The Abdus Salam
International Centre
for Theoretical Physics

2359-8

Joint ICTP-IAEA Workshop on Physics of Radiation Effect and its Simulation for Non-Metallic Condensed Matter

13 - 24 August 2012

INTRODUCTORY: Part I and Part II

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An overview of the electronic properties of semiconductor and insulator materials.

Bibliography

Books:

S.M. Sze, *“Semiconductor Devices”,* 2nd edition, John Wiley and Sons, 2002

Links:

http://britneyspears.ac/lasers.htm
http://ece-www.colorado.edu/~bart/book/contents.htm
(http://jas2.eng.buffalo.edu/applets/index.html)

An overview of the electronic properties of semiconductor and insulator materials.

Part I

- Conductors, semiconductors, insulators
- Carrier transport phenomena
- Fundamental equations
- Examples

Part II

- Major semiconductor devices
  - pn junction diodes & Schottky diodes
  - Bipolar Junction Transistor
  - Field Effect Transistors

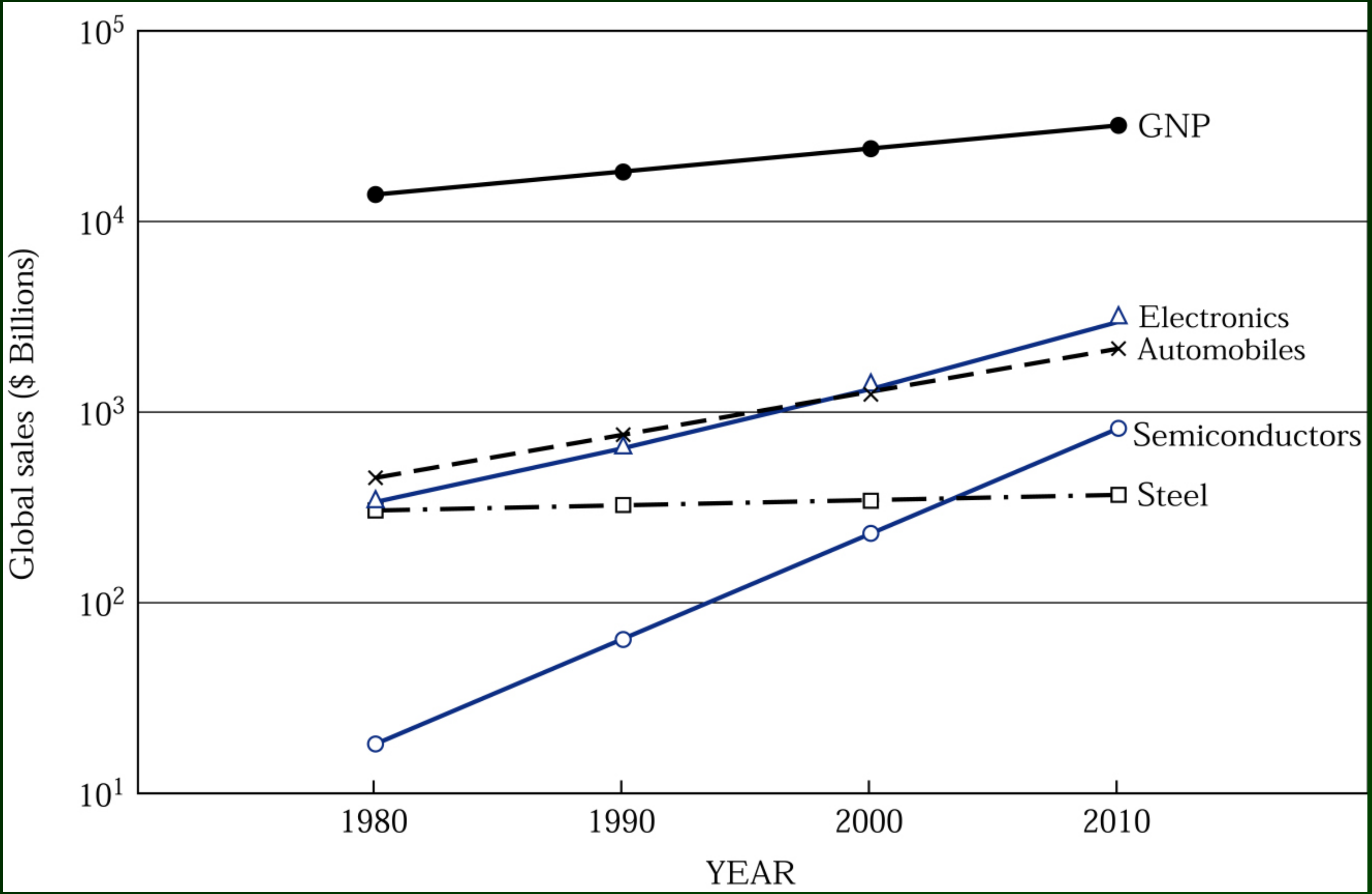


Figure 1.1. Gross world product (GWP) and sales volumes of the electronics, automobile, semiconductor, and steel industries from 1980 to 2000 and projected to 2010.[1,2]

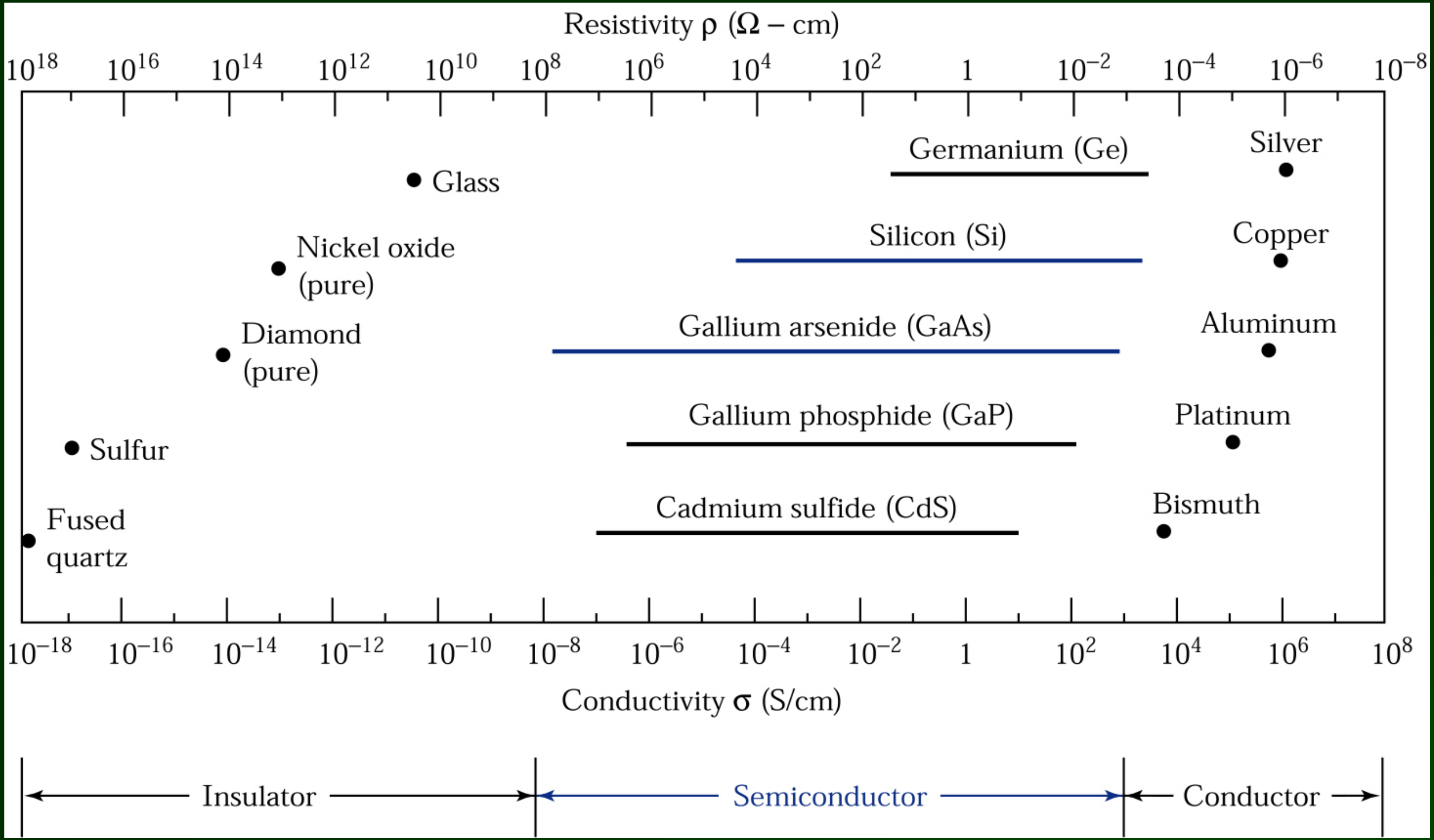
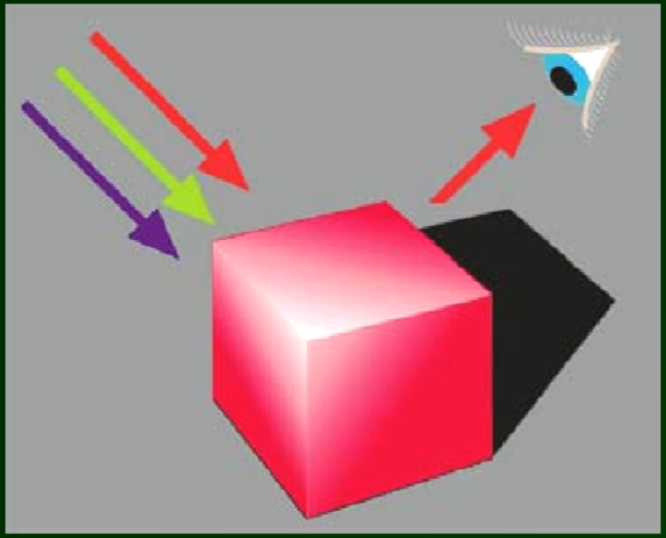
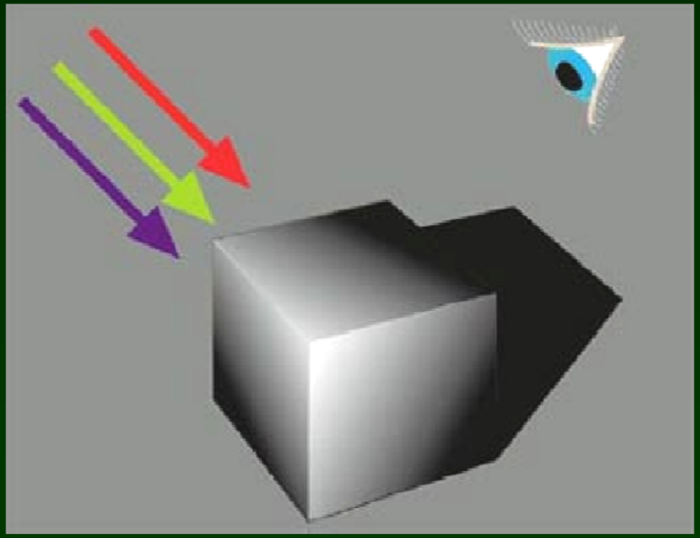


Figure 2.1. Typical range of conductivities for insulators, semiconductors, and conductors.

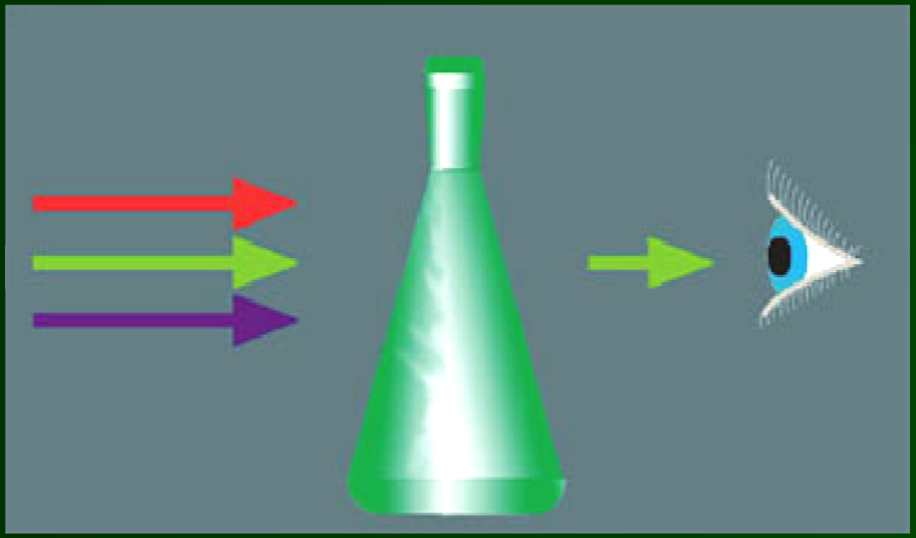
$$\mathrm{J} = (\mathrm{Ch}\arg \mathrm{e})\cdot\left(\mathrm{Carrier\ density}\right)\cdot\left(\mathrm{Transport\ properties}\right)$$



Reflection



Absorption



Transmission

$$\lambda[\text{nm}] \cong \frac{1240}{E[\text{eV}]} \Rightarrow E[\text{eV}] \cong \frac{1240}{\lambda[\text{nm}]}$$

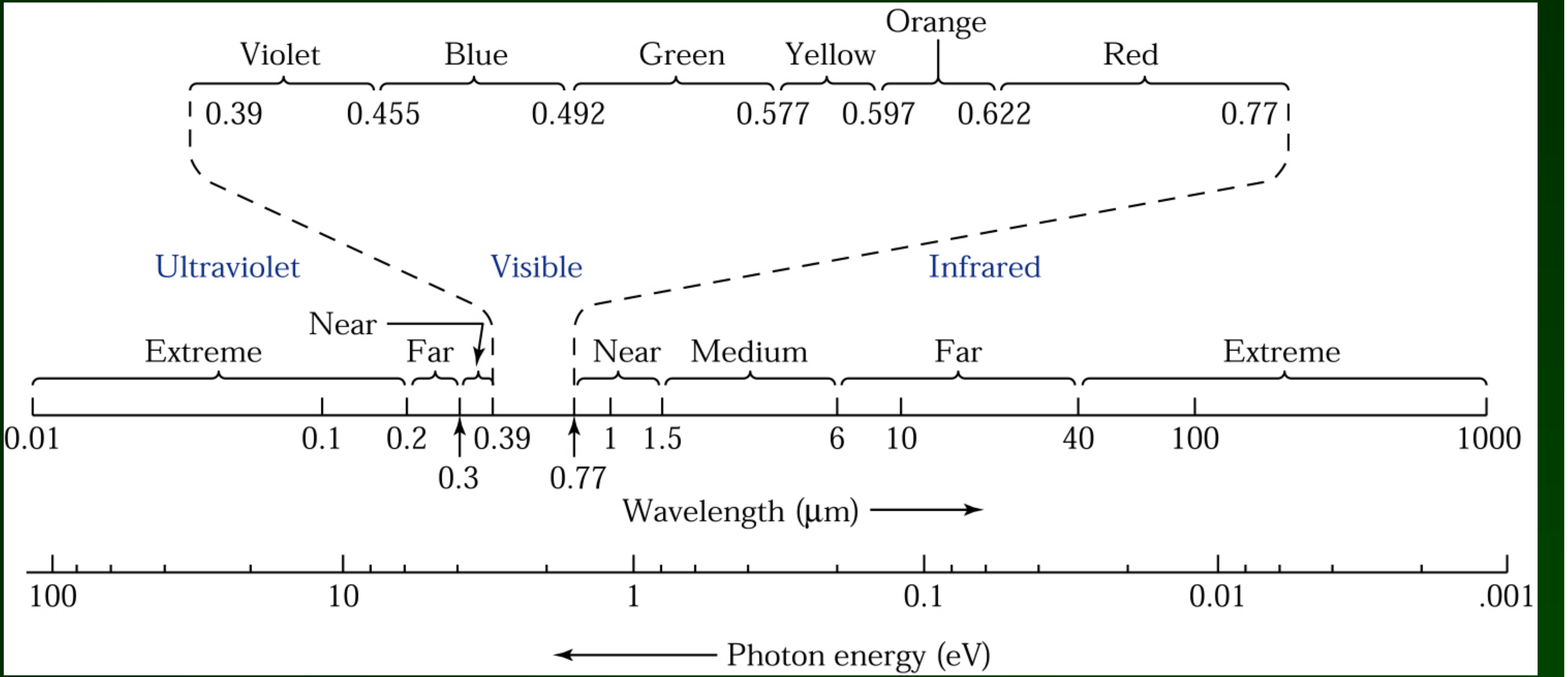
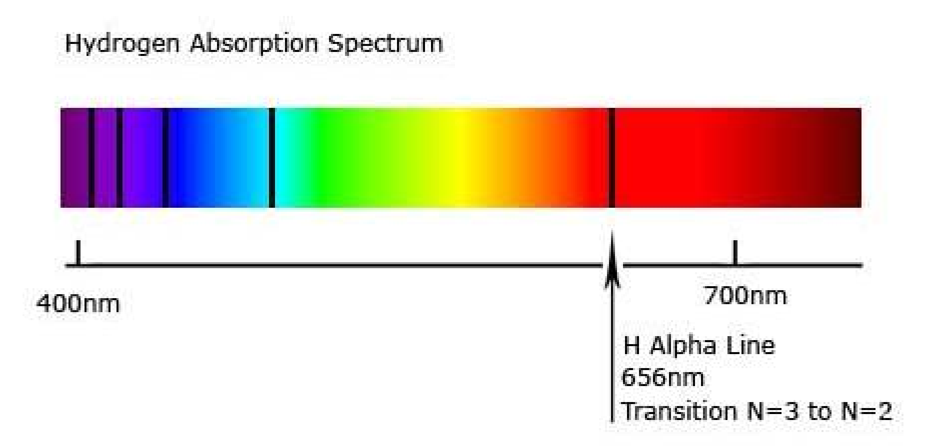
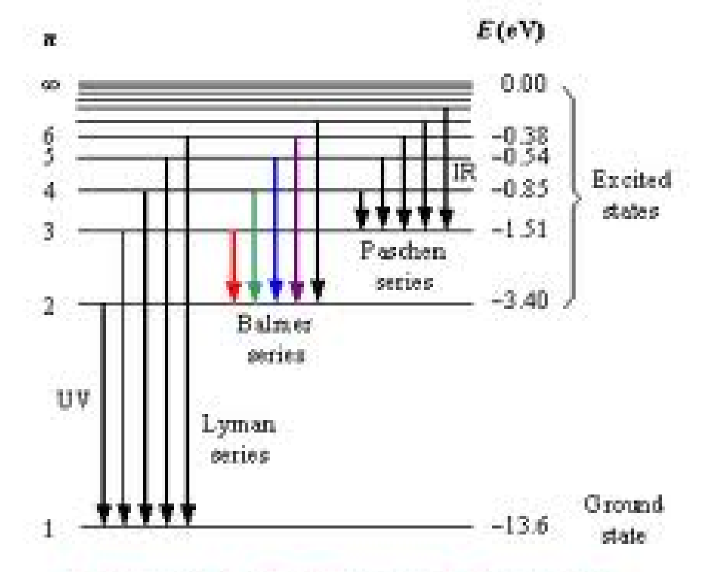


Figure 9.1. Chart of the electromagnetic spectrum from the ultraviolet region to the infrared region.

ATOMIC ABSORPTION (HYDROGEN)





Energy levels of the hydrogen atom with some of the transitions between them that give rise to the spectral lines indicated

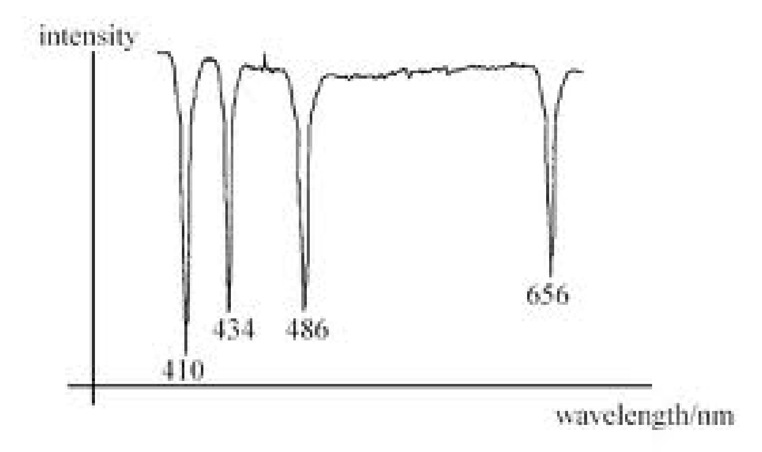
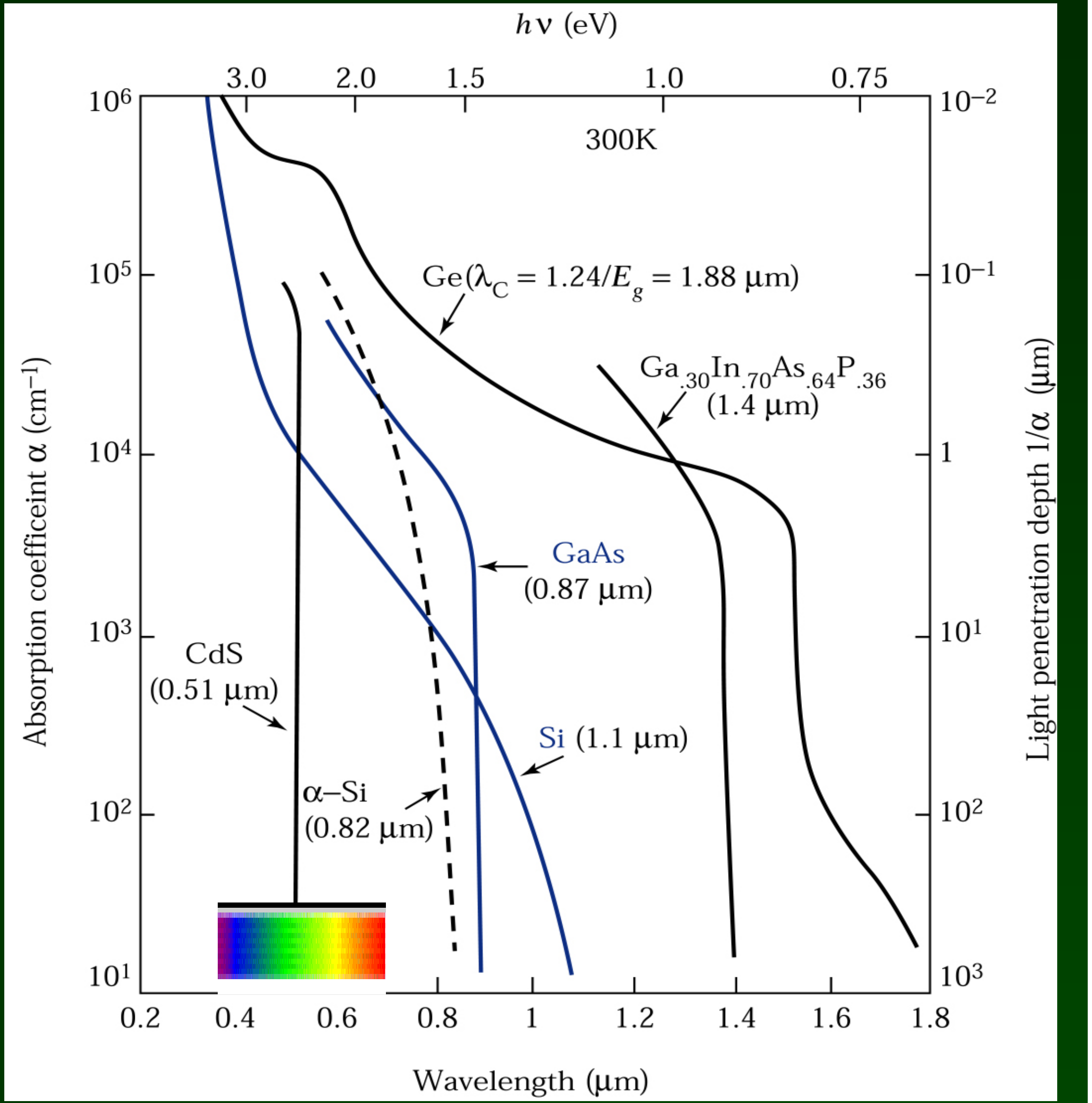


Figure 9.5. Optical absorption coefficients for various semiconductor materials.[2]. The value in the parenthesis is the cutoff wavelength.



