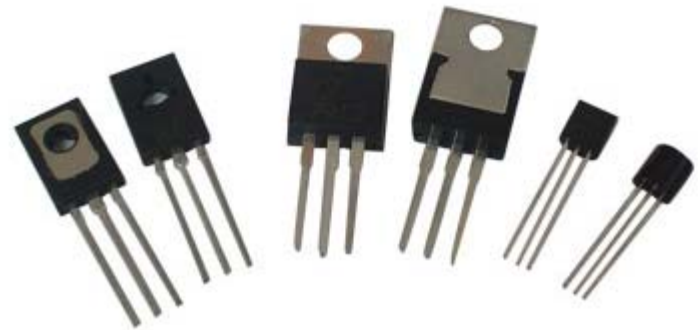


Introduction to Transistors

- **Transistors** form the basic building blocks of all computer hardware.
- Invented by William Shockley, John Bardeen and Walter Brattain in 1947, replacing previous vacuum-tube technology
 - Won Nobel Prize for Physics in 1956
- Used for applications such as amplification, switching and digital logic design.



Intro to Electricity

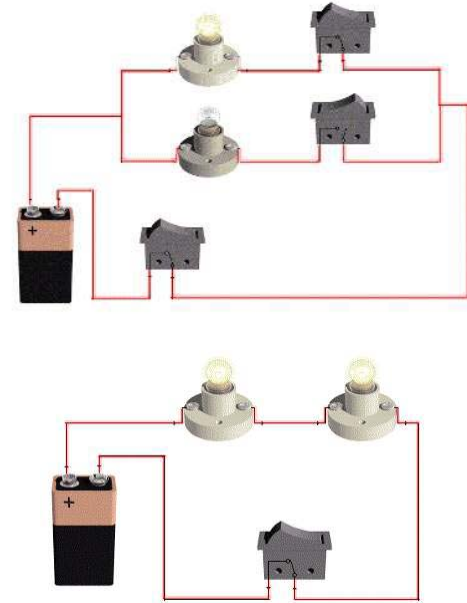
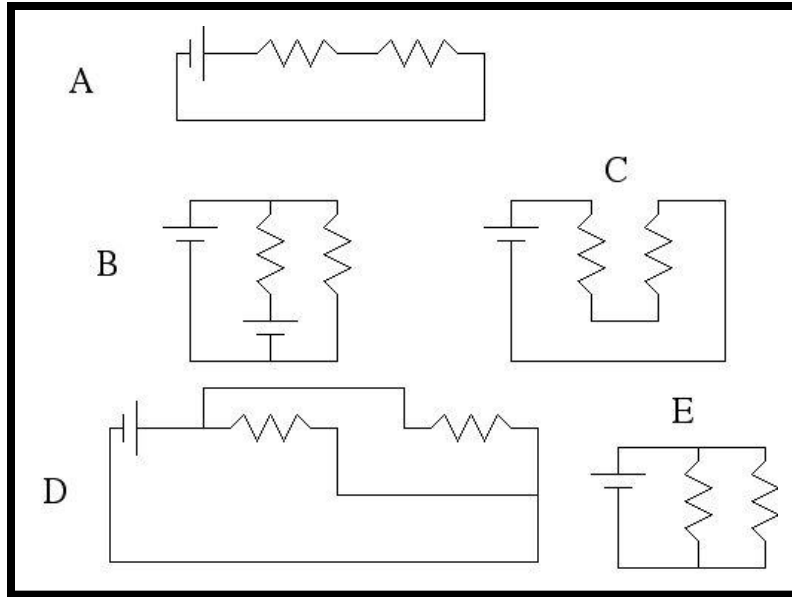
- Before we can understand how transistors work, we have to review some basics of electricity.
- Electricity is the phenomenon caused by the presence or flow of electric charge, usually in the form of electrically-charged particles
 - **Voltage** is the electrical potential associated with some point in a circuit, relative to a reference point (aka **ground**)
 - measured in **volts** (V)
 - **Current** is the flow of electrically-charged particles
 - measured in **amperes** (A)
 - An **electric field** is the effect produced by the force exerted by an electrically-charged object on other electrically-charged objects or particles.
 - Similar to magnetic fields, which cause magnetically-charged objects to attract or repulse each other.

