

ELECTRONIC SYSTEMS and TECHNOLOGIES

Master in Management Engineering

Prof. Marco Sampietro

GROUND CONCEPTS ON ELECTRONICS

The semiconductor materials

The very BIG player

PERIODIC CHART OF THE ELEMENTS

IA	IIA	IIIB	IVB	VB	VIB	VII B	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	INERT GASES		
1 H 1.00797															2 He 4.0026		
3 Li 6.939	4 Be 9.0122										5 B 10.811	6 C 12.0112	7 N 14.0067	8 O 15.9994	9 F 18.9984	10 Ne 20.180	
11 Na 22.98976	12 Mg 24.304										13 Al 26.9815	14 Si 28.086	15 P 30.9738	16 S 32.064	17 Cl 35.453	18 Ar 39.948	
19 K 39.102	20 Ca 40.08	21 Sc 44.956	22 Ti 47.88	23 V 50.942	24 Cr 51.996	25 Mn 54.9380	26 Fe 55.847	27 Co 58.9332	28 Ni 58.71	29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.9216	34 Se 78.96	35 Br 79.909	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.905	40 Zr 91.22	41 Nb 92.906	42 Mo 95.94	43 Tc [99]	44 Ru 101.07	45 Rh 102.905	46 Pd 106.4	47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
55 Cs 132.905	56 Ba 137.34	*57 La 138.91	72 Hf 178.49	73 Ta 180.948	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.08	79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	†89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (262)	108 Hs (265)	109 Mt (268)	110 ? (271)	111 ? (272)	112 ? (277)						

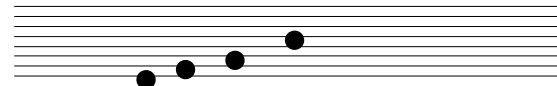
• **Si¹⁴**: 14 electrons, $1s^2 2s^2 2p^6 3s^2 3p^2$

4 electrons in the outest shell

• Medium Electronegativity (tendency to “share” electrons more than “catch” or “release” them)

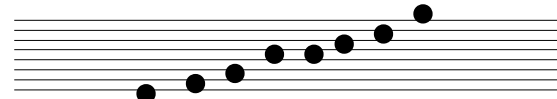
A closer view to a Silicon atom

8 possible states
occupied by 4 e⁻



n = 3 } Valence electrons

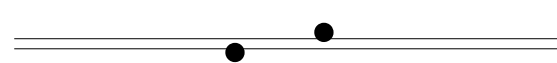
8 possible states
occupied by 8 e⁻



n = 2

Few eV

2 possible states
occupied by 2 e⁻



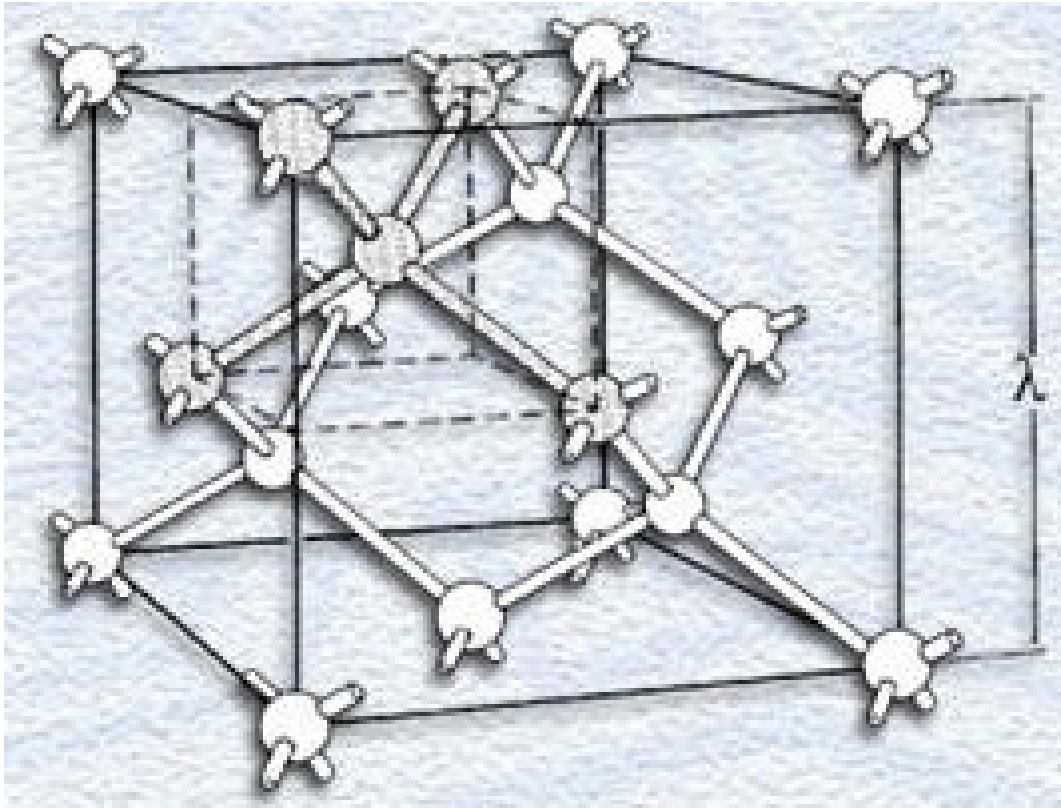
n = 1

The energy Unit of charge
carriers in Electronics is the
ElectronVolt, eV

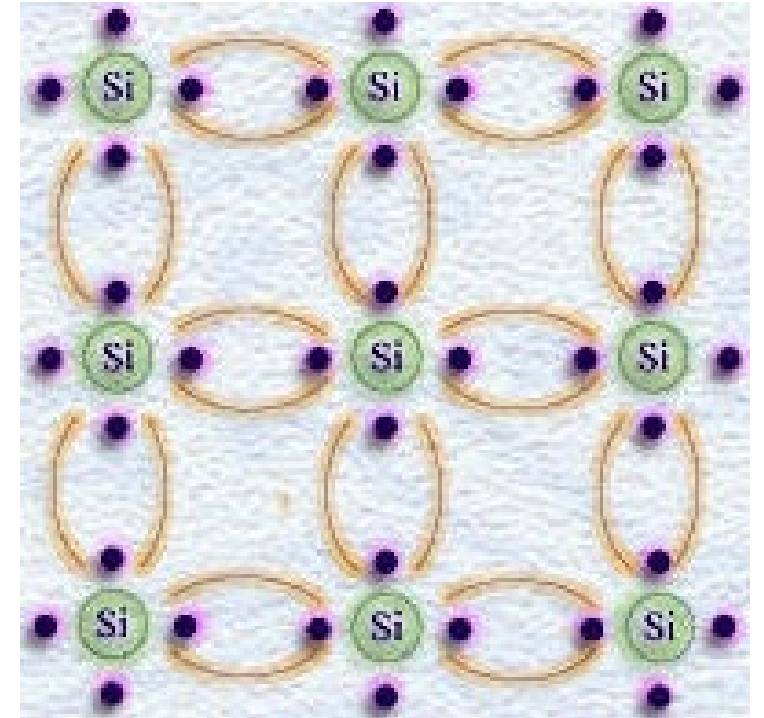
14 +

1 eV = $1.6 \cdot 10^{-19}$ Joules

Cristalline structure of Silicon



$\sim 0.5 \text{ nm}$



Very dense : $5 \times 10^{22} \text{ atomi/cm}^3$

Silicon ingot



Silicon wafers in a carrier



Silicon Wafer

Small size(76/50.8/25.4mm)

