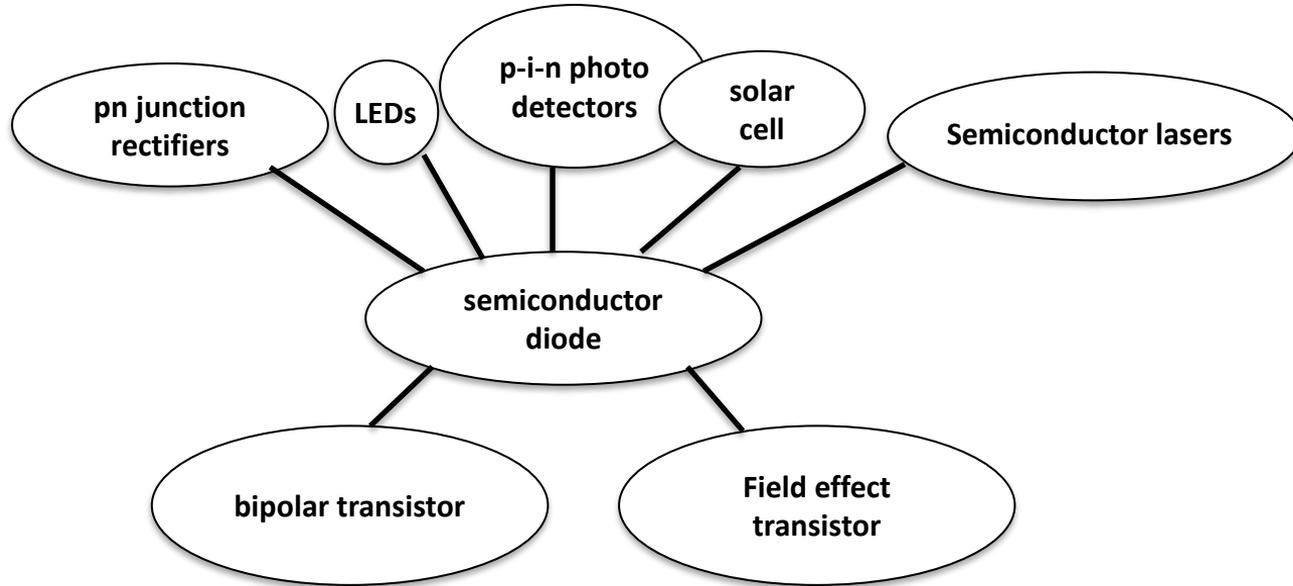


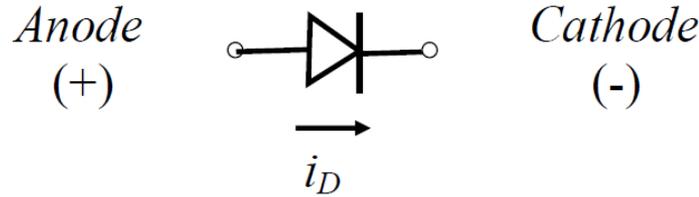
p-n junction. Operation principles of a semiconductor diode

Why we are discussing diodes? Because understanding the diode operation principles is the first step to understanding the operation principles of most of the electronic devices



