

# ELEC2104 – Week 2

## Semiconductor Physics



THE UNIVERSITY OF  
SYDNEY



How do circuits work?



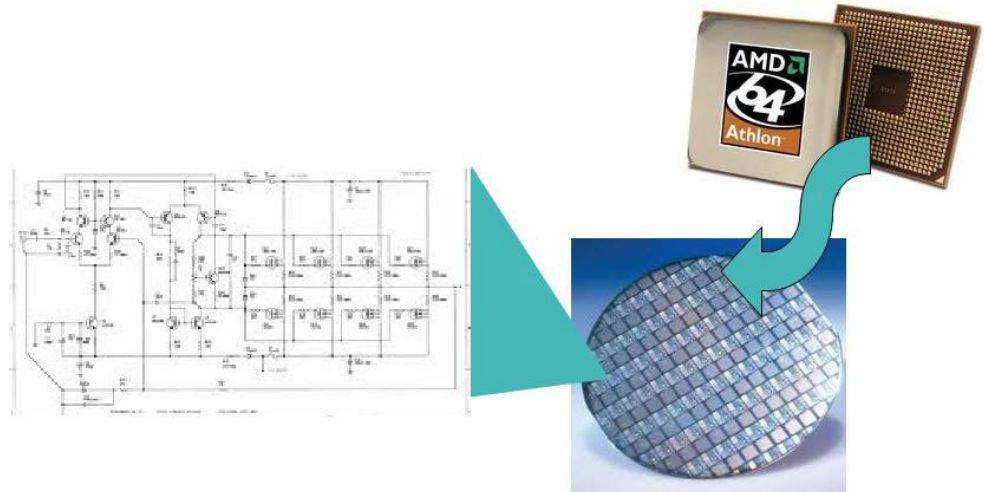
How do circuit devices  
work?



How does solid-state  
material work?

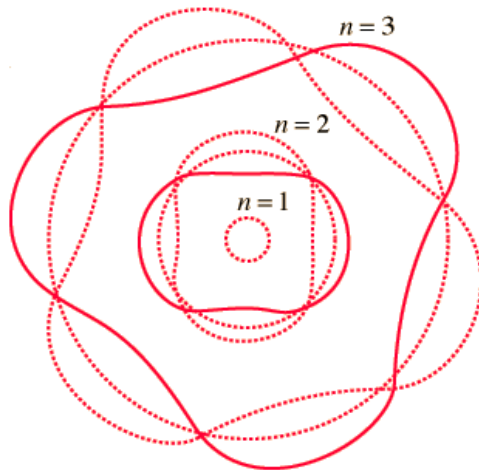


**SOLID-STATE PHYSICS**



## ➤ Atoms and Electrons

- The electrons in an atom have different energy levels, called atomic orbitals (even though they are not really orbitals)
- The energy levels are really waves, represented by a wave function
- The wavefunction indicates where electrons are allowed to be.

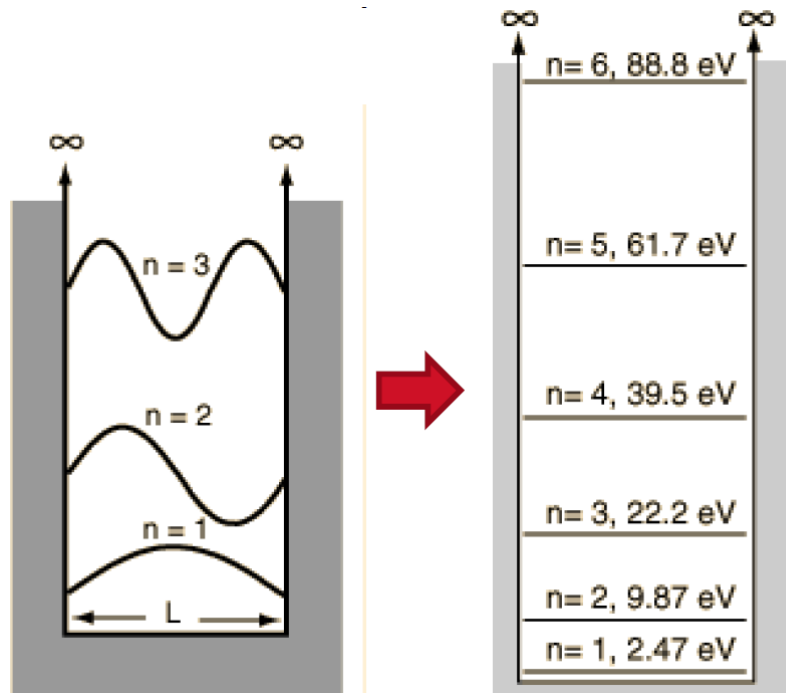


$$\Psi(x, t)$$



## ➤ Atoms and Electrons

- These energy level waves are confined to a box
- Only certain wavelengths can fit in the box
- Thus, energy levels are quantized

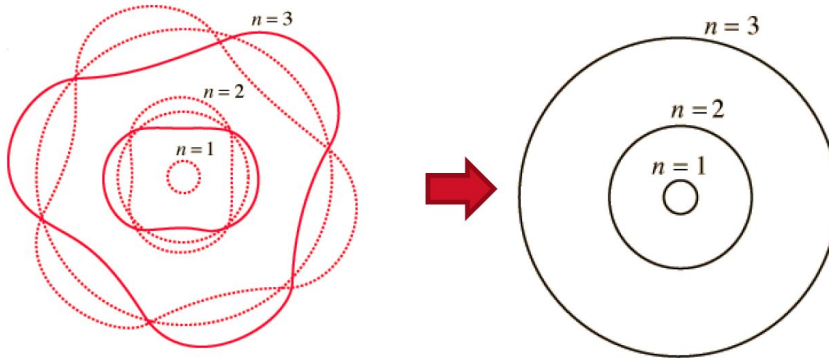


Wave function

Energy levels

## ➤ Electrons in an atom orbit the nucleus in different “shells”

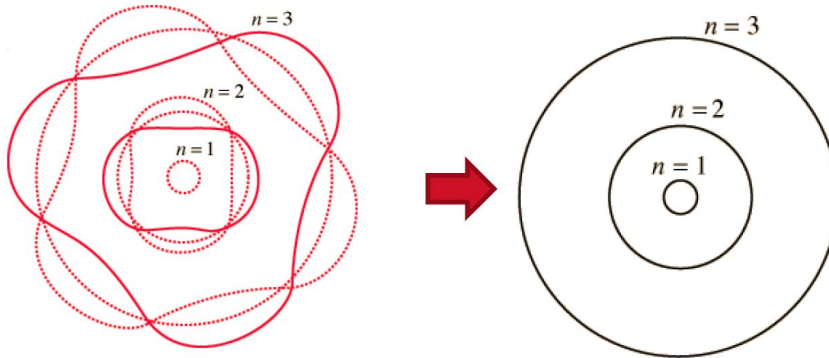
- Electrons in an atom orbit the nucleus in different “shells”
- Atom’s chemical activity is determined by
  - Electrons in the outermost shell -> “valence” electrons
  - How complete this shell is



		IIIA	IVA	VA	VIA
		510.811 <b>B</b> Boron	612.01115 <b>C</b> Carbon	714.0067 <b>N</b> Nitrogen	815.9994 <b>O</b> Oxygen
		1326.9815 <b>Al</b> Aluminum	1428.086 <b>Si</b> Silicon	1530.9738 <b>P</b> Phosphorus	1632.064 <b>S</b> Sulfur
IIB					
3065.37 <b>Zn</b> Zinc	3169.72 <b>Ga</b> Gallium	3272.59 <b>Ge</b> Germanium	3374.922 <b>As</b> Arsenic	3478.96 <b>Se</b> Selenium	
48112.40 <b>Cd</b> Cadmium	49114.82 <b>In</b> Indium	50118.69 <b>Sn</b> Tin	51121.75 <b>Sb</b> Antimony	52127.60 <b>Te</b> Tellurium	
80200.59 <b>Hg</b> Mercury	81204.37 <b>Tl</b> Thallium	82207.19 <b>Pb</b> Lead	83208.980 <b>Bi</b> Bismuth	84(210) <b>Po</b> Polonium	

## ➤ Electrons in an atom orbit the nucleus in different “shells”

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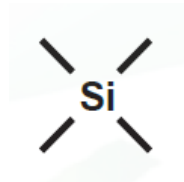


Interesting fact: Silicon is obtained from sand after a great deal of processing

		IIIA	IVA	VA	VIA					
	5	10.811	6	12.01115	7	14.0067	8	15.9994		
		<b>B</b>	<b>C</b>	<b>N</b>	<b>O</b>					
		Boron	Carbon	Nitrogen	Oxygen					
	13	26.9815	14	28.086	15	30.9738	16	32.064		
		<b>Al</b>	<b>Si</b>	<b>P</b>	<b>S</b>					
		Aluminum	Silicon	Phosphorus	Sulfur					
<b>IIB</b>	30	65.37	31	69.72	32	72.59	33	74.922	34	78.96
		<b>Zn</b>	<b>Ga</b>	<b>Ge</b>	<b>As</b>	<b>Se</b>				
		Zinc	Gallium	Germanium	Arsenic	Selenium				
	48	112.40	49	114.82	50	118.69	51	121.75	52	127.60
		<b>Cd</b>	<b>In</b>	<b>Sn</b>	<b>Sb</b>	<b>Te</b>				
		Cadmium	Indium	Tin	Antimony	Tellurium				
	80	200.59	81	204.37	82	207.19	83	208.980	84	(210)
		<b>Hg</b>	<b>Tl</b>	<b>Pb</b>	<b>Bi</b>	<b>Po</b>				
		Mercury	Thallium	Lead	Bismuth	Polonium				

› Silicon is a group IV element

- It has 4 valence electrons

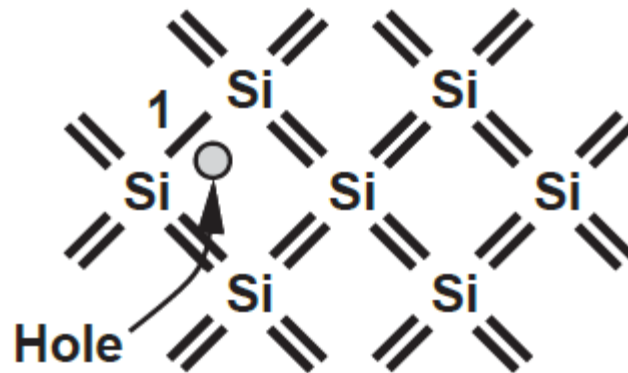


- Silicon material can form a “crystal”
  - Each atom shares one valence electron with its neighbors
  - Sharing of valence electrons to form “bonds”
  - They form bonds because that way the orbitals are filled up (8). They like their orbitals to be filled up as it is the lowest-energy configuration.
- › Silicon crystal behaves as an insulator for  $T \rightarrow 0\text{K}$ .
- All orbitals filled; no electrons can move
- › At higher temperatures
- Electrons gain thermal energy
  - Become free electrons



# Covalent bond

- › When freed from a covalent bond, an electron leaves a “void” behind because the
- › Bond is now incomplete

