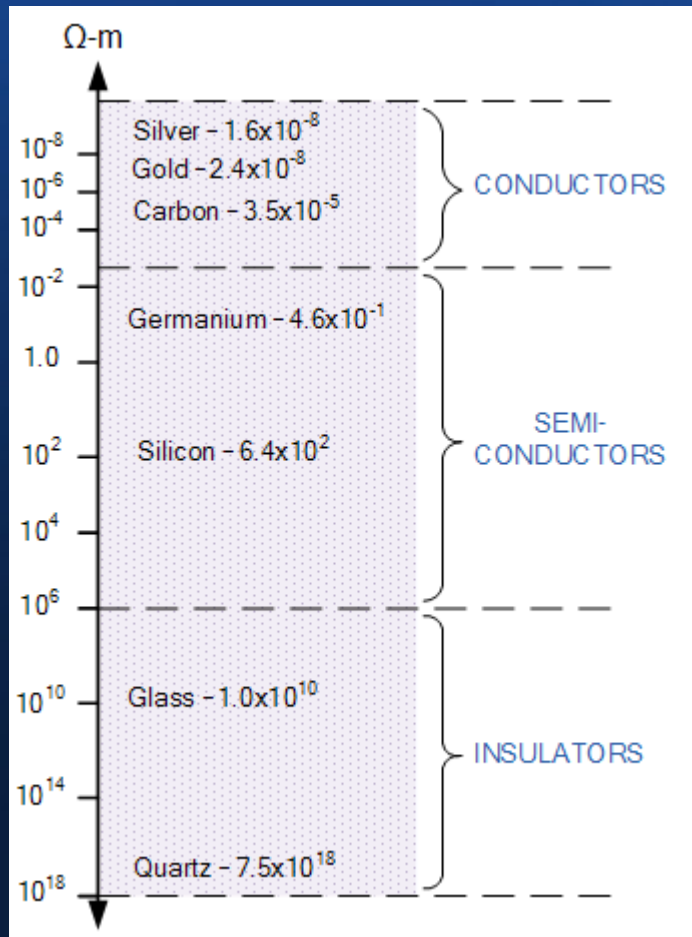


Electrical resistivity quantifies how strongly a given material opposes the flow of electric current.



A low resistivity indicates a material that readily allows the movement of electric charge. Resistivity is commonly represented by the Greek letter  $\rho$ .

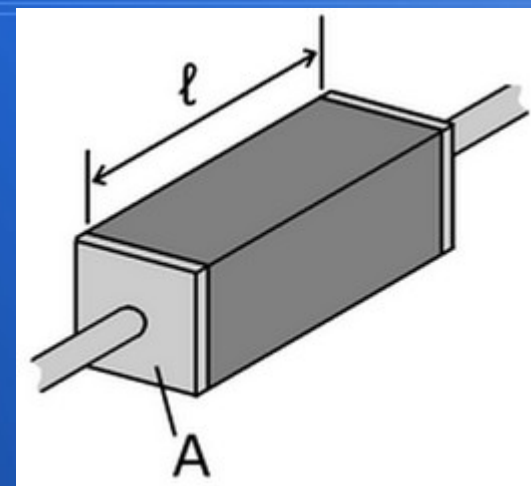
The SI unit of electrical resistivity is the ohm·metre ( $\Omega\cdot\text{m}$ )

Electrical conductivity is the reciprocal of electrical resistivity.

If a  $1\text{ m} \times 1\text{ m} \times 1\text{ m}$  solid cube of material has sheet contacts on two opposite faces, and the resistance between these contacts is  $1\ \Omega$ , then the resistivity of the material is  $1\ \Omega\cdot\text{m}$ .

$$\rho = R \frac{A}{\ell}$$

In a hydraulic analogy, passing current through a high-resistivity material is like pushing water through a pipe full of sand—while passing current through a low-resistivity material is like pushing water through an empty pipe.



If the pipes are the same size and shape, the pipe full of sand has higher resistance to flow. Resistance, however, is not solely determined by the presence or absence of sand. It also depends on the length and width of the pipe: short or wide pipes have lower resistance than narrow or long pipes. All copper wires, irrespective of their shape and size, have approximately the same resistivity, but a long, thin copper wire has a much larger resistance than a thick, short copper wire.

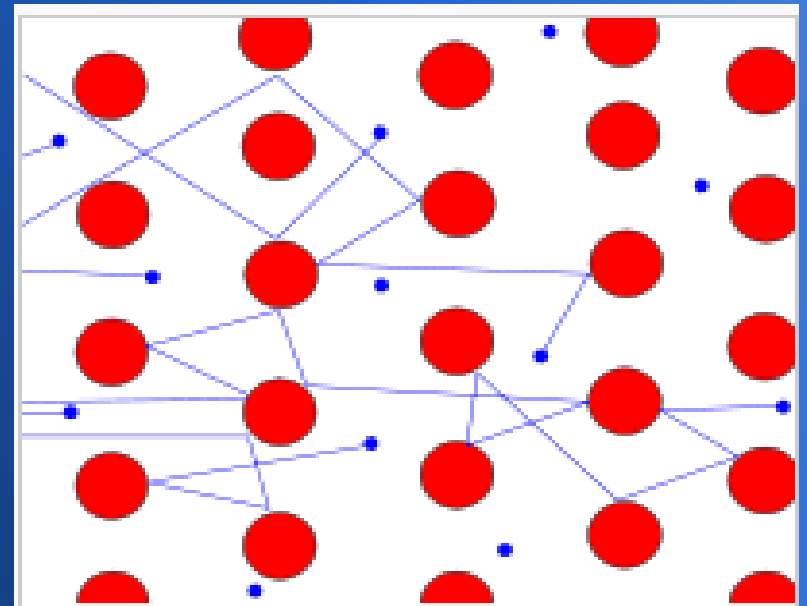
# Drude model was proposed in 1900 by Paul Drude to explain the transport properties of electrons in materials.

The Drude model treats electrons (or other charge carriers) like pinballs bouncing among the ions that make up the structure of the material.

Electrons will be accelerated in the opposite direction to the electric field by the average electric field at their location.

With each collision, though, the electron is deflected in a random direction with a velocity that is much larger than the velocity gained by the electric field.

The net result is that electrons take a zigzag path due to the collisions, but generally drift in a direction opposing the electric field.



This simple classical Drude model provides a very good explanation of DC and AC resistivity in metals

Electrical resistivity (also known as resistivity, specific electrical resistance, or volume resistivity) is an intrinsic property that quantifies how strongly a given material opposes the flow of electric current

The resistance of a given object depends primarily on two factors: What material it is made of, and its shape.

For a given material, the resistance is inversely proportional to the cross-sectional area; for example, a thick copper wire has lower resistance than an otherwise identical thin copper wire.

