Session 0:

Review of Solid State Devices

# From Atom to Transistor

To Understand: how "Diodes," and "Transistors" operate!

p	n

p+	n	p-

n+		n+
p		
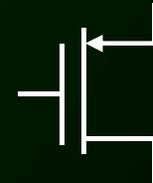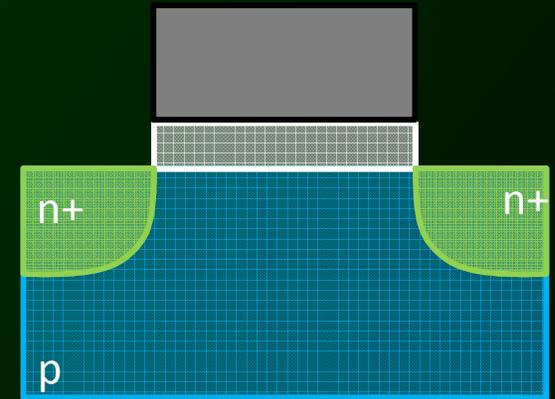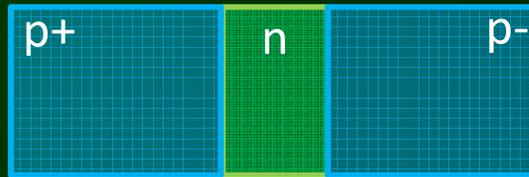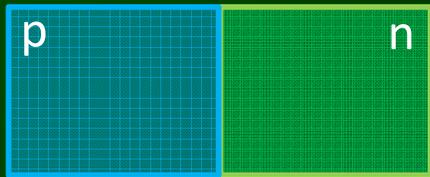
21 Century Alchemy!
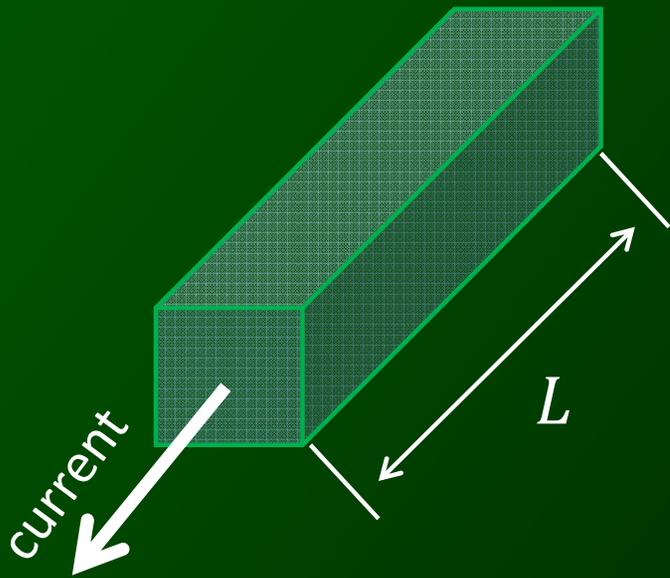
Ohm's law

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

Resistivity is characteristic of the material

current

L

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

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

$\longleftrightarrow$

SiO_2

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

Insulator

Periodic Table of Elements
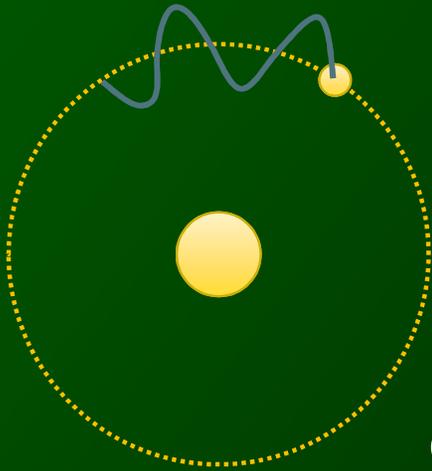
Bohr Atomic Model

wave-particle duality

$$\lambda = h/p$$

$$mvr = n\hbar$$

de Broglie standing wave

Energy Bands:

