EE 204 - Analog Circuits
Lecture 3

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August 16, 2023

Contents

1 Vacuum Tube

Vacuum tube diodes and triodes are fundamental components of early electronic circuits, predating modern semiconductor technology. They operate based on the principles of electron flow in a vacuum within a sealed glass envelope.

The first vacuum tube diodes designed for rectifier application in power supply circuits were introduced in April 1915 by Saul Dushman of General Electric.

A brief summary of their basic operation and electrical circuits is as follows:

1.1 Vacuum Tube Diode

A vacuum tube diode is a two-electrode device consisting of an anode (plate) and a cathode (filament).

The cathode emits electrons when heated, creating a cloud of negatively charged particles. The anode, being positively charged, attracts these electrons. The resulting flow of electrons from the cathode to the anode forms an electric current.

Importantly, the flow of current occurs only in one direction, from the cathode to the anode. This property makes the vacuum tube diode a rectifying device, allowing it to convert alternating current (AC) into direct current (DC) by allowing current to pass only during half of the AC cycle.

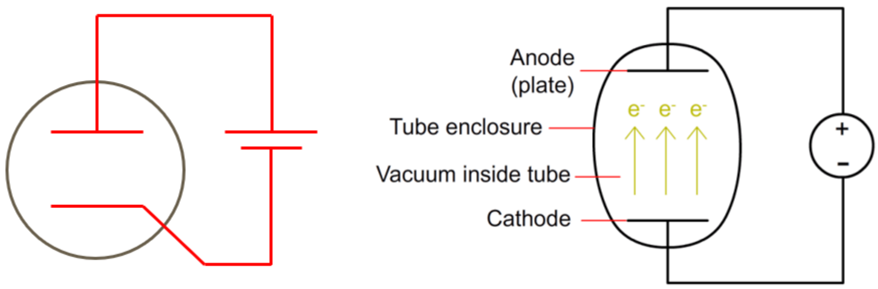

Figure 1: Circuit representation of a Vacuum Tube Diode

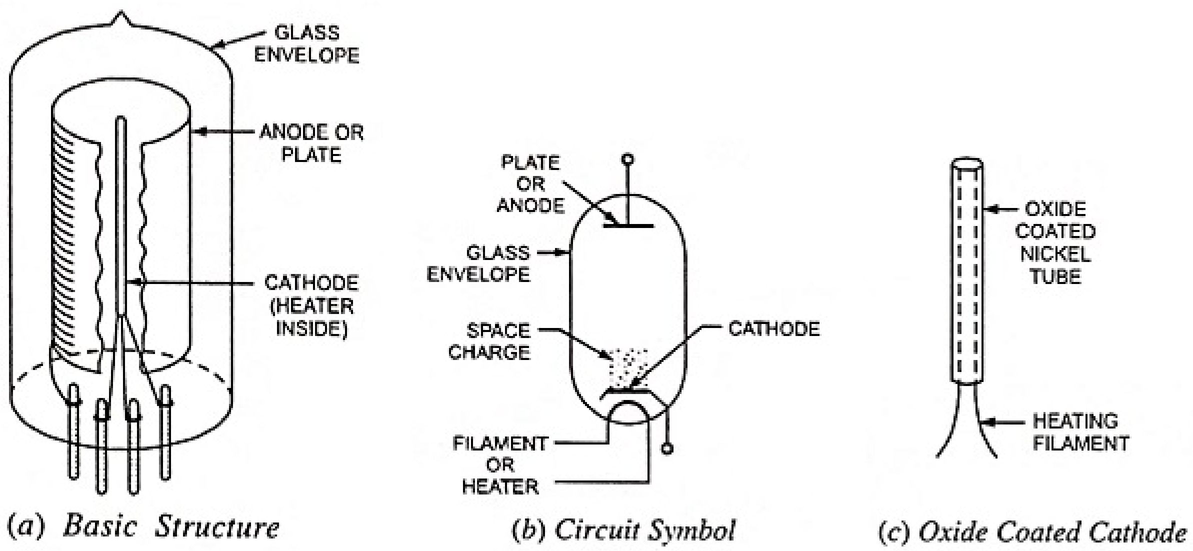

Figure 2: Internal construction of a Vacuum Tube Diode

1.2 Vacuum Tube Triode

A vacuum tube triode extends the functionality of the diode by introducing a third electrode called the grid, placed between the cathode and the anode. The grid is typically negatively charged.