Also, for a given material, the resistance is proportional to the length; for example, a long copper wire has higher resistance than an otherwise-identical short copper wire.

Electrical resistance shares some conceptual parallels with the mechanical notion of friction

# SEMICONDUCTORS

A semiconductor has electrical conductivity intermediate to that of a conductor and an insulator.

Semiconductor materials are useful because their behaviour can be manipulated by the addition of impurities, known as doping.

The comprehensive theory of semiconductors relies on the principles of quantum physics to explain the motions of electrons through a lattice of atoms.



## Variable conductivity

A pure semiconductor is a poor electrical conductor as a consequence of having just the right number of electrons to completely fill its valence bonds.

Through various techniques (e.g., doping or gating), the semiconductor can be modified to have excess of electrons (becoming an n-type semiconductor) or a deficiency of electrons (becoming a p-type semiconductor).

In both cases, the semiconductor becomes much more conductive (the conductivity can be increased by one million fold or more). Semiconductor devices exploit this effect to shape electrical current.

A semiconductor has electrical conductivity intermediate to that of a conductor and an insulator

Electrical resistivity is a property of a material; it quantifies how strongly the material opposes the flow of electric current

In copper, every single copper atom donates one movable electron to the "sea of charge."

Copper's "electric fluid" is very dense; just as dense as the copper metal

In doped silicon, only one in every billion atoms donates a movable charge. Silicon is like a big empty space with an occasional wandering charge

# Lithography

Lithography originally used an image drawn with oil, fat, or wax onto the surface of a smooth, level lithographic limestone plate.

The stone was treated with a mixture of acid and gum arabic, etching the portions of the stone which were not protected by the grease-based image.

When the stone was subsequently moistened, these etched areas retained water; an oil-based ink could then be applied and would be repelled by the water, sticking only to the original drawing.



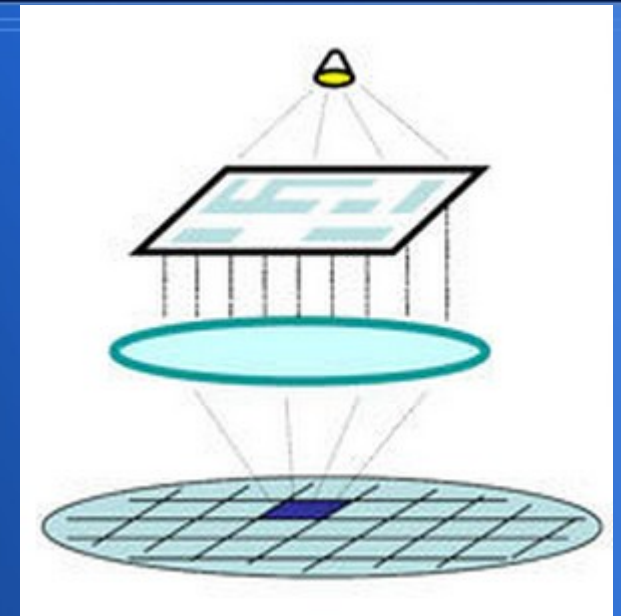


The word lithography comes from the Greek lithos, meaning stones, and graphia, meaning to write. It means quite literally writing on stones.

In the case of semiconductor photolithography, our stones are silicon wafers and our patterns are written with a light-sensitive polymer called photoresist.

To build the complex structures that make up a transistor and the many wires that connect the millions of transistors of a circuit, lithography and pattern transfer steps are repeated at least 10 times, but more typically are done 20 to 30 times to make one circuit.

Each pattern being printed on the wafer is aligned to the previously formed patterns and slowly the conductors, insulators, and selectively doped regions are built up to form the final device.



Photolithography is the process of transferring geometric shapes on a mask to the surface of a silicon wafer.

Integrated circuits having sub micron geometric features are manufactured by optically projecting patterns of light onto silicon wafers.

Prior to exposure, the wafers are coated with a photo resistive material that either hardens or softens when exposed to light.

Removing extraneous photo resist leaves patterns of exposed silicon.

The exposed regions are then implanted with dopant atoms to create a semiconductor material having the electrical properties of transistors and the logical properties of gates

Any of a number of semiconductor materials can be and are used, indeed the first transistor was actually a Germanium (Ge) transistor. the real reason Si is so dominant comes down to 4 principal reasons ( but #1 is the primary reason):

- 1) It forms an oxide that is of very high quality, seals the surface with very few pin holes or gaps. - this allows gap MOSFETs to be more easily made as the  $\text{SiO}_2$  forms the insulating layer for the Gate, -  $\text{SiO}_2$  has been called the chip designers friend.
- 2) It forms a very tough Nitride,  $\text{Si}_3\text{N}_4$  Silicon Nitride forms a very high bandgap insulator which is impermeable. - this is used to passivate (seal) the die. - this also used to make hard masks and in other process steps
- 3) Si has a very nice bandgap of  $\sim 1.12$  eV, not too high so that room temperature can't ionize it, and not so low that it has to high leakage current.

4) it forms a very nice gate material. Most modern FET's used in VLSI (up until the latest generations) have been called MOSFET but in actual fact have used Si as the gate material. It turns out that it is very easy to deposited non-crystalline Si on surfaces and it is easily etched to great precision.

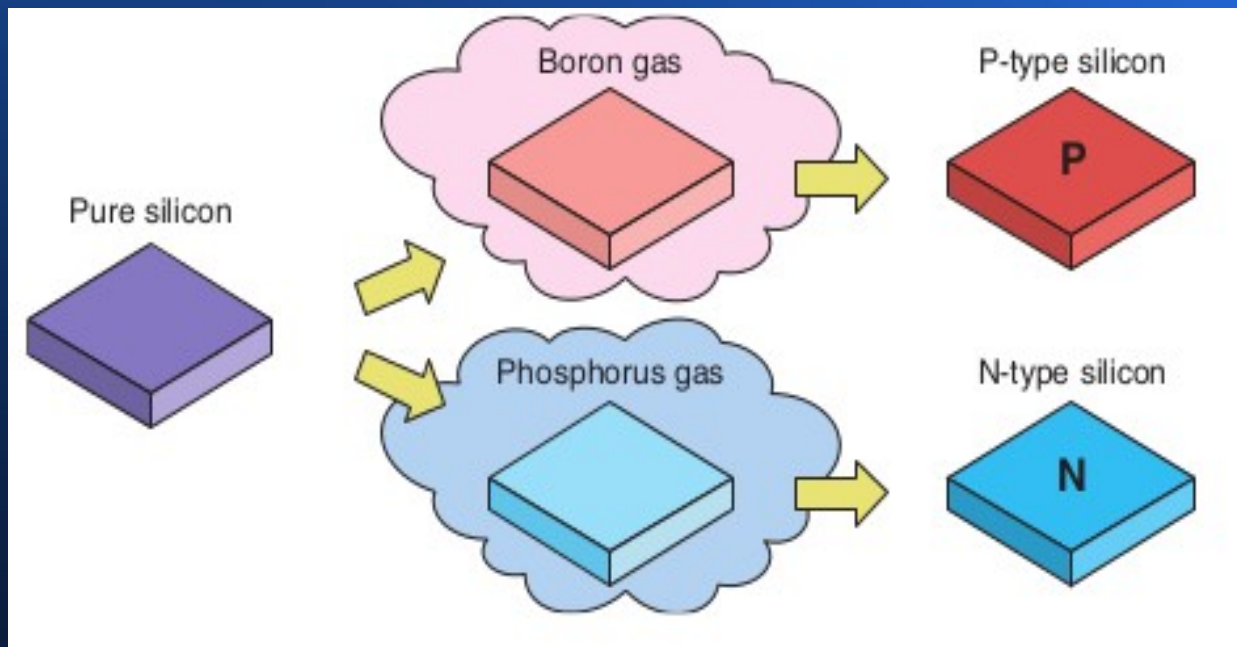
Basically the success of Si is the success of MOSFET, which with scaling and extreme integration has driven the industry. Mosfet's are not so easily manufactured in other material systems, and you can't drive the same level of integration in other semicondcutors.

