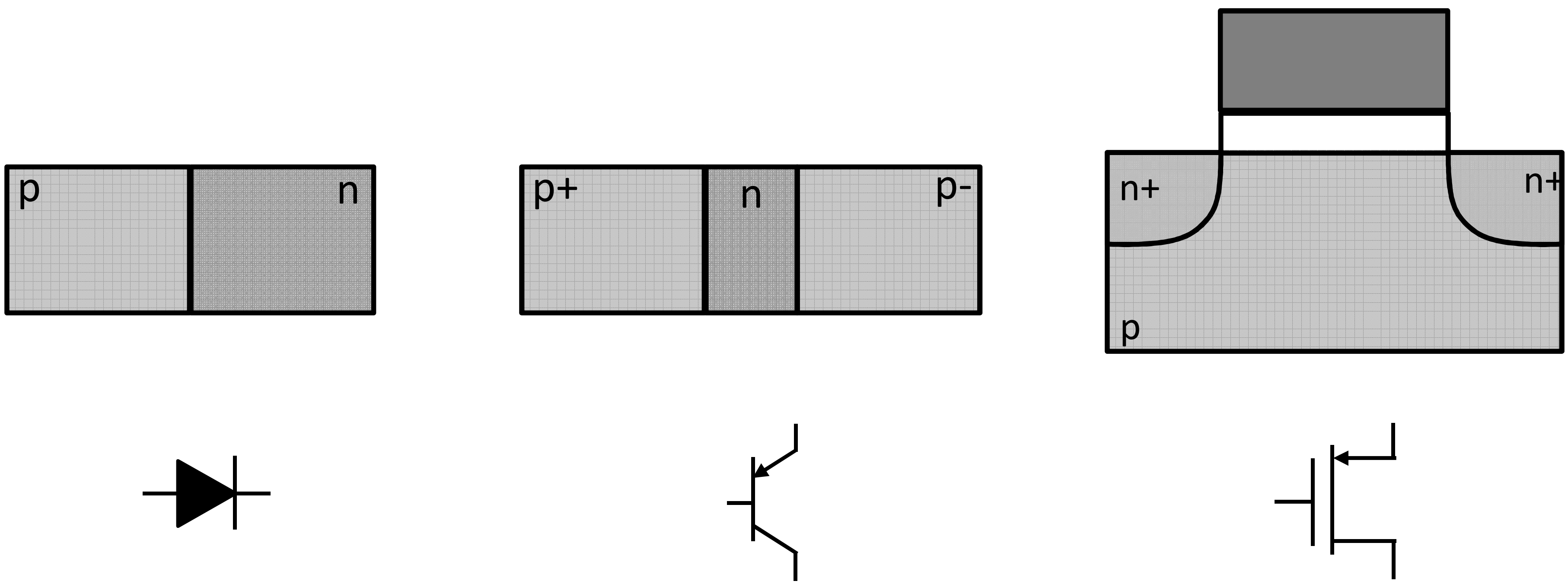
Session 0: Solid State Physics

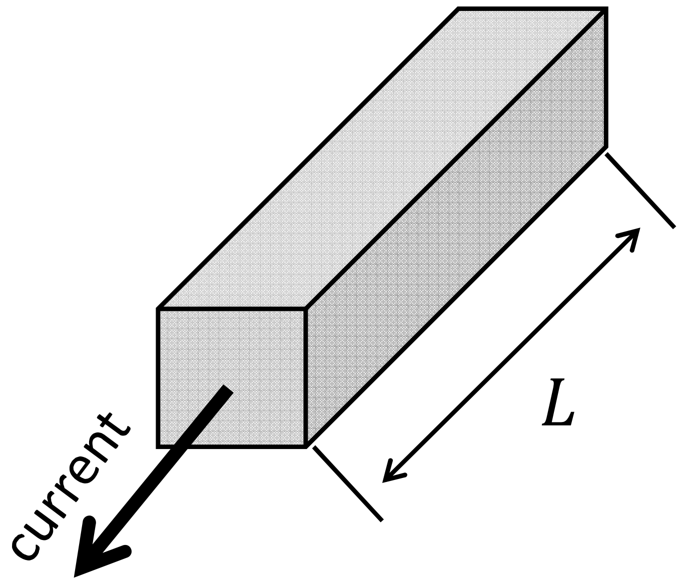
From Atom to Transistor

Objective

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



21 Century Alchemy!



Ohm's law

$$R = \frac{V}{I} \rightarrow \rho = R\frac{A}{L}$$ 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.

Conductor

Al , Cu ⟷ SiO_2

$\rho_{Al} \approx 10^{-6}\ [\Omega cm]$ $\rho_{SiO_2} \approx 10^{16}\ [\Omega cm]$

Insulator

Periodic Table of Elements

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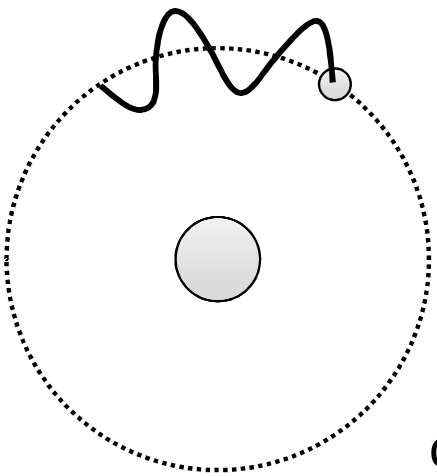


Bohr Atomic Model

wave-particle duality

$$\lambda = h/p$$

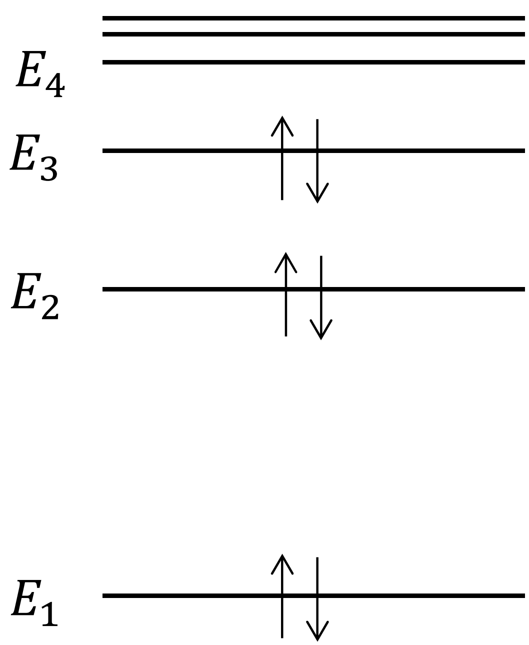
$$mvr = n\hbar$$

de Broglie standing wave

Abbreviated Periodic Table

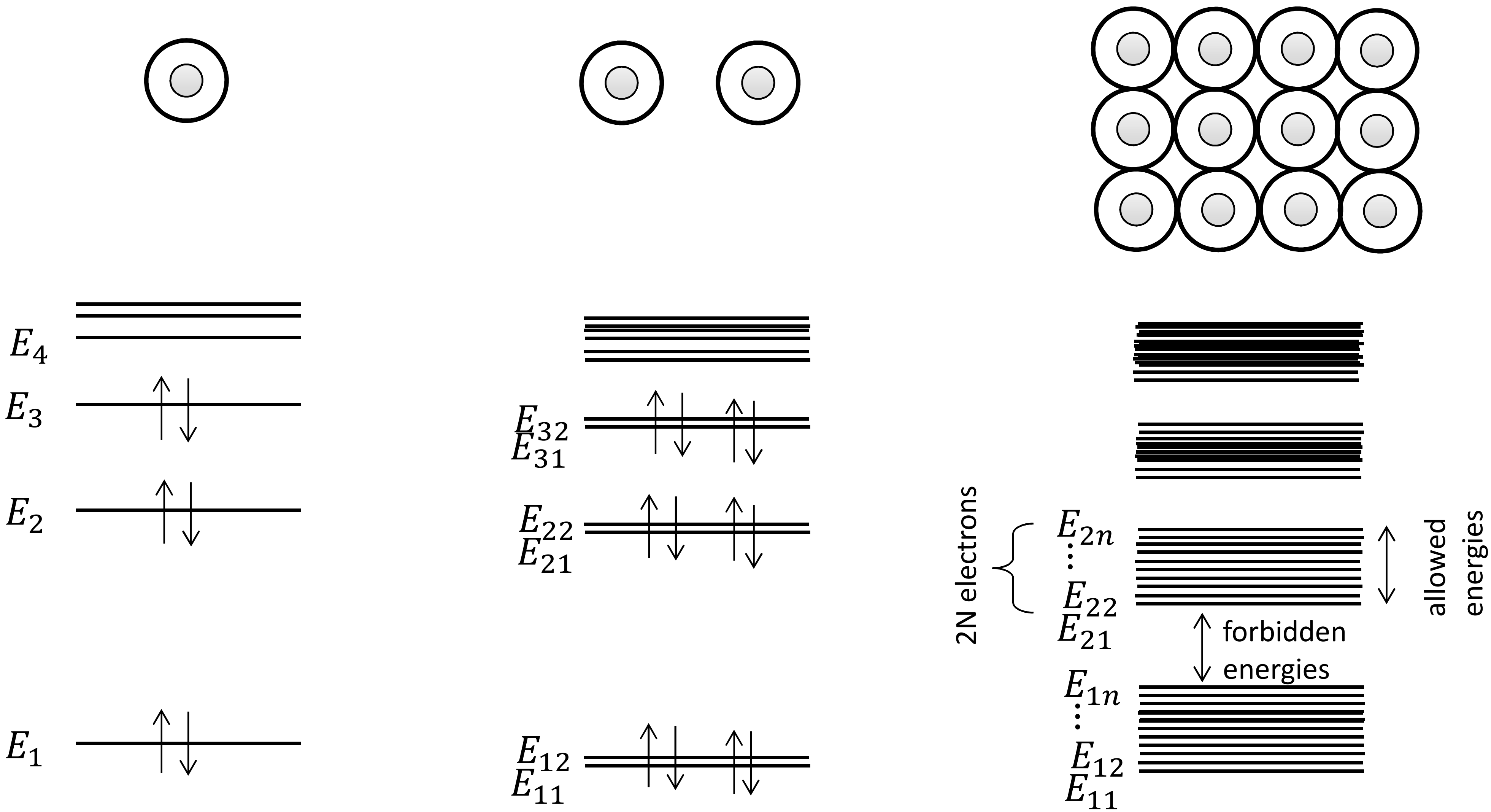
II	III	IV	V	VI
4 Be	5 B	6 C	7 N	8 O
12 Mg	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te
80 Hg	81 Tl	82 Pb	83 Bi	84 Po

Energy Bands:



Bohr Atomic Model

Single atom: 2 atoms: N atoms:



Pauli exclusion principle

Materials

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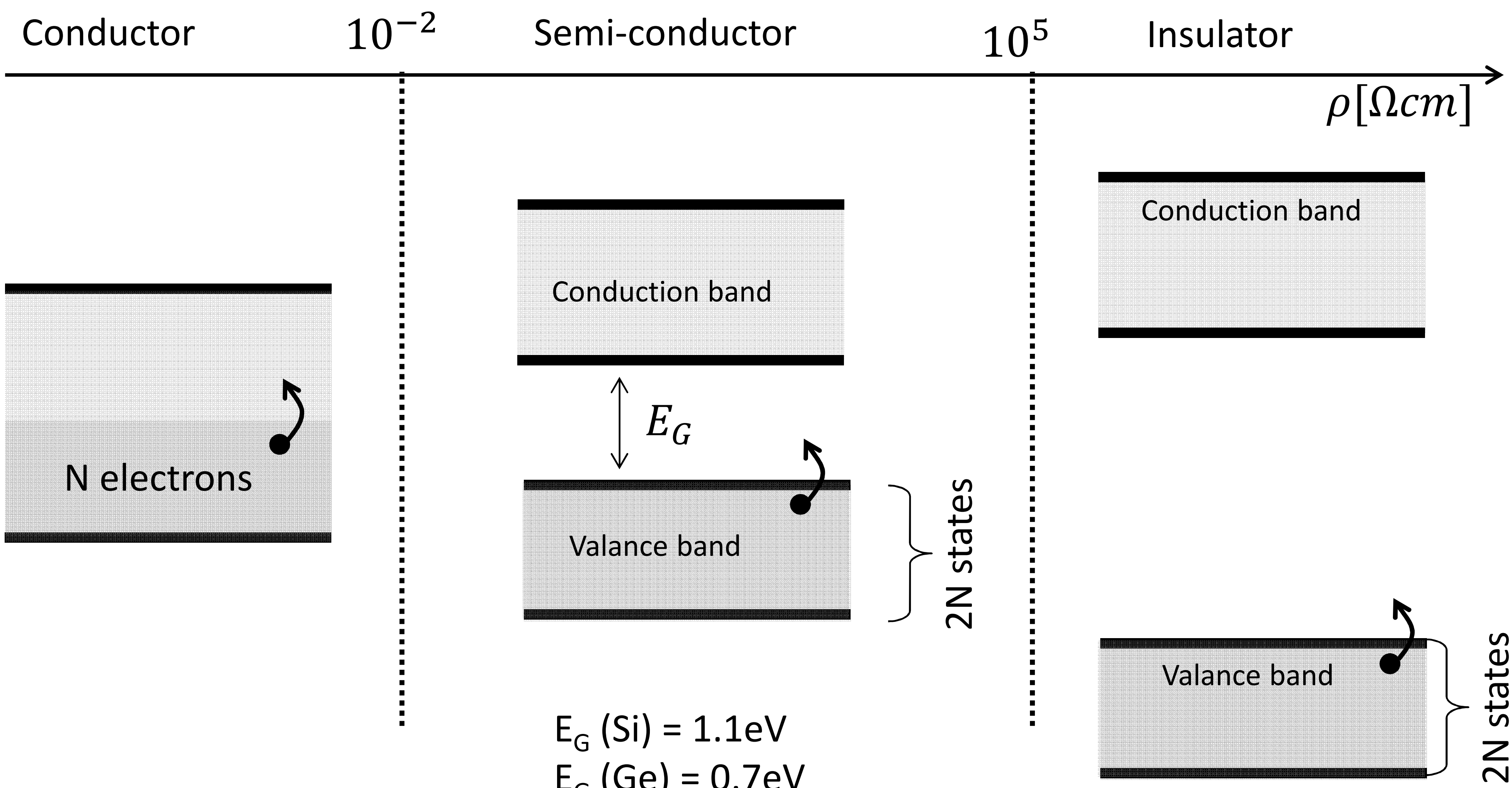