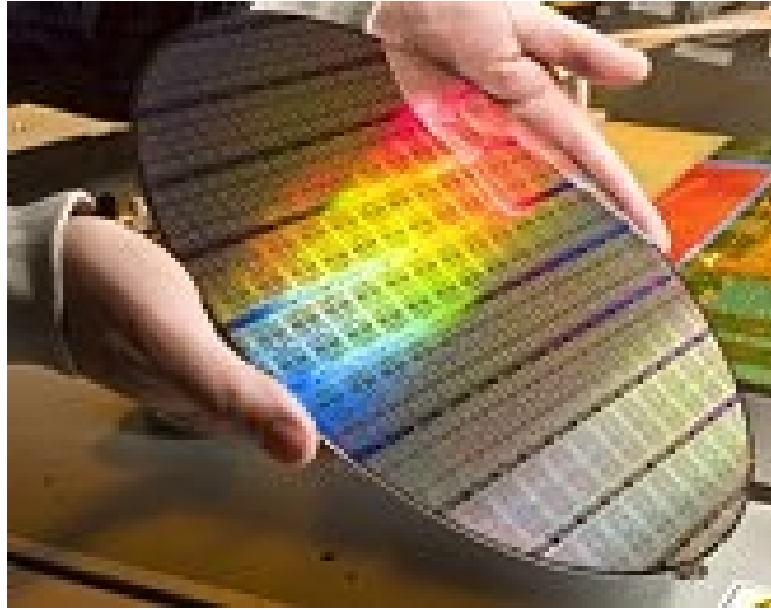
4 inch(100mm) Polished Wafer

5 inch(125mm) Polished Wafer

6 inch(150mm) Polished Wafer

8 inch(200mm) Polished Wafer

12 inch(300mm) Polished Wafer



GlobalWafers Italian Subsidiary, MEMC SPA, launches 300mm Expansion Plan



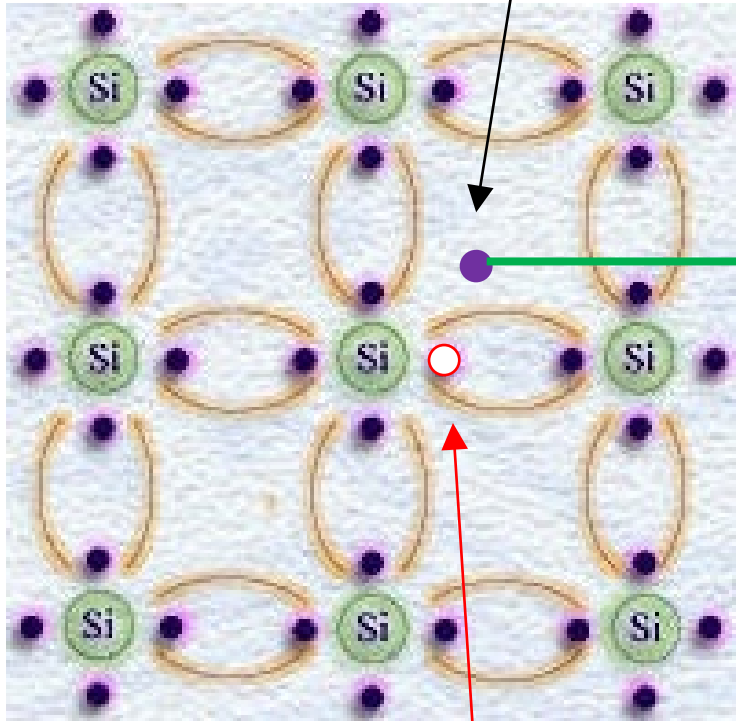
Novara (NO), Italy - 18 February 2022 - MEMC Electronic Materials SpA (MEMCSPA), GlobalWafers Group (GWC)

On February 10th 2022, MEMCSPA Board of Directors, following up GWC BoD decision, has finally approved the expansion of its existing facility located in Novara (Italy), that's currently producing 200mm silicon wafers, by adding a new 300mm wafers production module.

The global race toward 300nm

Electrons and Holes and Currents

This **electron** has broken the valence bond and can move freely in the crystal



HOLE
missing of a valence electron



ELECTRON can be pulled
by the Electric Field

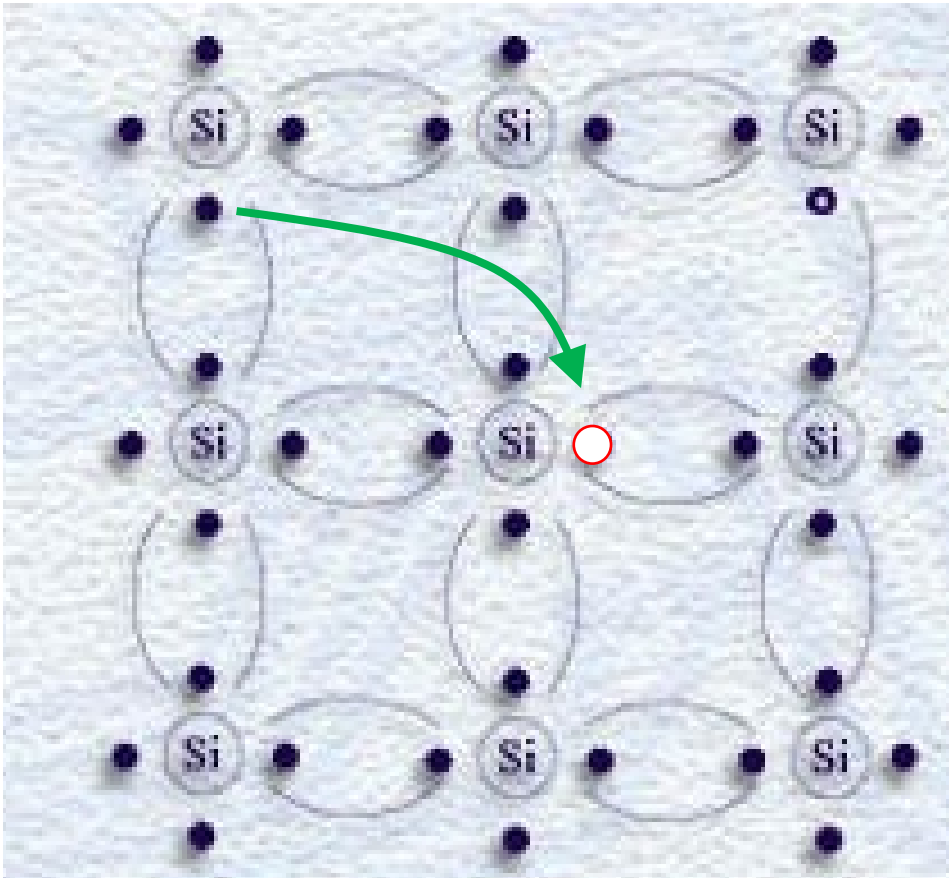
The movement of charges
produce a current