Water Analogy

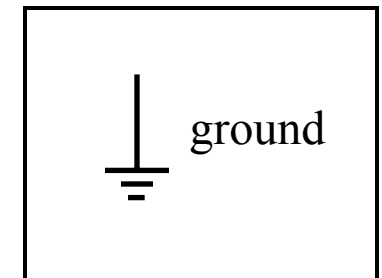
- When trying to picture electrical concepts such as voltage and current, picture the waterfall model:
 - The “charged particles” are the drops of water
 - “Voltage” is the elevation of the water above the ground
 - “Current” is the flow of water from one level to another
 - Note: current always flows from a point of high voltage to a point of lower voltage. Just like waterfalls.



Example Circuit Diagrams

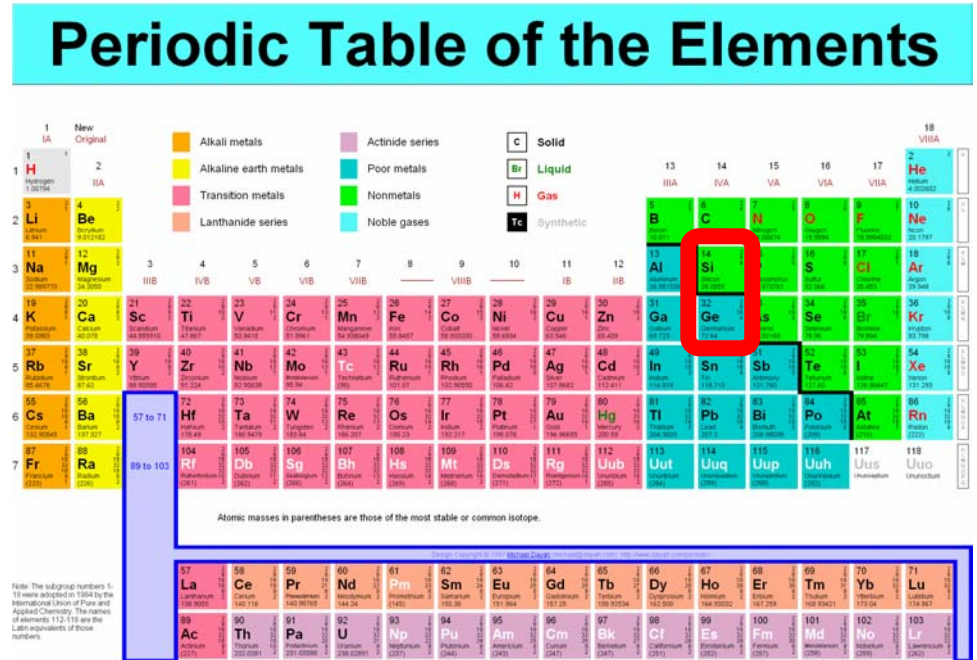


- Circuit diagrams are composed of:
 - Sources (voltage source, current source)
 - Components (resistors, capacitors, inductors)
 - Connectors (switches & leads)



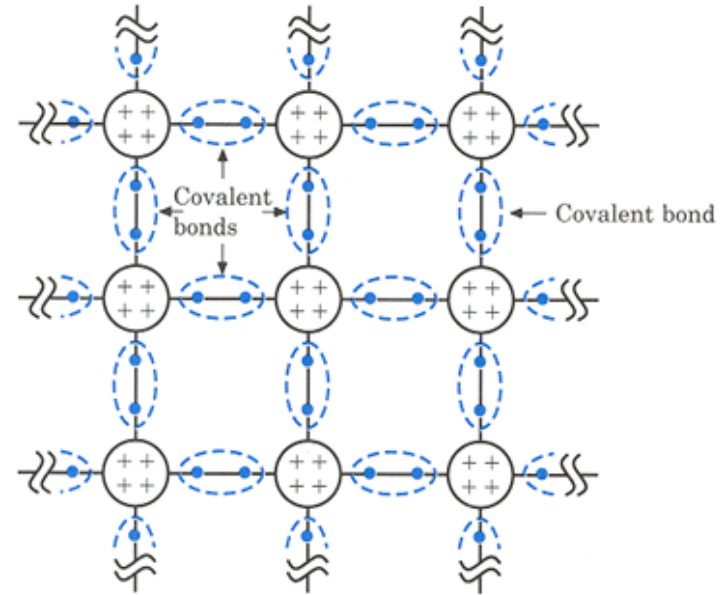
Conductivity of Materials

- Electricity can flow freely through a solid if it is a good **conductor**, that is, if there are free valence electrons after the solid is formed.
- Semiconductor materials (silicon, germanium) straddle the boundary between conductors and **insulators**, behaving like one or the other, depending on factors like temperature and **impurities** in the material.