GeO<sub>2</sub> - is partially soluble GaAs - does not form a oxide  
CO<sub>2</sub> - is a gas

Semiconductors are used because with selective contamination (called dopants) you can control the properties of the material and tailor it's operation and operational mechanisms.



If a piece of pure silicon is surrounded by a gas containing boron or phosphorus and heated in a high-temperature oven, the boron or phosphorus atoms will permeate the crystal lattice and displace some silicon atoms without disturbing other atoms in the vicinity



Boron atoms have only three electrons in their outermost electron shells, phosphorous atoms have five electrons in their outermost electron shells



# Acceptors, p-type Silicon dopants

Boron is a p-type dopant. Its diffusion rate allows easy control of junction depths. Common in CMOS technology. Can be added by diffusion of diborane gas. The only acceptor with sufficient solubility for efficient emitters in transistors and other applications requiring extremely high dopant concentrations. Diffuses about as fast as phosphorus.

Aluminium, used for deep p-diffusions. Not popular in VLSI and ULSI. Also a common unintentional impurity.

Nitrogen is important for growing defect-free silicon crystal. Improves mechanical strength of the lattice, increases bulk microdefect generation, suppresses vacancy agglomeration.

Gallium is a dopant used for long-wavelength infrared photoconduction silicon detectors in the 8-14  $\mu\text{m}$  atmospheric window. Gallium-doped silicon is also promising for solar cells, due to its long minority carrier lifetime with no lifetime degradation; as such it is gaining importance as a replacement of boron doped substrates for solar cell applications.

Indium is a dopant used for long-wavelength infrared photoconduction silicon detectors in the 3-5  $\mu\text{m}$  atmospheric window.

## Donors, n-type

Phosphorus is a n-type dopant. It diffuses fast, so is usually used for bulk doping, or for well formation. Used in solar cells. Can be added by diffusion of phosphine gas. Bulk doping can be achieved by nuclear transmutation, by irradiation of pure silicon with neutrons in a nuclear reactor. Phosphorus also traps gold atoms, which otherwise quickly diffuse through silicon and act as recombination centers.

Arsenic is a n-type dopant. Its slower diffusion allows using it for diffused junctions. Used for buried layers. Has similar atomic radius to silicon, high concentrations can be achieved. Its diffusivity is about a tenth of phosphorus or boron, so is used where the dopant should stay in place during subsequent thermal processing. Useful for shallow diffusions where well-controlled abrupt boundary is desired. Preferred dopant in VLSI circuits. Preferred dopant in low resistivity ranges.

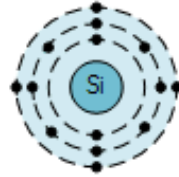
Antimony is a n-type dopant. It has a small diffusion coefficient. Used for buried layers. Has diffusivity similar to arsenic, is used as its alternative. Its diffusion is virtually purely substitutional, with no interstitials, so it is free of anomalous effects. For this superior property, it is sometimes used in VLSI instead of arsenic. Heavy doping with antimony is important for power devices. Heavily antimony-doped silicon has lower concentration of oxygen impurities; minimal autodoping effects make it suitable for epitaxial substrates.

Bismuth is a promising dopant for long-wavelength infrared photoconduction silicon detectors, a viable n-type alternative to the p-type gallium-doped material.

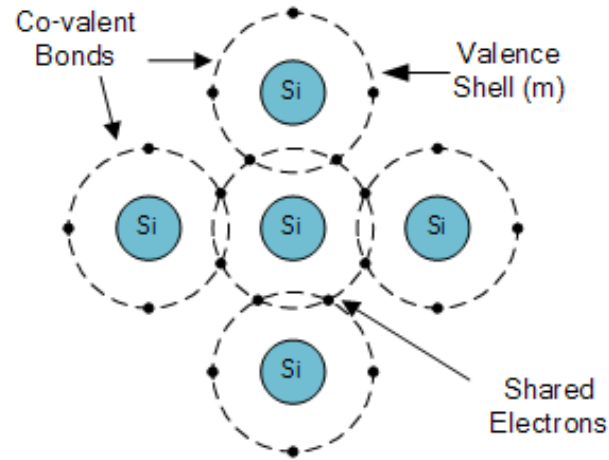
Lithium is used for doping silicon for radiation hardened solar cells. The lithium presence anneals defects in the lattice produced by protons and neutrons. Lithium can be introduced to boron-doped p<sup>+</sup> silicon, in amounts low enough to maintain the p character of the material, or in large enough amount to counterdope it to low-resistivity n type.

