Advanced Physics Lab - Semiconductors

Advanced Physics Lab, PHYS 3600
Don Heiman, Northeastern University, 2021

This Week

1a-INTRO-a & 1b-INTRO-b: Introduction to the Course
motivation, boiler plate (syllabus/labs)
Fermi questions, exercises

2-ERRORS: Errors and Uncertainties
accuracy, precision, round off, propagation of errors

3-OPTICS: Optical Properties
EM spectrum, photo detectors, light emitters

4-SEMICOND: Semiconductors
band gap, Fermi energy, resistivity, Hall effect

5-ACOUSTICS:
sound, beats, Fourier transform, music

6-EXPERIMENTS: Intro to Lab Experiments
Virtual tour my research lab

Semiconductors and Optoelectronics

Where would we be today
without **semiconductor electronics**?

Then and **Now**

Communications →

Recordings →

Information →

4.5B web pages

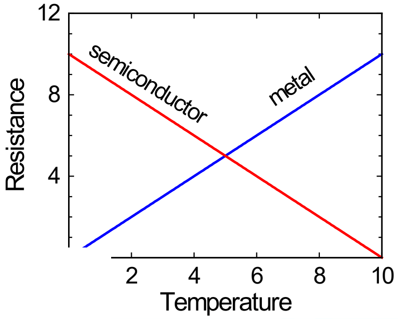
Semiconductors and Optoelectronics

Brief History of Semiconductors

1833: First Semiconductor Effect is Recorded
Michael Faraday describes the "extraordinary case" of his discovery of electrical conduction increasing with temperature in silver sulfide crystals, opposite to that observed in copper.

1901: Semiconductor Rectifiers Patented as "Cat's Whisker" Detectors
Radio pioneer Jagadis Chandra Bose patents the use of a semiconductor crystal rectifier for detecting radio waves.

1926: Field Effect Semiconductor Device Concepts Patented
Julius Lilienfeld files a patent describing a three-electrode amplifying device based on the semiconducting properties of copper sulfide. Attempts to build such a device continue through the 1930s.

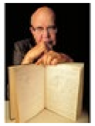


1931: "The Theory Of Electronic Semi-Conductors" is Published
Alan Wilson uses quantum mechanics to explain basic semiconductor properties, and later by Boris Davydov (USSR), Nevill Mott (UK), and Walter Schottky (Germany).

1931: *"One shouldn't work on semiconductors, that is a filthy mess; who knows if they really exist!"* -- Wolfgang Pauli

1952: Bell Labs Licenses Transistor Technology
Bell Labs technology symposia and licensing of transistor patents encourages semiconductor development.

1953: Transistorized Computers Emerge
A transistorized computer prototype demonstrates the small size and low-power advantages of semiconductors compared to vacuum tubes.



1958: All semiconductor "Solid Circuit" is demonstrated
Jack Kilby produces a microcircuit with both active and passive components fabricated from semiconductor material.

2014: iPhone 6 (A8), 2-billion transistors.
2017: iPhone 8 (A11), 4-billion transistors
2018: iPhone XS (A12), 6.9-billion transistors
2021: iPhone 13 (A13), 8.5-billion transistors

Semiconductors and Optoelectronics

Labs with Semiconductors

Electronics - all
Photocell - RUBY, FUEL, SOL, FR
Laser - RUBY, SOL, FR

Material	Resistance
Insulator (glass, ceramic)	Very high
Semiconductor (Si, GaAs, InN)	medium **adjustable**
Metal (Al, Cu)	low

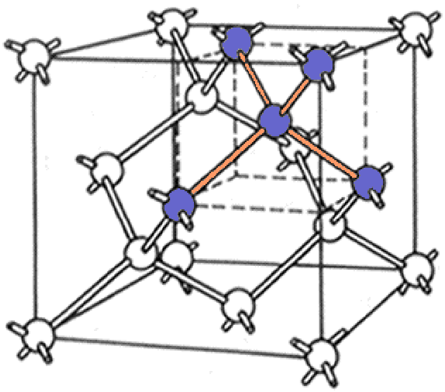
- **Semiconductors**
  Si, GaAs, crystal structure
- **Hall Effect**
  resistivity, electron density
- **Spectral Response**
  semiconductor band, bandgap
- **Light Detectors/Emitters**
  Si**,** AlGaAs, LED, Laser Diode (LD)
- **Band Structure**

Types of Semiconductors

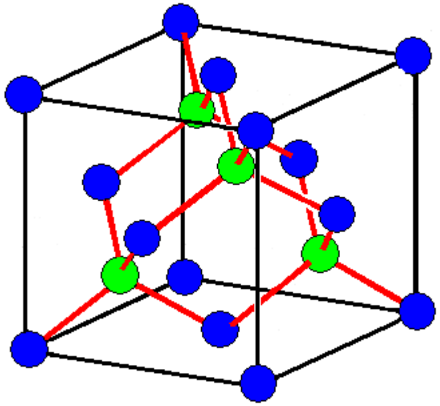
Periodic Table of Semiconductors

II	III	IV	V	VI
	B	C	N	O
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te
Hg				

Si IV - all of our electronics
InGaAs III-V - high frequency
AlGaAs III-V - red LED
InGaN III-V - blue LED



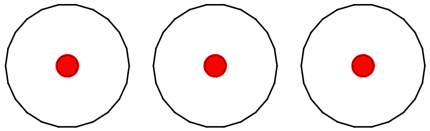
Silicon
"diamond structure"
but not carbon



GaAs
"zincblende structure"

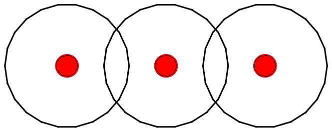
Concept of a Semiconductor

Overlap of Valence Electron Orbits



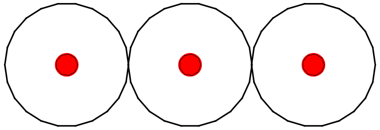
insulator
ionic crystal
Na-Cl

Filled shells



metal
metallic crystal
Al, Cu

Overlapping orbits



semiconductor
colavlent crystal
Si, GaAs

Electrical Properties - Semiconductors

Resistivity – ρ
Conductivity – σ = 1/ρ
Carrier Density – *n* or *p*
Mobility – μ

Property	Designation	Units
Resistivity	ρ	Ωcm
Conductivity	σ = 1/ρ	1/Ωcm
Carrier type (electron, hole)	*n* or *p*	
Carrier Density	*n* or *p*	#/cm³
Mobility	μ	cm²/Vs
relations	**σ = *ne*μ** **ρ = 1/*ne*μ**	

