TRANSISTORS – History

• Studied in labs in 1830’s
• Electricity used to communicate (telegraphs, telephone, later radio) in 1874 – used rectifiers
• Ferdinand Braun uses first ‘rectifier’ (diode) to create cat’s whisker diode – first semiconductor
TRANSISTORS – Basic Definition

• A transistor is a three-terminal device with an input and an output, the properties of which cause the input to affect the output, but the output to have very little effect on the input.

• This unidirectional property allows the design of complicated circuits, containing hundreds or thousands of loops and nodes, without necessitating all the calculations of a circuit that could flow both ways.

TRANSISTORS – Basic Uses

• The most common use of the transistor is as a switch – a Boolean logic gate that composes the basic architecture of a microprocessor.

• Transistors can also be used for amplification,
TRANSISTORS – Basic Properties

• A transistor is composed to two opposing diodes next to one another
  – What’s a diode?

• A diode is a pn junction, the properties of which allow unidirectional flow only
  – What’s a pn junction?

TRANSISTORS – PN Junctions

• A semiconductor is a substance, usually silicon, that has been doped – had impurities added to them, such as boron, carbon, or any number of elements – to affect the electrical properties of the material
TRANSISTORS – P-Type Silicon

• P-Type – silicon has been doped to have a positive tendency
  – Usually with boron or gallium
  – Three outer electrons causes an extra hole to be available when the element bonds with silicon
  – The extra hole causes electrical current to have a more difficult time flowing
  – Positive tendency -> P-type

TRANSISTORS – N-Type Silicon

• N-Type – silicon that has been doped to have a negative tendency
  – Usually with phosphorous or arsenic
  – Five outer electrons causes an extra electron to be available when the element bonds with silicon
  – The extra electron causes electrical current to flow more easily, with only a small quantity of energy to induce current flow
  – Negative tendency -> N-type
TRANSISTORS – Diodes

- Most basic semiconductor – a simple **sandwich** of a P-Type and an N-Type silicon
- Allows current to flow in one direction, not the other (**unidirectional flow**)
- Two possible configurations for diodes – a **reverse biased** diode and a **forward biased** diode

TRANSISTORS – Forward-Biased

- By adding a power source whose **current-flow tendency is in the direction** of the diode, current is allowed to continually flow through the diode
- A **small amount of voltage initially is required** for silicon to approximate that of an ideal diode – for silicon, this is about 0.7 V; for germanium, this is about 0.2 V
TRANSISTORS – Reverse-Biased

- By adding a power source whose current-flow tendency is in opposition to the direction of the diode, current is not allowed to flow through the diode.
- A small amount of current is allowed to flow in all diodes – for silicon, this is about 10 microamps.
- Also, in the extreme cases of reverse voltages being applied, the diode will eventually break down and let current through.

TRANSISTORS – Bias Analogy

Forward-Bias

Reverse-Bias
TRANSISTORS – PN Junction

- Diffusion and Recombination – holes and electrons drift towards one another at the junction, combining there
- Depletion Region – as the area around the junction fills with recombined holes and electrons, a deficiency of carriers occurs due to recombinations
- Uncovered Charges – the recombined charges on the n- and p-sides bound into the lattice structure begin to act as opposing currents, acting like a charged capacitor, creating a drift current of electrons towards the n-side and holes to the p-side
- Dynamic Equilibrium – an equilibrium between the two processes is eventually reached

TRANSISTORS – Bias Analogy
TRANSISTORS – Dual Diodes

• If a transistor is simply opposing diodes, why does current flow at all?
• By applying a small voltage to the center layer of the sandwich (junction), a much larger current can flow through the whole sandwich
• This allows the transistor to function as a switch, which gives it the ability to work as a boolean gate, and in turn allows the creation of a microprocessor
• Two types of setups for these bipolar junction transistors (BJT) – npn and pnp

TRANSISTORS – Types of BJT

• Bipolar Junction Transistors (BJT)
• Field Effect Transistors, Specifically Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET)
TRANSISTORS – NPN BJT

• Three leads of the transistor connected to three layers – collector, base and emitter
• Base-to-Emitter junction is forward biased – current flows easily
• Base-to-Collector junction is reverse biased – ordinarily prevents current from flowing – however, in this case, most electrons accelerate from emitter through base into the collector
  – Junction is manufactured to be very thin
  – Emitter region more heavily doped than the base
• End result: small current (conventional current flows opposite electrons) flows from base to emitter; large current flows from collector to emitter