E_4

E_3

E_2

E_1
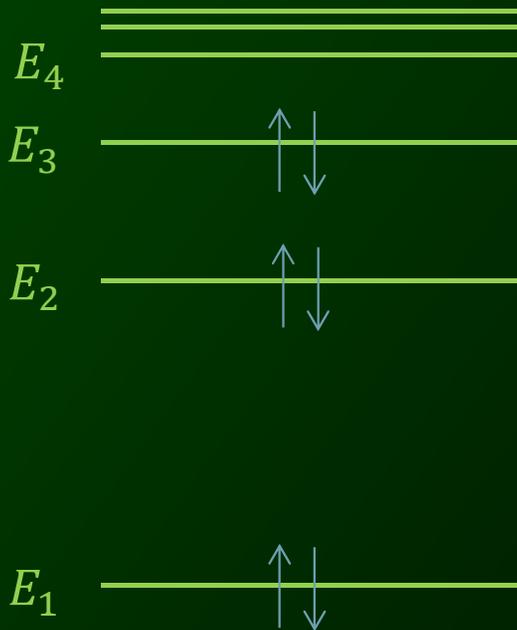
Abbreviated Periodic Table

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

Single atom:

2 atoms:

N atoms:

E_4

E_3

E_2

E_1

E_{32}
E_{31}

E_{22}
E_{21}

E_{12}
E_{11}

2N electrons

E_{2n}
$\vdots$
E_{22}
E_{21}

E_{1n}
$\vdots$
E_{12}
E_{11}

forbidden energies
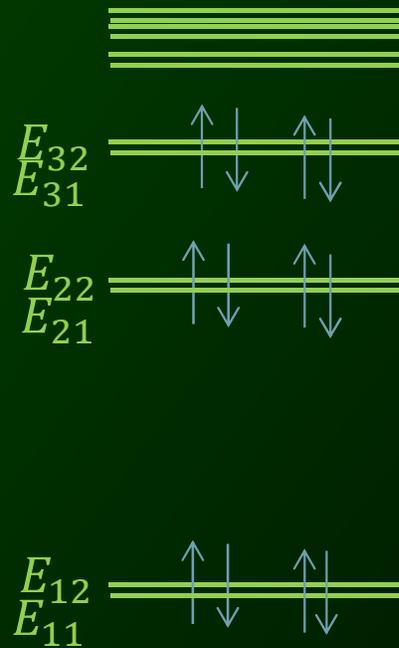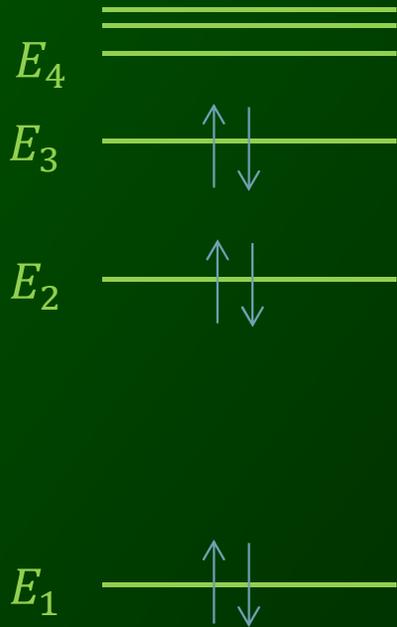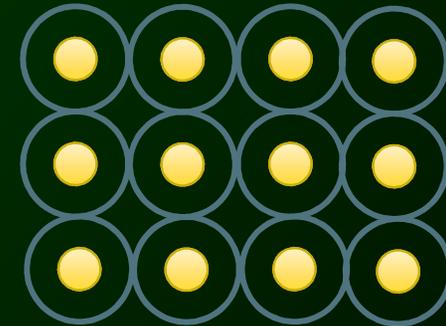
allowed energies
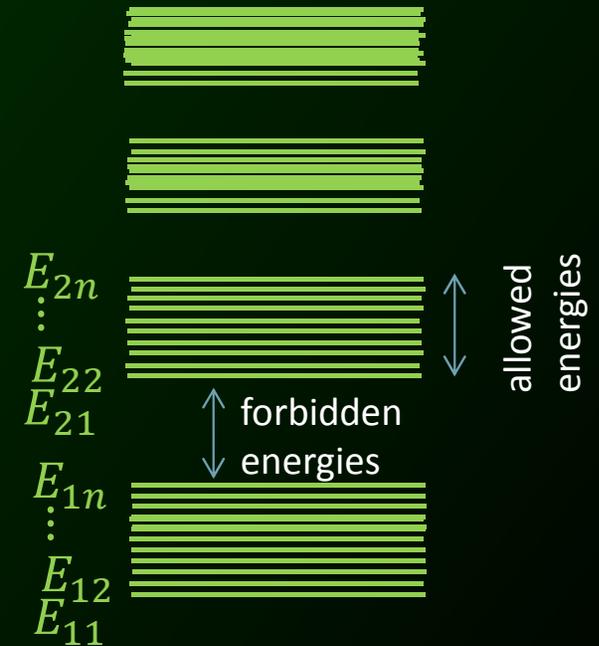
Pauli exclusion principle

