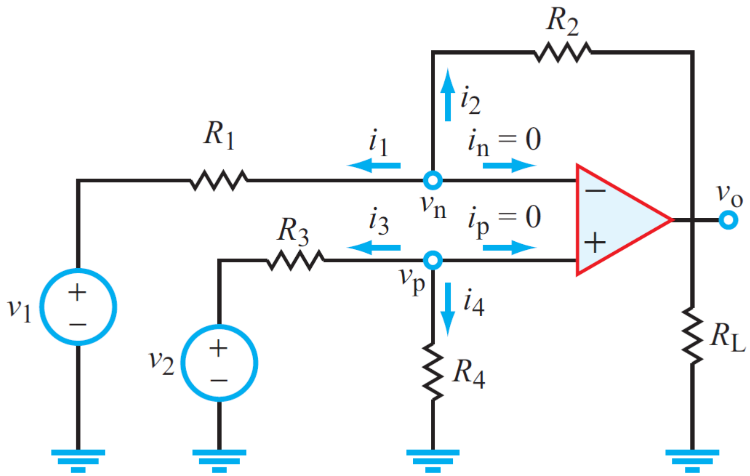


Summing Amplifier

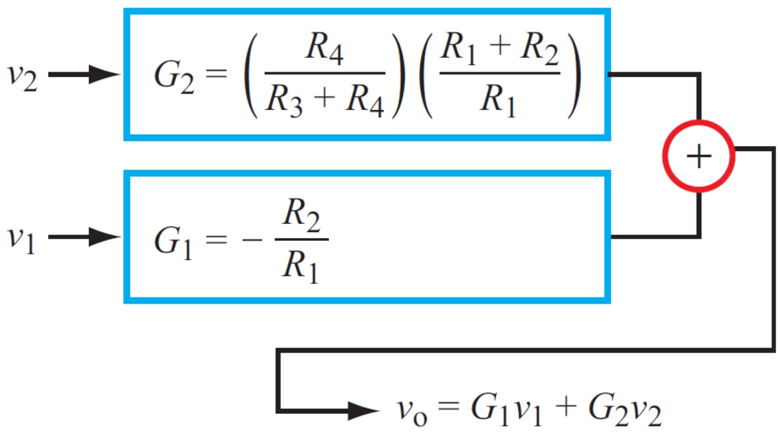




Difference Amplifier



At node v_n



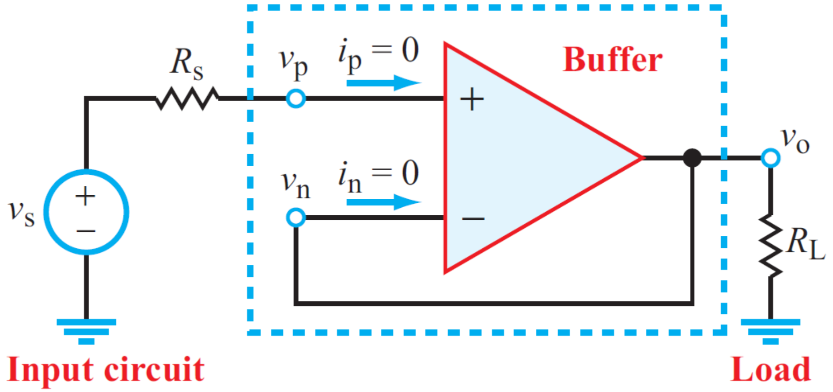
Note negative gain of channel 1

Voltage Follower

"Buffers" Sections of Circuit

$$v_o = \frac{v_s R_L}{R_s + R_L} \qquad \text{(without voltage follower)}$$

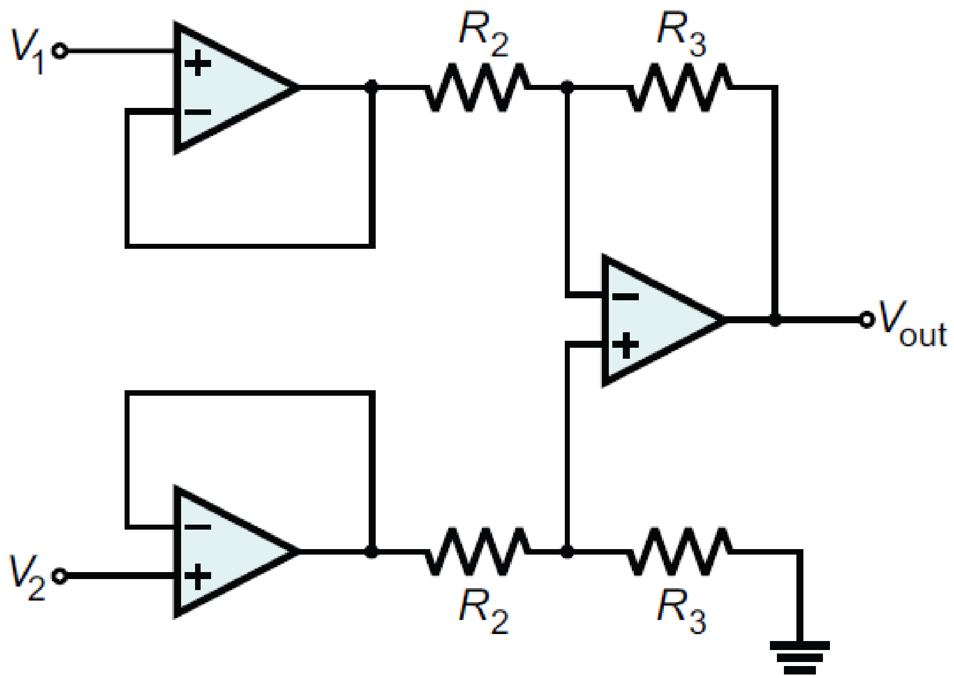