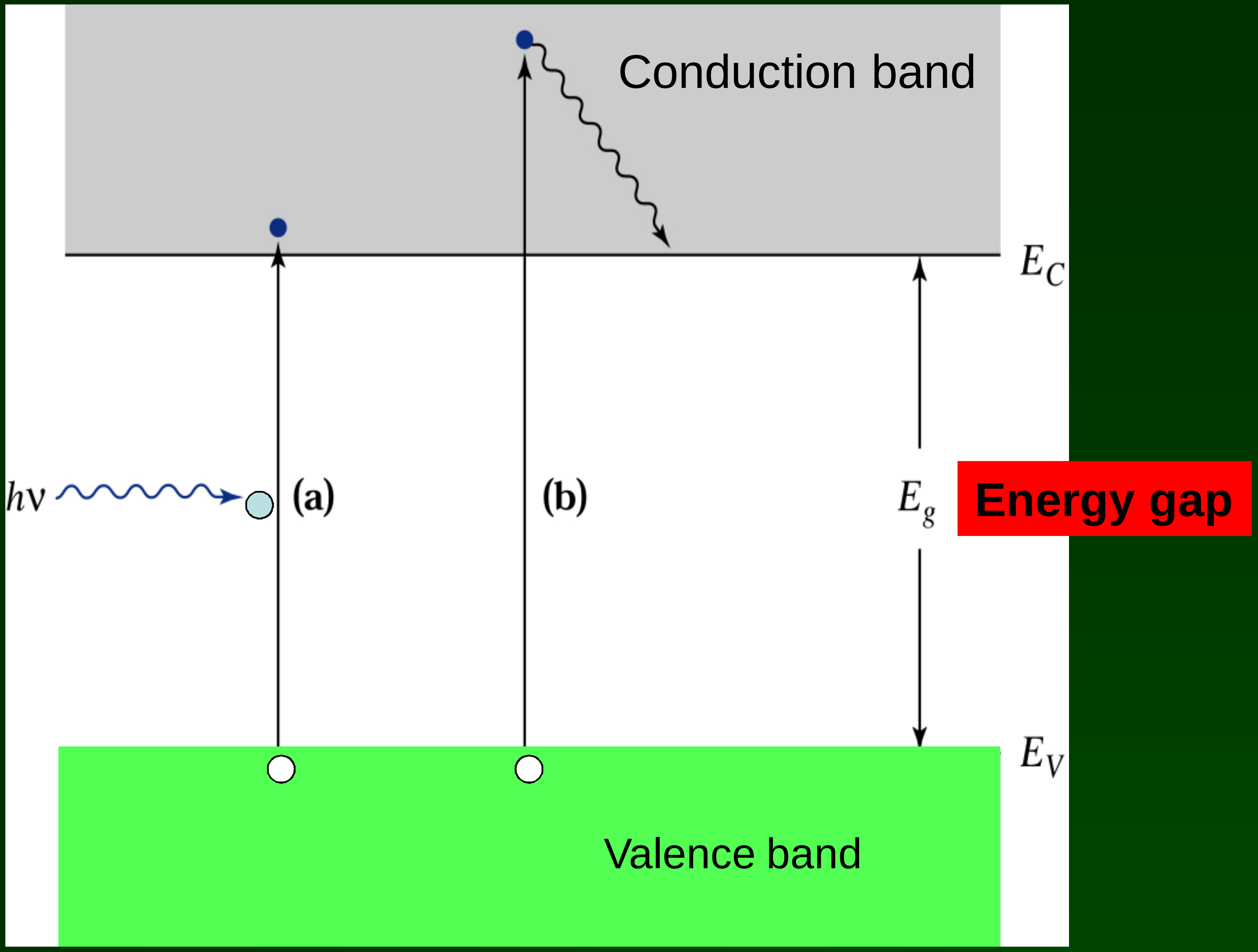


Figure 9.3. Optical absorption: photon energy ≥ Eg

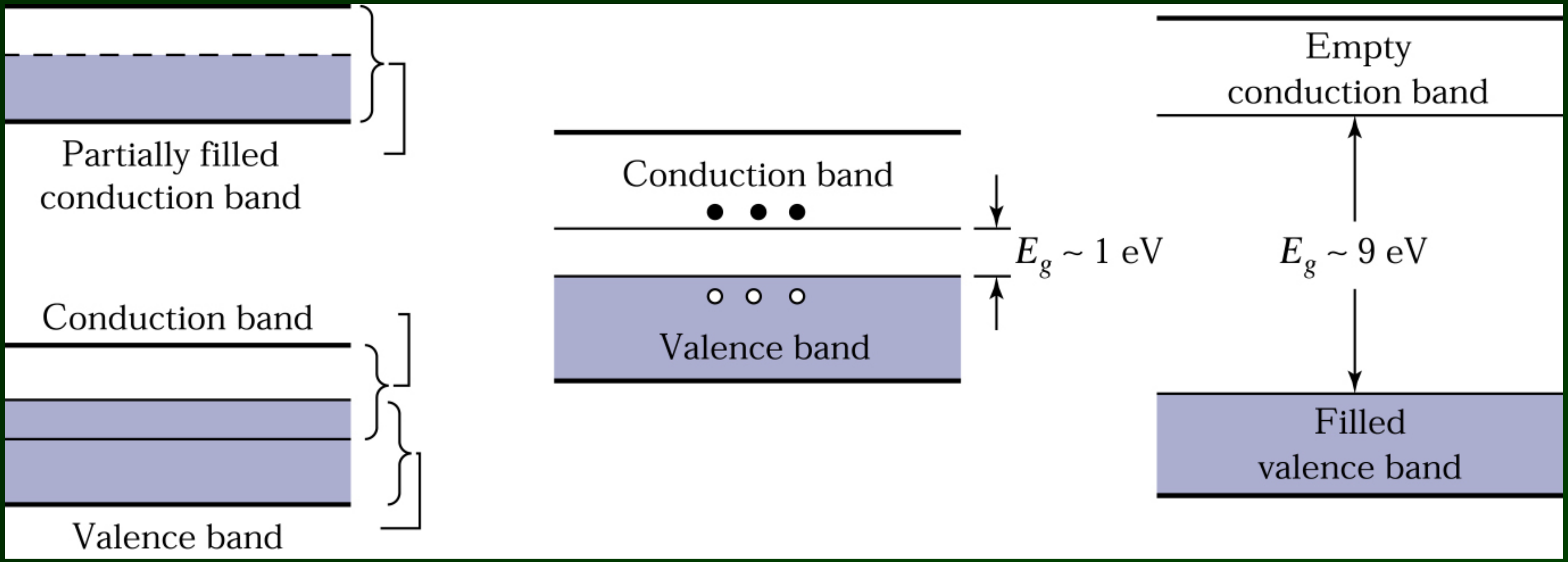


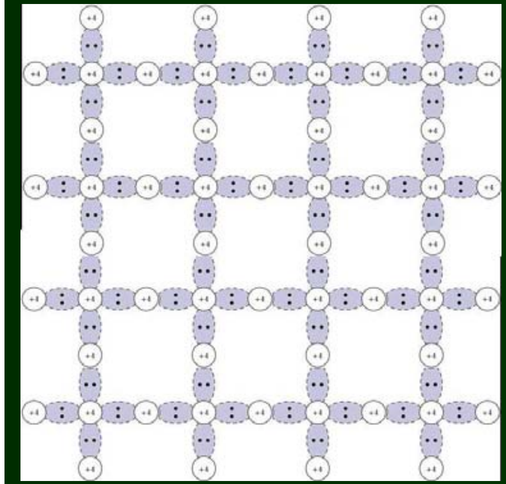
Figure 2.19. Schematic energy band representations of (*a*) a conductor with two possibilities (either the partially filled conduction band shown at the upper portion or the overlapping bands shown at the lower portion), (*b*) a semiconductor, and (*c*) an insulator.

Fonte: Dispense del corso di Dispositivi Elettronici, Prof. Carlo Naldi, Ed. CELID, 1996

THERMAL EQUILIBRIUM; LOW TEMPERATURE

VALENCE BAND: 4N STATES, 4N ELECTRONS
CONDUCTION BAND: 4N STATES, 0 ELECTRONS

SHOCKLEY PARKING GARAGE MODEL



UPPER LEVEL=CONDUCTION BAND

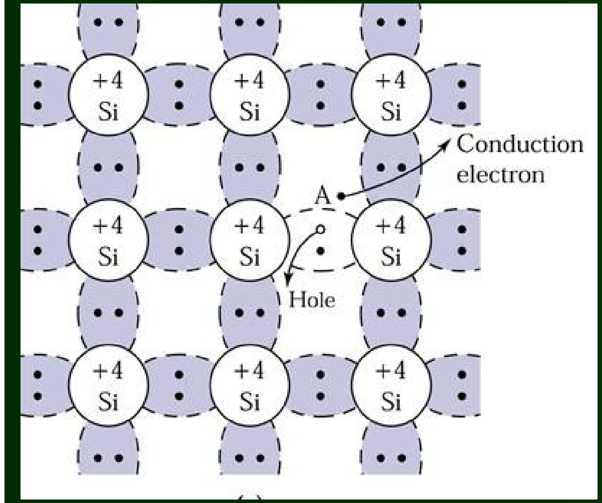
LOWER LEVEL=VALENCE BAND

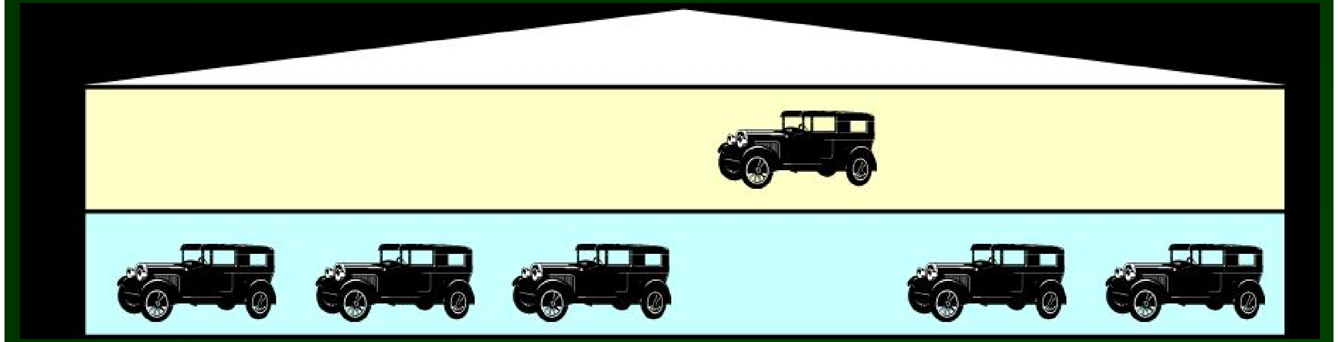
NO TRAFFIC POSSIBLE

Excitation

VALENCE BAND: 4N STATES, 4N-1 ELECTRONS
CONDUCTION BAND: 4N STATES, 1 ELECTRONS

SHOCKLEY PARKING GARAGE MODEL



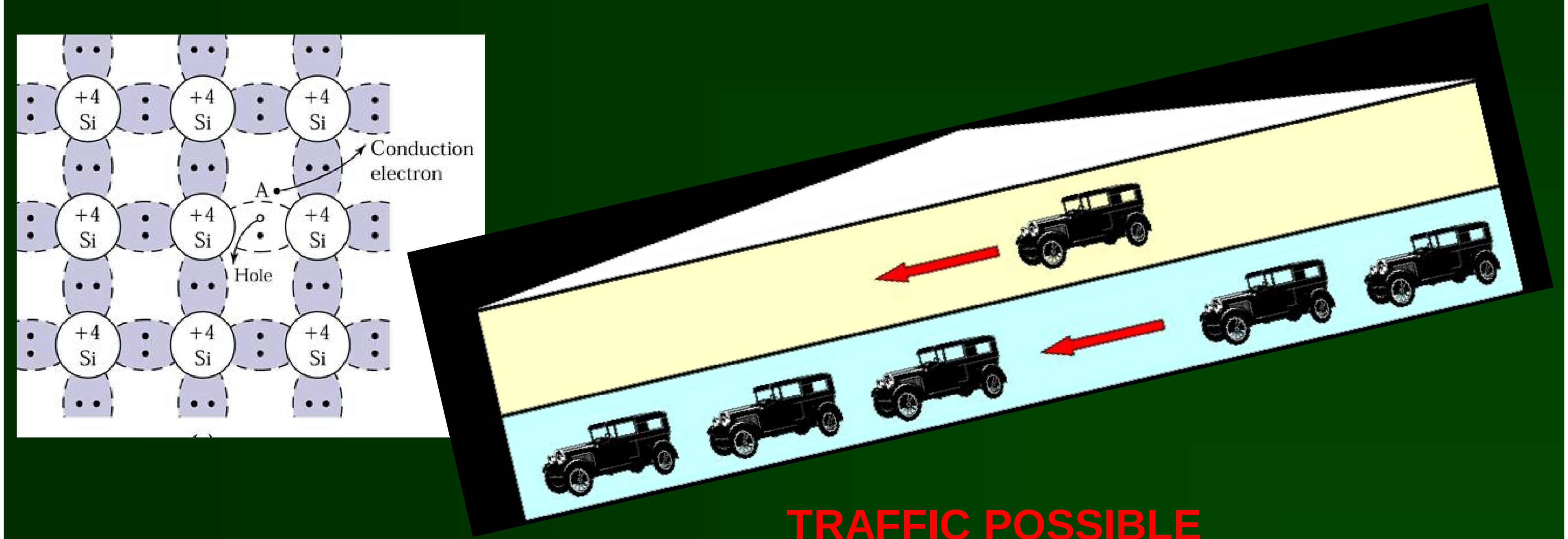


TRAFFIC POSSIBLE

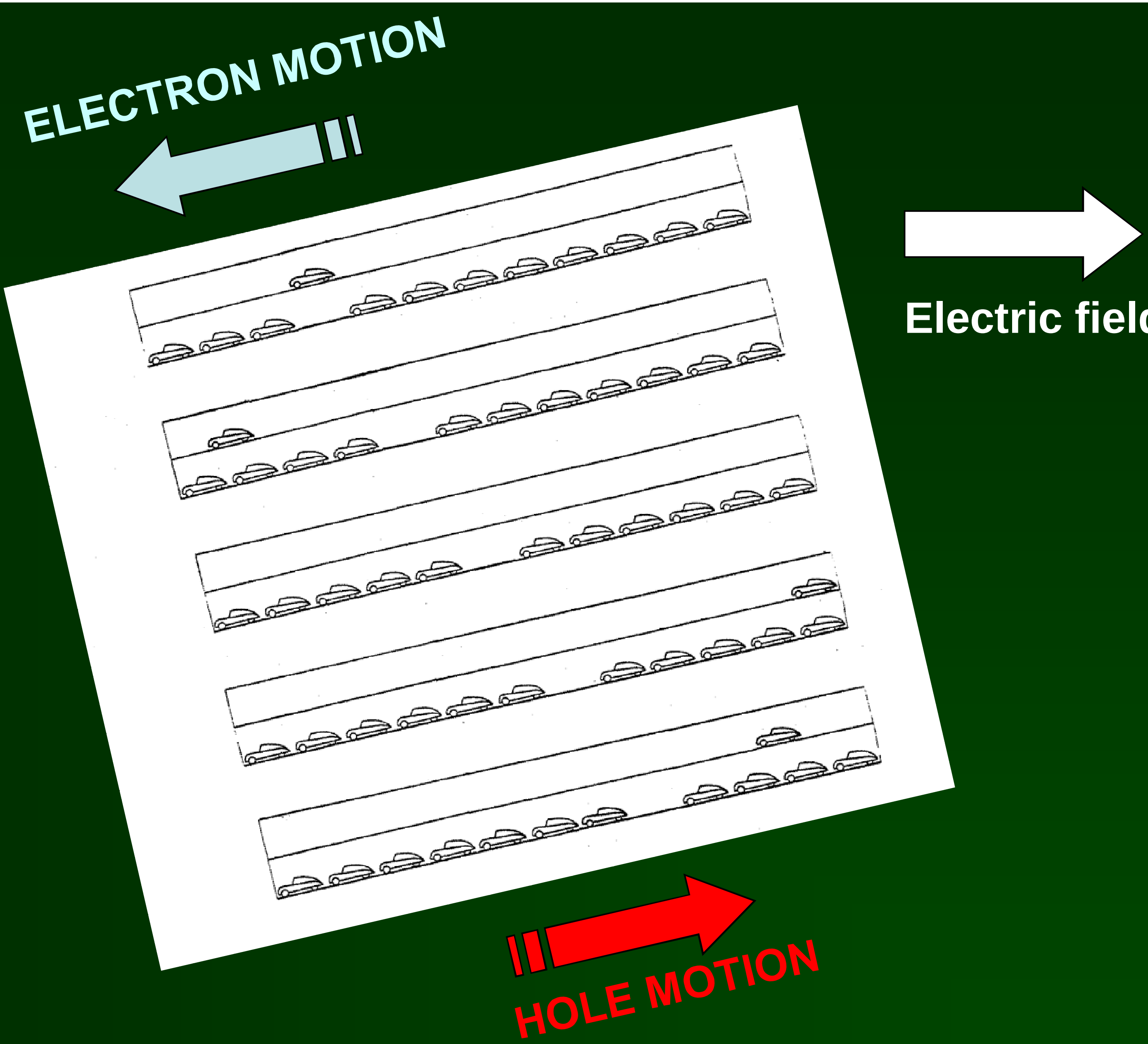
Excitation+Electric field

VALENCE BAND: 4N STATES, 4N-1 ELECTRONS
CONDUCTION BAND: 4N STATES, 1 ELECTRONS

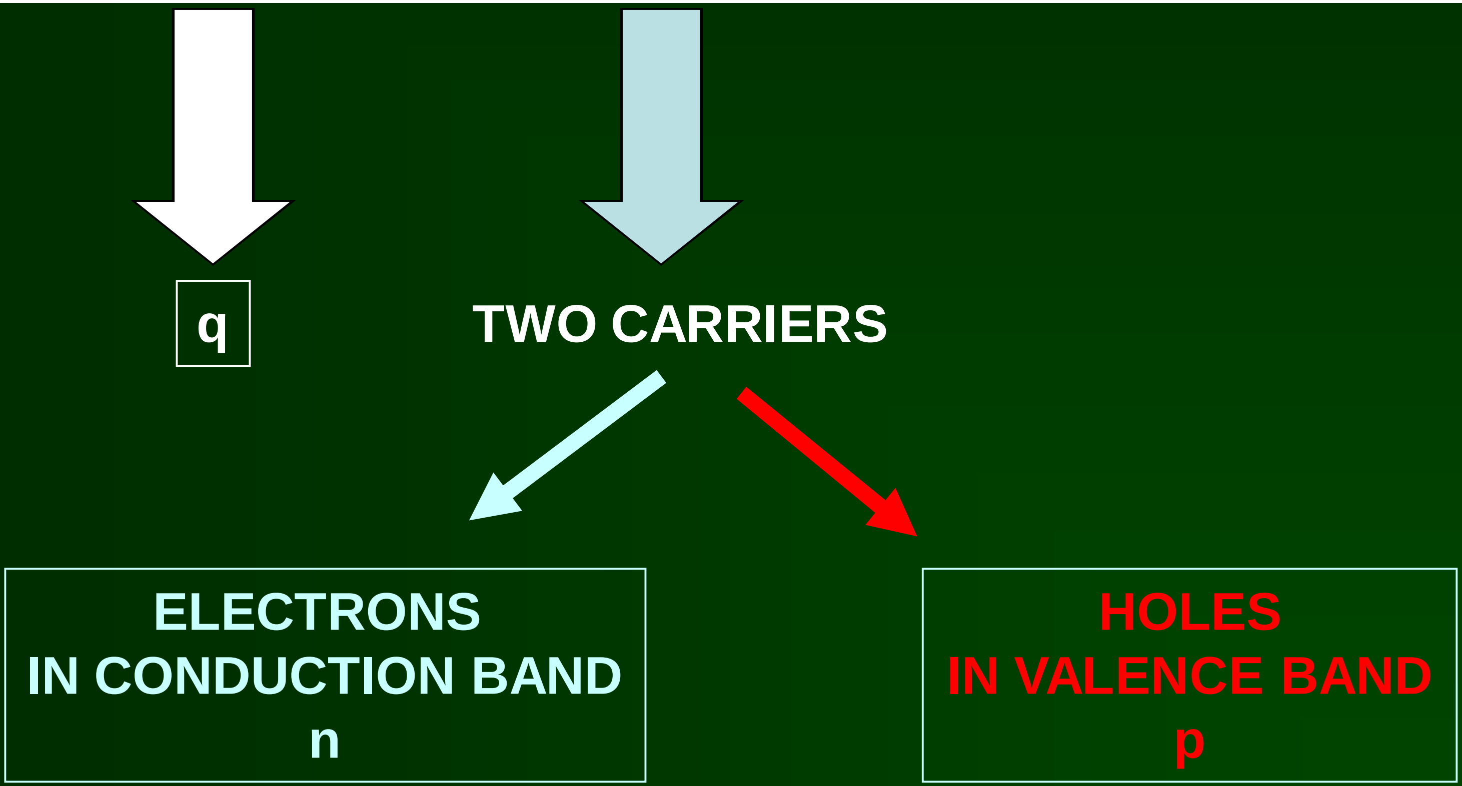
SHOCKLEY PARKING GARAGE MODEL



TRAFFIC POSSIBLE


ELECTRON MOTION
Electric field
HOLE MOTION

$$J = (\text{Charge}) \cdot (\text{Carrier density}) \cdot (\text{Transport properties})$$



q

TWO CARRIERS

ELECTRONS
IN CONDUCTION BAND
n

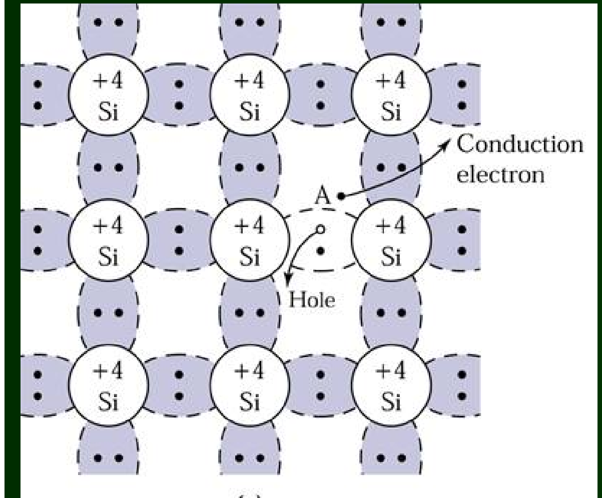
HOLES
IN VALENCE BAND
p

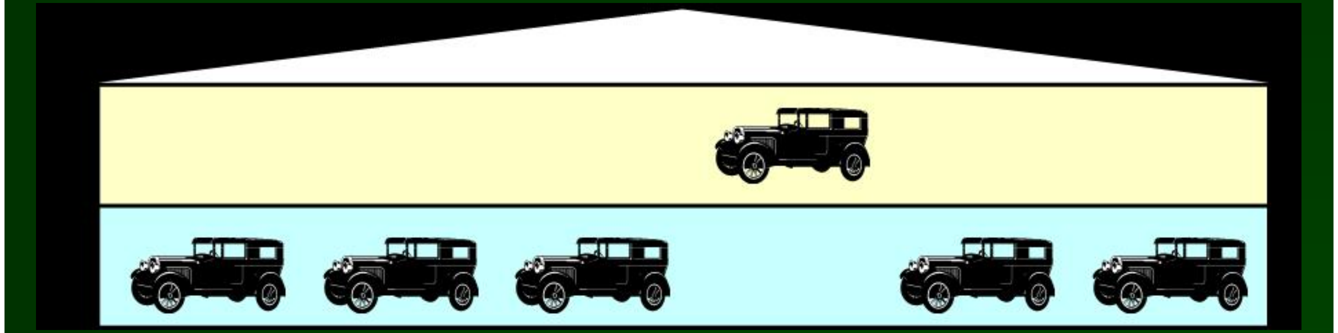
Fonte: Dispense del corso di Dispositivi Elettronici, Prof. Carlo Naldi, Ed. CELID, 1996

THERMAL EQUILIBRIUM

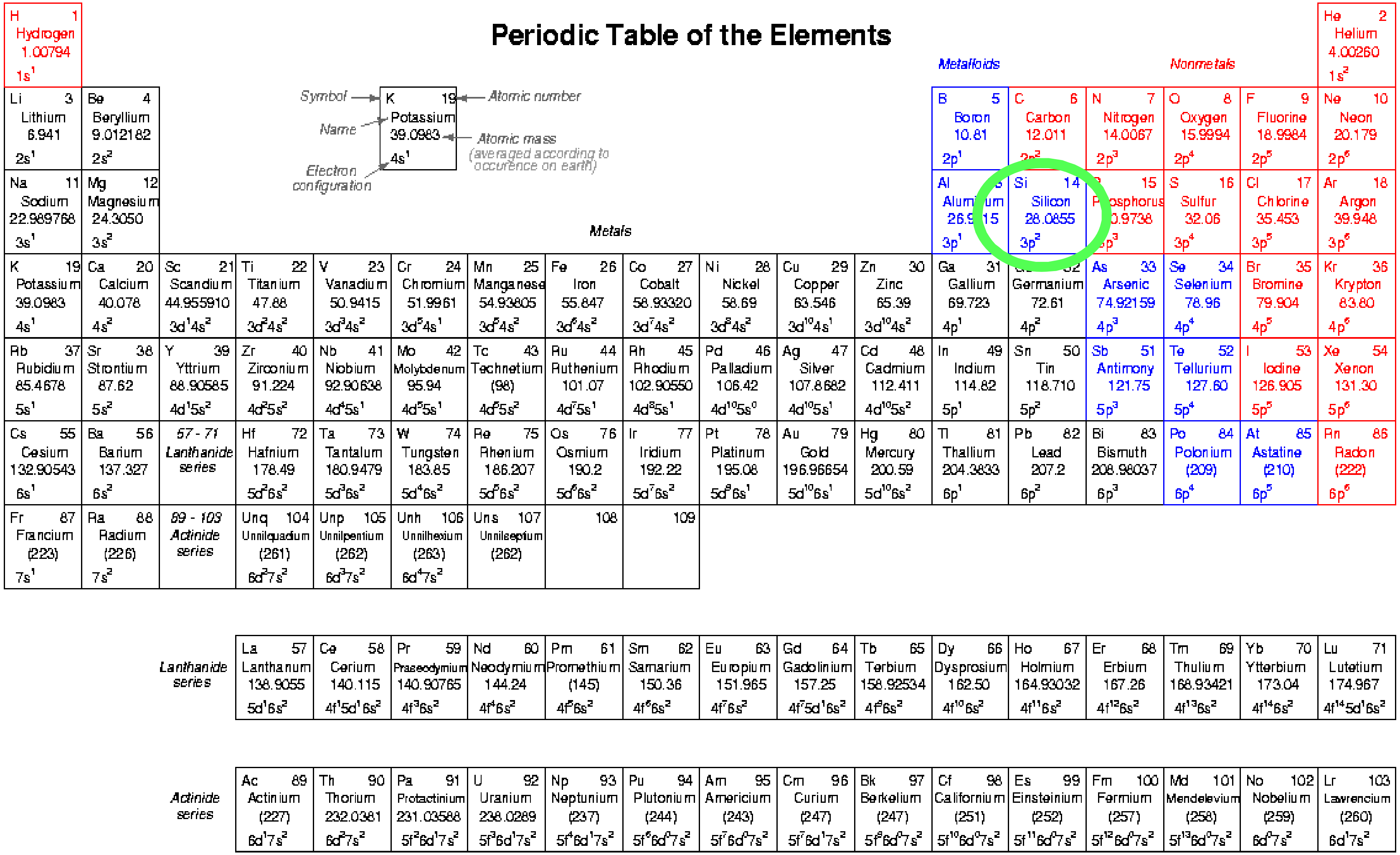
VALENCE BAND: 4N STATES, 4N ELECTRONS
CONDUCTION BAND: 4N STATES, 0 ELECTRONS

SHOCKLEY PARKING GARAGE MODEL





INTRINSIC SEMICONDUCTOR
THERMAL EXCITATION
In Si @ T=300 K
$n=p\approx10^{10}$ cm^{-3}