E_G (Si) = 1.1eV
E_G (Ge) = 0.7eV

E_G (SiO_2) = 9eV

empty seat / filled seat

Intrinsic Semiconductor

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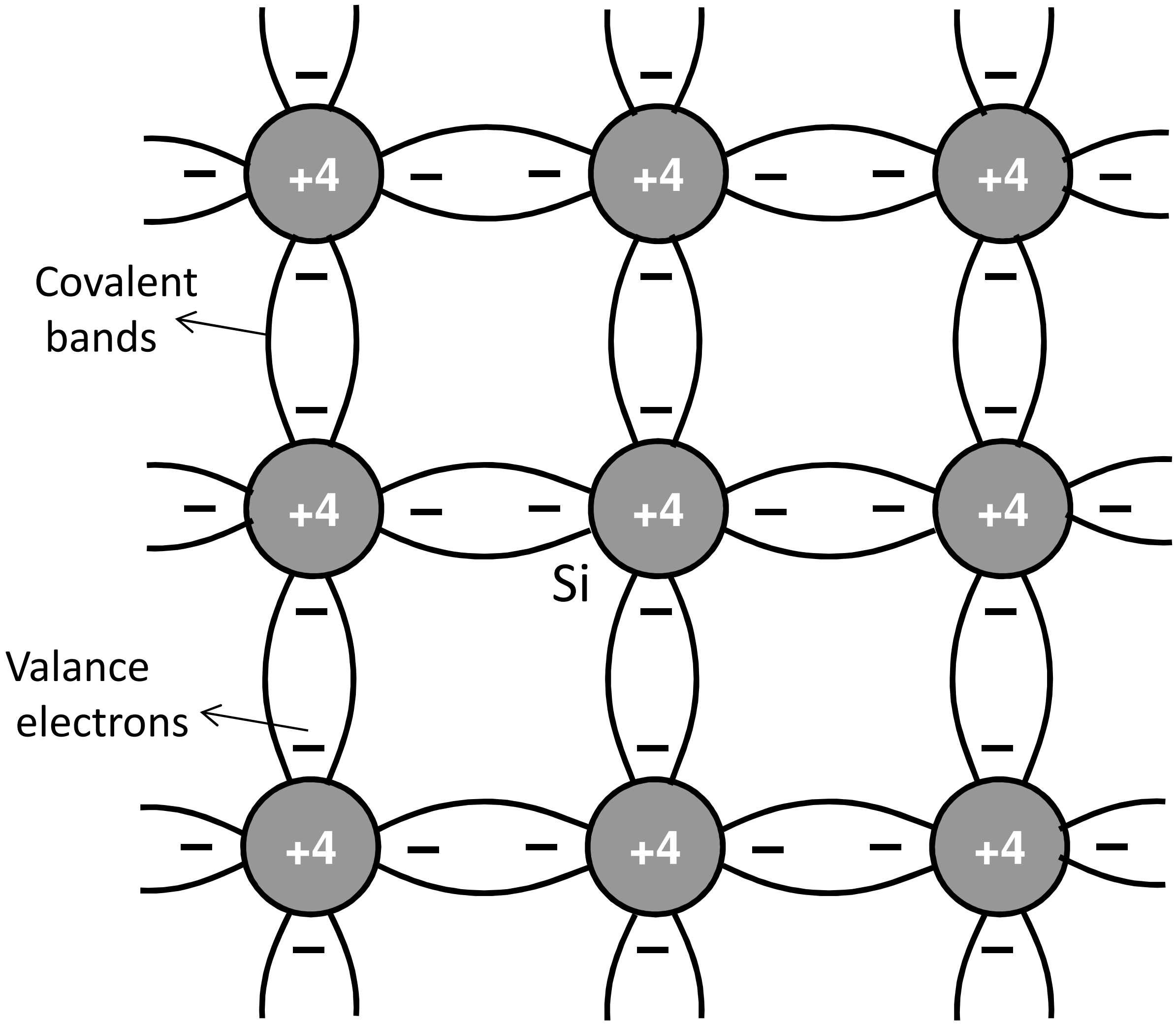
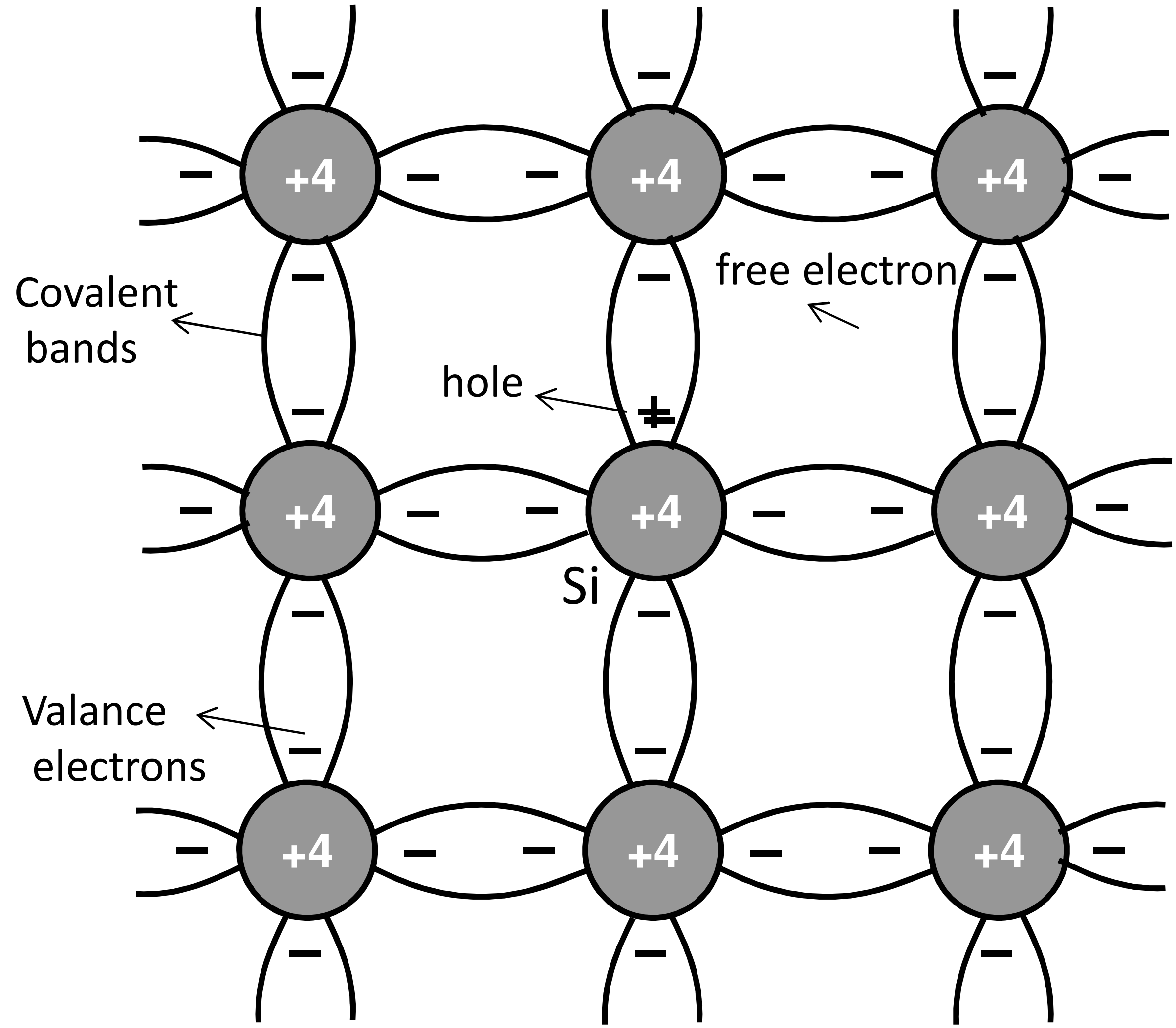


Intrinsic Semiconductor



n_0 electron density

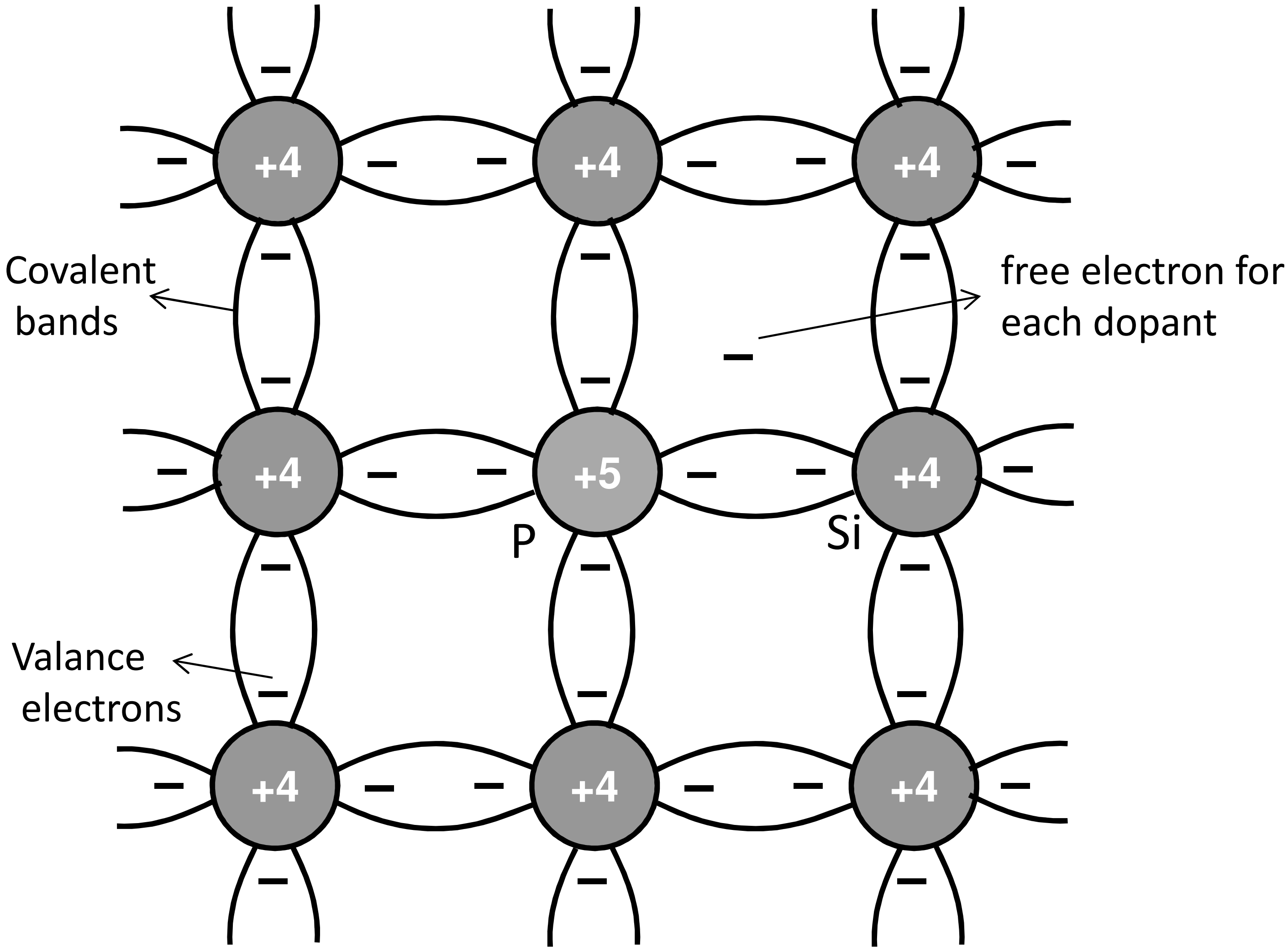
p_0 hole density

$$n_0 = p_0 = n_i$$

☹ useless!!

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

n-type Semiconductor



Donor: P , As , Sb

n_0 electron density

p_0 hole density

$$n_0 = N_D$$

$$n_0 p_0 = n_i^2$$

N_D *up to* $10^{19}\ cm^{-3}$

☺ $n(Si) = 2 \times 10^{23} cm^{-3}$

p-type Semiconductor

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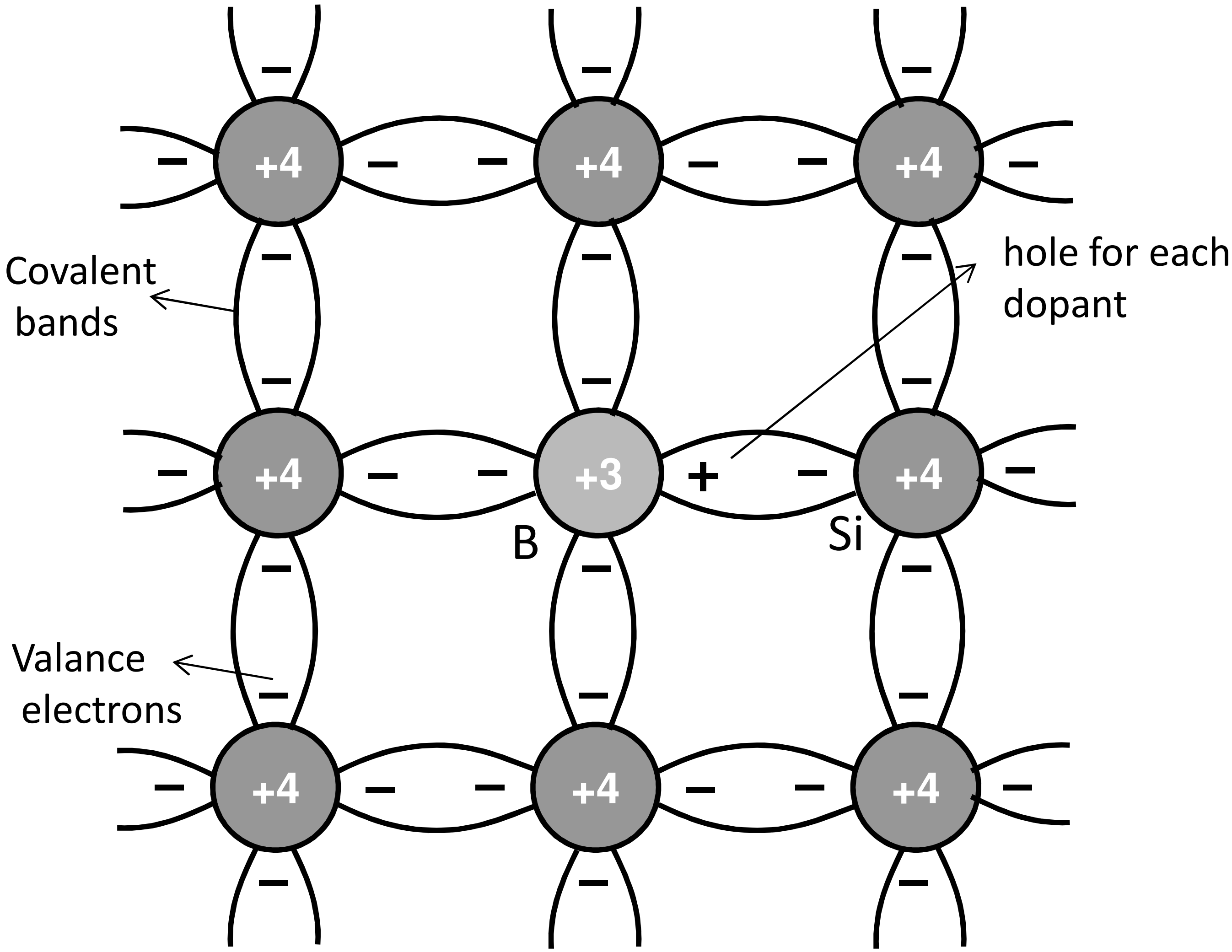

Acceptor: B , Ga , In

n_0 electron density

p_0 hole density

$$n_0 = N_A$$

$$n_0 p_0 = n_i^2$$

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

☺ $n(Si) = 2 \times 10^{23} cm^{-3}$

Energy Diagrams

1.
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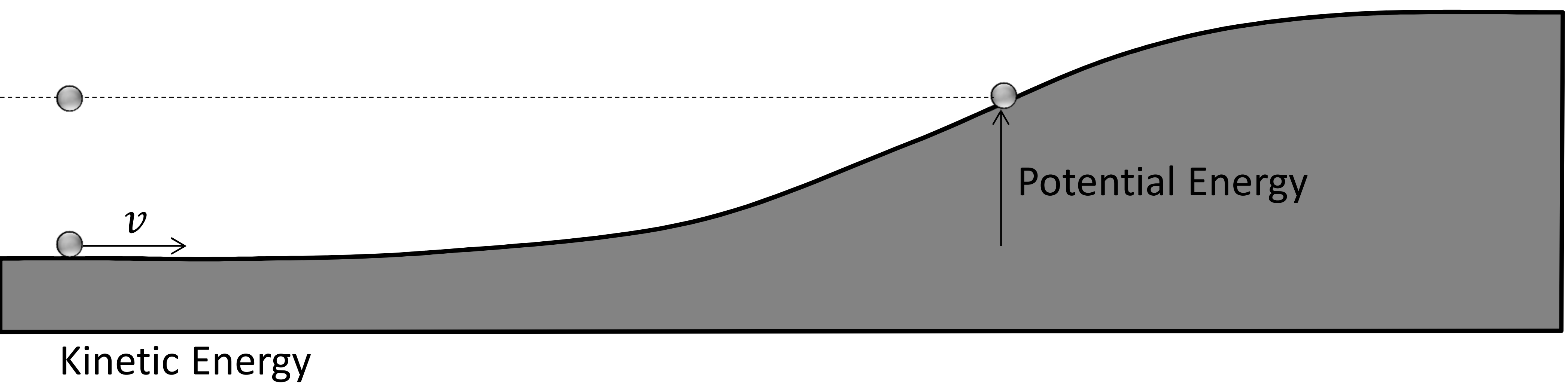

Energy Diagrams

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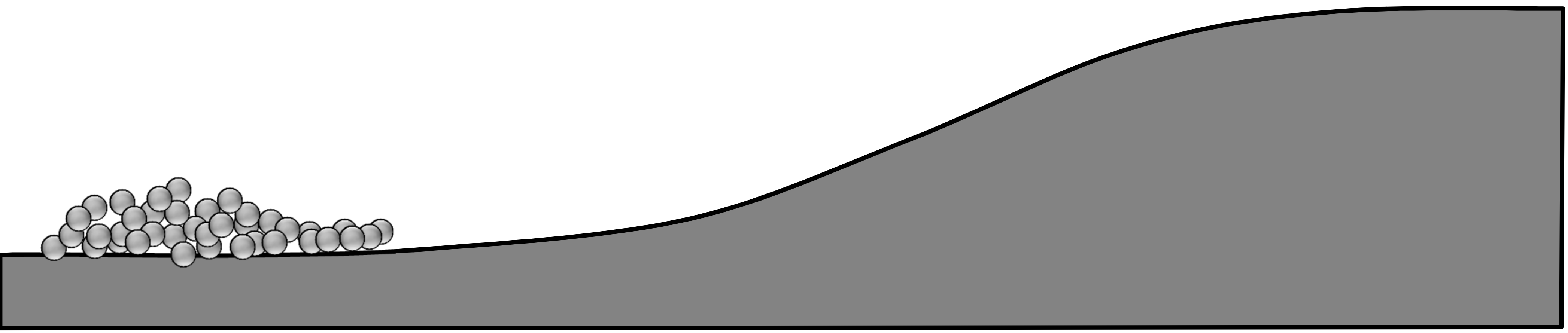