Semiconductor Conductivity

- Silicon and germanium have four valence electrons, and four spaces in its valence layer to fill. When the solid forms, the atoms share electrons with neighbouring atoms, similar to the diagram on the right.
- Even though this solid is stable, energy can make electrons from the valence layer become loose. At room temperature, a weak current will flow through the material, much less than that of a conductor.

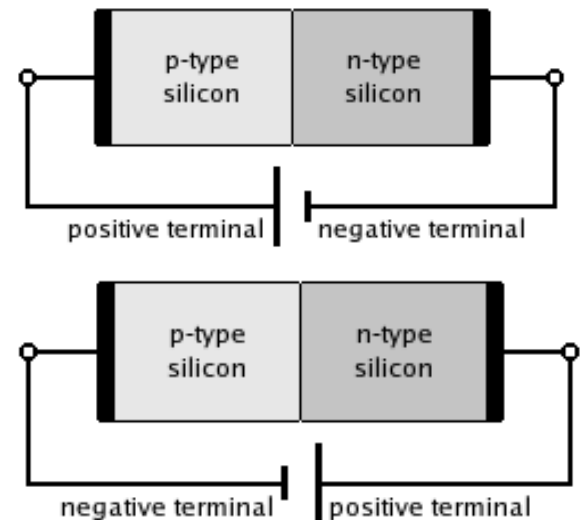


Semiconductor Impurities

- To encourage the semiconductor's conductivity, **impurities** can be introduced in the fabrication process, to increase the number of charge **carriers**.
 - **n-type**: adding elements from group 15, which have 5 electrons in its valence layer (e.g. phosphorus, arsenic)
 - **p-type**: adding elements from group 13, which have 3 electrons in its valence layer (e.g. boron)
 - Process is also referred to as **doping** the semiconductor
- In the case of n-type semiconductors, the carriers are electrons that are not bound to the solid, and can flow more freely through the material. For p-type semiconductors, the carriers are called **holes**, to represent the electron gap as a particle as well.

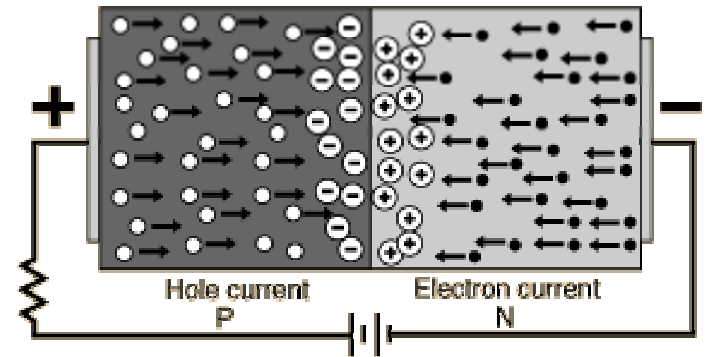
p-n Junctions

- Q: Why do we care about semiconductors, anyway?
 - A: Because it's useful to have materials that can change from conductor to insulator, given some outside stimulus.
- This comes into play when we consider integrating p-type and n-type semiconductors together into a single device (a **p-n junction**, for instance).
- By placing a chunk of p-type material next to a chunk of n-type material and applying a voltage from one end to the other, we get differing current flow behaviour.



p-n Junctions

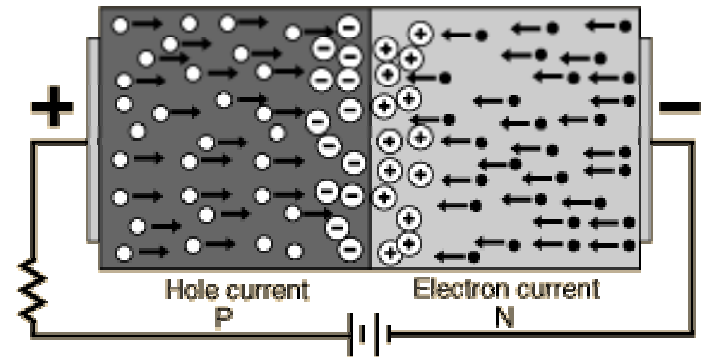
- When left alone, the electrons from the n half of the junction will mix with the holes of the p half of the junction, cancelling each other out, and creating a **depletion layer**.