Example:
Phosphorus-Doped Silicon

$n = 10^{16}\ e/cm^3$
$\mu = 1450\ cm^2/Vs$

$\rho = 1/ne\mu$
$= 1/(10^{16} * 1.6\text{x}10^{-19} * 1450)$

ρ = 0.4 Ωcm

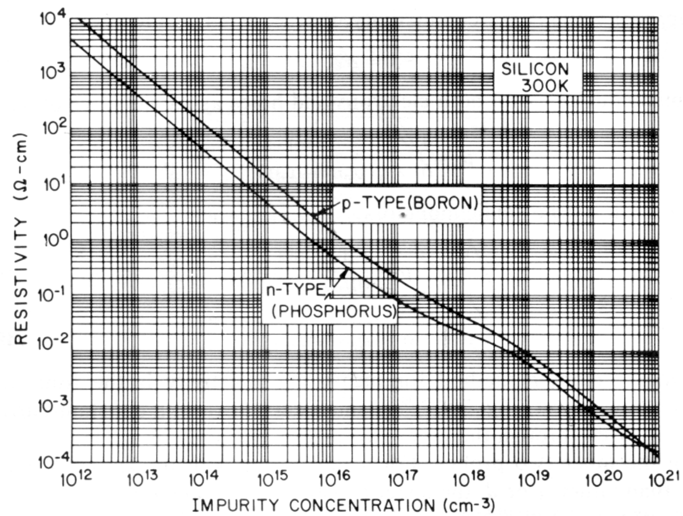


Fig. 21 Resistivity versus impurity concentration for silicon at 300 K. (After Beadle, Plummer, and Tsai, Ref. 38.)

Resistivity

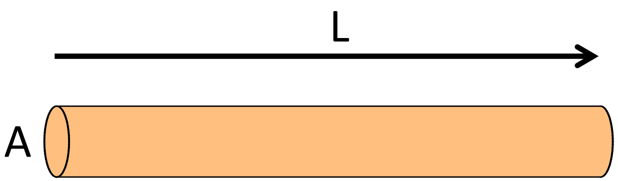
Semiconductors can be doped with impurities to generate a density of free carriers (electrons or holes).

This leads to adjustable “resistivity.”

Resistivity ρ or a wire

“**intrinsic** or **material** property”
independent of the amount of stuff

Resistance of wire $R = \rho\, L/A$



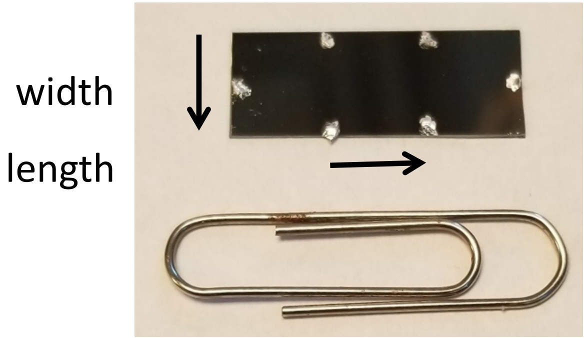
Resistivity ρ of Silicon

Resistance of silicon

$R = V/I = \rho\, L/A$

A = width x thickness

L = length between inner contacts



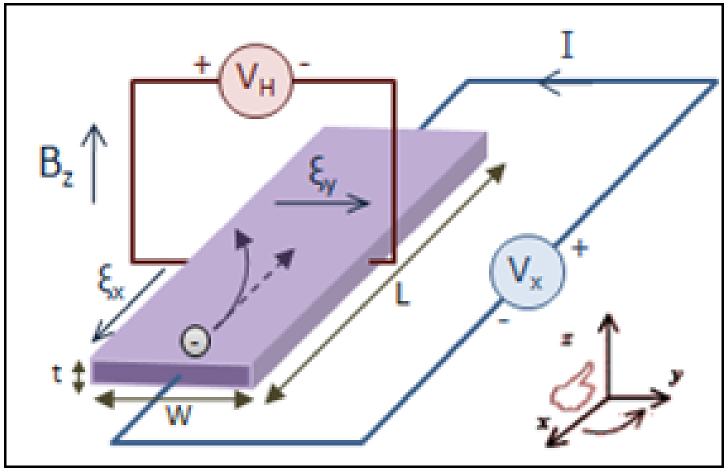
Hall Effect

Hall effect is used to
measure the density of the carriers, ***n***

Force on an electron

$$\overline{F} = e\left(\overline{v} \times \overline{B}\right)$$

moving in a magnetic field



V_H = (1/*n*e) BI/t

V_H – Hall voltage
I – current
B – magnetic field
t – thickness

n = density of electrons
***n* = BI/*e*tV_H**

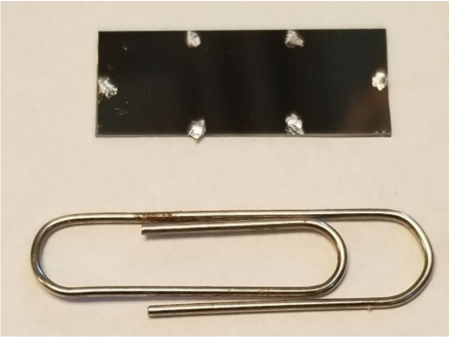
Carrier "Type"
Electrons or Holes
from the polarity of V_H

Carrier Density, Type and Mobility

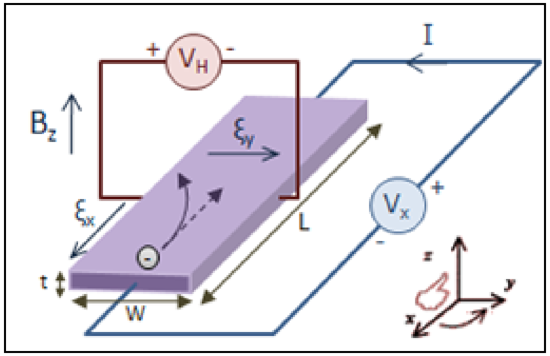
Combine results from resistance and Hall measurements