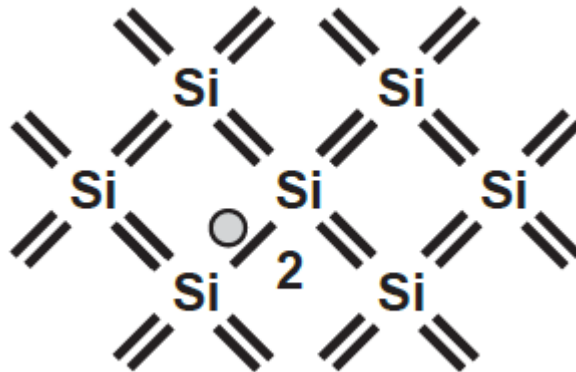




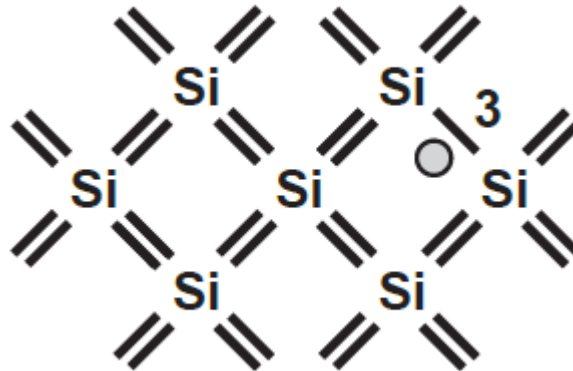


# Covalent bond

- An electron (charge  $-q = -1.602 \times 10^{-19} \text{ C}$ ) from adjacent bond can fill this vacancy, creating a new vacancy in another position
- Moving vacancy  $\rightarrow$  behaves like particle with charge  $+q \rightarrow$  called a hole



- Hole density is represented by symbol  $p$  (holes/cm<sup>3</sup>)
- Electron density is represented by symbol  $n$  (electrons/cm<sup>3</sup>)
- Intrinsic carrier density:  $n_i$  (cm<sup>-3</sup>)
  - $n_i$  is a constant for one material at certain temperature



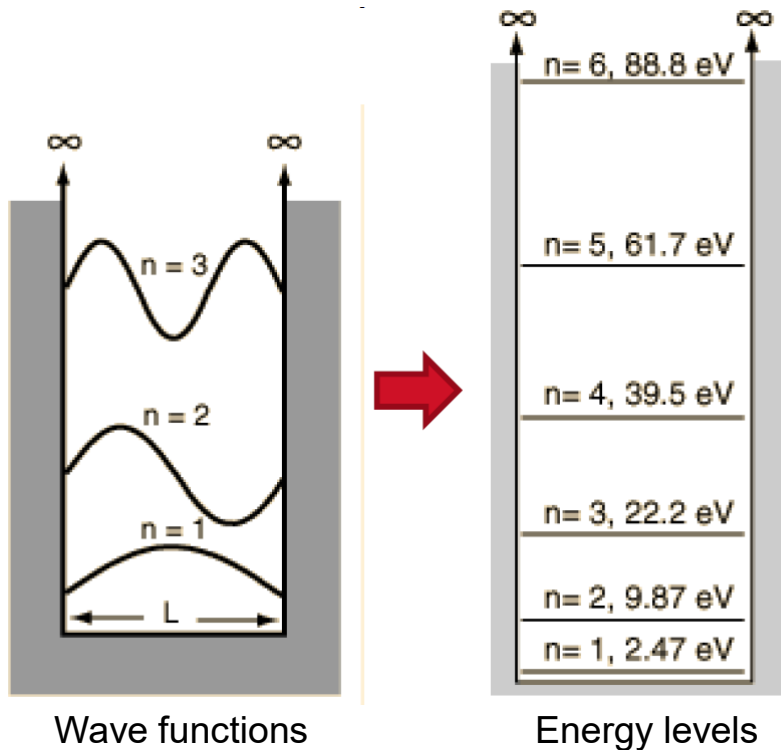
For intrinsic silicon,  $n = n_i = p$

$$pn = n_i^2 \quad \text{at thermal equilibrium}$$

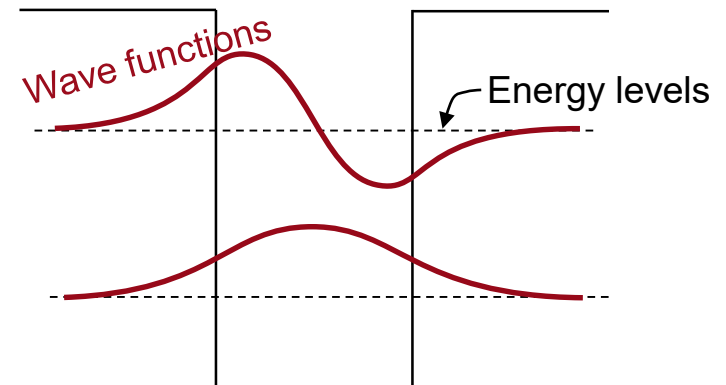


# Single quantum well

## › Band gap



Infinite well



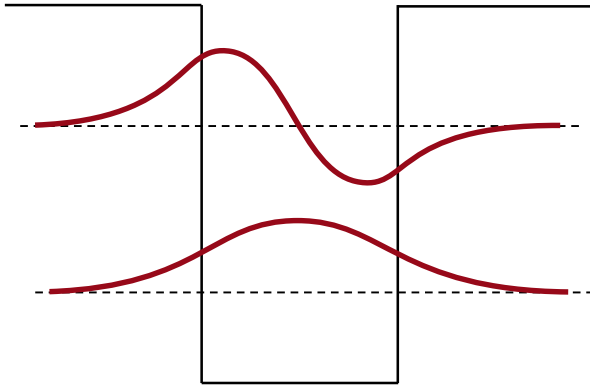
Finite well  
Wavefunction penetrates into  
the barrier



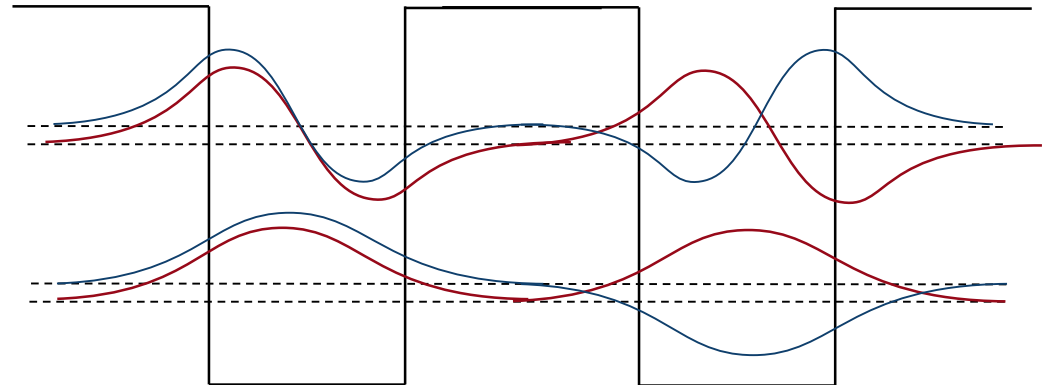
# Multiple quantum wells

## › Band gap

States with the same energy and their  
Wavefunctions  $\psi_1, \psi_2$  overlapping:  
energy splits, wavefunctions also becomes  
 $\psi_1 + \psi_2$  and  $\psi_1 - \psi_2$



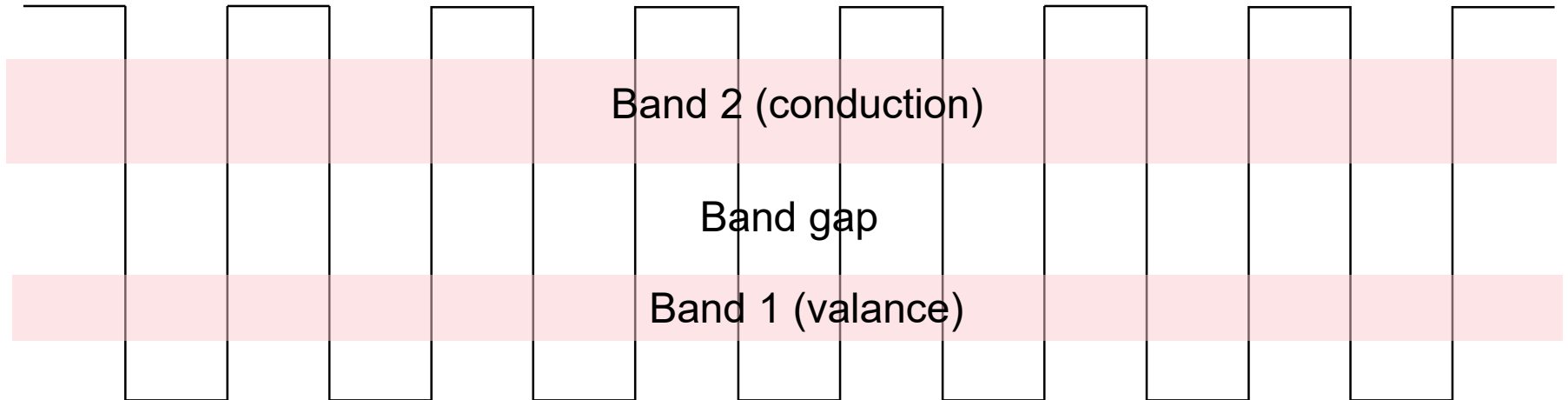
One well



Two wells



## › Band gap

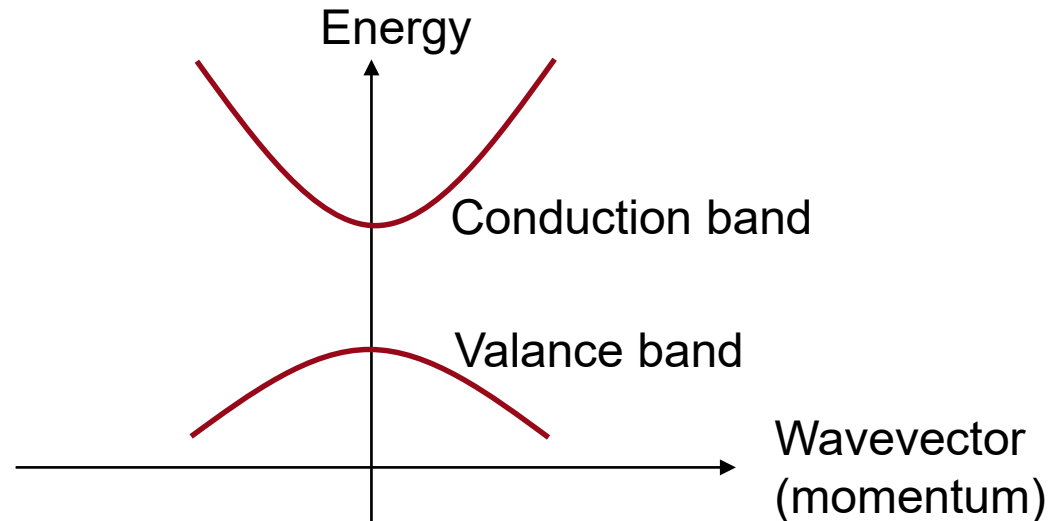
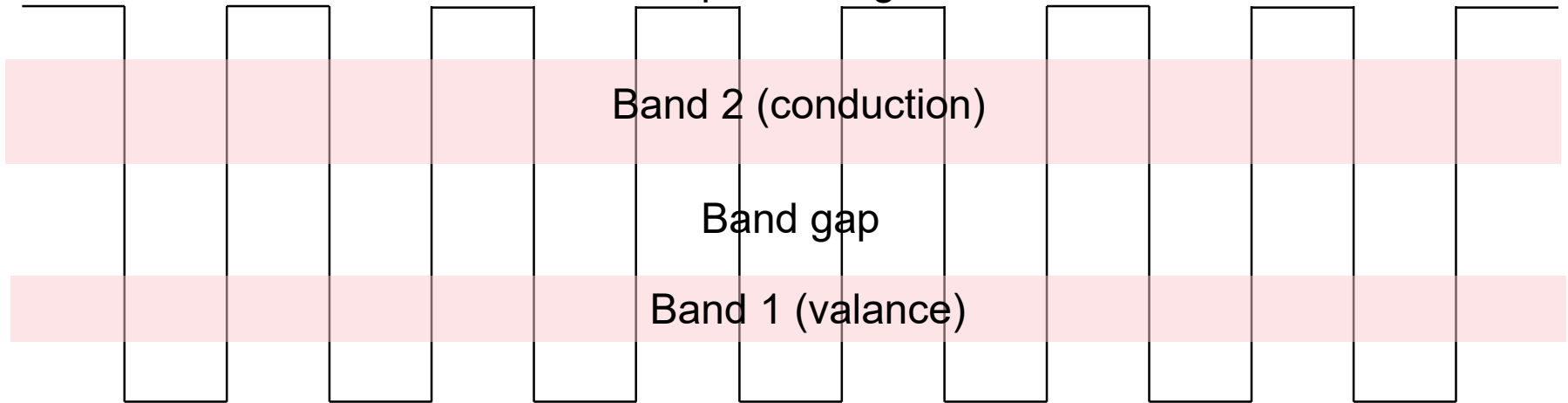