- Once this depletion layer is wide enough, it creates an electric field that sends holes back to the p layer, and sends electrons back to the n layer.
 - The current caused by this field is called **drift**.
 - The current caused by carrier recombination is called **diffusion**.
- At rest, these two currents reach **equilibrium**.

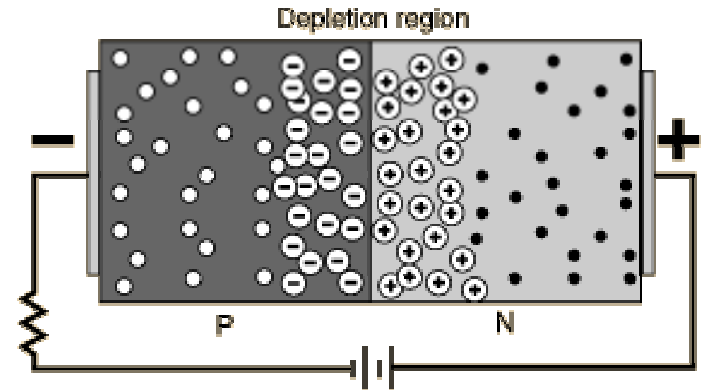
Forward Bias

- When a voltage is applied to this junction (with the positive terminal attached to the p-type section and the negative terminal attached to the n-type section), electrons are continuously injected into the n-type section, narrowing the depletion layer and increasing the electron diffusion rate.
- With a smaller depletion layer, the electrons travel more easily through to the p-type section, and back into the other terminal of the voltage source
 - electron velocity is too fast to be absorbed by the p-type material, as in the case of electron drift.



Reverse Bias

- When a p-n junction is reverse biased (the negative terminal of the voltage source is applied to the p-type section and the positive terminal is applied to the n-type section), the depletion region at the junction becomes wider, preventing the carriers from passing.
 - a small current still flows through the circuit, but it is weak and does not increase with an increase in the applied voltage.
- So when a junction is forward biased, it becomes like a virtual **short-circuit**, and when the junction is reverse biased, it becomes like a virtual **open-circuit**.
 - idea behind a **diode** (e.g. LED)

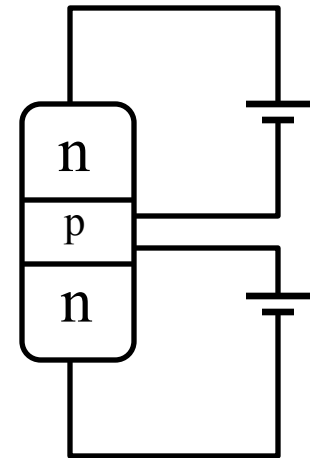


Transistors Again

- Transistors use the characteristics of p-n junctions to create more interesting behaviour.
- Three main types:
 - Bipolar Junction Transistors (BJTs)
 - Metal Oxide Semiconductor Field Effect Transistor (MOSFET)
 - Junction Field Effect Transistor (JFET)
- The last two are part of the same family, but we'll only look at the MOSFET for now.
- Note: There are two arrangement of n-type and p-type semiconductors in every transistor design. By reversing the voltage sources and swapping the n-type and p-type sections, you get the same transistor.