Diode in electronic circuits

Symbolic representation of a Diode in circuits



An ideal diode conducts the current only in one direction

“Arrow” shows direction of the current in circuit

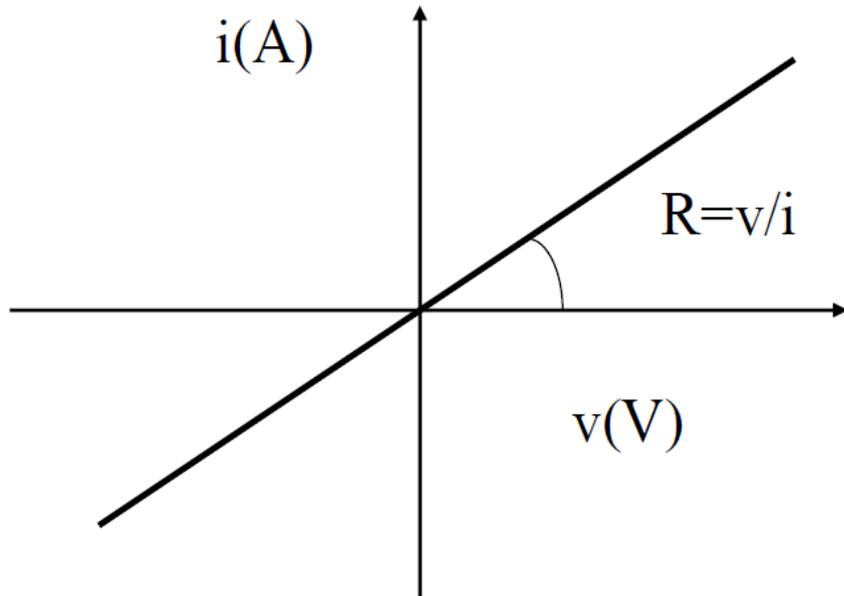
Positive polarity of the voltage at an anode and negative one at a cathode correspond to a forward bias condition

Minus at the anode and plus at the cathode correspond to reverse biasing

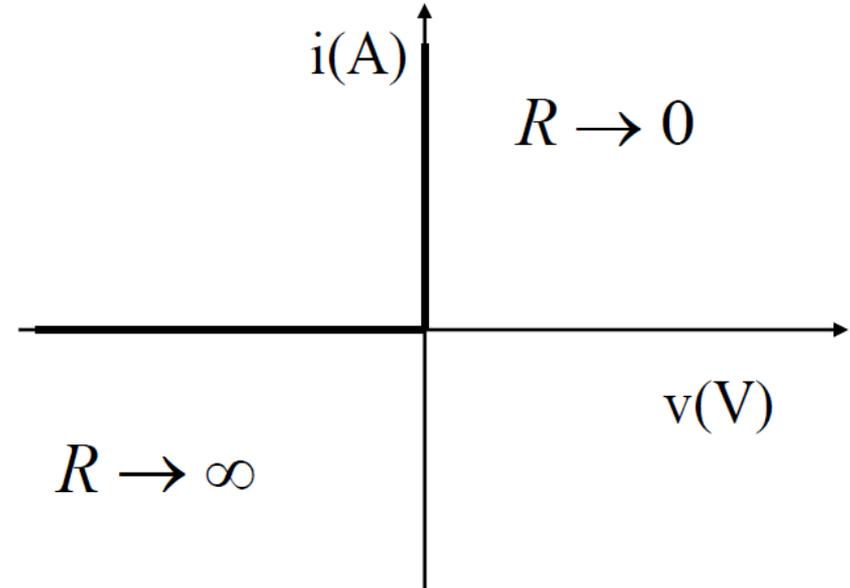
Diode as a non-linear resistor

Current-Voltage (I-V) Characteristics

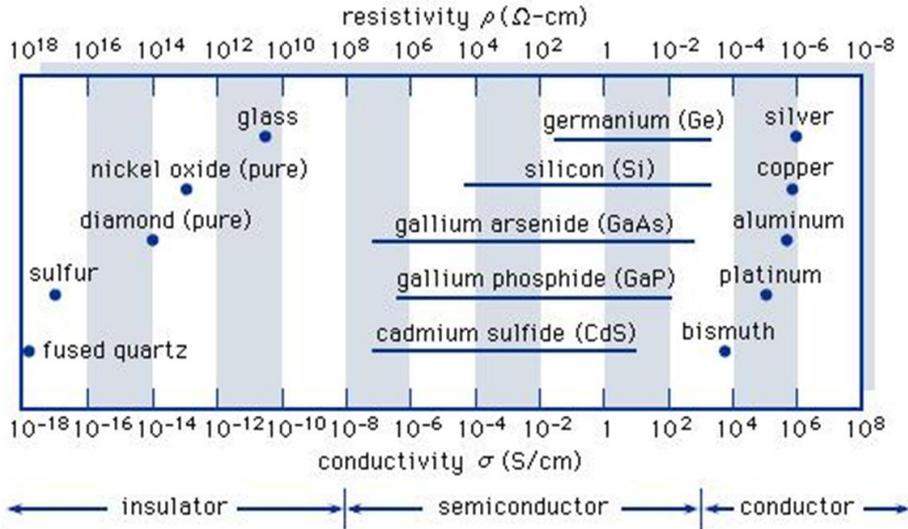
I-V of a LINEAR RESISTOR



I-V of an IDEALIZED DIODE



Why semiconductors?