The direction of the Current is
opposite to that of electrons

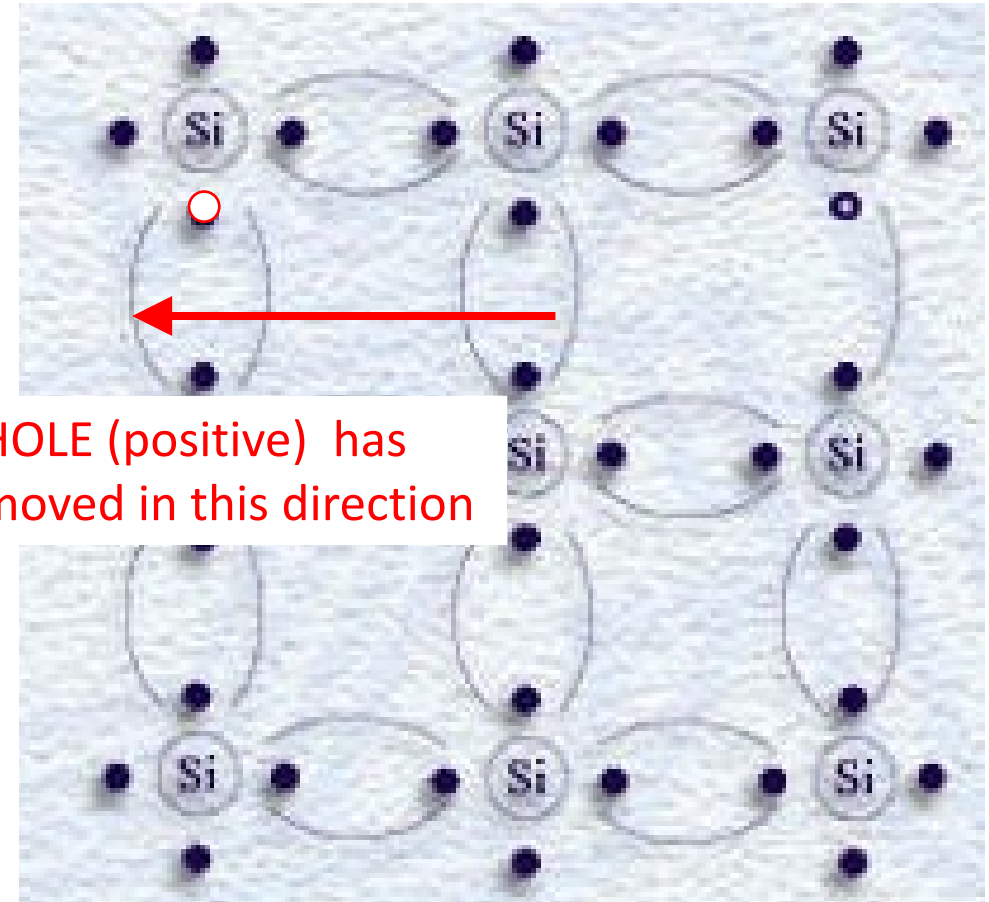


Conduction of Holes

A valence electron can occupy the site of the HOLE

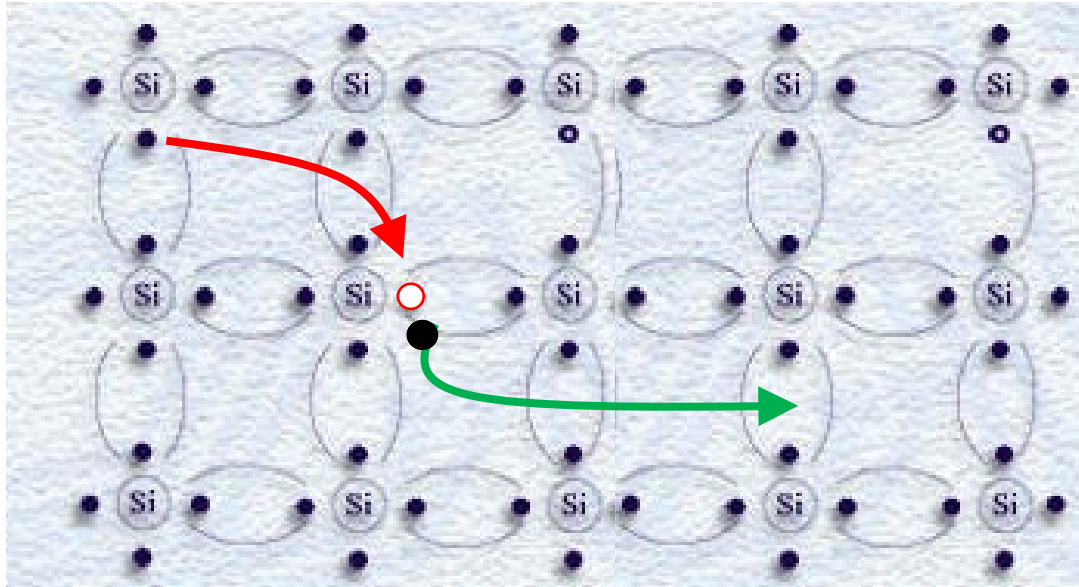


... freeing a HOLE in the site where it was



Same direction of the current

Meaning of «Semiconductor» (1)



Conduction by means of **electrons** and **holes**

Limited number of electrons and holes (*as compared to a metal, where all atoms generate an electron – 10^{23} electrons/cm³*)

More electrons → higher possible current

Exercise 1

If the temperature of a pure silicon crystal is increased, the number of holes per cm^3 increases or decreases? And that of electrons?

Exercise 2

The diamond is a crystal exactly the same as silicon but made with carbon atoms (C).

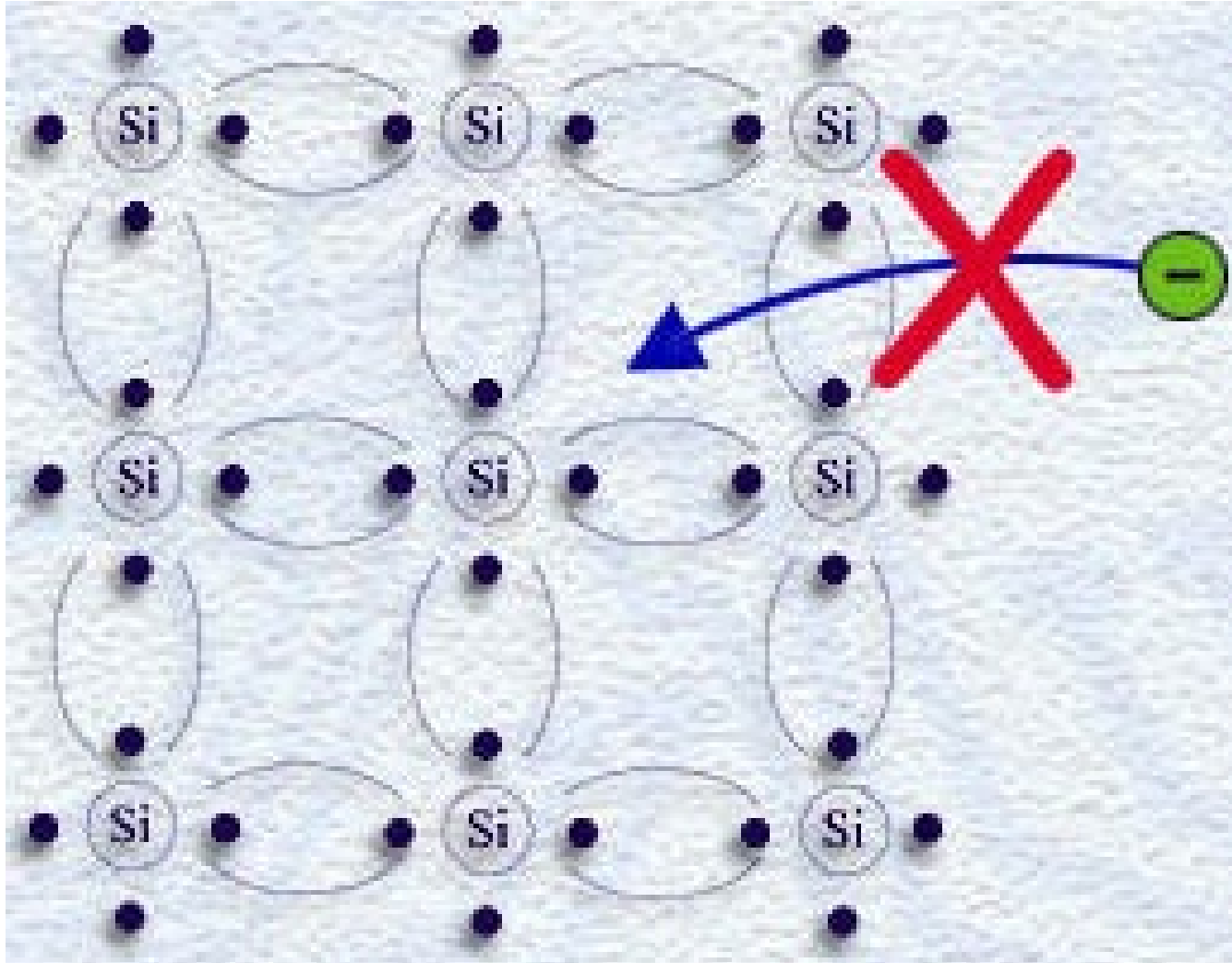
At room temperature it is considered an insulator.