Think of each well representing an atom in a lattice



# Band structure

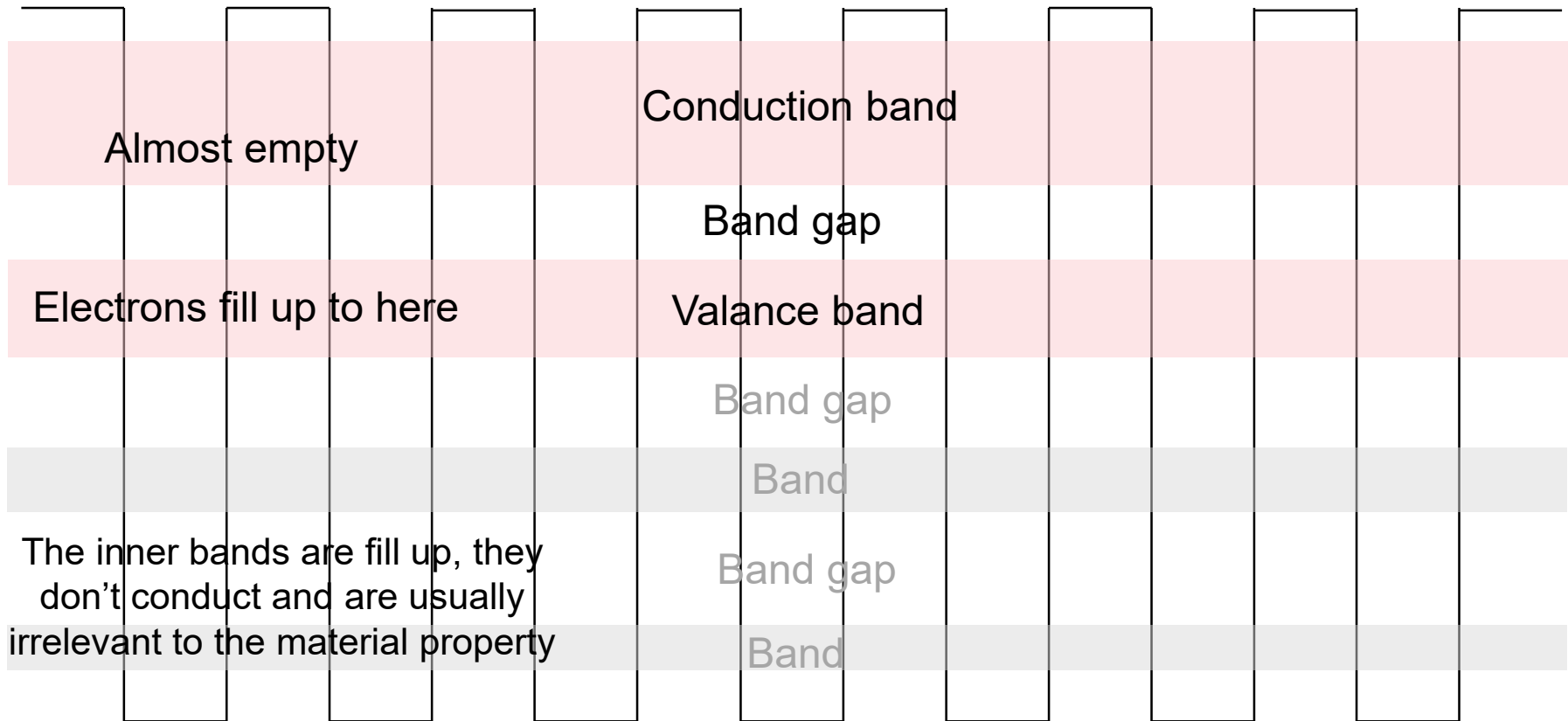
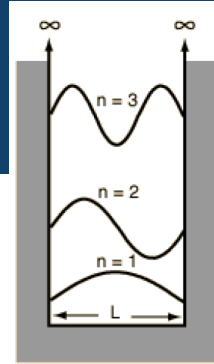
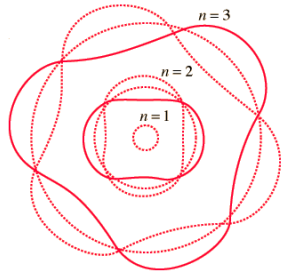
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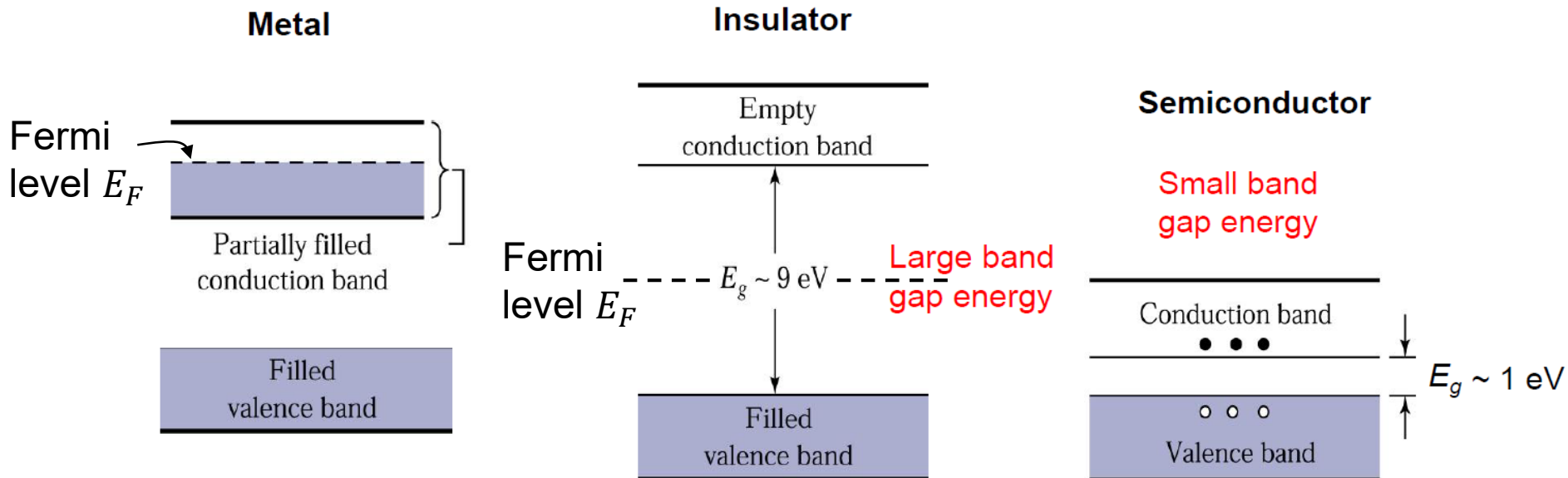


# Band gap in silicon

## > Band gap



## ➤ Bandgap energy and Fermi level



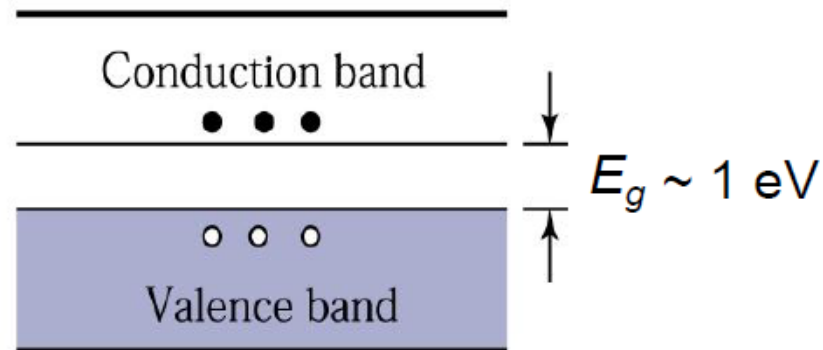
- The Fermi level, in plain words, marks the energy level to which the electrons would have filled up.
  - “Would have” as the Fermi level might be in the band gap, as the case for semiconductors.
  - For undoped silicon, it is roughly half-way in the band gap.
  - Technically, Fermi level is where the filling probability is  $\frac{1}{2}$  - more on this next week.



## › Bandgap for semiconductor

### Semiconductor

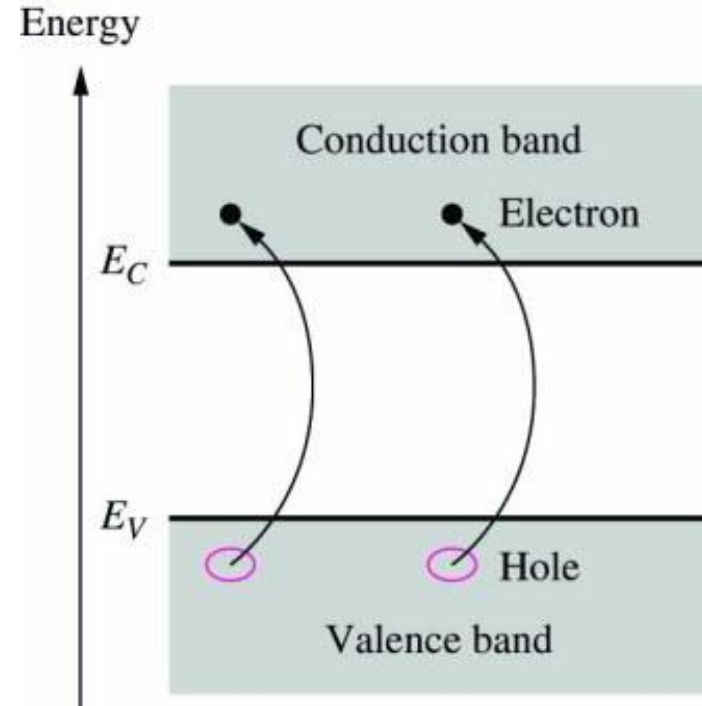
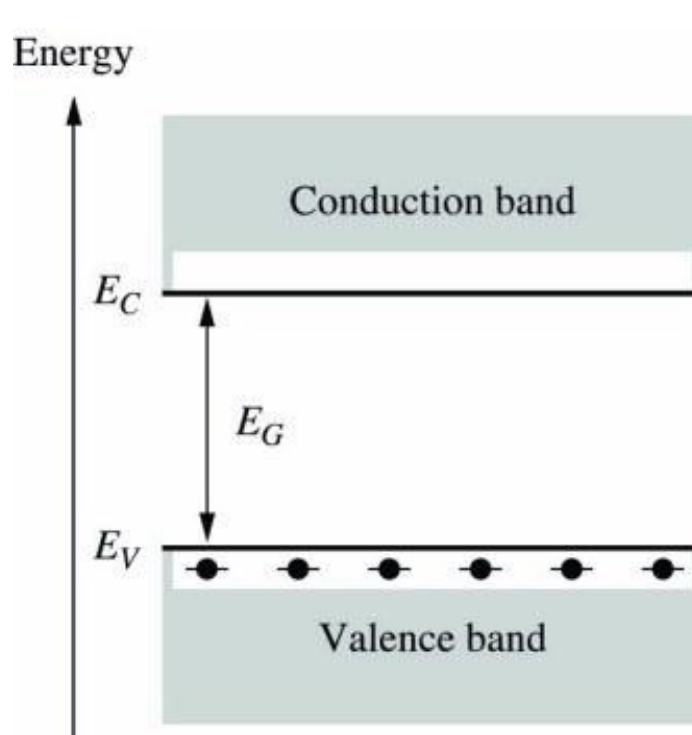
Small band  
gap energy