1. Semiconductors can be manufactured with conductivity varying within a wide range.

2. Semiconductors possess mobile charges with two opposite signs: (-) and (+).

3. External electric field can penetrate the semiconductor and thus suppress or reinforce the internal atomic electric field.

The principal nature of p-n junction performance is based on the above semiconductor properties. These properties do not characterize either insulators or metals. Insulators do not possess enough free charges to conduct current. On the other hand, the concentration of free carriers in metals is too high to allow external electric field to penetrate creating the screening effect.

Below is the periodic table of elements. Our elements of interest are highlighted. Chemical compositions of these elements and some elements are semiconductors: Si, Ge, GaAs, PbTe etc.

hydrogen 1 H 1.0079																				helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180		
sodium 11 Na 22.990	magnesium 12 Mg 24.305											aluminum 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948			
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80			
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29			
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]		
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [269]	ununnium 110 Uun [271]	ununium 111 Uuu [272]	unubium 112 Uub [277]		ununquadium 114 Uuq [289]						

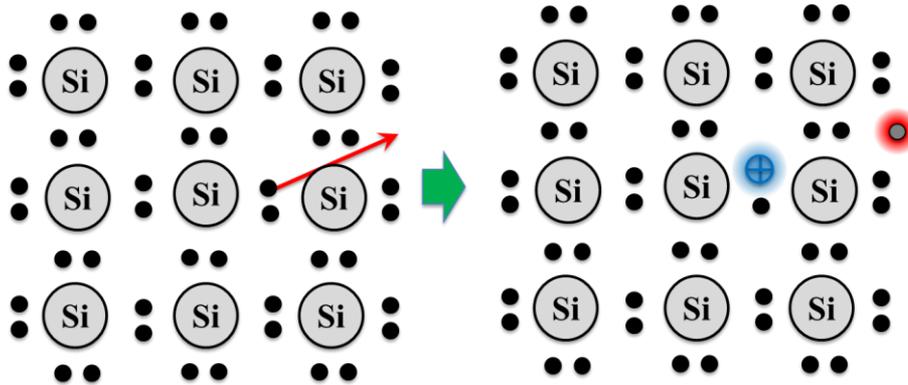
* Lanthanide series

** Actinide series

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

Charge transport in semiconductors: electrons and holes

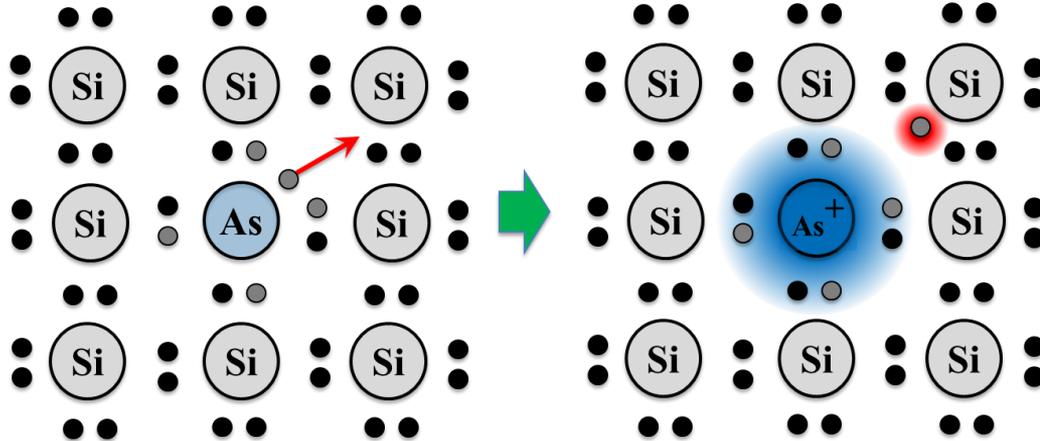
Below at the right side is a simplified scheme of a Si crystal. Each Si atom has 4 "hands" – outer electrons which form chemical bonds. In Figure below these electrons are shown as the black dots. One pair of dots is the "handshake" between Si atoms. So each atom can connect with 4 others and form a crystal – solid material where atoms are in almost perfect order. Electrons are bound to atoms and cannot move. However, if we spend some energy (illuminate or heat the crystal), and rip the electron out of the bond, the electron will be able to move in the crystal and transfer the electric current. If there are many of such electrons, the material becomes conductive.