v_o depends on both input and load resistors



$$v_o = v_p = v_s \qquad \text{(with voltage follower)}$$

v_o is immune to input and load resistors

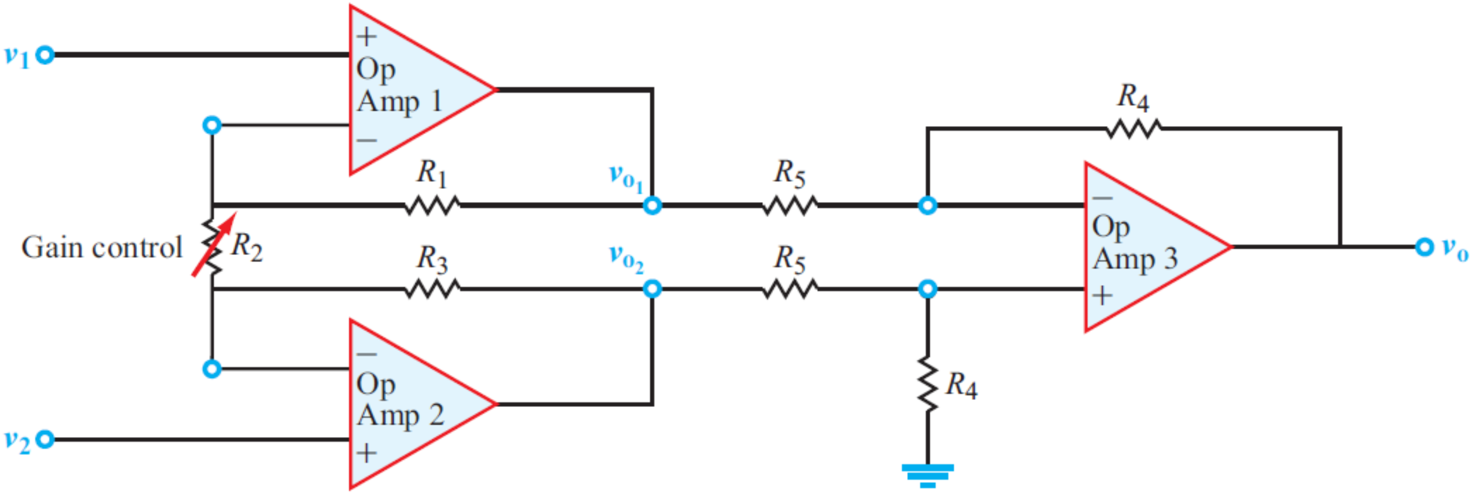
Instrumentation Amplifier



- Two unity-gain buffers are used to buffer the input signal. A difference amplifier is used to provide a gain of R_3/R_2.

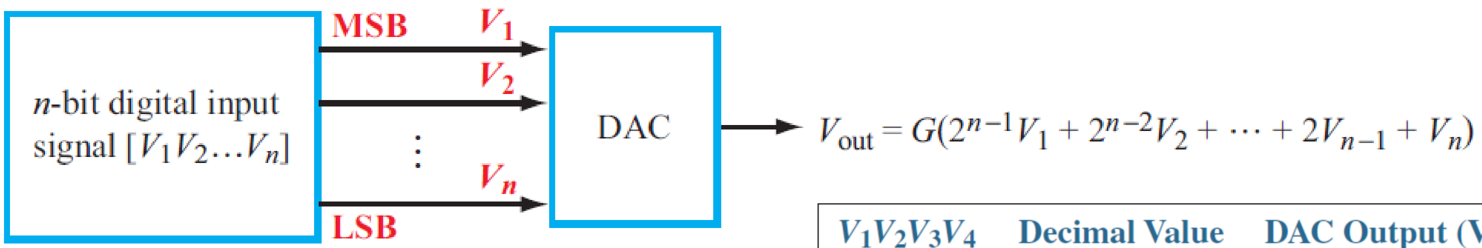
Instrumentation Amplifier (version 2)