Energy Diagrams

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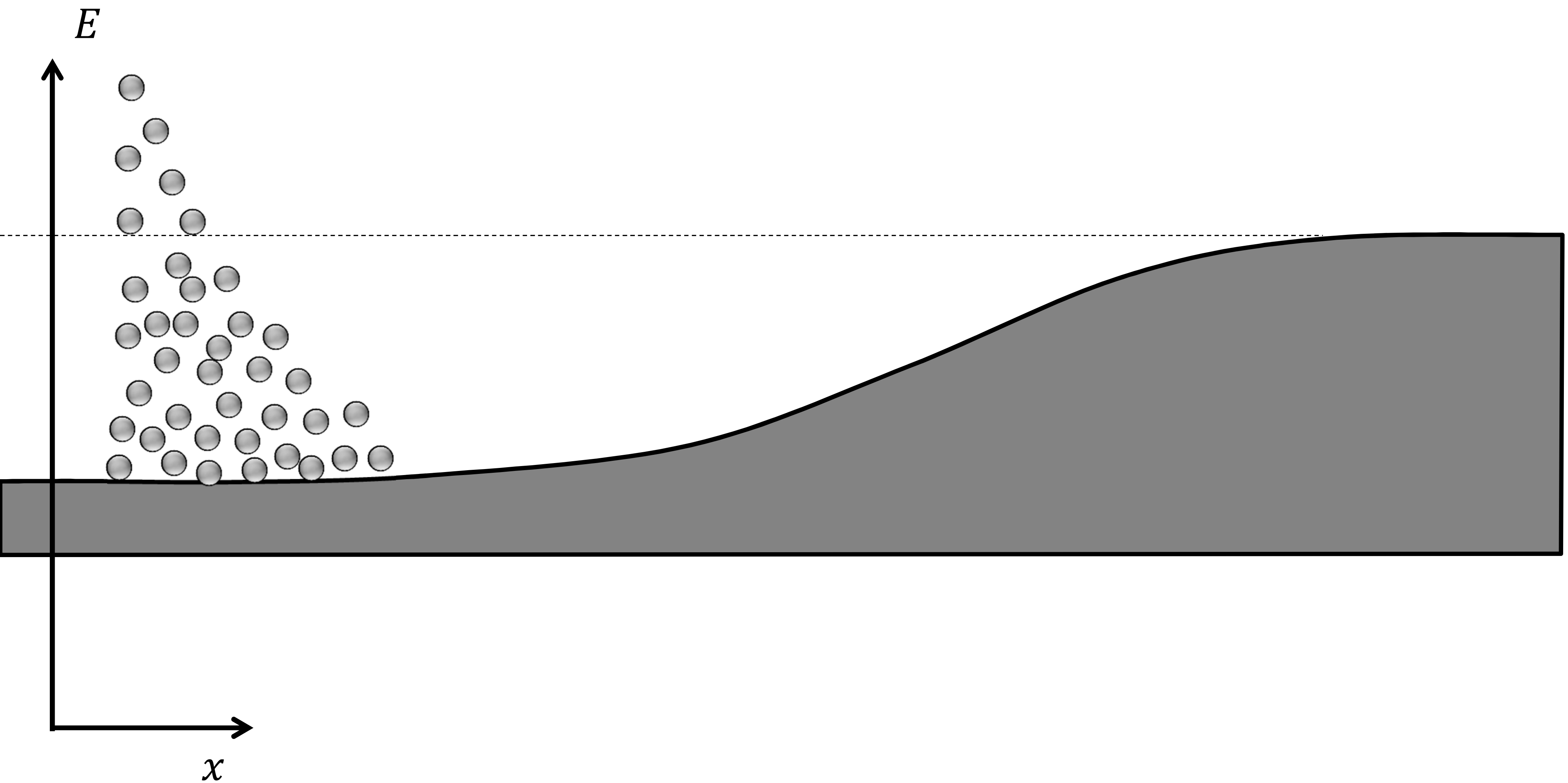
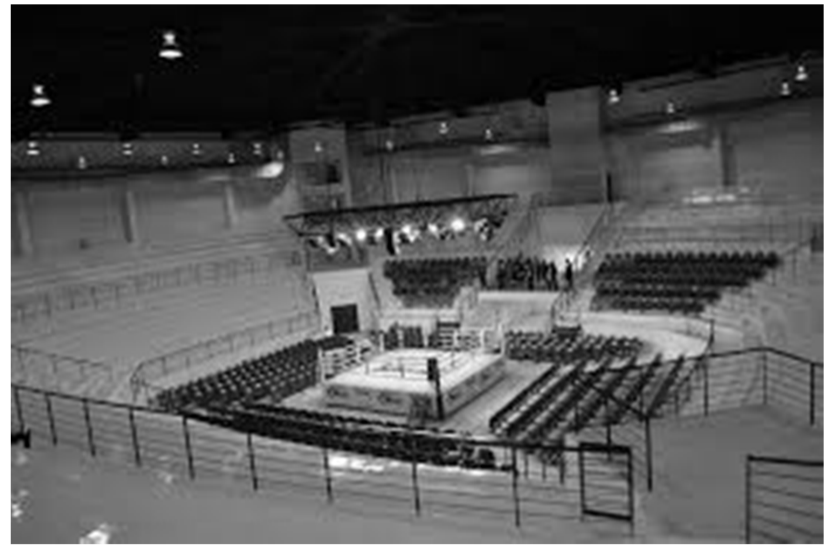


Density of States

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

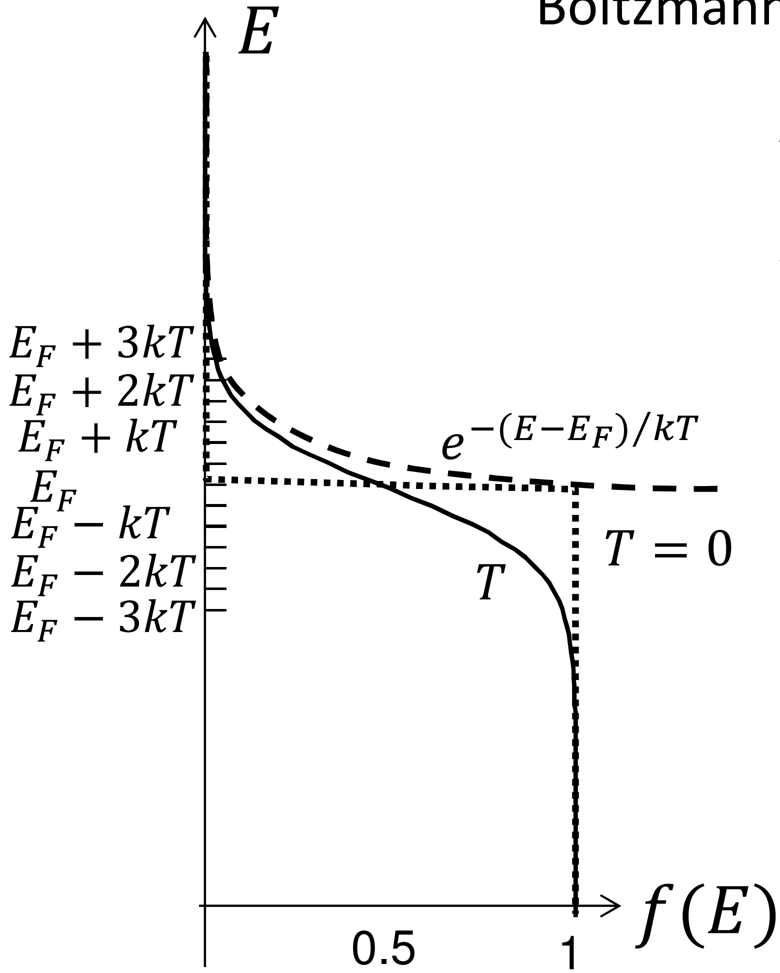
$$f(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$$

E_f is called the Fermi energy or the Fermi level.

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

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

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



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

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

Materials

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2. [illegible]
3. [illegible]
4. [illegible]
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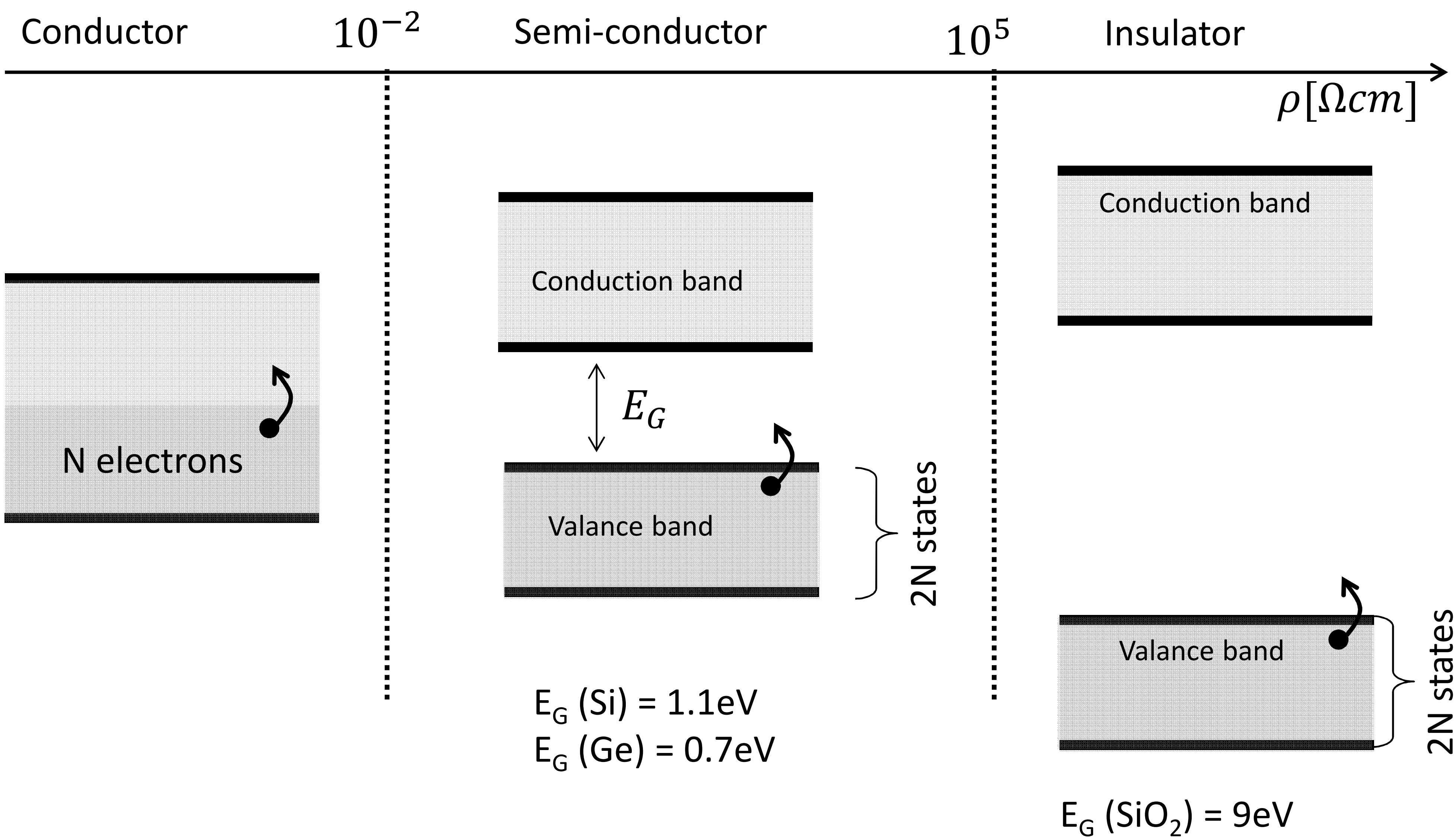


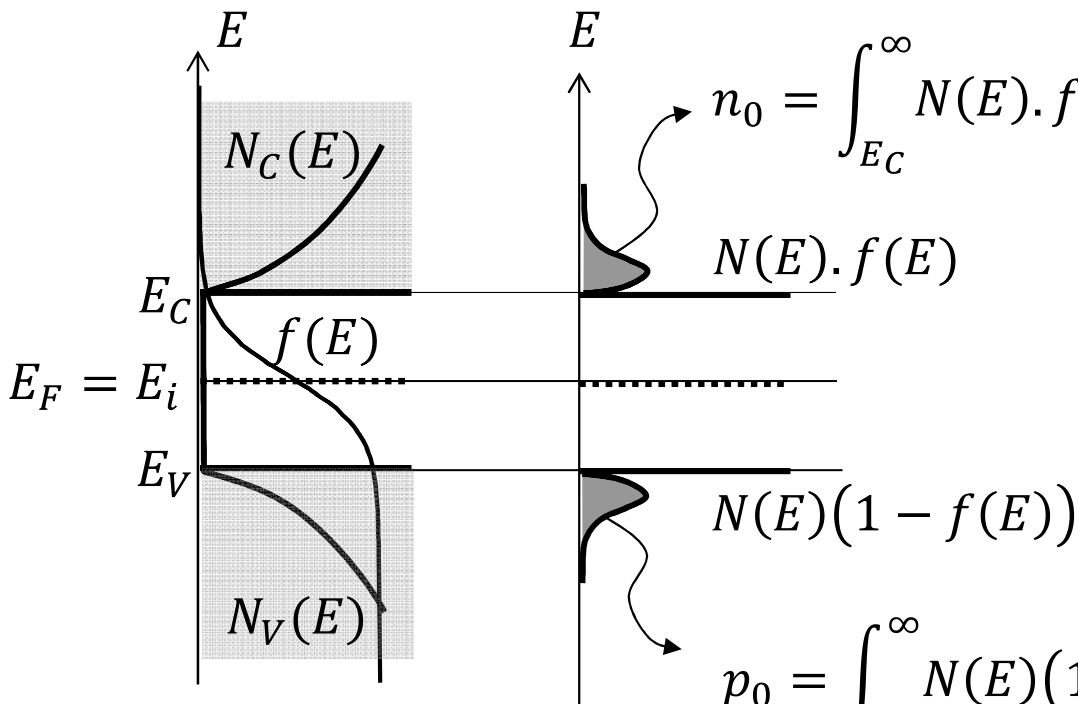
empty seat / filled seat

Electron / Holes : Intrinsic

intrinsic

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

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



$$n_0 = \int_{E_C}^{\infty} N(E).\,f(E)dE$$

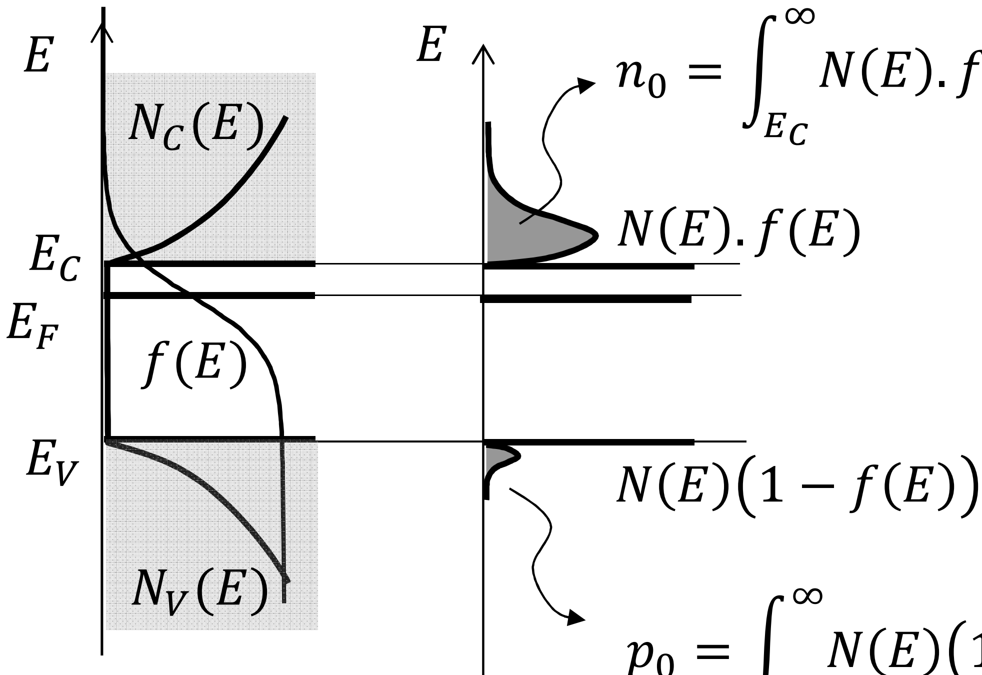
$$p_0 = \int_{E_C}^{\infty} N(E)\big(1 - f(E)\big)dE$$