By applying a small voltage to the grid relative to the cathode, the flow of electrons from the cathode to the anode can be controlled or modulated. This voltage on the grid creates an electric field that can either enhance or hinder the flow of electrons from cathode to anode.

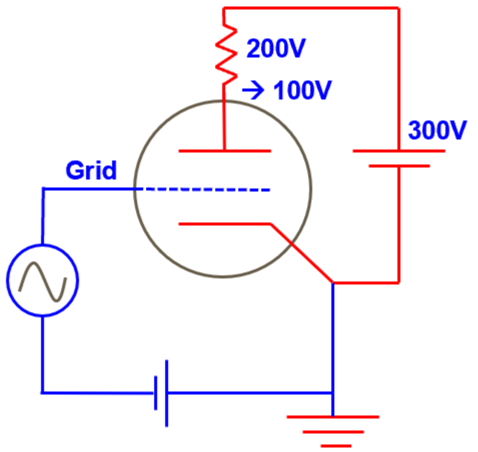

Figure 3: Circuit representation of a Vacuum Tube Triode

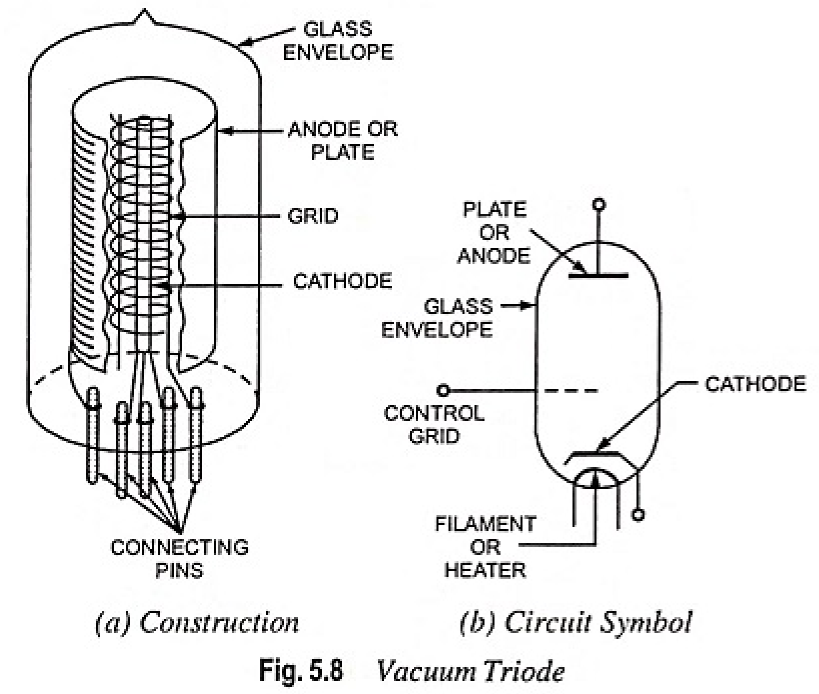

Figure 4: Internal construction of a Vacuum Tube Triode

Thus, the vacuum tube triode can amplify and control electrical signals. It serves as an amplification device, allowing small input signals to control larger output signals. The ability to control the flow of electrons using the grid gave rise to a wide range of electronic applications, including amplifiers and oscillators.

1.3 Limitations of Vacuum Tubes

Enlisted below are some of the glaring limitations of Vacuum Tubes:

1. **Size and Fragility:** Vacuum tubes were large and bulky, making them impractical for miniaturized electronics. They were also fragile and prone to mechanical failure.
2. **Heat and Power Consumption:** Vacuum tubes generated a significant amount of heat, requiring cooling mechanisms. They consumed a lot of power, limiting their efficiency.
3. **Limited Lifespan:** Vacuum tubes had a relatively short lifespan due to the wear and tear on their components, leading to frequent replacements and maintenance.
4. **High Voltage Requirements:** Vacuum tubes needed high voltages for operation, posing safety risks and requiring specialized power supplies.
5. **Slow Operation:** The movement of electrons in vacuum tubes was relatively slow, which limited

their operational speed and response times.

