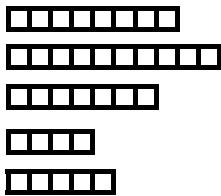


Session 0: Solid State Physics

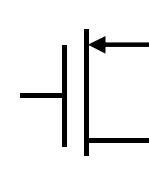
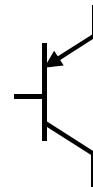
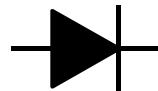
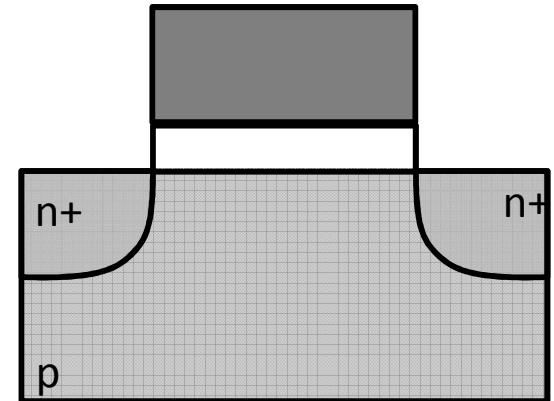
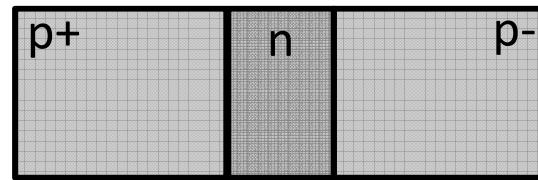
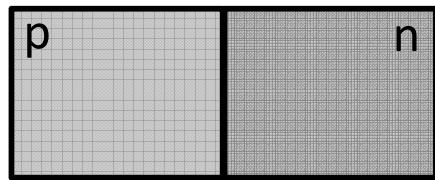
# **From Atom to Transistor**

# Objective

- 1.
- 2.
- 3.
- 4.
- 5.

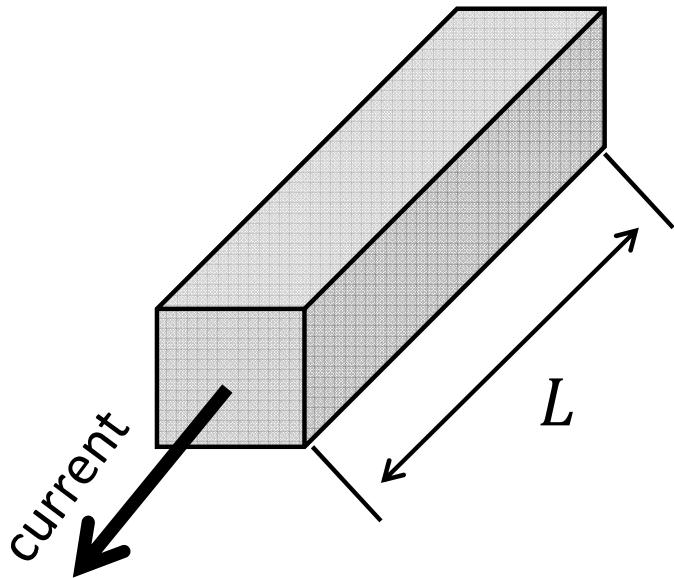
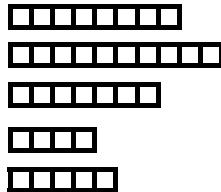


To Understand: how “Diodes,” and “Transistors” operate!



# 21 Century Alchemy!

- 1.
- 2.
- 3.
- 4.
- 5.



Ohm's law

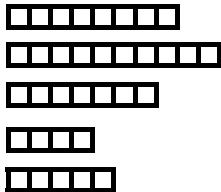
$$R = \frac{V}{I} \rightarrow \rho = R \frac{A}{L} \quad \text{resistivity}$$

Resistivity is characteristic of the material

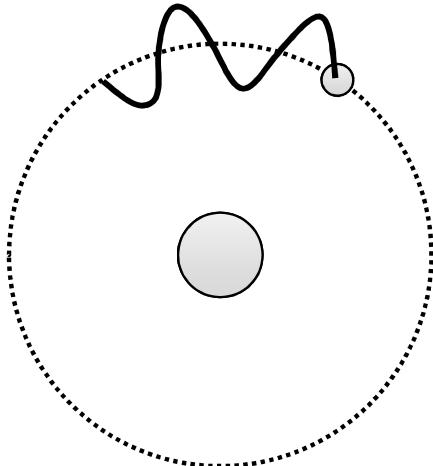
Art of VLSI design is:  
to put together materials with different resistivity's next to each other to perform a certain task.



- 1.
- 2.
- 3.
- 4.
- 5.



# Periodic Table of Elements



Bohr Atomic Model

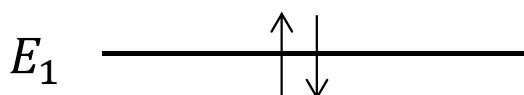
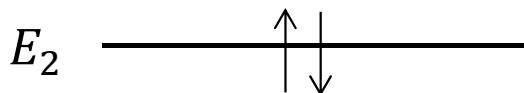
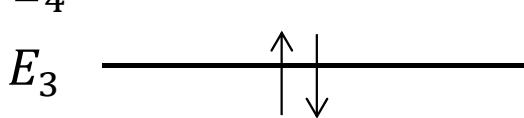
wave-particle duality

$$\lambda = h/p$$

$$mvr = n\hbar$$

de Broglie standing wave

Energy Bands:

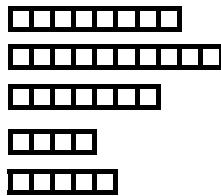


## Abbreviated Periodic Table

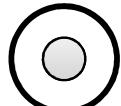
II	III	IV	V	VI
4 Be	5 B	6 C	7 N	8 O
12 Mg	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te
80 Hg	81 Tl	82 Pb	83 Bi	84 Po

# Bohr Atomic Model

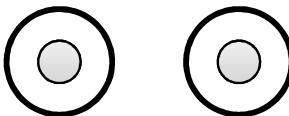
- 1.
- 2.
- 3.
- 4.
- 5.



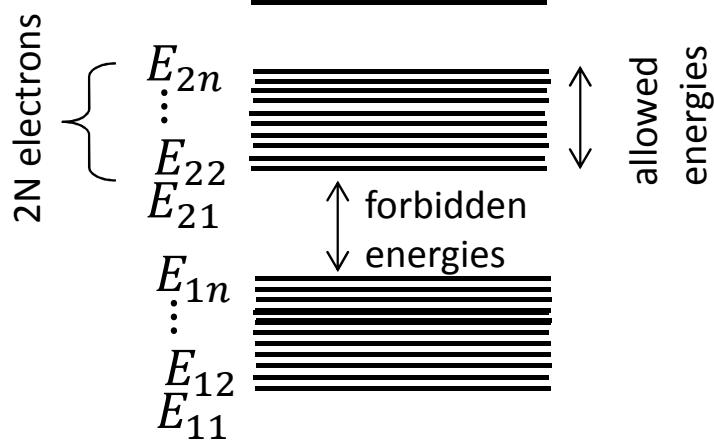
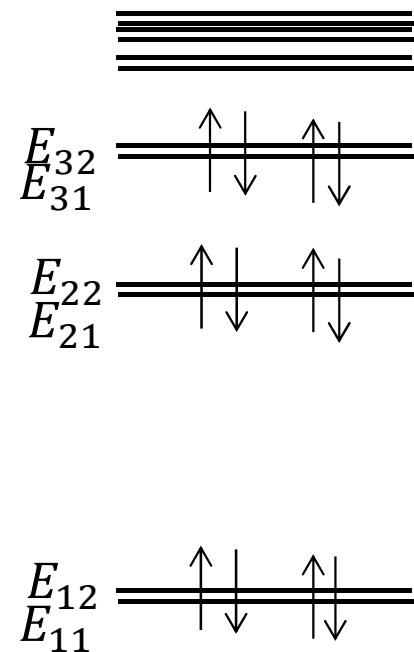
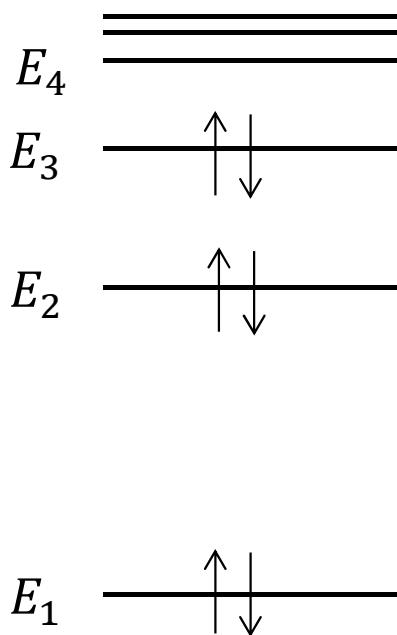
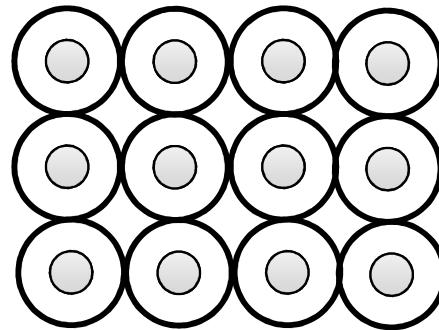
Single atom:



2 atoms:



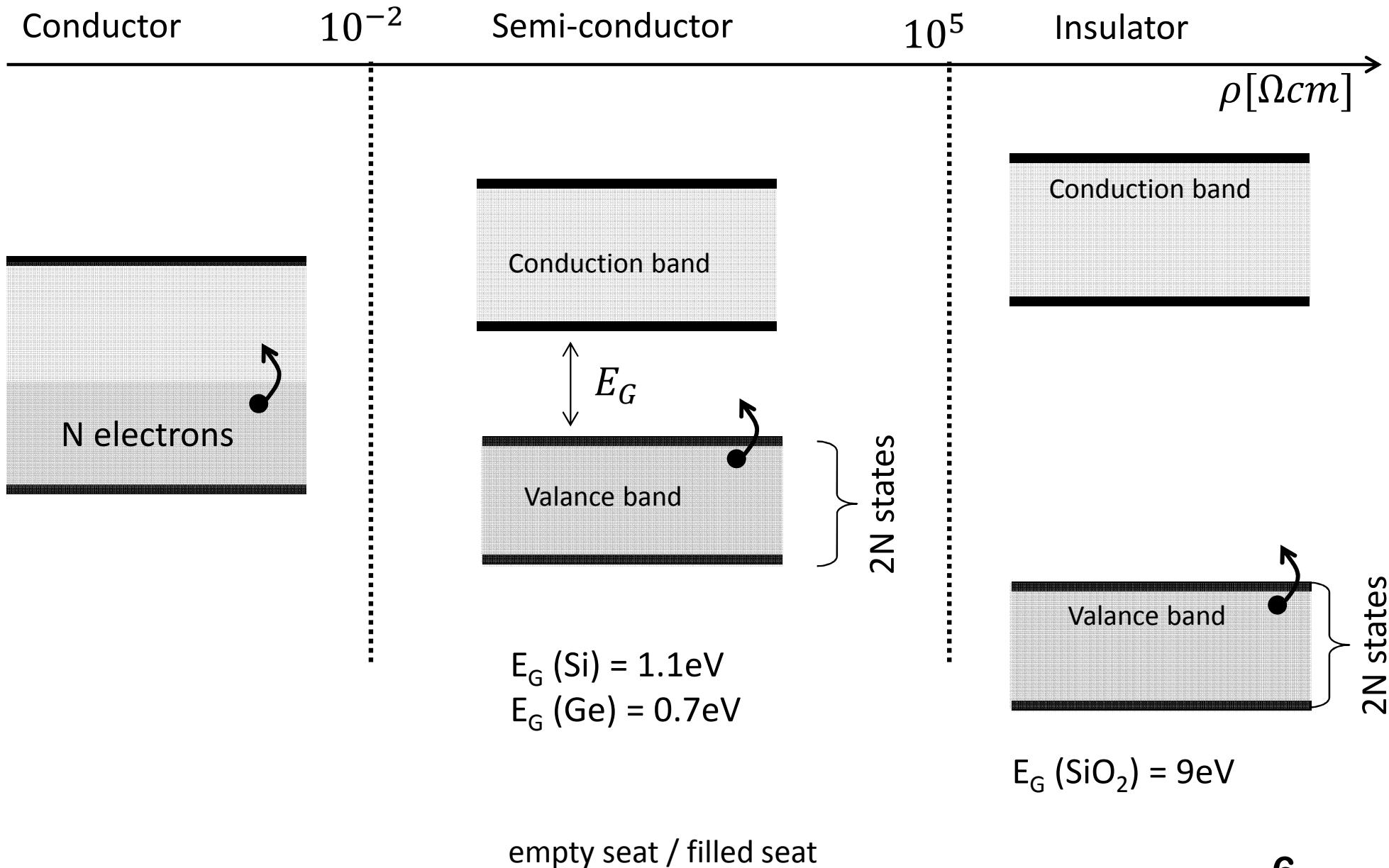
N atoms:



Pauli exclusion principle

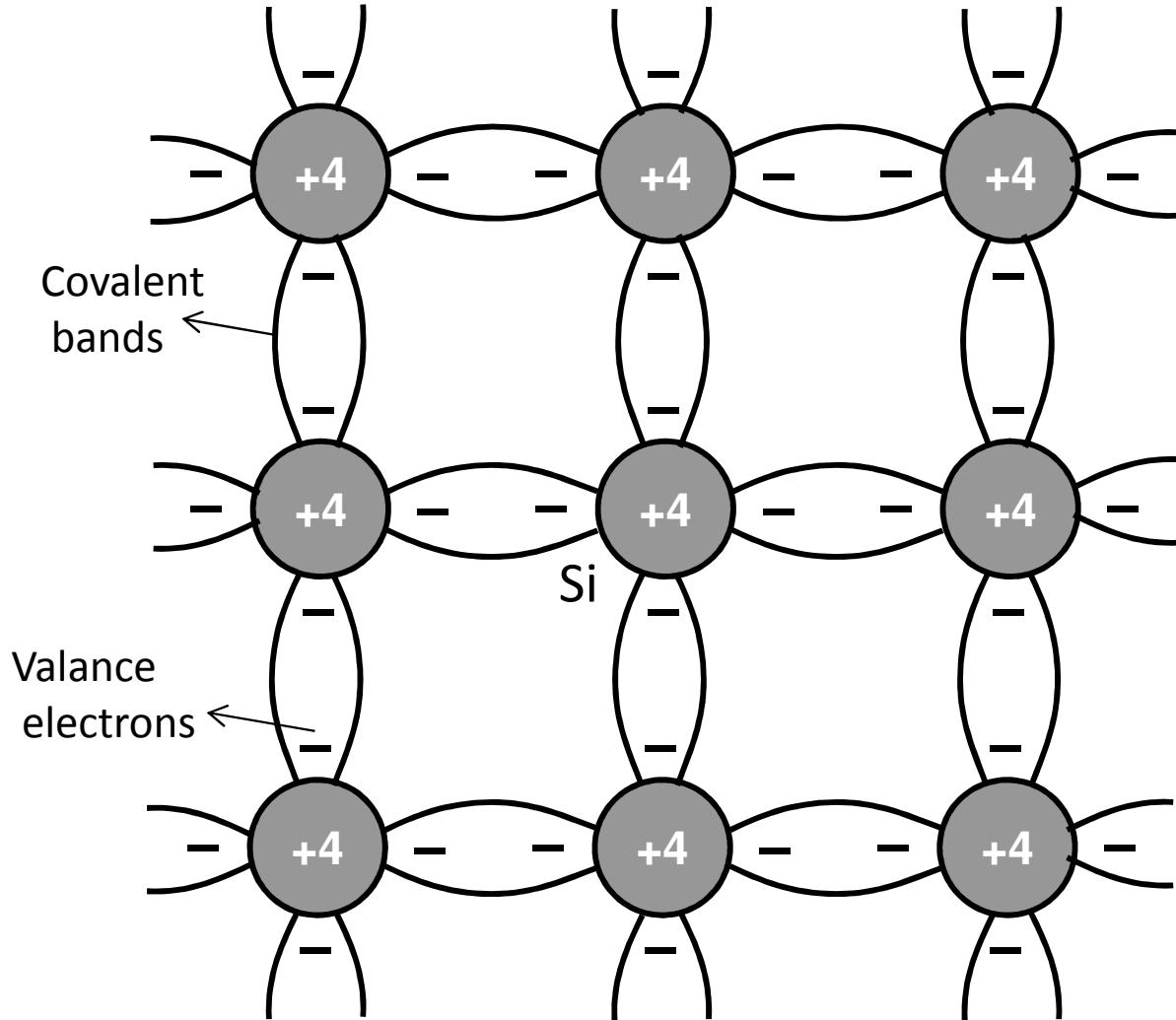
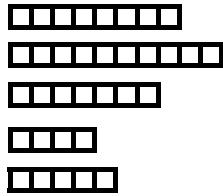
# Materials

- 1.
  - 2.
  - 3.
  - 4.
  - 5.
- 
- The diagram illustrates the relationship between material type and carrier density. It shows five categories: 1. Conductor, 2. Semi-conductor, 3. Insulator, 4. Semimetal, and 5. Superconductor. Category 1 has the highest carrier density, followed by category 2, then category 5, then category 4, and finally category 3 with the lowest carrier density. Each category is represented by a grid of squares where each square represents one carrier.