Electron / Holes : n-type

n-type

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

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



$$n_0 = \int_{E_C}^{\infty} N(E).\,f(E)dE$$

$$p_0 = \int_{E_C}^{\infty} N(E)\big(1 - f(E)\big)dE$$

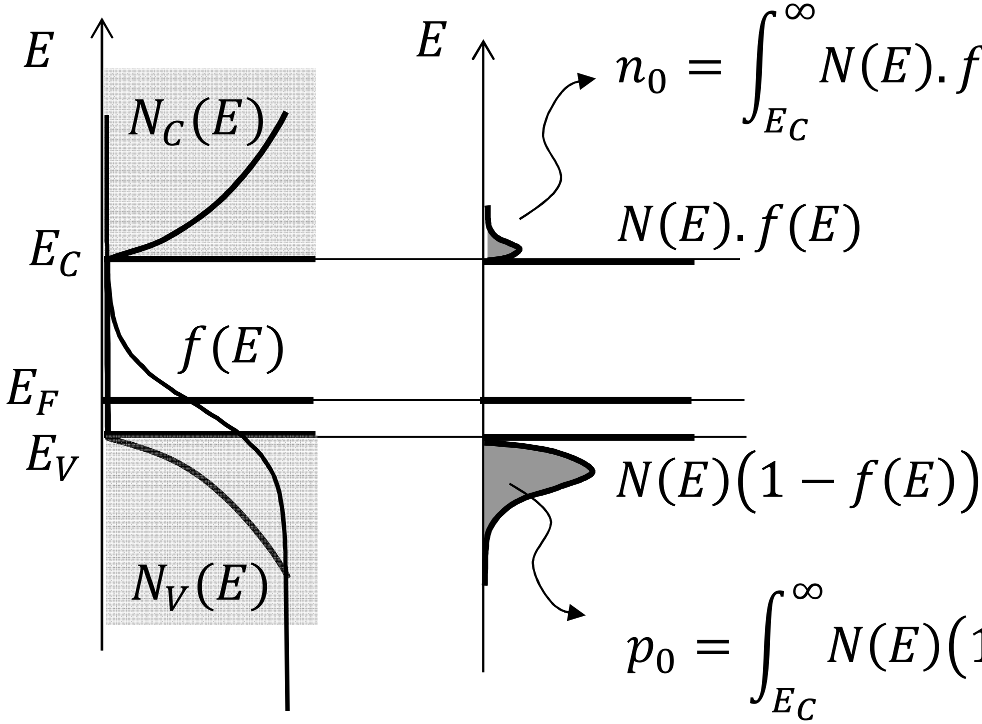
$n_0 \gg p_0$

Electron / Holes : p-type

p-type

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

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

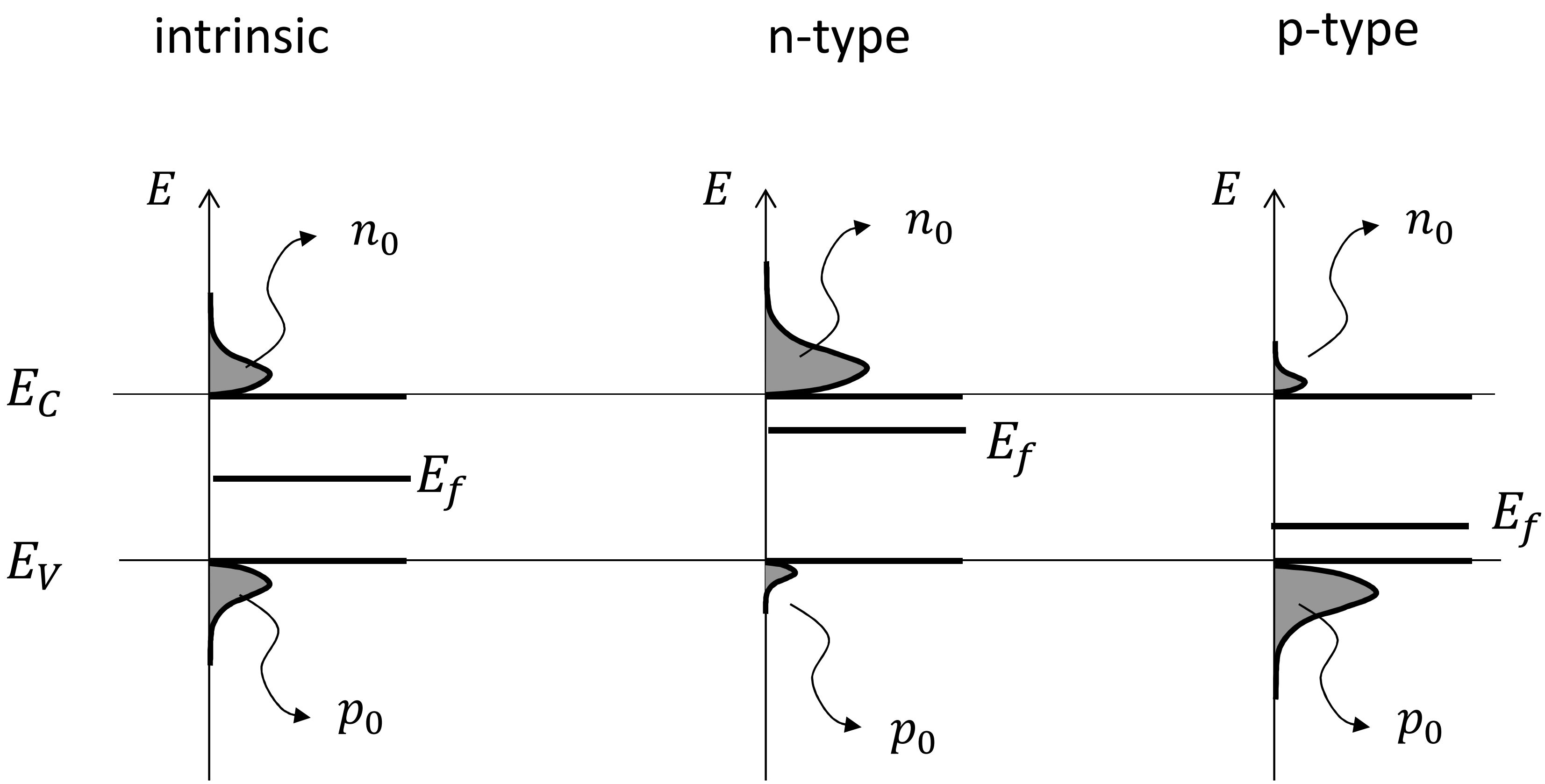


$$n_0 = \int_{E_C}^{\infty} N(E).f(E)dE$$

$$p_0 = \int_{E_C}^{\infty} N(E)\big(1 - f(E)\big)dE$$

$$p_0 \gg n_0$$

Fermi Energy



Fermi Energy

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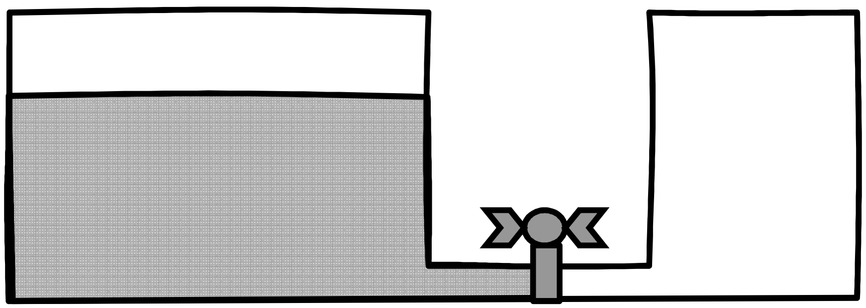

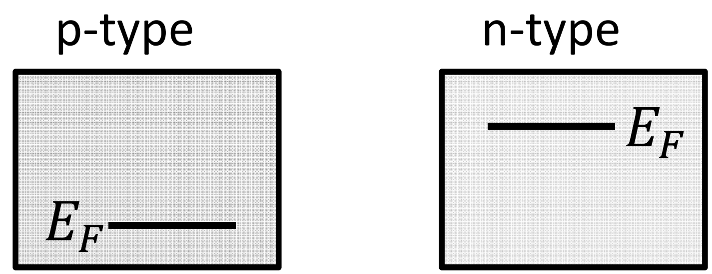

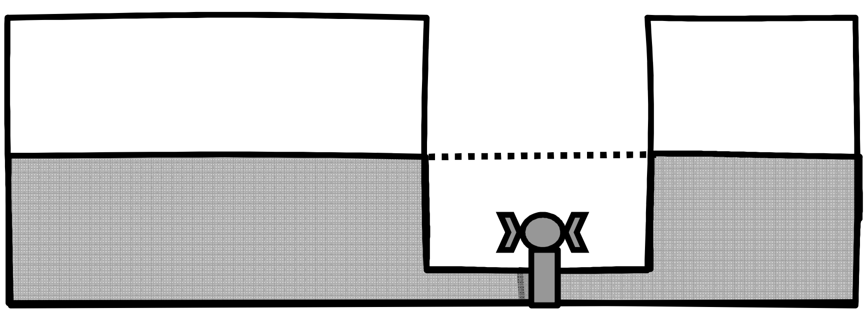

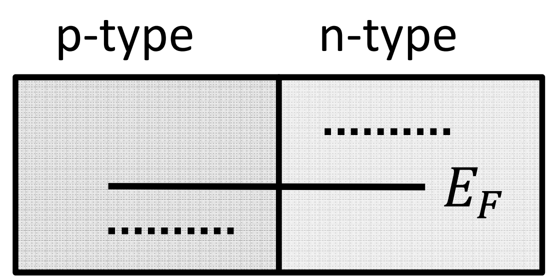

Flow of Charge

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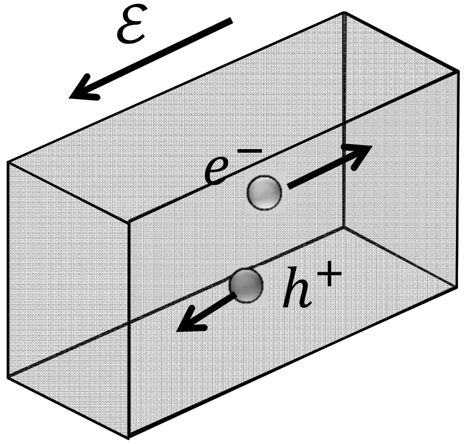
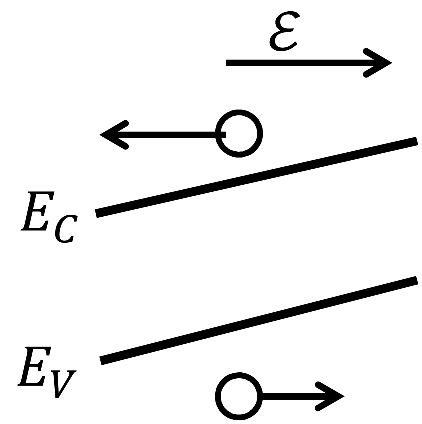
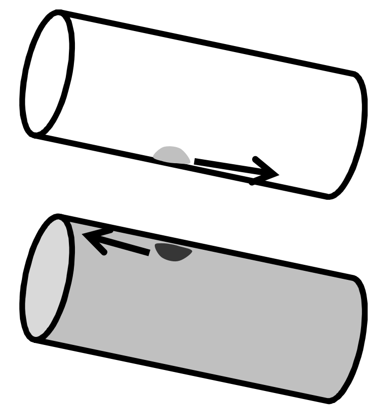
Drift