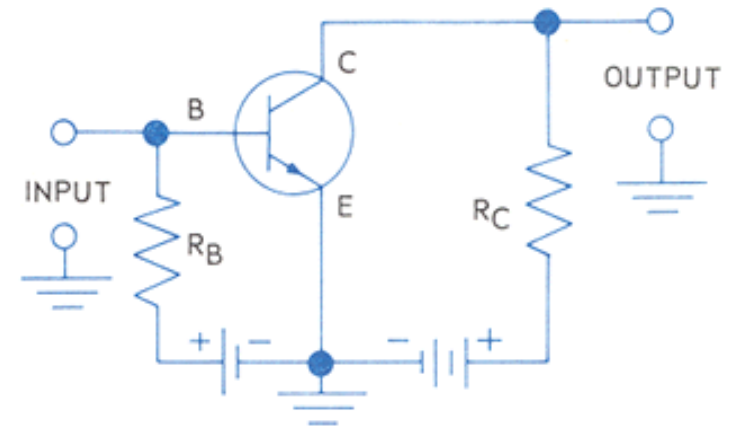
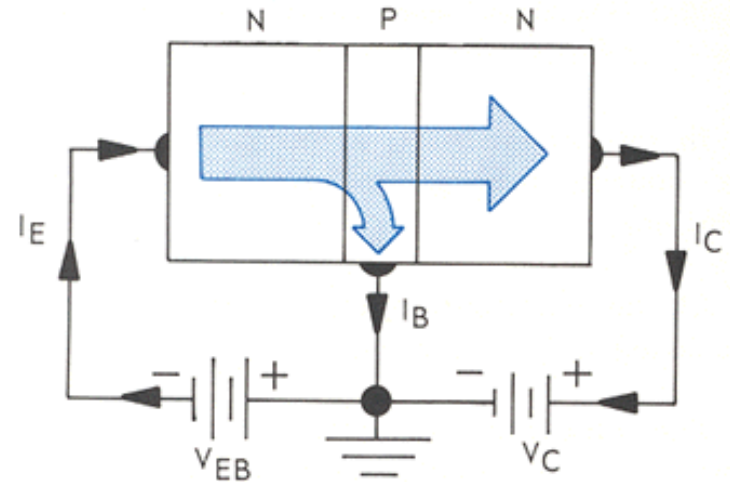
Bipolar Junction Transistors

- When a p-n junction is reverse biased, the depletion layer prevents the electrons from passing through the p section into the n section where they could be collected by the positive voltage terminal.
- This could be overcome by altering the temperature, or by artificially injecting more electrons through the p-region.
 - make p-region narrower
 - inject electrons at a high velocity, so they don't have time to recombine
- Solution: Use a forward biased p-n junction to inject electrons into the reverse biased p-n junction!



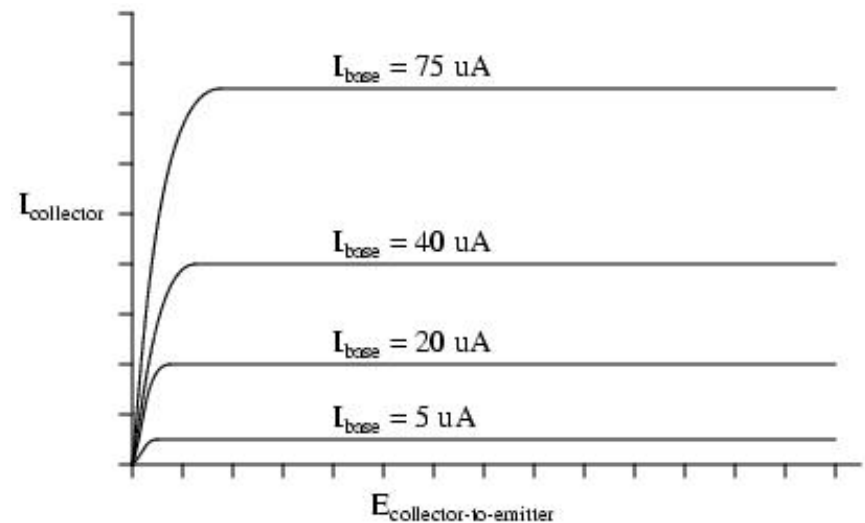
Bipolar Junction Transistors

- A BJT has three contact points:
 - the **base** (middle layer)
 - the **emitter** (the source of the injected electrons)
 - the **collector** (the recipient of the injected electrons)
- By increasing the voltage between the base and the emitter, we can make the current from the base to the collector go from zero ($V_{EB} = 0$) to higher values.