H



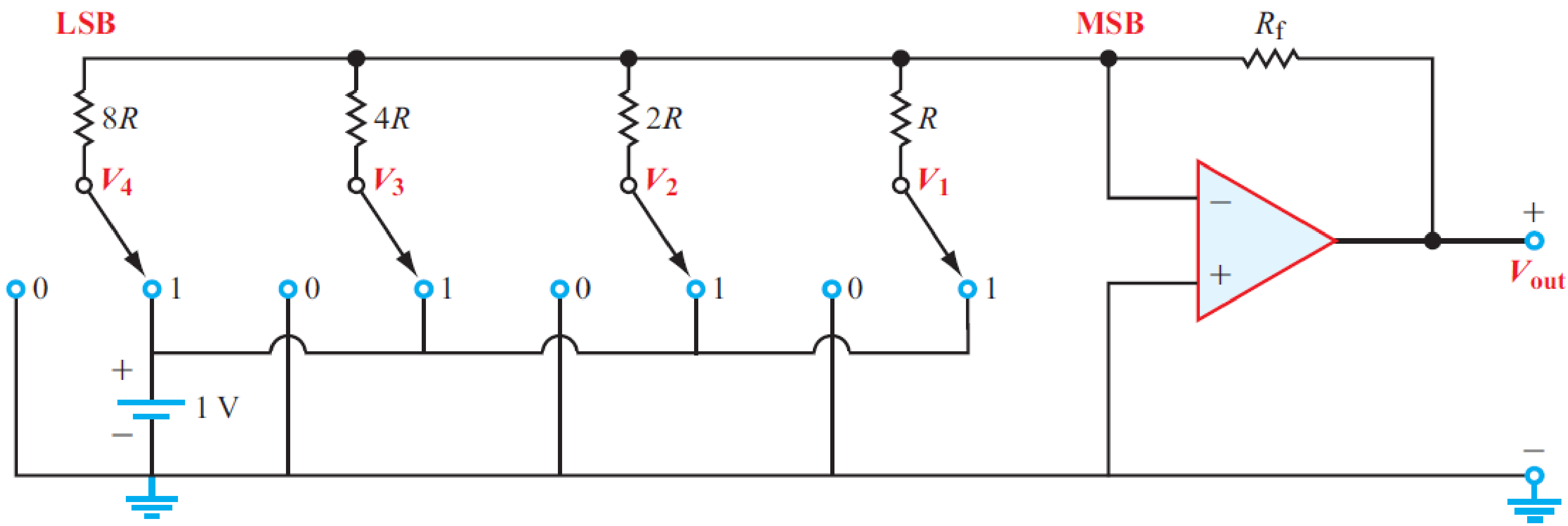
Digital to Analog Converter

Converts digital value into analog voltage



$V_1V_2V_3V_4$	Decimal Value	DAC Output (V)
0000	0	0
0001	1	−0.5
0010	2	−1
0011	3	−1.5
0100	4	−2
0101	5	−2.5
0110	6	−3
0111	7	−3.5
1000	8	−4
1001	9	−4.5
1010	10	−5
1011	11	−5.5
1100	12	−6
1101	13	−6.5
1110	14	−7
1111	15	−7.5

Digital to Analog Converter



$$V_{out} = -\frac{R_f}{R} V_1 - \frac{R_f}{2R} V_2 - \frac{R_f}{4R} V_3 - \frac{R_f}{8R} V_4$$

$$= \frac{-R_f}{8R}(8V_1 + 4V_2 + 2V_3 + V_4), \qquad G = -\frac{R_f}{8R}$$

$$V_{out} = G(2^{n-1}V_1 + 2^{n-2}V_2 + \cdots + 2V_{n-1} + V_n)$$

Ideal Voltage Amplifiers

- An ideal voltage amplifier, the input signal is a pure voltage, and the amplifier faithfully “copies" the input to the output while increasing the magnitude of the voltage (regardless of the load)

$$v_{out} = A_v v_{in}$$

- where A_v is the voltage gain of the amplifier. The voltage gain is usually specified using a dB scale

$$A_v[\mathrm{dB}] = 20 \cdot \log(A_v)$$

- so a gain of 100 is 40dB.
- The input current flowing into the amplifier is ideally zero

$$i_{in} \approx 0$$

- which means that the *input resistance of the amplifier* is infinite. Note that the power flow into the input is therefore zero, which means the amplifier has infinite power gain.