Can you imagine why?

In what situation would it manifest semiconductor properties instead?

	IIIB	IVB	VB	VIB	
	5 B Boron 10.811 $1s^2 2s^2 2p^1$ 8.2990	6 C Carbon 12.0107 $1s^2 2s^2 2p^2$ 11.2603	7 N Nitrogen 14.00674 $1s^2 2s^2 2p^3$ 14.5341	8 O Oxygen 15.9994 $1s^2 2s^2 2p^4$ 13.6181	
	13 Al Aluminum 26.98154 $1s^2 2s^2 2p^6 3s^2 3p^1$ 5.3856	14 Si Silicon 28.0855 $1s^2 2s^2 2p^6 3s^2 3p^2$ 8.1517	15 P Phosphorus 30.97376 $1s^2 2s^2 2p^6 3s^2 3p^3$ 10.4867	16 S Sulfur 32.066 $1s^2 2s^2 2p^6 3s^2 3p^4$ 10.3600	
IIIB	30 Zn Zinc 65.38 $1s^2 2s^2 2p^6 3s^2 3p^4$ 5.2942	31 Ga Gallium 69.723 $1s^2 2s^2 2p^6 3s^2 3p^4$ 5.2093	32 Ge Germanium 72.61 $1s^2 2s^2 2p^6 3s^2 3p^4$ 7.8684	33 As Arsenic 74.92160 $1s^2 2s^2 2p^6 3s^2 3p^4$ 5.7885	34 Se Selenium 78.96 $1s^2 2s^2 2p^6 3s^2 3p^4$ 5.7524
	48 Cd Cadmium 112.411 $1s^2 2s^2 2p^6 3s^2 3p^4$ 5.9508	49 In Indium 114.818 $1s^2 2s^2 2p^6 3s^2 3p^4$ 5.7884	50 Sn Tin 118.710 $1s^2 2s^2 2p^6 3s^2 3p^4$ 7.3400	51 Sb Antimony 121.760 $1s^2 2s^2 2p^6 3s^2 3p^4$ 5.6084	52 Te Tellurium 127.60 $1s^2 2s^2 2p^6 3s^2 3p^4$ 5.0088

How to change the concentration of Electrons (or Holes)



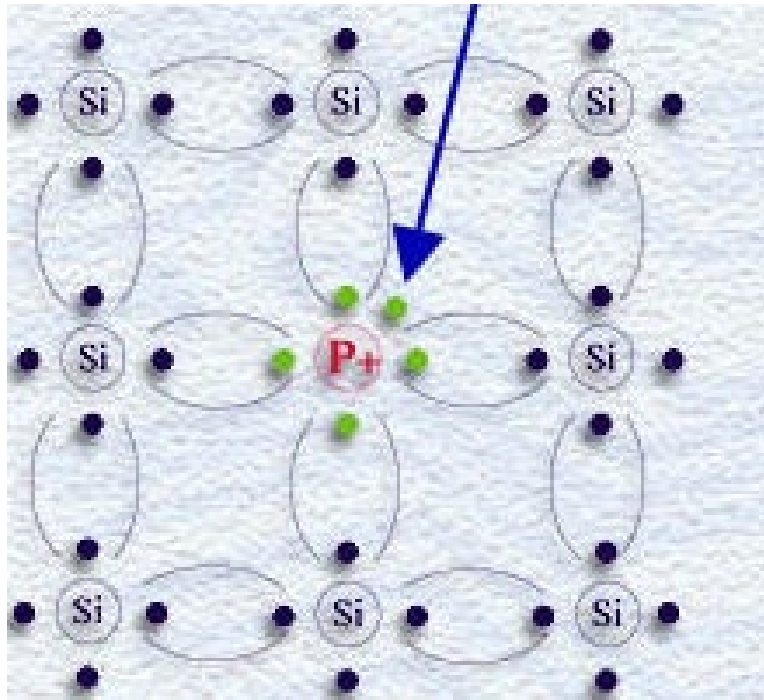
You can not
insert electrons !

*Your material
will charge up
and explode !*

Phosphorus doping : n-type semiconductors

Substitution of one atom with another atom

This electron can easily be set free to move



IIIB	IVB	VB	VIB
5 B Boron 10.811 [He] 2s ² 2p ¹	6 C Carbon 12.011 [He] 2s ² 2p ²	7 N Nitrogen 14.007 [He] 2s ² 2p ³	8 O Oxygen 15.999 [He] 2s ² 2p ⁴
13 Al Aluminum 26.982 [Ne] 3s ² 3p ¹	14 Si Silicon 28.086 [Ne] 3s ² 3p ²	15 P Phosphorus 30.974 [Ne] 3s ² 3p ³	16 S Sulfur 32.065 [Ne] 3s ² 3p ⁴
31 Ga Gallium 69.723 [Ar] 3d ¹⁰ 4s ¹ 4p ²	32 Ge Germanium 72.64 [Ar] 3d ¹⁰ 4s ² 4p ²	33 As Arsenic 74.922 [Ar] 3d ¹⁰ 4s ² 4p ³	34 Se Selenium 78.96 [Ar] 3d ¹⁰ 4s ² 4p ⁴

By doping with $N_D = 10^{16}$ P atoms/cm³ we obtain
 n (density of free electrons) = 10^{16} electrons/cm³