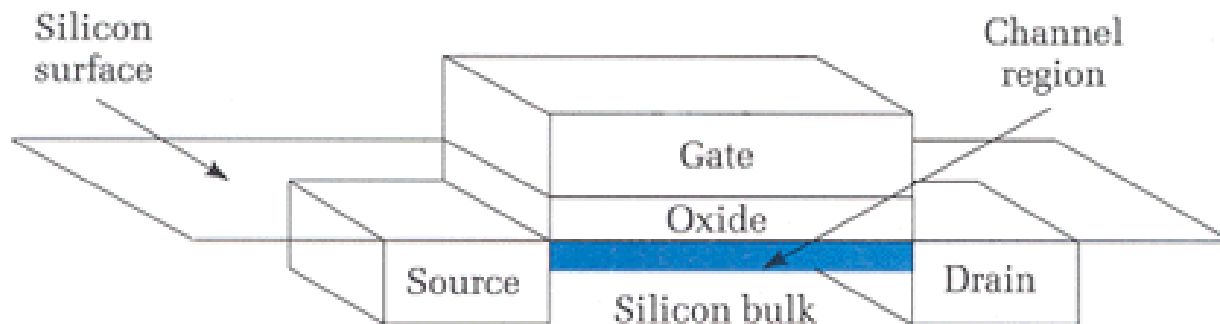
Bipolar Junction Transistors

- Note: Not all the electrons are injected directly from emitter to collector. Some are absorbed into the positive voltage terminal at the base, some are absorbed by the p-type section, some stay in one of the n-type sections, etc.
- Most make it through though, and cause the constant current output to increase as V_{EB} rises
– **amplification!**



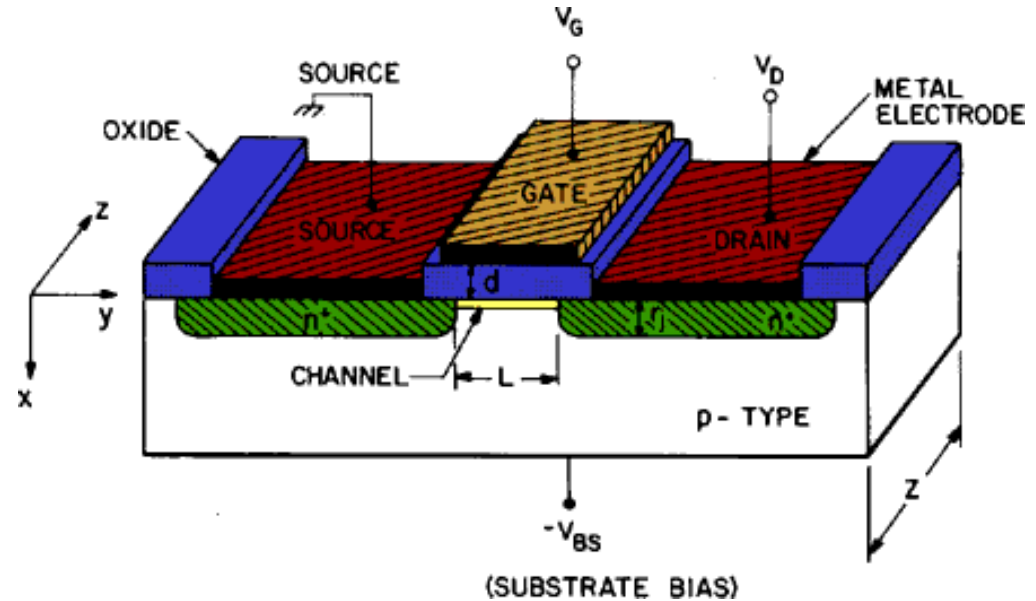
MOSFETs

- Metal Oxide Semiconductor Field Effect Transistors can be broken down into two components:
 - The “field effect” is an electric field that creates a channel between two n-type regions for electrons to pass through.
 - This field is generated by an electrically-charged metal layer that is shielded from the semiconductor material by an insulating oxidized layer (thus the MOS component).