Silicon:  $1.1 \text{ eV} \sim 1.1 \mu\text{m}$   
(ideal for solar cell)

# Bandgap energy

- › Near absolute zero temperature, all bonds are complete. All electrons are sitting in the valence band and no electrons are in the conduction band



- › Increasing temperature adds energy to the system and breaks bonds in the lattice.
- › An electron enters the conduction band and leaves a hole in the valence band.
- › Only half-filled bands can conduct. Electrons can move to a vacancy nearby (or equivalently the vacancy is moving)

- Bandgap energy defined by a material
- Intrinsic carrier density  $n_i$  ( $\text{cm}^{-3}$ ) depends on material properties and temperature

$$n_i^2 = BT^3 e^{-\frac{E_g}{kT}} \quad (\text{cm}^{-6})$$

where  $E_g$  = semiconductor bandgap energy (eV)

$k$  (or  $k_B$ ) = Boltzmann's constant,  $8.62 \times 10^{-5} \text{ eV/K}$

$T$  = absolute temperature, K

$B$  = material-dependent parameter,  $1.08 \times 10^{31} \text{ K}^{-3} \cdot \text{cm}^{-6}$  for Si

Room temperature (300K):  
 $k_B T = 25.9 \text{ meV}$

- › The unit eV (electron volt) represents the energy necessary to move one electron across a potential difference of 1 V.

$$-1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

We almost always work with eV in this course.



- › Determine the density of electrons at room temperature ( $T = 300\text{K}$ )

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$$n_i^2 = BT^3 e^{-\frac{E_g}{kT}} \quad (cm^{-6})$$

**For Si,**

$$B = 1.08 \times 10^{31} K^{-3} . cm^{-6}$$

$$E_g = 1.12 \text{ eV}$$

$$n_i (T = 300K) = 6.73 \times 10^9 cm^{-3}$$

Note silicon has  $5 \times 10^{22}$  atoms/cm<sup>3</sup>  
Still a poor conductor at room temperature.

This is to say, 1 conducting  
electron per  $10^{12}$  atoms

What can we do  
to make silicon  
more useful?



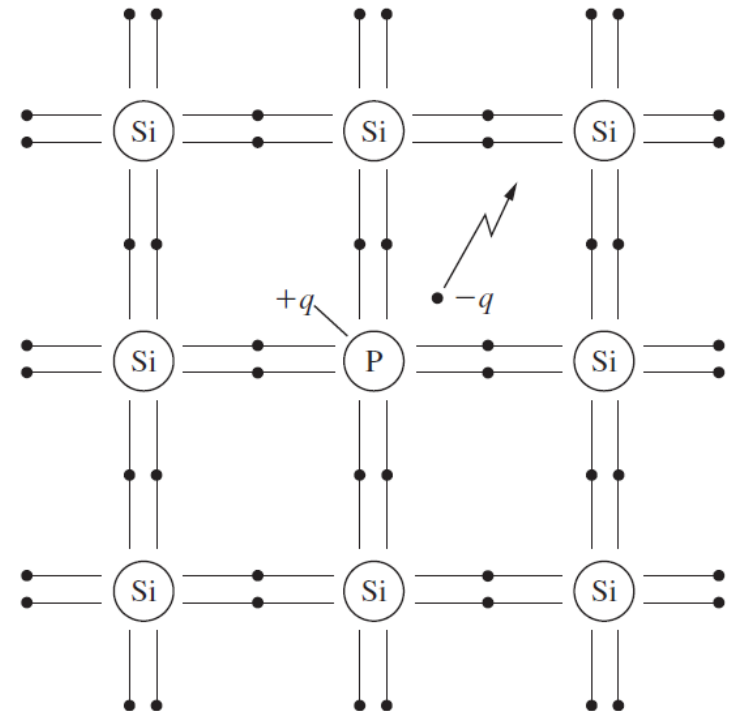
- › Pure silicon is semiconducting
  - Why would that be interesting? It is not conducting well, nor is it insulating well.
- › We need to be able to modify and control its conductivity
  - By doping.

From silicon to a chip

<https://www.youtube.com/watch?v=g8Qav3vlv9s>

## › Modification of silicon carrier densities

- Donor impurities
  - Column V  $\rightarrow$  5 valence electrons in the outer shell
  - E.g. Phosphorus, arsenic, and antimony
  - Replaces a silicon atom in the crystal lattice
  - 4 electrons in the outer shell fill the covalent bond structure
  - The extra electron is free to move, serving as a charge carrier



Introduction of impurities to an intrinsic (pure) semiconductor is called

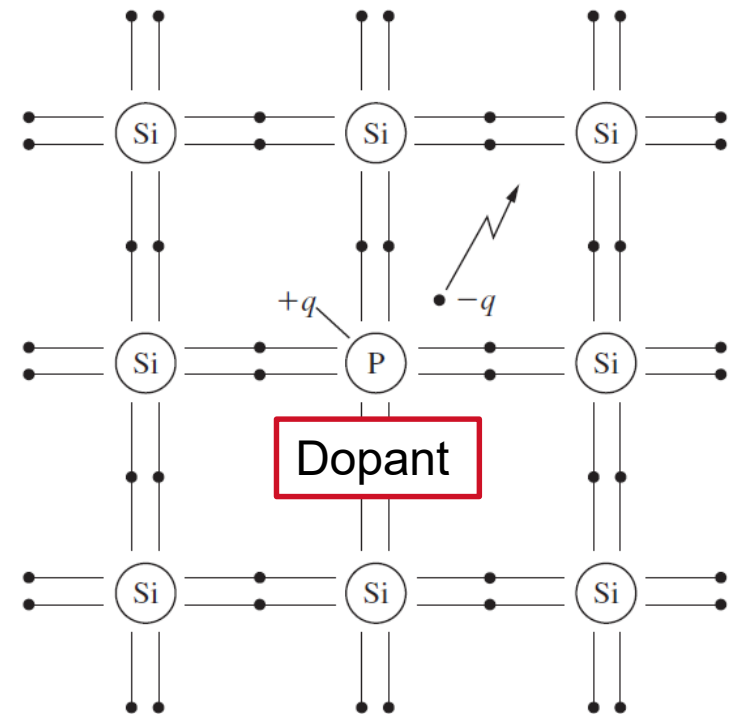
**DOPING**



**Doped semiconductors**

## › Modification of silicon carrier densities

- Donor impurities
  - Column V  $\rightarrow$  5 valence electrons in the outer shell
  - Phosphorus, arsenic, and antimony
  - At room temperature, these dopants are fully ionized
  - 1 dopant = 1 electron
  - electron density  $\approx$  dopant density (why?)



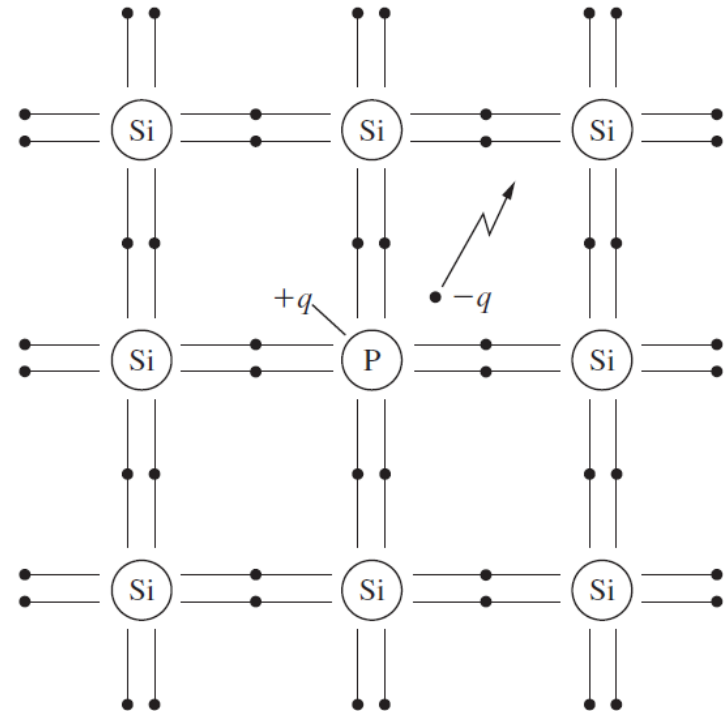


## › Modification of silicon carrier densities

Recall for intrinsic semiconductor :

$$pn = n_i^2$$

How about extrinsic semiconductor?



## › Modification of silicon carrier densities

Recall for intrinsic semiconductor :

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How about extrinsic semiconductor?

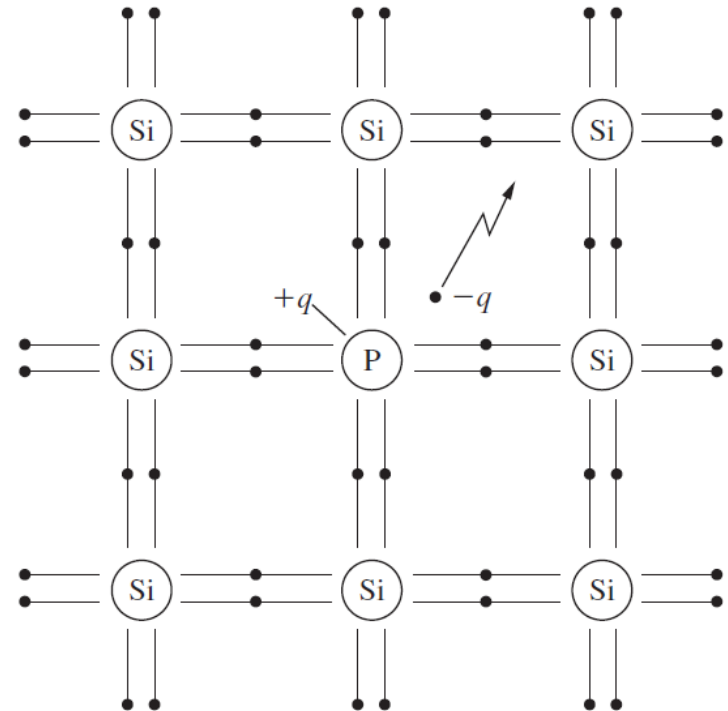
**STILL**

$$pn = n_i^2$$

Hole and  
carrier  
densities in  
extrinsic  
semiconductor

Densities in  
intrinsic  
semiconductor

(independent of doping level)



How could it be that  $n$  is  
now higher, but  $n_i$  is  
unchanged?