Electric field → gravitational field

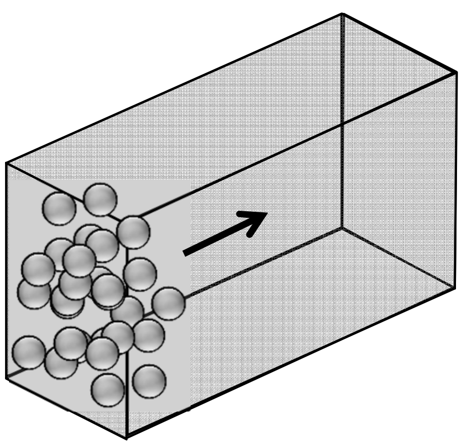






$$J \propto \mathcal{E}$$

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

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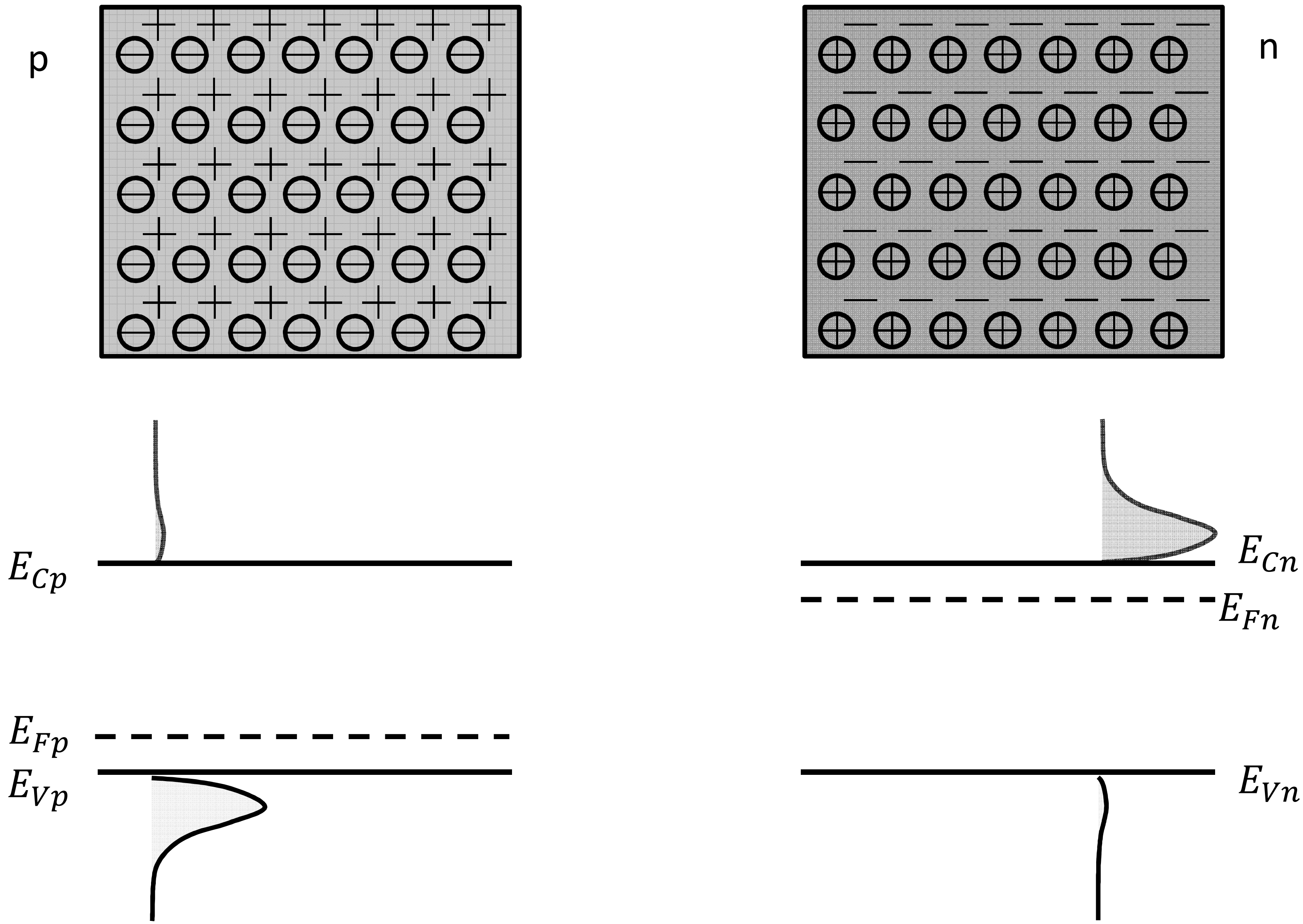
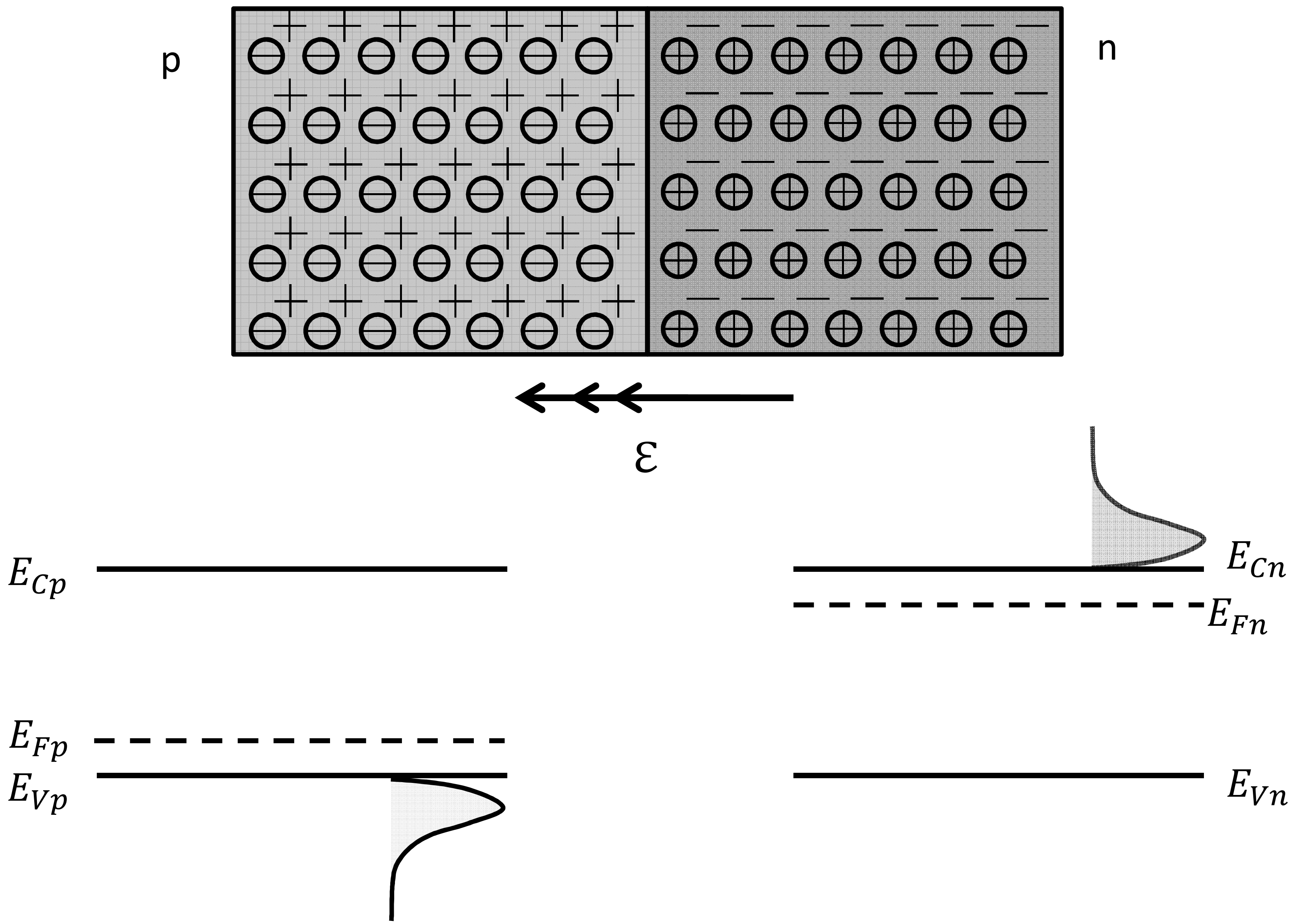
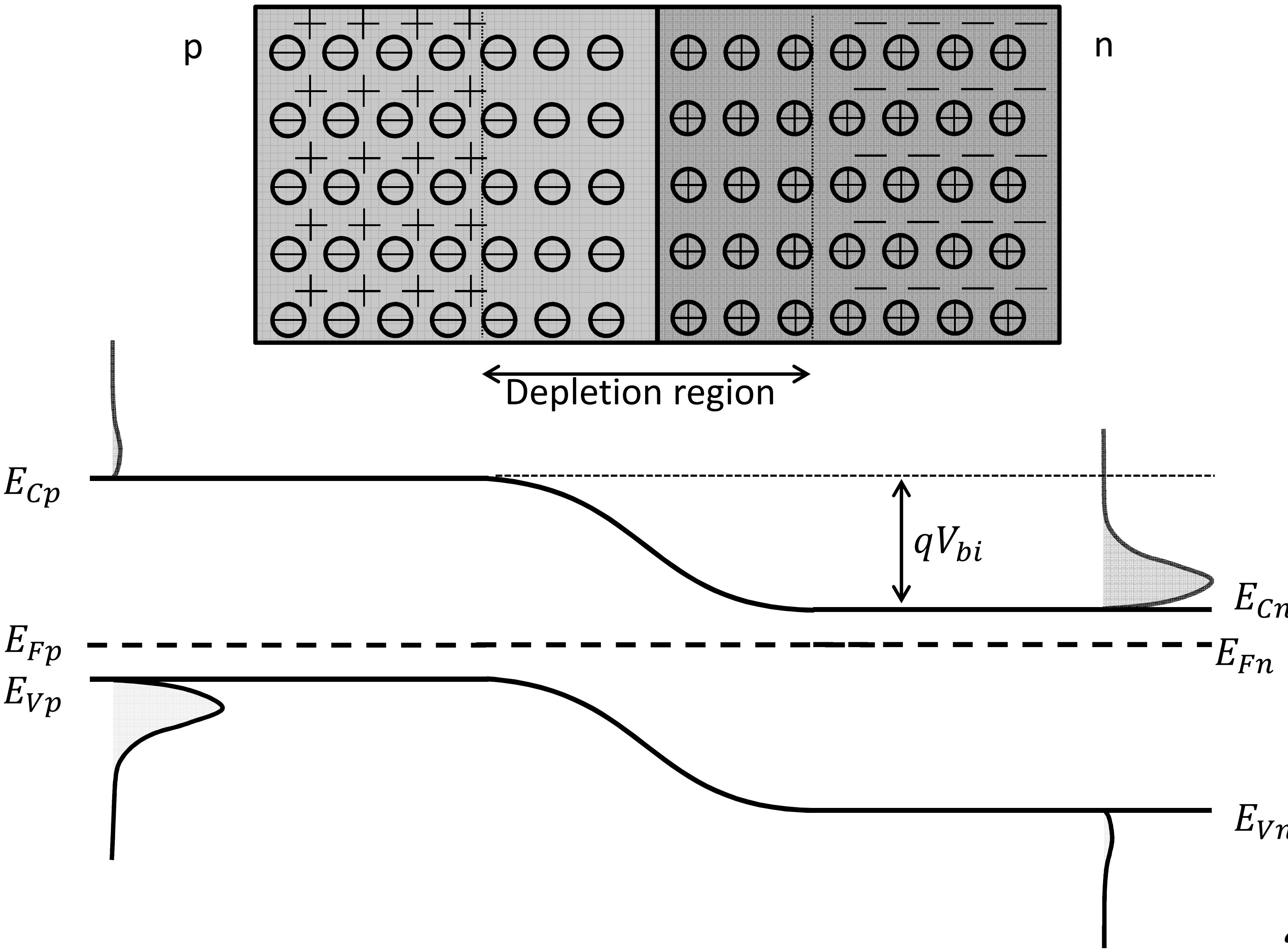


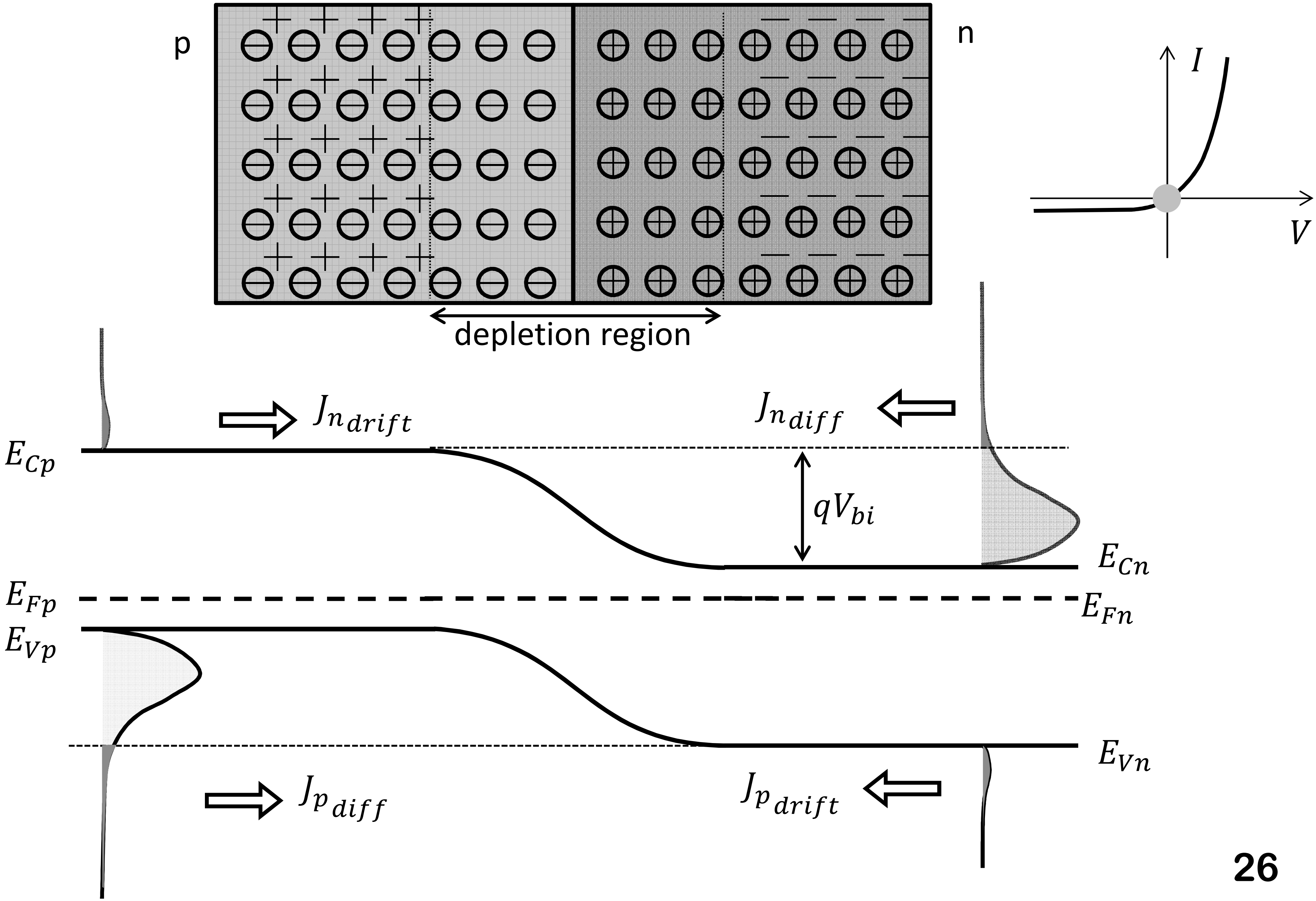
PN junctions



PN junctions



PN junctions



PN junctions , Reverse Biased

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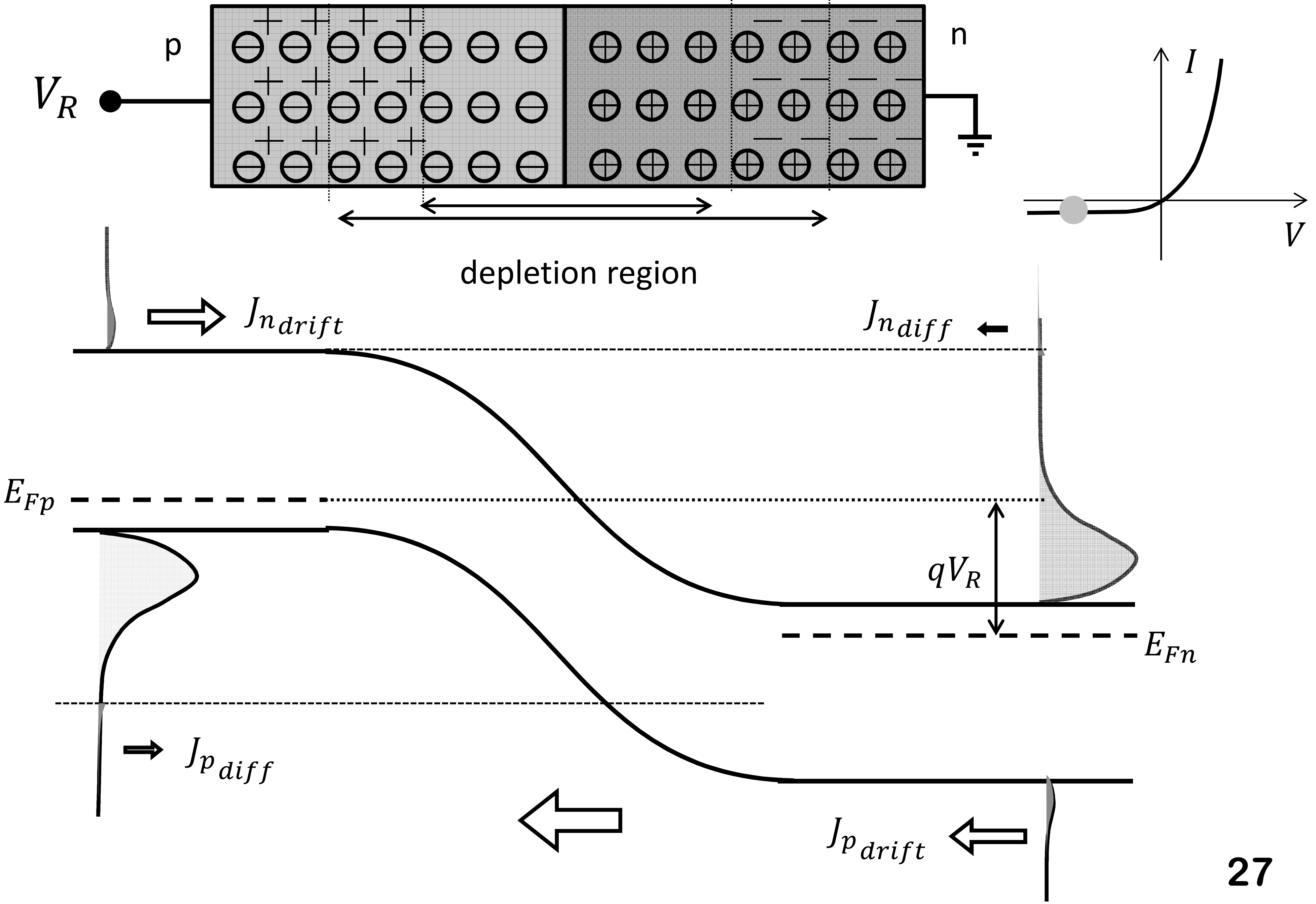
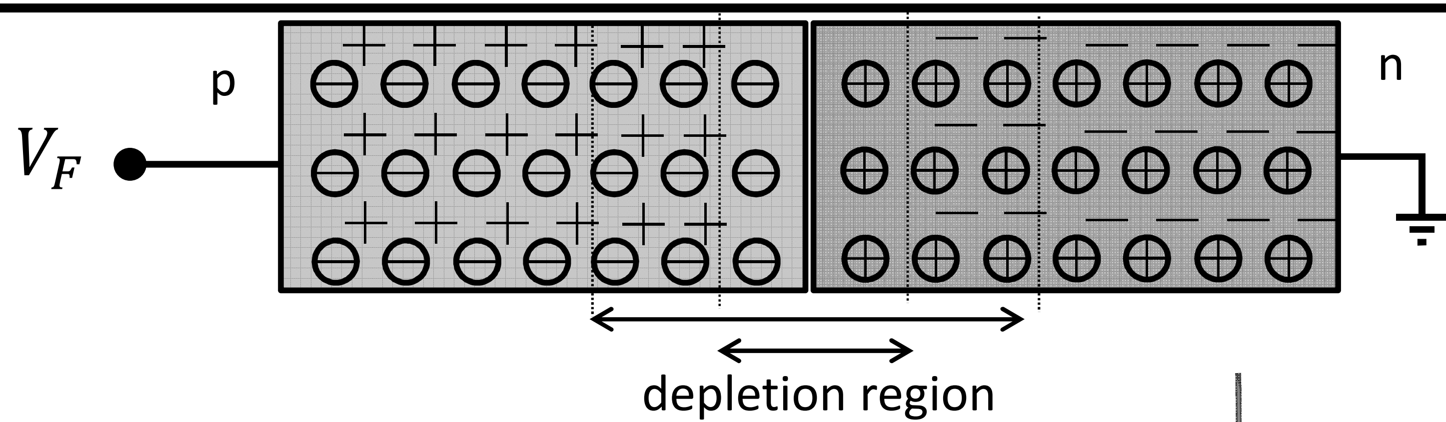
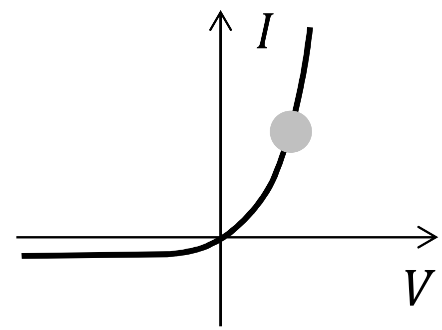
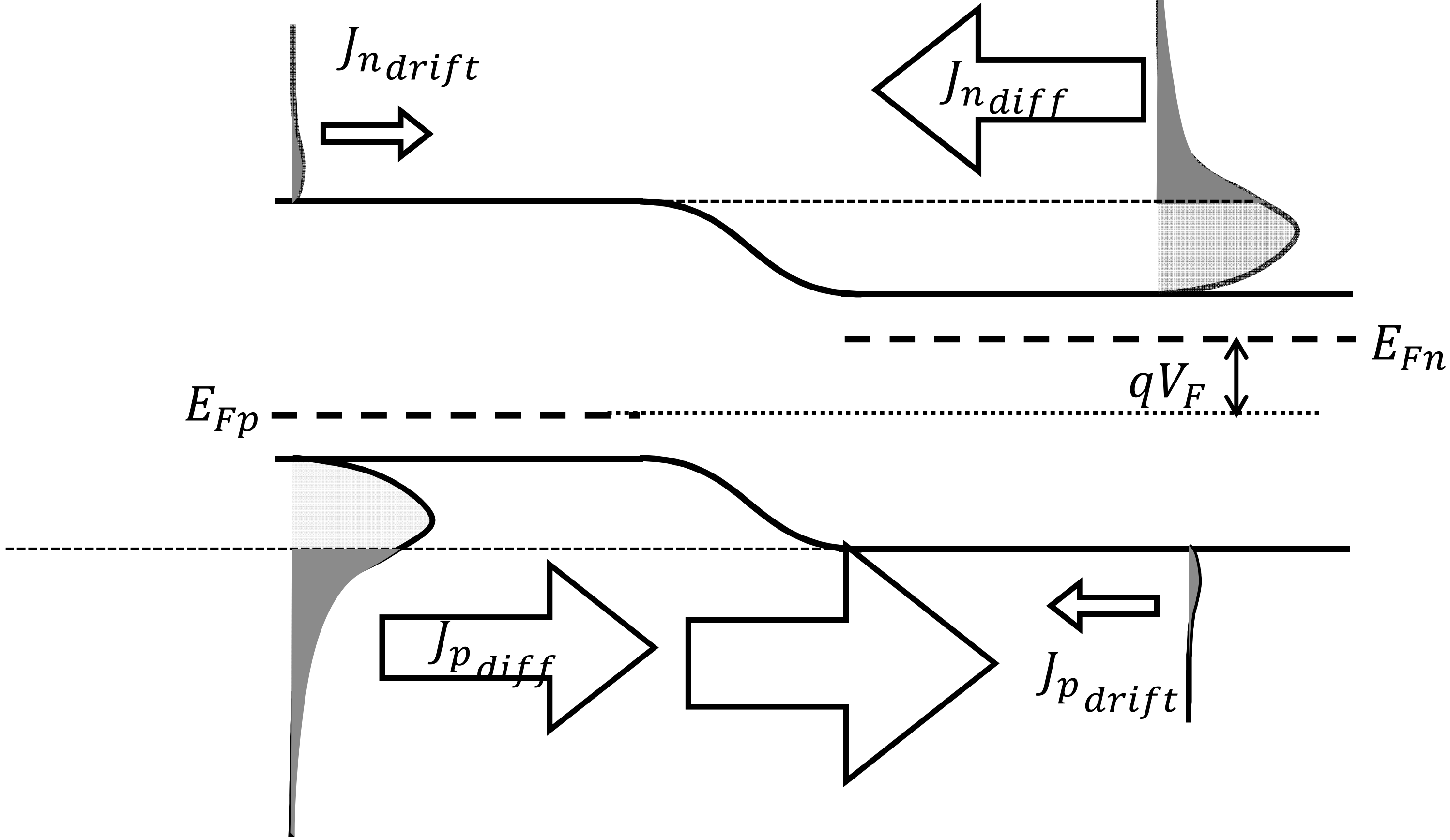