Periodic Table of the Elements

Symbol → K 19 ← Atomic number
Name → Potassium
39.0983 ← Atomic mass (averaged according to occurence on earth)
Electron configuration → $4s^1$

Metalloids *Nonmetals* *Metals*

H 1 Hydrogen 1.00794 $1s^1$																	He 2 Helium 4.00260 $1s^2$
Li 3 Lithium 6.941 $2s^1$	Be 4 Beryllium 9.012182 $2s^2$											B 5 Boron 10.81 $2p^1$	C 6 Carbon 12.011 $2p^2$	N 7 Nitrogen 14.0067 $2p^3$	O 8 Oxygen 15.9994 $2p^4$	F 9 Fluorine 18.9984 $2p^5$	Ne 10 Neon 20.179 $2p^6$
Na 11 Sodium 22.989768 $3s^1$	Mg 12 Magnesium 24.3050 $3s^2$											Al 3 Alumi um 26.9 15 $3p^1$	Si 14 Silicon 28.0855 $3p^2$	15 P osphorus 0.9738 p^3	S 16 Sulfur 32.06 $3p^4$	Cl 17 Chlorine 35.453 $3p^5$	Ar 18 Argon 39.948 $3p^6$
K 19 Potassium 39.0983 $4s^1$	Ca 20 Calcium 40.078 $4s^2$	Sc 21 Scandium 44.955910 $3d^1 4s^2$	Ti 22 Titanium 47.88 $3d^2 4s^2$	V 23 Vanadium 50.9415 $3d^3 4s^2$	Cr 24 Chromium 51.9961 $3d^5 4s^1$	Mn 25 Manganese 54.93805 $3d^5 4s^2$	Fe 26 Iron 55.847 $3d^6 4s^2$	Co 27 Cobalt 58.93320 $3d^7 4s^2$	Ni 28 Nickel 58.69 $3d^8 4s^2$	Cu 29 Copper 63.546 $3d^{10} 4s^1$	Zn 30 Zinc 65.39 $3d^{10} 4s^2$	Ga 31 Gallium 69.723 $4p^1$	2 Germanium 72.61 $4p^2$	As 33 Arsenic 74.92159 $4p^3$	Se 34 Selenium 78.96 $4p^4$	Br 35 Bromine 79.904 $4p^5$	Kr 36 Krypton 83.80 $4p^6$
Rb 37 Rubidium 85.4678 $5s^1$	Sr 38 Strontium 87.62 $5s^2$	Y 39 Yttrium 88.90585 $4d^1 5s^2$	Zr 40 Zirconium 91.224 $4d^2 5s^2$	Nb 41 Niobium 92.90638 $4d^4 5s^1$	Mo 42 Molybdenum 95.94 $4d^5 5s^1$	Tc 43 Technetium (98) $4d^5 5s^2$	Ru 44 Ruthenium 101.07 $4d^7 5s^1$	Rh 45 Rhodium 102.90550 $4d^8 5s^1$	Pd 46 Palladium 106.42 $4d^{10} 5s^0$	Ag 47 Silver 107.8682 $4d^{10} 5s^1$	Cd 48 Cadmium 112.411 $4d^{10} 5s^2$	In 49 Indium 114.82 $5p^1$	Sn 50 Tin 118.710 $5p^2$	Sb 51 Antimony 121.75 $5p^3$	Te 52 Tellurium 127.60 $5p^4$	I 53 Iodine 126.905 $5p^5$	Xe 54 Xenon 131.30 $5p^6$
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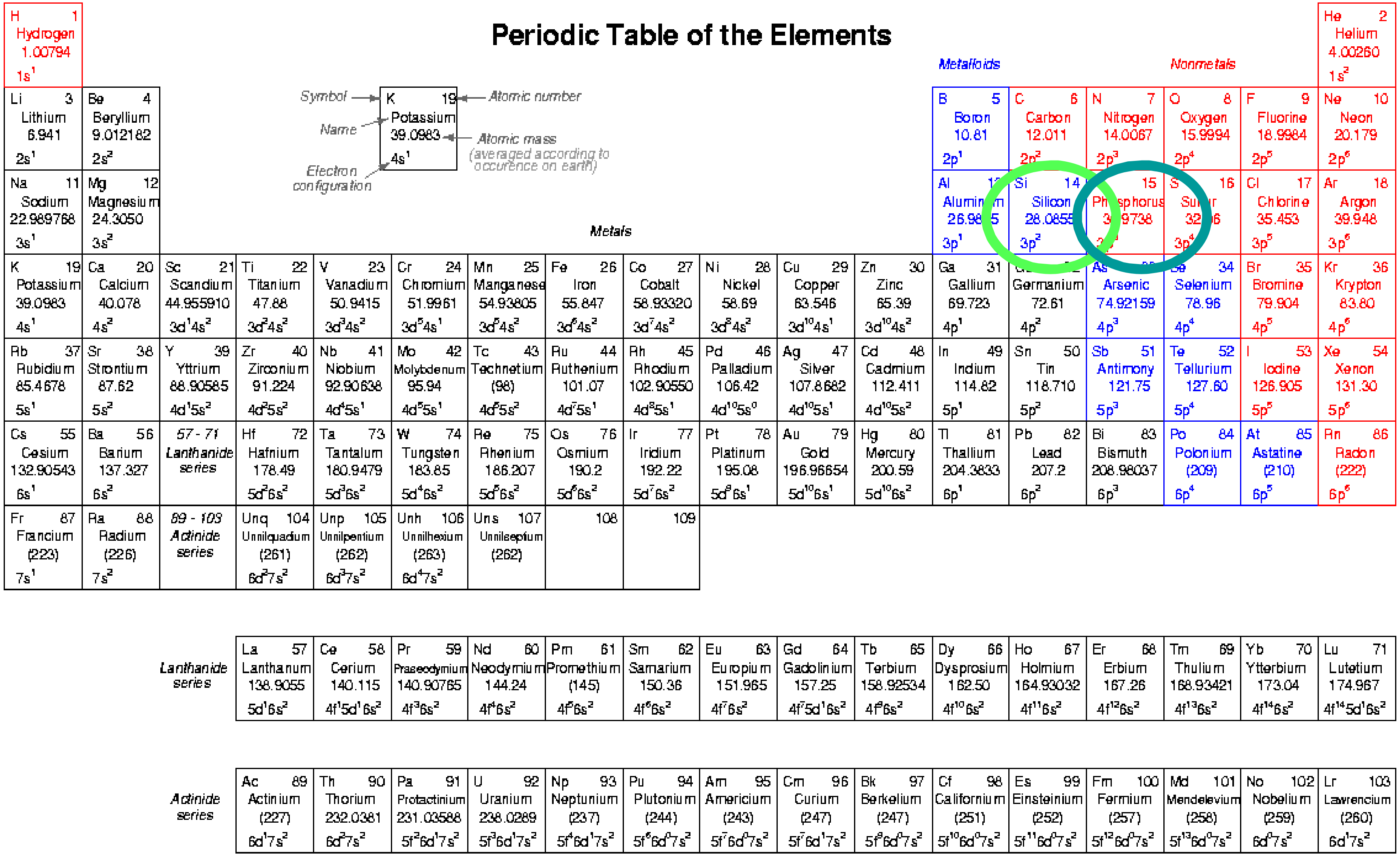

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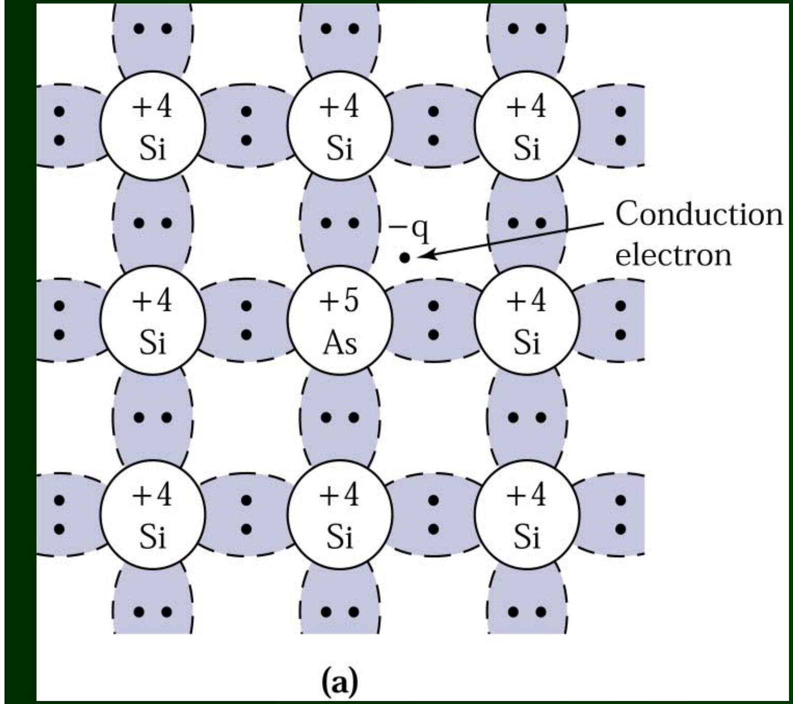
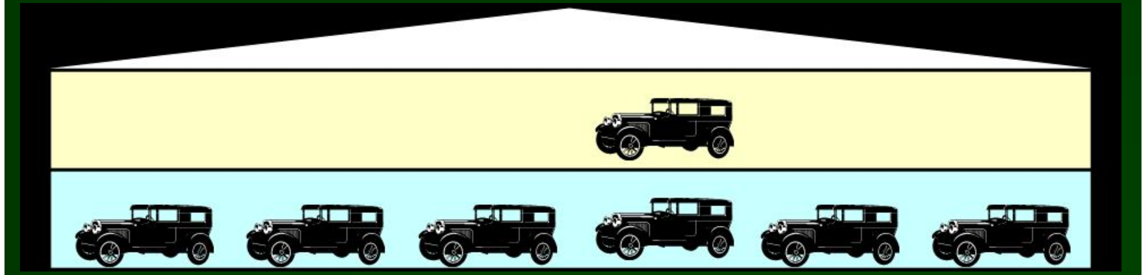
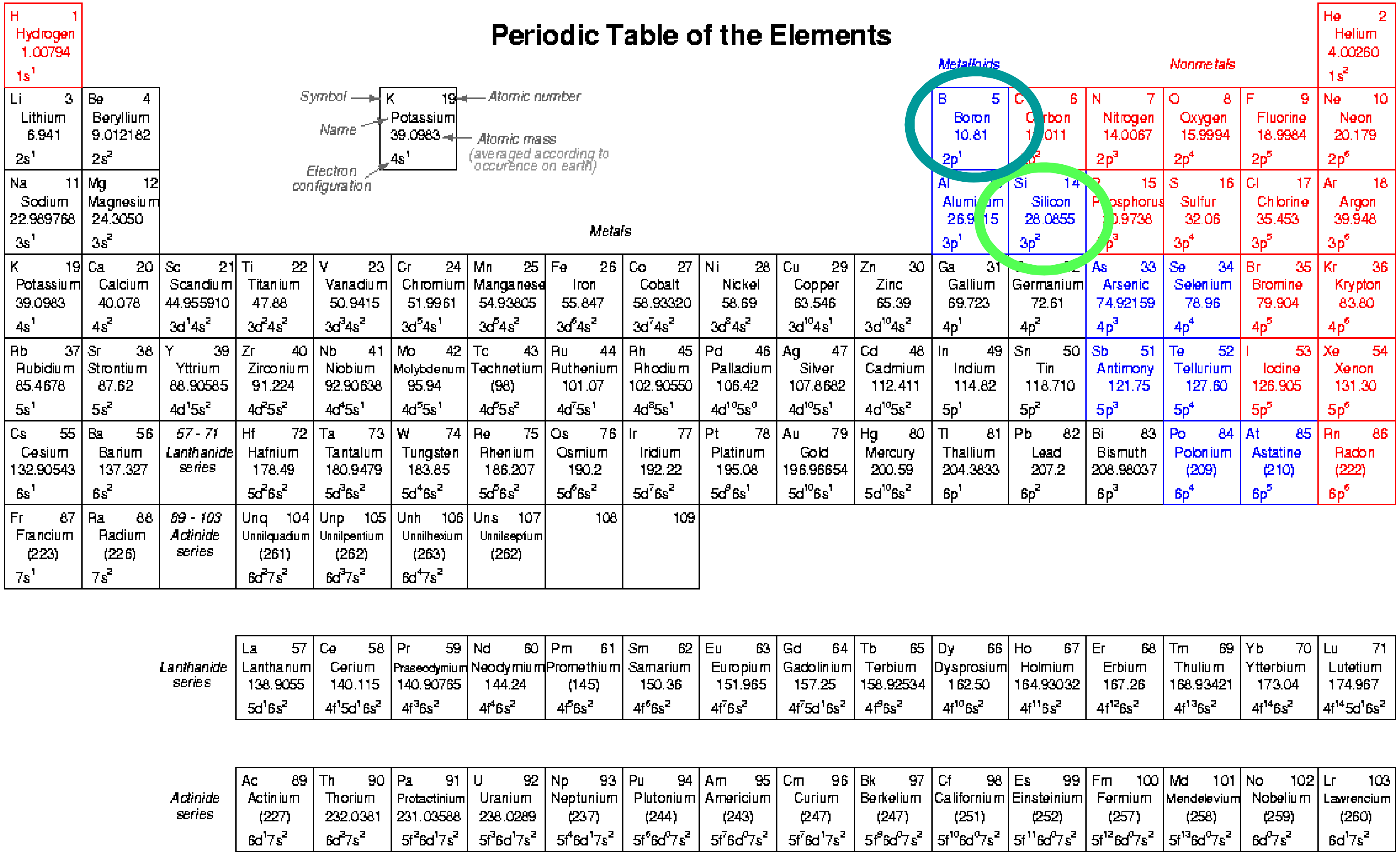
n-type Si with donor (phosphorous)



(a)



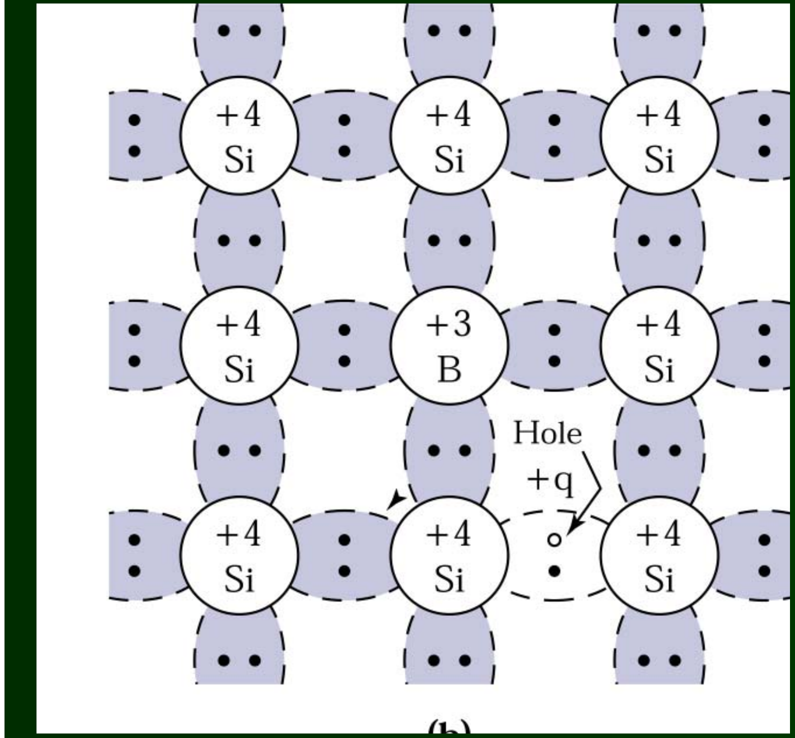


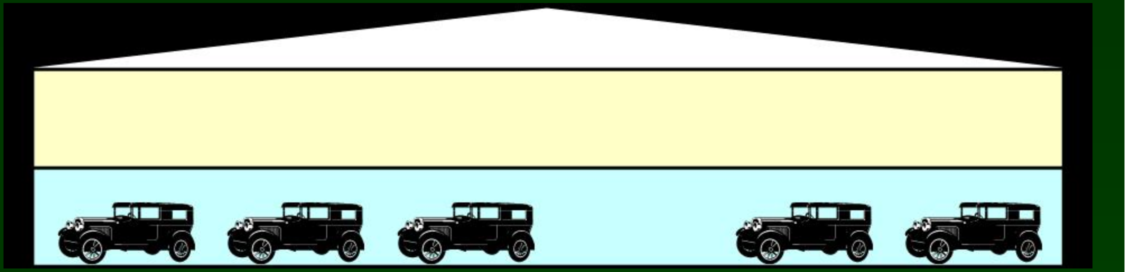
Periodic Table of the Elements

H 1 Hydrogen 1.00794 $1s^1$																	He 2 Helium 4.00260 $1s^2$
Li 3 Lithium 6.941 $2s^1$	Be 4 Beryllium 9.012182 $2s^2$											B 5 Boron 10.81 $2p^1$	C 6 Carbon 12.011 $2p^2$	N 7 Nitrogen 14.0067 $2p^3$	O 8 Oxygen 15.9994 $2p^4$	F 9 Fluorine 18.9984 $2p^5$	Ne 10 Neon 20.179 $2p^6$
Na 11 Sodium 22.989768 $3s^1$	Mg 12 Magnesium 24.3050 $3s^2$											Al 13 Aluminum 26.9815 $3p^1$	Si 14 Silicon 28.0855 $3p^2$	P 15 Phosphorus 30.9738 $3p^3$	S 16 Sulfur 32.06 $3p^4$	Cl 17 Chlorine 35.453 $3p^5$	Ar 18 Argon 39.948 $3p^6$
K 19 Potassium 39.0983 $4s^1$	Ca 20 Calcium 40.078 $4s^2$	Sc 21 Scandium 44.955910 $3d^1 4s^2$	Ti 22 Titanium 47.88 $3d^2 4s^2$	V 23 Vanadium 50.9415 $3d^3 4s^2$	Cr 24 Chromium 51.9961 $3d^5 4s^1$	Mn 25 Manganese 54.93805 $3d^5 4s^2$	Fe 26 Iron 55.847 $3d^6 4s^2$	Co 27 Cobalt 58.93320 $3d^7 4s^2$	Ni 28 Nickel 58.69 $3d^8 4s^2$	Cu 29 Copper 63.546 $3d^{10} 4s^1$	Zn 30 Zinc 65.39 $3d^{10} 4s^2$	Ga 31 Gallium 69.723 $4p^1$	Ge 32 Germanium 72.61 $4p^2$	As 33 Arsenic 74.92159 $4p^3$	Se 34 Selenium 78.96 $4p^4$	Br 35 Bromine 79.904 $4p^5$	Kr 36 Krypton 83.80 $4p^6$
Rb 37 Rubidium 85.4678 $5s^1$	Sr 38 Strontium 87.62 $5s^2$	Y 39 Yttrium 88.90585 $4d^1 5s^2$	Zr 40 Zirconium 91.224 $4d^2 5s^2$	Nb 41 Niobium 92.90638 $4d^4 5s^1$	Mo 42 Molybdenum 95.94 $4d^5 5s^1$	Tc 43 Technetium (98) $4d^5 5s^2$	Ru 44 Ruthenium 101.07 $4d^7 5s^1$	Rh 45 Rhodium 102.90550 $4d^8 5s^1$	Pd 46 Palladium 106.42 $4d^{10} 5s^0$	Ag 47 Silver 107.8682 $4d^{10} 5s^1$	Cd 48 Cadmium 112.411 $4d^{10} 5s^2$	In 49 Indium 114.82 $5p^1$	Sn 50 Tin 118.710 $5p^2$	Sb 51 Antimony 121.75 $5p^3$	Te 52 Tellurium 127.60 $5p^4$	I 53 Iodine 126.905 $5p^5$	Xe 54 Xenon 131.30 $5p^6$
Cs 55 Cesium 132.90543 $6s^1$	Ba 56 Barium 137.327 $6s^2$	*57 - 71* *Lanthanide series*	Hf 72 Hafnium 178.49 $5d^2 6s^2$	Ta 73 Tantalum 180.9479 $5d^3 6s^2$	W 74 Tungsten 183.85 $5d^4 6s^2$	Re 75 Rhenium 186.207 $5d^5 6s^2$	Os 76 Osmium 190.2 $5d^6 6s^2$	Ir 77 Iridium 192.22 $5d^7 6s^2$	Pt 78 Platinum 195.08 $5d^9 6s^1$	Au 79 Gold 196.96654 $5d^{10} 6s^1$	Hg 80 Mercury 200.59 $5d^{10} 6s^2$	Tl 81 Thallium 204.3833 $6p^1$	Pb 82 Lead 207.2 $6p^2$	Bi 83 Bismuth 208.98037 $6p^3$	Po 84 Polonium (209) $6p^4$	At 85 Astatine (210) $6p^5$	Rn 86 Radon (222) $6p^6$
Fr 87 Francium (223) $7s^1$	Ra 88 Radium (226) $7s^2$	*89 - 103* *Actinide series*	Unq 104 Unnilquadium (261) $6d^2 7s^2$	Unp 105 Unnilpentium (262) $6d^3 7s^2$	Unh 106 Unnilhexium (263) $6d^4 7s^2$	Uns 107 Unnilseptium (262)	108	109									

Lanthanide series	La 57 Lanthanum 138.9055 $5d^1 6s^2$	Ce 58 Cerium 140.115 $4f^1 5d^1 6s^2$	Pr 59 Praseodymium 140.90765 $4f^3 6s^2$	Nd 60 Neodymium 144.24 $4f^4 6s^2$	Pm 61 Promethium (145) $4f^5 6s^2$	Sm 62 Samarium 150.36 $4f^6 6s^2$	Eu 63 Europium 151.965 $4f^7 6s^2$	Gd 64 Gadolinium 157.25 $4f^7 5d^1 6s^2$	Tb 65 Terbium 158.92534 $4f^9 6s^2$	Dy 66 Dysprosium 162.50 $4f^{10} 6s^2$	Ho 67 Holmium 164.93032 $4f^{11} 6s^2$	Er 68 Erbium 167.26 $4f^{12} 6s^2$	Tm 69 Thulium 168.93421 $4f^{13} 6s^2$	Yb 70 Ytterbium 173.04 $4f^{14} 6s^2$	Lu 71 Lutetium 174.967 $4f^{14} 5d^1 6s^2$
Actinide series	Ac 89 Actinium (227) $6d^1 7s^2$	Th 90 Thorium 232.0381 $6d^2 7s^2$	Pa 91 Protactinium 231.03588 $5f^2 6d^1 7s^2$	U 92 Uranium 238.0289 $5f^3 6d^1 7s^2$	Np 93 Neptunium (237) $5f^4 6d^1 7s^2$	Pu 94 Plutonium (244) $5f^6 6d^0 7s^2$	Am 95 Americium (243) $5f^7 6d^0 7s^2$	Cm 96 Curium (247) $5f^7 6d^1 7s^2$	Bk 97 Berkelium (247) $5f^8 6d^0 7s^2$	Cf 98 Californium (251) $5f^{10} 6d^0 7s^2$	Es 99 Einsteinium (252) $5f^{11} 6d^0 7s^2$	Fm 100 Fermium (257) $5f^{12} 6d^0 7s^2$	Md 101 Mendelevium (258) $5f^{13} 6d^0 7s^2$	No 102 Nobelium (259) $6d^0 7s^2$	Lr 103 Lawrencium (260) $6d^1 7s^2$

p-type Si with acceptor (boron)