Silicon Wafer

Resistivity ρ
From the resistance



Carrier Density *n*
From the Hall effect



Values for the Silicon Wafer

Resistivity ρ
comes from measuring the resistance

Carrier Density *n*
comes from measuring the Hall effect

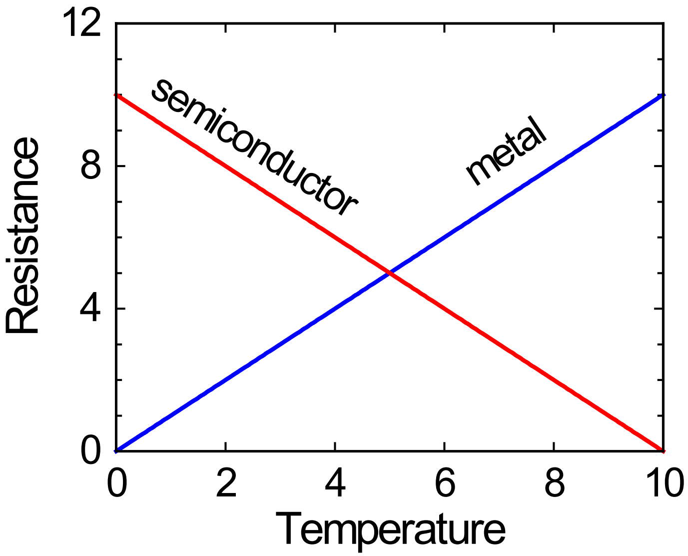
Combining ρ and *n*
gives a value
for the **mobility** of carriers μ
using $\rho = 1/ne\mu$

Carrier Density, Type and Mobility

Summary of Hall experiment

Obtain Measured Values for

Resistivity ρ
Carrier Density n
Carrier type (electrons or holes)
Carrier mobility μ



Difference in R(T) for metals and semiconductors
from $\rho = 1/ne\mu$, and $R=\rho L/A$

In Semiconductors
the carrier density n increases, so R decreases

In Metals
the carrier mobility μ decreases, so R increases

Semiconductor Properties

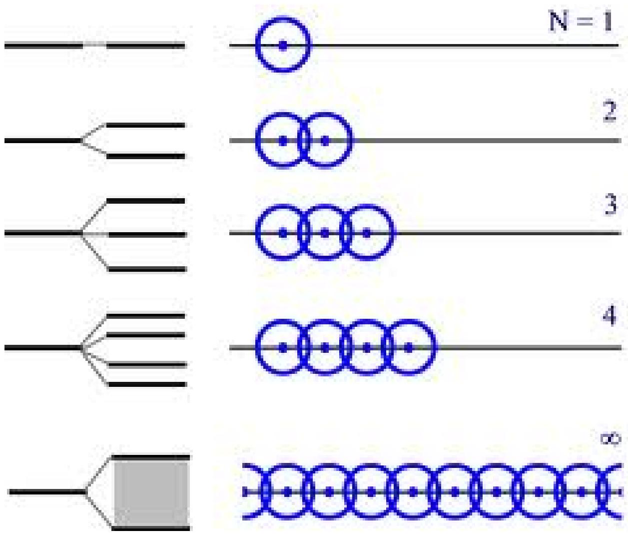
- What is an **Energy Band**?
- What is a **Bandgap**?
- What is the **Fermi Energy**?
- What is **Band Dispersion**?

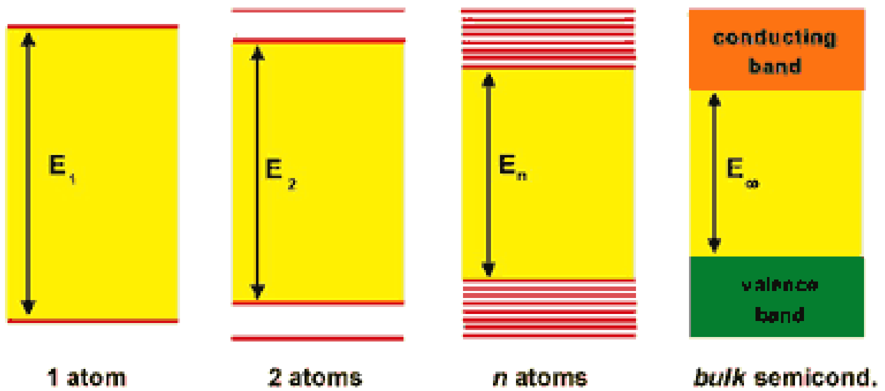
Semiconductor Energy “Bands”

Why do they call the energy states “bands”?

The more atoms you have with overlapping electron orbitals, the larger the number of accessible energy states.

With a very large number of atoms (~10^{20}) you have a continuum of states, hence “bands.”