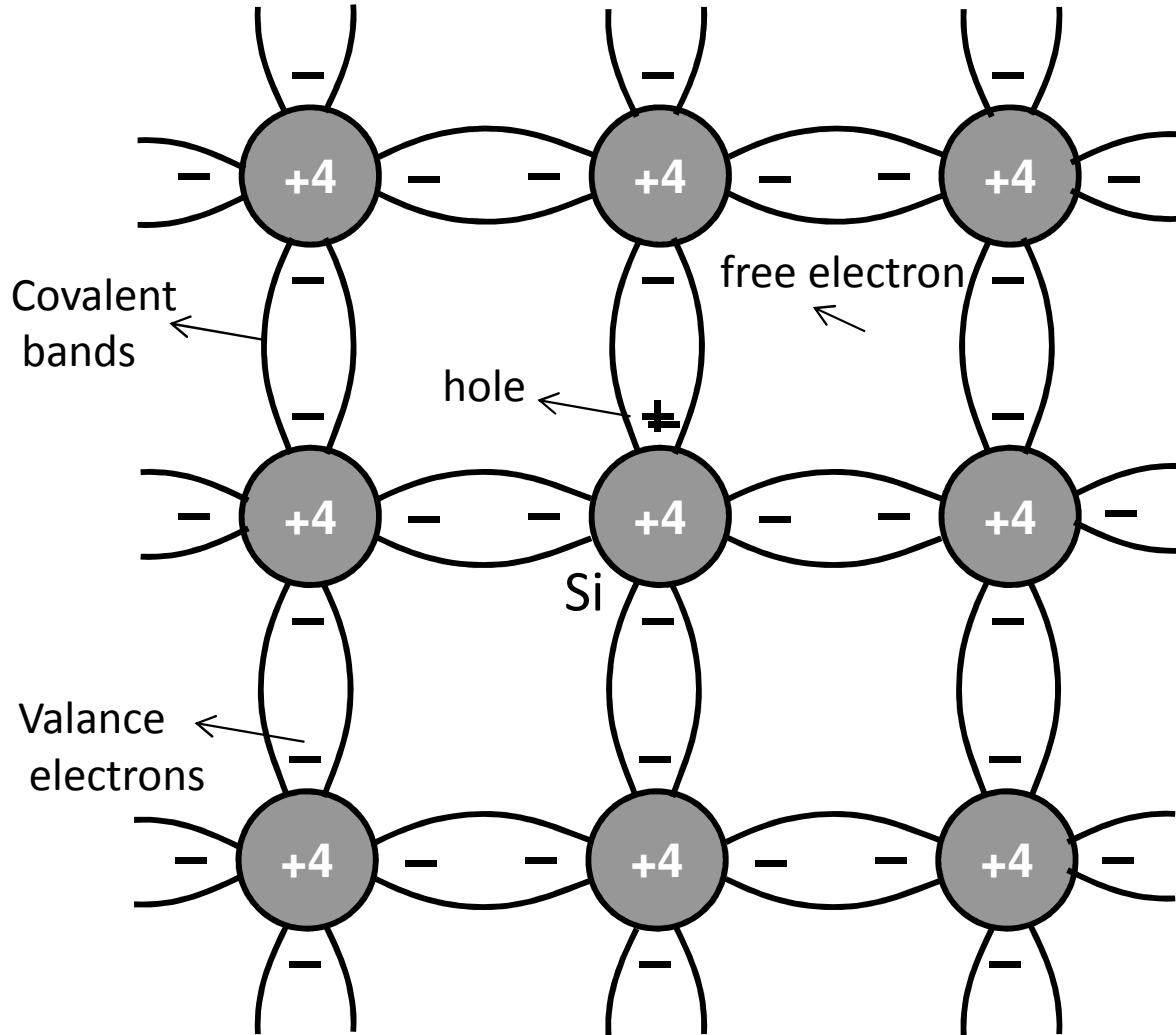
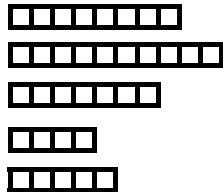
# Intrinsic Semiconductor

- 1.
- 2.
- 3.
- 4.
- 5.



# Intrinsic Semiconductor

- 1.
- 2.
- 3.
- 4.
- 5.



$n_0$  electron density

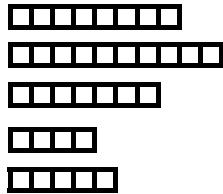
$p_0$  hole density

$$n_0 = p_0 = n_i$$

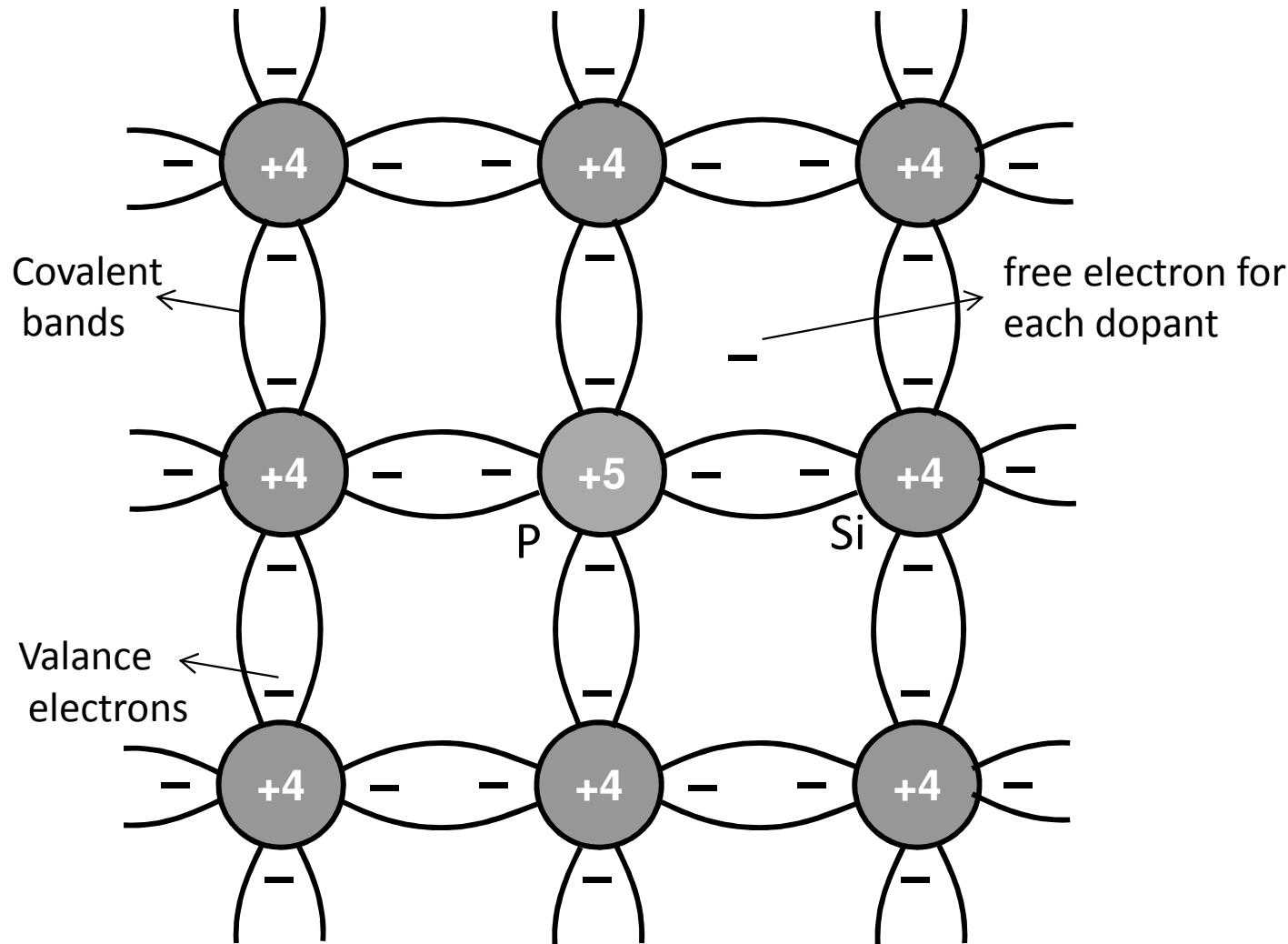
:( useless!!

$$n_i \Big|_{T=300K} = 10^{10} \text{ cm}^{-3} \ll n(\text{Si}) = 2 \times 10^{23} \text{ cm}^{-3}$$

- 1.
- 2.
- 3.
- 4.
- 5.



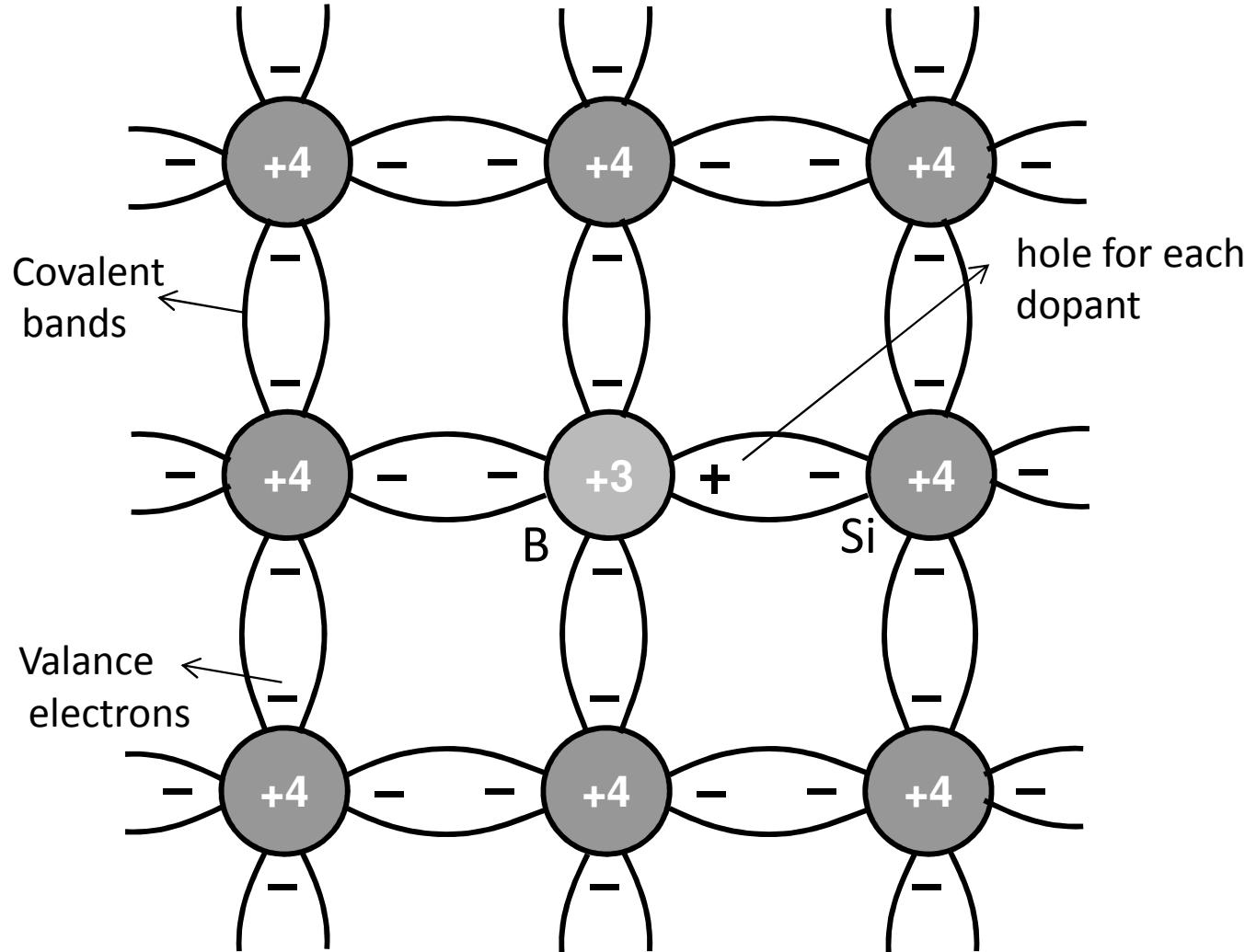
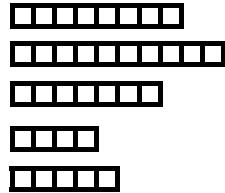
# n-type Semiconductor



☺  $n(\text{Si}) = 2 \times 10^{23} \text{ cm}^{-3}$

# p-type Semiconductor

- 1.
- 2.
- 3.
- 4.
- 5.



$N_A$  up to  $10^{19} \text{ cm}^{-3}$

☺  $n(\text{Si}) = 2 \times 10^{23} \text{ cm}^{-3}$

Acceptor: B , Ga , In

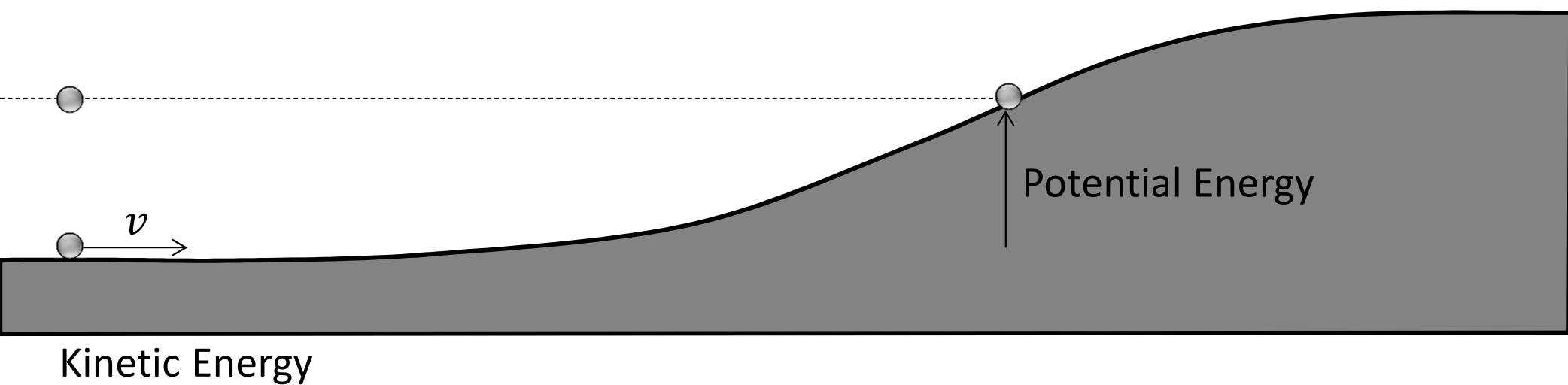
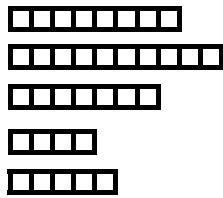
$$n_0 \text{ electron density}$$
$$p_0 \text{ hole density}$$

$$n_0 = N_A$$

$$n_0 p_0 = n_i^2$$

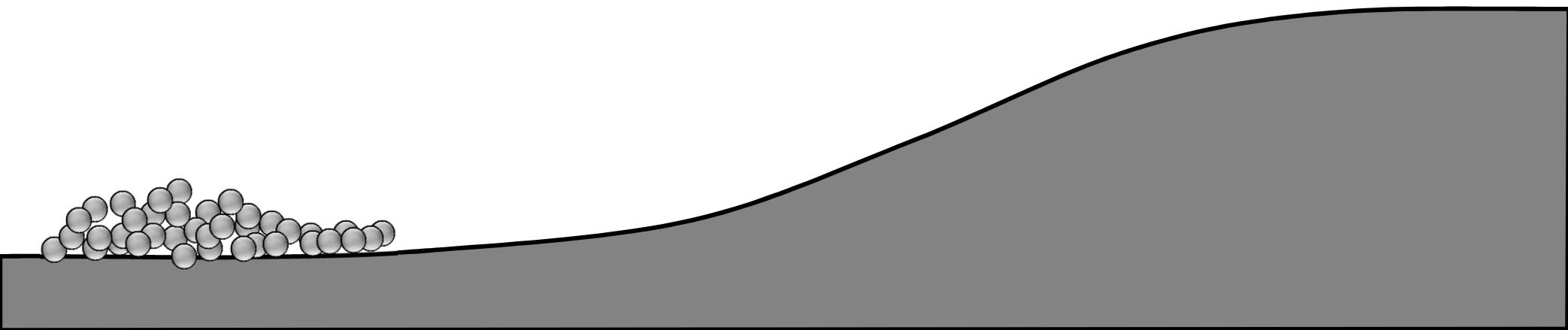
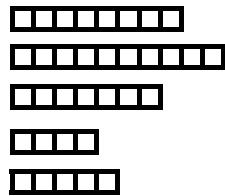
# Energy Diagrams

- 1.
- 2.
- 3.
- 4.
- 5.