## A Silicon Atom Structure

A Silicon Atom,  
Atomic number = "14"



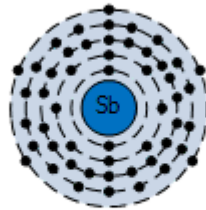
Silicon atom showing  
4 electrons in its outer  
valence shell (m)



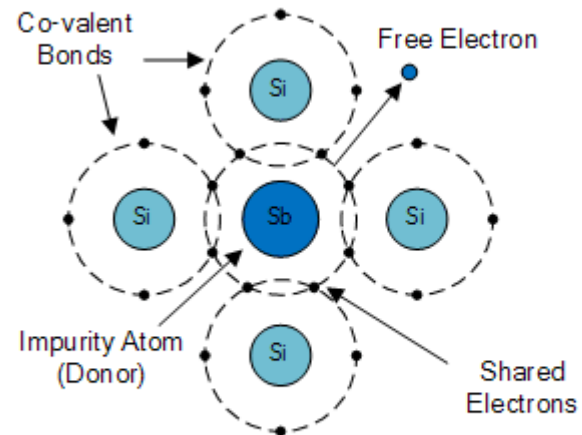
Silicon Crystal Lattice

## Antimony Atom and Doping

An Antimony Atom,  
Atomic number = "51"



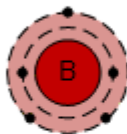
Antimony atom showing  
5 electrons in its outer  
valence shell (o)



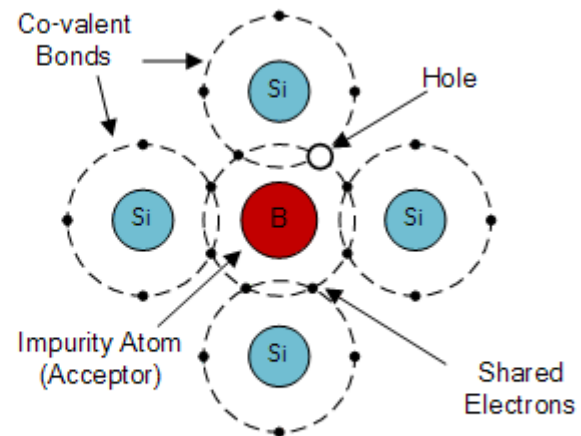
N-Type  
Semiconductor

## Boron Atom and Doping

A Boron Atom,  
Atomic number = "5"

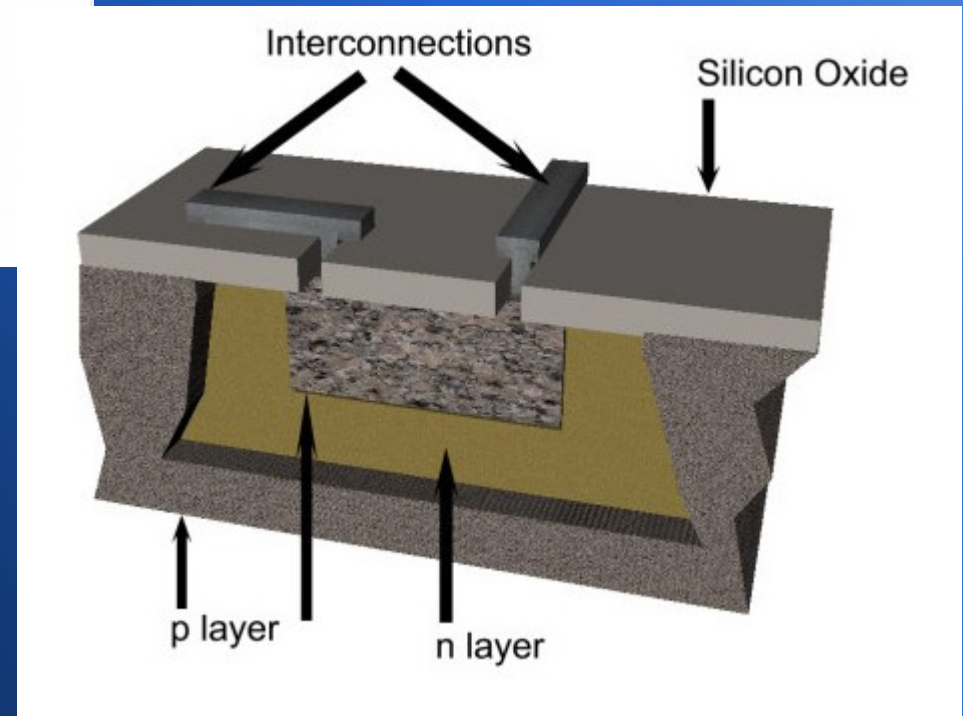
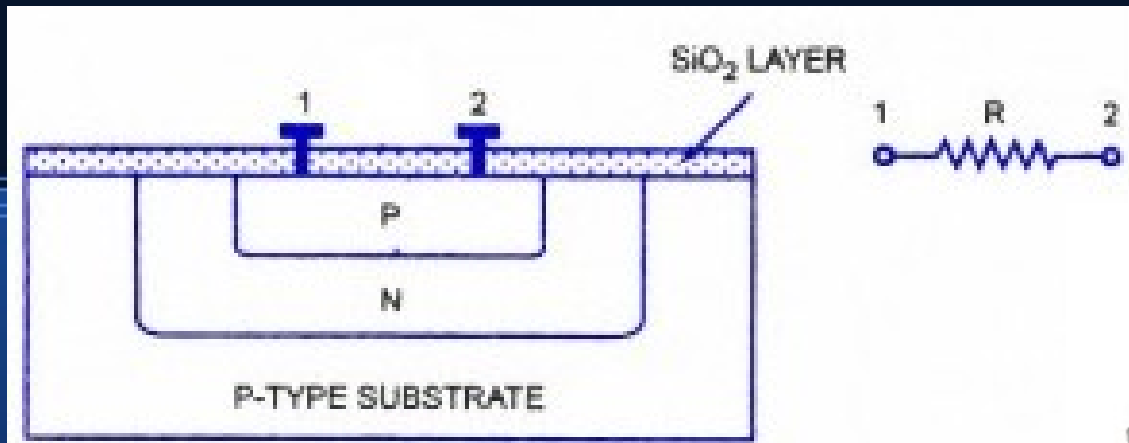


Boron atom showing  
3 electrons in its outer  
valence shell (L)



P-Type  
Semiconductor

# Integrated Circuit Resistor



In IC resistors, the resistance value can be controlled by varying the concentration of doping impurity and depth of diffusion. The range of resistor values that may be produced by the diffusion process varies from ohms to hundreds of kilohms. The typical tolerance, however, may be no better than  $\pm 5\%$ , and may even be as high as  $\pm 20\%$



# Depletion

When doped semiconductors are joined to metals, to different semiconductors, and to the same semiconductor with different doping, the resulting junction often strips the electron excess or deficiency out from the semiconductor near the junction.