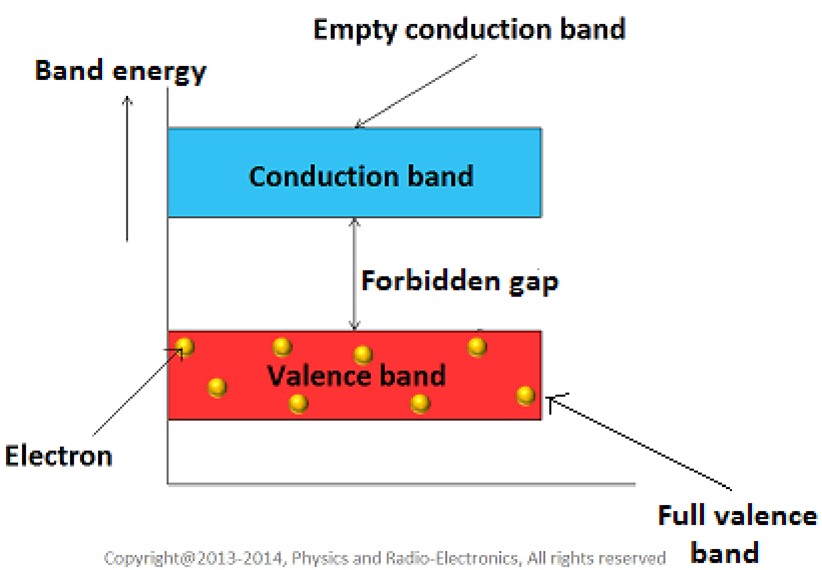
$E_1 > E_2 > E_n > E_\infty$

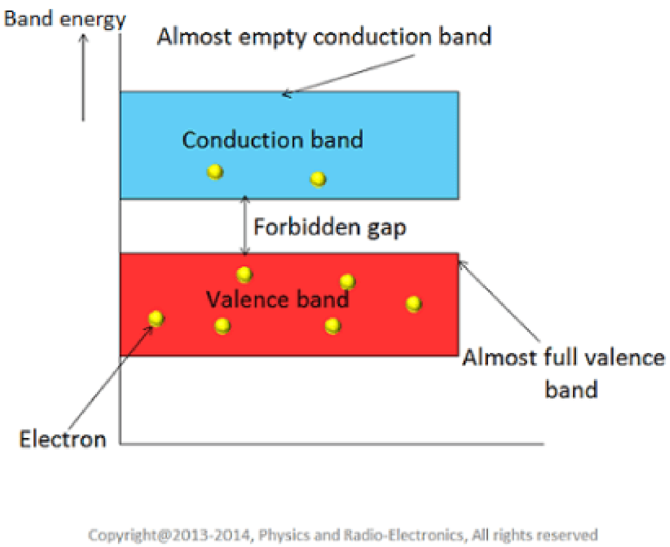
For more details, check out
[Energy Bands and Semiconductors](#) 22:01
[Electron Band Structure](#) 10:00
[Intro to SC bands](#) 12:14

Conduction and Valence "Bands"

In all materials, the bands associated with the bonding electrons are characterized in basically two groups. The **conduction** band lies above the **valence** band and these bands are separated by the "bandgap" (forbidden energy gap).

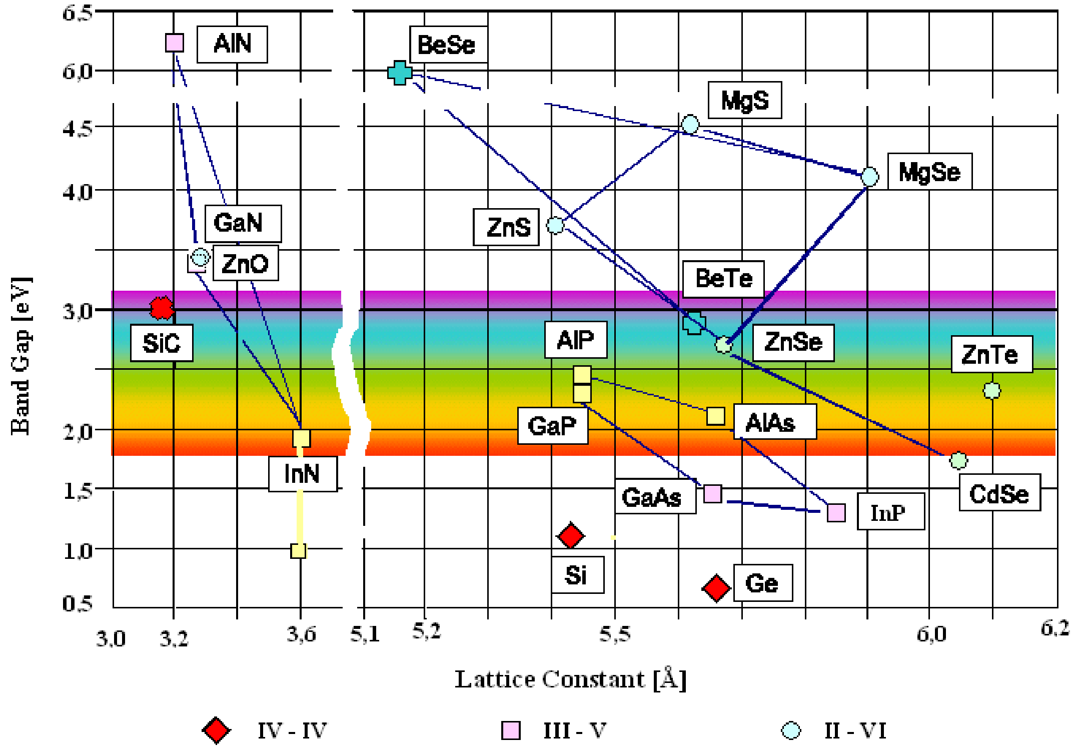
In insulators and pure semiconductors the valence band is full of electrons and conduction band is empty of electrons. Thus, these materials do not conduct electricity unless an electron in the valence band can be raised up into the conduction band. This can be done by several means, such as absorbing energy in the form of light, by an applied voltage, and by impurity doping.





Semiconductor "Bandgap"

The semiconductor bandgap energy is measured in **electron volts** (eV).



Material	Eg (eV)	λ (μm)
HgCdTe	0.12 eV	10.6 IR
InSb	0.25	5
Ge	0.7	1.1 near-IR
Si	1.12	1.1
GaAs	1.42	0.9
GaP	2.3	0.5 green
ZnSe	2.8	0.44
GaN	3.4	0.36 UV

Light Detectors and Emitters

Light in – Current out

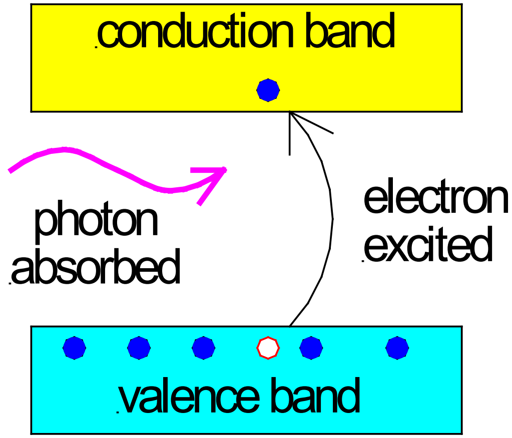
The free electron is available to provide a current

Current in – Light out

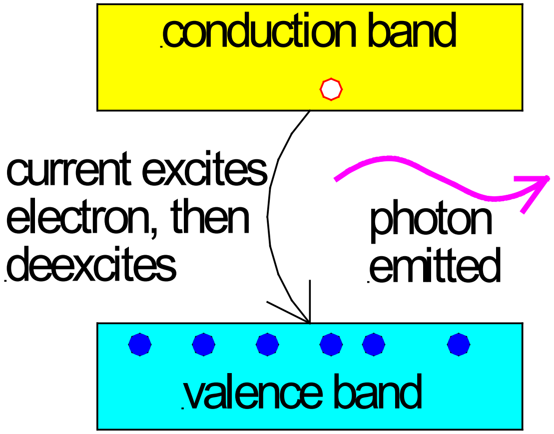
Current excites an electron

Photon is emitted as electron falls back down

Light Detector
(photovoltaic)