## › Modification of silicon carrier densities

Extrinsic semiconductor?

**STILL**

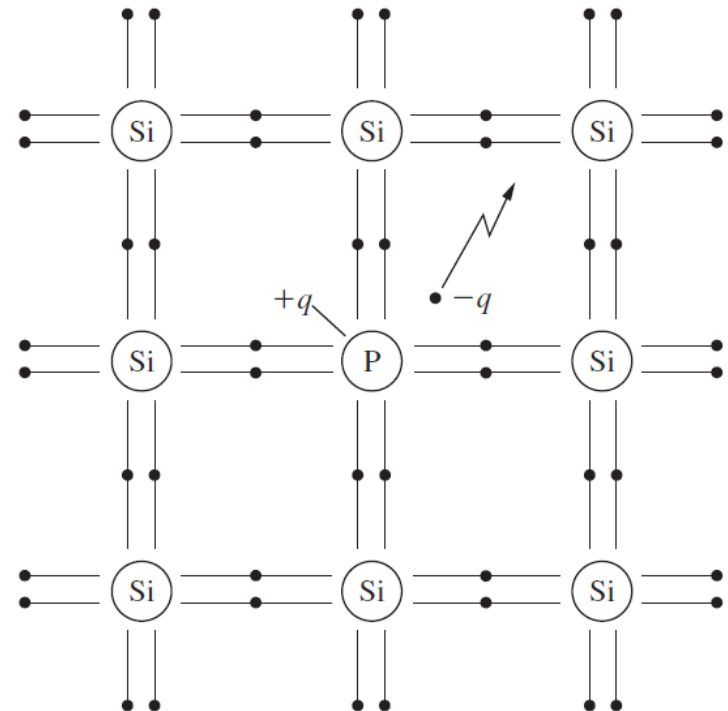
$$pn = n_i^2$$

Hole and  
carrier  
densities in  
extrinsic  
semiconductor

Densities in  
intrinsic  
semiconductor

(independent of doping level)

Reason: more electrons will be able to recombine with holes. Making less holes. So in the end the equation is still valid.  
 $p$  must be much smaller than  $n_i$





- › A piece of crystalline silicon is doped uniformly with phosphorus atoms. The doping density is  $10^{16}$  atoms/cm<sup>3</sup>. Determine the electron and hole densities in this material at room temperature.

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$$\begin{aligned} &\text{No. of additional electrons/cm}^3 \\ &= 10^{16} \quad \gg n_i (\approx 10^{10} \text{ from previous example}) \end{aligned}$$

$$\text{Assume } n = 10^{16} \text{ electrons/cm}^3$$

$$pn = n_i^2$$

$$p = 10^4 \text{ holes/cm}^3$$

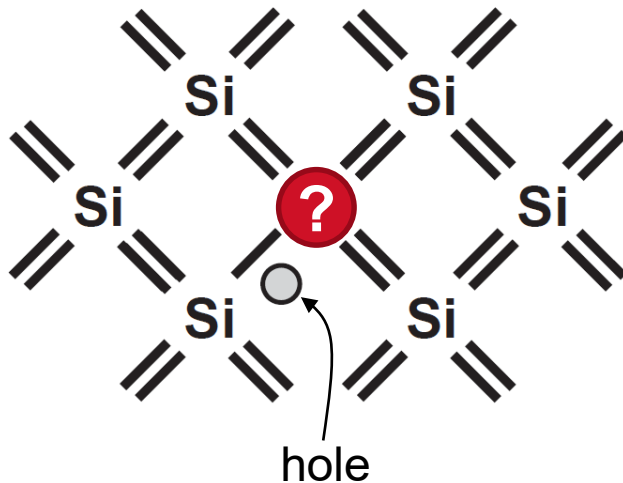
Hole density has dropped below the intrinsic level by 6 orders of magnitude.

Thus electrons become the “majority carriers” and holes “minority carriers” in a n-type semiconductor

**Can the roles of electrons and holes be reversed?**

## › Modification of silicon carrier densities

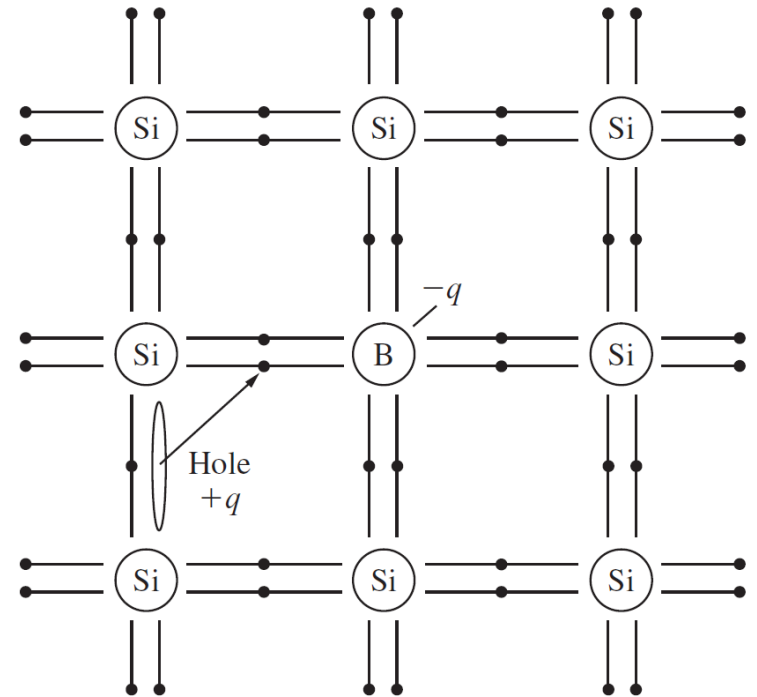
- Acceptor impurities
- Dope with atoms that provide insufficient number of electrons to form incomplete covalent bonds
- 4<sup>th</sup> bond -> hole



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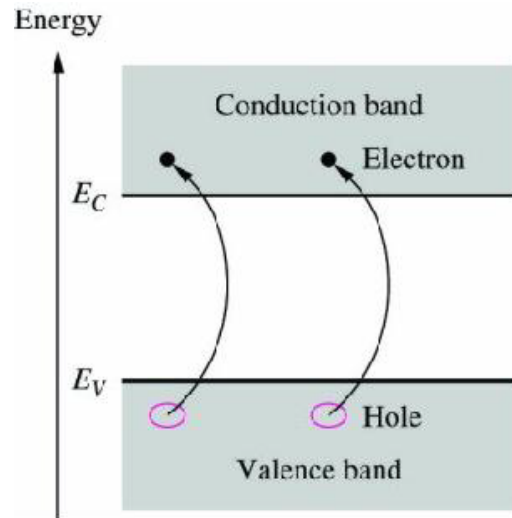
## › Modification of silicon carrier densities

- Acceptor impurities
  - Column III  $\rightarrow$  3 valence electrons in the outer shell
  - E.g. Boron
  - Vacancy exists in the bond structure
  - Nearby electrons move into this vacancy, creating another vacancy in the bond structure
  - Hole visualized as a particle with a charge  $+q$
  - Acceptor atom becomes ionized by accepting an electron and has a net immobile fixed charge of  $-q$  in the crystal lattice

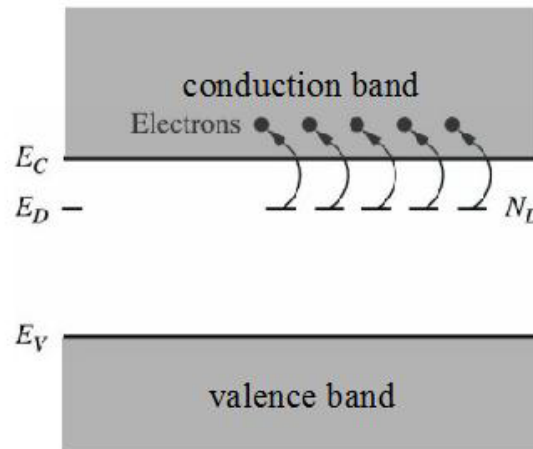


# Dopant levels in the bandgap

- › The energy level of the extra donor electron is much closer to the energy level of the conduction band than the valence band
- › Since  $E_D$  is close to  $E_C$ , (about 0.045 eV for phosphorous), it is easy for donor electrons to move up into the conduction band.



Undoped Si energy bands

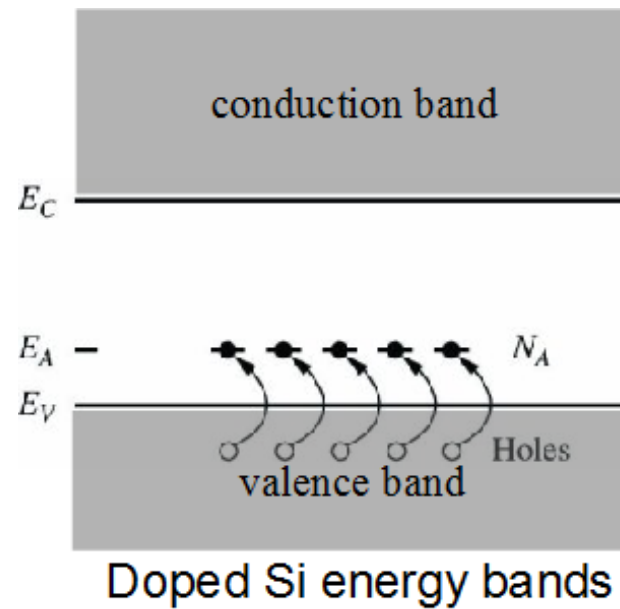


Doped Si energy bands



# Dopant levels in the bandgap

- › Semiconductor with acceptor or p-type dopants. The donor atoms have unfilled covalent bonds with energy state  $E_A$
- › Since  $E_A$  is close to  $E_V$ , (about 0.044 eV for boron), it is easy for electrons in the valence band to move up into the acceptor sites and complete covalent bond pairs.