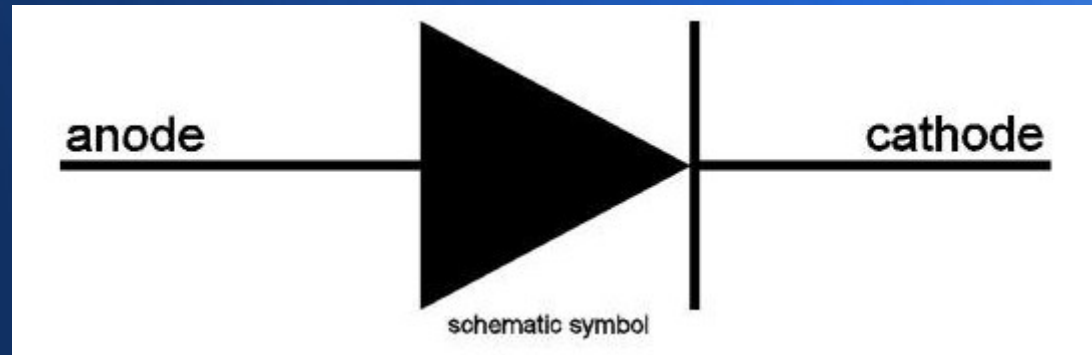
This depletion region is rectifying (only allowing current to flow in one direction), and used to further shape electrical currents in semiconductor devices.

# Semiconductor Diode

In electronics, a diode is a two-terminal electronic component with asymmetric transfer characteristic, with low (ideally zero) resistance to current flow in one direction, and high (ideally infinite) resistance in the other.

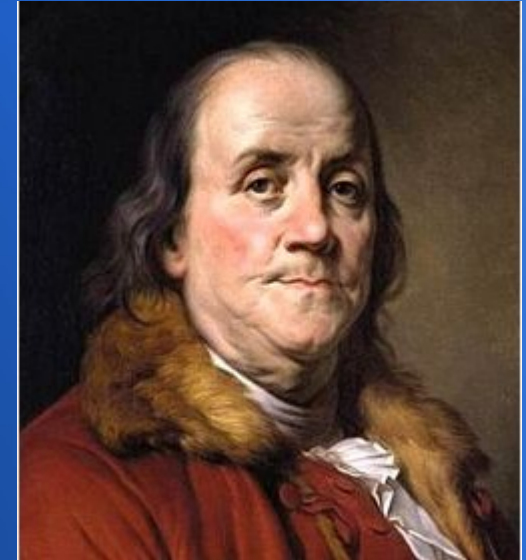
A semiconductor diode, the most common type today, is a crystalline piece of semiconductor material with a p-n junction connected to two electrical terminals

In a diode, the cathode is the negative terminal at the pointed end of the arrow symbol, where current flows out of the device



Benjamin Franklin (1706 - 1790) was one of the Founding Fathers of the United States

When Benjamin Franklin was theorising about the nature of an electric current (long before the discovery of atoms), he thought that it was some sort of 'fluid' that flowed from an area of high pressure, which he labelled as 'positive', to an area of low pressure, which he labelled as 'negative'.



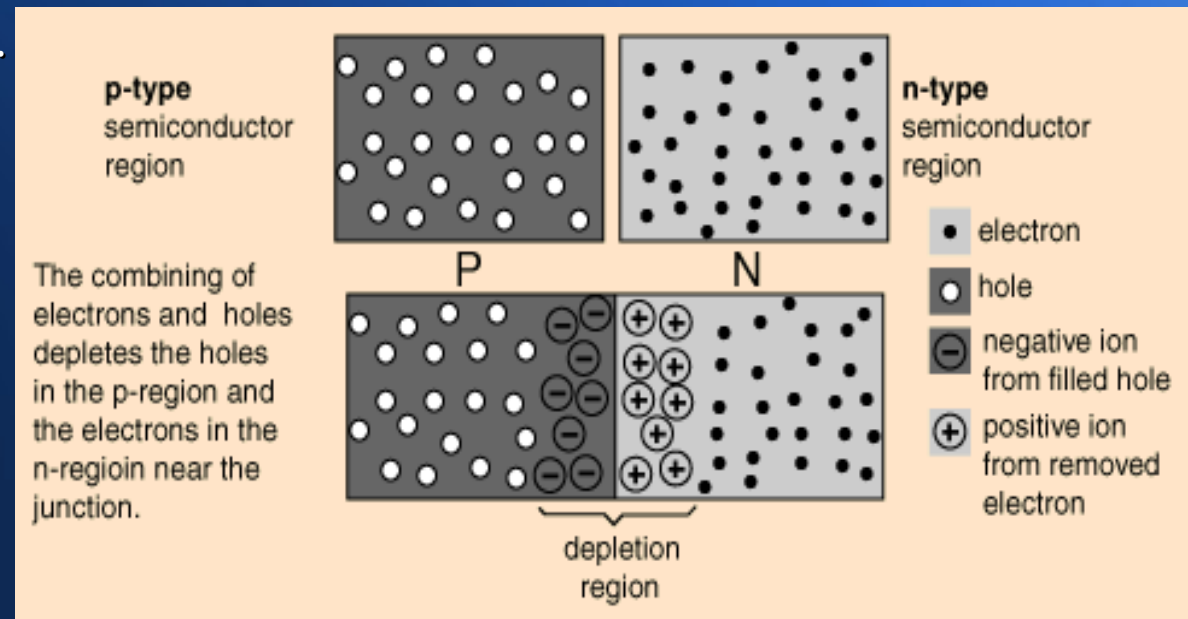
Although we know that, in a metal conductor at least, an electric current is a flow of negative charges (electrons) that flow from negative to positive, many (but by no means all) textbooks still use Franklin's current direction which is called 'Franklinian Flow' or, more commonly, 'Conventional Flow'

Electrons are negatively charged, and so are attracted to the positive end of a battery and repelled by the negative end. So when the battery is hooked up to something that lets the electrons flow through it, they flow from negative to positive

# Depletion Region

The P-Type semiconductor has excess holes. The N-Type semiconductor has excess electrons. Due to this difference, some of the electrons get attracted to the corresponding nearest holes and are eliminated by recombination. This process takes place until an equilibrium is reached in the surrounding region of the contact surface.

The net result is the diffused electrons and holes are gone, leaving behind the charged ions adjacent to the interface in a region with no mobile carriers (called the depletion region)





The Depletion layer appears when electrons fall into holes, so the silicon has turned into an insulator

Following transfer, the diffused electrons come into contact with holes on the P-side and are eliminated by recombination.