PN junctions , Forward Biased







BJT Electrostatics

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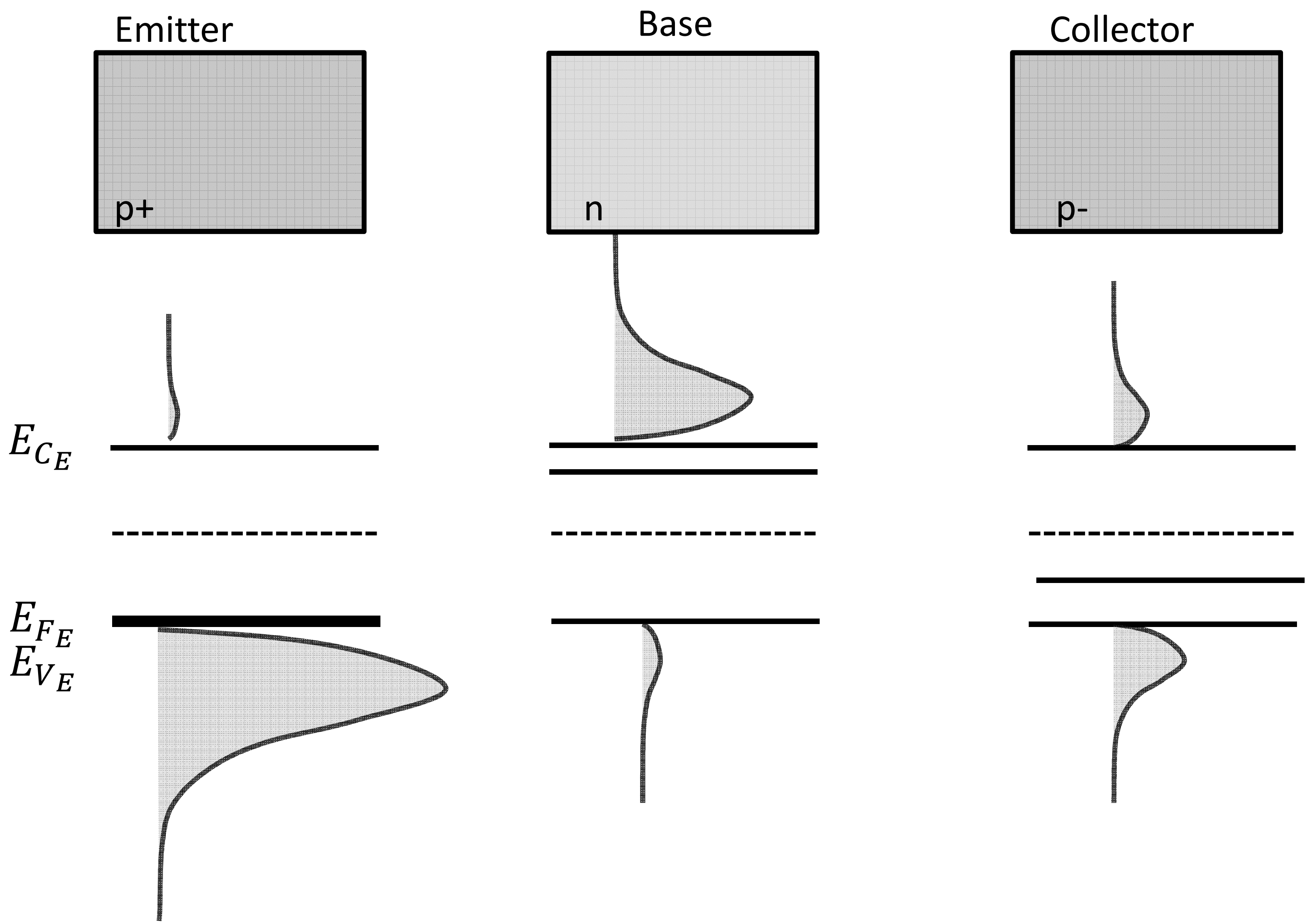
pnp



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

BJT Electrostatics

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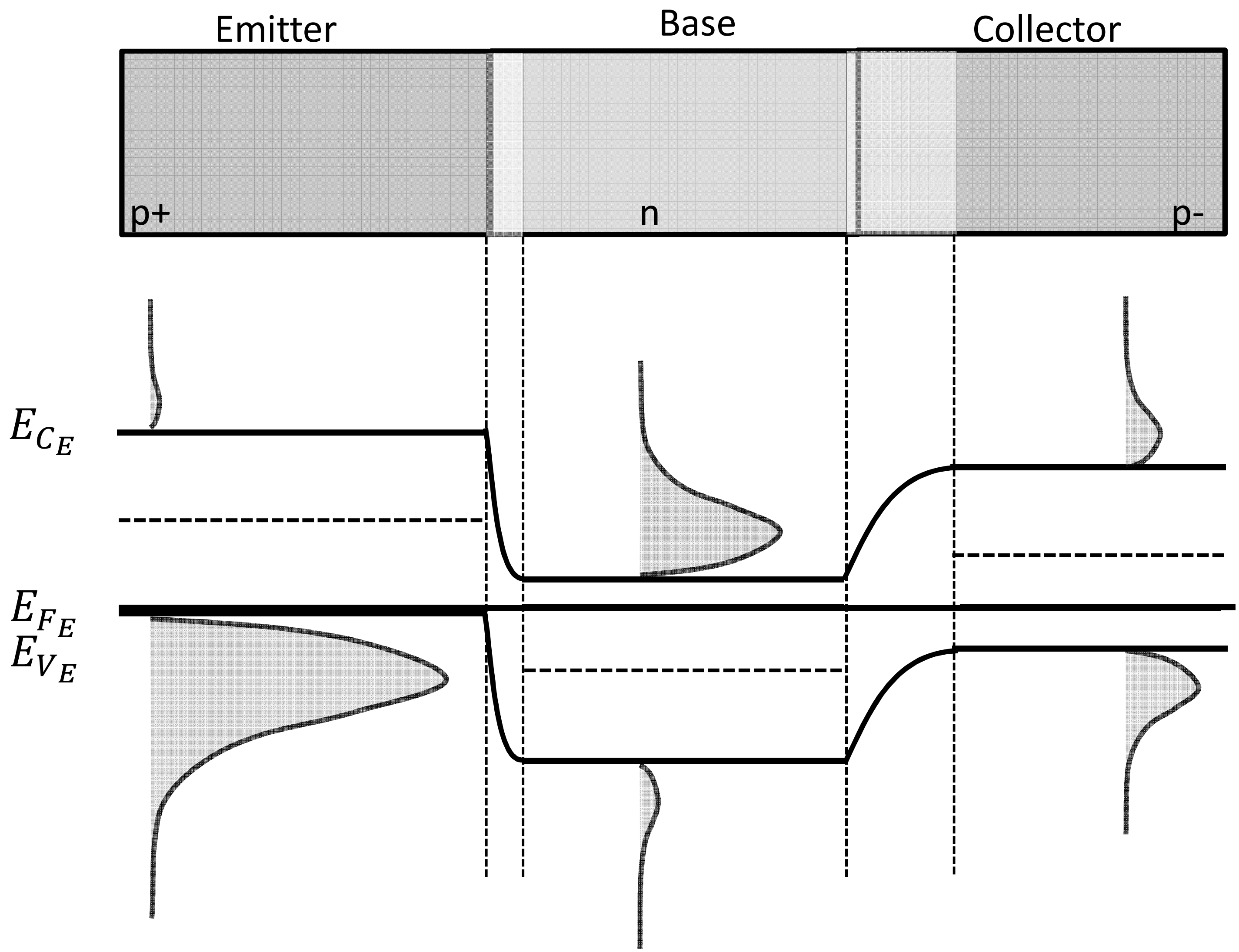
pnp



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

BJT Electrostatics

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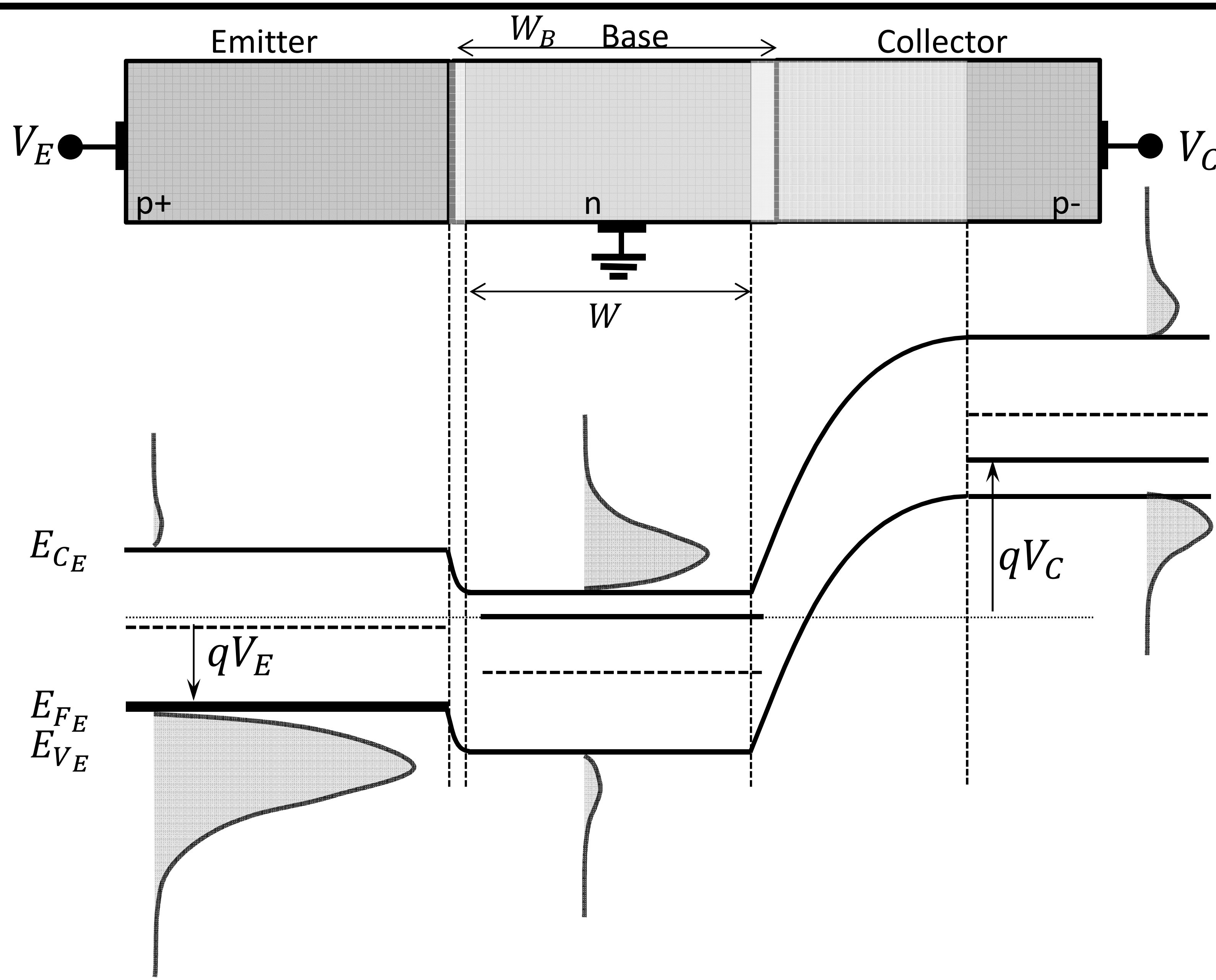
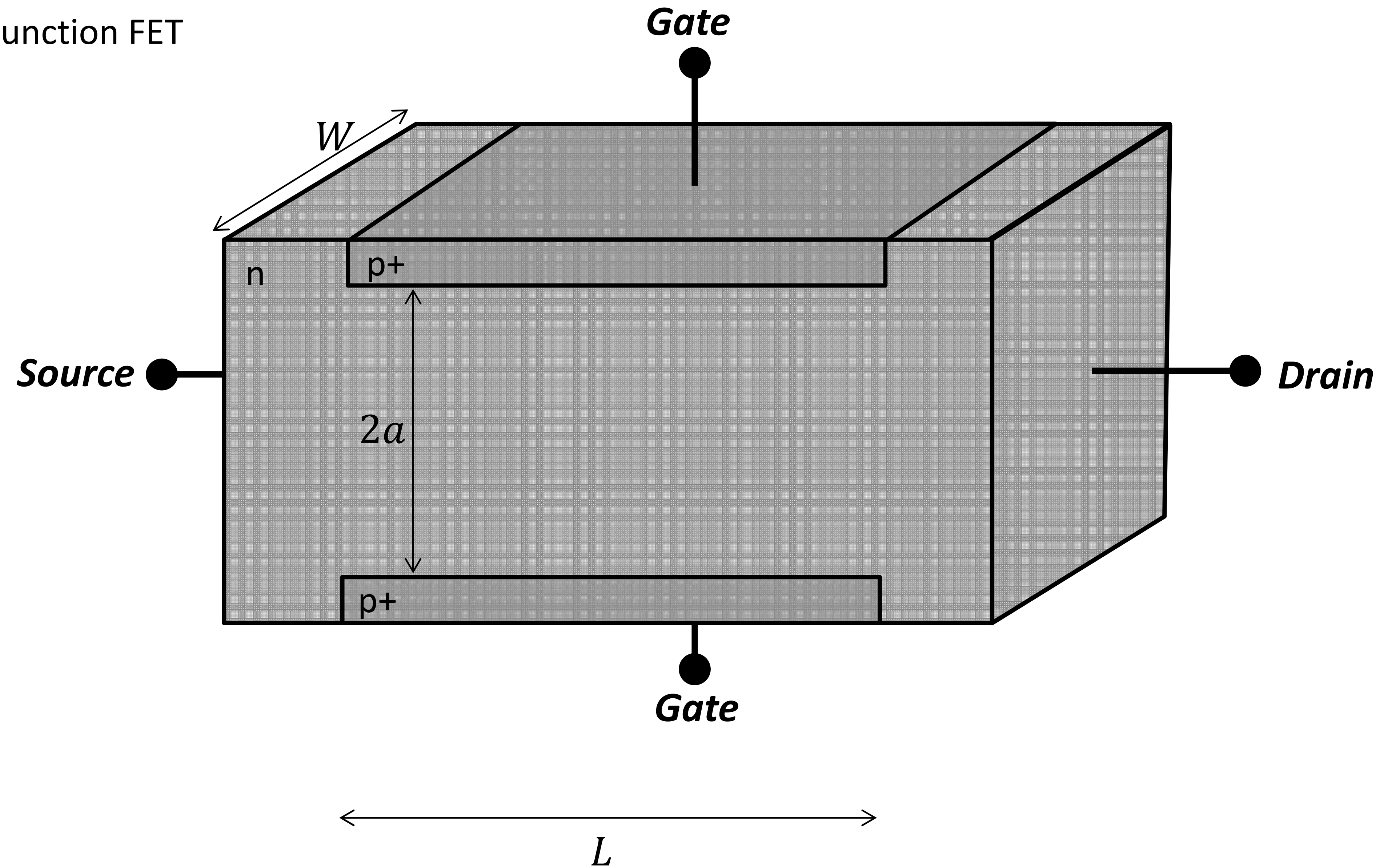
pnp