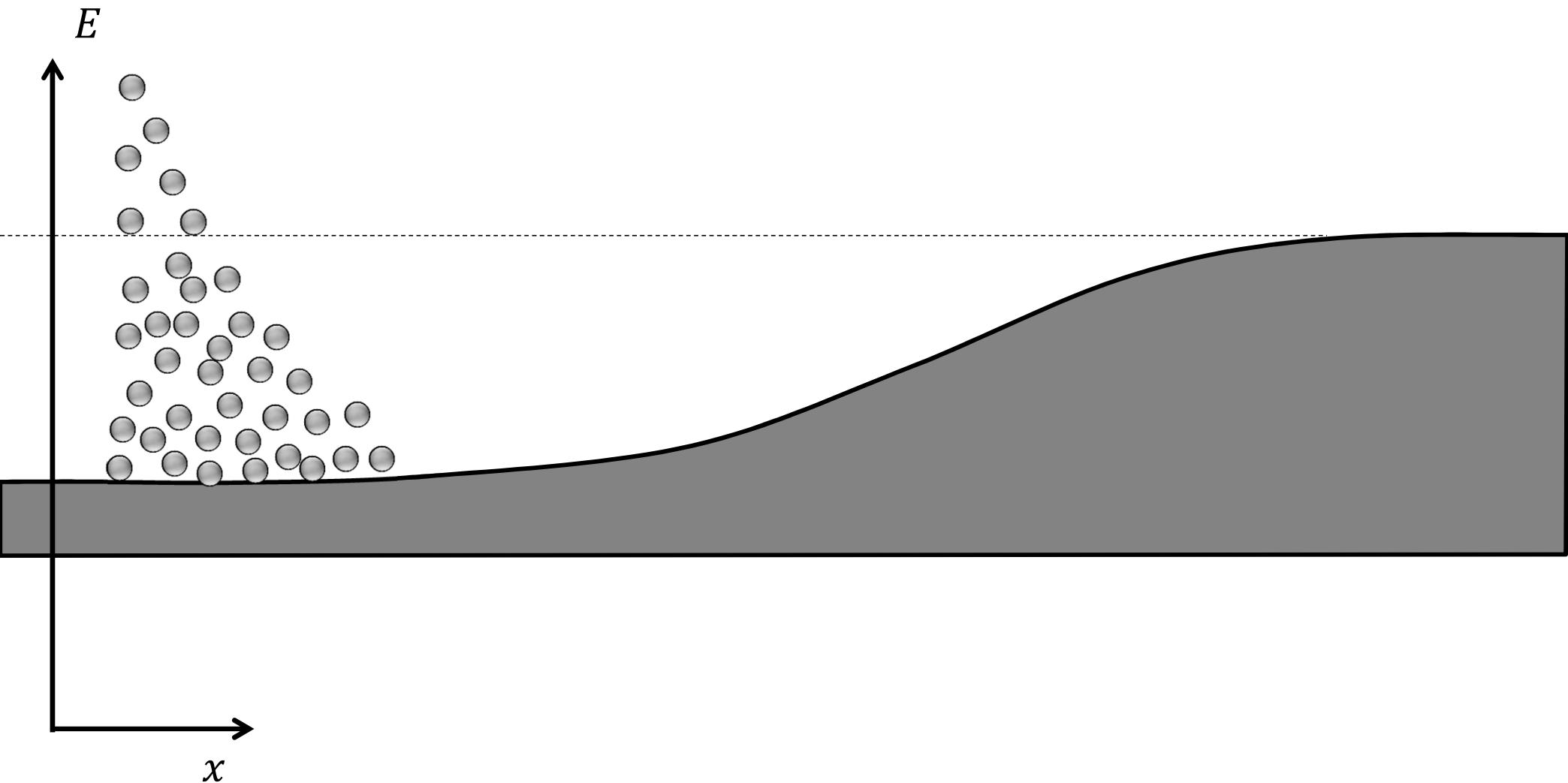
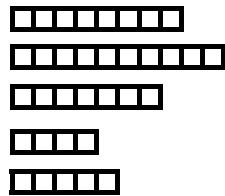
# Energy Diagrams

- 1.
- 2.
- 3.
- 4.
- 5.

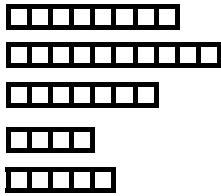


# Energy Diagrams

- 1.
- 2.
- 3.
- 4.
- 5.



- 1.
- 2.
- 3.
- 4.
- 5.

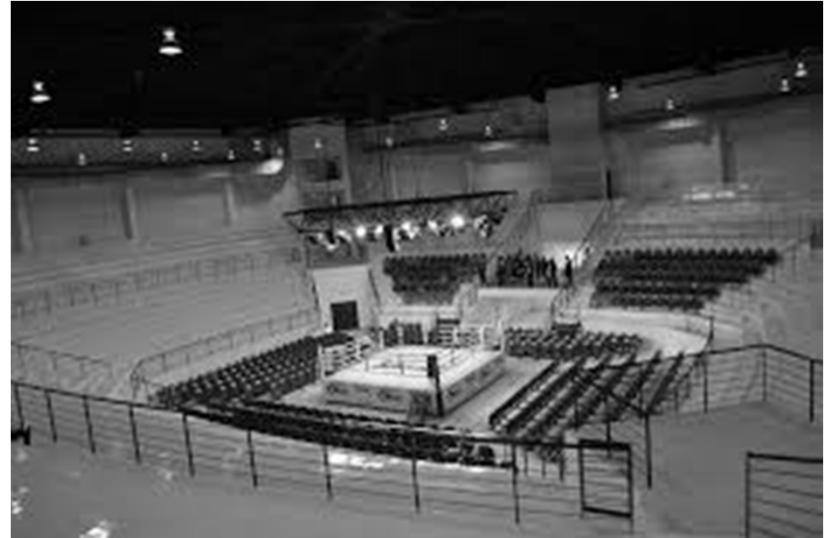


# Density of States

Azadi stadium



Boxing stadium



In Stadium: Number of available seats could be a function of distance from the center so ....

$N$ : number of available states for the electrons could be function of “Energy” :  $N(E)$

Seats are not the same for fans so empty states for electrons!

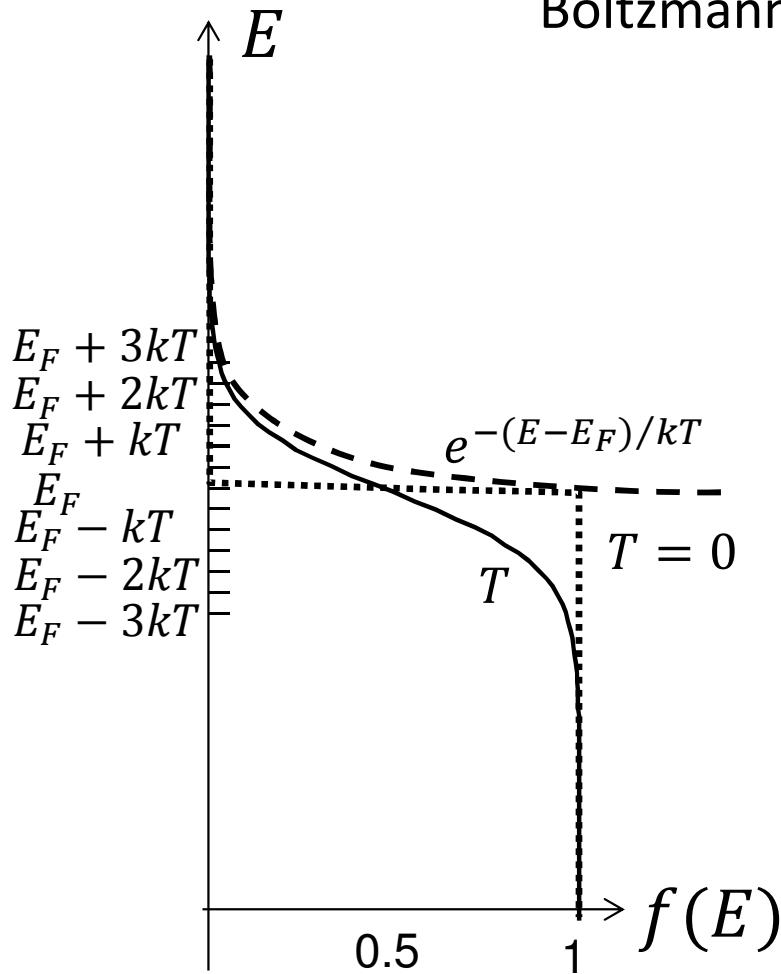
# Fermi Function

# Probability of Electron Distribution

1. 
  2. 
  3. 
  4. 
  5. 

$$f(E) = \frac{1}{1 + e^{(E-E_F)/kT}} \quad E_f \text{ is called the Fermi energy or the Fermi level.}$$

If we are  $3kT$  away from the Fermi energy then we might use Boltzmann approximation:



$$f(E) \approx e^{-(E-E_F)/kT} \quad \text{if} \quad E - E_F \gg kT$$

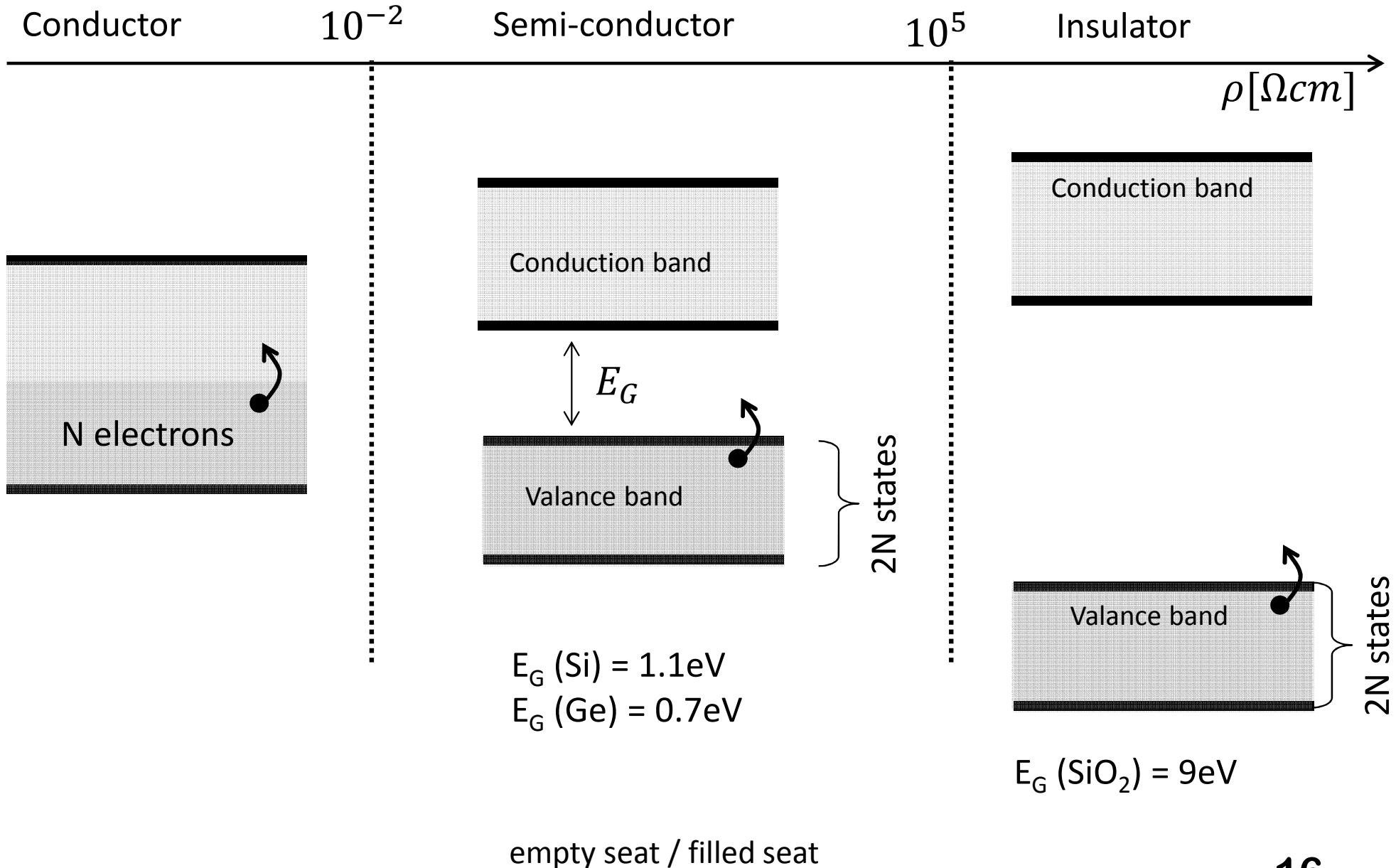
$$f(E) \approx 1 - e^{-(E_f - E)/kT} \quad \text{if} \quad E - E_F \ll -kT$$

$N(E) f(E) =$  # of electrons at energy E

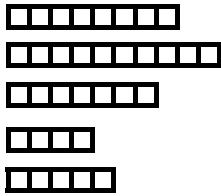
$$N(E)(1 - f(E)) = \# \text{ of holes at energy } E$$

# Materials

- 1.
  - 2.
  - 3.
  - 4.
  - 5.
- 
- The diagram illustrates the relationship between material properties and electron density. It features a horizontal axis labeled  $\rho [\Omega cm]$  with logarithmic scales for conductors ( $10^{-2}$ ), semi-conductors ( $10^5$ ), and insulators. Above the axis, five numbered boxes represent increasing electron density: 1. (empty) to 5. (filled). Below the axis, three diagrams show the electronic structure of a conductor, a semi-conductor, and an insulator. The conductor has a single band filled with  $N$  electrons. The semi-conductor has two bands: a lower Valence band and an upper Conduction band separated by energy  $E_G$ . Electrons can move between these bands. The insulator has a single Valence band completely filled with  $2N$  electrons.



- 1.
- 2.
- 3.
- 4.
- 5.

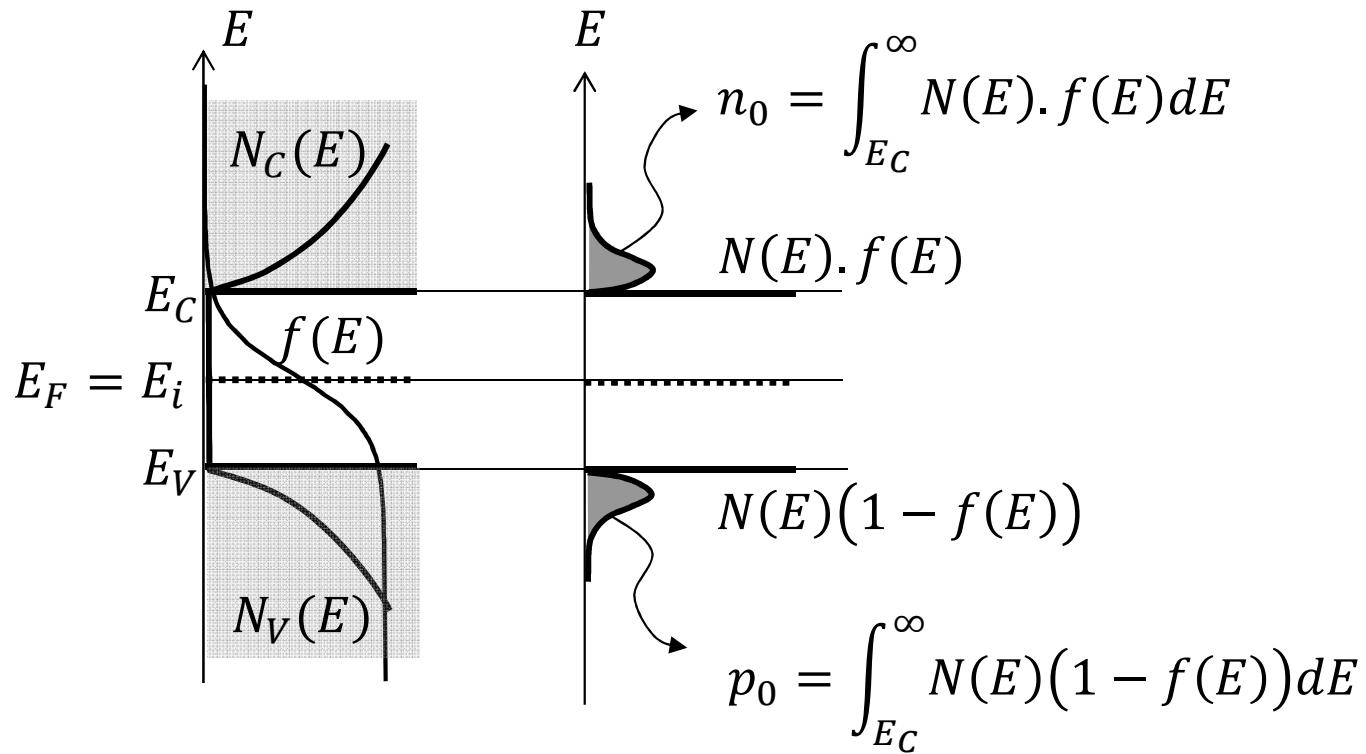


# Electron / Holes : Intrinsic

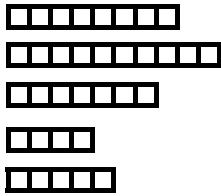
intrinsic

$N(E) f(E)$  = # of electrons at energy E

$N(E)(1 - f(E))$  = # of holes at energy E



- 1.
- 2.
- 3.
- 4.
- 5.