Light Emitter
(LED, LD)



Optical band gaps and absorption 5:20-7:00

Light Detectors – Solar Cell

SKIP

First publication about a
pn-junction solar cell

D. M. Chapin. C.S. Fuller, and G.L. Pearson
Bell Telephone Laboratories, Murray Hill, NJ
Journal of Applied Physics, 1954

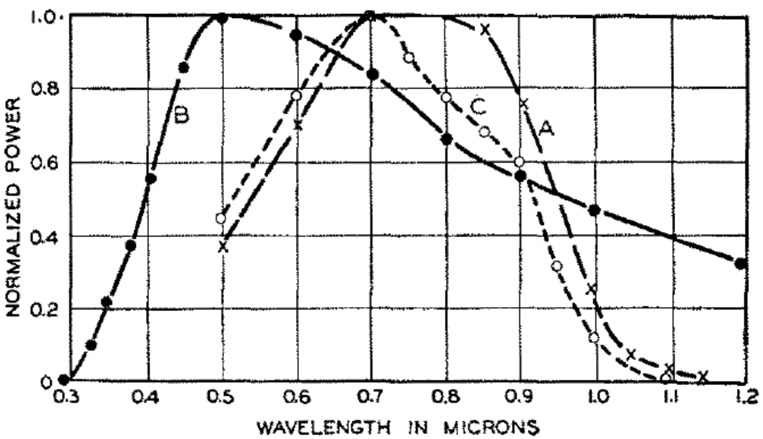


FIG. 1. Normalized spectral energy distribution. (A) Silicon photocell equi-energy response. (B) Solar energy at earth's surface. (C) Curve *A* times Curve *B*.

FIG. 1. End view of 0.50 caliber cylindrical steel projectile after it has passed through a 0.005-in. lead target at 45 deg striking angle. The actual diameter of this cylinder is 0.428 in.

Figure 1 is a photograph of the end of a 0.50 caliber cylindrical steel projectile after it has penetrated a 0.005-in. lead target aligned at a 45 deg striking angle. Figure 2 is a photomicrograph of a cross section of a cylinder that shows the wave structure of the ridges. Although the mechanism responsible for production of these waves is somewhat obscure, the critical angle 2φ is believed to be the same critical angle discussed by the Los Alamos group[1] in a paper that deals with metal plates accelerated together by high explosive charges. The Los Alamos group has discussed the asymmetric collision of dissimilar solids, but has not yet reported any experimental data. The specimens shown in Figs. 1 and 2 correspond to the asymmetric case.

The experiment was modified to obtain symmetric collision. Steel projectiles with conical noses specified by the half-angle $\pi/2-\theta$ were fired into steel targets aligned at the striking angle θ. Plastic deformation occurs along one of the elements of the cone provided that $2\theta>2\varphi$. Negligible plastic deformation occurs if $2\theta<2\varphi$. The critical angle 2φ determined by this experiment is in excellent agreement with the predicted[1] value for iron. Two preliminary determinations indicate the value $2\varphi=7.7$ deg for a projectile velocity of 0.87 mm/μsec. This velocity corresponds to the plate velocity $v_p=0.43$ mm/μsec of Fig. 15 in reference 1.

The experiment discussed is believed to be equivalent to that of the Los Alamos group. No theoretical or experimental difficulty is expected if the technique is extended to higher velocities and to solids other than steel. The experiment is expected to be of value in checking and determining equation of state data of solids in the megabar pressure regime. As a basis for comparison, the compressibility of pure iron has been measured up to a maximum pressure of only 0.03 megabar.[2] The pressure produced at the critical angle 2φ by the symmetric collision of steel is 0.47 megabar, a value calculated from the published[1] equation of state of iron.

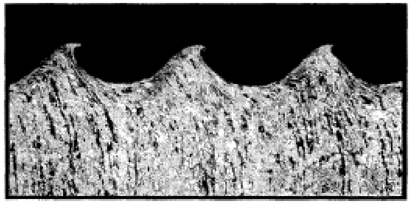


FIG. 2. Photomicrograph of a cross section of a projectile which shows the wave structure formed by 45 deg impact on a 0.010-in. lead target. The average distance from crest to crest is 0.033 in.

[1] Walsh, Shreffler, and Willig, J. Appl. Phys. 24, 349 (1953).
[2] P. W. Bridgman, Revs. Modern Phys. 18, 1 (1946).

A New Silicon *p-n* Junction Photocell for Converting Solar Radiation into Electrical Power

D. M. CHAPIN, C. S. FULLER, AND G. L. PEARSON
Bell Telephone Laboratories, Inc., Murray Hill, New Jersey

(Received January 11, 1954)

THE direct conversion of solar radiation into electrical power by means of a photocell appears more promising as a result of recent work on silicon *p-n* junctions. Because the radiant energy is used without first being converted to heat, the theoretical efficiency is high.

Photons of 1.02 electron volts ($\lambda=1.2$ microns) are able to produce electron-hole pairs in silicon. In the presence of a *p-n* barrier, these electron-hole pairs are separated and made to do work in an external circuit. All of the light of wavelength shorter than 1.2 microns is potentially useful for generating electron-hole pairs but the efficiency of energy conversion decreases for short wavelengths because the energy above the necessary 1.02 electron volts is wasted. Allowing for this loss and assuming a working voltage of 0.5 volt, which is near the maximum measured, a computation over the entire solar spectrum indicates a limiting efficiency of approximately 22 percent for a cell of negligible internal losses and for utilization of all possible electron-hole pairs.

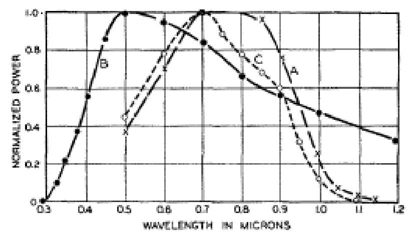
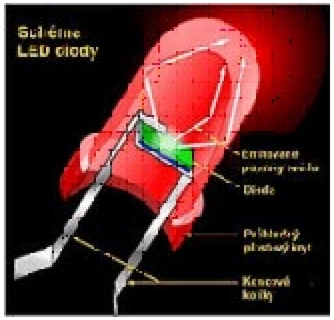


FIG. 1. Normalized spectral energy distribution. (A) Silicon photocell equi-energy response. (B) Solar energy at earth's surface. (C) Curve *A* times Curve *B*.