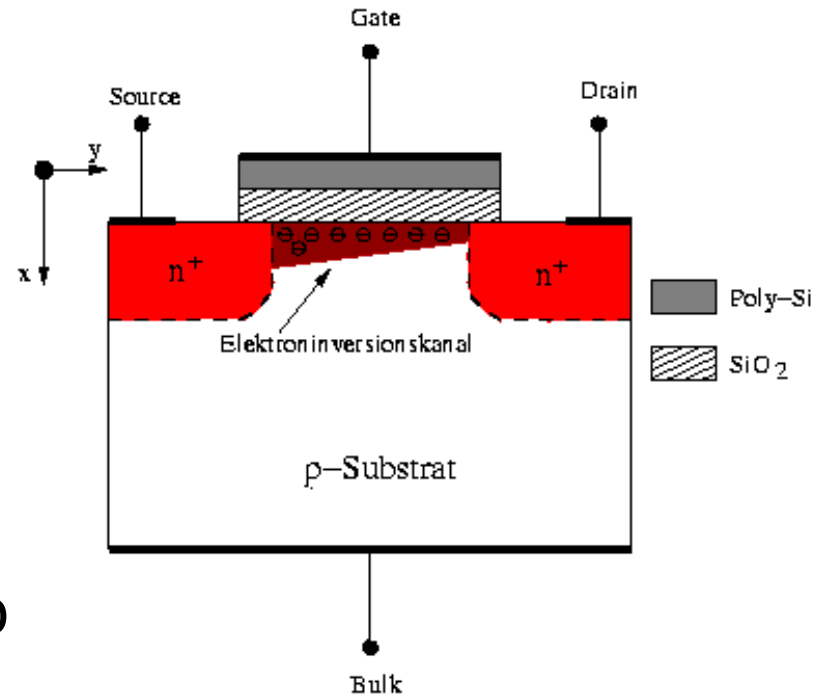
MOSFETs

- The semiconductor sections are two pockets of n-type material, resting on a **substrate** layer of p-type material.
- A voltage is applied across the two n-type sections, called the **drain** and the **source**. No current will pass through though, because of the intermediate p layer.

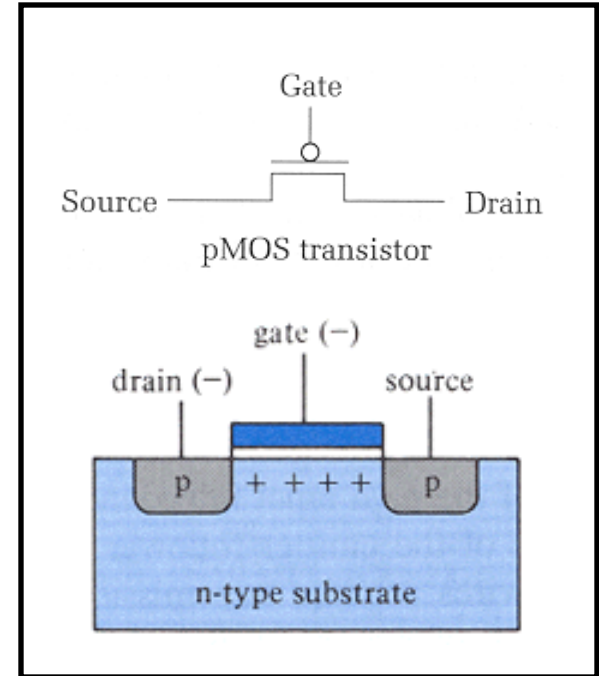
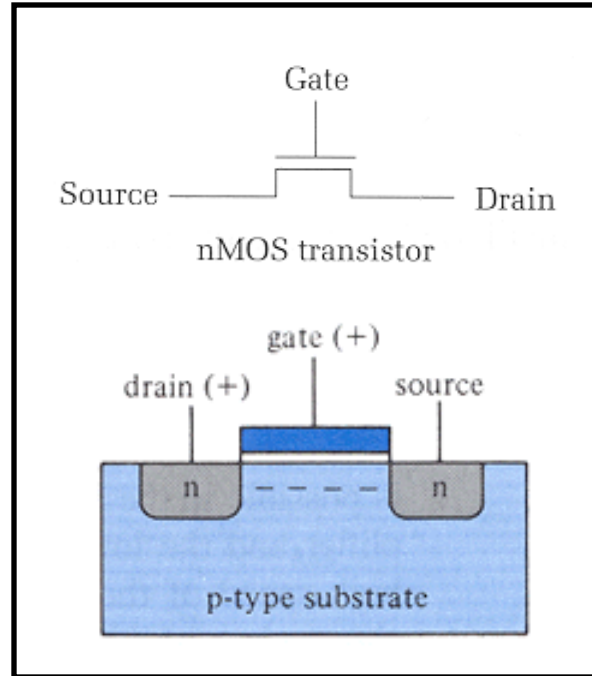
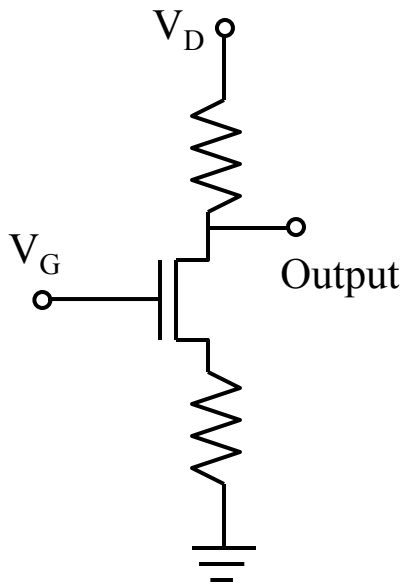