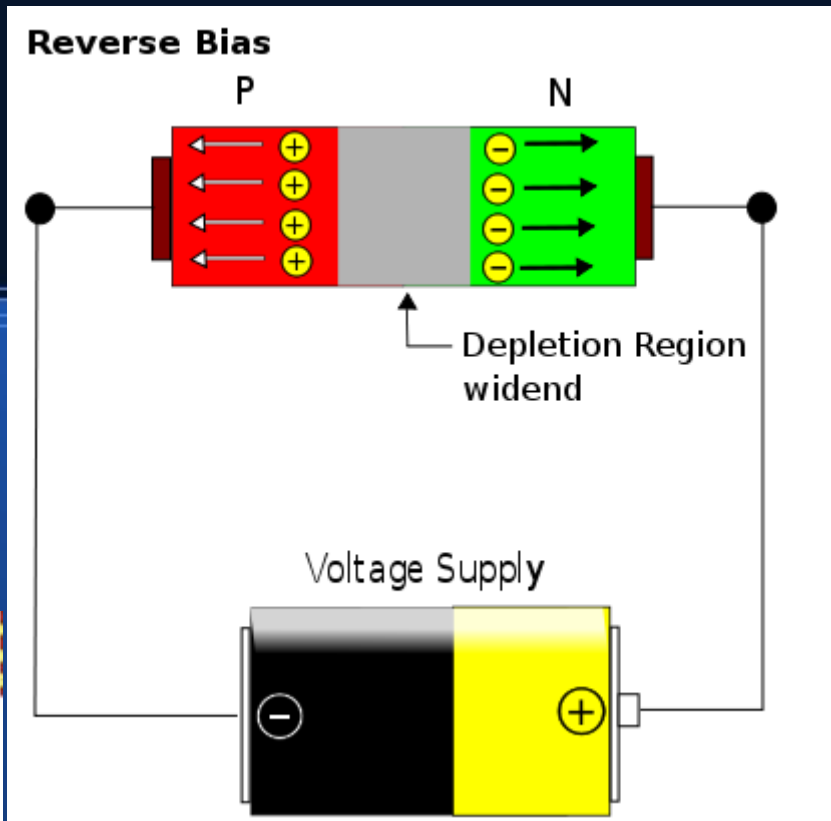
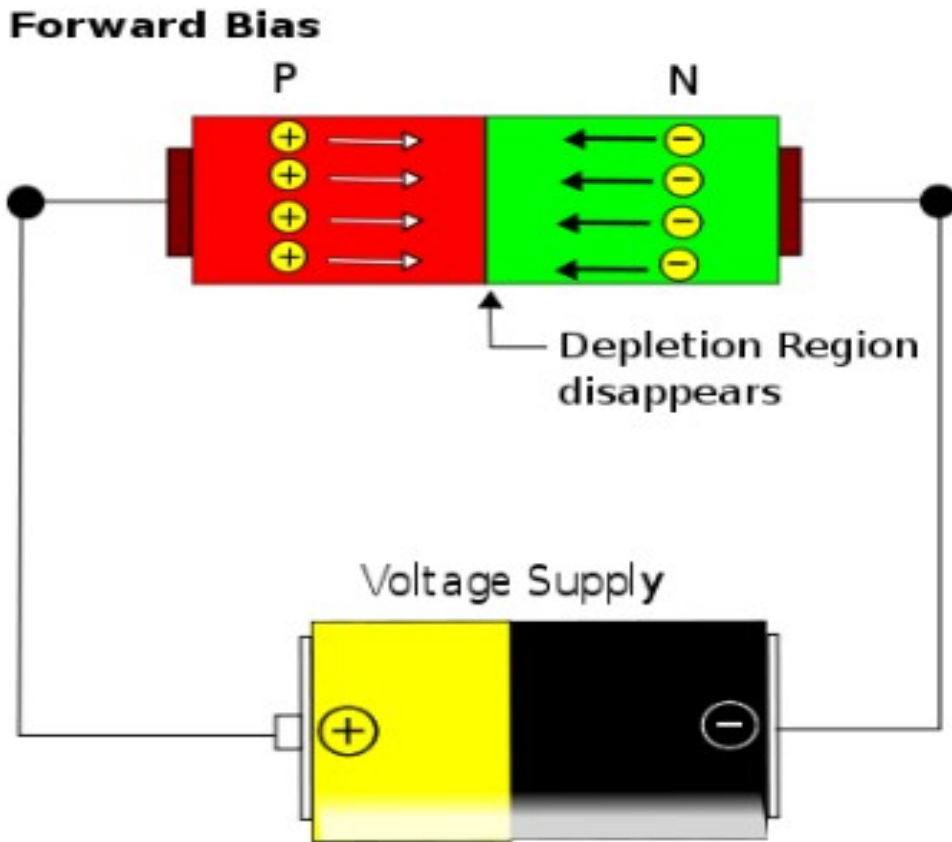
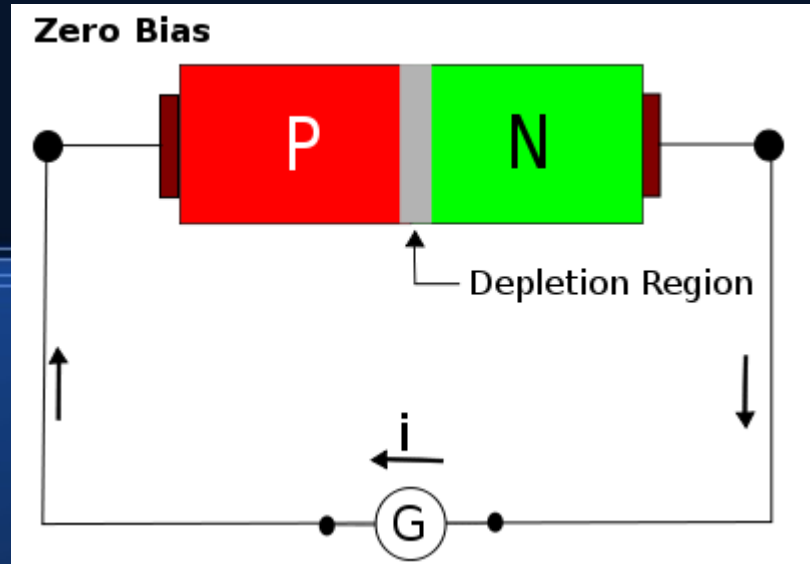
Likewise for the diffused holes on the N-side.

The net result is the diffused electrons and holes are gone, leaving behind the charged ions adjacent to the interface in a region with no mobile carriers (called the depletion region).

The uncompensated ions are positive on the N side and negative on the P side.

This creates an electric field that provides a force opposing the continued exchange of charge carriers.