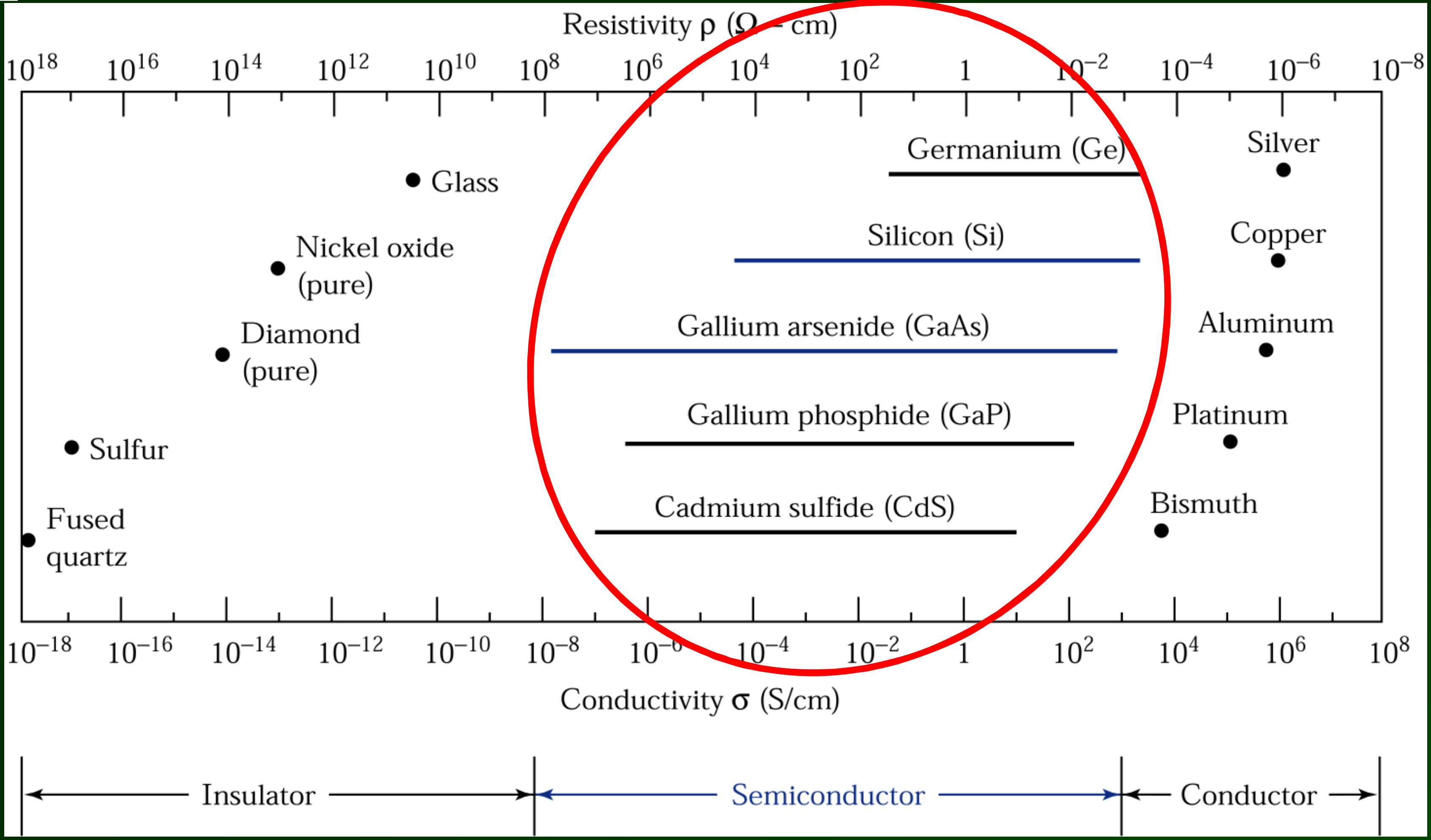
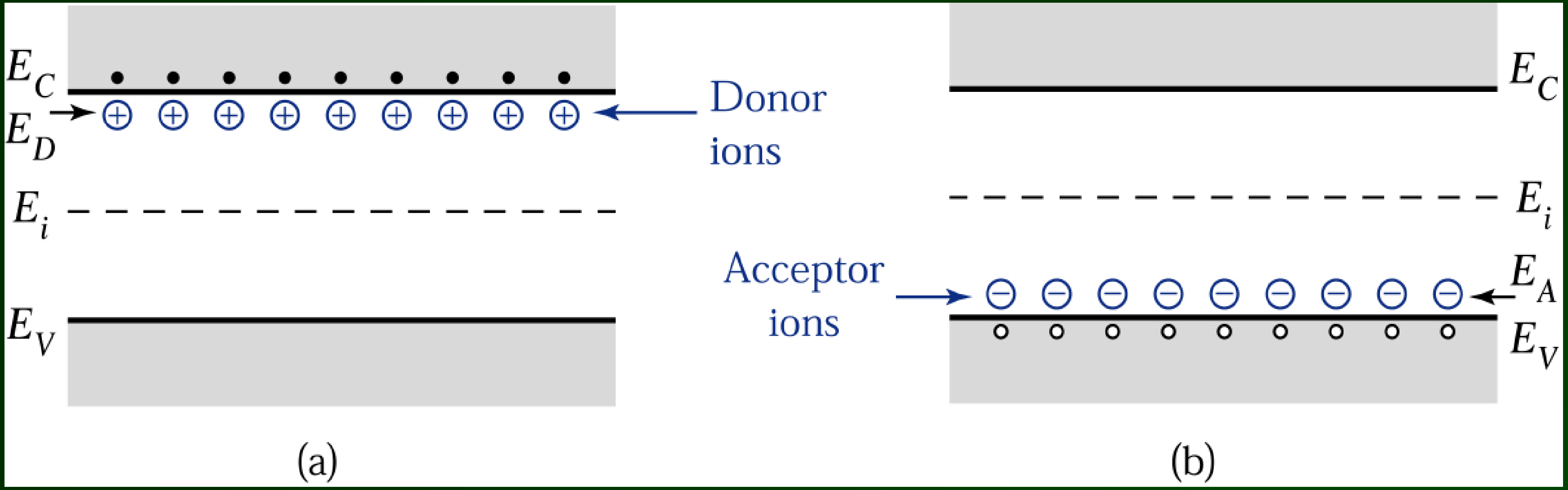


Figure 2.1. Typical range of conductivities for insulators, semiconductors, and conductors.

Figure 2.25. Schematic energy band representation of extrinsic semiconductors with (*a*) donor ions and (*b*) acceptor ions.



http://jas.eng.buffalo.edu/

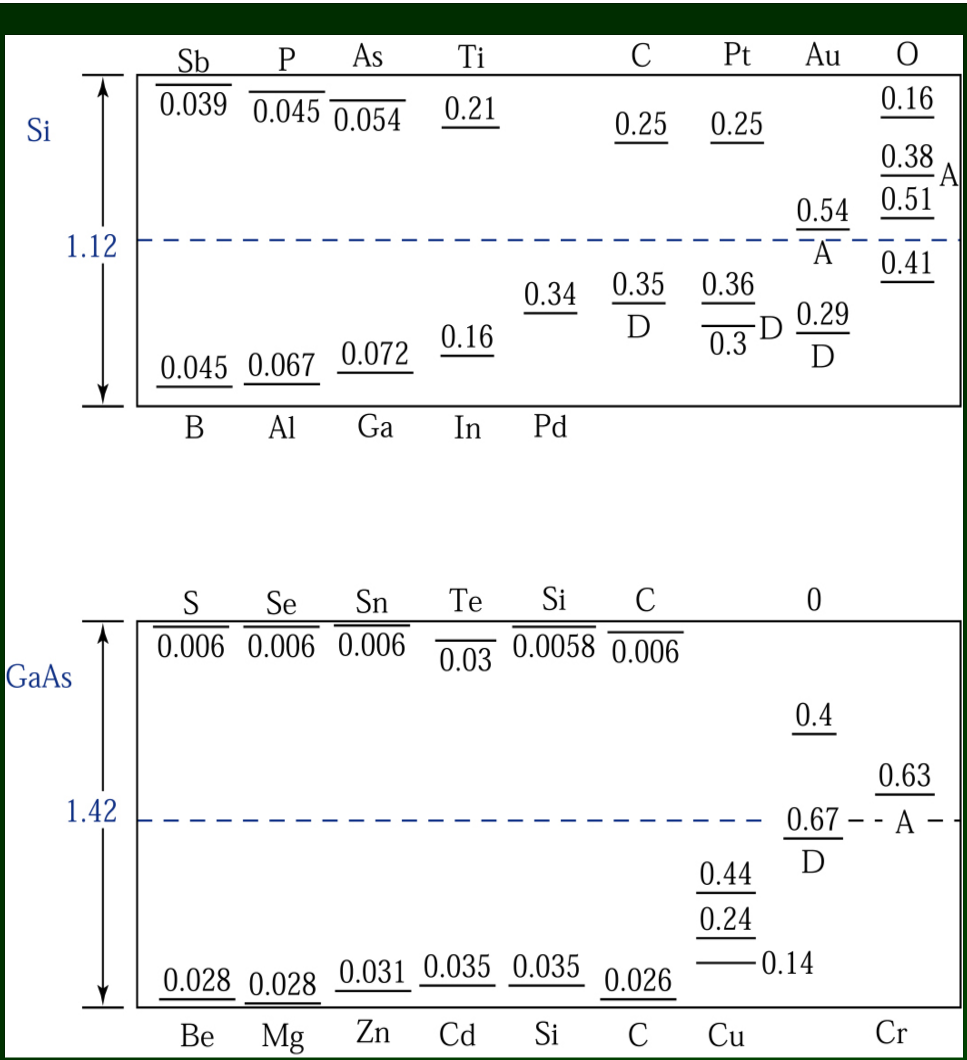
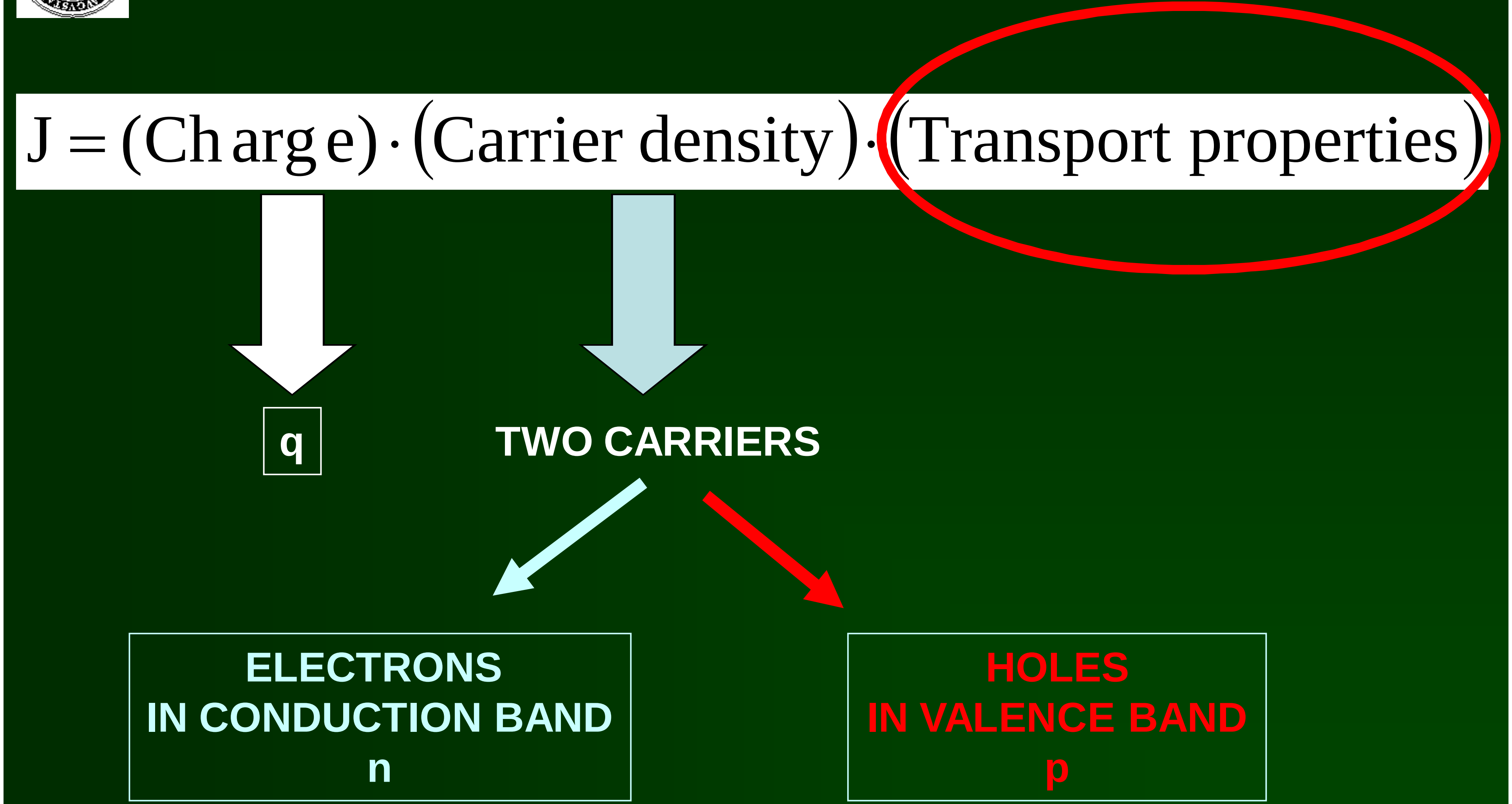


Figure 2.24. Measured ionization energies (in eV) for various impurities in Si and GaAs. The levels below the gap center are measured from the top of the valence band and are acceptor levels unless indicated by *D* for donor level. The levels above the gap center are measured from the bottom of the conduction band and are donor levels unless indicated by *A* for acceptor level.[8]



$$J = (\text{Charge}) \cdot \left(\text{Carrier density}\right) \cdot \left(\text{Transport properties}\right)$$

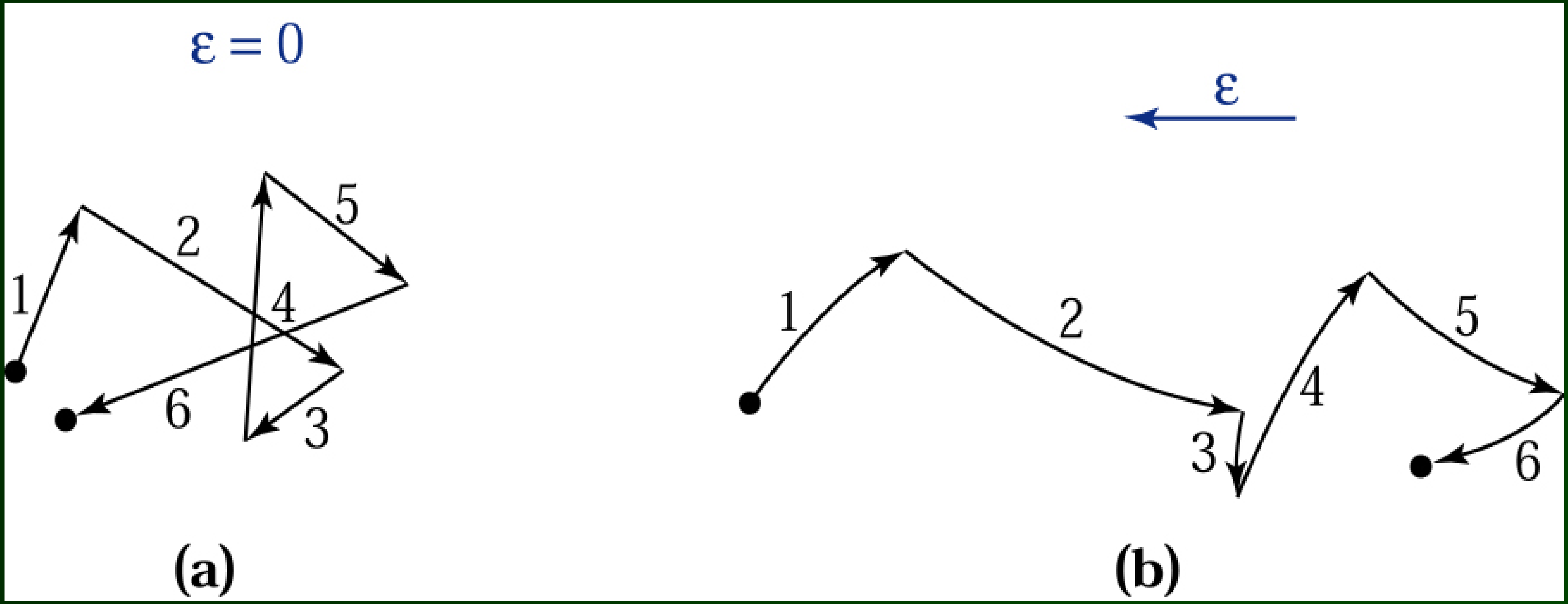
q

TWO CARRIERS

ELECTRONS
IN CONDUCTION BAND
n

HOLES
IN VALENCE BAND
p

Figure 3.1. Schematic path of an electron in a semiconductor. (*a*) Random thermal motion. (*b*) Combined motion due to random thermal motion and an applied electric field.



Electric field

Average drift velocity

$$v_n = \frac{-q \cdot F \cdot \tau}{m_n}$$

Relaxation time

Effective mass

Carrier mobility

$$\mu_n = \frac{q \cdot \tau_n}{m_n} \quad \Rightarrow \quad v = \mu \cdot F$$

In Si @ 300 K:

$\mu_n \approx 1350\ cm^2 \cdot V^{-1} \cdot s^{-1}$; $\mu_p \approx 450\ cm^2 \cdot V^{-1} \cdot s^{-1}$

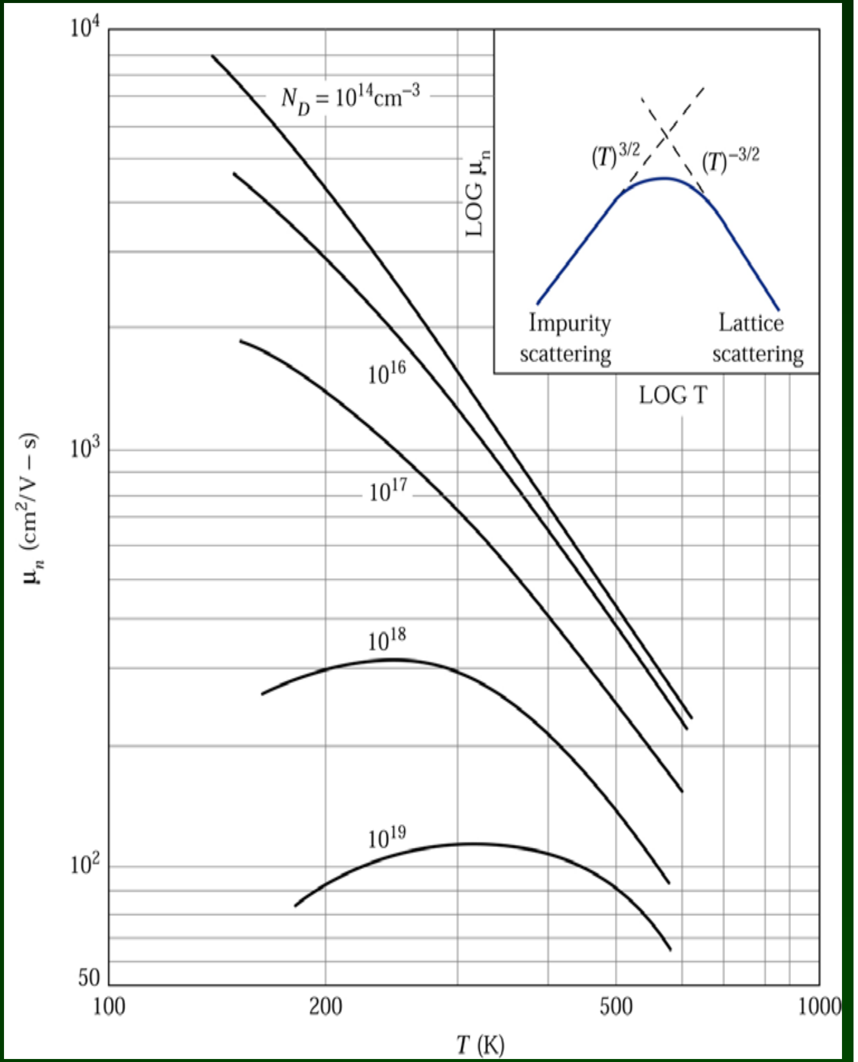
Figure 3.2.

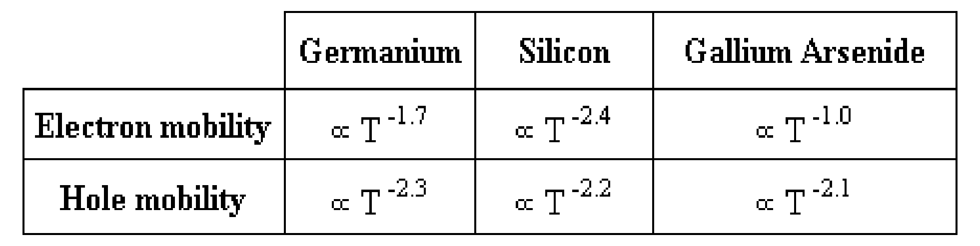
Electron mobility in silicon versus temperature for various donor concentrations. Insert shows the theoretical temperature dependence of electron mobility.[3]

At low doping conc.,
mobility decreases
with temperature increases.

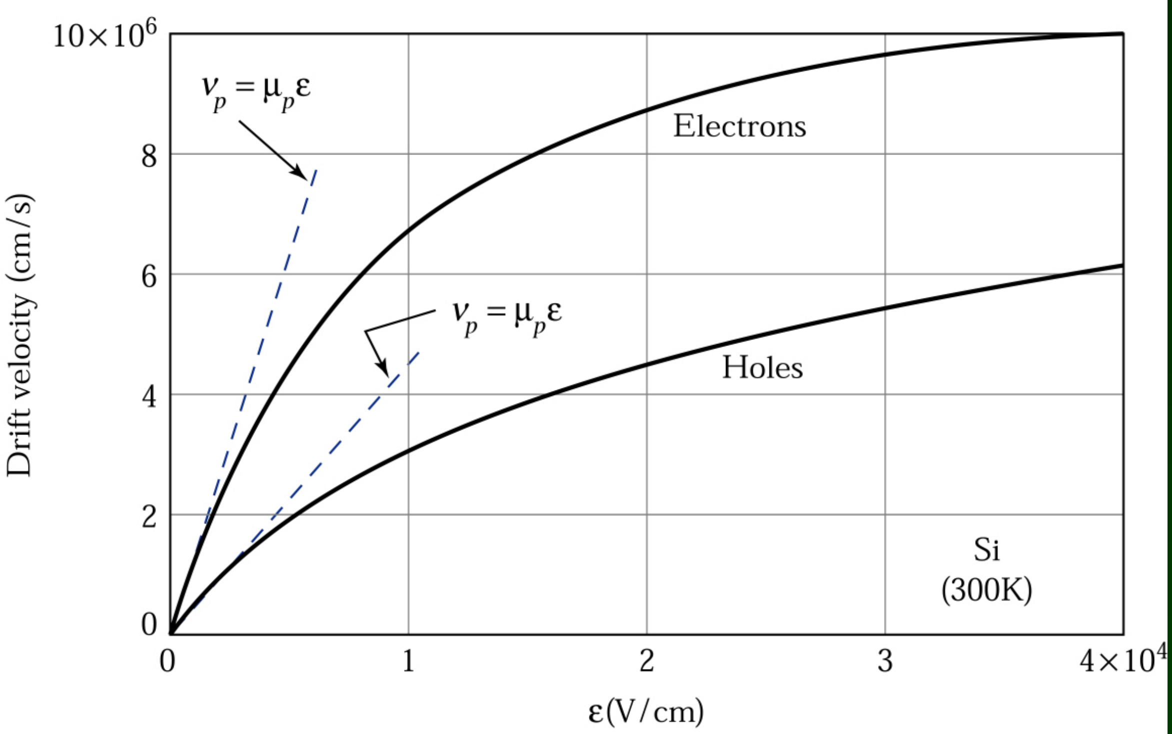
At a given temp.,
mobility decreases
with doping conc. increases.

At high doping conc.,
mobility is affected by both the impurity and the lattice scattering.