Several practical factors lower this figure. The untreated silicon surface reflects about half of the incident radiation. Some of this can be saved by proper surface treatment. The second serious loss is recombination of electron-hole pairs before they reach the *p-n* barrier. Penetration of radiation over most of the useful spectrum is extremely shallow so that it becomes necessary to place the *p-n* junction as near to the surface as possible except for the third serious loss. This is the I^2R loss caused by resistance in the surface layer and by contact resistance. Extremely small cells minimize the resistance loss and give useful data. For cells of several square centimeters, special geometry of contacts will minimize resistance losses.

Present work on silicon *p-n* photocells uses a thin layer of *p*-type silicon formed over an *n*-type base. The surface layer is less than 0.0001 inch thick. Figure 1 shows the spectral response for one such cell. Curve *A* is the measured power output for equal intensities of weak radiation as a function of wavelength. Maxi-

Solid State Light Sources



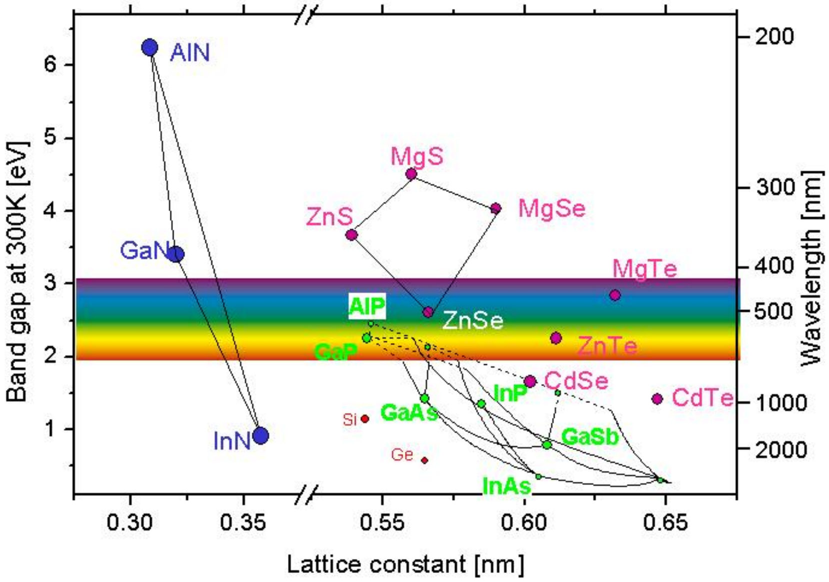
LED – Light Emitting Diode

Emitted Wavelength –
The photon energy is approximately equal to the "bandgap" of the semiconductor.

$$\hbar\omega = hc/\lambda \approx Eg$$

$$E(eV) = 1.2395130 / \lambda(\mu m)$$

Forward-biased *pn*-junction diode produces light of nearly a single wavelength, with a width Δλ ~ 30-40 nm.



Change wavelength of LED by alloying semiconductors,

such as GaAs + GaP → $GaAs_{1-x}P_x$
or InN + GaN → $In_{1-x}Ga_xN$

Example: $GaAs_{1-x}P_x$ (IR to green)

$$Eg = Eg_{GaAs} + x(Eg_{GaP} - Eg_{GaAs})$$

$$Eg_{GaAs} = 1.42 \text{ eV}$$

$$Eg_{GaP} = 2.26 \text{ eV}$$

$$Eg\ (eV) = 1.42 + 0.84x$$

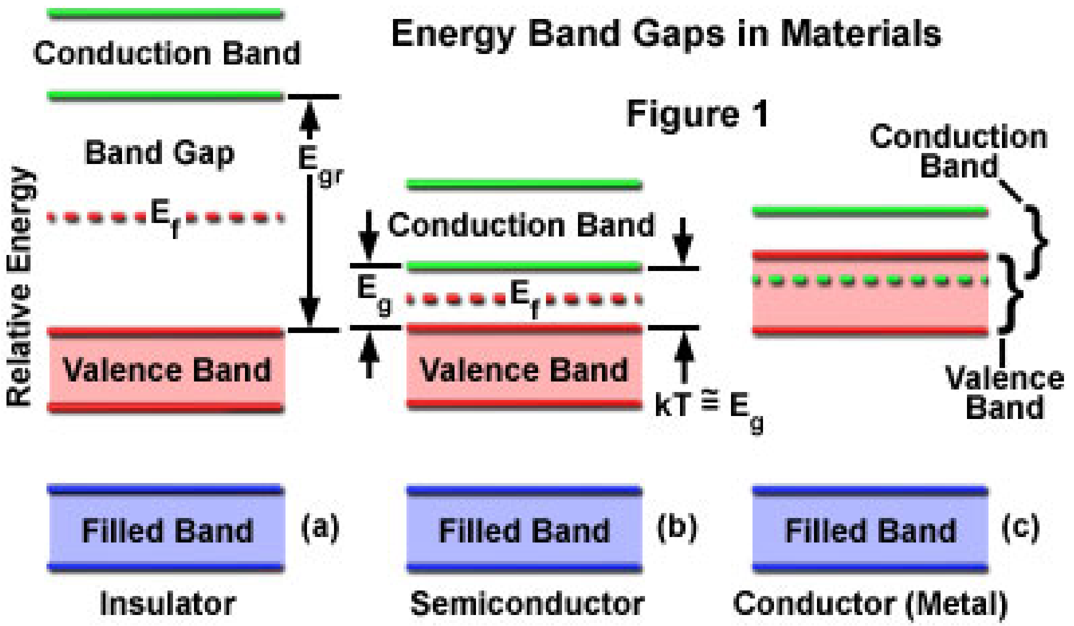
Fermi Energy

The simplest explanation of the Fermi energy (E_f) is the following. Electrons fill up all the **available** band states only **below** the E_f, whereas all the **available** band states **above** E_f are empty. Thus, to get electrons to conduct, they must rise up in energy to cross the
Fermi energy - All materials have a bandgap (insulators, semiconductors, metals), but the conduction depends on the energy of the **Fermi** level.