1.4 Summary

In summary, vacuum tube diodes and triodes are foundational components in early electronics. Diodes allow current to flow in one direction, making them useful for rectification, while triodes introduce amplification and signal control capabilities through the use of the grid. These vacuum tube devices paved the way for the development of modern electronics by demonstrating the principles of amplification, signal modulation, and rectification.

2 Transistors and their Origins

Transistors are semiconductor devices that replaced vacuum tubes in many electronic applications due to their smaller size, lower power consumption, and greater reliability. The development of transistors revolutionized electronics by enabling miniaturization and paving the way for modern integrated circuits.

The first transistor was invented at Bell Labs in **1947** by John Bardeen, Walter Brattain, and William Shockley. This initial design was a point-contact transistor, which was soon followed by the more efficient bipolar junction transistor (BJT).

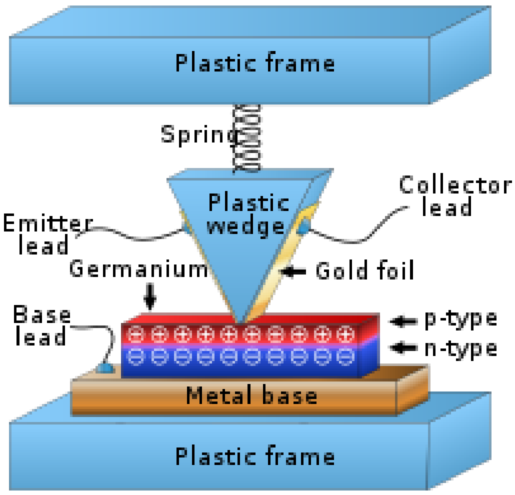

Figure 5: Point-contact Transistor

There are two kinds of (BJT) transistors, the PNP type and the NPN type. This nomenclature is due to the doping of the emitter, base and the collector, the three terminals of the transistor. This will be reviewed in a bit more detail in the next section.

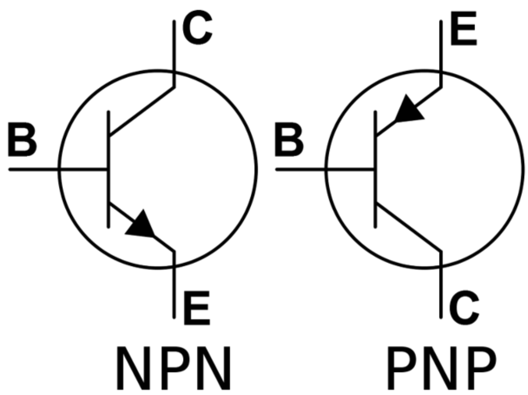

Figure 6: Bipolar-junction Transistors (popularly called as BJTs)

3 Semiconductor Transistors and Biasing

Semiconductor transistors, particularly BJTs, are made from semiconductor materials such as silicon or germanium. They consist of three layers: an emitter, a base, and a collector. There are two types of BJTs: NPN (negative-positive-negative) and PNP (positive-negative-positive).

The operation of a BJT involves controlling the flow of current between the emitter and collector terminals by varying the current at the base terminal.

To make a BJT work properly, it needs to be biased. Biasing involves applying appropriate voltages to the emitter-base and collector-base junctions to ensure the transistor operates in the desired region. There are three common biasing modes:

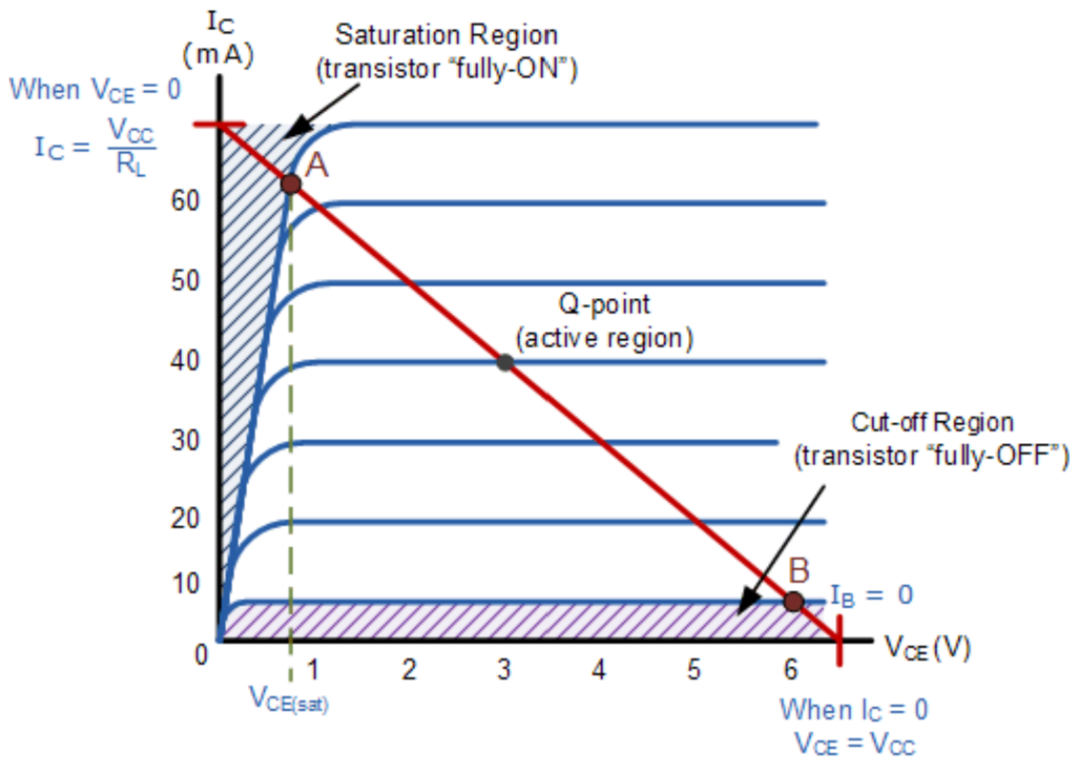

Figure 7: Operating Regions of a BJT

1. **Active Mode:** In this mode, the base-emitter junction is forward-biased, allowing a small current to flow from emitter to base. This current controls the much larger collector current, resulting in amplification.
2. **Cut-off Mode:** The base-emitter junction is reverse-biased, preventing any significant current from flowing between emitter and base. This turns the transistor off.
3. **Saturation Mode:** Both the base-emitter and base-collector junctions are forward-biased, allowing maximum current to flow from collector to emitter. The transistor is effectively "ON" in this mode.

3.1 Advantages of Transistors over Vacuum Tubes

1. **Miniaturization:** Transistors are much smaller than vacuum tubes, allowing for the creation of compact electronic devices.
2. **Reliability:** Transistors are solid-state devices with no moving parts, leading to improved reliability and longer lifespans.
3. **Low Power Consumption:** Transistors consume far less power than vacuum tubes, reducing heat generation and energy costs.
4. **Durability:** Transistors are solid and resistant to mechanical shocks, unlike the fragile vacuum

tubes.

5. **Faster Operation:** Transistors operate much faster than vacuum tubes due to the quick movement of charges within semiconductor materials.
6. **Lower Voltage Requirements:** Transistors can operate at lower voltage levels, enhancing safety and reducing power supply complexities.
7. **Integration:** Transistors can be easily integrated into complex circuits on a single semiconductor chip, leading to the development of integrated circuits and microprocessors.

These advantages of transistors addressed the limitations of vacuum tubes, making them the preferred choice for modern electronics and leading to the eventual shift from vacuum tubes to semiconductor-based technology.

In the subsequent section we will analyse the relations for a pnp transistor, using which we can similarly derive the equations for an npn transistor.