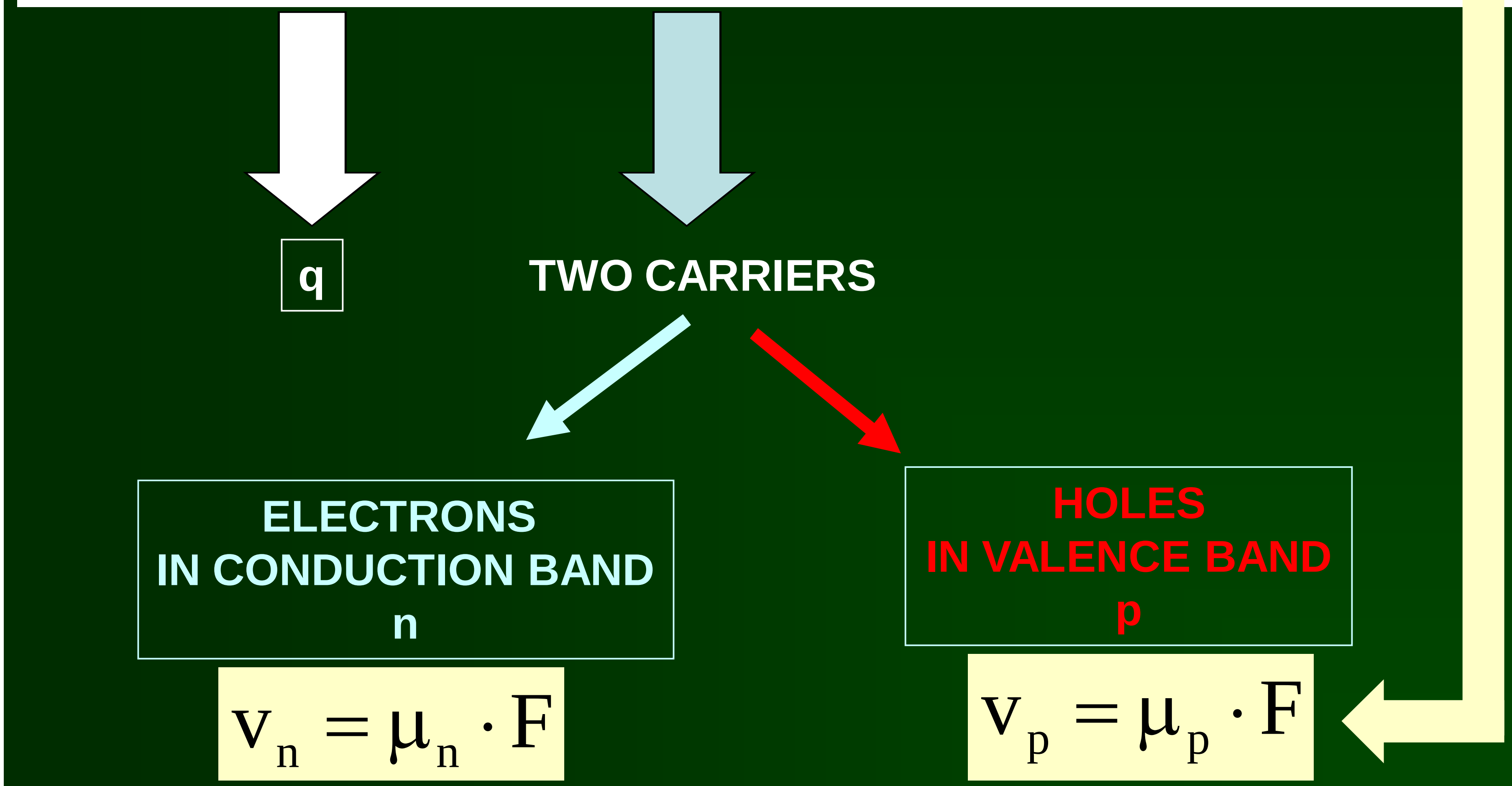
	Germanium	Silicon	Gallium Arsenide
Electron mobility	$\propto T^{-1.7}$	$\propto T^{-2.4}$	$\propto T^{-1.0}$
Hole mobility	$\propto T^{-2.3}$	$\propto T^{-2.2}$	$\propto T^{-2.1}$



Drift velocity versus electric field in Si.

$$v(\mathcal{E})=\frac{\mu\mathcal{E}}{1+\frac{\mu\mathcal{E}}{v_{sat}}}$$

$$J = (\mathrm{Charge}) \cdot (\mathrm{Carrier\ density}) \cdot (\mathrm{Transport\ properties})$$



q

TWO CARRIERS

ELECTRONS
IN CONDUCTION BAND
n

$$v_n = \mu_n \cdot F$$

HOLES
IN VALENCE BAND
p

$$v_p = \mu_p \cdot F$$

TRANSPORT PROPERTIES

Carrier drift:

$$J_n^{Drift} = q \cdot n \cdot \mu_n \cdot F$$

$$J_p^{Drift} = q \cdot p \cdot \mu_p \cdot F$$

Carrier diffusion:

$$J_n^{Diff} = q \cdot D_n \cdot \nabla n$$

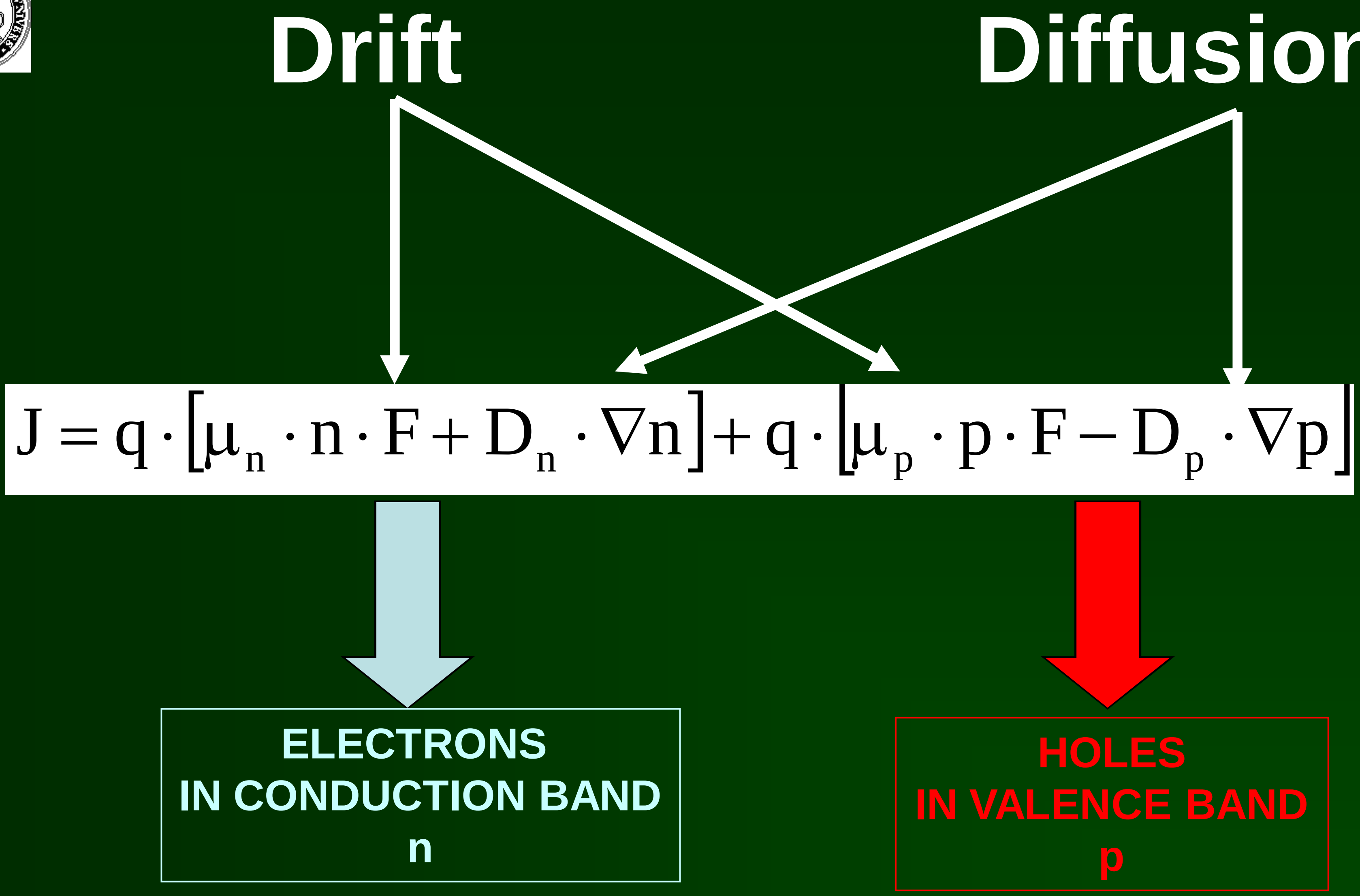
$$J_p^{Diff} = -q \cdot D_p \cdot \nabla p$$

Einstein relationship:

$$D = \frac{k_B \cdot T}{q} \cdot \mu$$

In Si @ 300 K:

$$D_n \approx 35 \text{ cm}^2 \cdot \text{s}^{-1} \; ; \; \mu_p \approx 10 \text{ cm}^2 \cdot \text{s}^{-1}$$



Drift

Diffusion

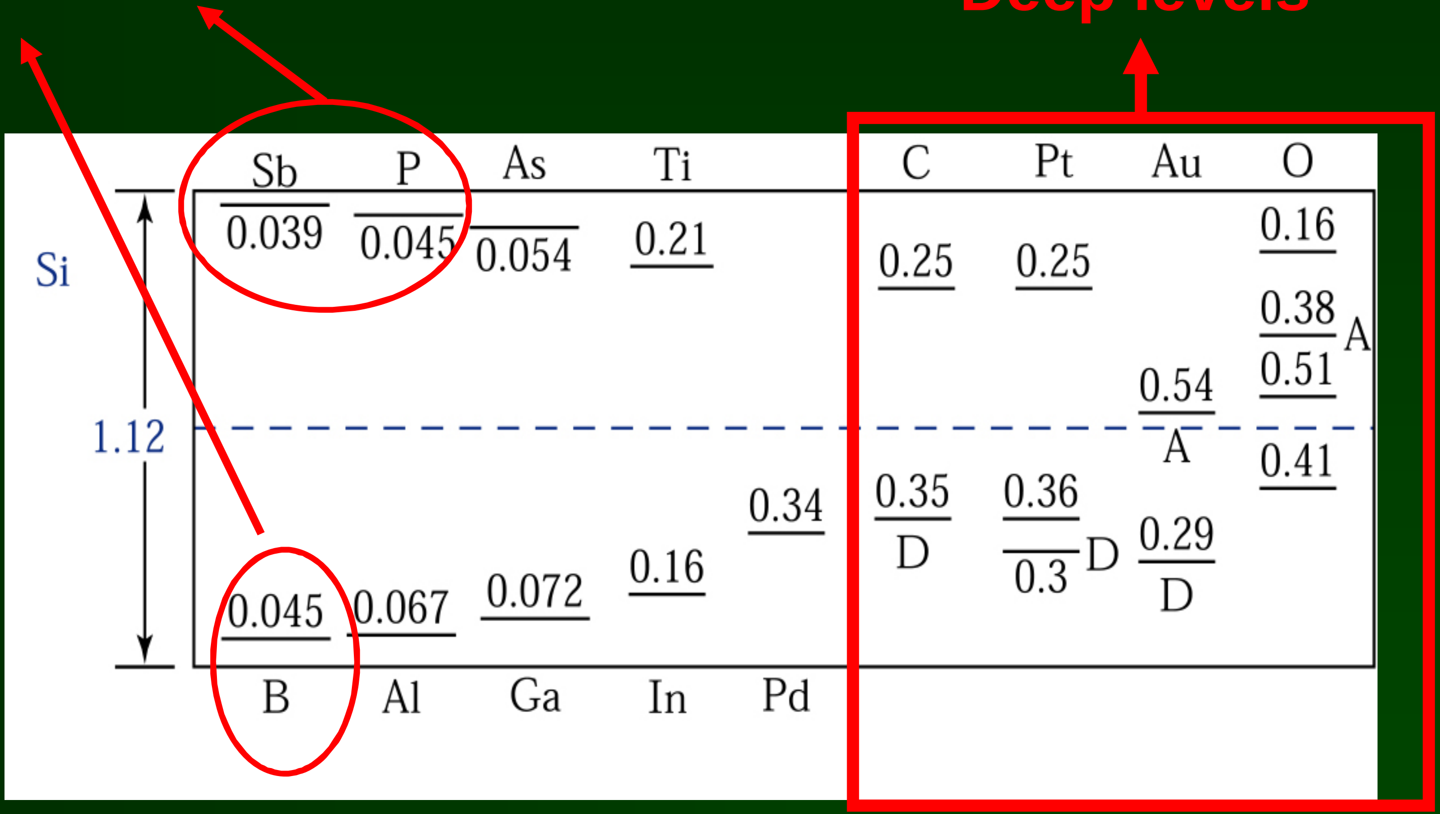
$$J = q \cdot \left[\mu_n \cdot n \cdot F + D_n \cdot \nabla n\right] + q \cdot \left[\mu_p \cdot p \cdot F - D_p \cdot \nabla p\right]$$

ELECTRONS
IN CONDUCTION BAND
n

HOLES
IN VALENCE BAND
p

Doping
Shallow levels

Recombination centers
Deep levels



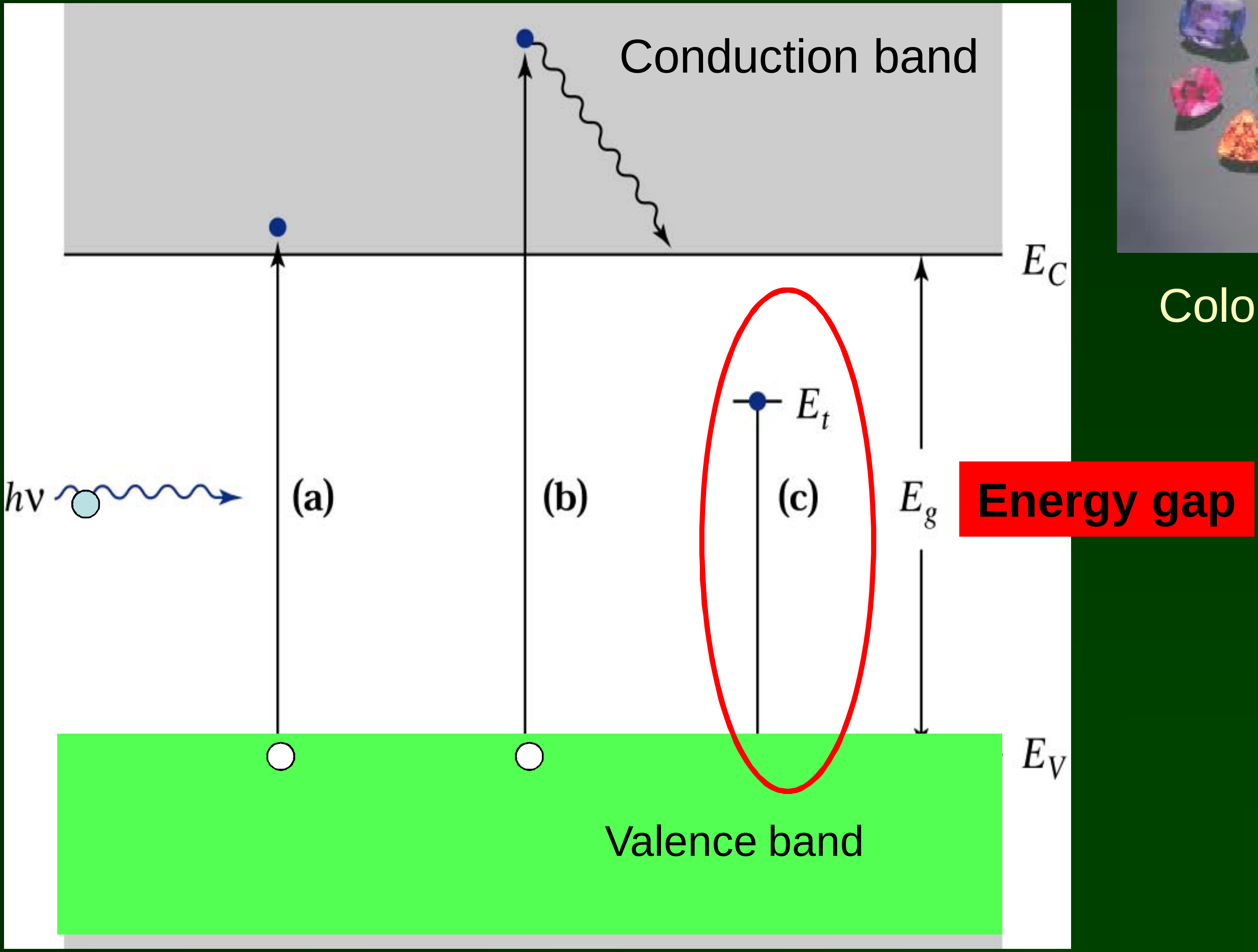


Figure 9.3. Optical absorption

Coloured irradiated diamond

Shockley-Read-Hall Model

Applet Recombination

Excess carrier lifetime

$$\tau = \frac{1}{N_{trap} \cdot \sigma \cdot v_{th}}$$

Trap density

Capture cross section

Thermal velocity

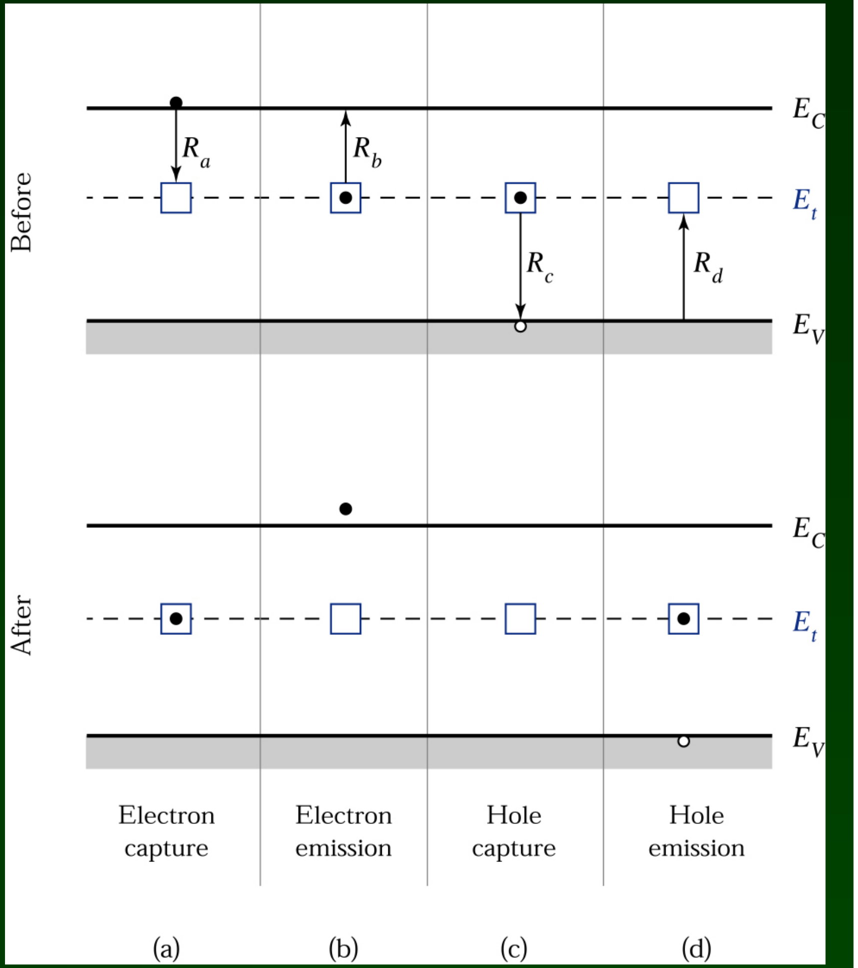


Figure 3.12.
Indirect generation-recombination processes

Continuity equation

Electrons

$$\frac{\partial n}{\partial t} = \nabla \cdot \left[+ \mu_n \cdot n \cdot F + D_n \cdot \nabla n \right] + G_n - R_n$$

Holes

$$\frac{\partial p}{\partial t} = \nabla \cdot \left[- \mu_p \cdot p \cdot F + D_p \cdot \nabla p \right] + G_p - R_p$$

Recombination rate

Generation Rate

Poisson equation

$$\Delta \psi = -\nabla \cdot F = -\frac{q}{\varepsilon} \cdot \left(p - n + N_D - N_A \right)$$

Acceptor concentration

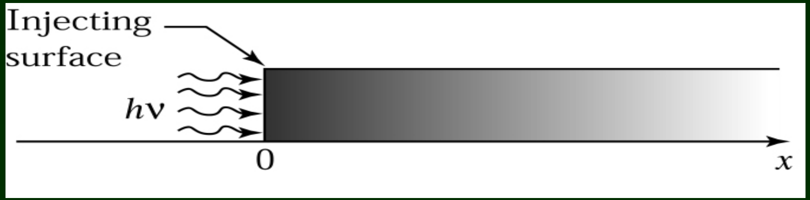
Electric potential

Dielectric constant

Donor concentration

Steady-state carrier injection from one side.

N-type semiconductor; Hole=minority carrier



$$\frac{\partial p}{\partial t} = \nabla\cdot\left[-\mu_p\cdot p\cdot F + D_p\cdot\nabla p\right] + G_p - R_p$$

Steady state conditions

No electric field

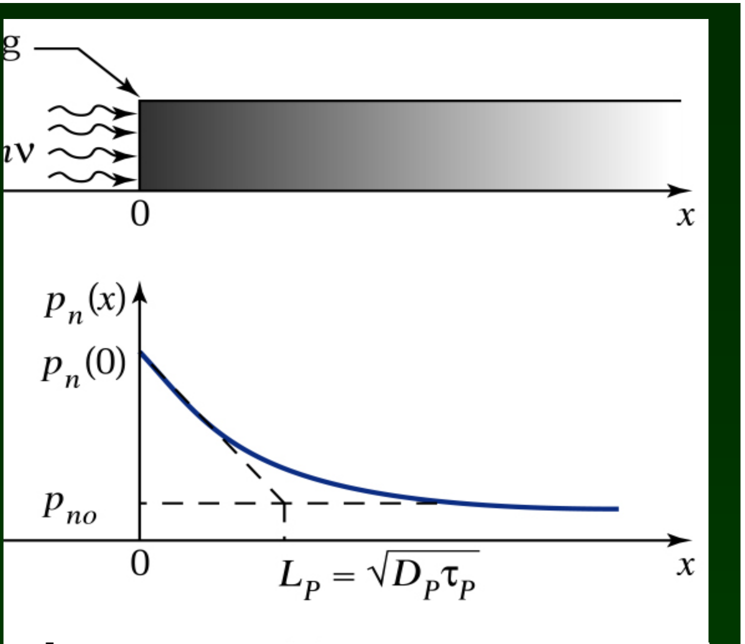
Generation at the surface

Hole concentration at equilibrium

$$0 = \nabla\cdot\left[0 + D_p\cdot\nabla p\right] + 0 - \frac{p-p_0}{\tau_p} \qquad \begin{cases} p(x=0) = P \\ p(x\to\infty) = p_0 \end{cases}$$

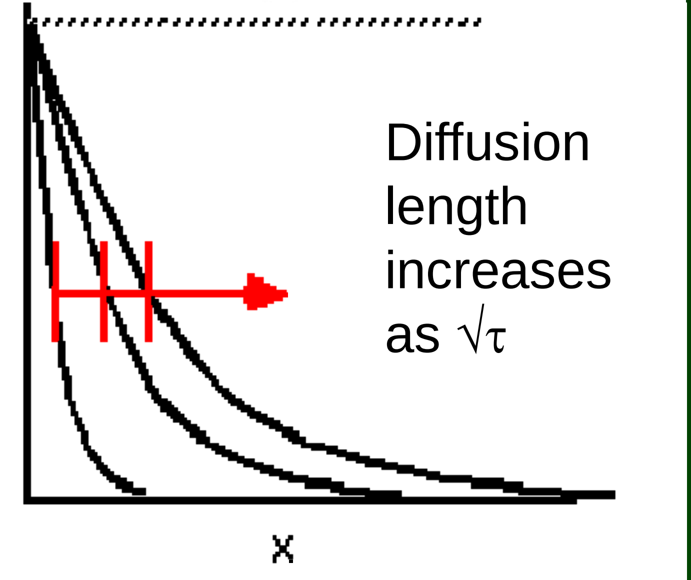
Figure 3.16. Steady-state carrier injection from one side. Semiinfinite sample.

$$D_p \cdot \frac{d^2p}{dx^2} - \frac{p-p_0}{\tau_p} = 0 \qquad \begin{cases} p(x=0)=P \\ p(x\to\infty)=p_0 \end{cases}$$



$$p = p_0 + [P - p_0]\cdot e^{-\frac{x}{L_p}}$$

$$L_p = \sqrt{D_p \cdot \tau_p} = \text{Hole Diffusion Length}$$



Diffusion length increases as $\sqrt{\tau}$

J.R. Haynes, W. Shockley,

“The mobility and life of injecting holes and electrons in germanium,

Phys. Rev. 81, (1951), 835-843.

$$\frac{\partial p}{\partial t} = \nabla \cdot \left[-\mu_p \cdot p \cdot F + D_p \cdot \nabla p\right] + G_p - R_p$$

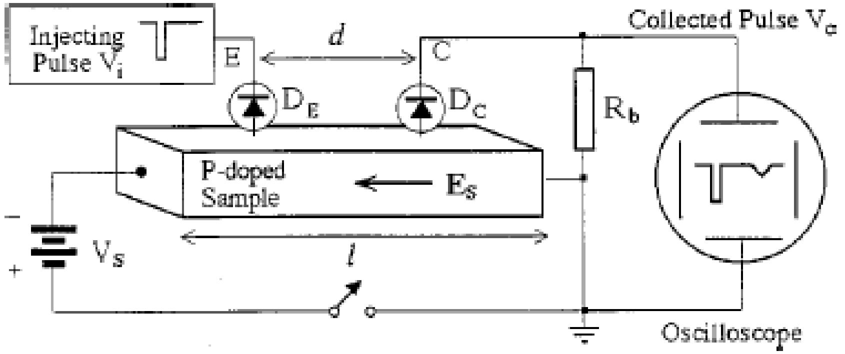


Fig. 1. Block diagram of the Haynes Shockley experiment: D_E and D_C are the emitter and collector point probes.

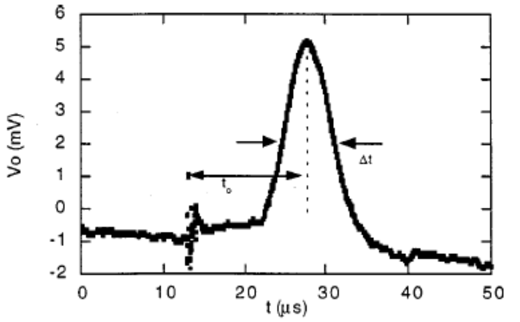
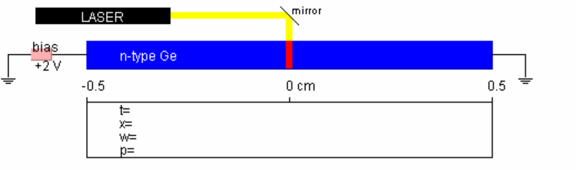


Fig. 12. Waveform observed in an N-doped Ge sample ($\rho=1\ \Omega$ cm) with optical injection.



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An overview of the electronic properties of semiconductor and insulator materials.

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S.M. Sze, *“Semiconductor Devices”,* 2nd edition, John Wiley and Sons, 2002

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http://britneyspears.ac/lasers.htm
http://ece-www.colorado.edu/~bart/book/contents.htm
(http://jas2.eng.buffalo.edu/applets/index.html)

An overview of the electronics properties of semiconductor and insulator materials.