Since the atoms are electrically neutral, after the electron leaves the atom it leaves a positively charged empty space, kind of a positively charged bubble – “the hole”. Another electron from the neighbor atom can fill in the empty space – it looks as the positively charged “hole” jumped the the next atoms. The holes, as well as the electrons can transfer the current.

n-type semiconductor: electrical current is a flow of the negatively charged electrons

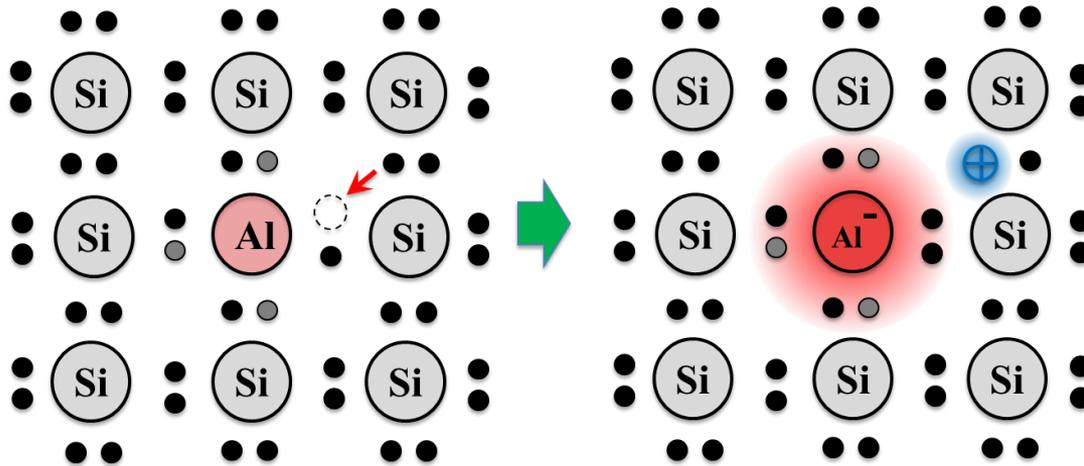
Normally, heating up or illuminating a pure semiconductor crystal we create equal amount of electrons and holes, so the current is transferred by both positive and negative charge carriers. But we can make a crystal which will contain mostly electrons or holes. Let us replace part of the Si atoms by As (arsenic) ones. Each As atom has 5 “hands” – 5 valence electrons. 4 of these will be occupied in the chemical bonds – connected to the neighbor Si atoms. The fifth one has no bond to fill in and is almost free. It takes just a little energy to rip these electron out of the As atom and send it to “free sail”. At room temperature most of the extra electrons are free. Introduction of As into Si or Ge crystal makes this crystal conductive and the current is transferred by negatively charged electrons. Such material is called “n-type semiconductor” and As or any other atom providing electrons is called “donor impurity” or simply “donor”