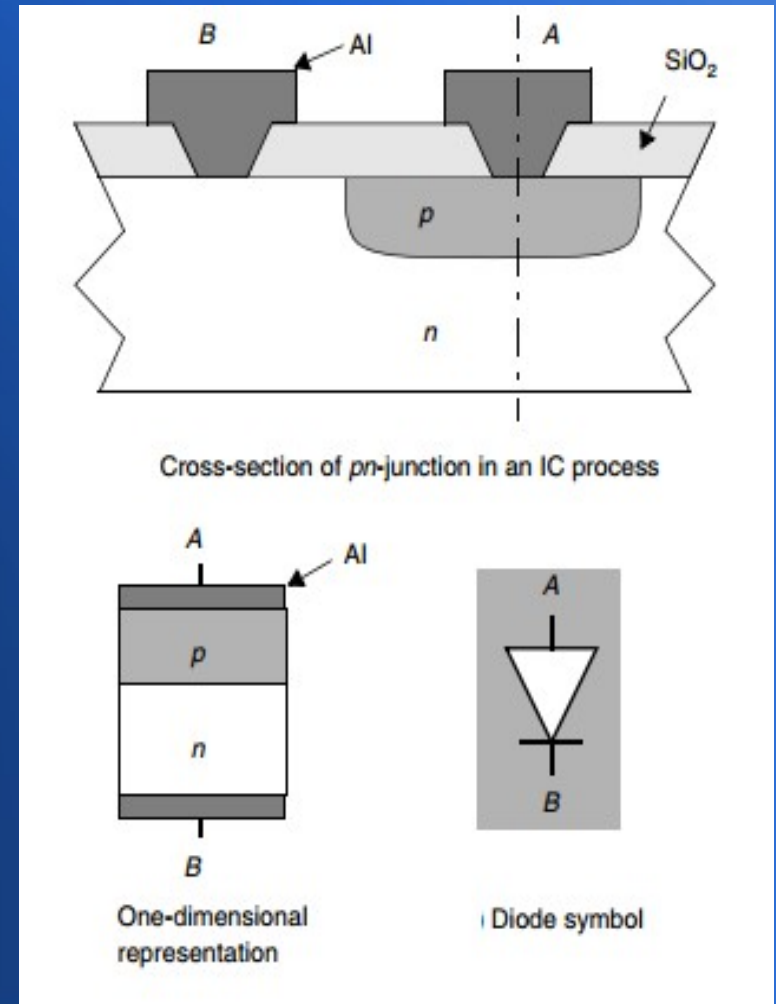
When the electric field is sufficient to arrest further transfer of holes and electrons, the depletion region has reached its equilibrium dimensions



A galvanometer is a type of sensitive ammeter: an instrument for detecting electric current. It is an analog electromechanical actuator that produces a rotary deflection of some type of pointer in response to electric current through its coil in a magnetic field.

If you connect the anode and cathode of the diode you might be able to observe a small voltage or current that is insignificant.

This is because the electromagnetic spectrum that is present in our environment by default knocks off electrons in the semiconductor lattice that constitutes current.



In the N-type region electrons are the majority carriers and in the P-type electron "holes" are the majority carriers.

If **forward-biased** (applying a positive voltage to the P region and a negative voltage to the N region), the depletion region of the diode decreases. The electrons on the N side are repelled and they move towards the P side thus reducing the size of the depletion layer.

If **reverse-biased**, the depletion region increases because the electrons are attracted towards the positive voltage and the holes are attracted towards the negative voltage, and hence the current gets reduced and the current flowing will be very small, on the order of micro amps



At one particular voltage level  $V_f$  called the threshold / firing / cut-off voltage the depletion layer disappears (overwhelmed by the charge) and hence from this point on the diode starts to conduct very easily.

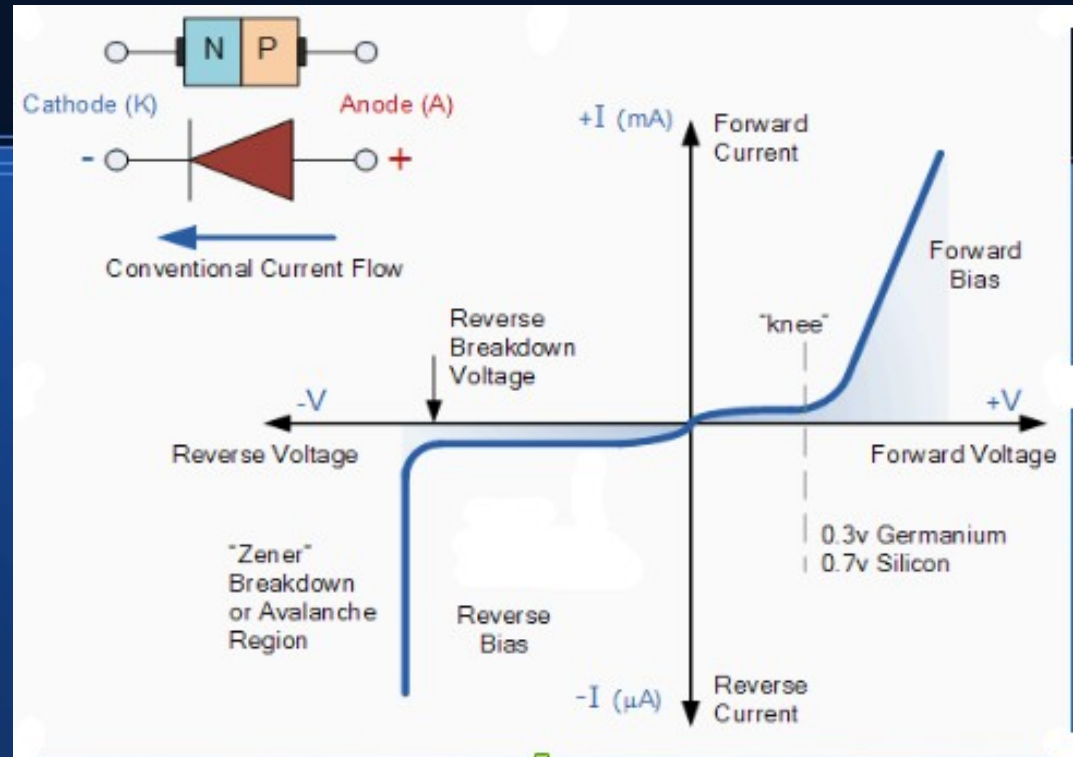
From this point on the diode current increases exponentially to the voltage applied.

# I-V Characteristics of a p-n junction diode

The negative current axis is on a different scale (showing millionths of an amp rather than thousandths) this is so we can indicate the very small leakage current which flows due to electron hole pair generation (ie due to the natural conduction properties of the pure silicon). The

leakage current flows in both directions but is too small to indicate on the current scale used on the forward part of the characteristic.

If a large enough reversed bias voltage is applied the diode will eventually conduct due to zener then avalanche breakdown (ie due to the natural conduction properties of the pure silicon).



For silicon diodes, the typical forward voltage is 0.7 volts, nominal.

For germanium diodes, the forward voltage is only 0.3 volts.

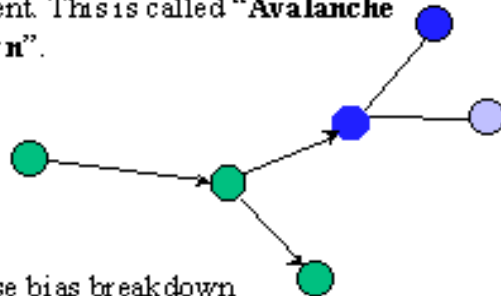
The chemical constituency of the P-N junction comprising the diode accounts for its nominal forward voltage figure, which is why silicon and germanium diodes have such different forward voltages.