Ideal Current Amplifiers

- An ideal current amplifier, the input signal is a pure current, and the amplifier faithfully “copies" the input to the output while increasing the magnitude of the current (regardless of the load)

$$i_{out} = A_i i_{in}$$

- where A_i is the current gain of the amplifier. The current gain is usually specified using a dB scale

$$A_i[\,\mathrm{dB}] = 20 \cdot \log(A_i)$$

- so a gain of 1000 is 60dB.
- The input voltage into the amplifier is ideally zero

$$v_{in} \approx 0$$

- which means that the *input resistance of the amplifier* is zero. Note that the power flow into the input is therefore zero, which means the amplifier has infinite power gain.

Ideal Transconductance Amplifiers

- An ideal transconductance amplifier, the input signal is a pure voltage, while the output is a current. The amplifier faithfully “copies" the input to the output (regardless of the load)

$$i_{out} = G v_{in}$$

- where G is the transconductance gain of the amplifier. The transconductance gain is usually specified using a dBS scale

$$G[\,\mathrm{dBS}] = 20 \cdot \log(G/1S)$$

- so a gain of 10^4S is 80dBS.
- The input current into the amplifier is ideally zero

$$i_{in} \approx 0$$

- which means that the *input resistance of the amplifier* is infinite. Note that the power flow into the input is therefore zero, which means the amplifier has infinite power gain.

Ideal Transresistance Amplifiers

- An ideal transresistance amplifier, the input signal is a pure current, while the output is a voltage. The amplifier faithfully “copies" the input to the output (regardless of the load)

$$v_{out} = Ri_{in}$$

- where R is the transresistance gain of the amplifier. The transresistance gain is usually specified using a dBΩ scale

$$R[\,\mathrm{dB}\Omega] = 20 \cdot \log(R/1\Omega)$$

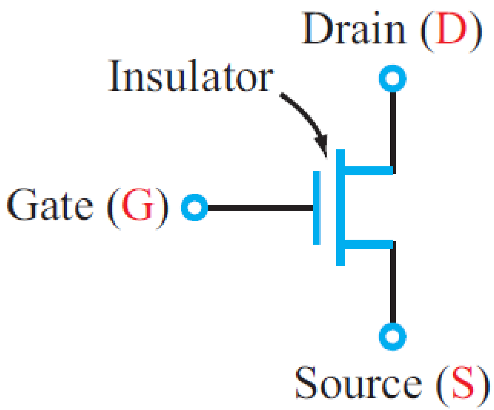
- so a gain of $10^6\Omega$ is 120dBΩ.
- The voltage current into the amplifier is ideally zero

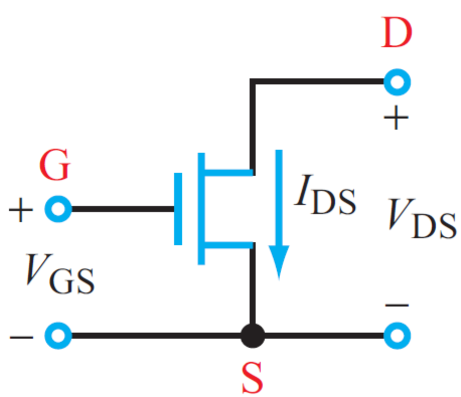
$$v_{in} \approx 0$$

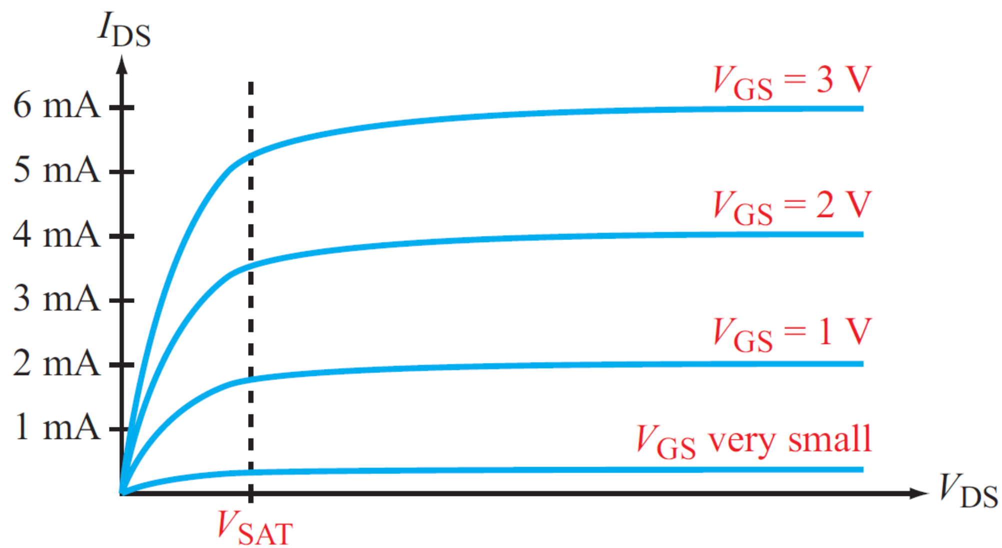
- which means that the *input resistance of the amplifier* is zero. Note that the power flow into the input is therefore zero, which means the amplifier has infinite power gain.