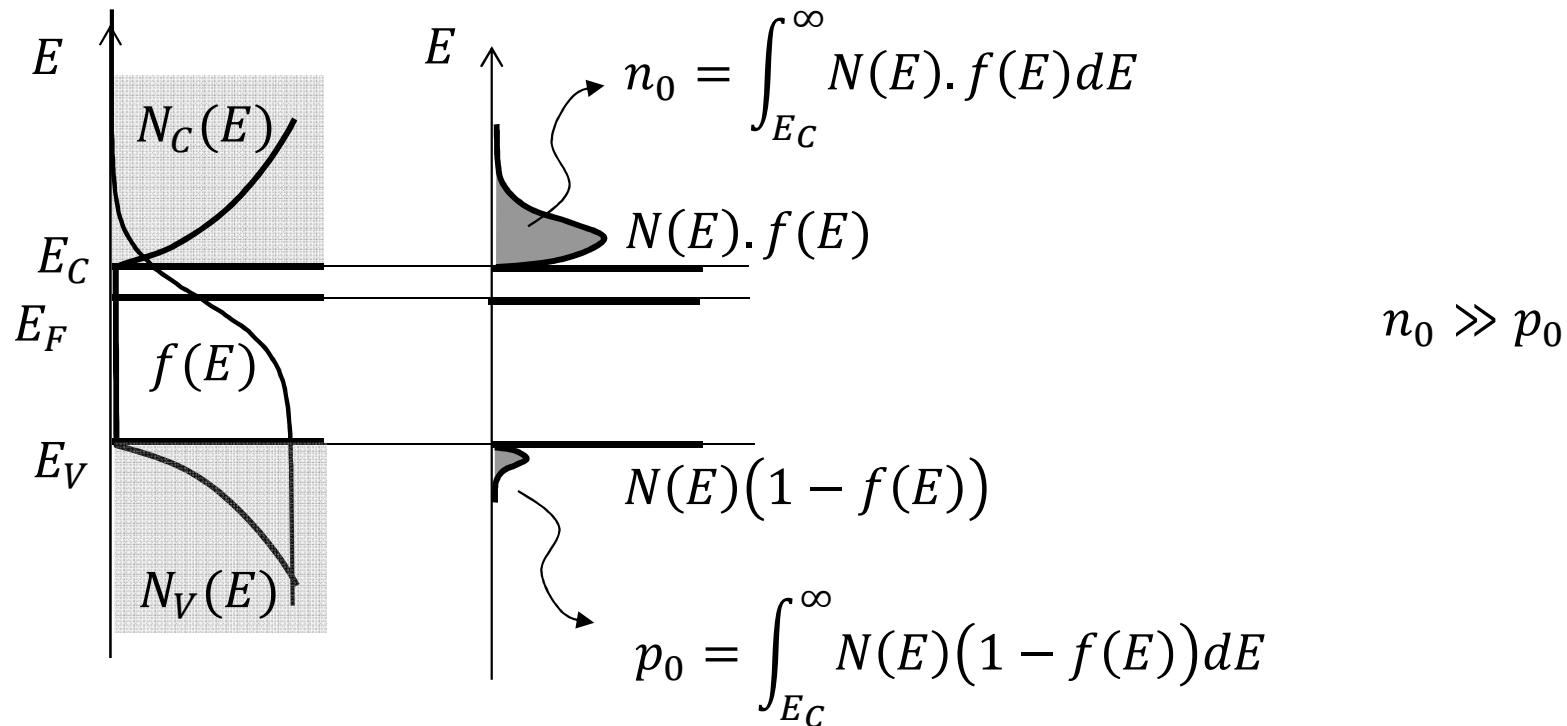


# Electron / Holes : n-type

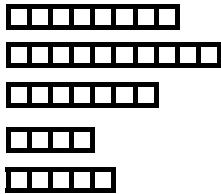
n-type

$N(E) f(E)$  = # of electrons at energy E

$N(E)(1 - f(E))$  = # of holes at energy E



- 1.
- 2.
- 3.
- 4.
- 5.

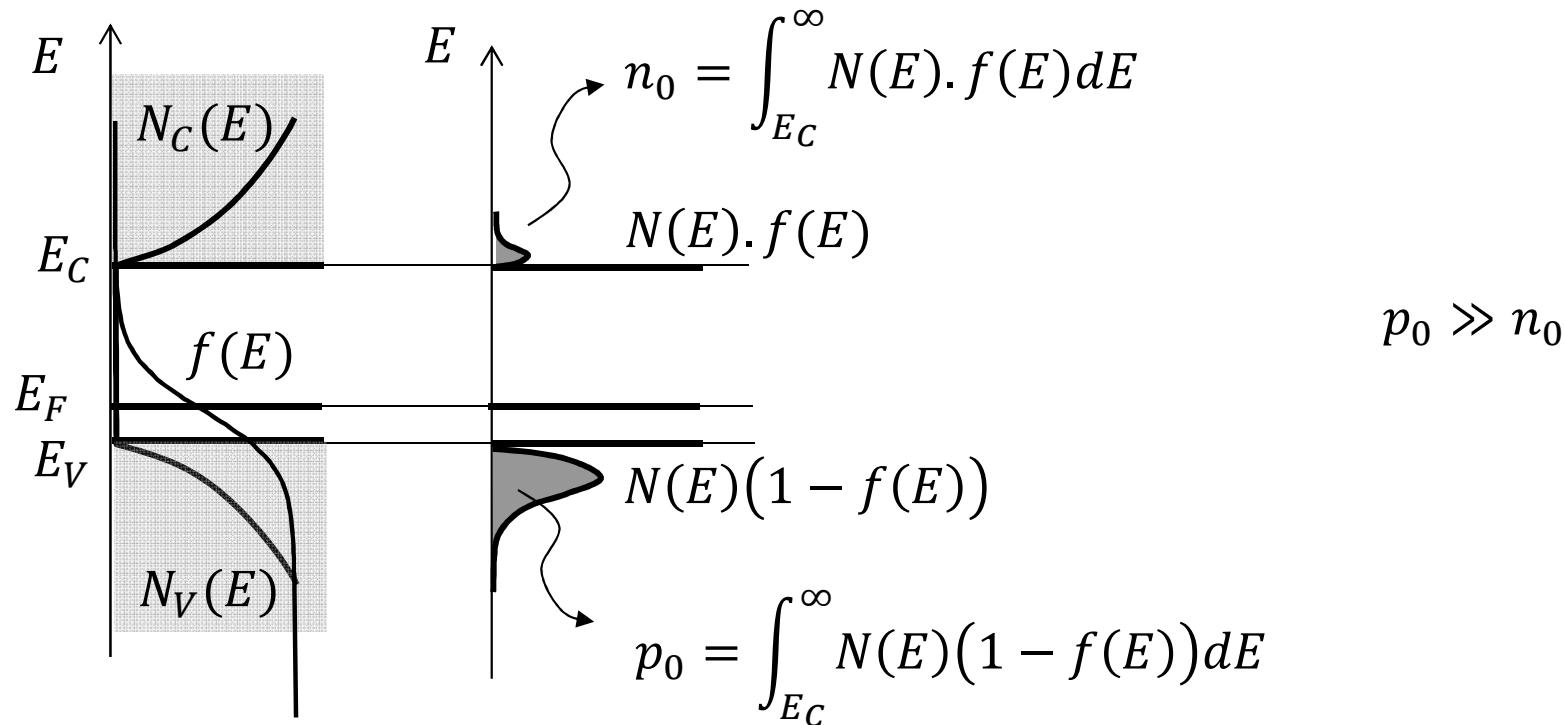


# Electron / Holes : p-type

p-type

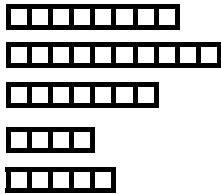
$N(E) f(E)$  = # of electrons at energy E

$N(E)(1 - f(E))$  = # of holes at energy E



# Fermi Energy

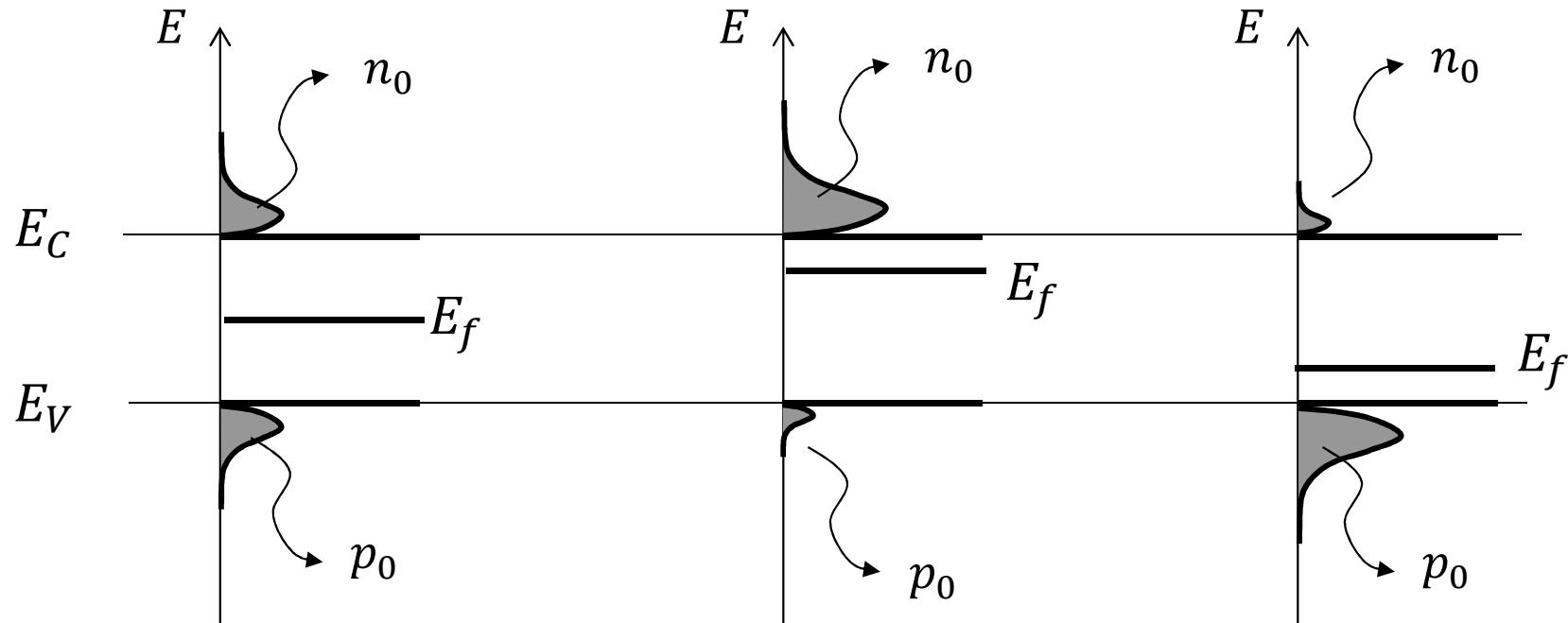
1.  
2.  
3.  
4.  
5.



intrinsic

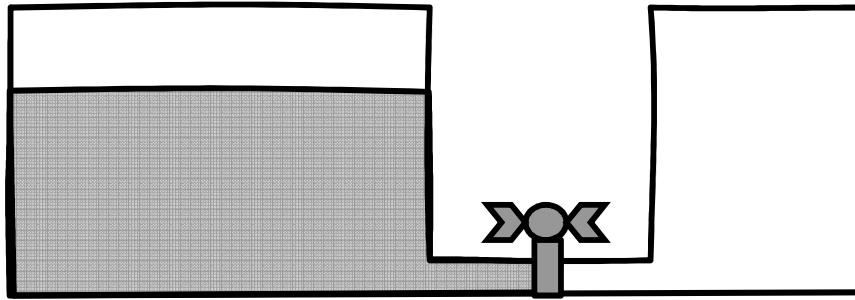
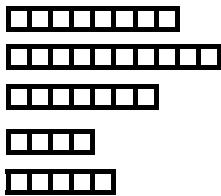
n-type

p-type

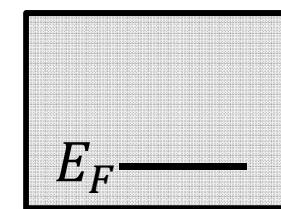


# Fermi Energy

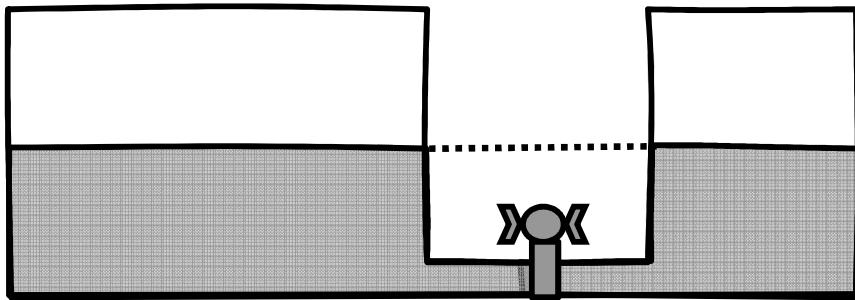
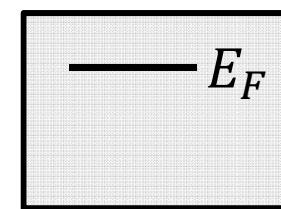
- 1.
- 2.
- 3.
- 4.
- 5.



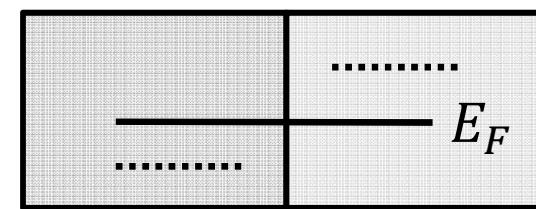
p-type



n-type

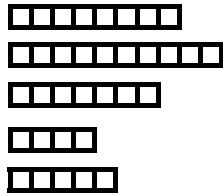


p-type



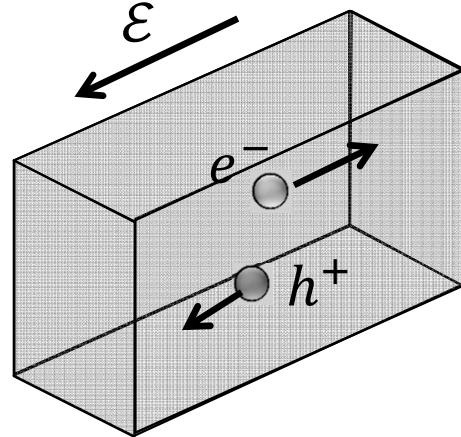
n-type

- 1.
- 2.
- 3.
- 4.
- 5.

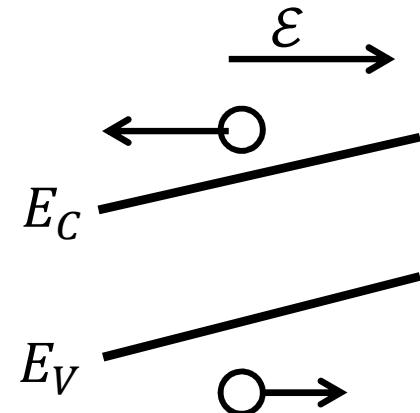


# Flow of Charge

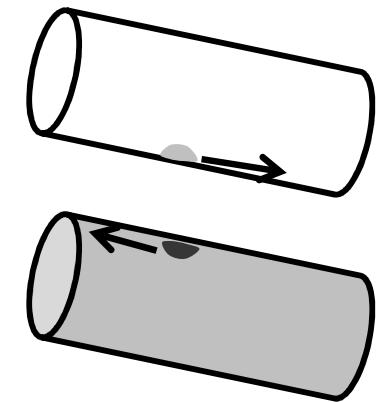
Drift



Electric field

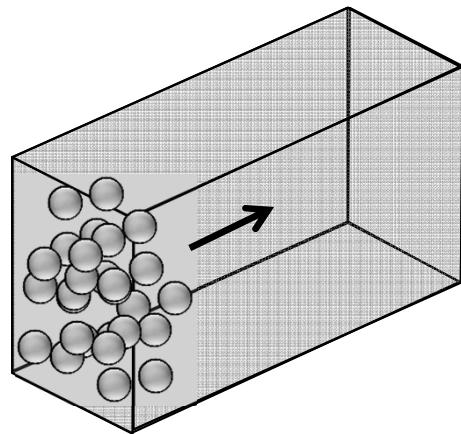


gravitational field



$$J \propto \varepsilon$$

Diffusion



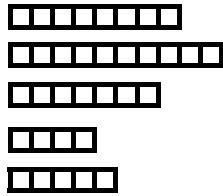
Charges move to be evenly distributed throughout space. Similar to perfume in room or heat in a solid

$$J_n = qD_n \frac{dn}{dx}$$

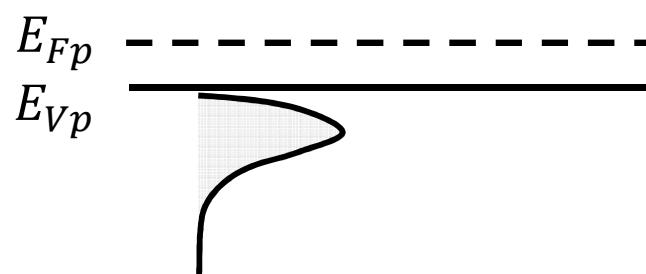
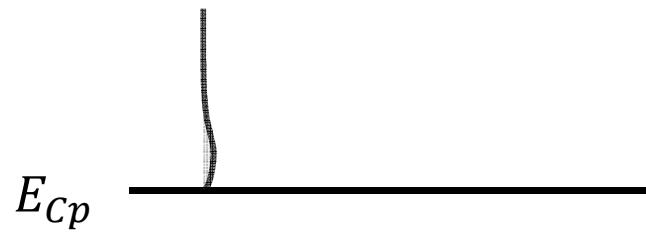
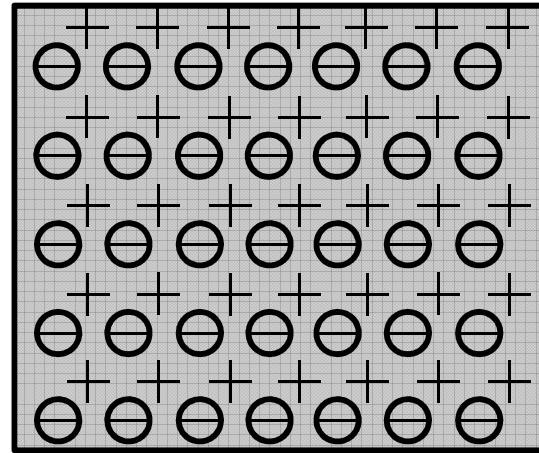
$$J_p = -qD_p \frac{dp}{dx}$$