TRANSISTORS – NPN BJT

Corresponds to:
NPN BJT Operation

Collector

n-type

p-type

n-type

Base

Emitter

NPN BJT Operation

Collector

n-type

p-type

n-type

Base

Emitter
NPN BJT Operation

Collector

Base

Emitter

n-type

p-type

n-type

TRANSISTORS – NPN BJT Operation

Collector

Base

Emitter

n-type

p-type

n-type

Depletion Area
TRANSISTORS – NPN BJT Operation

Direction of Electron Flow

Collector

Base

Emitter

Depletion Area
TRANSISTORS – NPN BJT Operation
Direction of Current Flow

Collector

Base

N

P

N

Emitter

TRANSISTORS – NPN BJT Operation

Corresponds to:

Collector

Base

N

P

N

Emitter

Corresponds to:
TRANSISTORS – Ratio $\beta$

- $\beta$ is the ratio of the collector current to the base current.

- Values for $\beta$ range from about 10 to 1000, but a common value is 100.

- Hence, $I_C = \beta I_B$

TRANSISTORS – PNP BJT

- Three leads of the transistor connected to three layers – collector, base and emitter
- Base-to-Emitter junction is forward biased – electrons flow more easily
- Base-to-Collector junction is reverse biased – current prevented from flowing
- End result: current flow in the PNP is opposite to current flow in the NPN
TRANSISTORS – PNP BJT

Field-Effect Transistors (FETs)

- There are several types of FETs, such as JFETs and MOSFETs, both of which are either p-channel or n-channel type.
- The n-channel enhanced MOSFET (NMOS) is the most common and most important type.
- Hence, this lecture will focus on the NMOS with a brief explanation of the n-channel JFET, leaving the details of the other types to the students.
Metallic-Oxide-Semiconductor Field-Effect Transistors (MOSFETs)

- Compared to BJTs, MOSFETs can occupy less chip space area and can be fabricated with fewer processing steps.
- They are used as logic gates, amplifiers, and for the construction of memory and microprocessor circuits.
- Specifically n-channel enhancement-mode MOSFETs (NMOS).

NMOS Electronic Symbol

Corresponds to:
NMOS Electronic Symbol

Corresponds to:

How the NMOS Works!

Silicon Dioxide
How the NMOS Works!

How the NMOS Works!
How the NMOS Works!

How the NMOS Works!
How the NMOS Works!
How the NMOS Works!

• Applying a sufficiently large positive voltage to the NMOS Gate produces an electrostatic field.

• The positive field attracts electrons to the Silicon Oxide insulator producing a n-channel.

• With the Gate at the threshold ($V_{th}$) and the Drain and Source connected to the appropriate potentials, current flows from the Source to the Drain.

• Under these conditions, a negligible amount of current flows through the Gate and Body!
How the NMOS Works!

- **Triode**: $V_{DS} \leq V_{GS} - V_{to}$
- **Saturation**: $V_{DS} \geq V_{GS} - V_{to}$

were $V_{to} = \text{Threshold Voltage}$
Operating in the Triode Region

• A MOSFET operating in the Triode region can be used a voltage controlled resistor.

• Remember the Inverting Op-Amp?

\[
\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}
\]

![Inverting Op-Amp Diagram]

JFET (n-channel) Electronic Symbol

Corresponds to:
JFET (n-channel) Operation

Power Transistors

- Any transistor designed to conduct large currents and dissipate more heat
- Usually physically larger than a regular transistor
- Used in applications where low current devices are interfaced with high current devices
- Also used for RF amplifiers, motor or solenoid control, lighting control, et cetera
Phototransistors

- A transistor where the junction between the base and emitter functions as a photodiode
- When used with a LED it can be used to detect the presence of an object
- If used with a LED, motor, and slotted disk, it can monitor angular position of the motor
When light passes to the phototransistor from the LED, 0V is produced at Vout, and when the light is interrupted 5V is produced at Vout.

Reference Material

- G. Randy Slone, Electricity and Electronics, Second Edition
- David G. Alciatore and Michael B. Histand, Introduction to Mechatronics and Measurement Systems