# Both p and n doped semiconductor

## › Define

$N_D$  = **donor impurity concentration**      atoms/cm<sup>3</sup>

$N_A$  = **acceptor impurity concentration**      atoms/cm<sup>3</sup>

## › Charge neutral:

$$N_D - N_A = n - p$$

## › Carriers:

$$np = n_i^2$$

## › n-type material

- Majority carrier is donor atoms ( $N_D > N_A$ )

$$n = \frac{(N_D - N_A) + \sqrt{(N_D - N_A)^2 + 4n_i^2}}{2} \quad \text{and} \quad p = \frac{n_i^2}{n}$$

$$n \cong (N_D - N_A) \quad \text{when} \quad (N_D - N_A) \gg 2n_i$$

## › p-type material

- Majority carrier is acceptor atoms ( $N_A > N_D$ )

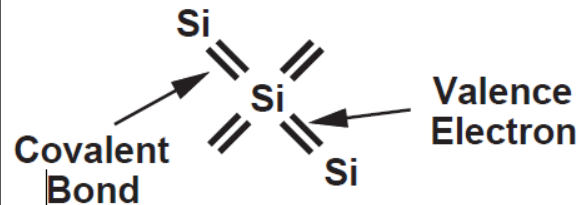
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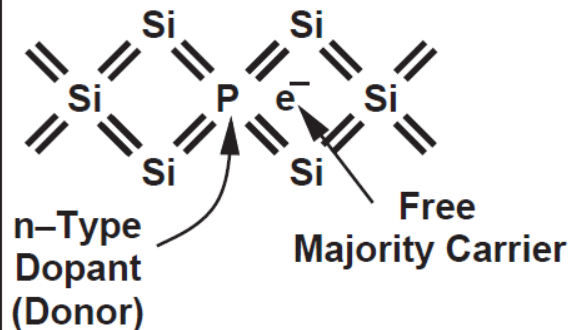
# Summary of charge carriers in silicon

## Intrinsic Semiconductor

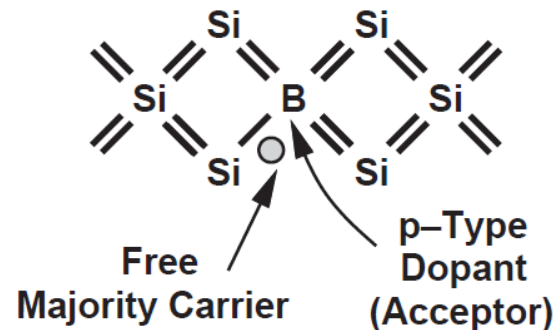


## Extrinsic Semiconductor

Silicon Crystal  
 $N_D$  Donors/cm<sup>3</sup>

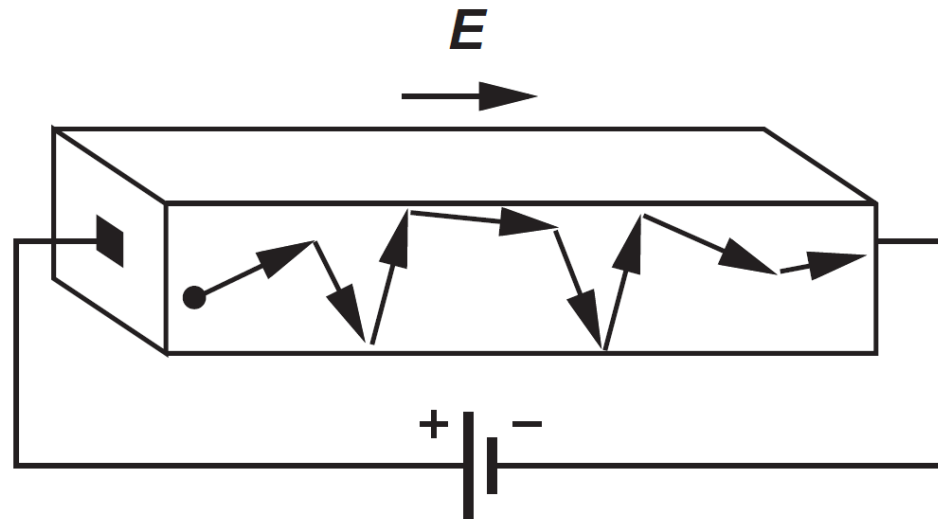


Silicon Crystal  
 $N_A$  Acceptors/cm<sup>3</sup>



Typical doping  
ranges are  
 $10^{14}/\text{cm}^3$  to  
 $10^{21}/\text{cm}^3$ .

- › How does charge carriers move in semiconductor?



How does current flow?

Ohm's law: a material can conduct current in response to a potential difference and hence an electric field

The field accelerates the charge carriers in the material, forcing some to flow from one end to the other.

Electrons can hit imperfections (defects, dopants, etc.), thus can't move at infinite speed.

- › Charged particles move (drift) in response to an applied electric field
  - Positive charges drift in the same direction as electric field
  - Negative charges drift in the opposite direction as electric field (diagram)
  - The charge carriers are accelerated by the field and accidentally collide with the atoms in the crystal, eventually reaching the other end and flowing into the battery.
  - The acceleration due to the field and the collision with the crystal counteract, leading to a constant velocity for the carriers.

- › Charged particles move (drift) in response to an applied electric field
  - Positive charges drift in the same direction as electric field
  - Negative charges drift in the opposite direction as electric field (diagram)
- › Carrier drift velocity  $v$  (cm/s) is proportional to the electric field  $E$  (V/cm)

$$v \propto E$$

- Constant of proportionality is called the mobility  $\mu$       Unit:  $\frac{\text{cm}^2}{\text{V}\cdot\text{s}}$

$$v_n = -\mu_n E$$

$$v_p = \mu_p E$$

where  $v_n$  = velocity of electrons (cm/s)

$v_p$  = velocity of holes (cm/s)

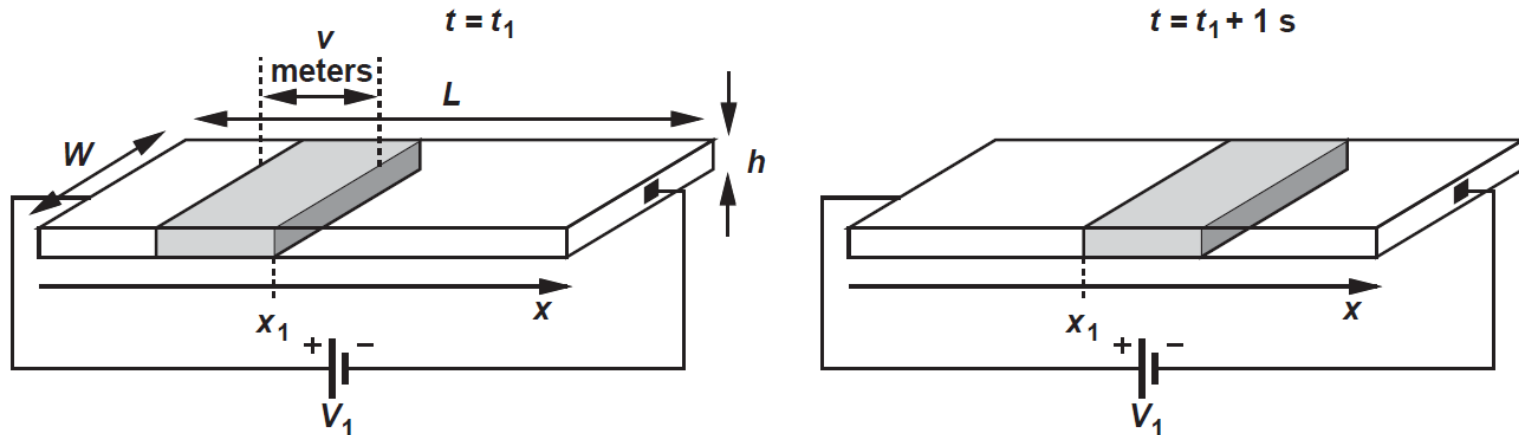
$\mu_n$  = electron mobility ( $1350 \frac{\text{cm}^2}{\text{V}\cdot\text{s}}$ ) in intrinsic Si

$\mu_p$  = hole mobility ( $500 \frac{\text{cm}^2}{\text{V}\cdot\text{s}}$ ) in intrinsic Si

World-record mobility: 36M, in  
Prof. Loren Pfeiffer's lab  
(Princeton University)

## › Drift current

- Charged particles move or drift in response to the electric field



- Drift current density  $J$

$$J = Qv \quad \text{A/cm}^2$$

where  $J$  = the charge in Coulombs moving through a unit cross section

$Q$  = charge density, the charge in a unit volume

$v$  = velocity of charge in an electric field

- › Electron and hole drift current densities

$$j_n^{drift} = Q_n v_n = (-qn)(-\mu_n E) = qn\mu_n E \quad \text{A/cm}^2$$

$$j_p^{drift} = Q_p v_p = (+qp)(+\mu_p E) = qp\mu_p E \quad \text{A/cm}^2$$

- › Total drift current densities

$$j_T^{drift} = q(n\mu_n + p\mu_p)E$$

$$= \sigma E$$

**Electrical conductivity ( $\Omega \cdot \text{cm}$ )<sup>-1</sup>**

- › Resistivity  $\rho$  is the reciprocal of conductivity

$$\rho = \frac{1}{\sigma} \quad (\Omega \cdot \text{cm})$$

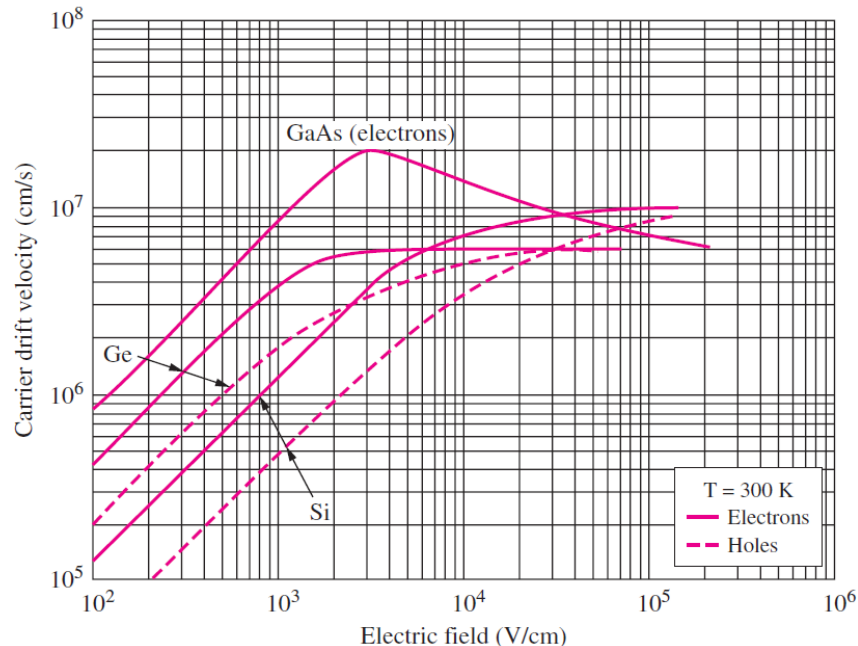
- ›  $\rho$  and  $\sigma$  characterise current flow in a material when an E-field is applied





# Velocity saturation

- › Can velocity of carriers increase indefinitely? What happens at high E-field?



In silicon, the linear velocity-field relationship is valid only for fields below approximately 5000 V/cm or 0.5 V/m. Then it saturates at  $v_{\text{sat}}$ .

Mainly due to excitation of optical phonon, i.e. create resonances in lattice itself.

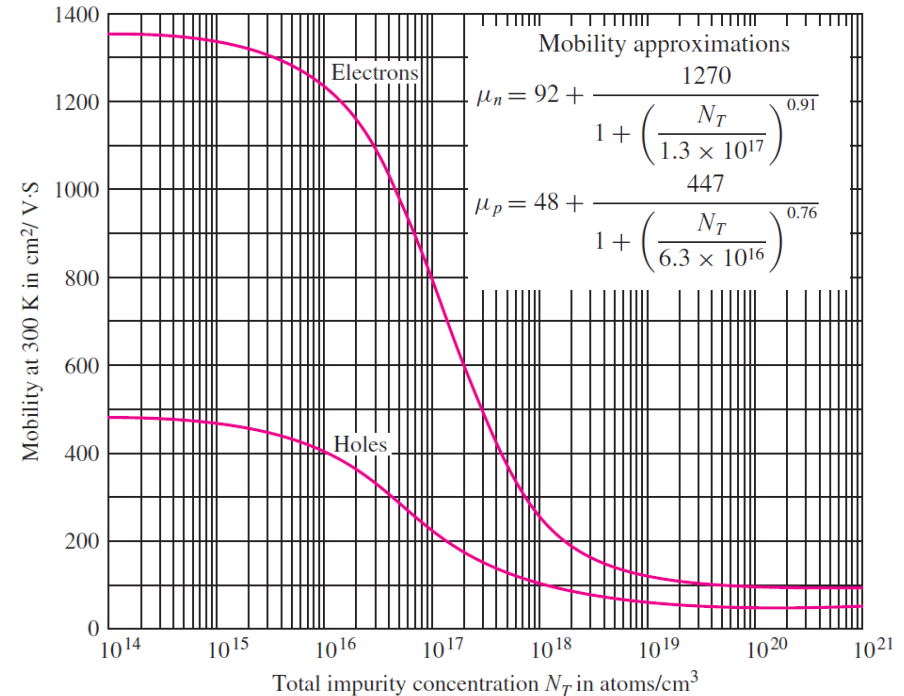
For electrons and holes in silicon,  $v_{\text{sat}}$  is approximately  $10^7$  cm/s.