Materials

Conductor 10^{-2} Semi-conductor 10^{5} Insulator

$$\rho[\Omega cm]$$

Conduction band

Conduction band

N electrons

E_G

Valance band

2N states

Valance band

2N states

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

E_G (SiO$_2$) = 9eV

empty seat / filled seat

6

Intrinsic Semiconductor

Covalent bands

Valance electrons

Si

Intrinsic Semiconductor

Covalent bands

free electron

hole

Si

Valance electrons
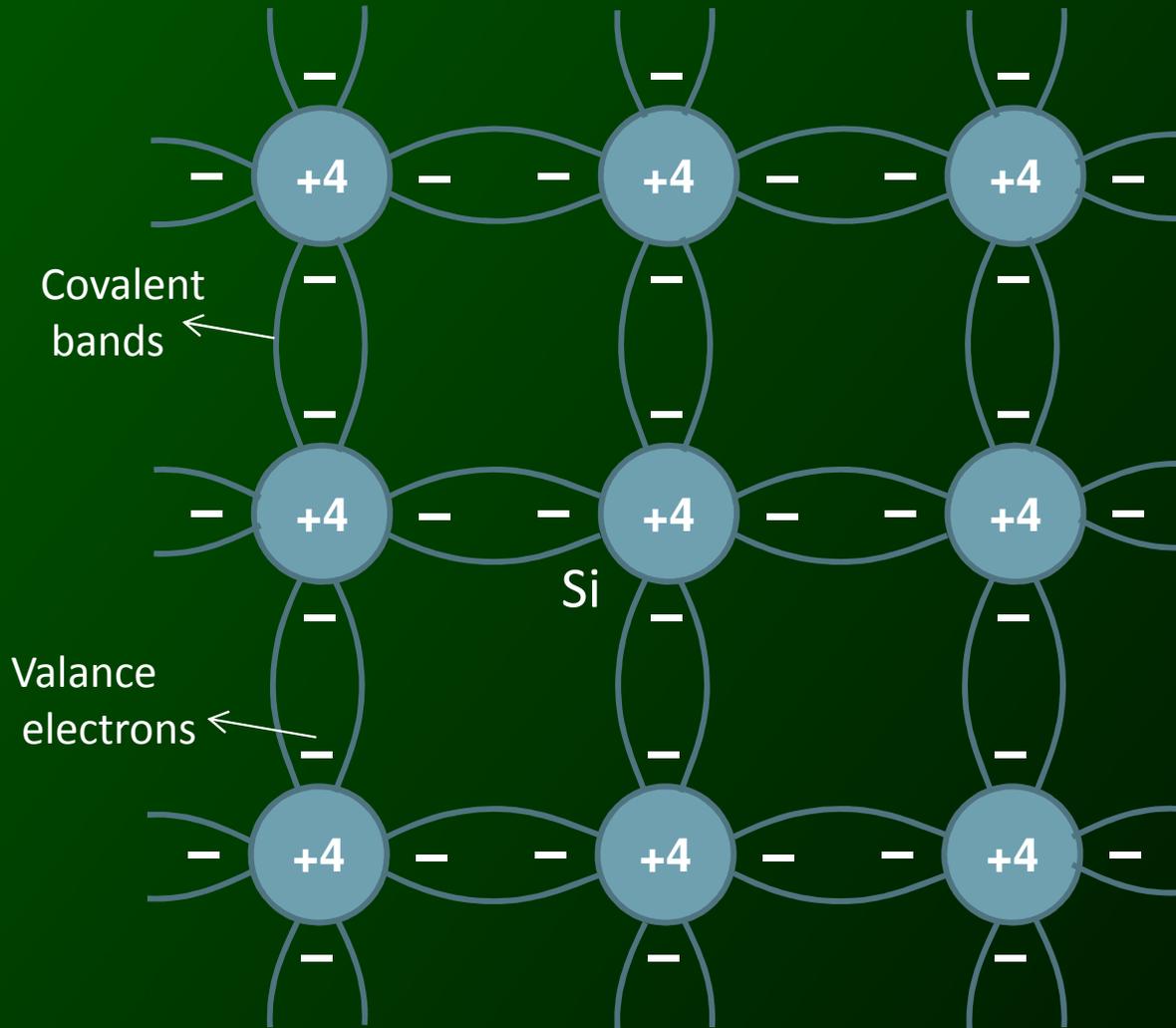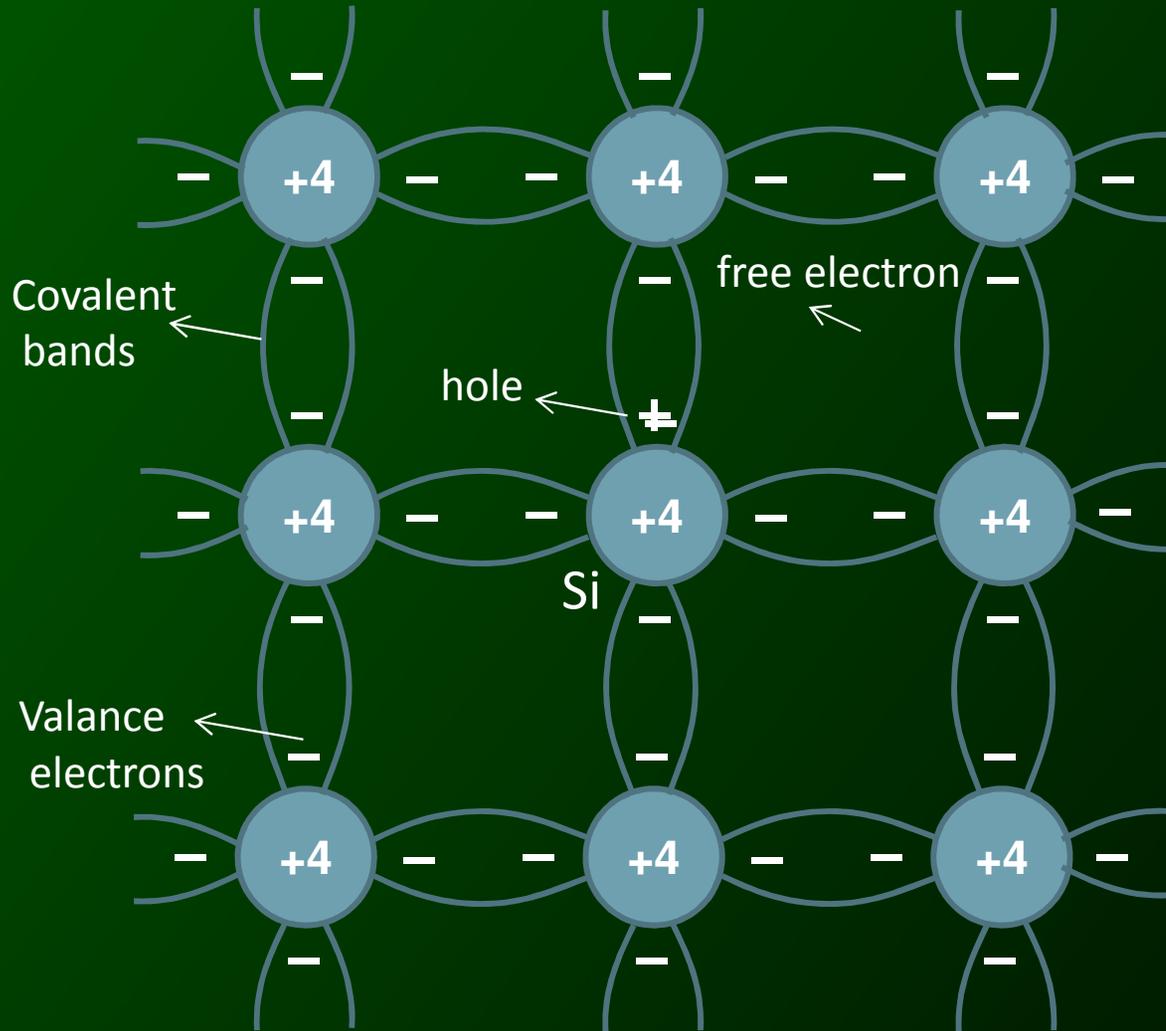
n_0 electron density

p_0 hole density

$$n_0 = p_0 = n_i$$

☹ useless!!