As is a or *donor impurity* for Si

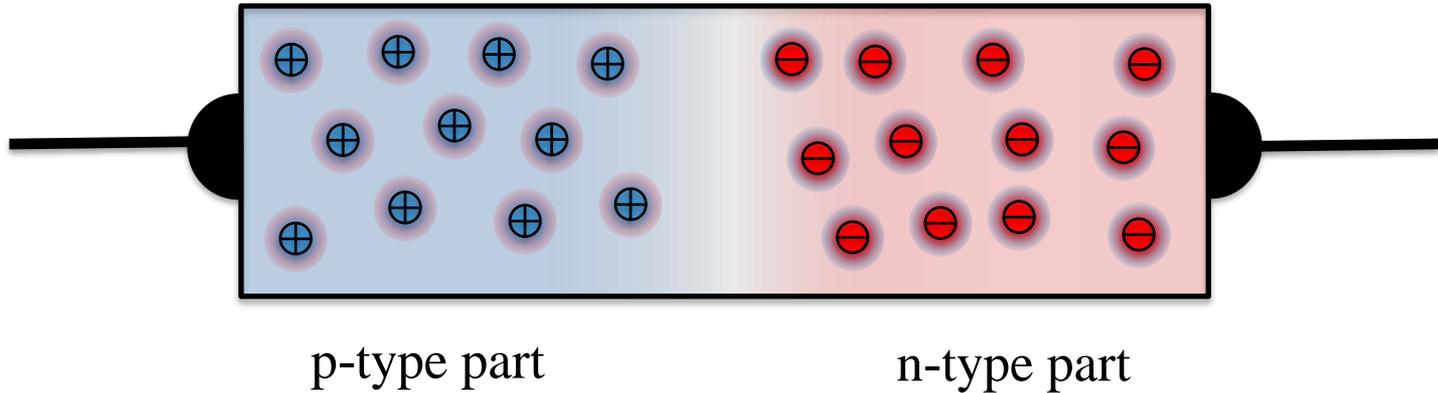
p-type material: electrical current is a flow of the positively charged vacancies – “holes”

Now, let us replace part of the Si atoms by Al (aluminum) ones. Each Al atom has just 3 valence electrons. All 3 valence electrons of Al will be occupied in the chemical bonds but one place will be empty. An electron from the neighbor atom can jump into the empty space and form a free, positively charged hole. Again, introduction of Al into Si or Ge crystal makes this crystal conductive and the current is transferred by positively charged holes. Such material is called “p-type semiconductor” and Al or any other atom having 3 or less valence electrons is called “acceptor impurity” or simply “acceptor”