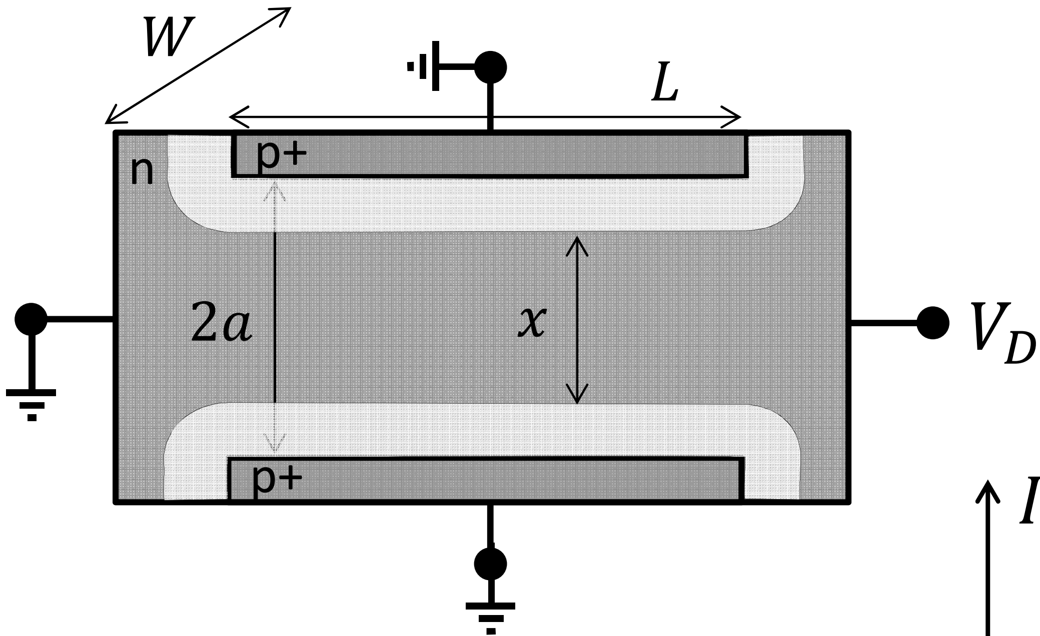


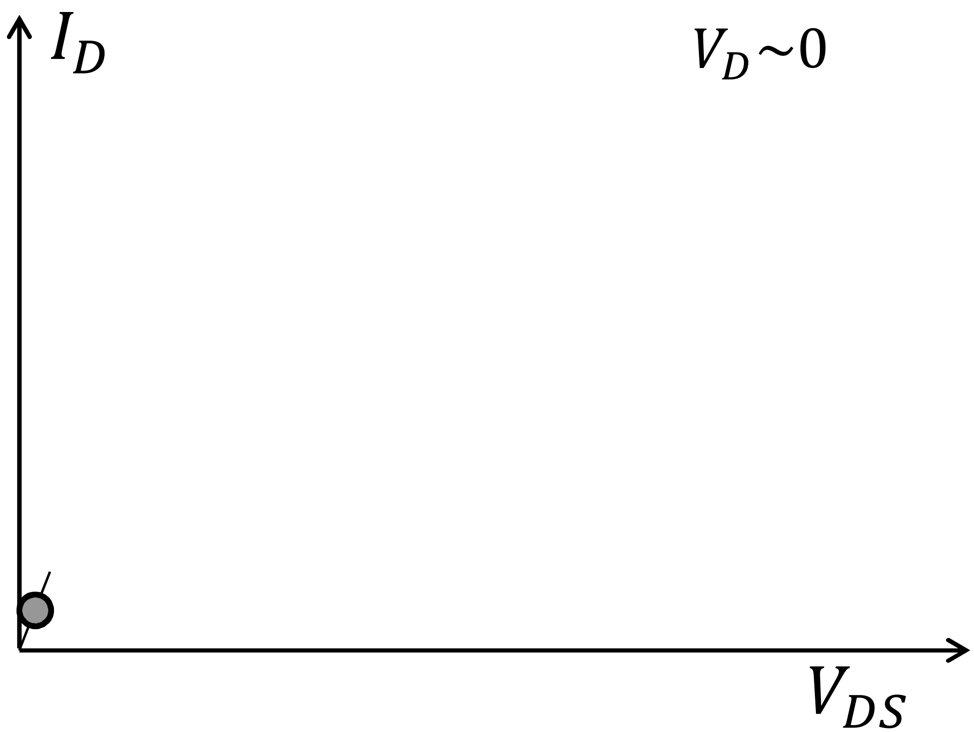
JFET

Junction FET



JFET





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

JFET

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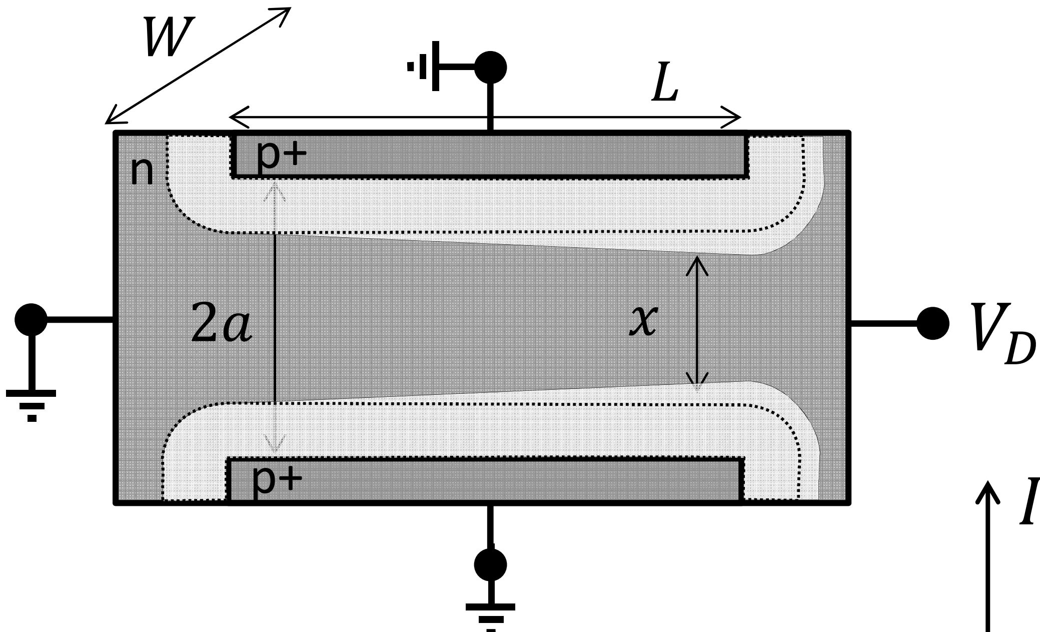
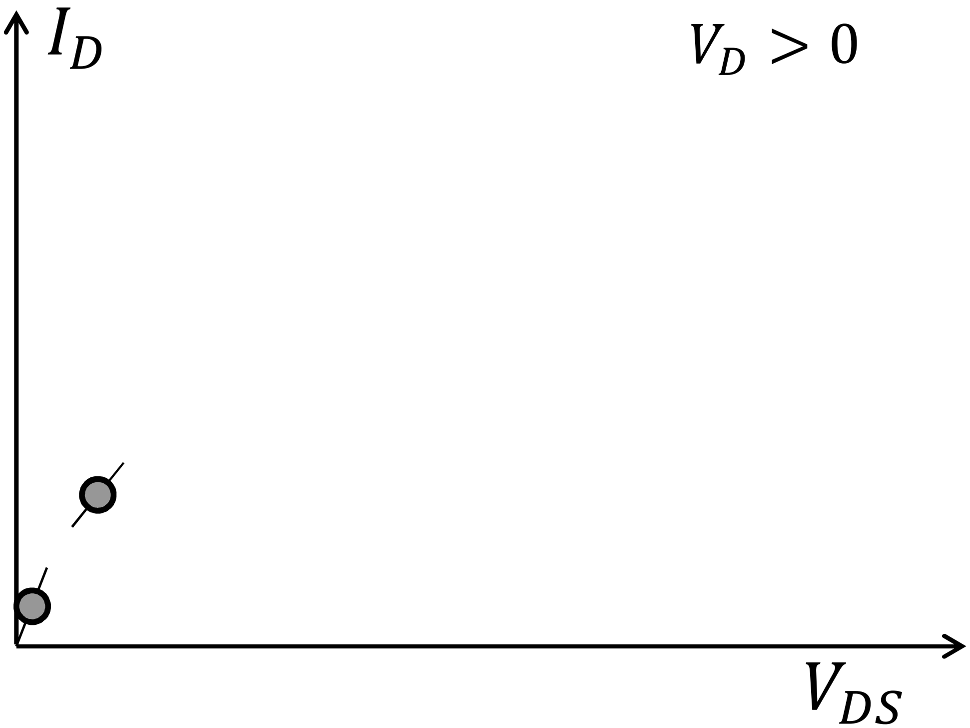


$$R = \rho \frac{L}{Wx}$$



JFET

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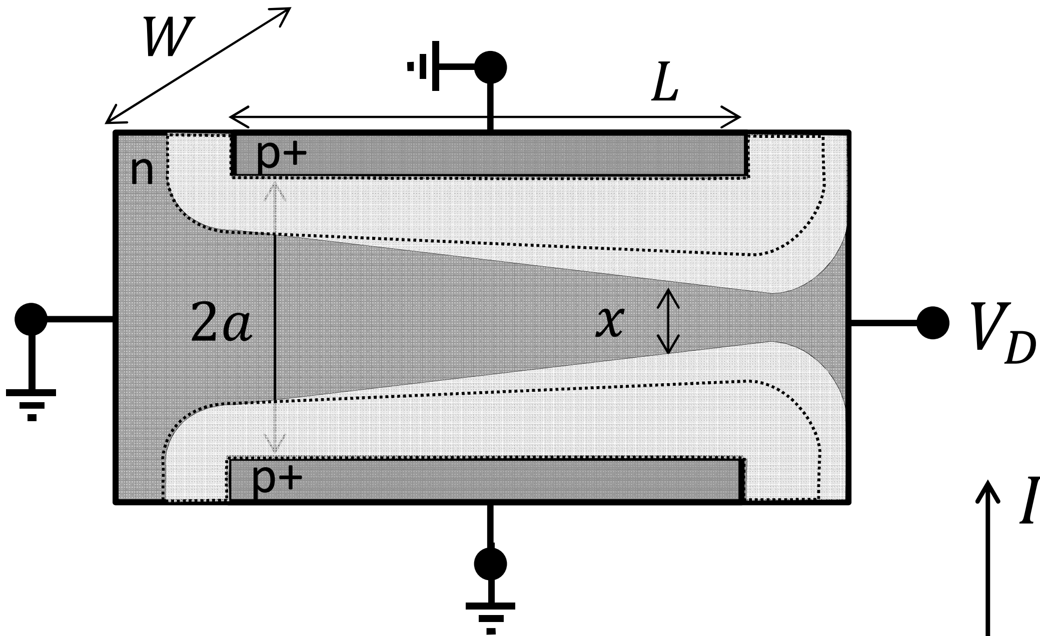