# PN Junction

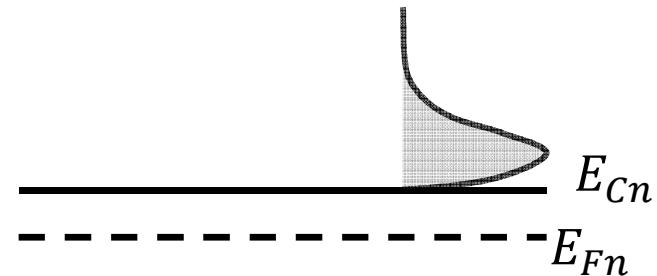
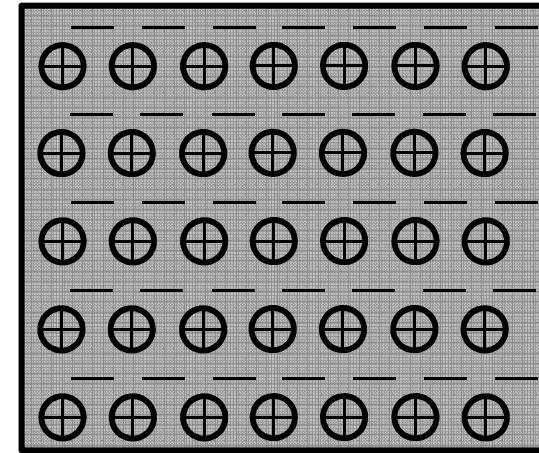
- 1.
- 2.
- 3.
- 4.
- 5.



p

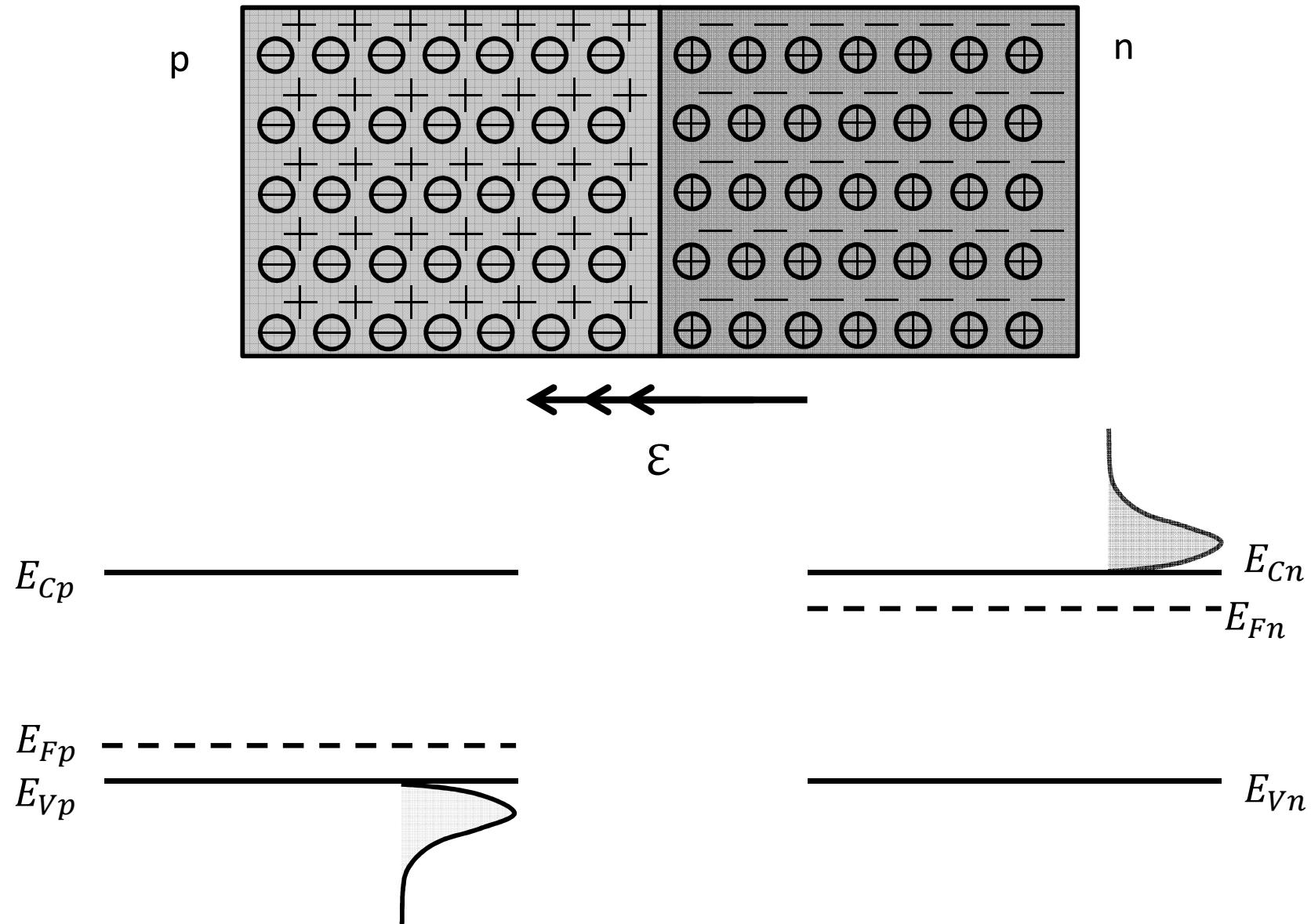
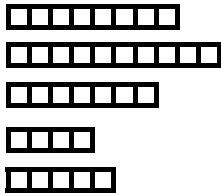


n



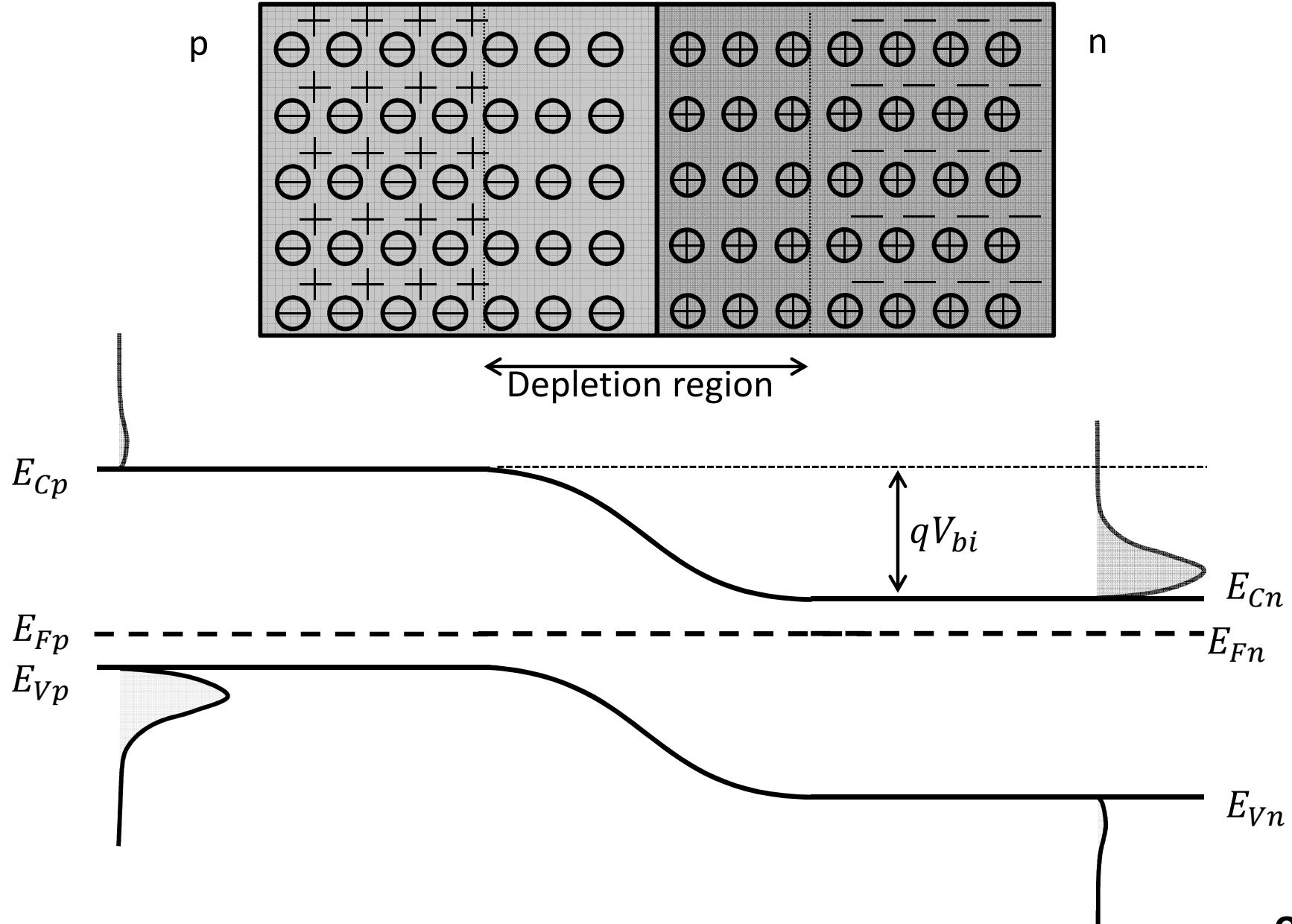
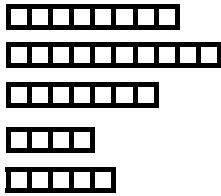
# PN junctions

1.  
2.  
3.  
4.  
5.



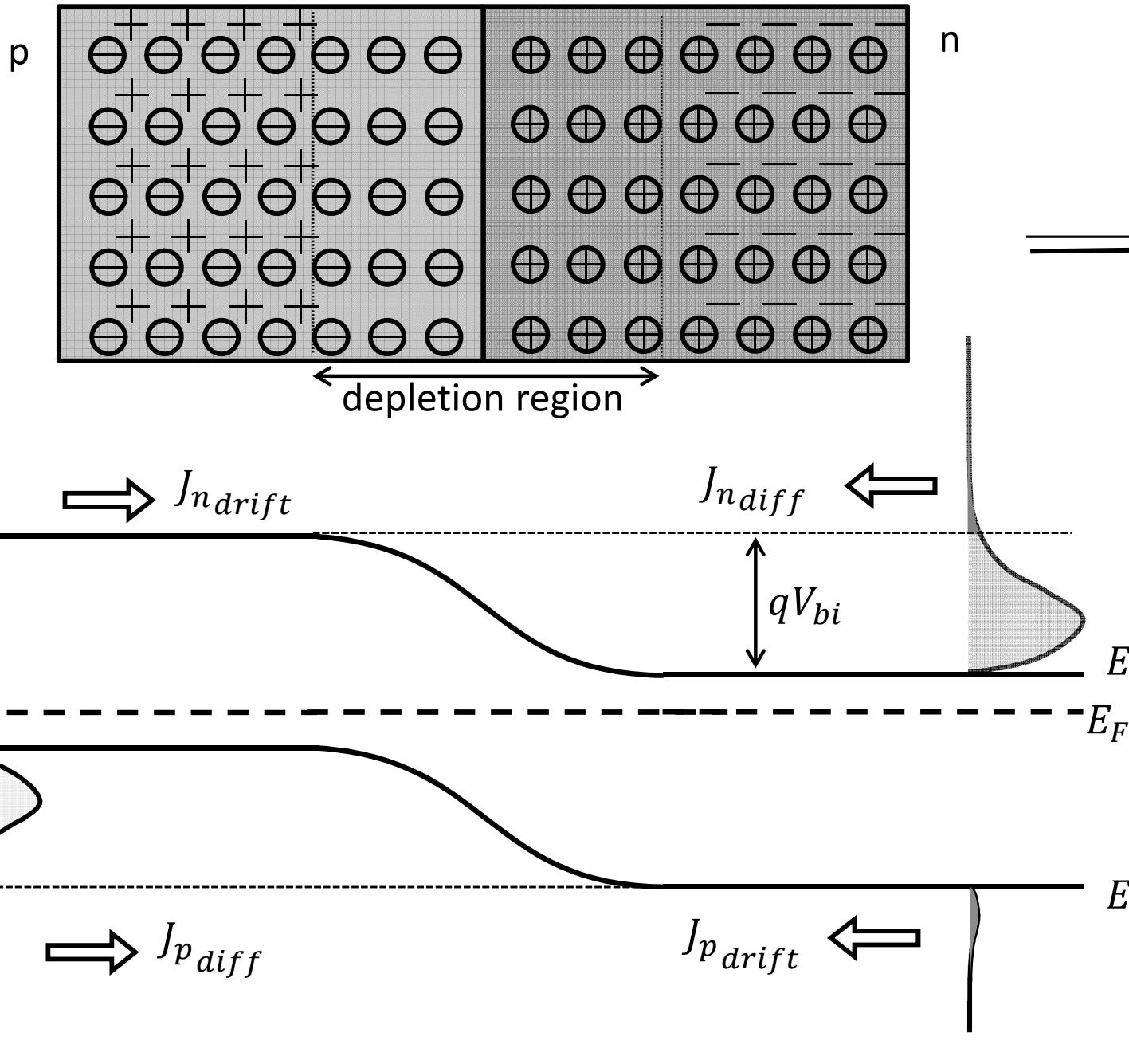
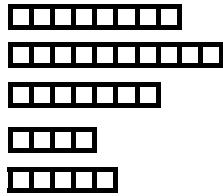
# PN junctions

- 1.
- 2.
- 3.
- 4.
- 5.



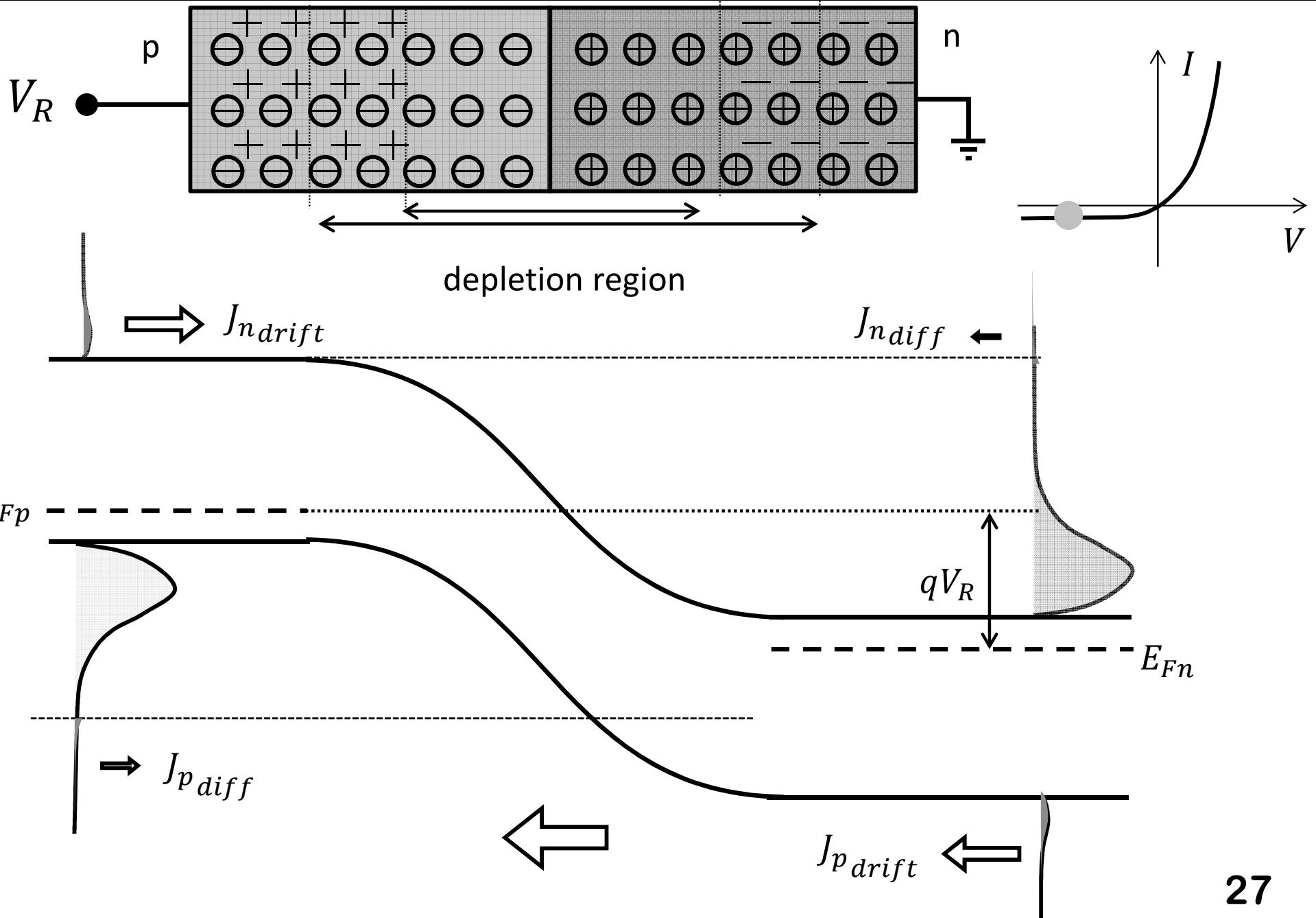
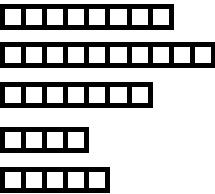
# PN junctions

- 1.
- 2.
- 3.
- 4.
- 5.