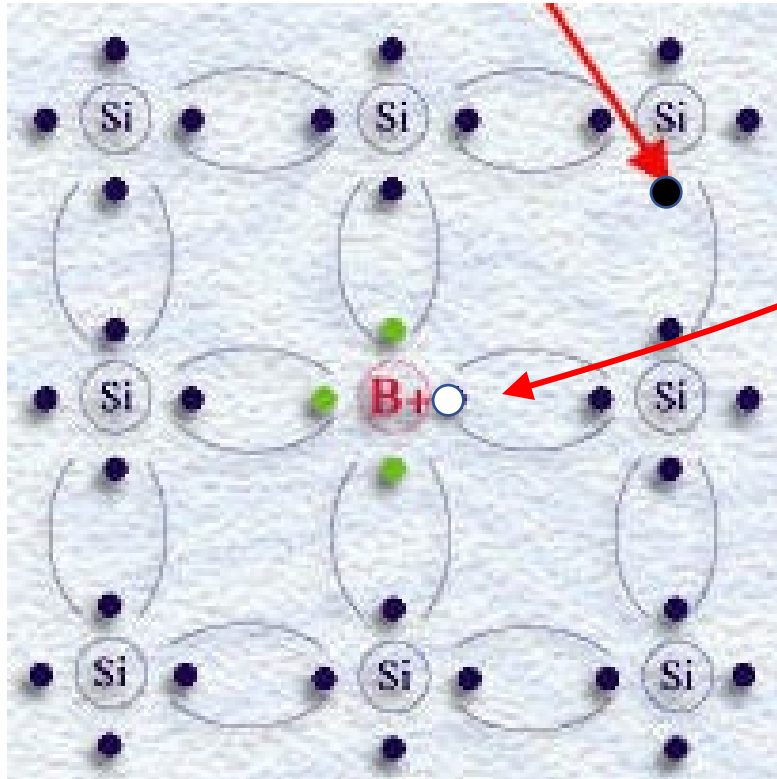
Locally, associated to the dopant ionized atom, we have a positive charge,
globally compensated, somewhere in the crystal, by its free electron.

The crystal, all together, remains **neutral**.

Boron doping : p-type semiconductors

III B	IV B	V B	VI B
5 ¹¹ B Boron 10.811 1s ² 2s ² 2p ¹	6 ¹² C Carbon 12.011 1s ² 2s ² 2p ²	7 ¹⁴ N Nitrogen 14.007 1s ² 2s ² 2p ³	8 ¹⁶ O Oxygen 15.999 1s ² 2s ² 2p ⁴
13 ¹³ Al Aluminum 26.982 1s ² 3s ² 3p ¹	14 ¹⁴ Si Silicon 28.086 1s ² 3s ² 3p ²	15 ¹⁵ P Phosphorus 30.974 1s ² 3s ² 3p ³	16 ¹⁶ S Sulfur 32.06 1s ² 3s ² 3p ⁴
31 ³¹ Ga Gallium 69.723 1s ² 3s ² 3p ¹	32 ³² Ge Germanium 72.61 1s ² 3s ² 3p ²	33 ³³ As Arsenic 74.922 1s ² 3s ² 3p ³	34 ³⁴ Se Selenium 78.96 1s ² 3s ² 3p ⁴

This valence electron can easily move to B

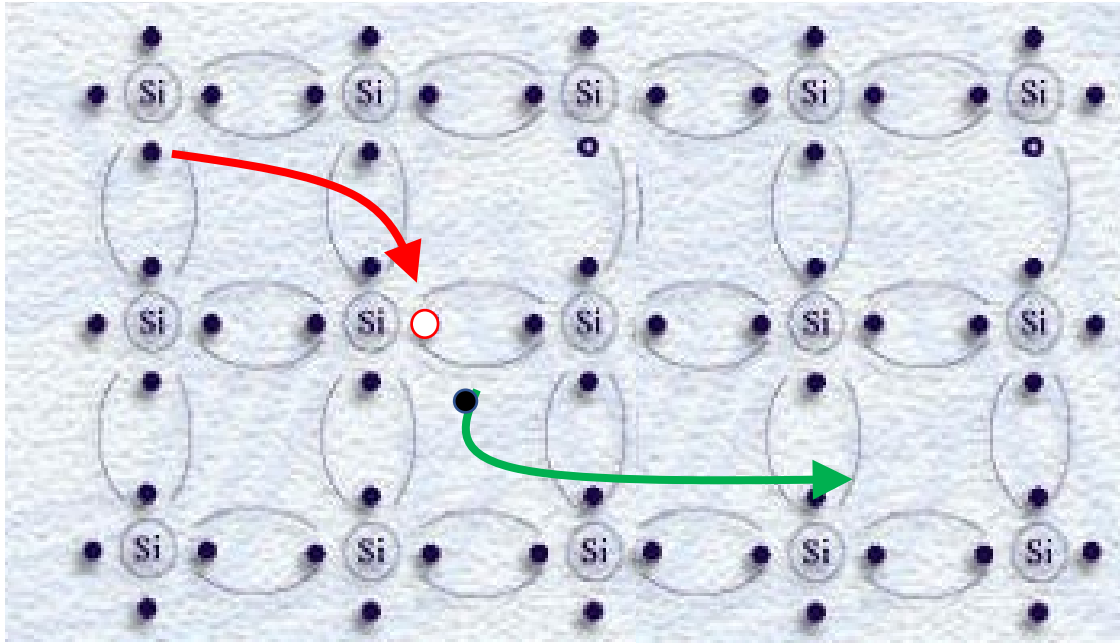


By doping with $N_A = 10^{15}$ B atoms/cm³ we obtain
 p (*density of free holes*) = 10^{15} holes/cm³

Locally, associated to the dopant ionized atom, we have a negative charge,
globally compensated, somewhere in the crystal, by its free hole.

The crystal, all together, remains neutral.

Meaning of «Semiconductor» (2)



Conduction by means of **electrons** and **holes**

Controlled number of electrons or holes, by the doping
(*in a metal instead the number is fixed to about 10^{23} electrons/cm³*)

Practical considerations on doping

Industry has the ability to produce crystalline silicon with a very high purity :

1 impurity atom every 10^{10} Si atoms
($< 10^{12}$ atoms/cm³ of impurities in the crystal)

With no other material, the technology has reached the same level !

In electronics we purify the silicon as much as possible and then we introduce the desired dopants. The position of the dopants in the lattice replacing the Si atoms is random.

density of Si atoms : $5 \cdot 10^{22}$ atoms/cm³

density of dopant atoms : $10^{12} < N_A, N_D < 10^{19}$ atoms/cm³

The dopant concentrations are small compared to the density of Si

Exercise 3

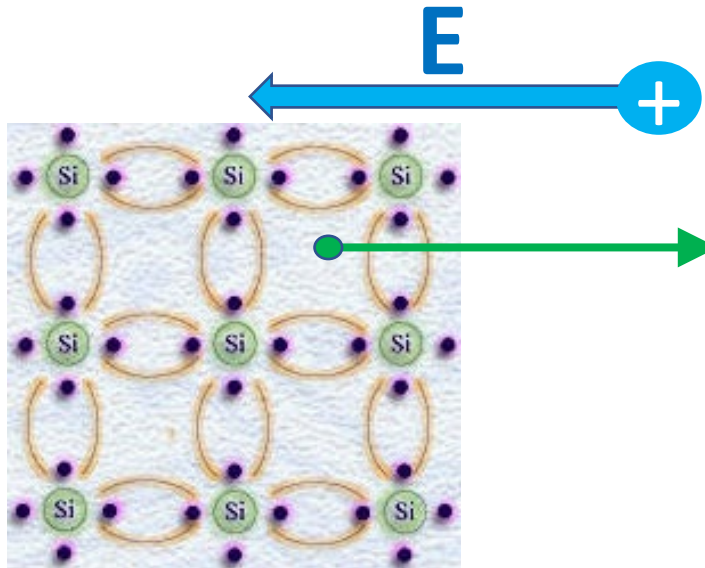
After having doped a Si crystal, kept at room temperature, with $5 \cdot 10^{16}$ atoms/cm³ of phosphorus, how many free electrons are there in the crystal?