MOSFET (Field Effect Transistor)

Active Device: Voltage Controlled Current Source

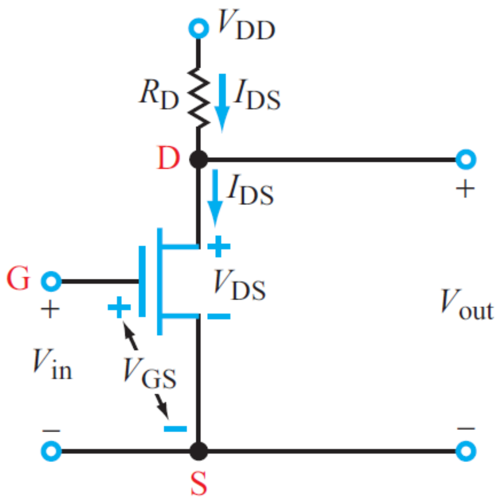


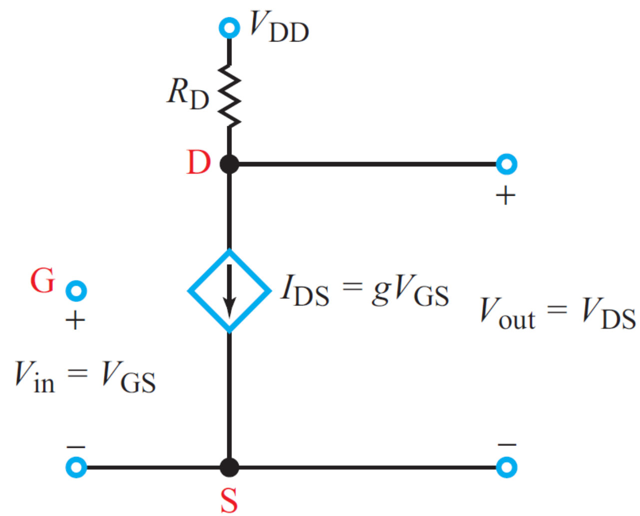


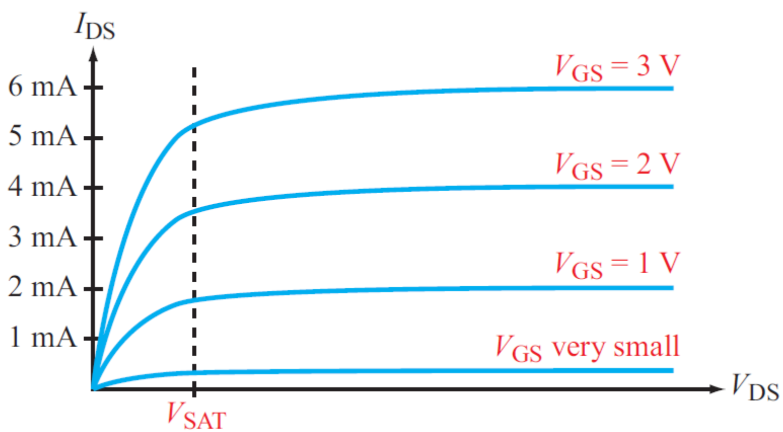


Gate voltage controls drain/source current

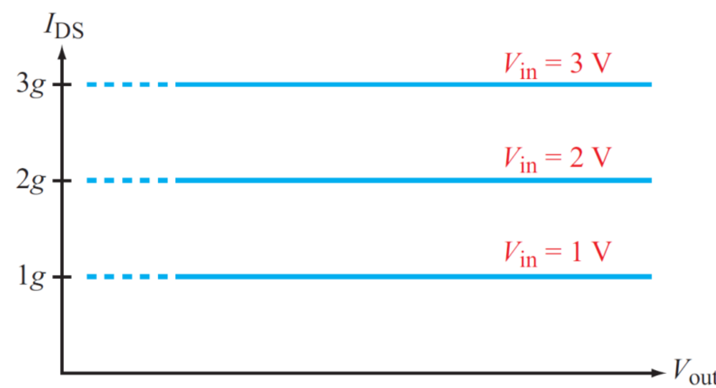
MOSFET Equivalent Circuit







Characteristic curves

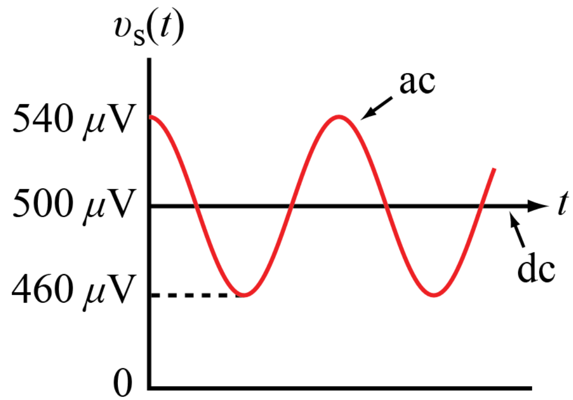


Idealized response

Example: MOSFET Amplifier