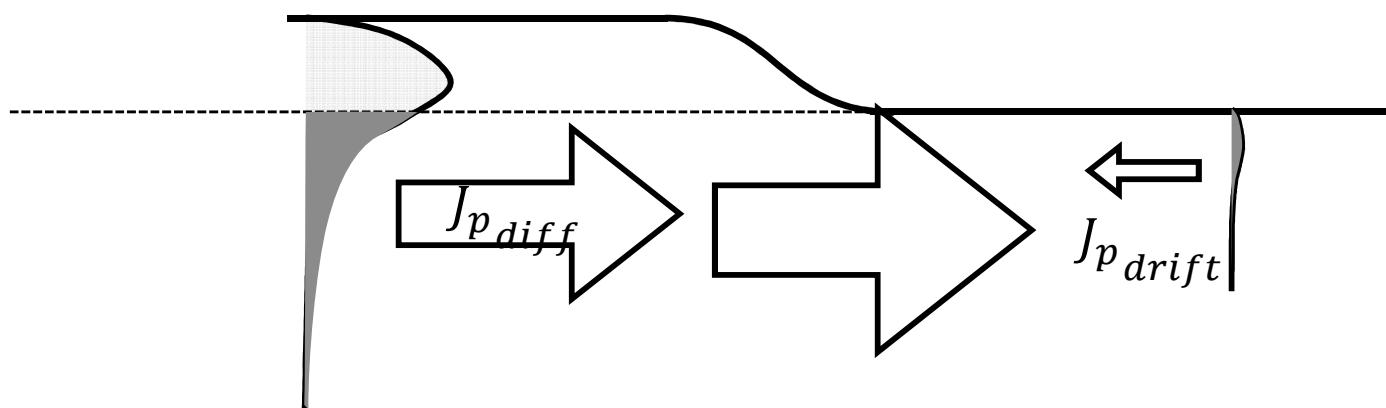
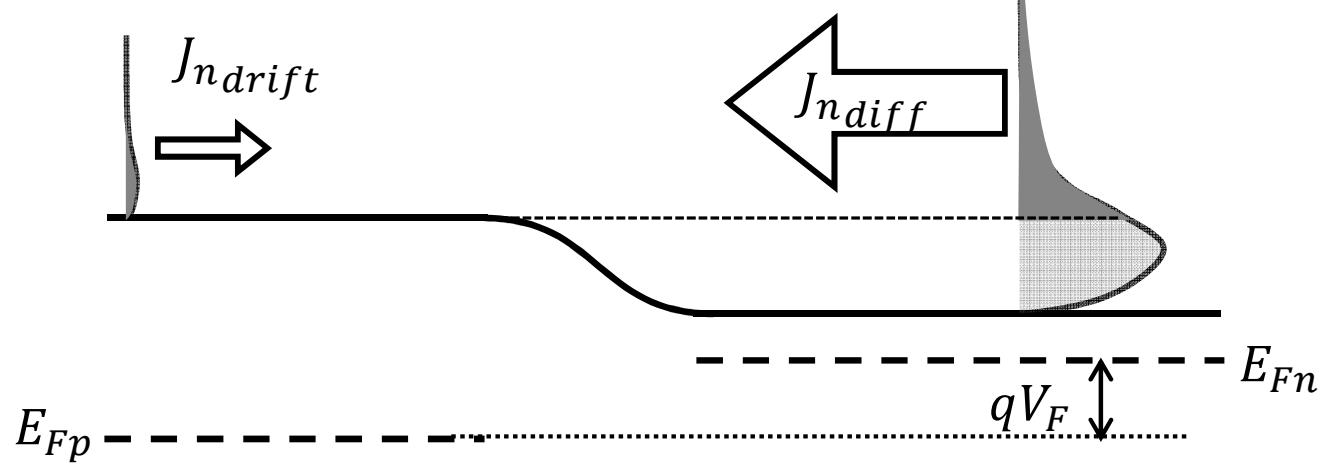
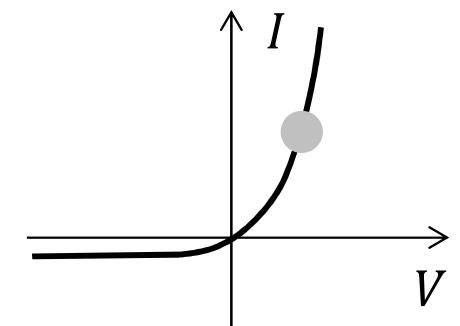
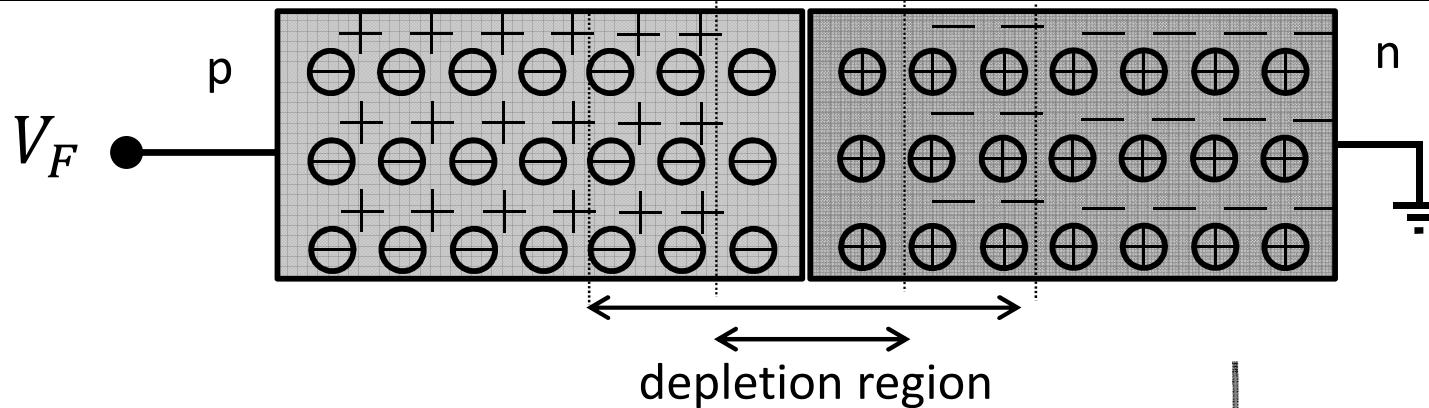
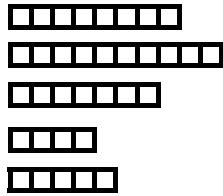
# PN junctions , Reverse Biased

1.  
2.  
3.  
4.  
5.

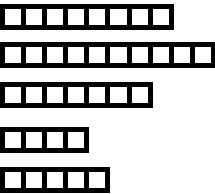


# PN junctions , Forward Biased

- 1.
- 2.
- 3.
- 4.
- 5.

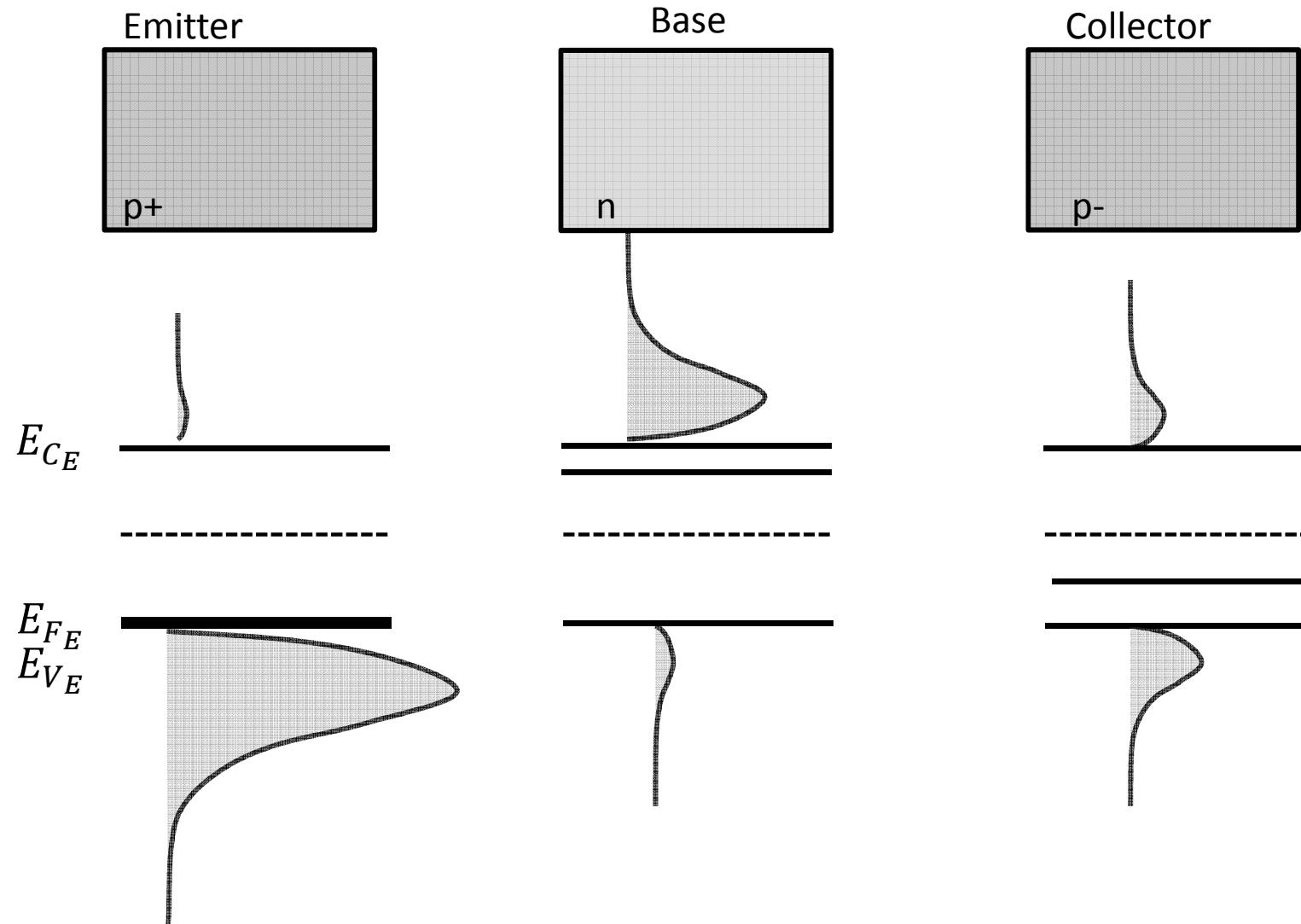


- 1.
- 2.
- 3.
- 4.
- 5.



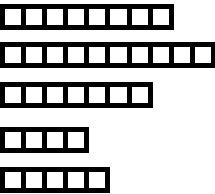
# BJT Electrostatics

*pnp*



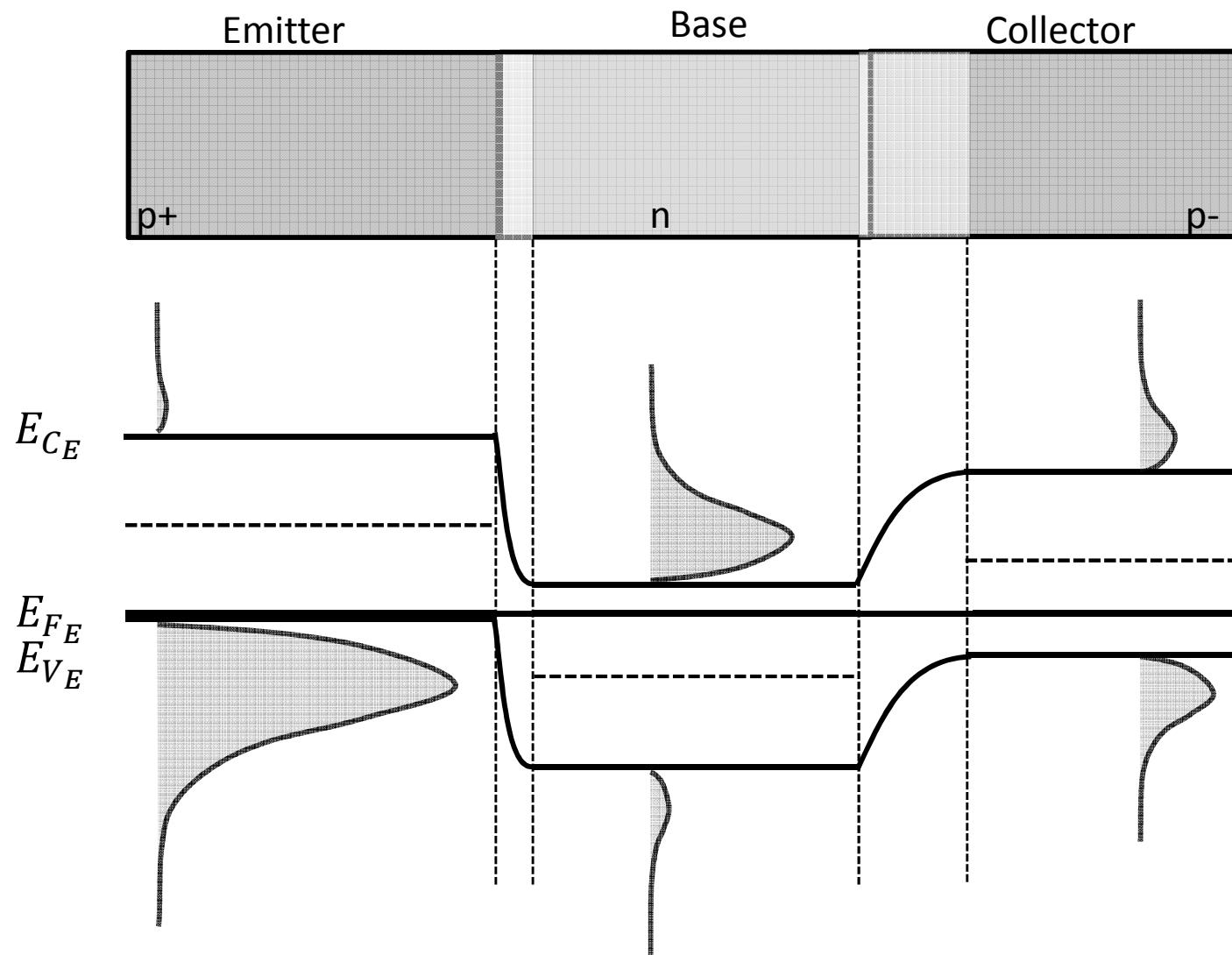
Under normal operating conditions, the BJT may be viewed electrostatically as two independent pn junctions

- 1.
- 2.
- 3.
- 4.
- 5.