MOSFETs

- However, when a voltage is applied between the source and the metal plate (called the **gate**), this causes a buildup of positive charge in the metal layer, which draws a layer of negative charge to the surface of the substrate.
- This layer of electrons creates a virtual n-type channel between the drain to the source, allowing current to flow between them.
 - the wider the channel, the higher the current



MOSFETs



- Note: Two different types of MOSFET exist, based on the semiconductor type of the drain and source.
- The small circle in the **pMOS** diagram indicates an inverted input (in this case, a negative channel)

Transistors to Gates

- In the end, we want to model basic logic functions by using transistors.
- Consider then, the truth table that results from the various combinations of transistor inputs:

BJT (slide 14)

V_{EB}	V_C	Output
Low	Low	Low
Low	High	High
High	Low	Low
High	High	Low

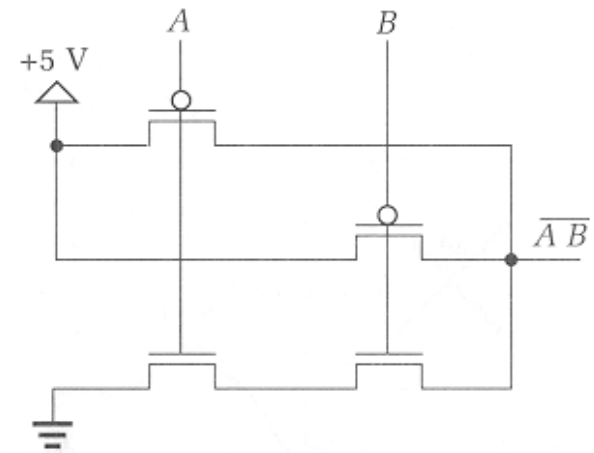
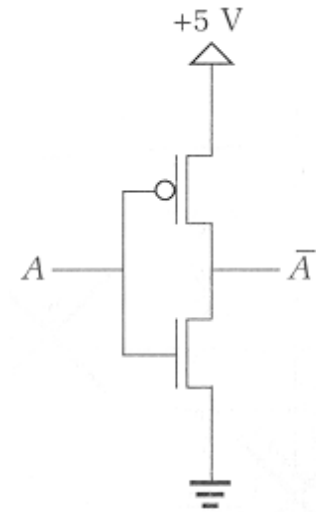
MOSFET

V_{DS}	V_{GS}	Output
Low	Low	Low
Low	High	Low
High	Low	High
High	High	Low

- Conclusion: Can be used to model logic operations.

Makin' Gates

- Since these transistors aren't simply on/off switches, digital logic gates (**AND**, **OR**, **NOT**) are created by a combination of transistors
 - Examples: inverter (NOT) at top, **NAND** gate at bottom
- Physical data:
 - "High" input = 5V
 - "Low" input = 0V
 - Switching time \approx 120 picoseconds
 - Switching interval \approx 10 ns
 - NAND is most common logic gate



Transistor Fabrication

- Transistors are not formed by pushing large chunks of n- and p-type semiconductors together.
- Transistors are now made by bombarding silicon with doping substances to create the layers for each junction
 - surface is oxidized in between stages to ensure that only the necessary sections are doped.