Forward voltage drop remains approximately constant for a wide range of diode currents, meaning that diode voltage drop is not like that of a resistor or even a normal (closed) switch.

For most simplified circuit analysis, the voltage drop across a conducting diode may be considered constant at the nominal figure and not related to the amount of current.

## Reverse bias breakdown

As the magnitude of the reverse bias voltage is increased, the current remains at  $I_0$  but eventually, the reverse bias field is so strong that thermally generated electrons (or holes) acquire enough kinetic energy to ionise atoms within the crystal structure. These in turn ionise other atoms leading to a very swift multiplication effect and a large current. This is called “**Avalanche breakdown**”.

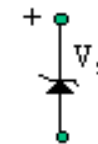
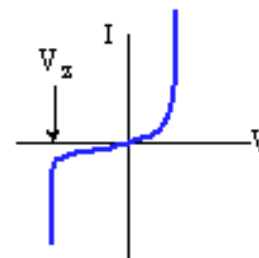


The reverse bias breakdown voltage is about 500V for Germanium and about 1kV for Silicon.

4 Data - 14

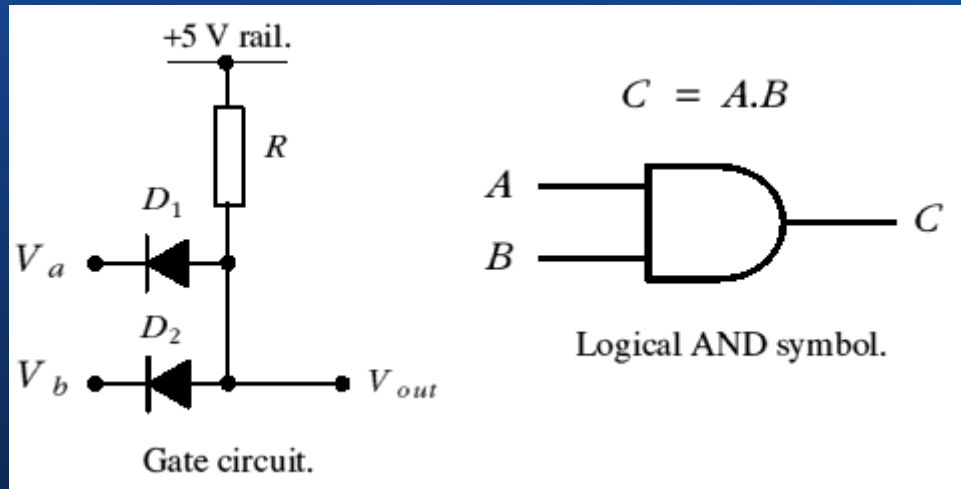
If the impurity doping density is high enough, then the depletion region is narrow enough (even in reverse bias) to allow the electric field across the region to be very high. The high accelerating field and narrow depletion region allows electrons to tunnel through. This is called “**Zener breakdown**”. Zener diodes are designed to breakdown in reverse bias. They can withstand a relatively large reverse current without damage. The reverse bias voltage leading to zener breakdown is adjustable during manufacture of the device.

Typical zener diodes have breakdown voltages anywhere between 2 to 200V depending on the application.



Diode logic (DL), or diode-resistor logic (DRL), is the construction of Boolean logic gates from diodes.

Diode logic was used extensively in the construction of early computers



If either input (A or B) is at ground potential (logic 0), then due to the higher potential on the anode side due to the positive voltage from resistor R, current will flow through the diode(s) and the voltage on the output will be equal to the forward voltage of the diode, 0.5v.

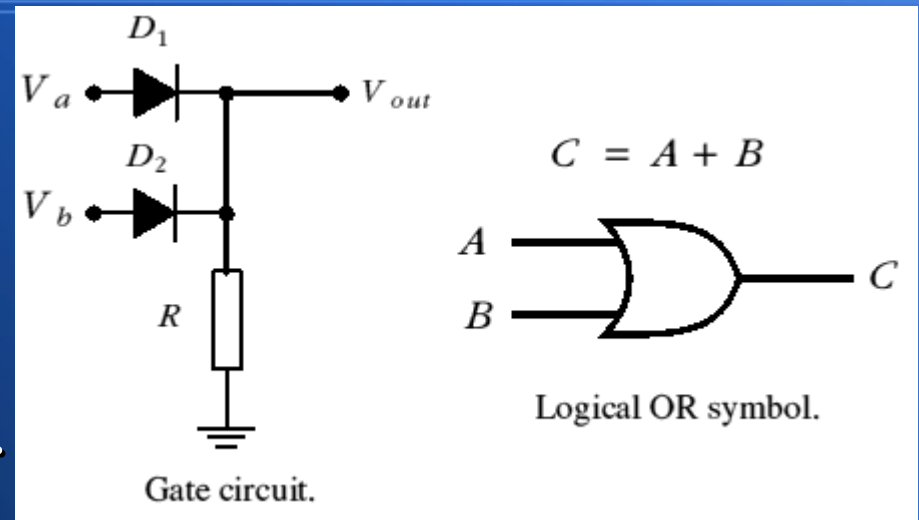
If both inputs to the AND gate are high (logic 1), then no current will pass through either diode, and the positive voltage through R will appear on the output

$V_a$ (V)	$V_b$ (V)	$V_{out}$ (V)	A	B	C
0	0	0.5	0	0	0
5	0	0.5	1	0	0
0	5	0.5	0	1	0
5	5	5	1	1	1



Current flows through a diode in the direction of the arrow.

In the case of the OR gate, if there is no potential (i.e. logic 0, or ground) on both inputs, no current will pass through either diode, and the pull-down resistor  $R$  will keep the output at ground (logic 0).



If either of the inputs has a positive (logic 1) voltage on its input (a or b), then current will pass through the diode(s) and appear on the output less the forward voltage of the diode (aka diode drop).

$V_a$ (V)	$V_b$ (V)	$V_{out}$ (V)	$A$	$B$	$C$
0	0	0	0	0	0
5	0	4.5	1	0	1
0	5	4.5	0	1	1
5	5	4.5	1	1	1

While diode logic has the advantage of simplicity, the lack of an amplifying stage in each gate limits its application.

Also note that it is not possible to construct an inverter with only diodes and resistors. AND and OR functions by themselves are not a complete logic without NOT.

Thus, there are some logic functions that cannot be implemented in diode-resistor logic. Fortunately, transistors solve all of these problems.