The velocity saturation phenomenon ultimately places an upper limit on the frequency response of solid-state Devices

# Mobility and resistivity in doped semiconductors

## › Impurities degrades mobility of the carriers

- Disrupts lattice periodicity due to difference in atom sizes
- Ionized impurity atoms creates localised charges
- Scattering of holes and electrons as they move through the semiconductor



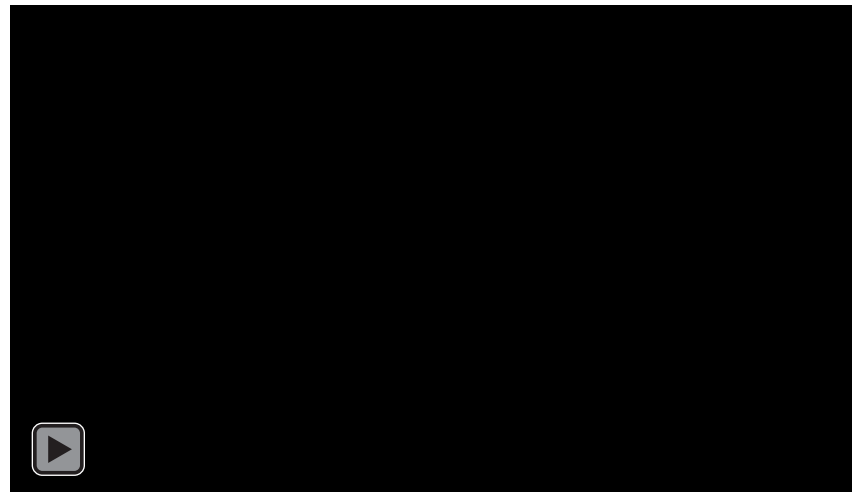
## › However, doping increases density of majority carriers

- Decrease in resistivity -> overcomes decreased mobility
- Majority of carrier concentration controls conductivity of material

$$\sigma \cong q\mu_n(N_D - N_A) \quad \text{for n-type material}$$

$$\sigma \cong q\mu_p(N_A - N_D) \quad \text{for p-type material}$$

- › Nonuniform doping in the semiconductor
  - Gradients in the electron and hole concentrations
  - Free carriers tend to move from high concentrations to low concentrations region



## **DIFFUSION**

Also create currents

## > Diffusion current

- Follows carrier concentration gradient :

$$I \propto Aq \frac{\partial n}{\partial x}$$

$n$ : carrier concentration

$A$ : area

$q$ : elementary charge

$x$ : distance

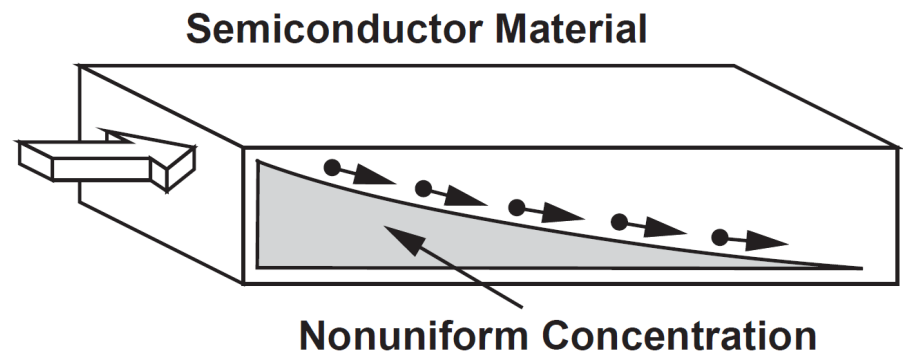
No electric field needed.

Imagine charge carriers are “dropped” (injected) into a semiconductor so as to create a nonuniform density.

## > Diffusion current density

$$J = qD_N \frac{\partial n}{\partial x}$$

**Diffusion constant**





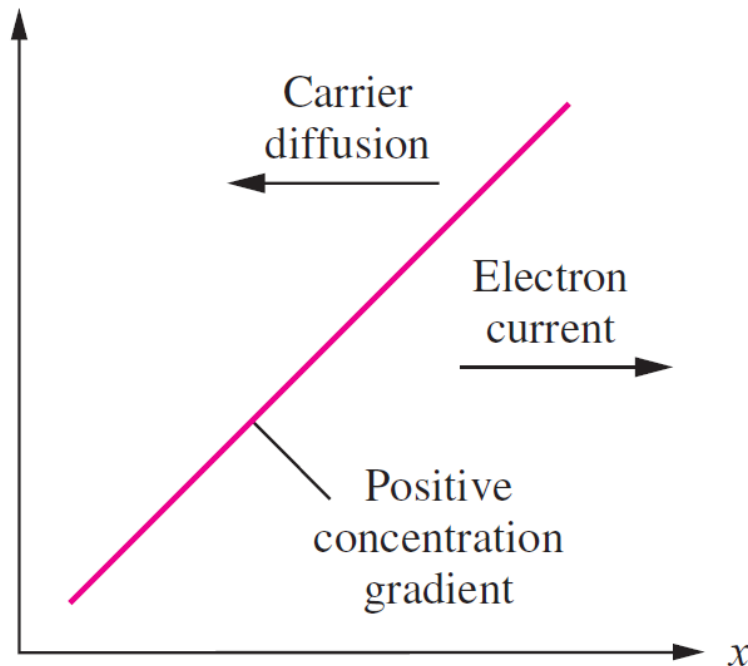
## › Electron current densities

$$j_n^{diff} = (-q)D_n \left( -\frac{\partial n}{\partial x} \right) = +qD_n \frac{\partial n}{\partial x} \quad \text{A/cm}^2$$

Sign of charge

Direction of particle movement

$n(x)$  or  $p(x)$





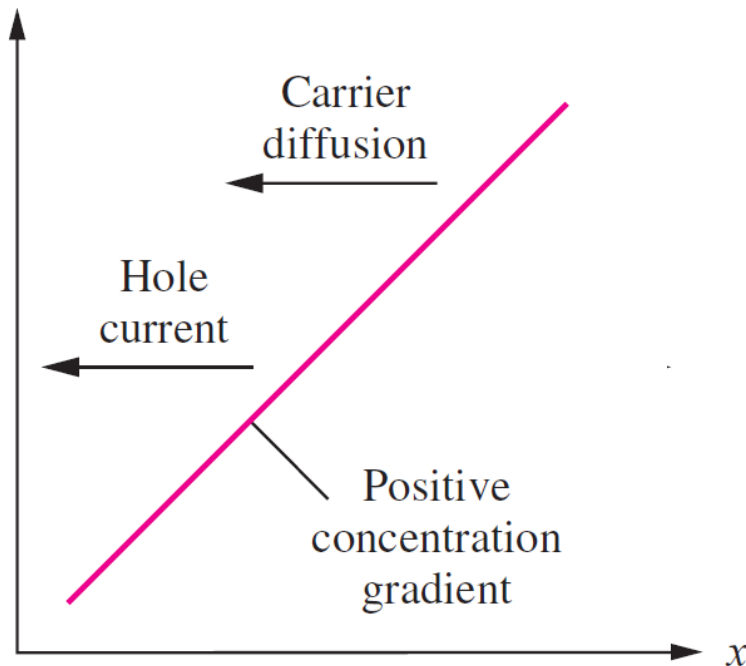
## › Hole current densities

$$j_p^{diff} = (+q)D_p \left( -\frac{\partial p}{\partial x} \right) = -qD_p \frac{\partial p}{\partial x} \quad \text{A/cm}^2$$

Sign of charge

Direction of particle movement

$n(x)$  or  $p(x)$

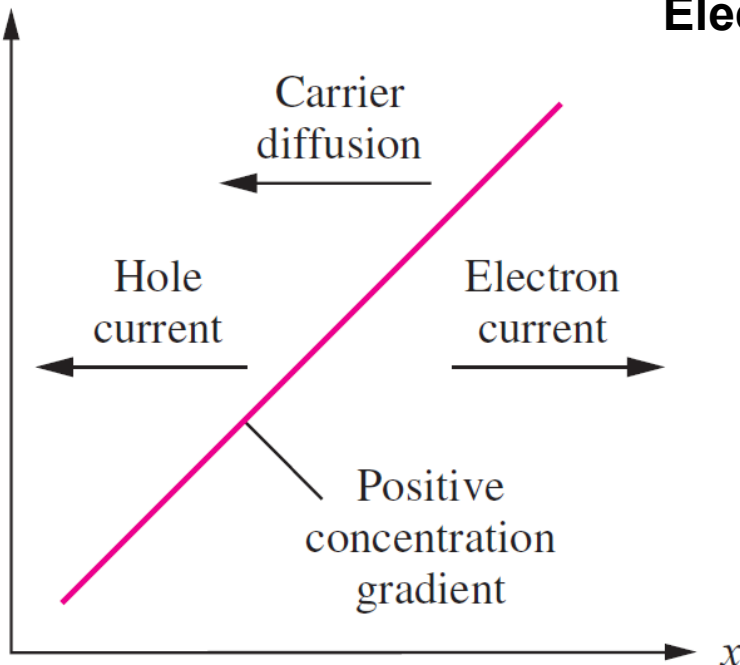


## › Electron and hole diffusion current densities

$$j_n^{diff} = (-q)D_n\left(-\frac{\partial n}{\partial x}\right) = +qD_n\frac{\partial n}{\partial x} \quad \text{A/cm}^2$$

$$j_p^{diff} = (+q)D_p\left(-\frac{\partial p}{\partial x}\right) = -qD_p\frac{\partial p}{\partial x} \quad \text{A/cm}^2$$

$n(x)$  or  $p(x)$



**Electron and hole diffusivities (cm<sup>2</sup>/s)**

- › Total electron and hole densities is the sum of drift and diffusion components

$$j_n^T = j_n^{drift} + j_n^{diff} = q\mu_n nE + qD_n \frac{dn}{dx}$$

$$j_p^T = j_p^{drift} + j_p^{diff} = q\mu_p pE - qD_p \frac{dp}{dx}$$

- › Total current

*Pay attention to signs.*

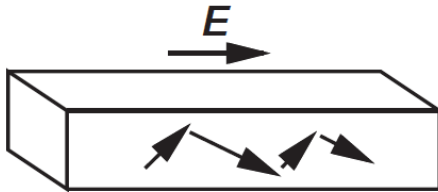
$$\begin{aligned} j^T &= j_n^T + j_p^T \\ &= q\mu_n nE + qD_n \frac{dn}{dx} + q\mu_p pE - qD_p \frac{dp}{dx} \end{aligned}$$





# Einstein relation

## Drift Current



$$J_n = q n \mu_n E$$

$$J_p = q p \mu_p E$$

Can we form a  
relationship between  
 $\mu_n$  and  $D_n$  ?