Part I

- Conductors, semiconductors, insulators
- Carrier transport phenomena
- Fundamental equations
- Examples

Part II

- Major semiconductor devices
  - pn junction diodes & Schottky diodes
  - Bipolar Junction Transistor
  - Field Effect Transistors

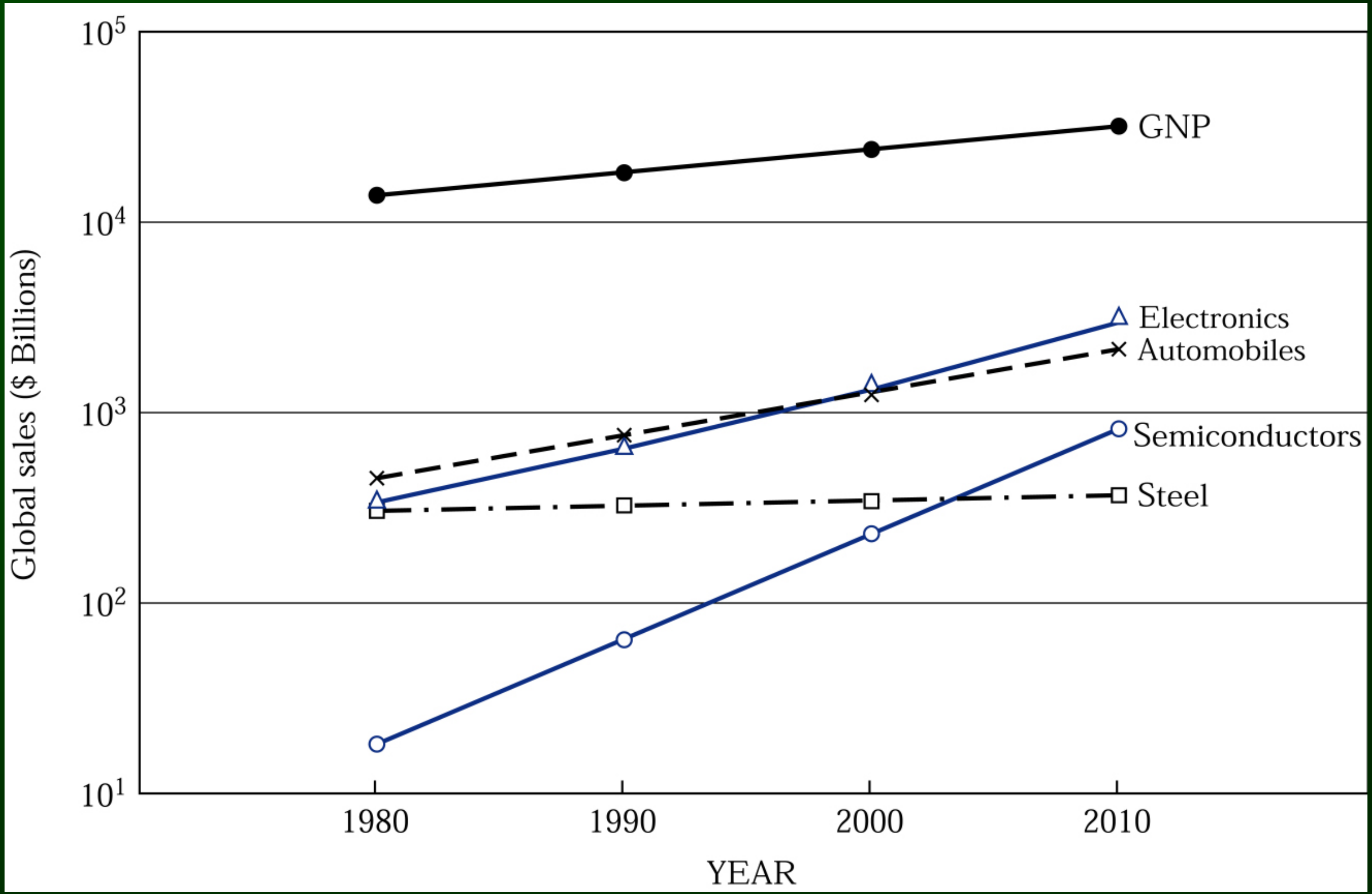
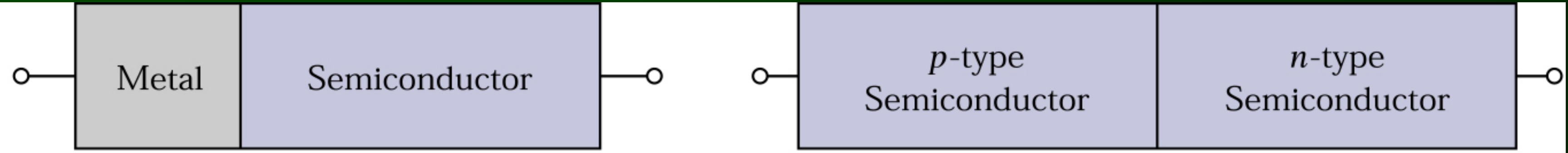
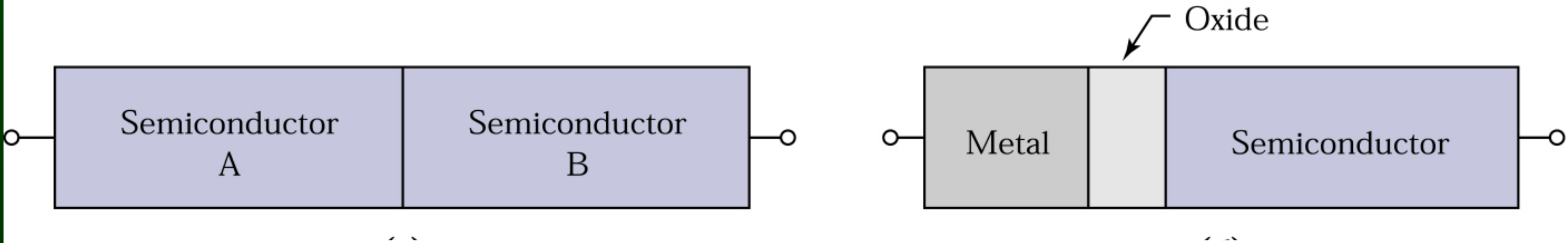


Figure 1.1. Gross world product (GWP) and sales volumes of the electronics, automobile, semiconductor, and steel industries from 1980 to 2000 and projected to 2010.[1,2]



Metal-Junction interface
(Schottky diode)

p-n junction



Heterojunction interface

Metal insulator (oxide)
Semiconductor structure

Figure 1.2. Basic device building blocks.

Semiconductor Devices, 2/E by S. M. Sze

p-n junction

p-type

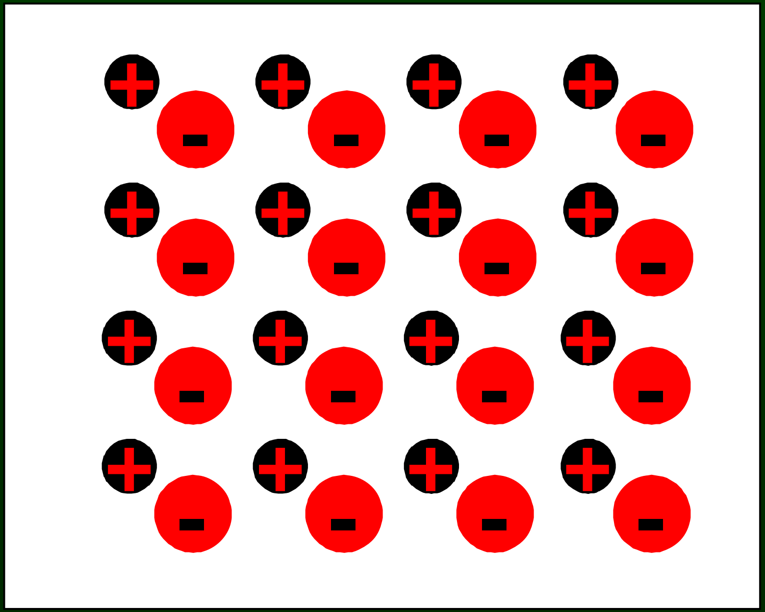
⊕ Majority carriers: holes

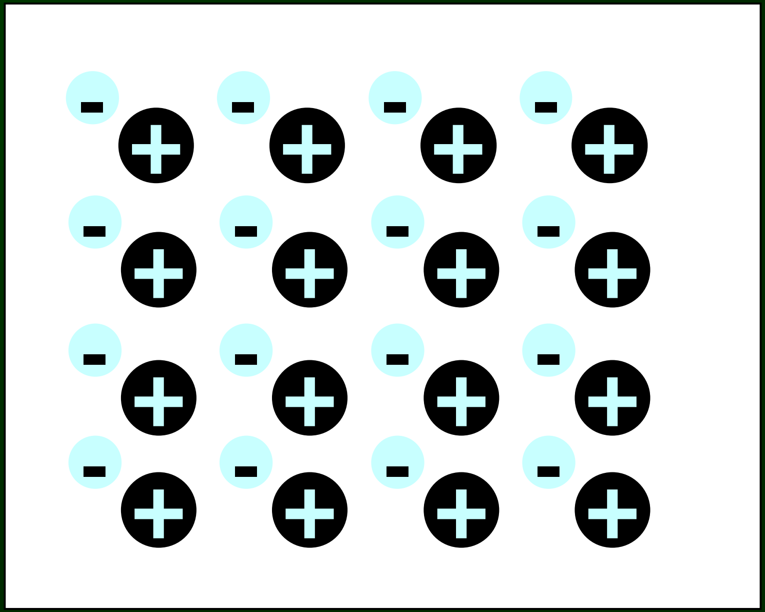
⊖ Acceptor concentration N_A^-

n-type

Majority carriers: electrons ⊖

Donor concentration N_D^+ ⊕

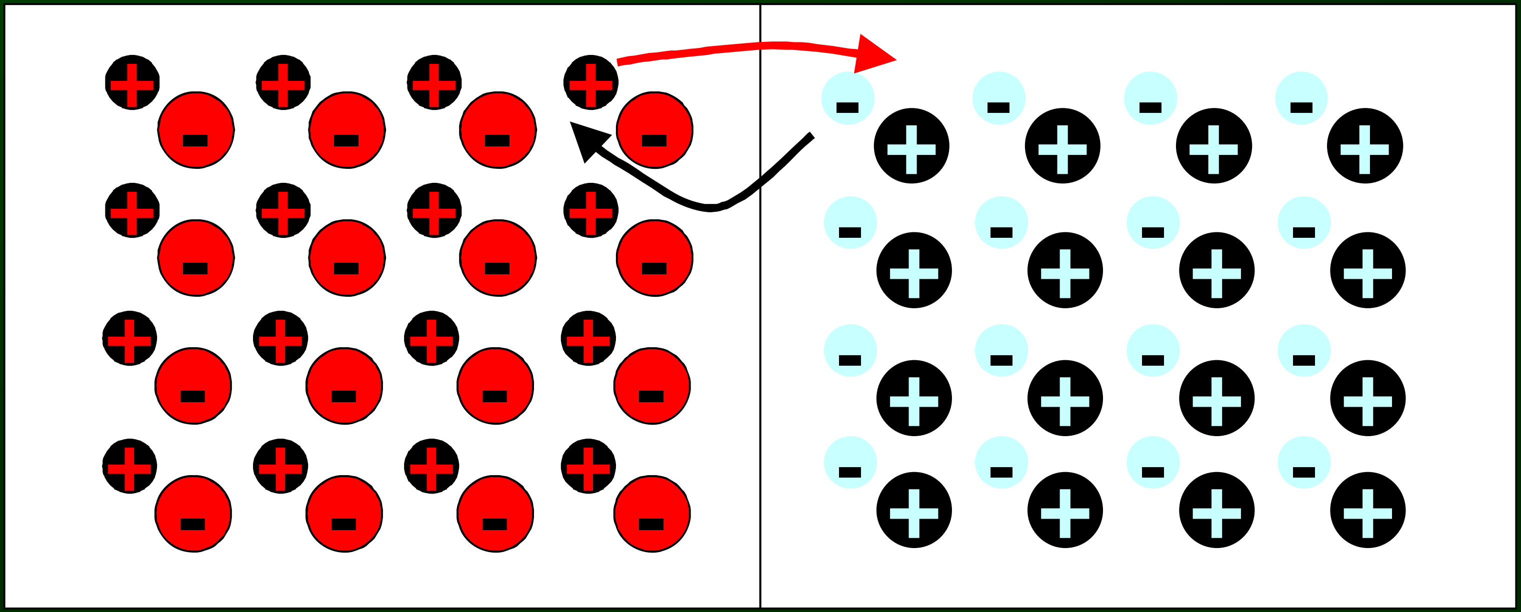




p-n junction

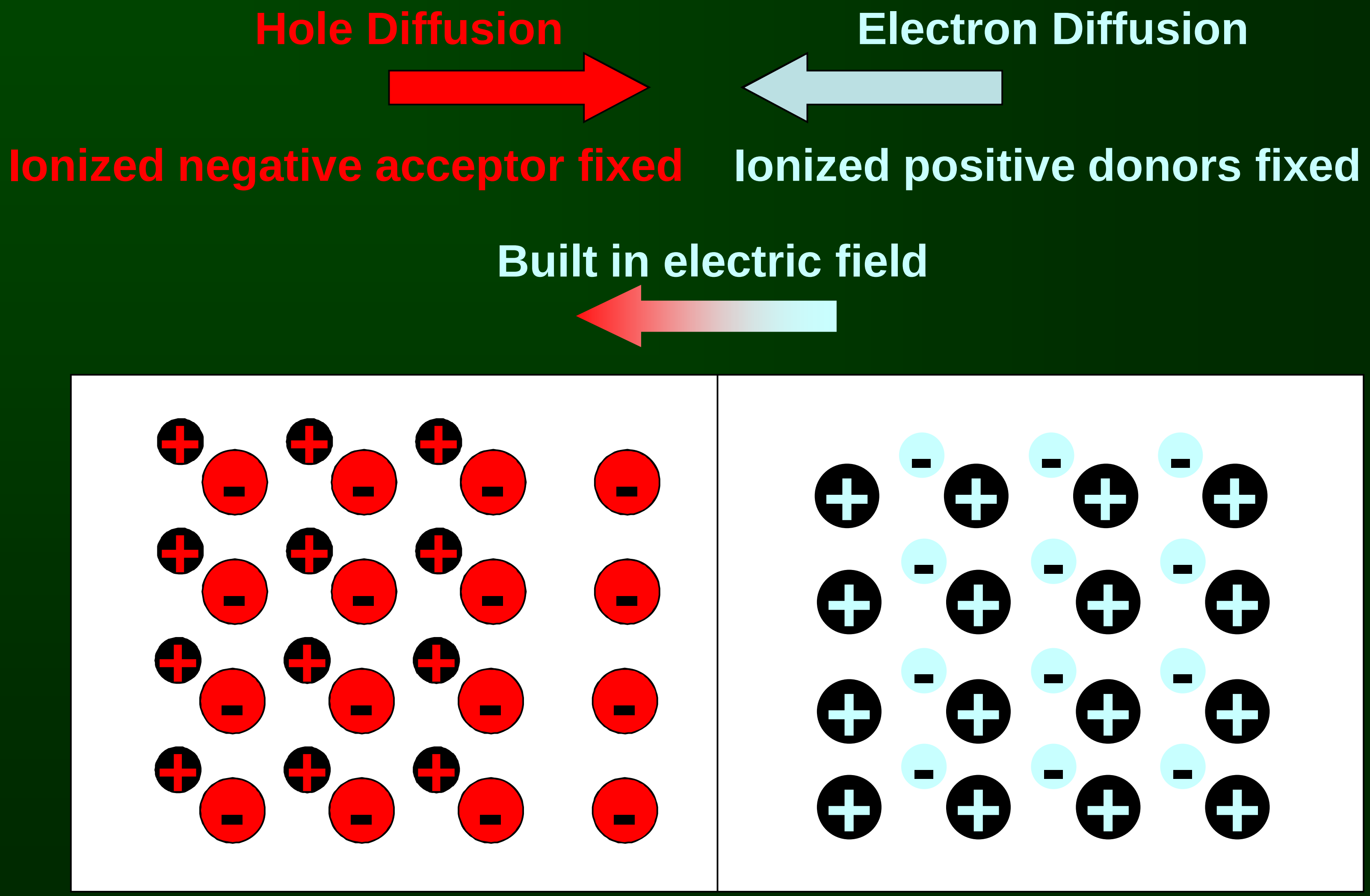
Hole Diffusion → ← **Electron Diffusion**

Ionized negative acceptor fixed **Ionized positive donors fixed**



p-n junction

Applet



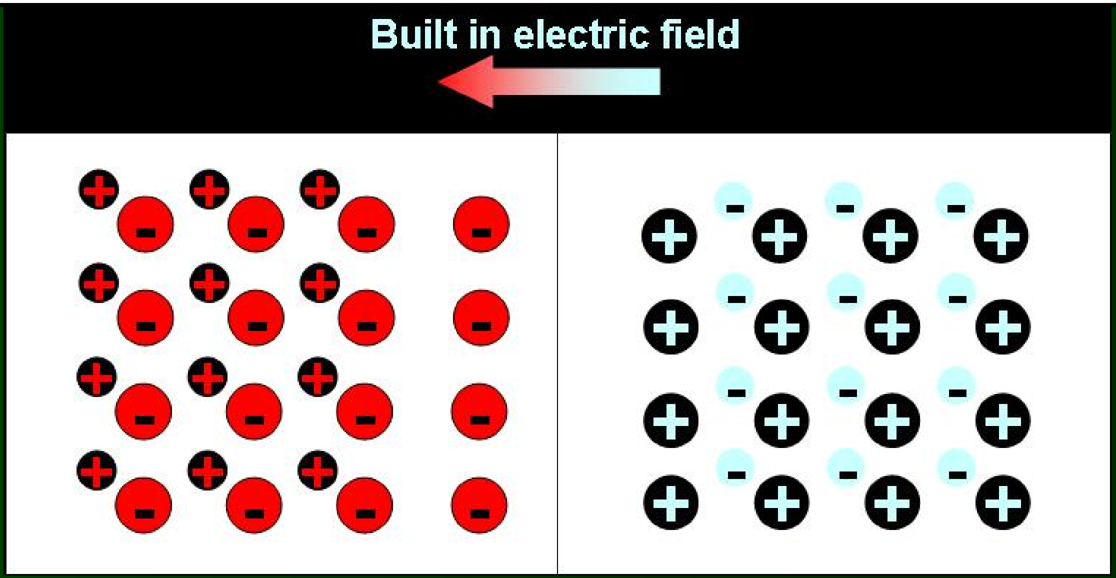
Hole Diffusion

Electron Diffusion

Ionized negative acceptor fixed

Ionized positive donors fixed

Built in electric field



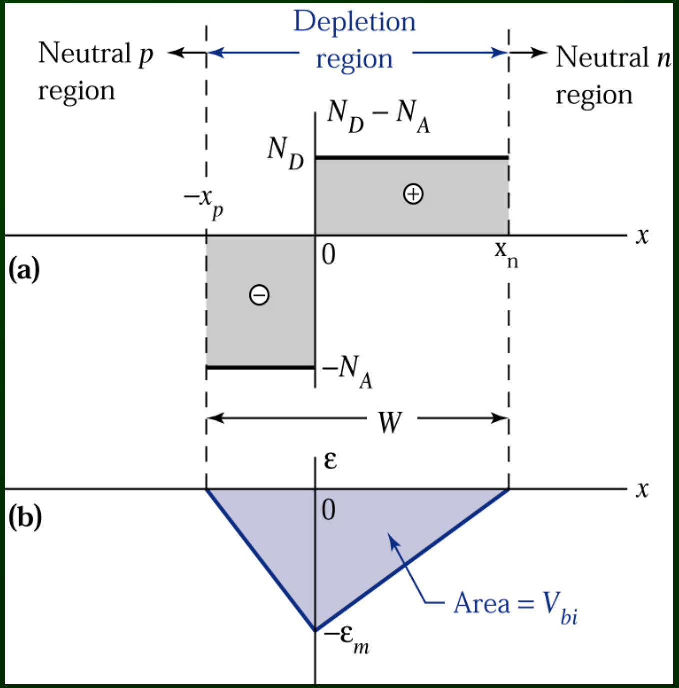
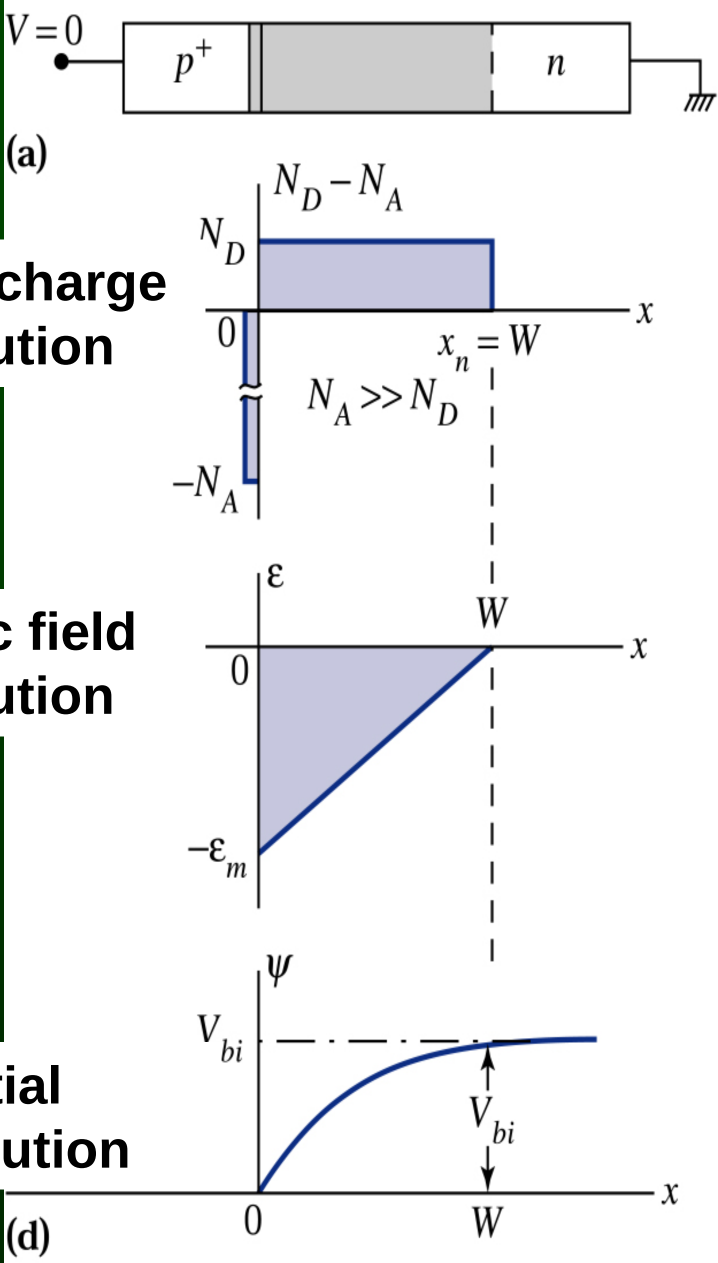


Figure 4.8.
Space charge distribution in the depletion region at thermal equilibrium.

Electric-field distribution.
The shaded area corresponds to the built-in potential.

Figure 4.9. One-sided abrupt junction (with $N_A >> N_D$) in thermal equilibrium.