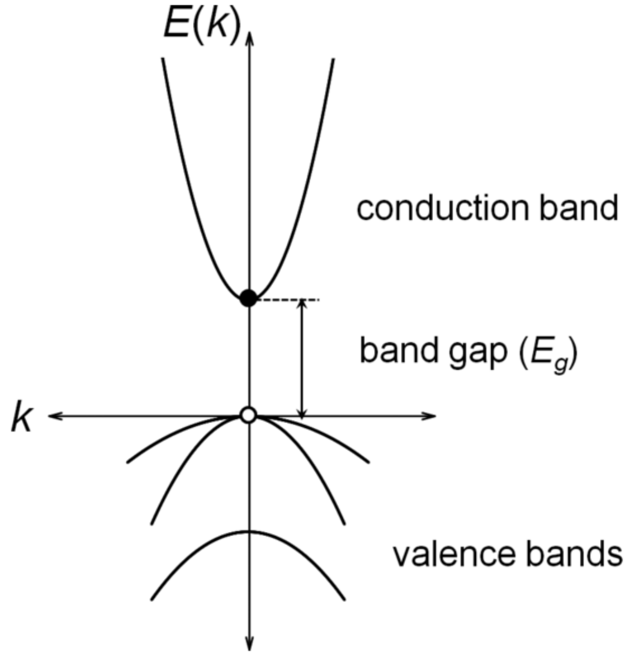
Insulator
E_F in middle of large bandgap

Semiconductor
E_F inside of small bandgap or can be moved into the conduction or valence bands

Metal
E_F is in conduction/valence band



Band "Dispersion"

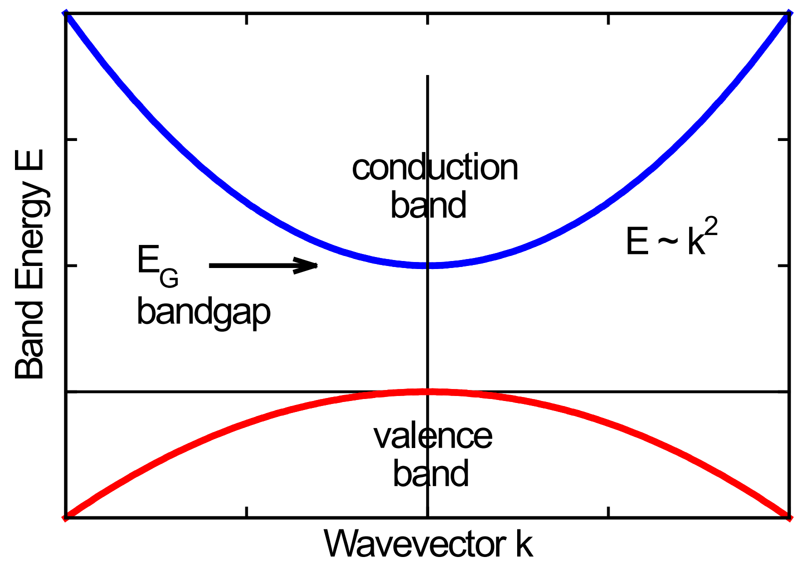


k is the wavevector, or the crystal momentum

$p = mv = \hbar k$

Electrons in the bands near the cb minima and vb maxima have **parabolic** energy dispersion.

$\mathbf{E_{cb}} = \frac{1}{2} mv^2 = p^2/2m = \mathbf{\hbar^2 k^2/2m}$
(note that momentum $p=mv=\hbar k$)



Silicon Band Structure

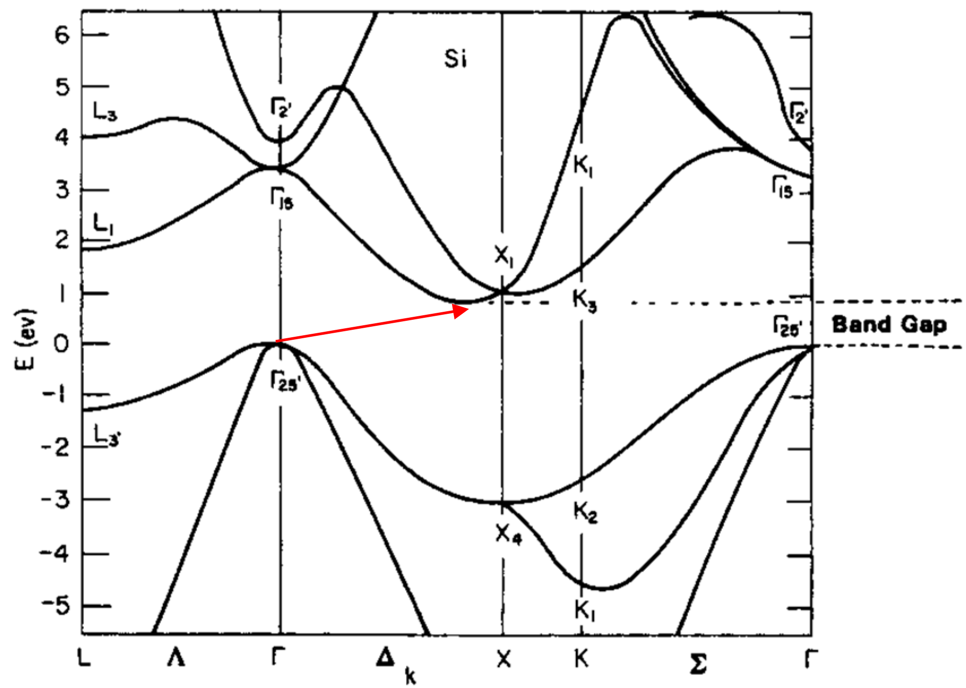
Materials have complex band dispersions

There are many bands in a crystal, which depend on the direction in the crystal.

The direction refers to the direction of the k-vector, or simply the direction that the electron is moving. An electron can move in any direction, and the various Greek letters (Γ,Δ,X Λ Σ) refer to going along certain crystallographic directions, such as a cube edge direction or a diagonal direction on one of the cube faces.

Band dispersion in silicon

Note that the band gap is "indirect" (not vertical).