Given: $V_{DD} = 10$ V $\quad R_D = 1$ k$\Omega \quad g = 10$ A/V

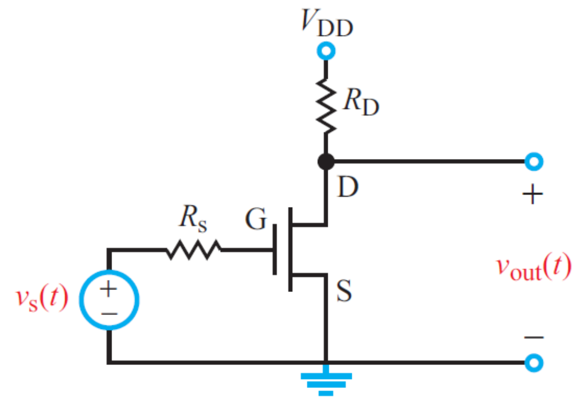
$$v_s(t) = [500 + 40\cos 300t] \qquad (\mu\text{V})$$



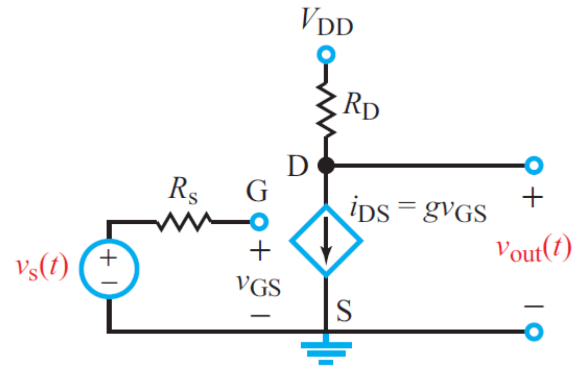
Determine $v_{out}(t)$

$$v_{out}(t) = V_{DD} - i_{DS}R_D = V_{DD} - gR_D v_{GS}(t)$$
$$= V_{DD} - gR_D v_s(t).$$

$$v_{out}(t) = 10 - 10 \times 10^3 \times (500 + 40\cos 300t) \times 10^{-6}$$
$$= 5 - 0.4\cos 300t \quad \text{V}.$$