3.2 PNP Transistor

The current component diagram for a pnp transistor is as follows:

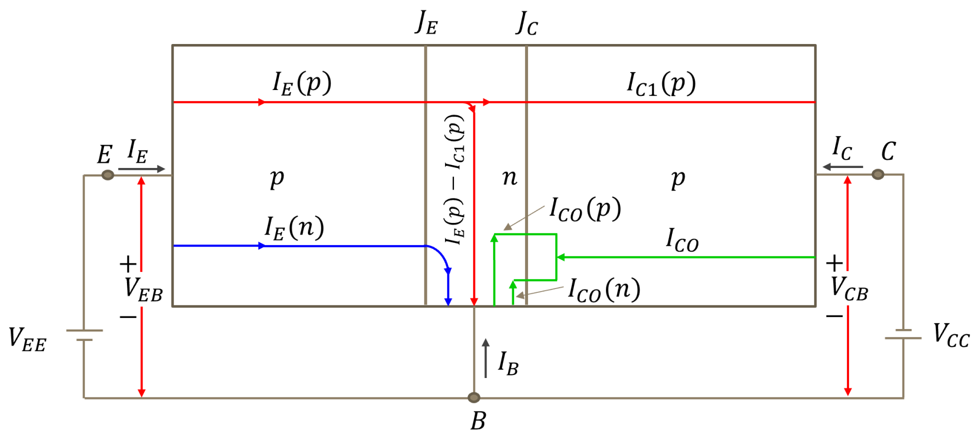

Figure 8: Current Components - pnp transistor

Using these notations, we will derive some basic relations relating to the various current components for a pnp transistor.

Emitter current $I_E = I_E(p) + I_E(n)$

As the emitter doping is much higher than the base doping in a commercial transistor, $I_E \approx I_E(p)$

In open condition, $I_E = 0$

Due to reverse collector base junction, a reverse saturation current flows: $-I_{CO} = I_{CO}(n) + I_{CO}(p)$

The total collector current when emitter is forward bias is -

$$I_C = I_{C1}(p) - I_{CO}$$

Usually, $I_{CO} \ll I_{C1}(p)$

For pnp transistor I_E is positive while both I_C and I_{CO} are negative. This means that the collector current actually flows in the direction of opposite that is indicated using arrows. The currents are reverse for npn transistors.

$\alpha =$ dc current gain $= -\frac{I_C}{I_E}$
and
β (or h_{FE}) = max. current gain $= \frac{I_C}{I_B}$
Therefore, α and β are related as:

$$\frac{1-\alpha}{\alpha} = \beta$$

and

$$I_C = \beta I_B + (\beta + 1) I_{CO}$$

In the following section, we will discuss MOSFETs which are very important components of any modern day electronics.

4 MOSFETs and Inverters:

The basic principle of the field-effect transistor was first patented by Julius Edgar Lilienfeld in 1925.
The main advantage of a MOSFET is that it requires almost no input current to control the load current, when compared with bipolar transistors (bipolar junction transistors/BJTs).
The structure resembling the MOS transistor was proposed by Bell scientists William Shockley, John Bardeen and Walter Houser Brattain, during their investigation that led to discovery of the transistor effect.
MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors) are another type of transistor that has become essential in modern electronics due to their low power consumption and ability to be easily integrated into integrated circuits.