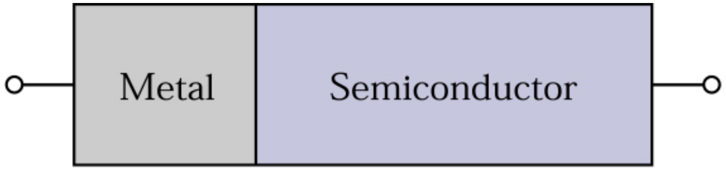


Space charge distribution

Electric field distribution

Potential distribution

Similar behaviour as Metal-semiconductor (Schottky) junction



Metal behaves as p+

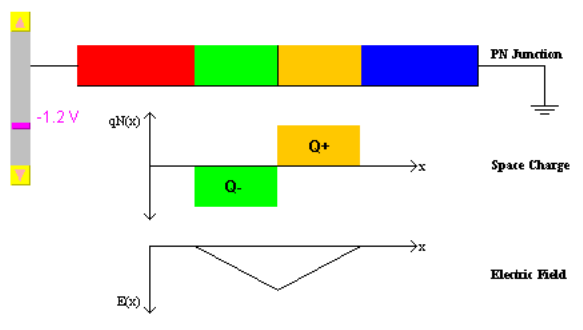
Applet p-i-n diode

Ideal current-voltage characteristics.
p-n junction diode

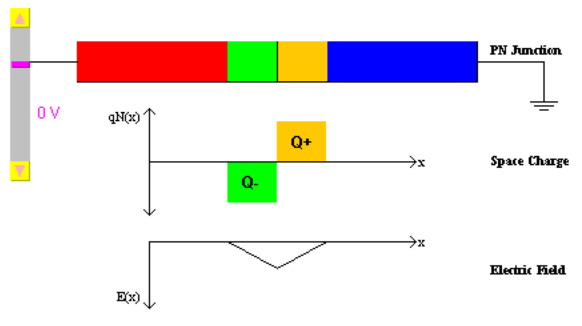
Applet 1

Applet 2

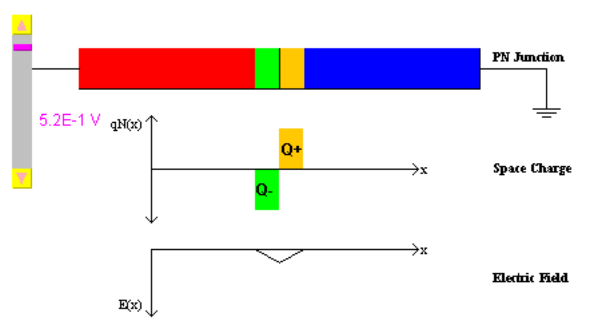
Reverse Bias

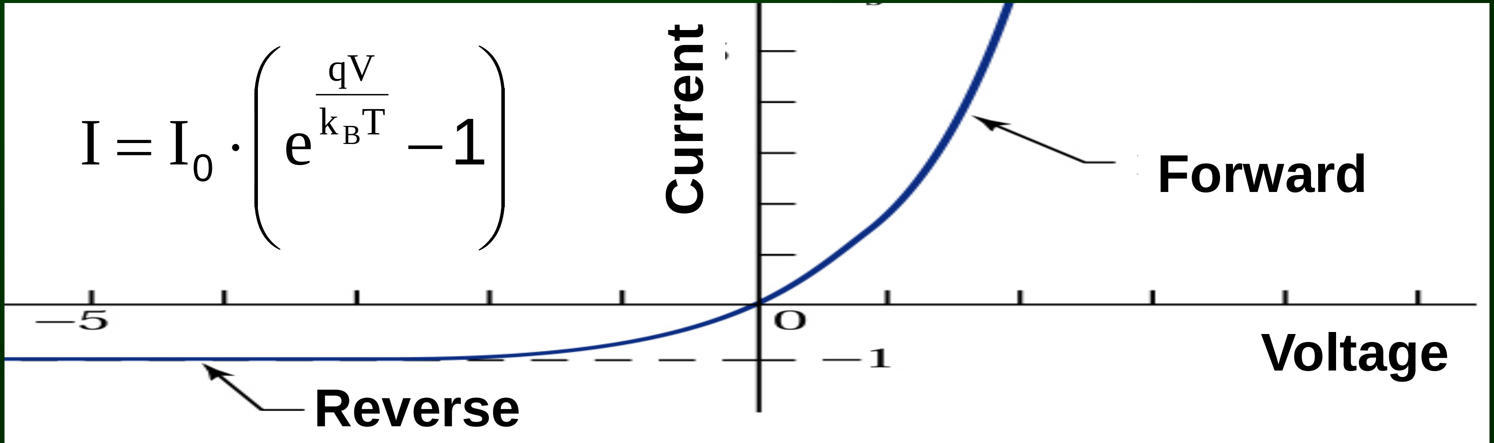


Zero Bias



Forward Bias



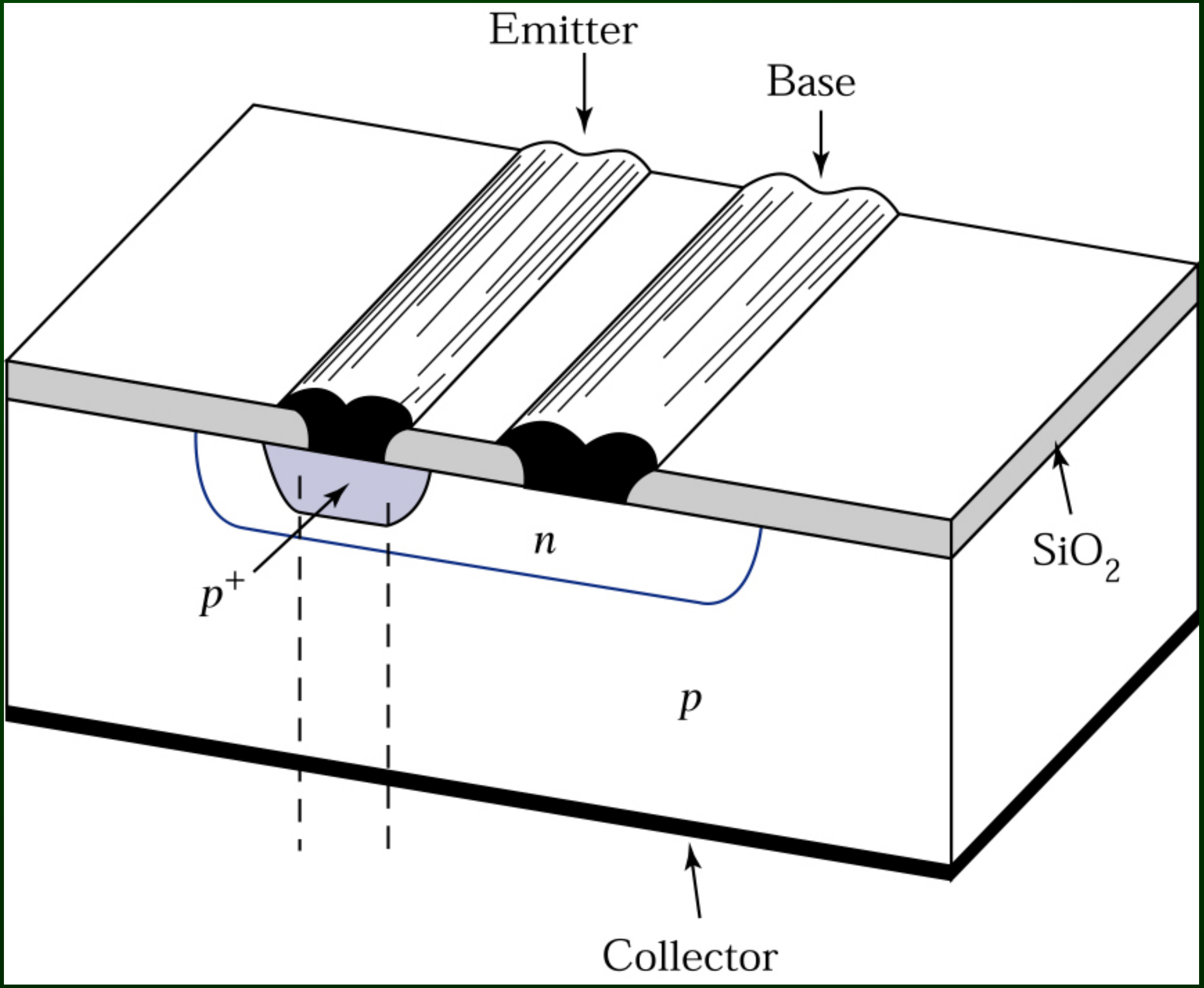


$$I = I_0 \cdot \left(e^{\frac{qV}{k_B T}} - 1 \right)$$

A solid state ionization chamber

BIPOLAR JUNCTION TRANSISTOR (BJT)

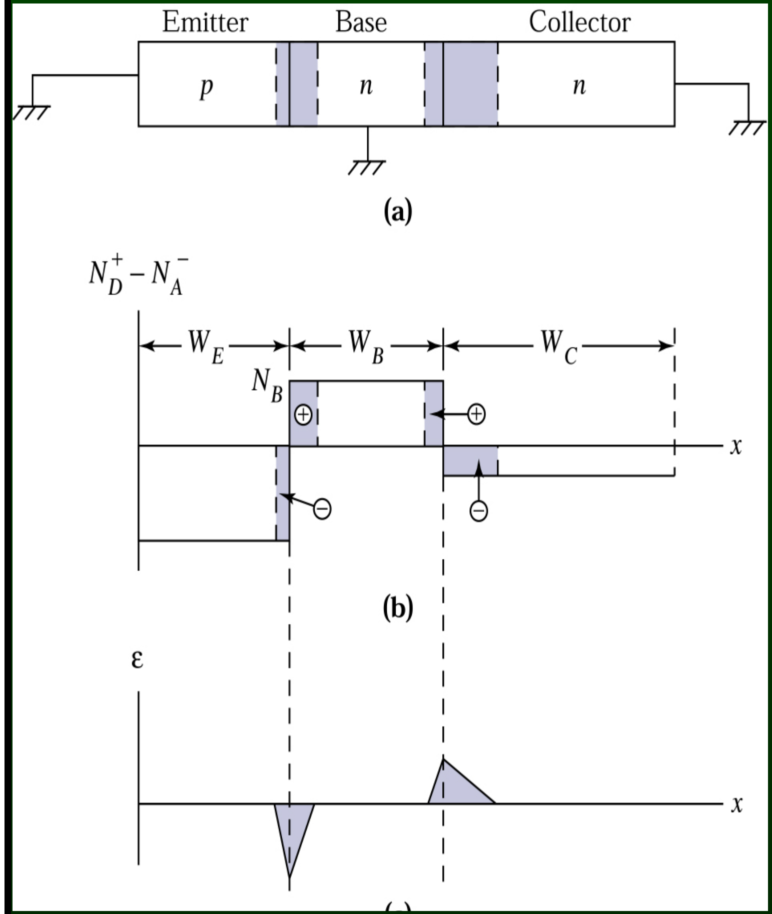
Figure 5-1. Perspective view of a silicon *p-n-p* bipolar transistor.



p-n-p transistor

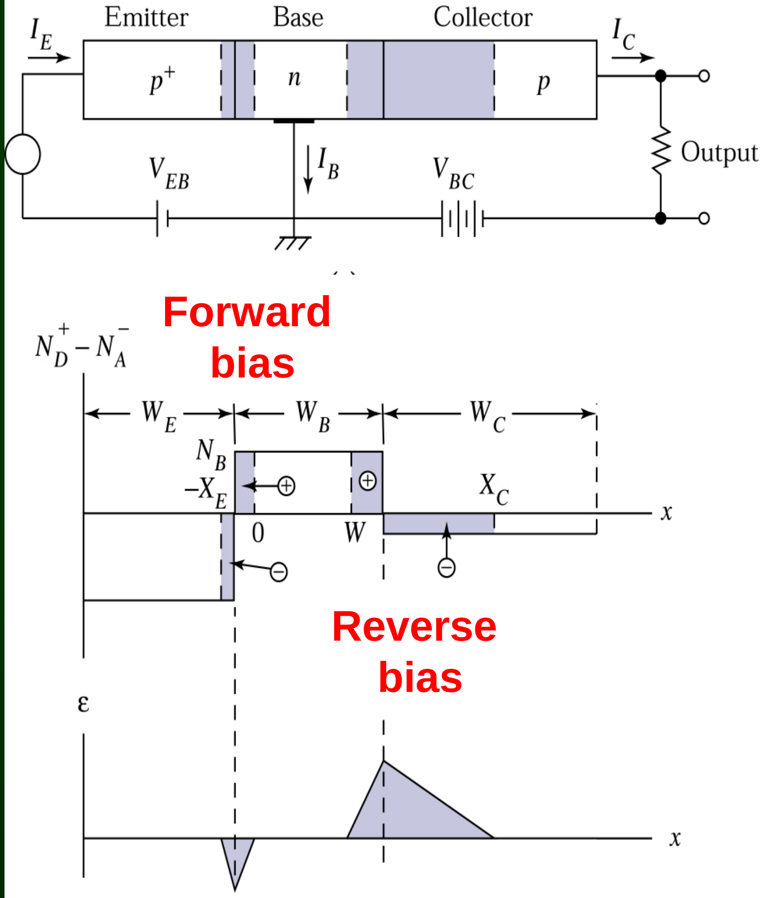
with all leads grounded
(at thermal equilibrium).

under the active mode
of operation



Doping
profile

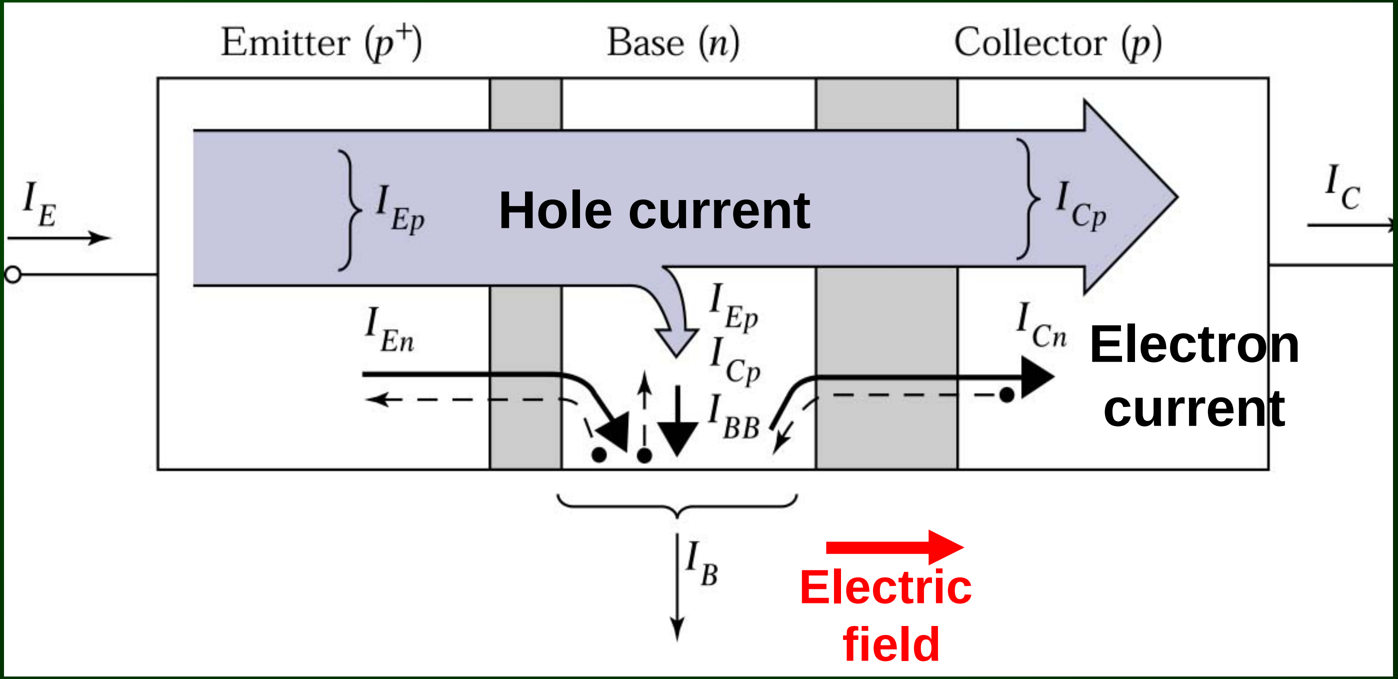
Electric-field
profile.



Forward bias

Reverse bias

Figure 5.5. Various current components in a *p-n-p* transistor under active mode of operation. The electron flow is in the opposite direction to the electron current.

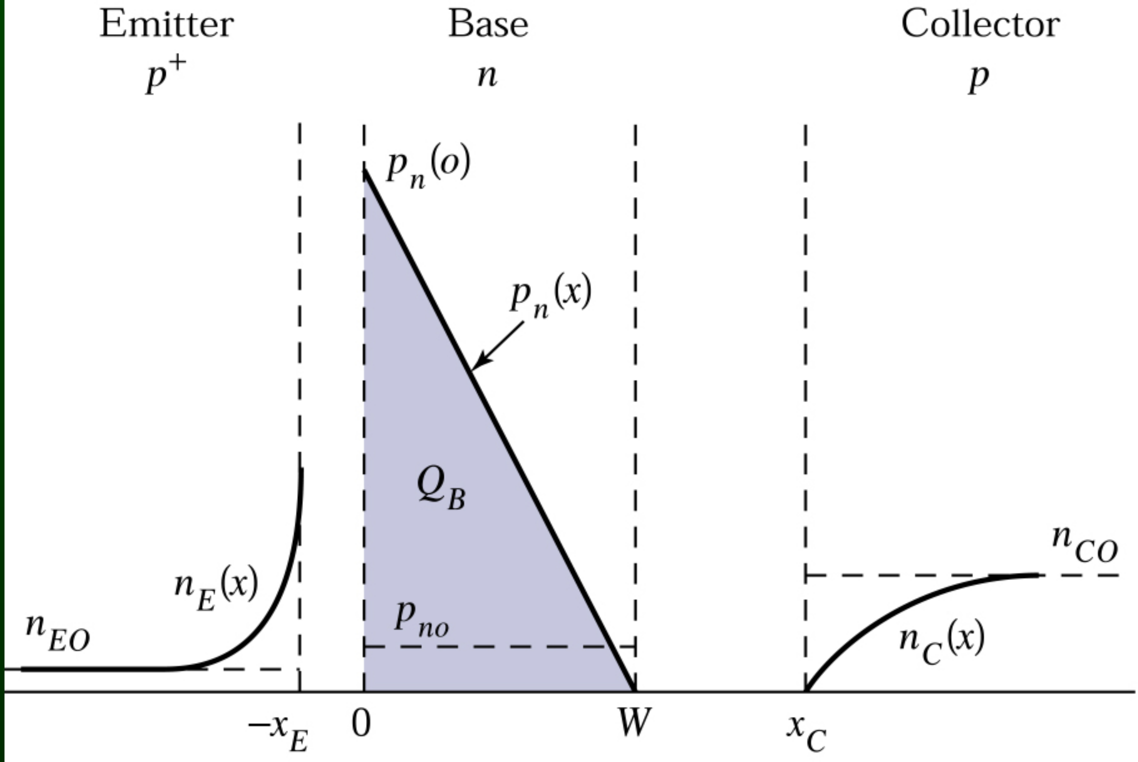


Emitter-base junction: forward bias → **Hole injection from emitter to base**

Hole diffusion in the base from emitter to collector

Base-collector junction: reverse bias → **Hole drift from base to collector**

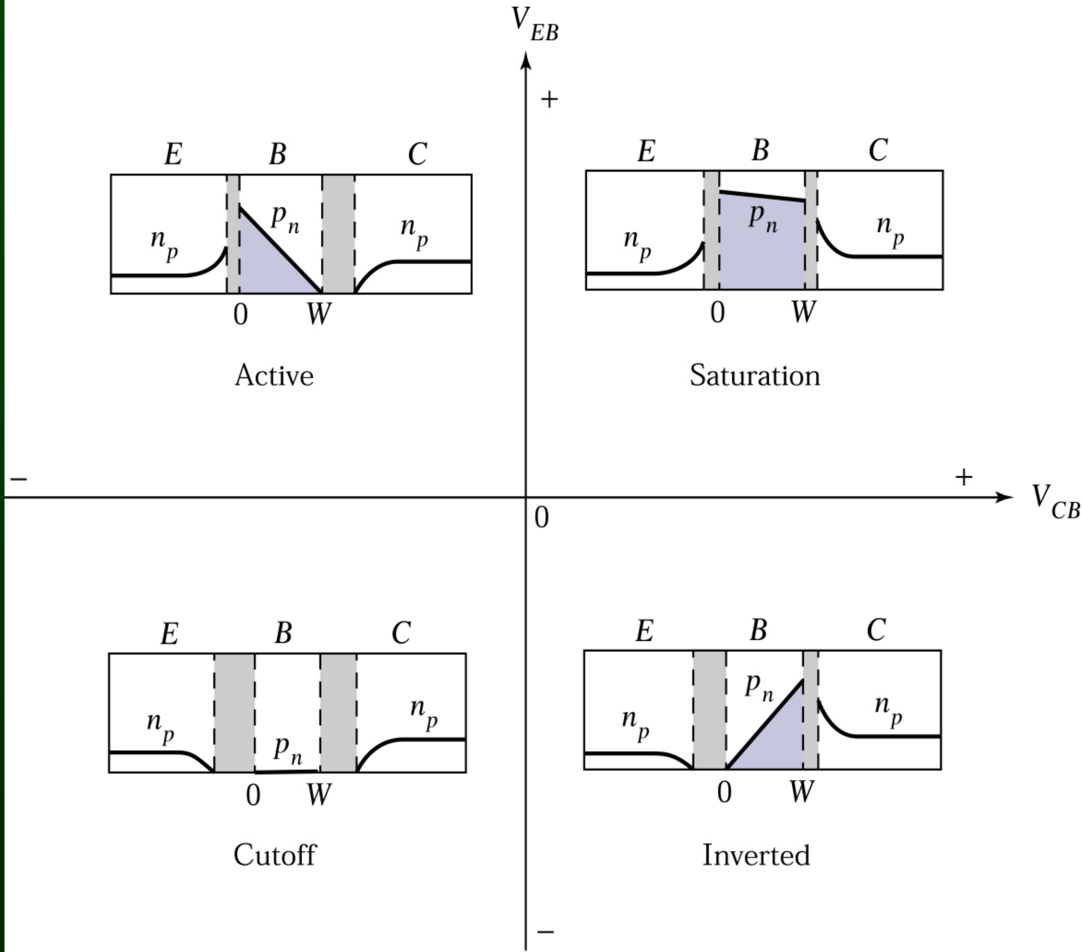
Figure 5.6. Minority carrier distribution in various regions of a *p-n-p* transistor under the active mode of operation.

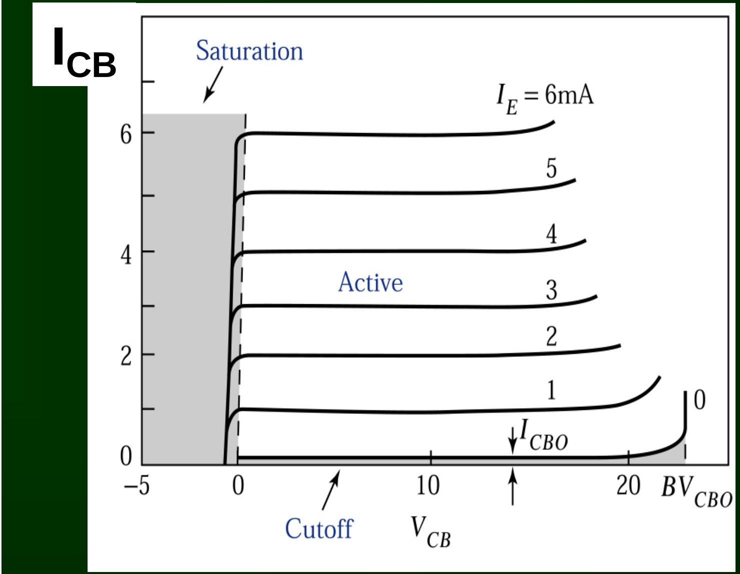


Applet

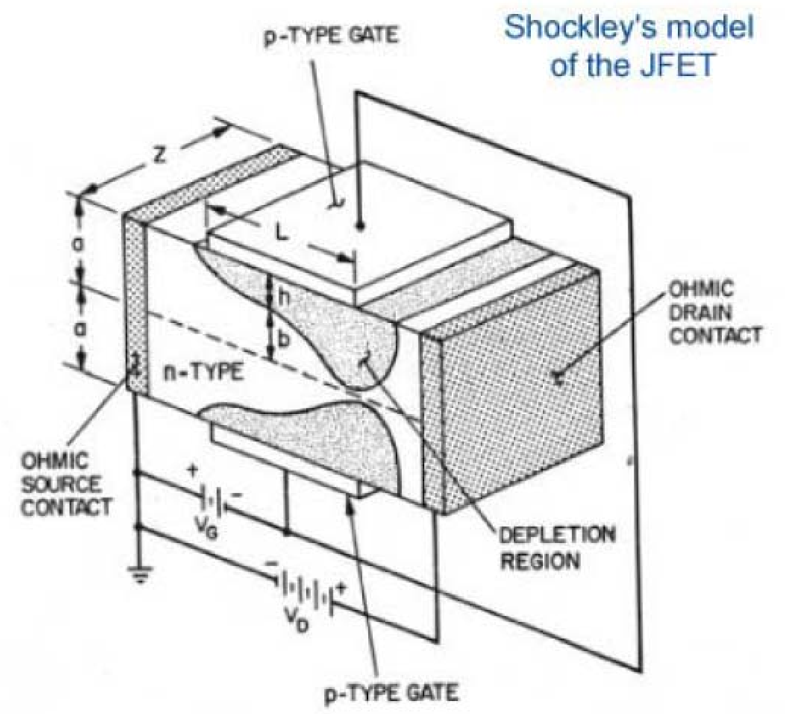
Base width narrower than the diffusion length $W_B < L_p$

Figure 5-7. Junction polarities and minority carrier distributions of a *p-n-p* transistor under four modes of operation.





Junction Field Effect Transistor : JFET

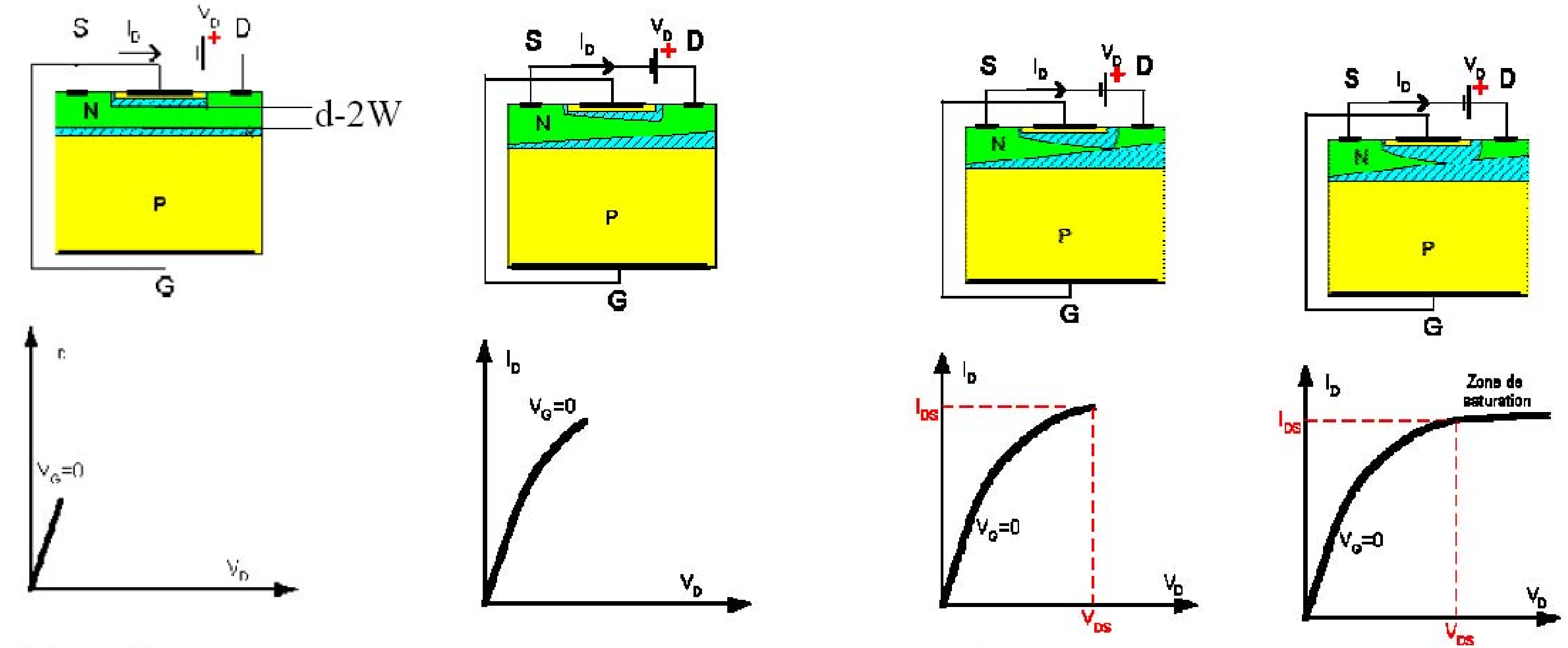


Shockley's model of the JFET

The JFET had been predicted as early as 1925 by Julius Lilienfeld, and the theory of operation of the device was sufficiently well known by the mid 1930's for a patent to be issued for it. However, technology at the time was not sufficiently advanced to produce doped crystals with enough precision for the effect to be seen until many years later. In 1947, researchers John Bardeen, Walter Houser Brattain, and William Shockley were attempting to construct a JFET when they discovered the bipolar junction transistor. The first practical JFETs were thus constructed many years after the first bipolar junction transistors, in spite of having been invented much earlier.