If the same Si crystal were kept at very low temperatures, close to 0°K, what would happen ?

How many electrons and how many holes would there be?

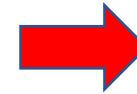
What if the same crystal were heated to very high temperatures (for example 500°C)?

How to move charges in a semiconductor crystal



ELECTRON can be pulled by the Electric Field

$$\vec{F} = q \cdot \vec{E} = m \cdot \vec{a}$$



In free space

~~$$\vec{a} = \frac{q}{m} \vec{E}$$~~

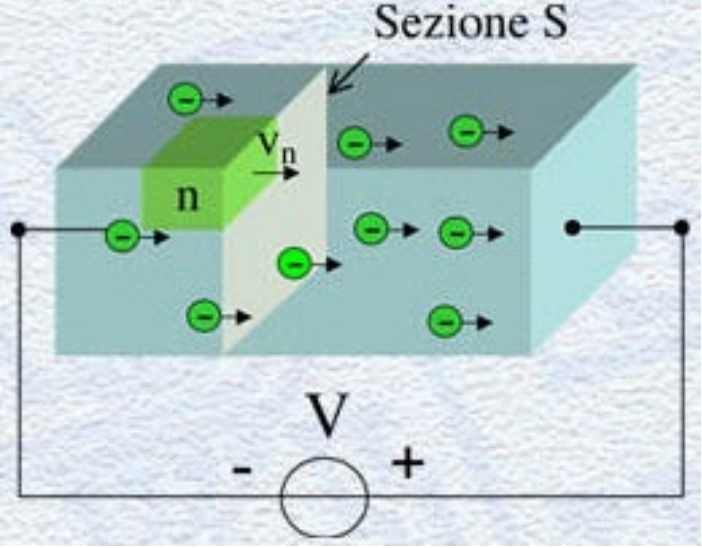
Electrons scatter with crystal atoms every τ and stop

$$\vec{v} \cong \frac{q\tau}{m} \vec{E} \quad \rightarrow \quad \vec{v} \cong \overset{\text{mobilità}}{\mu} \cdot \vec{E}$$

$$\mu_n \cong 1300 \frac{cm^2}{V \cdot s}$$

$$\mu_p \cong 400 \frac{cm^2}{V \cdot s}$$

Currents in a semiconductor crystal



$$I = q n v_n S$$

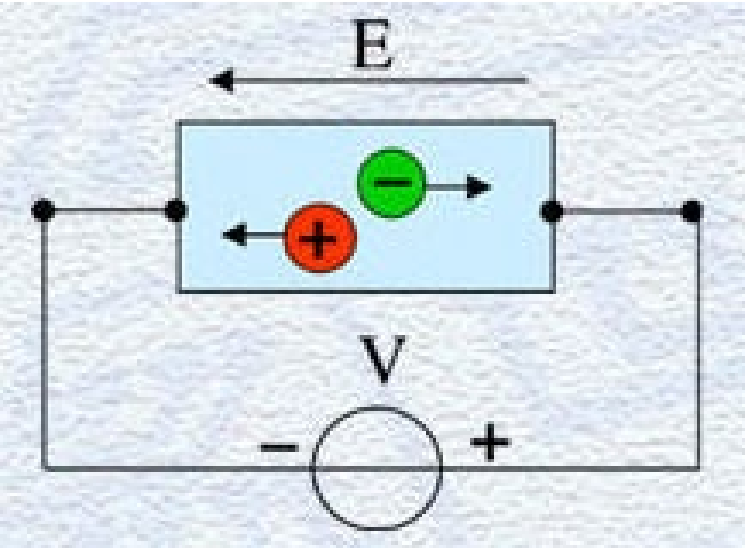
$$= q \cdot \frac{\text{elettroni}}{\text{cm}^3} \cdot \frac{\text{cm}}{\text{s}} \cdot \text{cm}^2$$

In n-type material (N_D) we have :

$$I \cong I_n = q n \mu_n E \cdot S$$

In p-type material (N_A) we have :