**YES!**

## Diffusion Current



$$J_n = q D_n \frac{dn}{dx}$$

$$J_p = -q D_p \frac{dp}{dx}$$

Thanks to Einstein:

$$\frac{D_n}{\mu_n} = \frac{kT}{q} = \frac{D_p}{\mu_p}$$

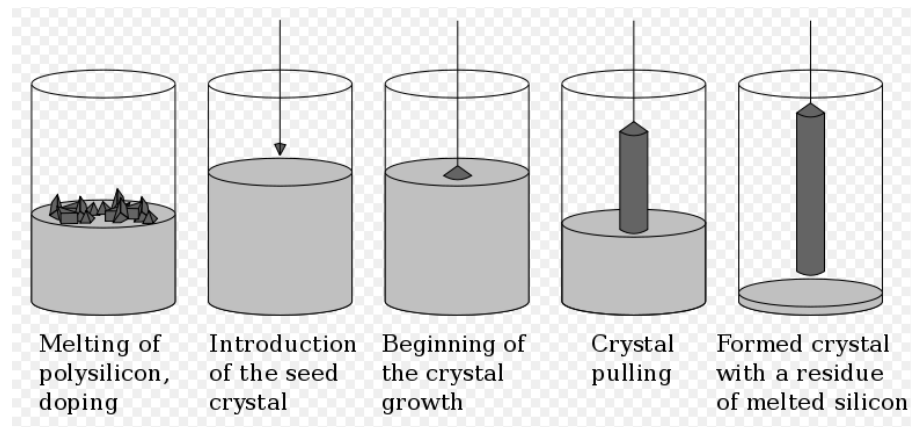
Thermal voltage,  $V_T$



- › Fabrication of semiconductors takes place in fabrication facilities i.e. clean rooms

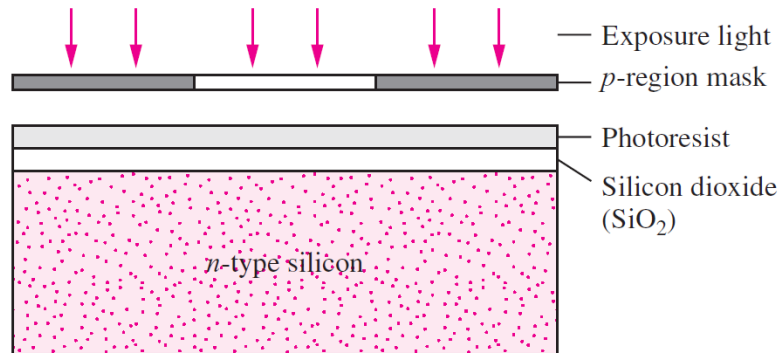


- › Silicon wafers are grown using crystallization process

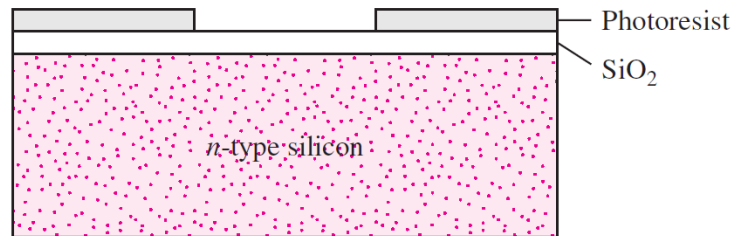




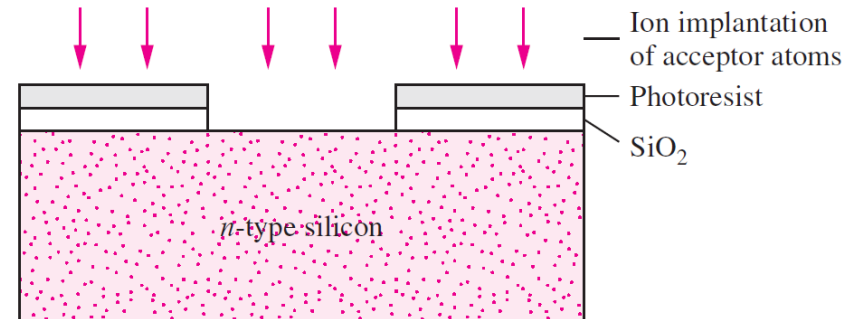
# Integrated Circuit Fabrication



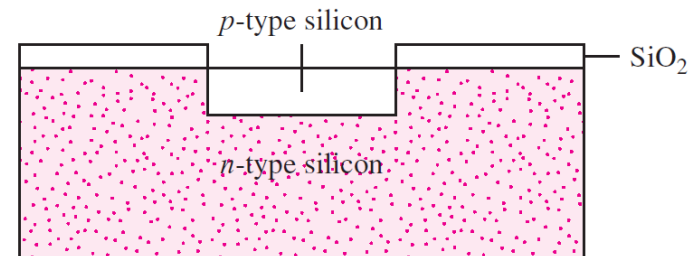
(a)



(b)



(c)

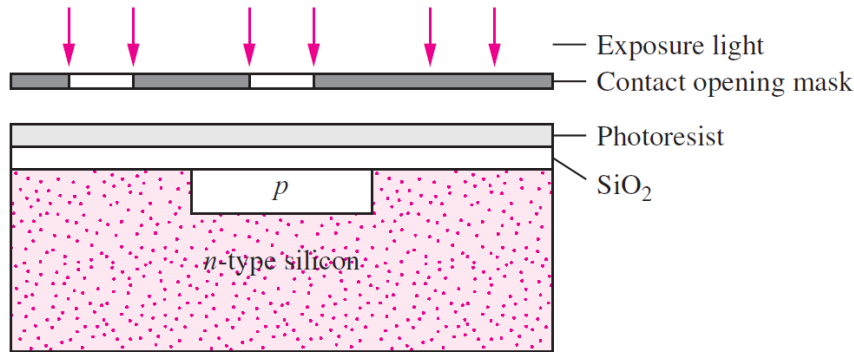


(d)

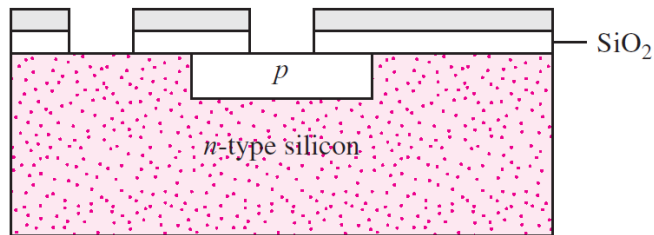
(a) First mask exposure, (b) post-exposure and development of photoresist, (c) after  $\text{SiO}_2$  etch, and (d) after implantation/diffusion of acceptor dopant.



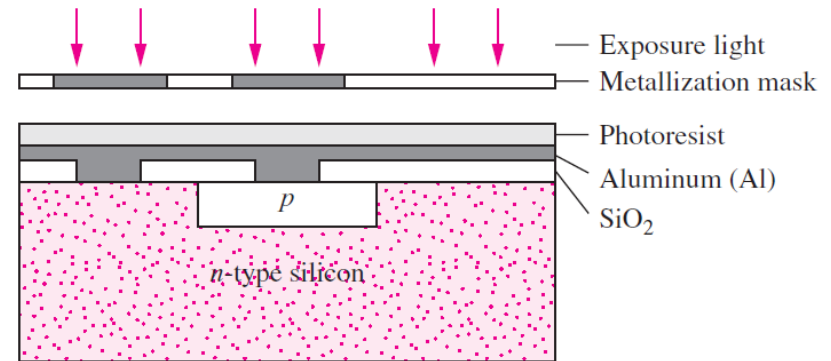
# Integrated Circuit Fabrication



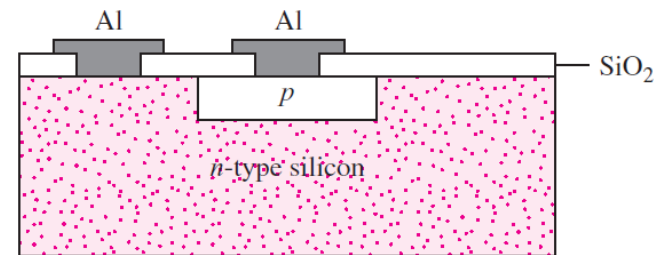
(e)



(f)



(g)

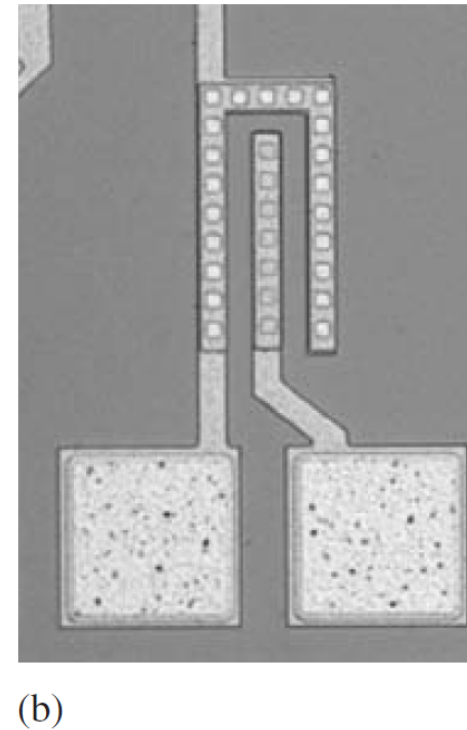
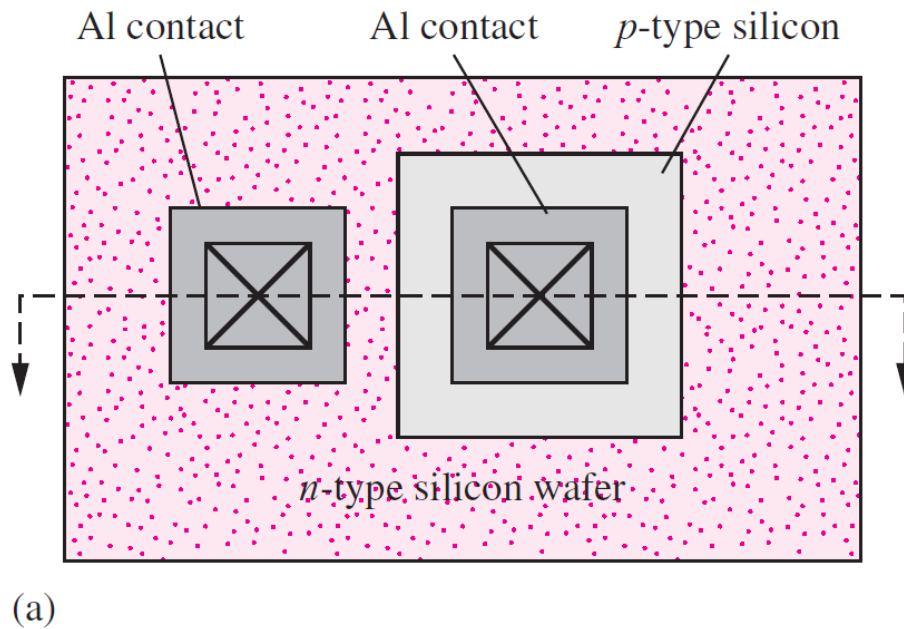


(h)

(e) Exposure of contact opening mask, (f) after resist development and etching of contact openings, (g) exposure of metal mask, and (h) After etching of aluminum and resist removal.



# Integrated Circuit Fabrication



## END PRODUCT

PN Diode integrated on a silicon wafer (Next Week)

› Main reference:

- Chapter 3, sections 3.1 and 3.2 of Sedra & Smith 6th

› Deeper dive into semiconductor physics:

- Device Electronics for Integrated Circuits 3rd Ed. by Richard S. Muller, Theodore I. Kamins, Mansun Chan
- Chapter 1, sections 1.1 and 1.2