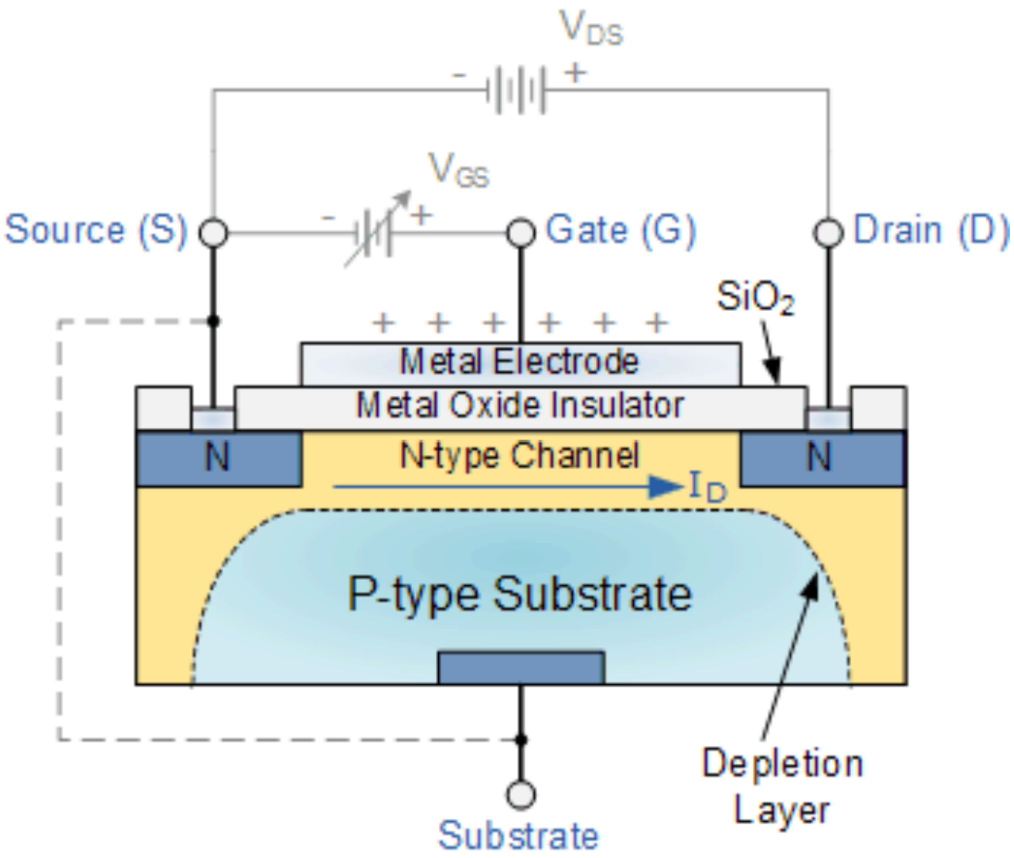

Figure 9: A typical MOSFET

MOSFETs have three terminals: gate, source, and drain. The gate terminal controls the flow of current between the source and drain terminals through an electric field generated by the voltage applied to the gate.
One common application of MOSFETs is in inverters. An inverter is a circuit that takes an input signal and produces an inverted output signal (1s become 0s and vice versa).
MOSFETs in an inverter are used to switch between two voltage levels (typically high and low) based

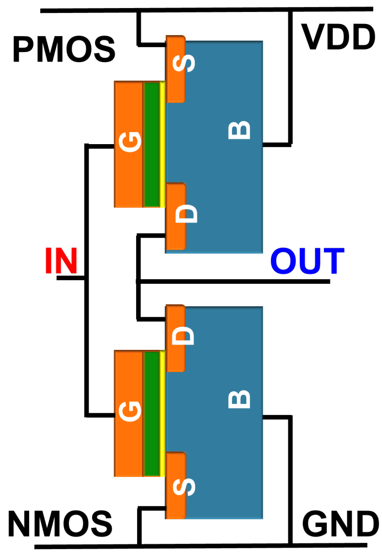

Figure 10: Elaborate diagram for Inverter using MOSFET

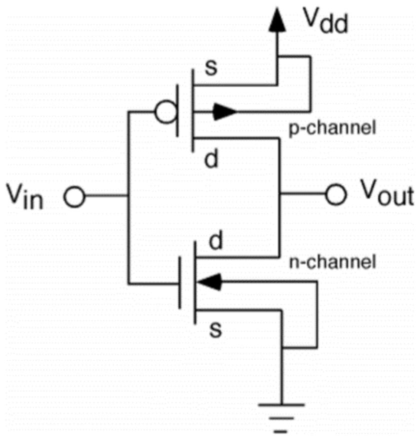

Figure 11: Compact diagram for an Inverter

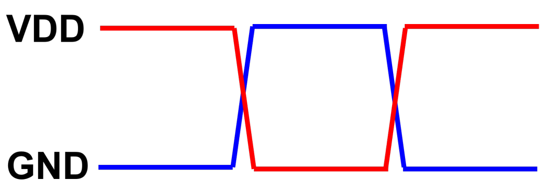

Figure 12: Typical Output of an Inverter

on the input signal. When the input signal is low, the MOSFET is off, and the output is high; when the input is high, the MOSFET is on, and the output is low.

In summary, transistors evolved from vacuum tubes and played a pivotal role in the advancement of electronics. Biasing is crucial to ensure proper transistor operation. MOSFETs are a key type of transistor used for various applications, including inverters that produce inverted output signals, which are fundamental components in digital logic circuits.