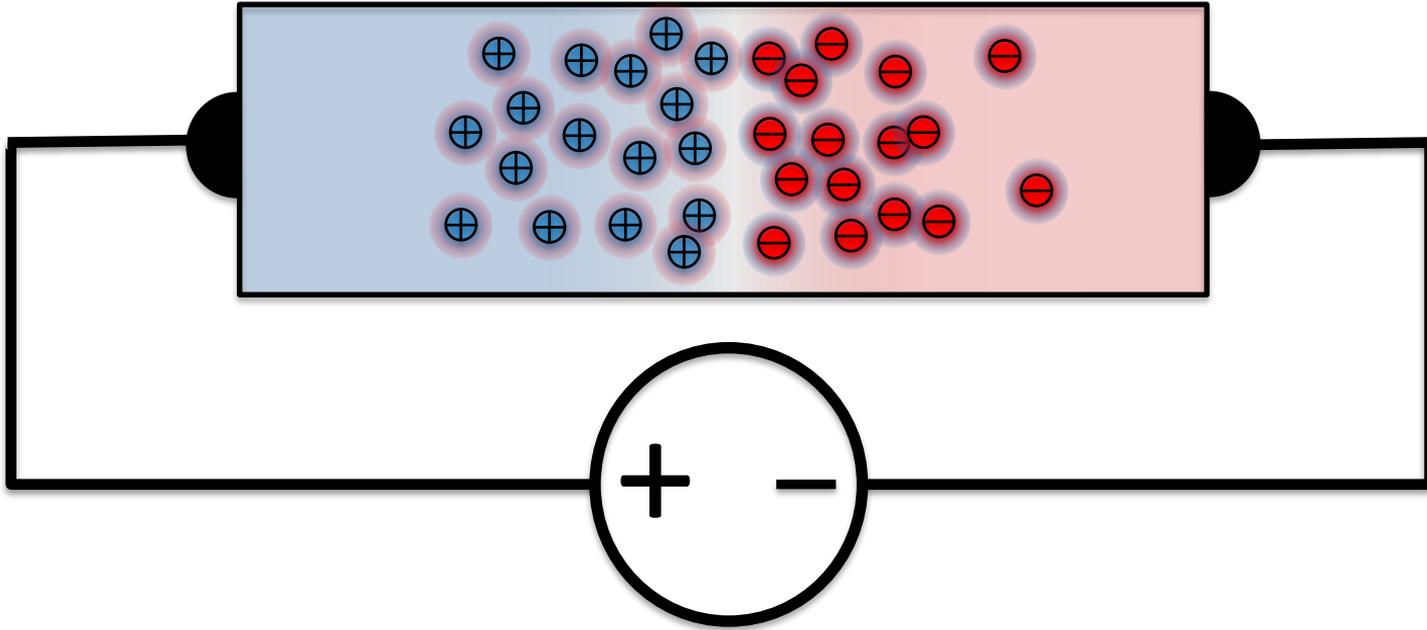
Al is an *acceptor impurity* for Si

The p-n junction is a semiconductor crystal, consisting of two parts: p-type and n-type . The p-n junction is the main element of a diode.



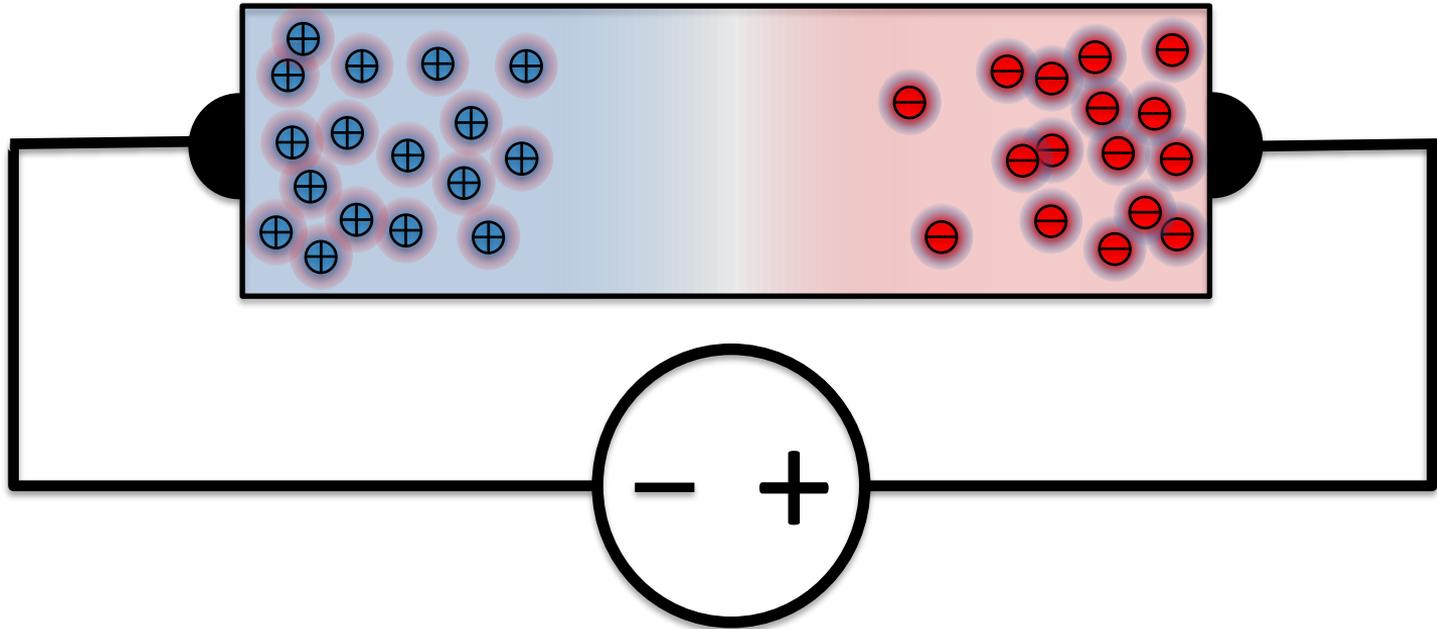
Forward bias (forward voltage): “+” to p-side, “-” to n-side. The current flows.