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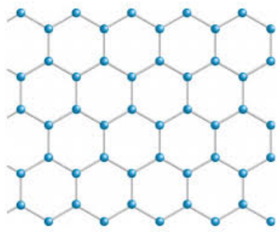
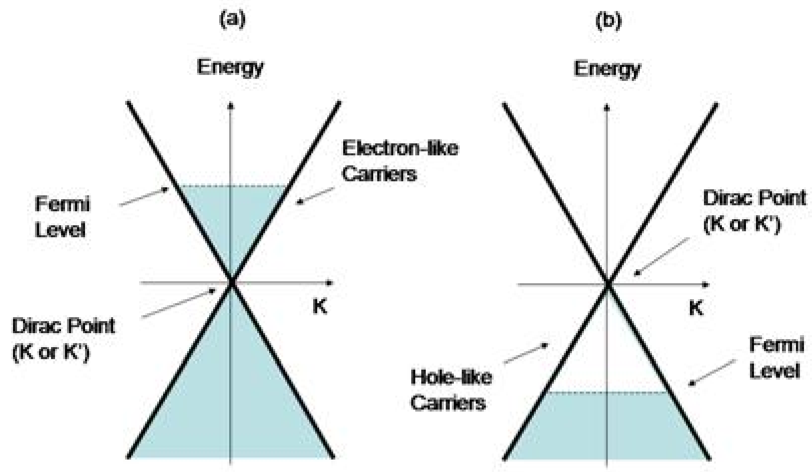
k=0

Dirac Dispersion

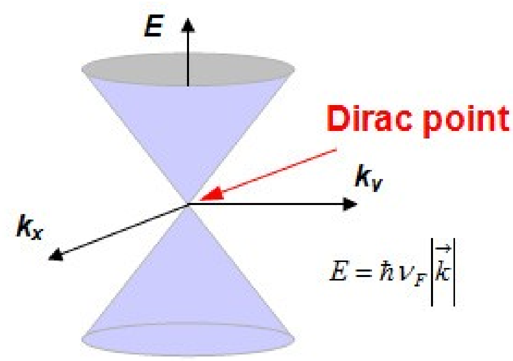
Graphene and Topological materials have a "Dirac" dispersion
E ~ k (linear in k)

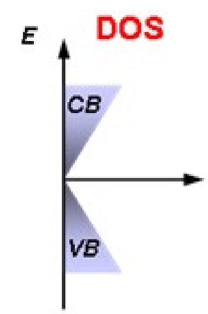
They thus have relativistic dispersion.





Electron dispersions are not one dimensional,
they can be 2 or 3-dimensional
(have k_x and k_y, etc.)





Semiconductors

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accuracy, precision, round off, propagation of errors

3-OPTICS: Optical Properties
EM spectrum, photo detectors, light emitters

4-SEMICOND: Semiconductors
band gap, Fermi energy, resistivity, Hall effect

5-ACOUSTICS:
sound, beats, Fourier transform, music

6-EXPERIMENTS: Intro to Lab Experiments
Virtual tour my research lab

END

Semiconductors

Extra Info on Doping

Group IV semiconductors

Group IV semiconductors

Si, Ge

- have 4 **valence** electrons
- tetrahedral coordination
- pairs of bonding (valence) electrons

Concept of Doping

Doping allows you to add **mobile** charges

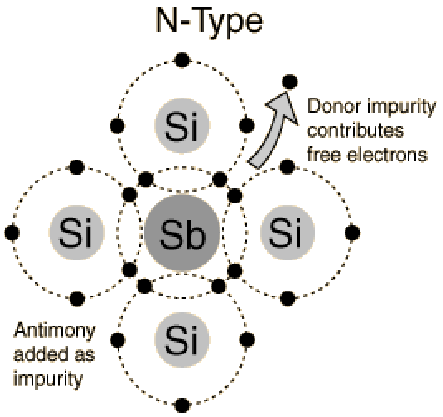
Doping - Add a small concentration of another type of atom (impurity)

II	III	IV	V	VI
	B	C	N	O
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te
Hg				

Dope Si with an Sb atom

Substitute a Si atom with Sb

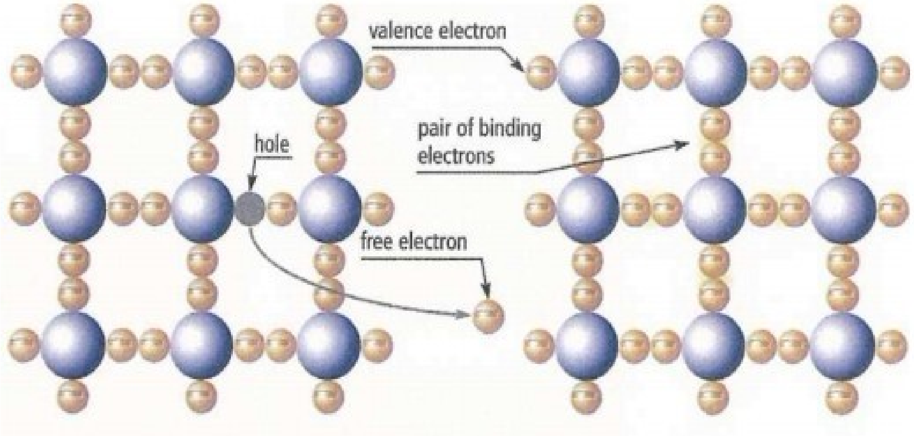
Replace the **4** valence electrons of Si (group-IV) with the **5** valence electrons of Sb (group-V)



Concept of a Hole

Hole

- positive charge
- missing electron



Holes are Mobile (Itinerant)

Analogy to bubbles

A hole in a liquid is a bubble or simply missing liquid.

The bubble (hole) moves as liquid moves into the area that is left behind.

The basis for all semiconductor devices relies on the ability to make them with an excess **electrons or holes.**

Doping Electrons or Holes

Semiconductors are doped with impurities (other atoms)
to generate a density or concentration
of free **carriers** (electrons or holes).

Doping in Silicon

- *n*-type, **donor**, add group-V (P, As,Sb)
  - has one extra electron
- *p*-type, **acceptor**, add group-III (B,Al,Ga,In)
  - has one less electron
  - leaves a hole behind

Note that doping leaves the semiconductor **neutral**

n-doping = electron plus positively charged atom
p-doping = hole plus a negatively charged atom

(1) Donor Impurity
Donates mobile electrons,
***n*-type** conductivity

(2) Acceptor Impurity
Donates mobile holes,
***p*-type** conductivity

II	III	IV	V	VI
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Zn	Ga	Ge	As	Se
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Use doping to make
pn-junction **diodes**
for
LEDs, Lasers, Solar Cells