# BJT Electrostatics

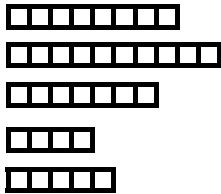
*pnp*



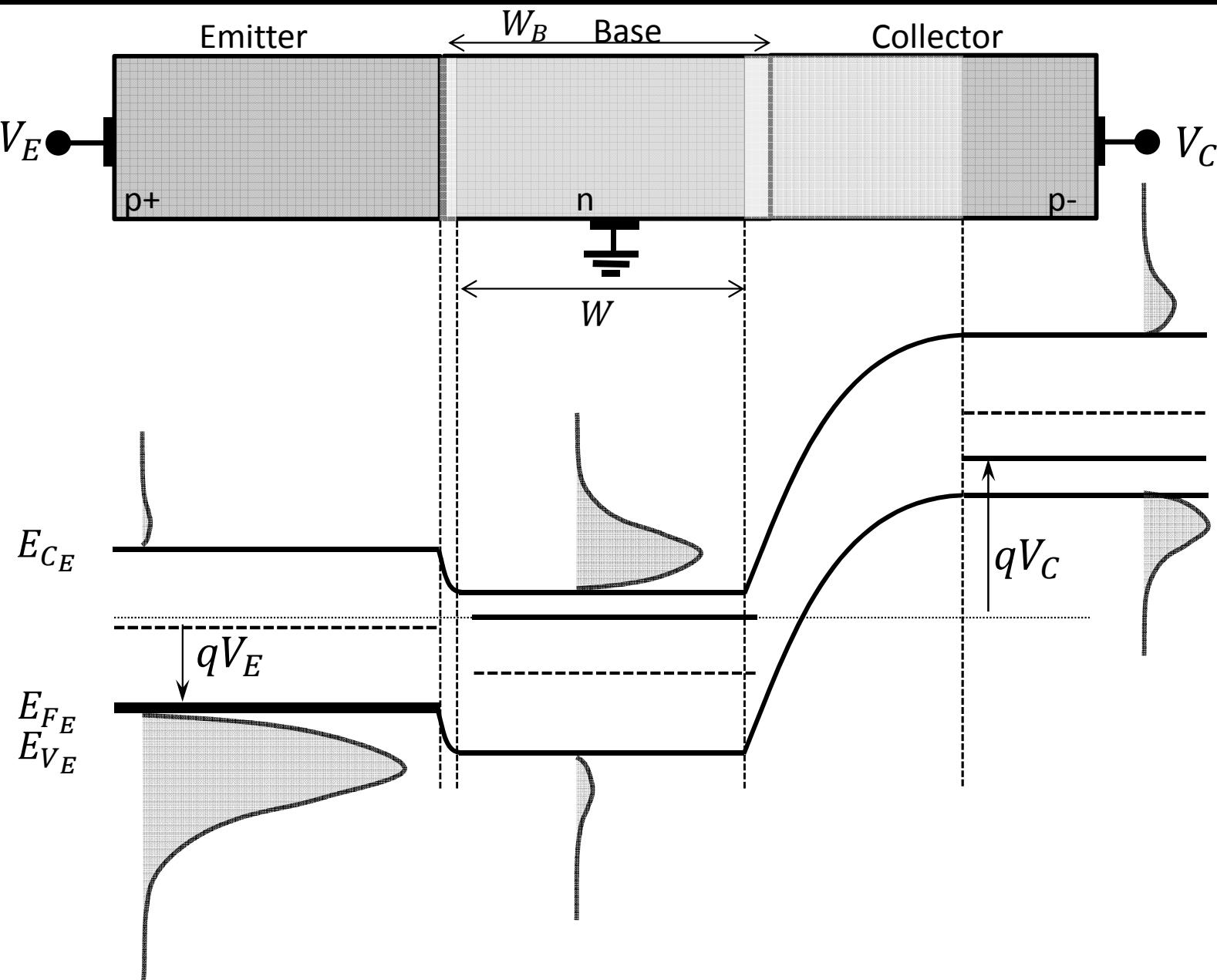
Under normal operating conditions, the BJT may be viewed electrostatically as two independent pn junctions

# BJT Electrostatics

1.  
2.  
3.  
4.  
5.

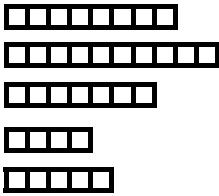


*pnp*

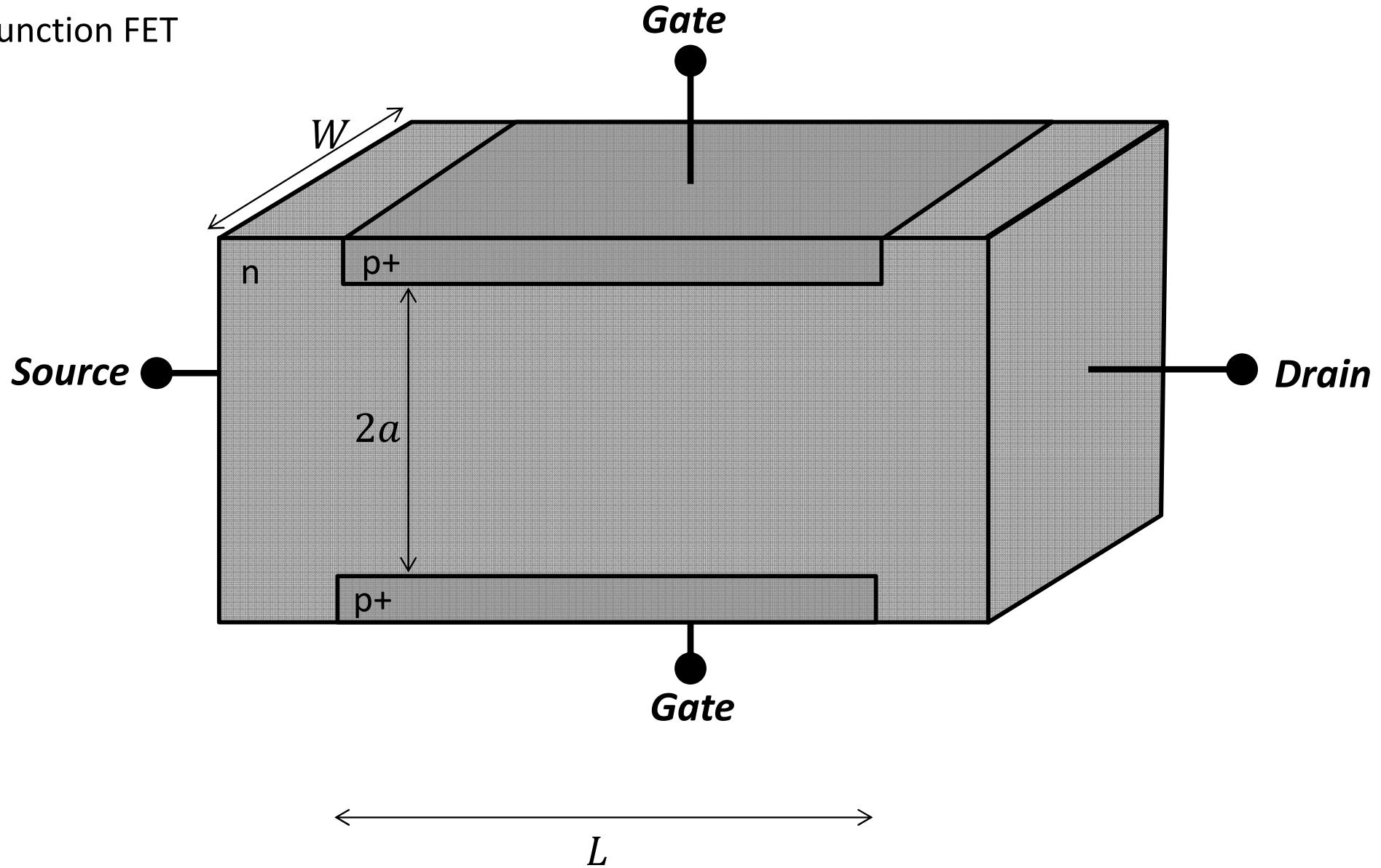


# JFET

- 1.
- 2.
- 3.
- 4.
- 5.

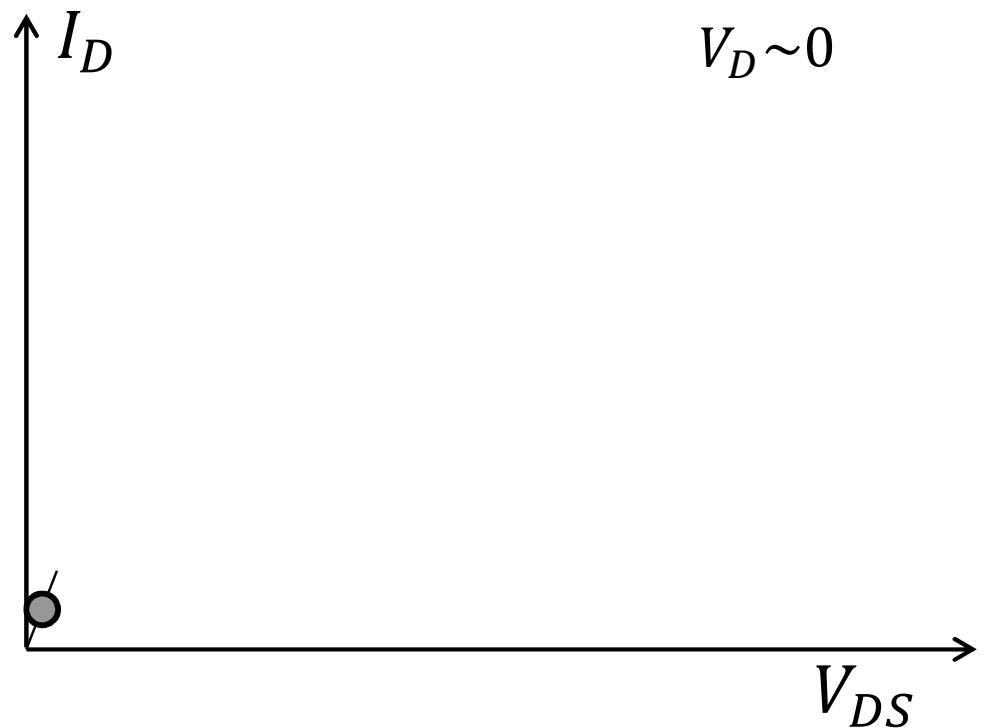
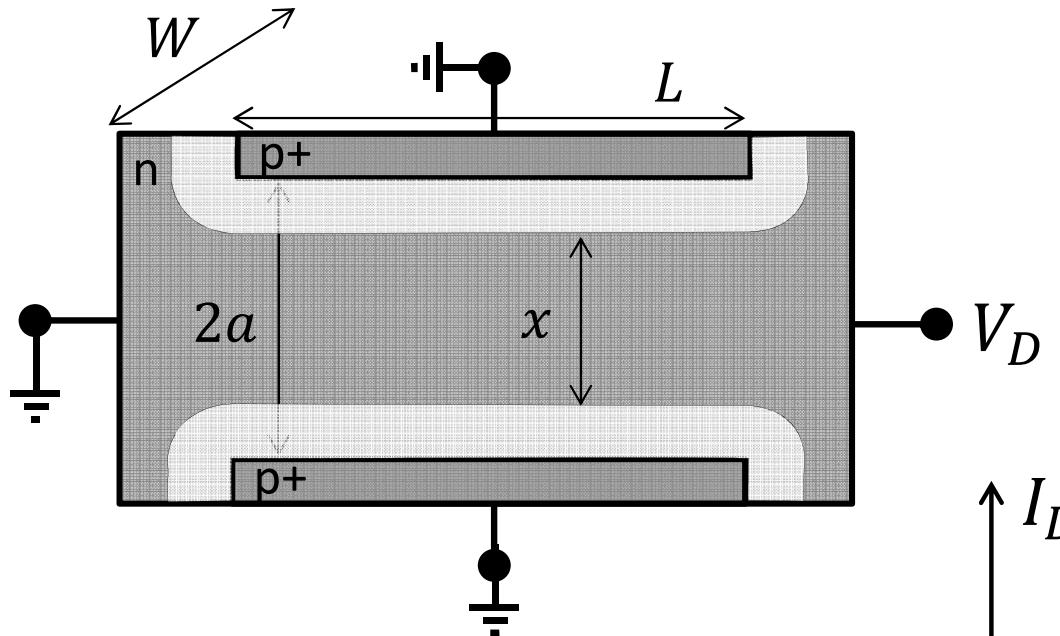
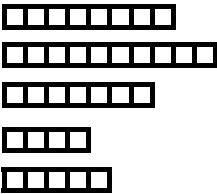


Junction FET



# JFET

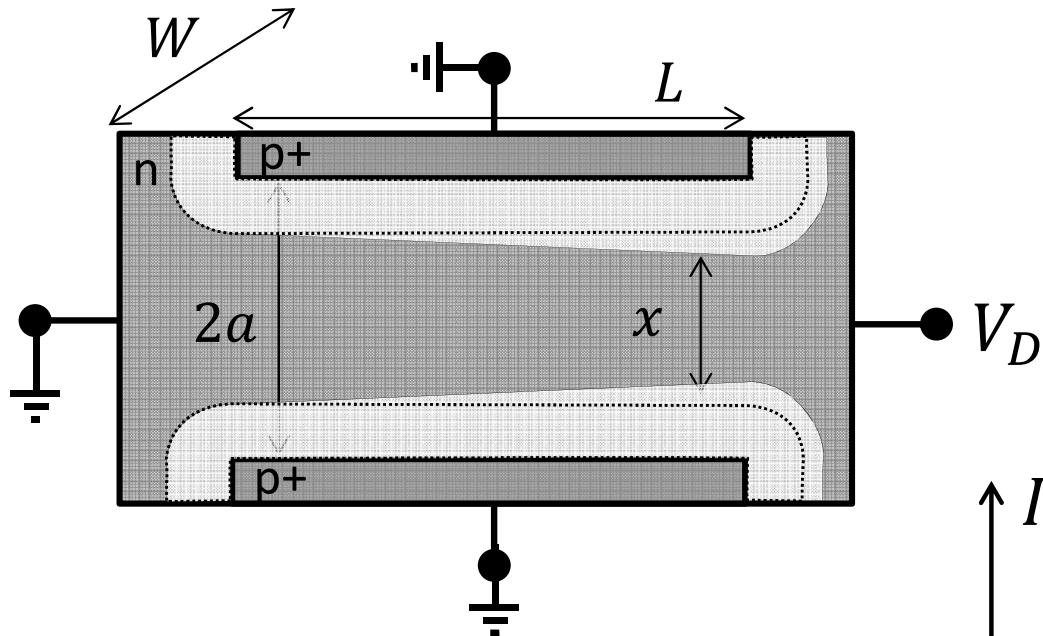
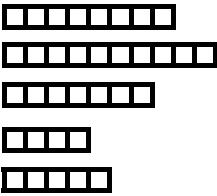
- 1.
- 2.
- 3.
- 4.
- 5.



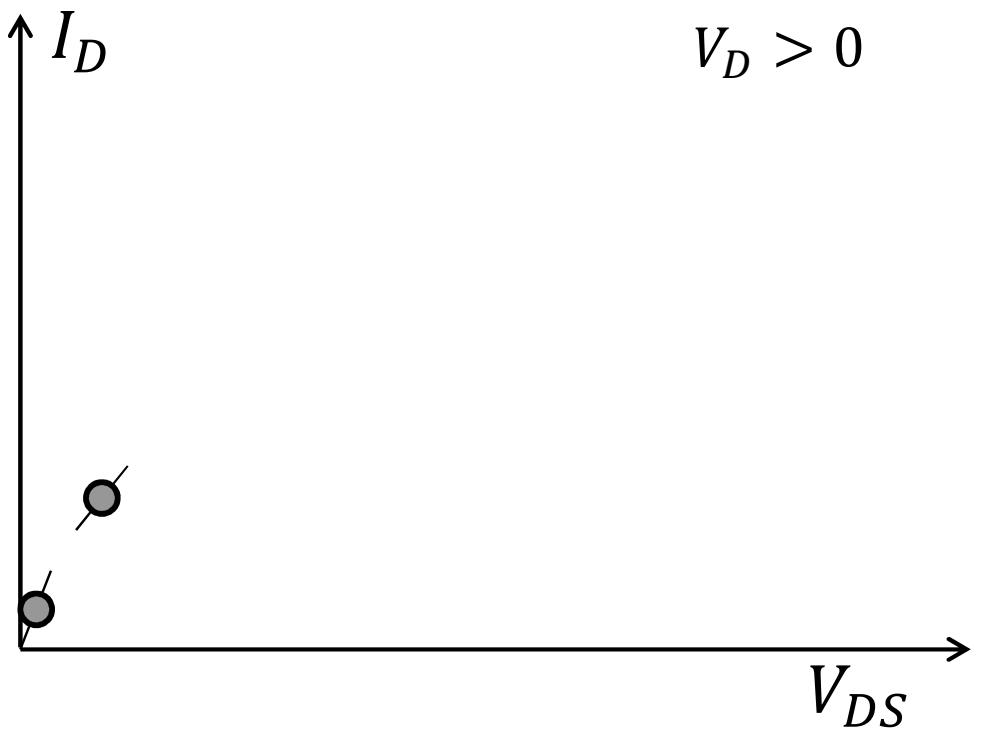
$$R = \rho \frac{L}{Wx}$$

# JFET

- 1.
- 2.
- 3.
- 4.
- 5.