If we apply direct voltage to the diode, which means “plus” to p-side, “minus” to n-side, the electrons and holes are pushed toward the middle of the crystal – to the junction between p- and n- ends. The electrons and holes meet each other. When the electron meets the hole, they annihilate and the current flows. New electrons enter the n-side from the wire, and exit from the p-side.



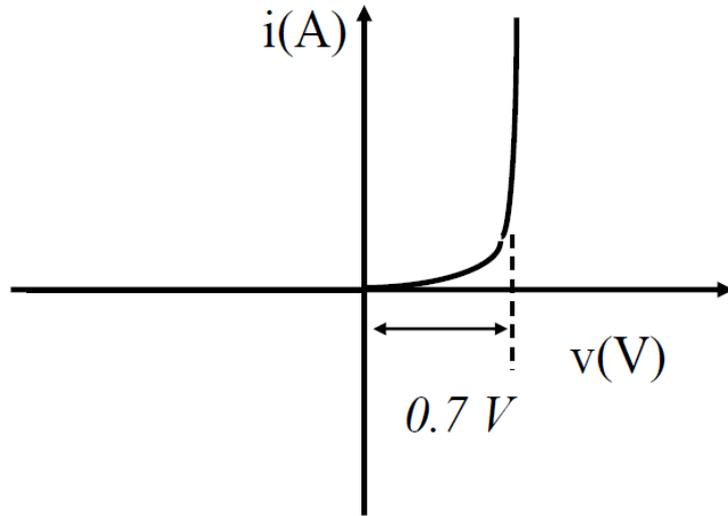
Reverse bias (reverse voltage): “+” to n-side, “-” to p-side. The current does not flow.

If we apply reverse voltage to the diode, which means “plus” to n-side, “minus” to p-side, the electrons and holes are “sucked” out of the junction and the current does not flow.

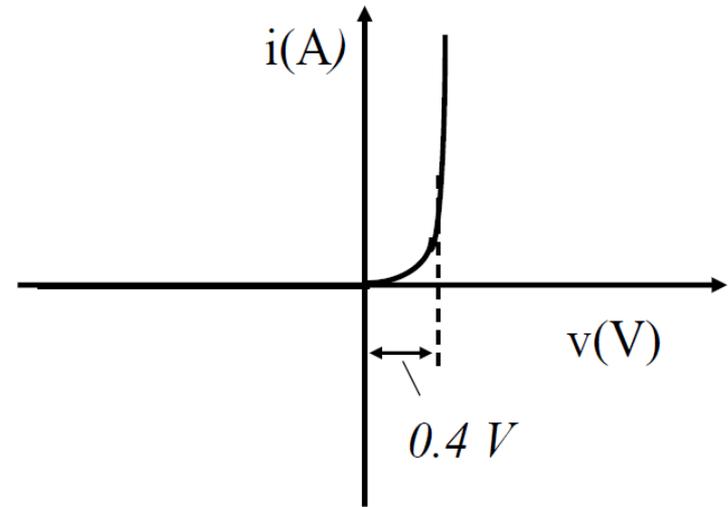


Current-voltage characteristic of a *real* diode

A Silicon (Si) Diode



A Germanium (Ge) Diode



- The *typical* voltage drop across a *Si* diode at forward bias is 0.7V

In a real diode, even under the forward bias, the current starts flowing if the voltage exceeds some threshold voltage, which is called “the opening voltage”. The opening voltage depends on the diode material and typically is 0.7V for Si-based diodes and 0.4V for Ge-based diodes.

Question:

What happens if we introduce both donors and acceptor impurities into the same crystal and distribute them evenly over the crystal volume?