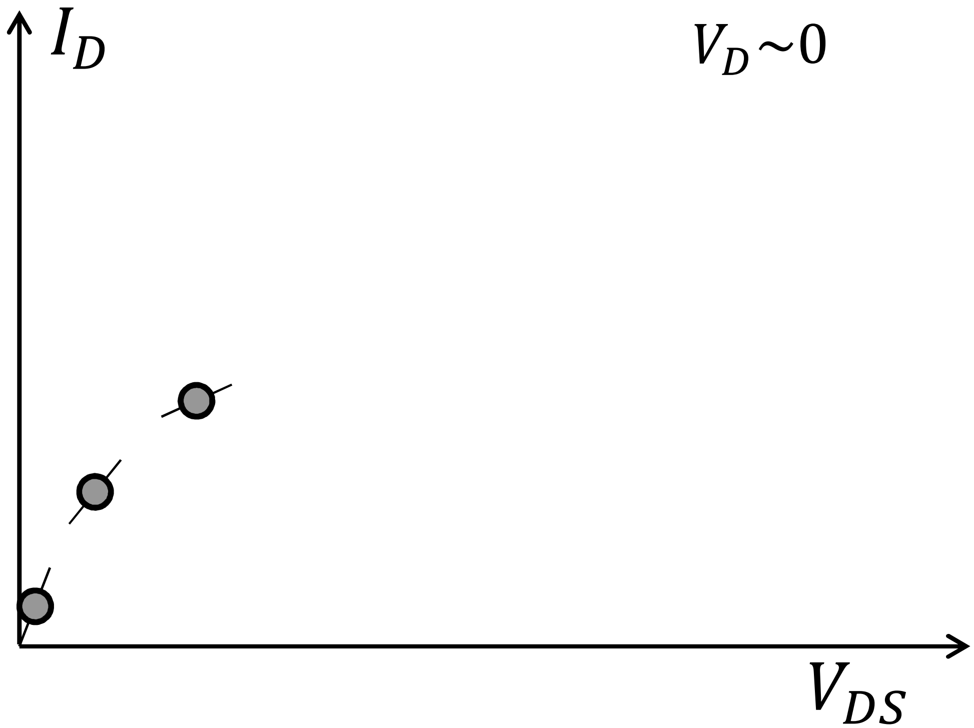

$$R = \rho \frac{L}{Wx}$$

JFET

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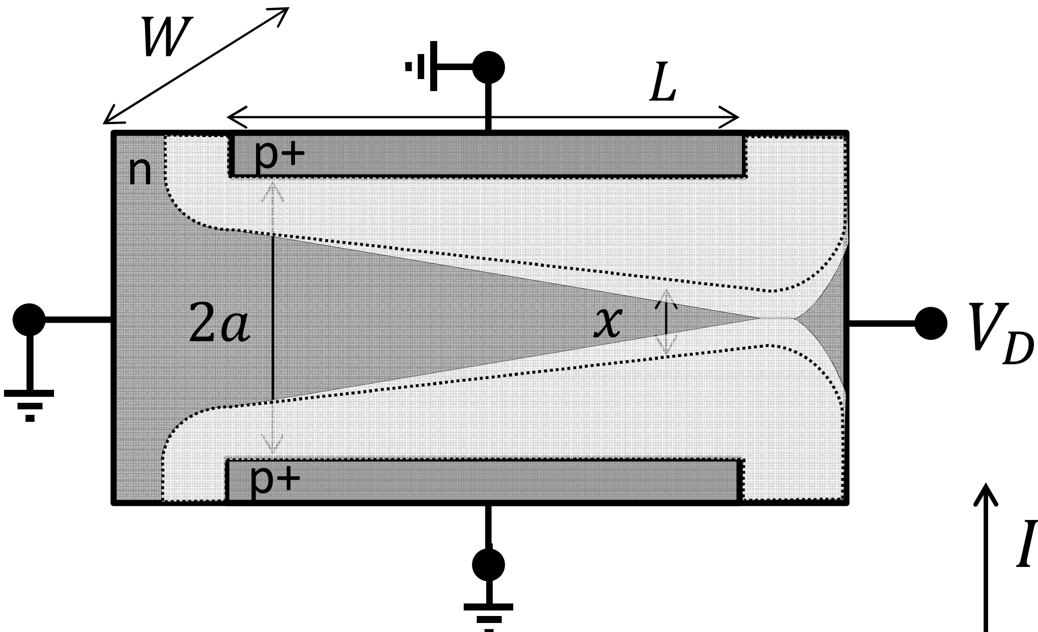
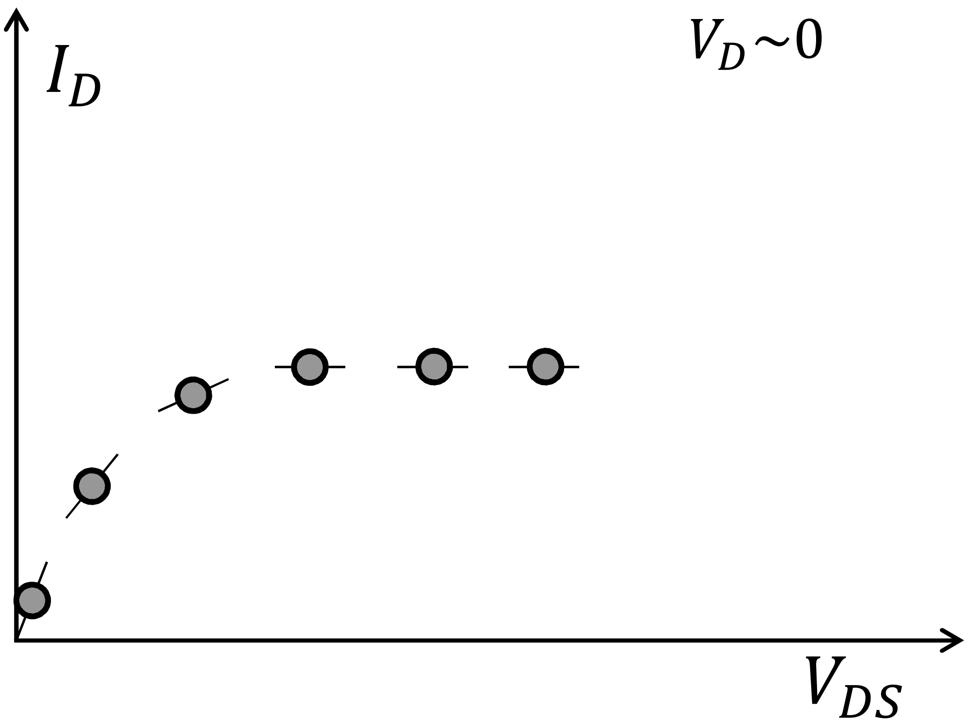


$$R = \rho \frac{L}{Wx}$$



JFET

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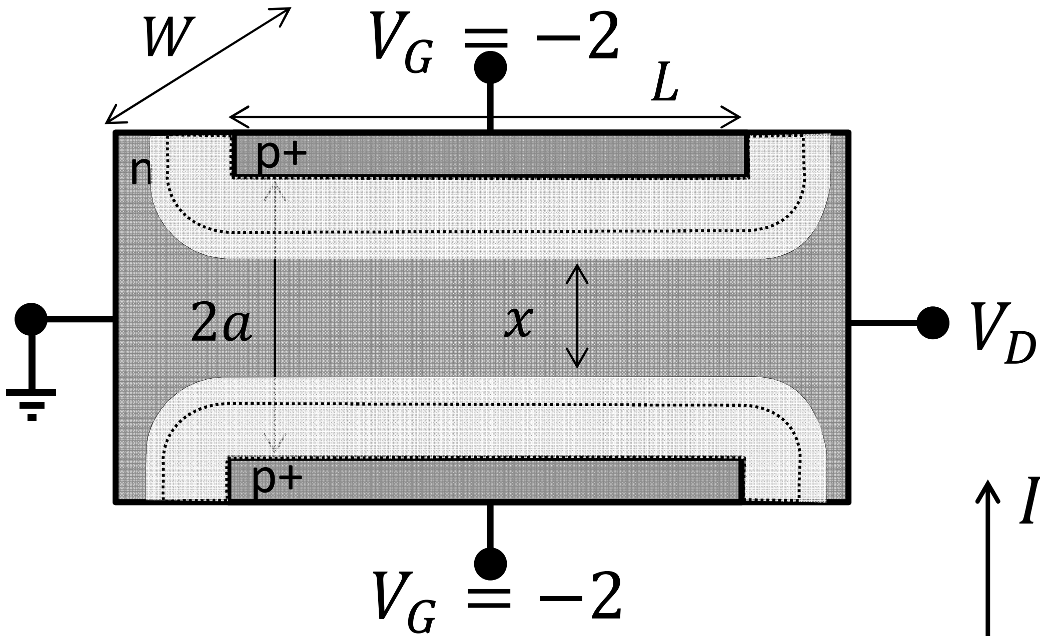
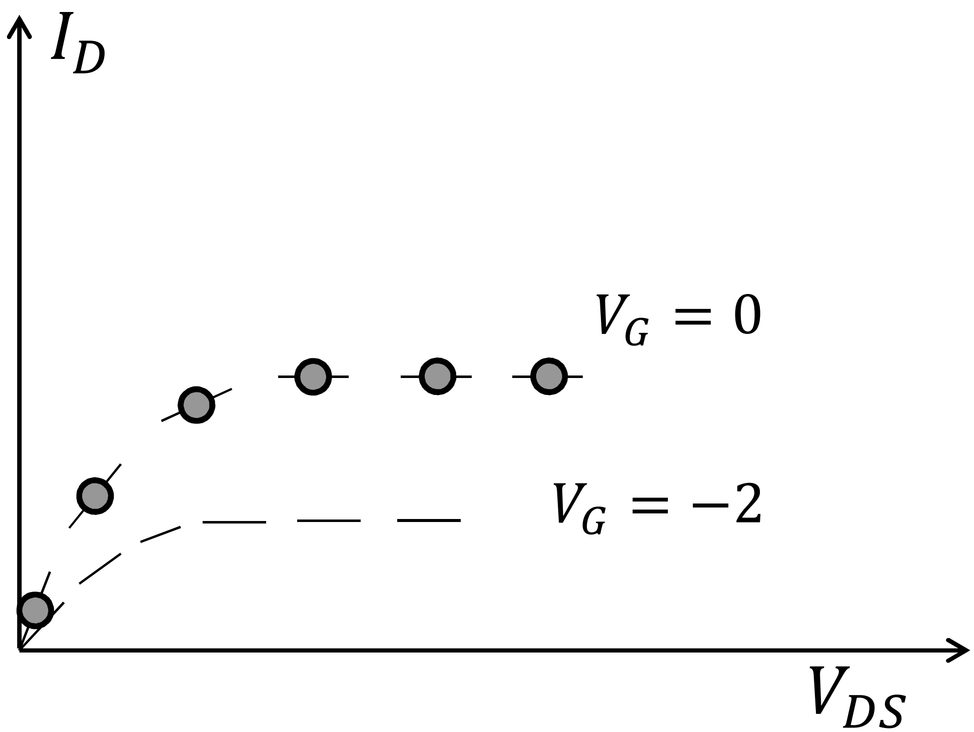
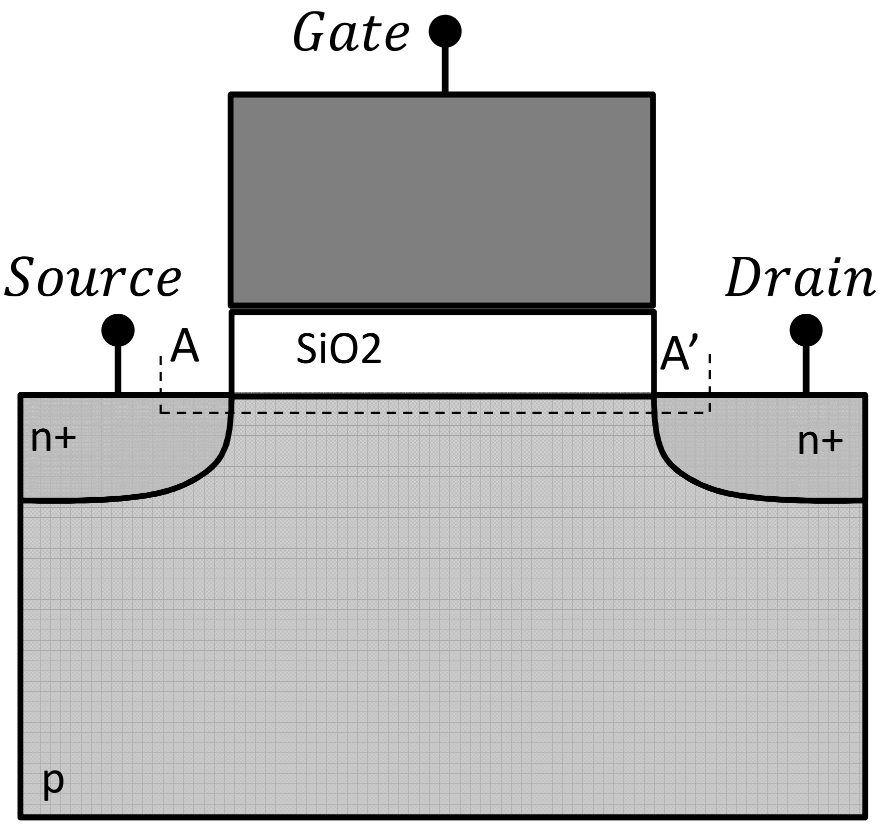
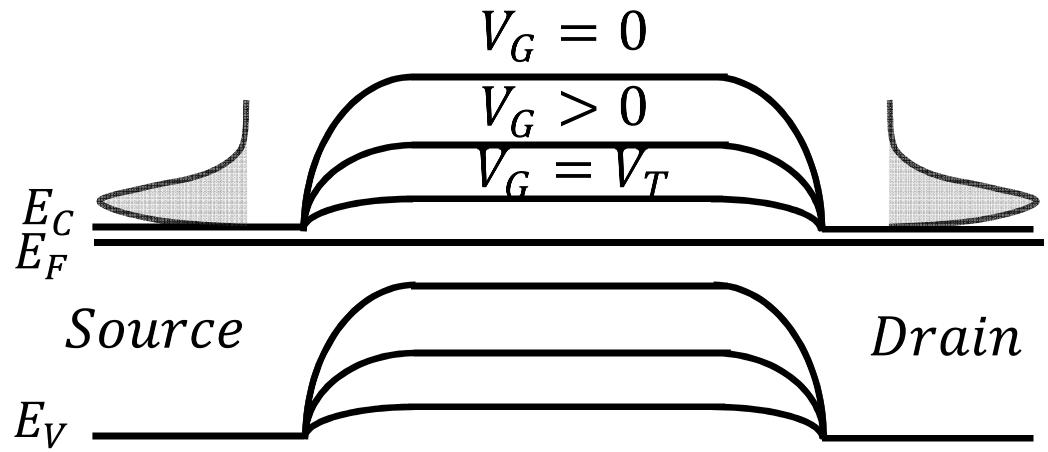




$$R = \rho \frac{L}{Wx}$$

Qualitative Theory of the NMOSFET





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

Qualitative Theory of the NMOSFET

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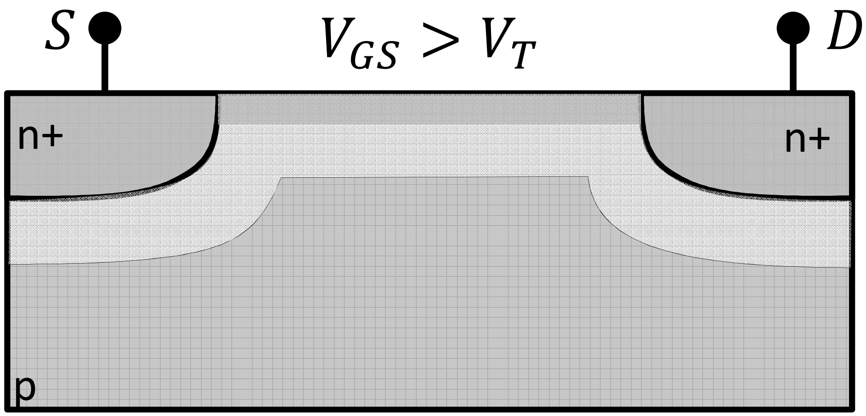
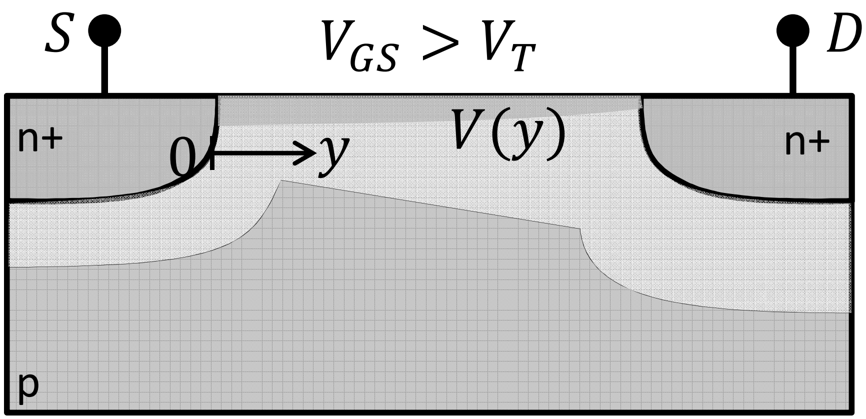
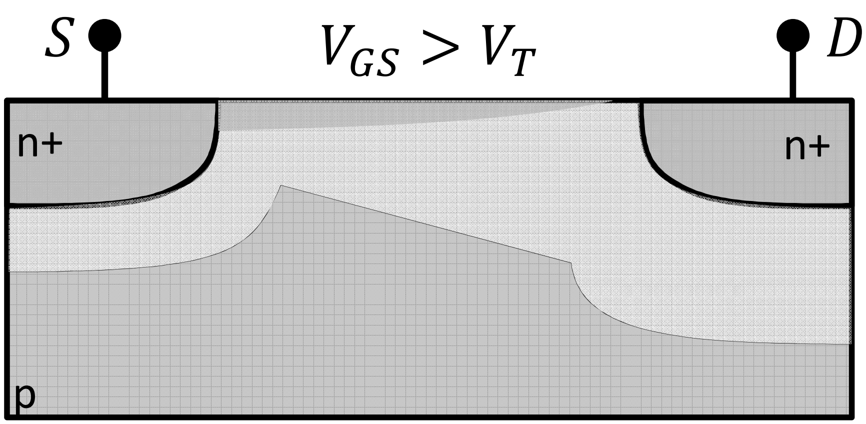


$V_{DS} \approx 0$



$V_{DS} > 0$



$V_{DS} > V_{GS} - V_T$

$$V_{DS_{sat}} = V_{GS} - V_T$$