Applet

IV curves



$$V_D << V_{bi}$$

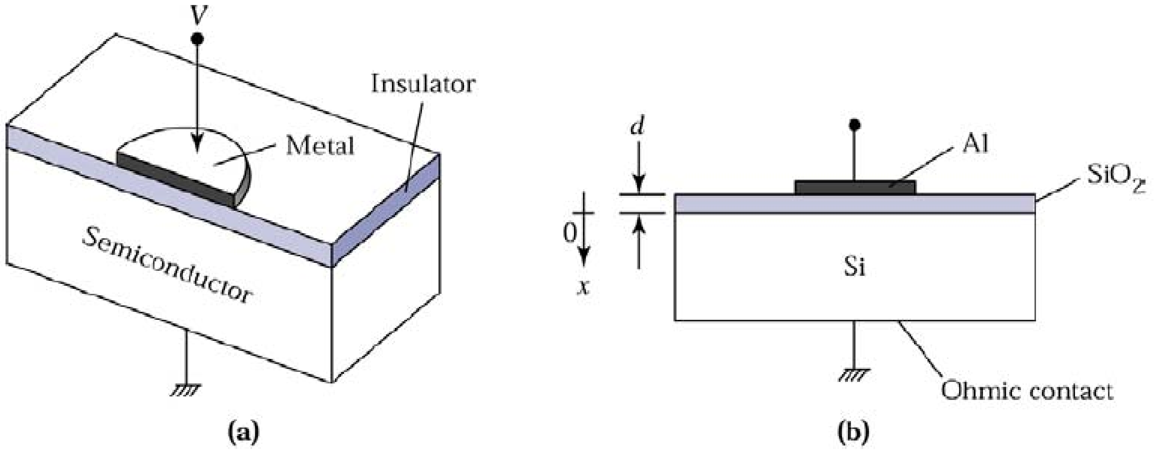
$$R = \frac{L}{q \cdot \mu_n \cdot N_D \cdot Z \cdot (d - 2W)}$$

$$W = \frac{d}{2}$$

$$V_{Dsat} = \frac{q \cdot N_D \cdot d^2}{8 \cdot \varepsilon_S} - V_{bi}$$

Metal-Oxide-Semiconductor (MOS)

Figure 6.1. (a) Perspective view of a metal-oxide-semiconductor (MOS) diode.
(b) Cross-section of an MOS diode.



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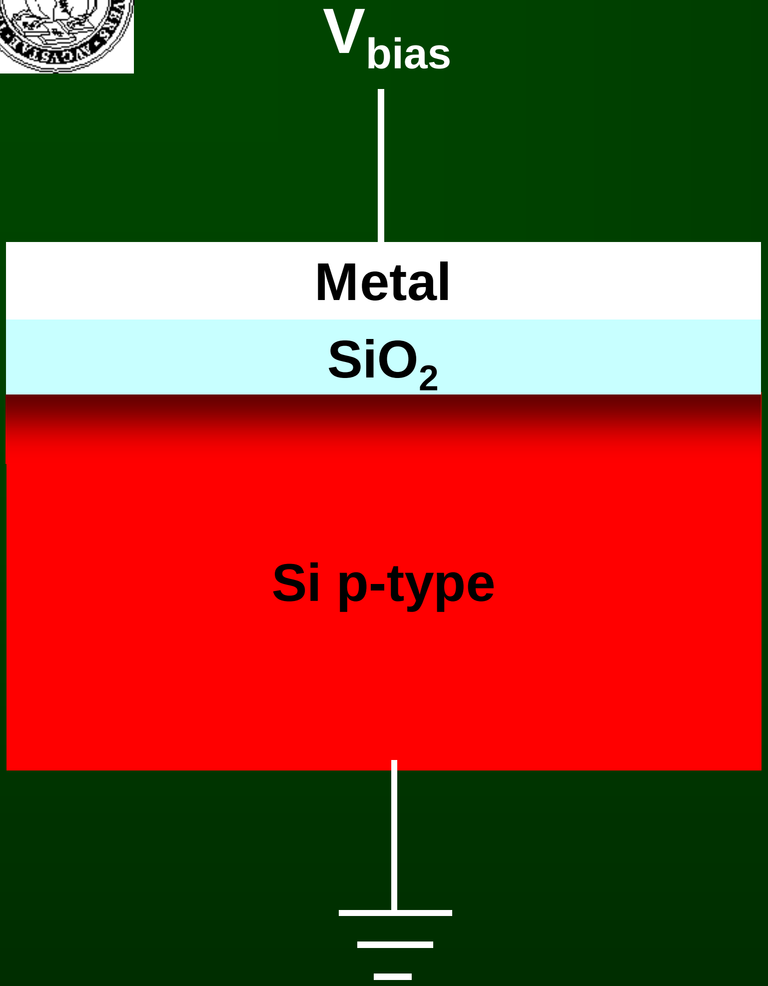
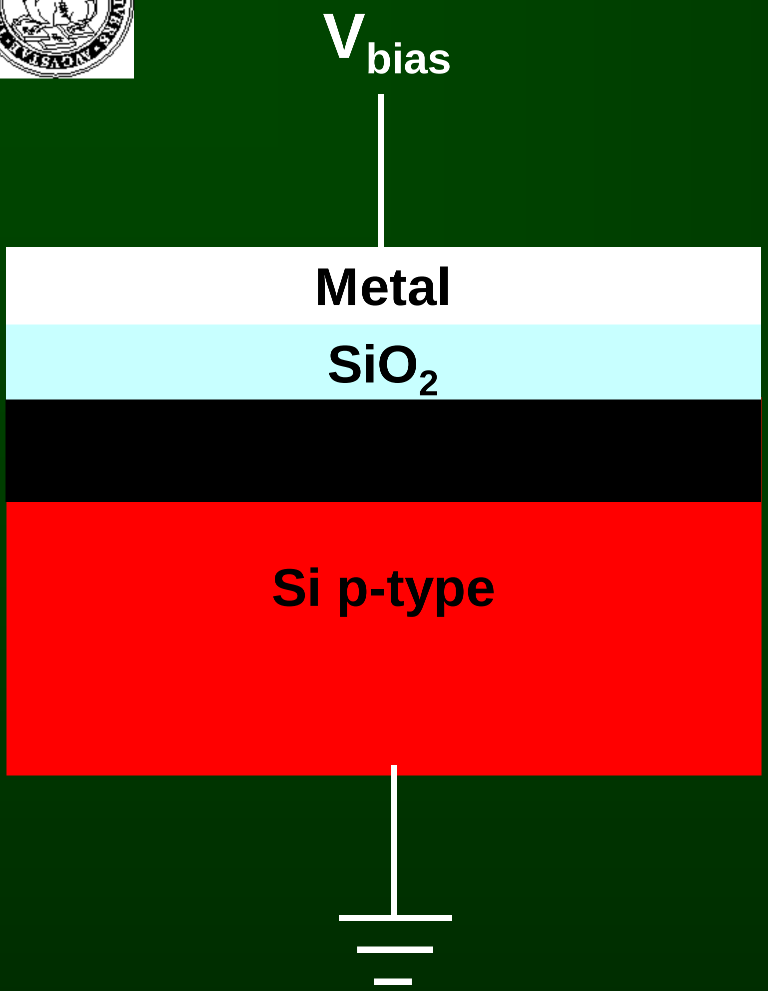


$V_{bias} < 0$

Hole accumulation at the Si/SiO_2 interface

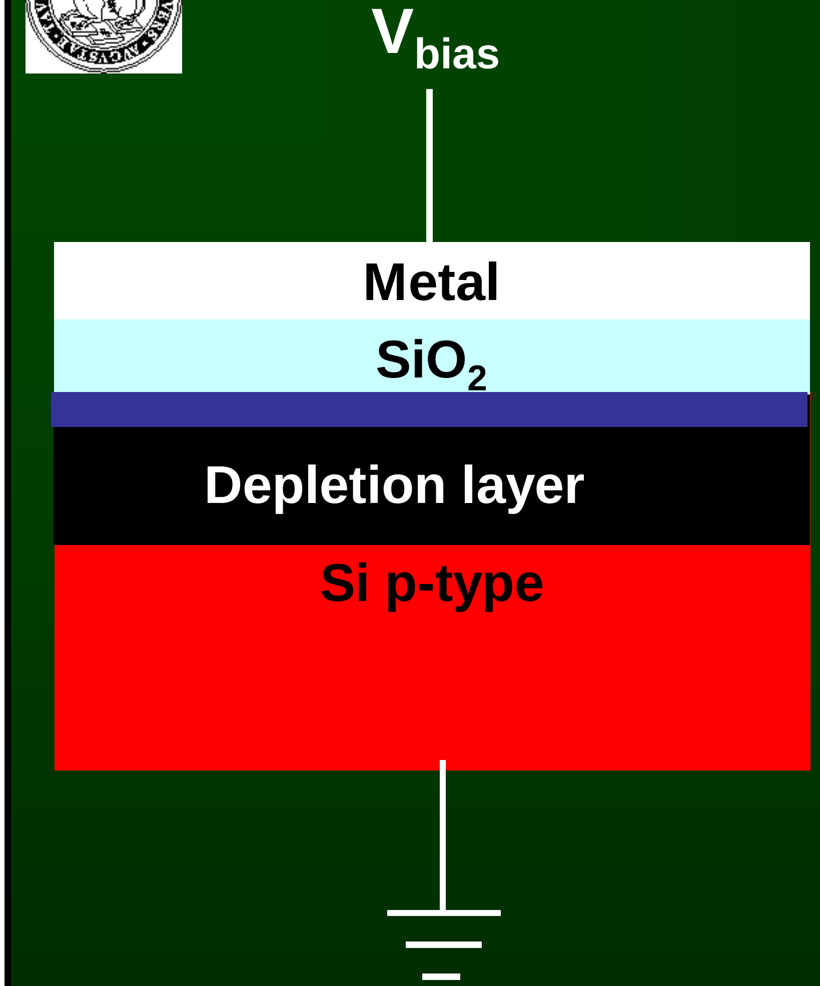
No current across the oxide



$V_{bias}>0$

Depletion under the Si/SiO_2 interface

No current across the oxide



V_{bias}>>0

Depletion
and
induction of electrons
at the Si/SiO2 interface

2D highly conductive inversion layer

Applet

Inversion occurs at the threshold voltage

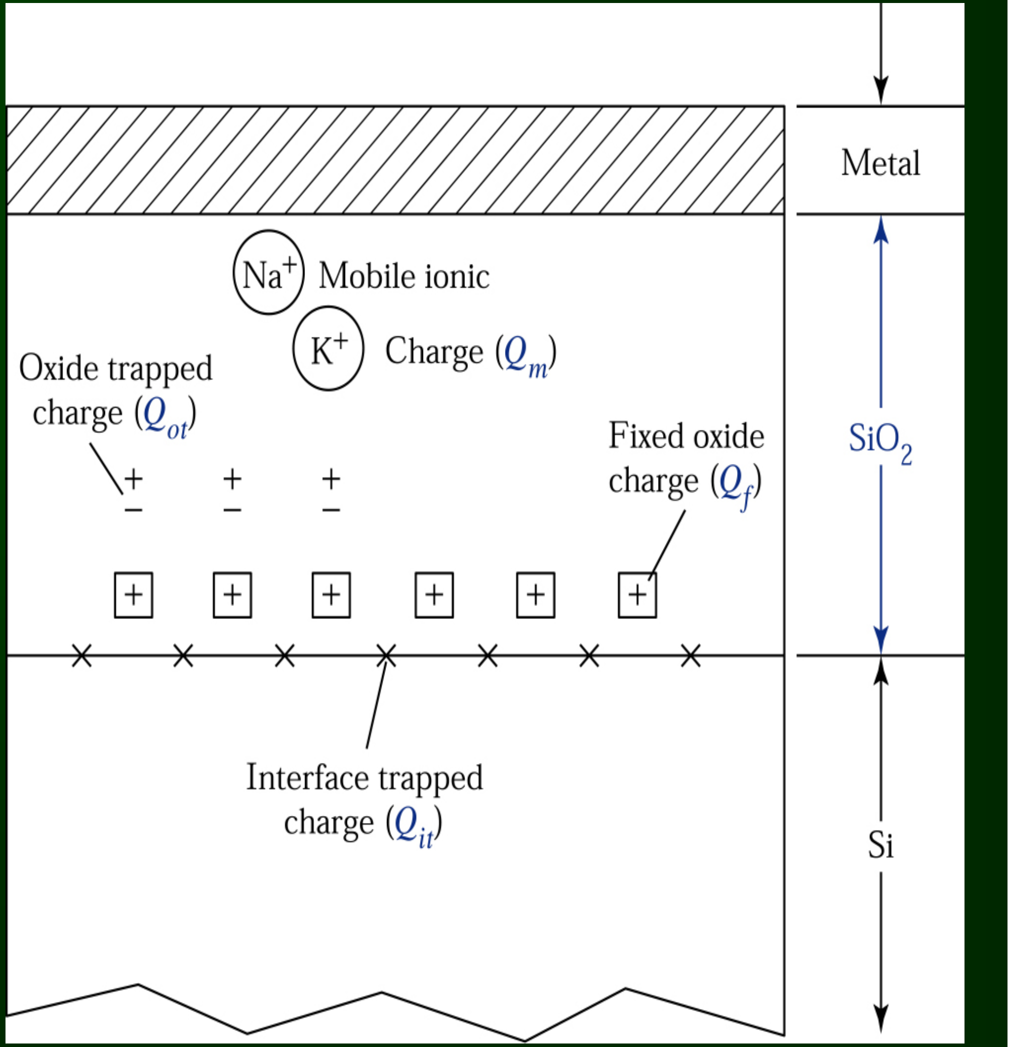
Threshold voltage depends upon

✓Substrate doping

✓Oxide thickness

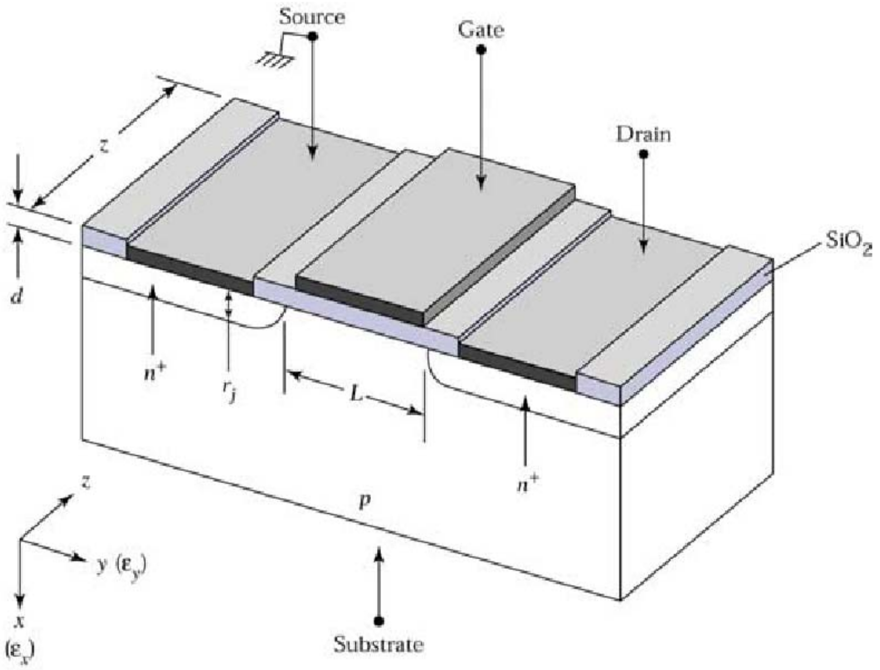
✓Metal work function

✓Charge trapped



Radiation induced effects

Figure 6.14. Perspective view of a metal-oxide-semiconductor field-effect transistor (MOSFET).



Applet

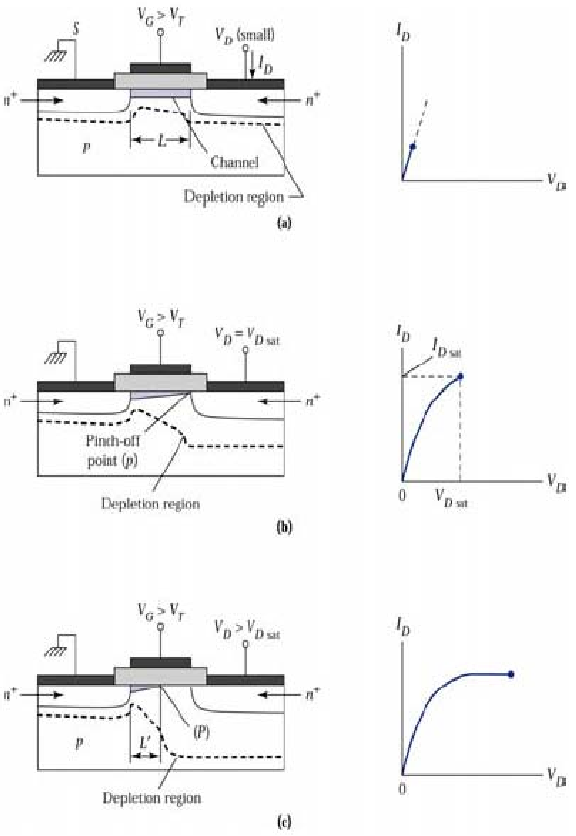
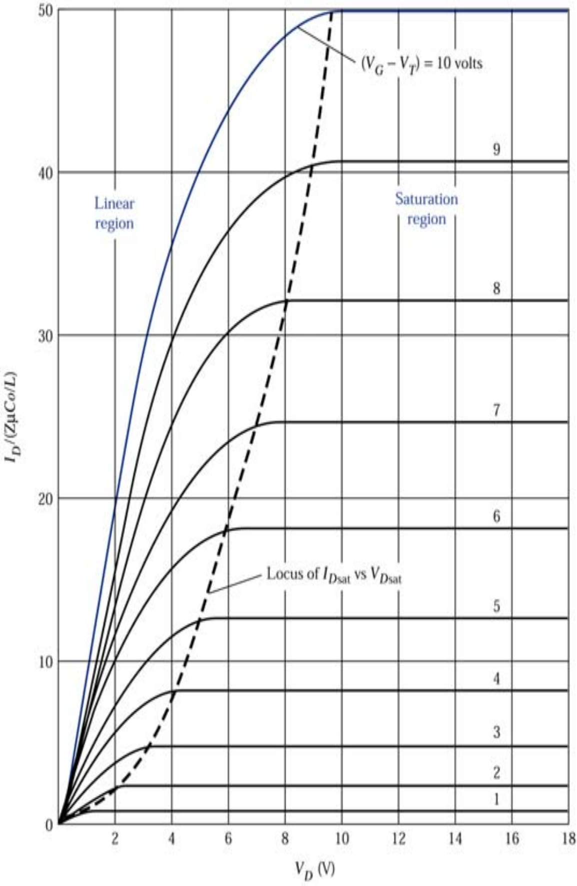
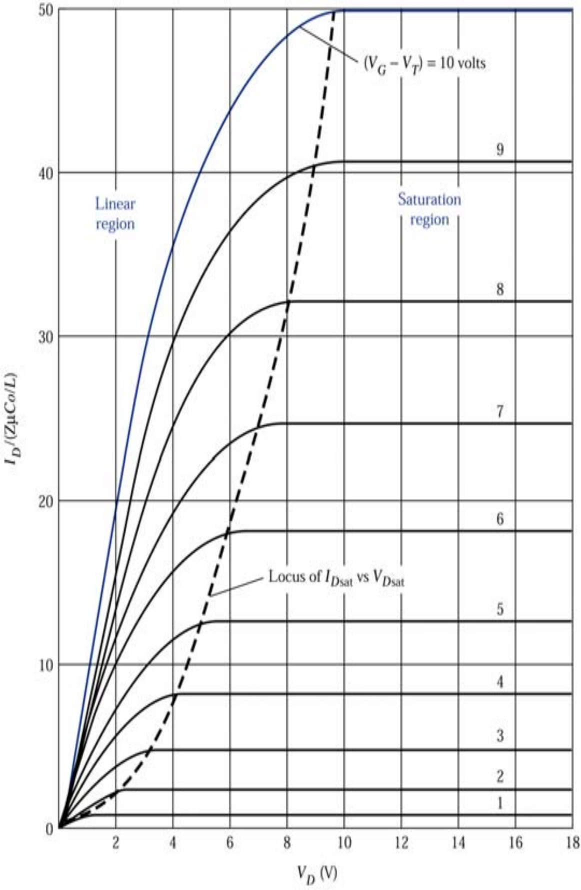
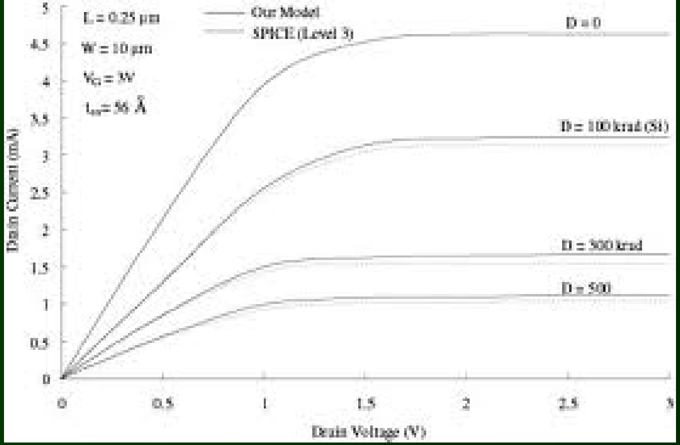


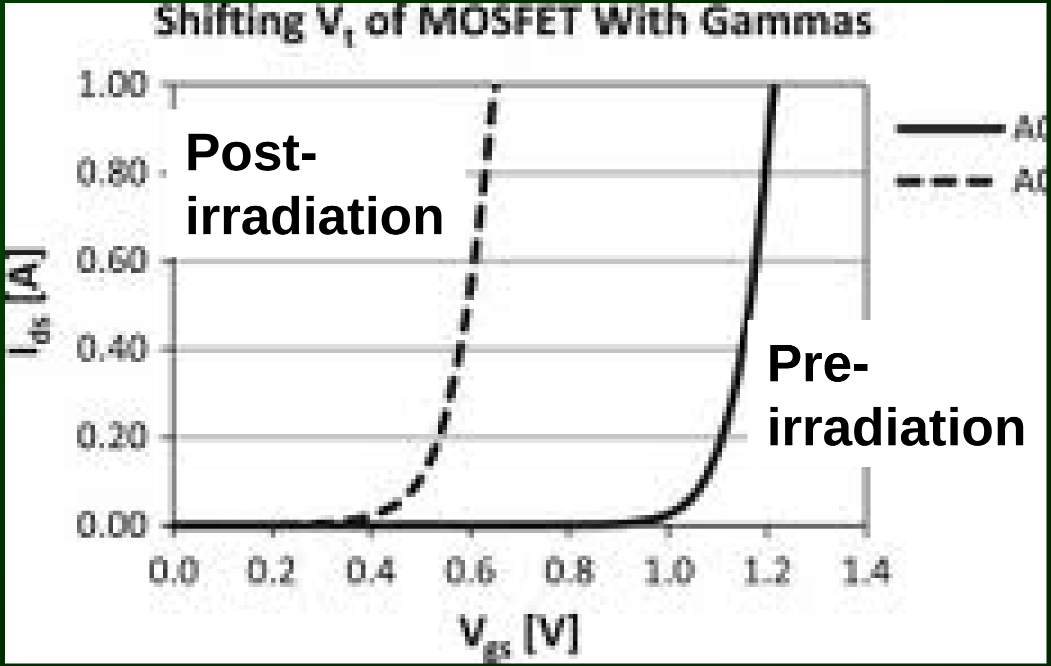
Figure 6.15.
Operations of the MOSFET and output *I-V* characteristics. (*a*) Low drain voltage. (*b*) Onset of saturation. Point *P* indicates the pinch-off point. (*c*) Beyond saturation.



MOS in inversion regime
→
Threshold voltage
→
Radiation sensitive






Shifting V_t of MOSFET With Gammas

MOS in inversion regime → **Threshold voltage** → **Radiation sensitive**

Thanks for your kind attention