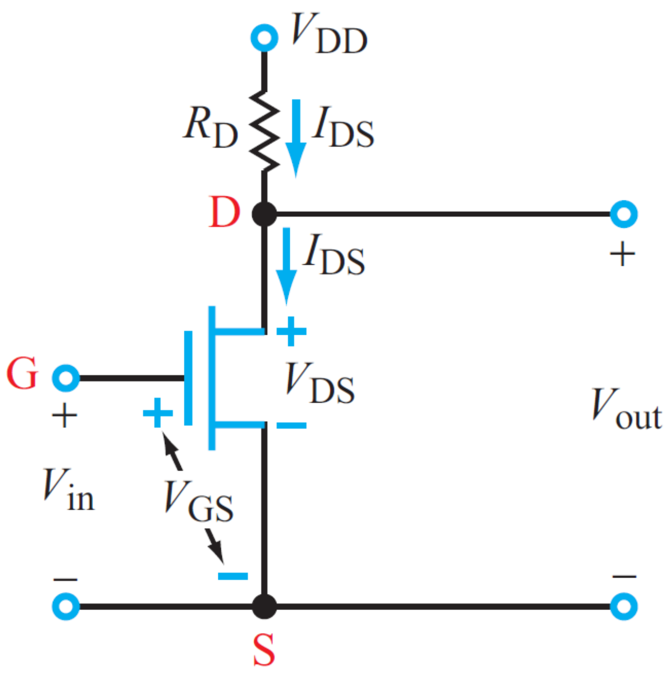


(a) MOSFET amplifier



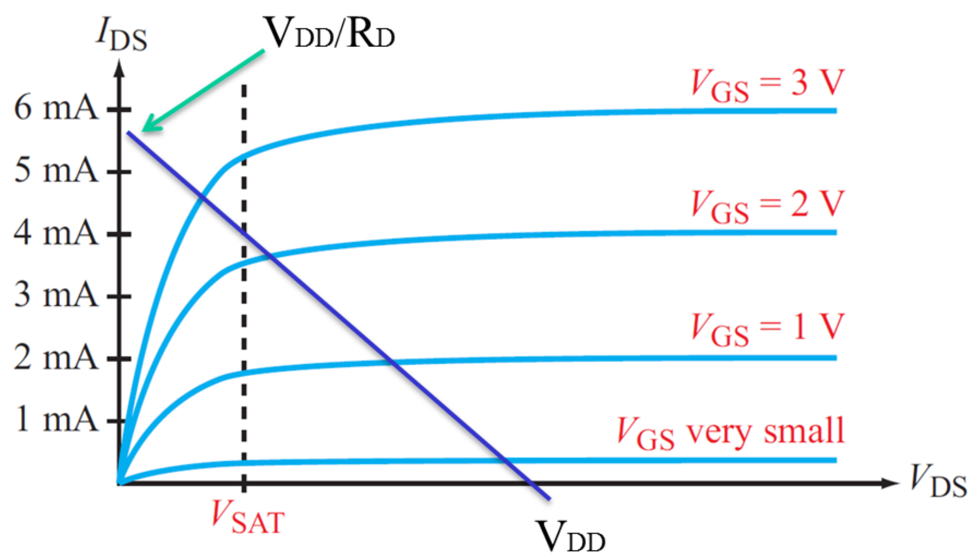
(b) Equivalent circuit

Load Line

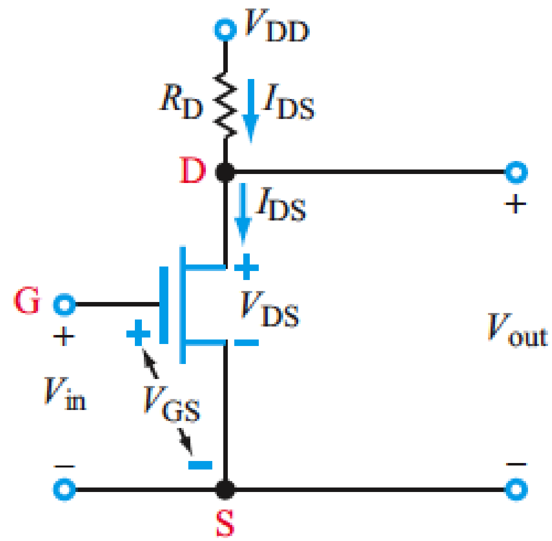


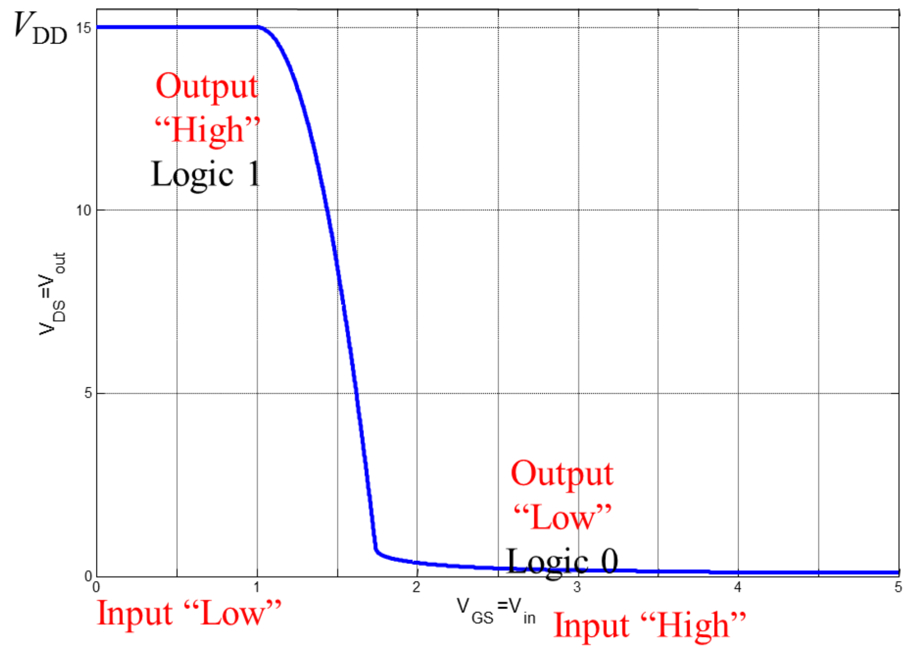
$$v_{out}(t) = V_{DD} - i_{DS} R_D$$

You can use a "load line" to graphically determine $V_{out} = V_{DS}$ for a given $V_{in} = V_{GS}$