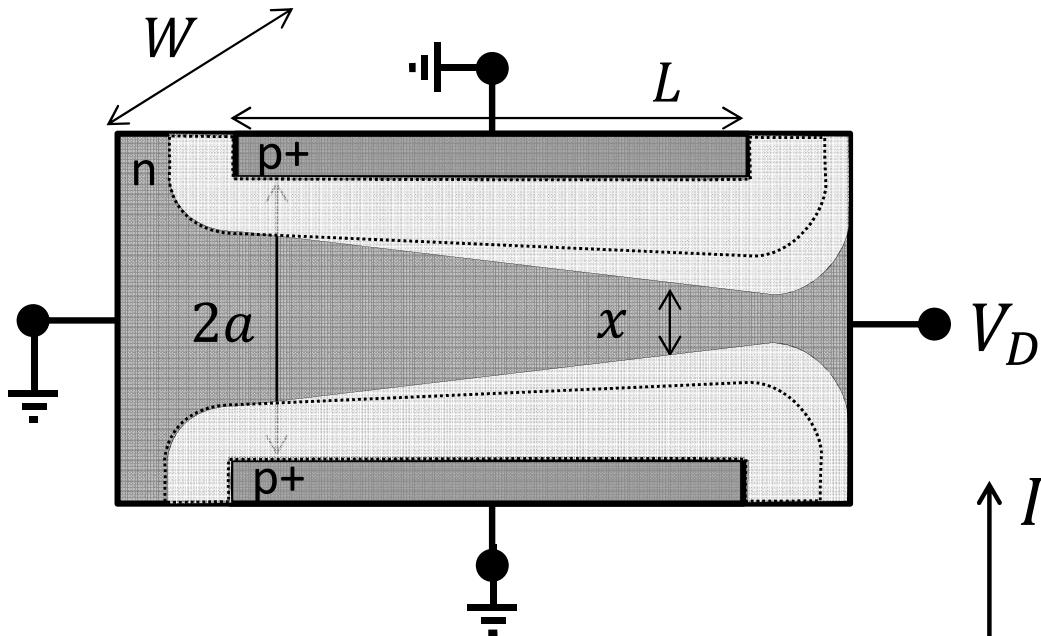
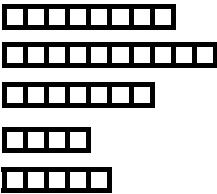


$$R = \rho \frac{L}{Wx}$$

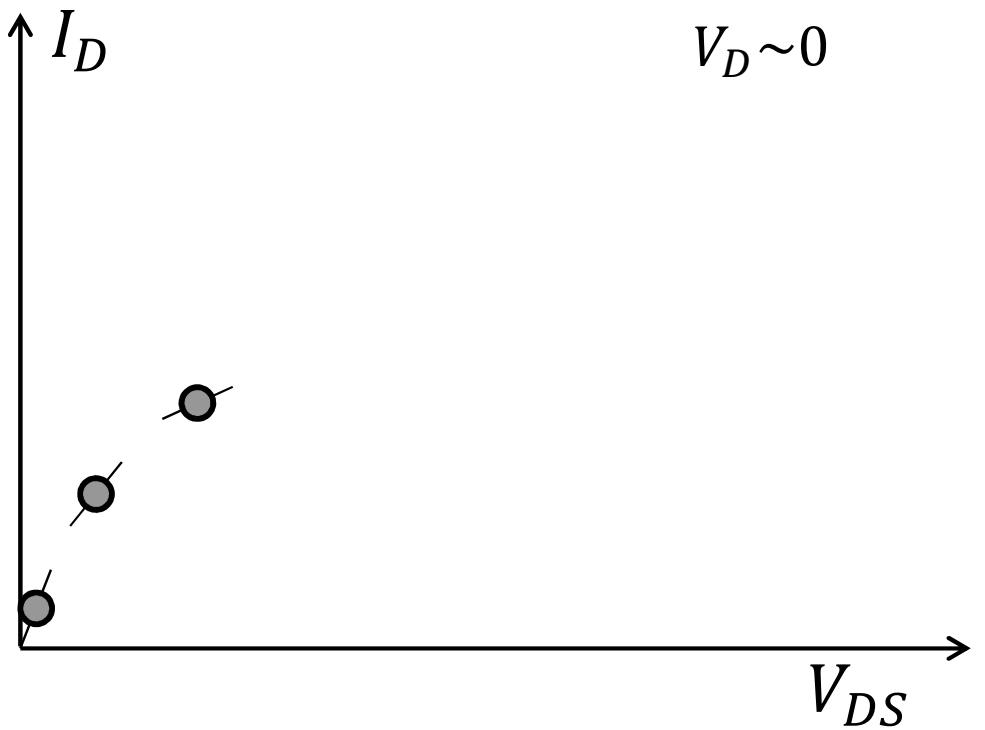


# JFET

- 1.
- 2.
- 3.
- 4.
- 5.

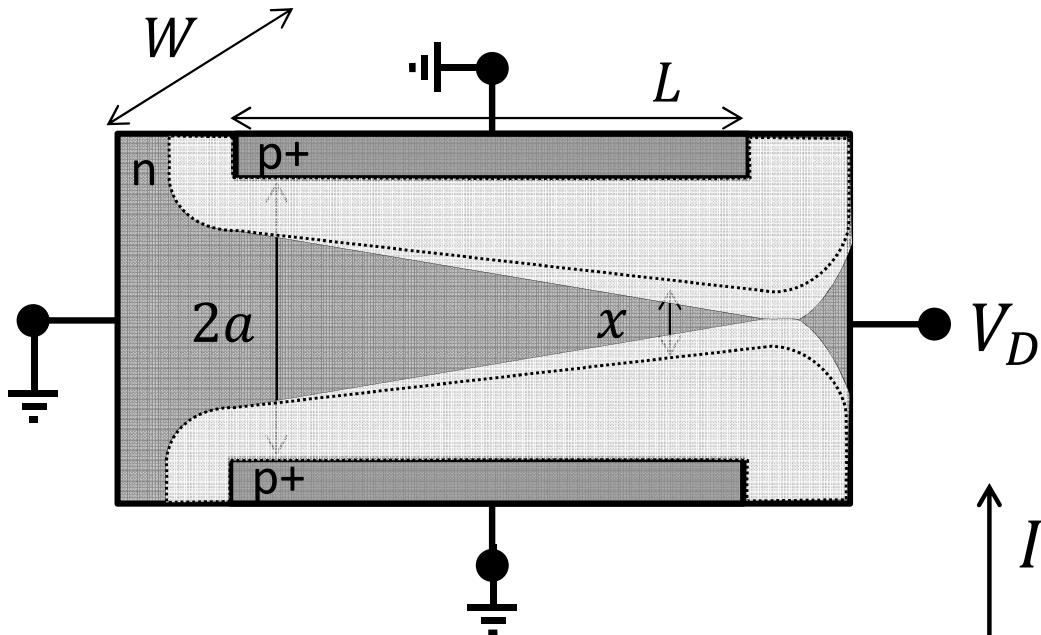
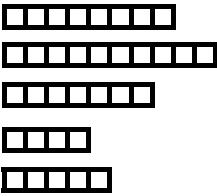


$$R = \rho \frac{L}{Wx}$$

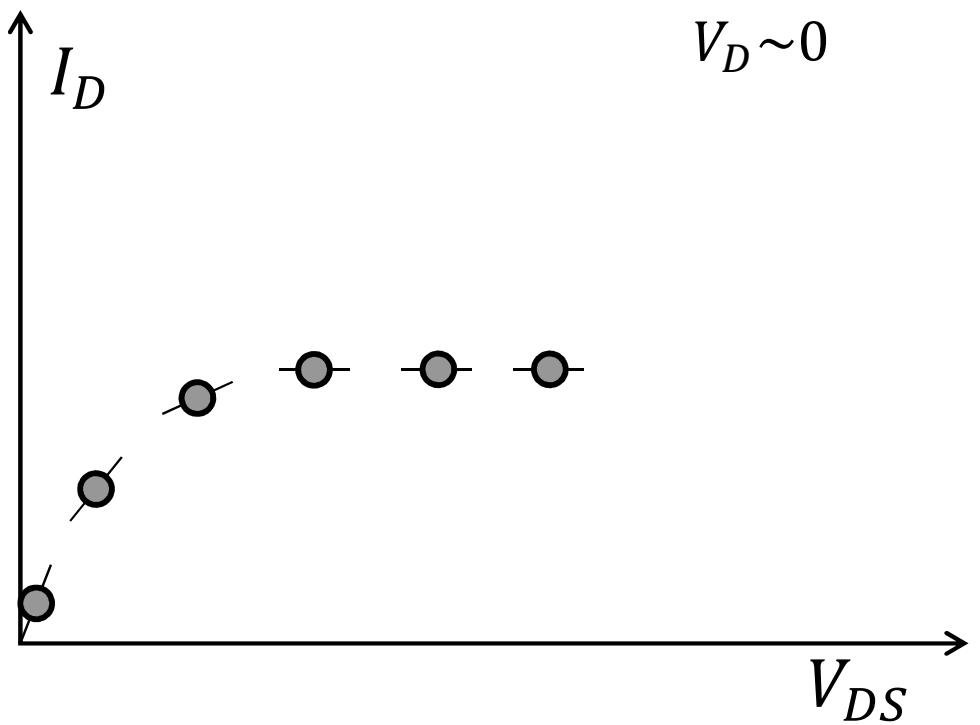


# JFET

- 1.
- 2.
- 3.
- 4.
- 5.



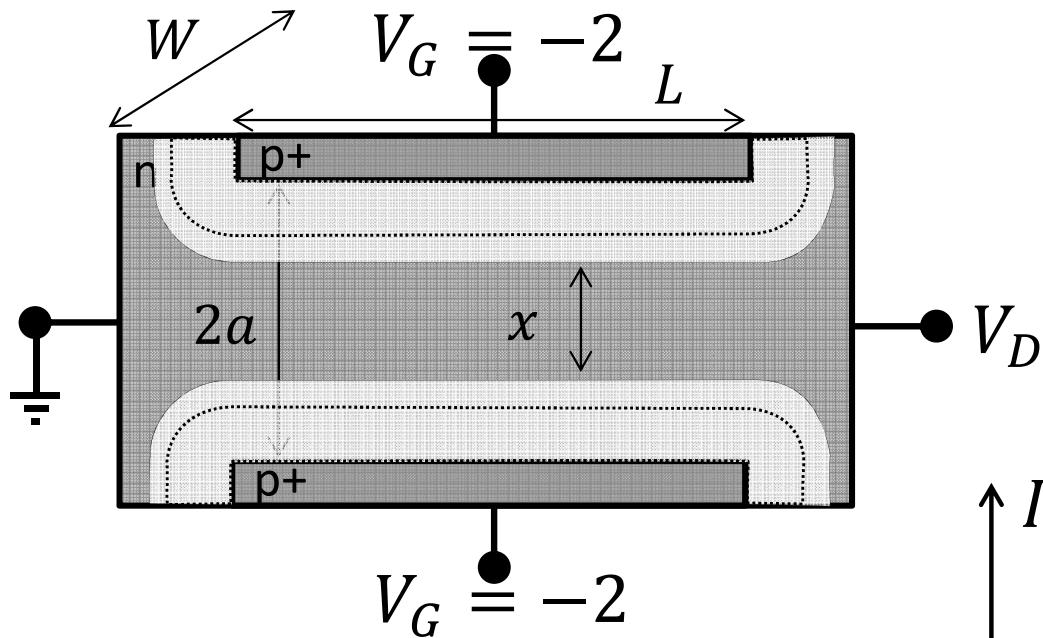
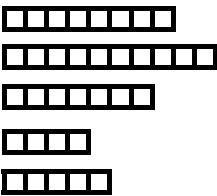
$$R = \rho \frac{L}{Wx}$$



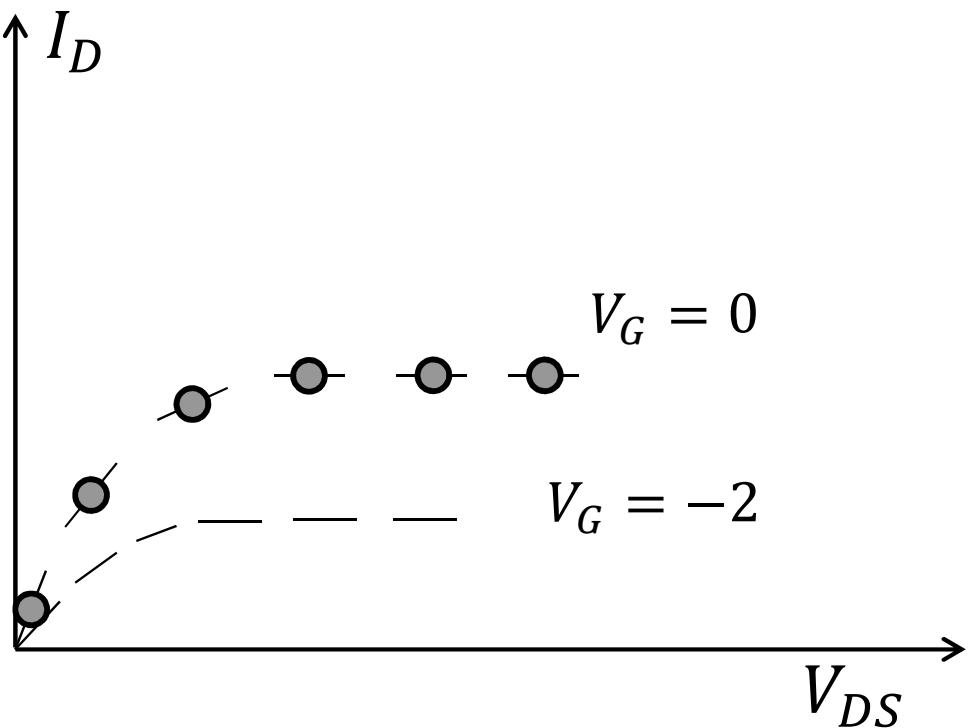
$V_D \sim 0$

# JFET

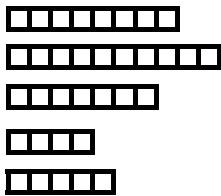
- 1.
- 2.
- 3.
- 4.
- 5.



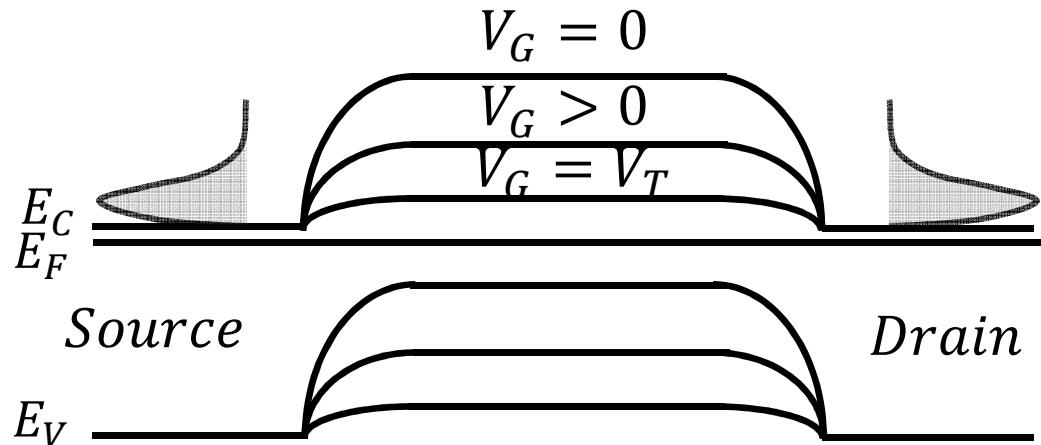
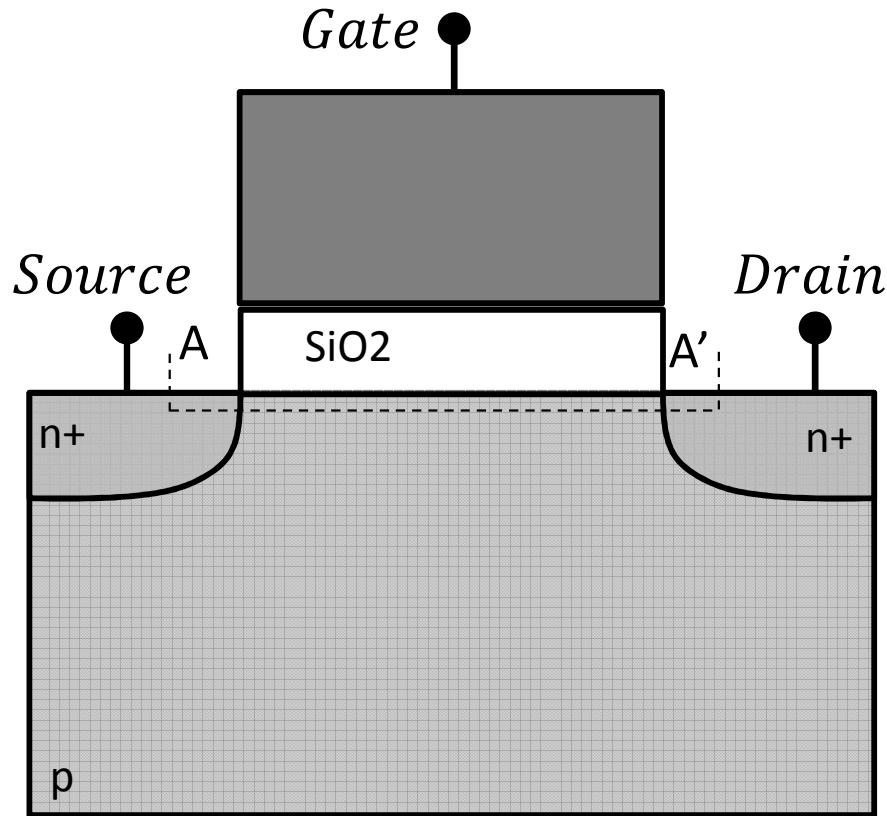
$$R = \rho \frac{L}{Wx}$$



- 1.
- 2.
- 3.
- 4.
- 5.

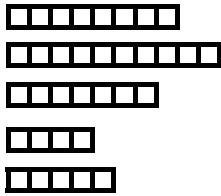


# Qualitative Theory of the NMOSFET



The potential barrier to electron flow from the source into the channel region is lowered by applying  $V_{GS} > V_T$

- 1.
- 2.
- 3.
- 4.
- 5.



# Qualitative Theory of the NMOSFET