$$I \cong I_p = q p \mu_p E \cdot S$$



Conductivity σ



$$\text{Resistivity } \rho = 1/\sigma$$

Ohm's law at the microscale

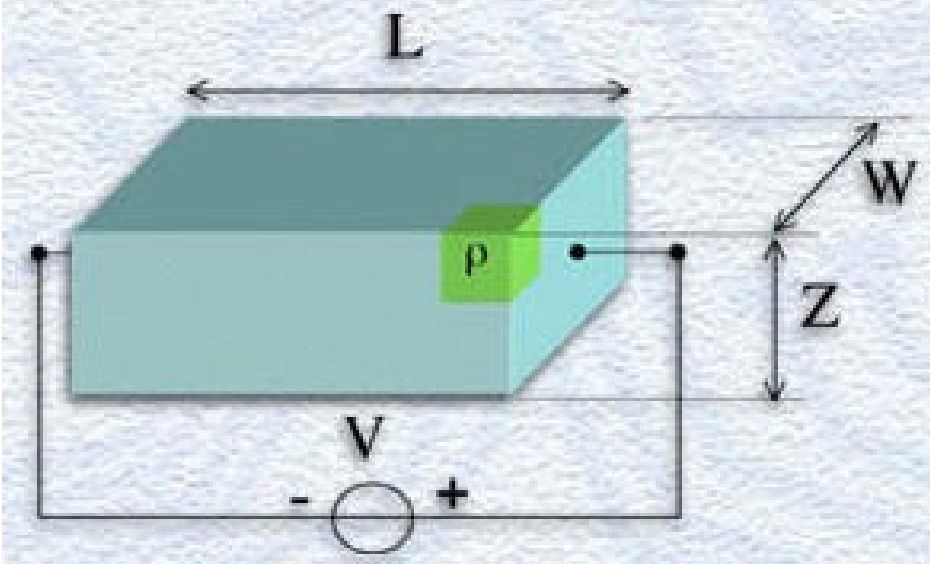
$$I_n = qn\mu_n ES$$



$$I_n = qn\mu_n \frac{V}{L} WZ$$



Ohm's law : $I = \frac{V}{R}$

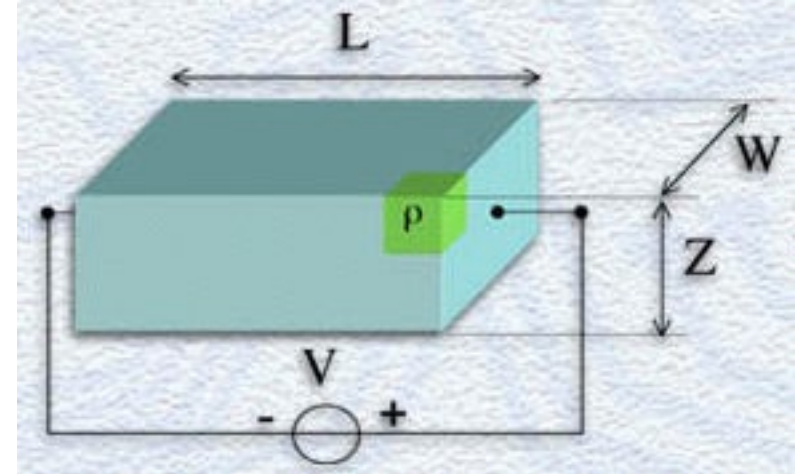


$$R = \rho \frac{L}{W \cdot Z}$$

Resistance [Ω]
of the device

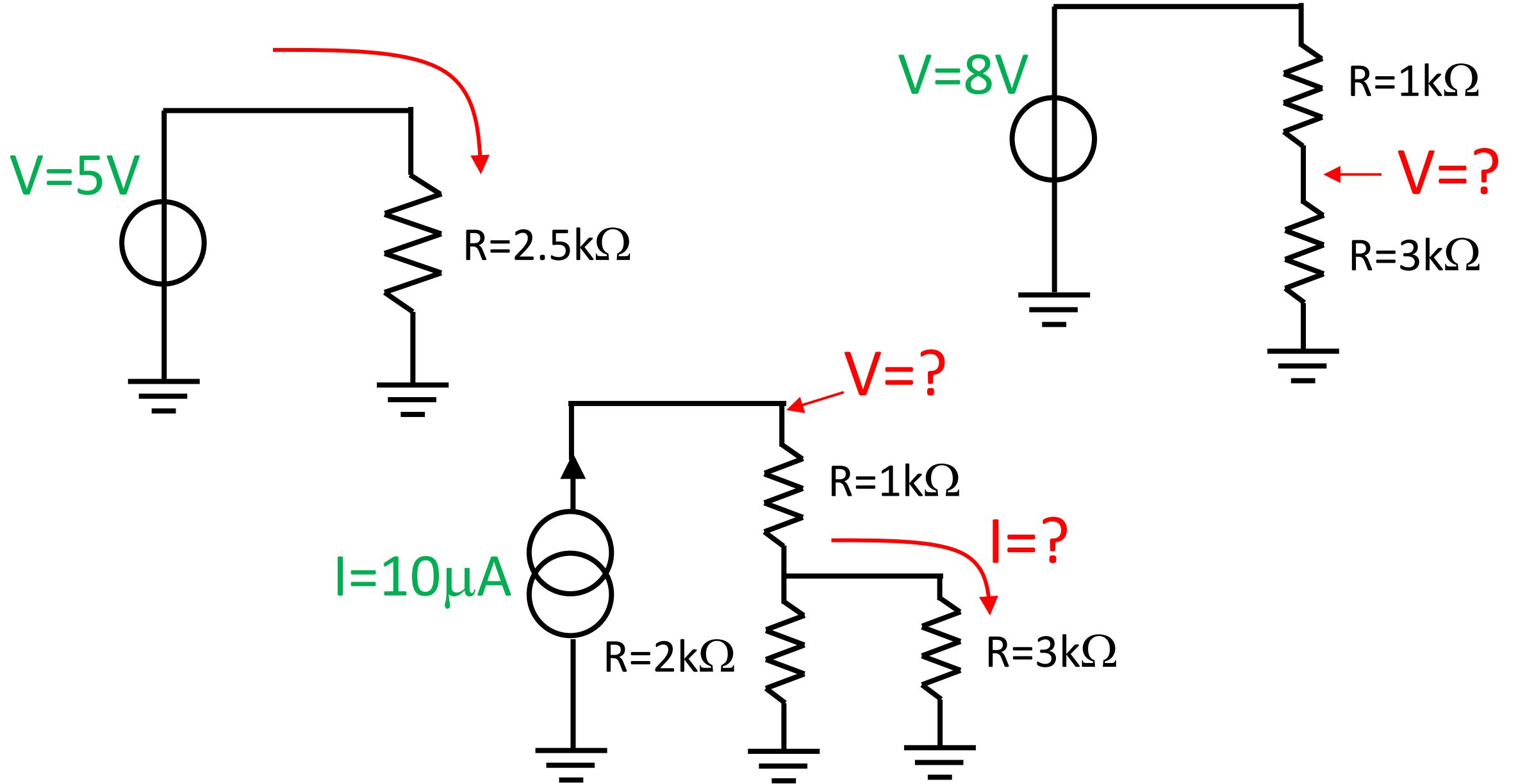
Exercise 4

Given a doped ($N_D = 10^{15}$ atoms/cm³) Silicon of dimensions $W=10$ mm, $Z=0.1$ mm and $L=1$ mm, calculate the current when a voltage of 1V is applied.



If the block had been doped $N_A = 10^{15}$ atoms/cm³, the total current would have been the same or not?

Exercises 5 Recap of Ohm's Law



Why **Silicon** has been the **PERFECT MATERIAL**

Si crystal

Si Oxide (SiO_2)