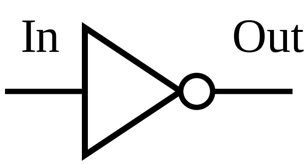


Digital Circuit: MOSFET Inverter



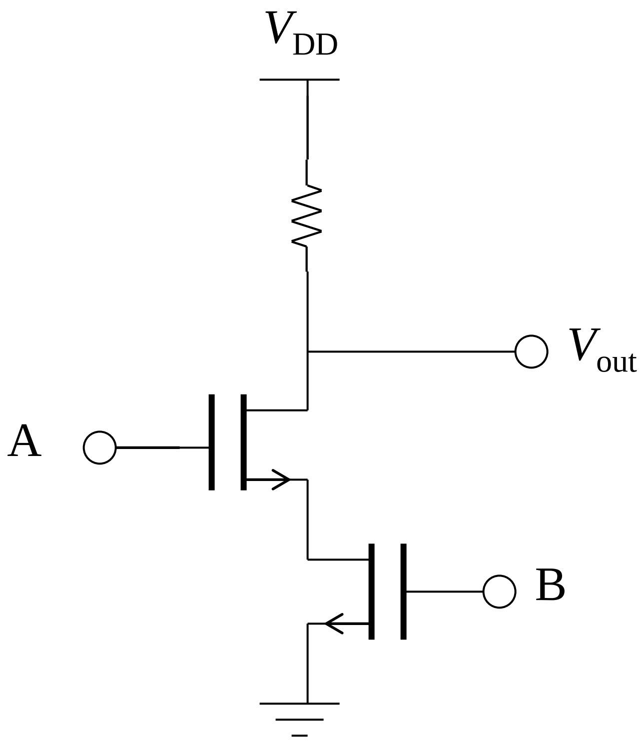


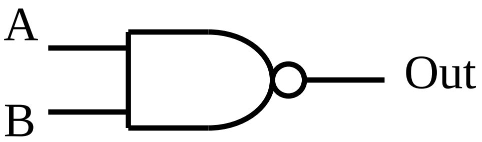
In	Out
0	1
1	0



Another Digital Circuit Element: NAND

No current flows through resistor, unless both A and B inputs turn their transistors on to “pull down” V_{out}



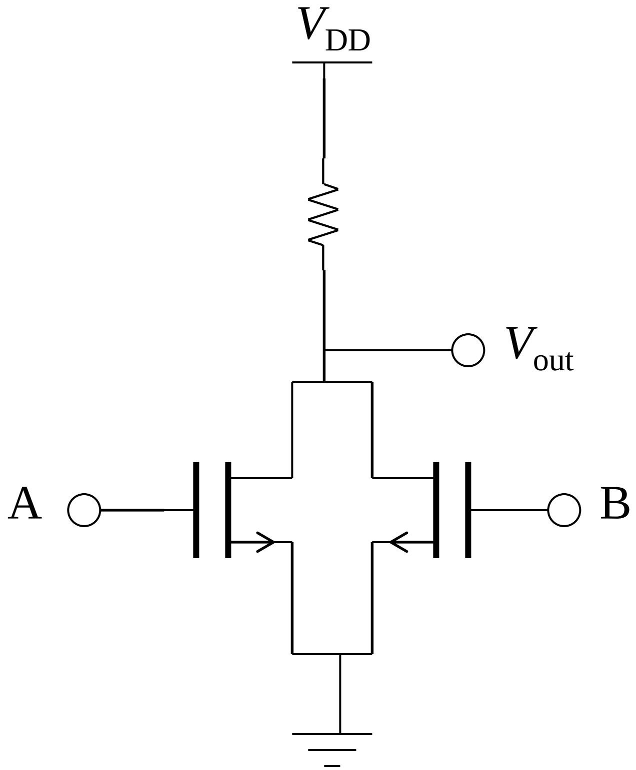


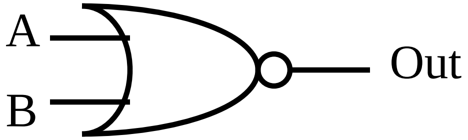
A	B	Out
0	0	1
0	1	1
1	0	1
1	1	0

NAND gates can be used to build any binary logic function

Another Digital Circuit Element: NOR

Current will flow if either A or B inputs turn their transistors on to "pull down" V_{out}





A	B	Out
0	0	1
0	1	0
1	0	0
1	1	0

NOR gates can be used to build any binary logic function