Compatible with metals

Easy to etch

semiconductor

insulator

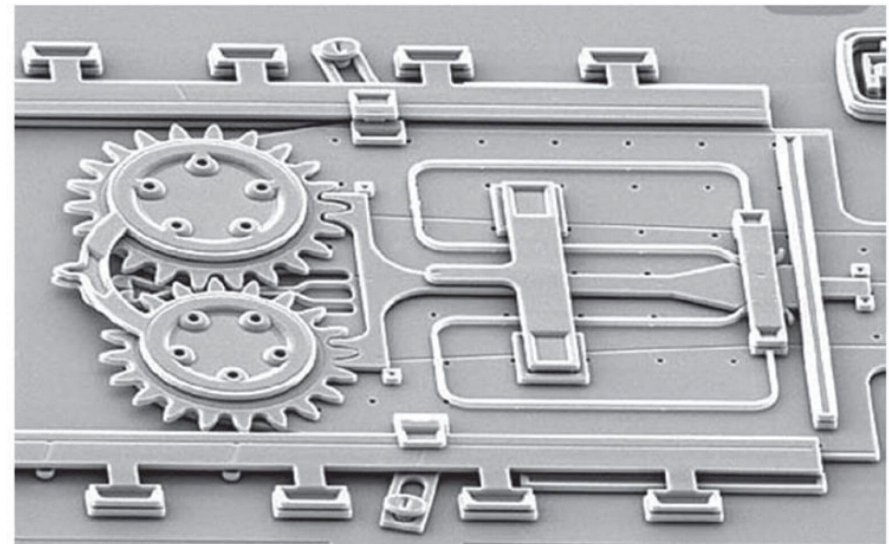
conductor

machining - MEMS

Disadvantages of Silicon

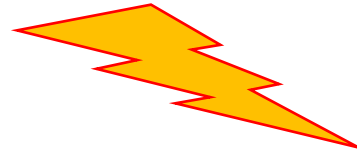
No production of light

No magnetic properties



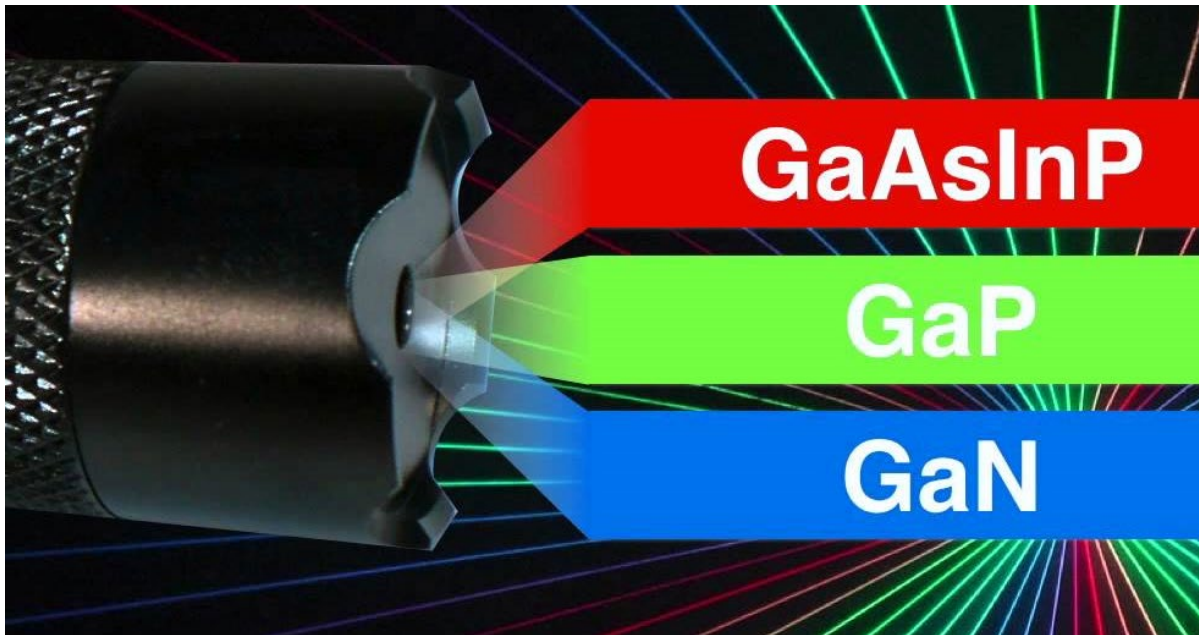
Semiconductors that emit light (for Diode, LED, Laser)

Few semiconductors have quantum properties that allow light emission



Different bonding forces → Different colors

Near Infrared & Telecom range



IIIB		IVB		VB		VIB			
5	³ P _{1/2} B Boron 10.811 1s ² 2s ² 2p ¹ 8.000	6	³ P _{3/2} C Carbon 12.0107 1s ² 2s ² 2p ² 11.2000	7	³ S _{1/2} N Nitrogen 14.00674 1s ² 2s ² 2p ³ 14.5341	8	³ P _{3/2} O Oxygen 15.9994 1s ² 2s ² 2p ⁴ 13.8181		
13	³ P _{1/2} Al Aluminum 26.98154 1s ² 2s ² 2p ⁶ 3s ² 3p ¹ 8.9858	14	³ P _{3/2} Si Silicon 28.0855 1s ² 2s ² 2p ⁶ 3s ² 3p ² 8.1817	15	³ S _{3/2} P Phosphorus 30.97376 1s ² 2s ² 2p ⁶ 3s ² 3p ³ 10.4867	16	³ P _{3/2} S Sulfur 32.066 1s ² 2s ² 2p ⁶ 3s ² 3p ⁴ 10.3600		
IIB		IIIB		IIIB		IIIB			
30	³ S _{1/2} Zn Zinc 65.38 1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 8.5942	31	³ P _{1/2} Ga Gallium 69.723 1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 4p ¹ 8.9003	32	³ P _{3/2} Ge Germanium 72.61 1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 4p ² 7.8884	33	³ S _{3/2} As Arsenic 74.92160 1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 4p ³ 7.8891	34	³ P _{3/2} Se Selenium 78.96 1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 4p ⁴ 8.7524
48	³ S _{1/2} Cd Cadmium 112.411 1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 4p ⁶ 4d ¹⁰ 5s ² 8.9508	49	³ P _{1/2} In Indium 114.818 1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 4p ⁶ 4d ¹⁰ 5s ² 5p ¹ 8.7081	50	³ P _{3/2} Sn Tin 118.710 1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 4p ⁶ 4d ¹⁰ 5s ² 5p ² 7.3433	51	³ S _{3/2} Sb Antimony 121.760 1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 4p ⁶ 4d ¹⁰ 5s ² 5p ³ 8.6084	52	³ P _{3/2} Te Tellurium 127.60 1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 4p ⁶ 4d ¹⁰ 5s ² 5p ⁴ 8.0088

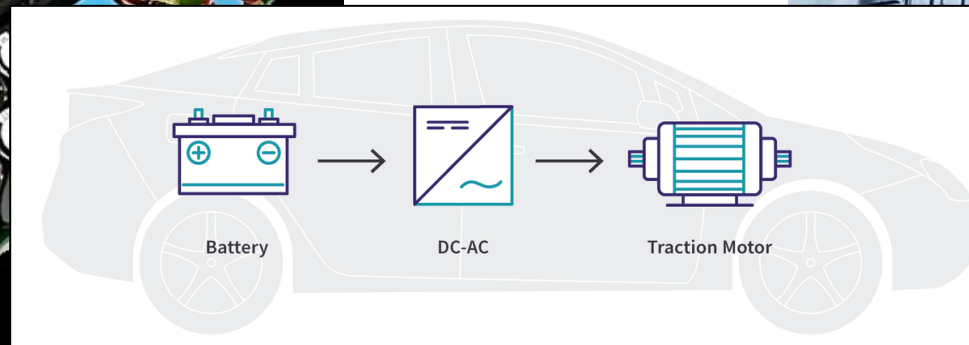
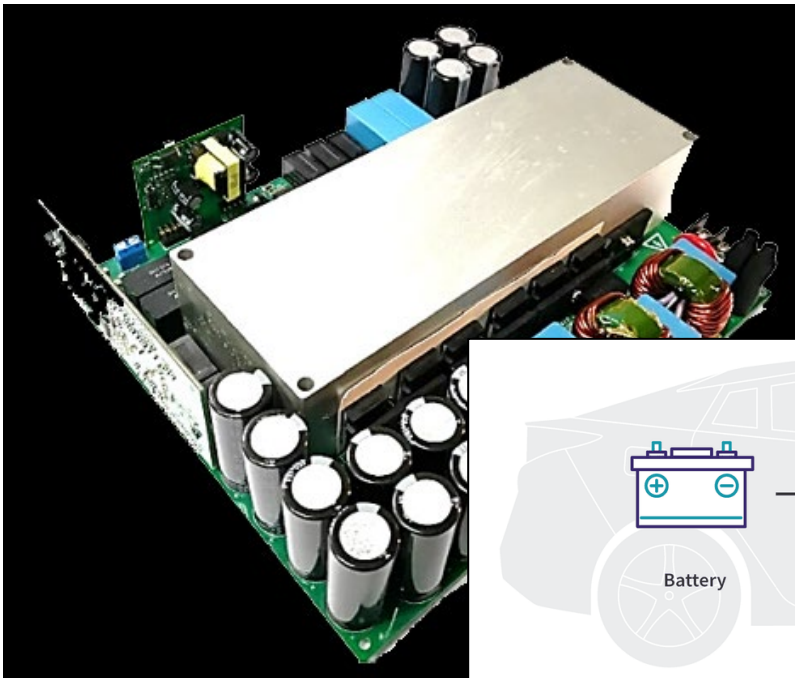
Semiconductors for high voltages & temperature

Silicon Carbide (SiC) devices deliver high-voltage and high-current, resisting at high-temperature as requested to build efficient automobiles.

5	6	7	8
IIIB	IVB	VB	VIB
B	C	N	O
13	14	15	16
IIIA	IVA	VA	VIA
Al	Si	P	S
31	32	33	34
IIIA	IIIA	IIIA	IIIA
Ga	Ge	As	Se

An EV's powertrain is responsible for taking energy stored in the vehicle's battery system and supplying it to the motors.

The amount of power to move a fully loaded vehicle is enormous, and delivery needs to be instantaneous.



The SEMICONDUCTOR : a new technological material, never existed before, where by doping with neutral atoms you obtain an equal amount of electrons. To be moved easily with an electric field !

End of the lesson