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

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n-type Semiconductor
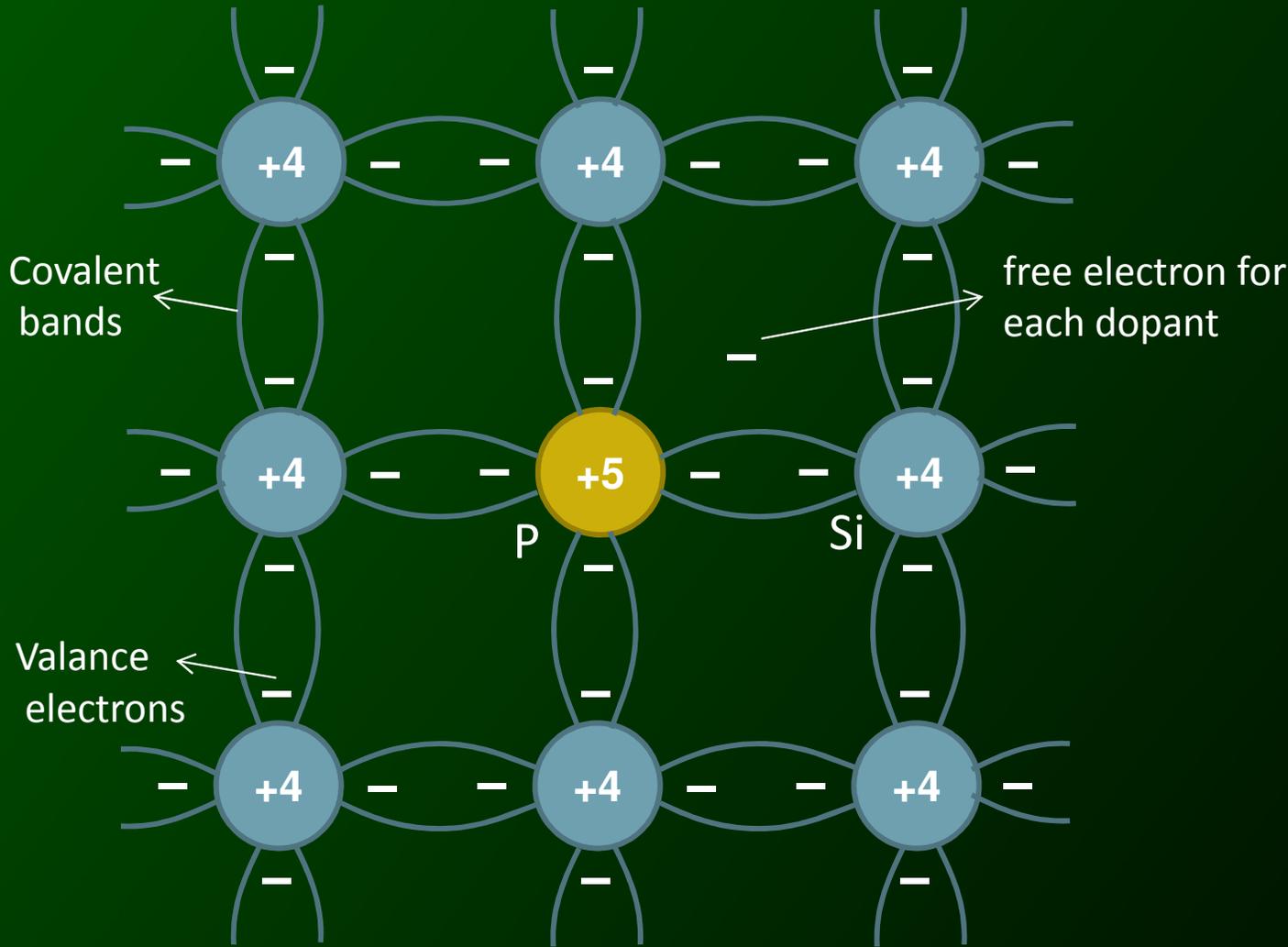
Donor: P , As , Sb

n_0 electron density

p_0 hole density

Covalent bands

free electron for each dopant

Valance electrons

P

Si

$$n_0 = N_D$$

$$n_0 p_0 = n_i^2$$

N_D up to 10^{19} cm^{-3}

☺ $n(Si) = 2 \times 10^{23} cm^{-3}$

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p-type Semiconductor
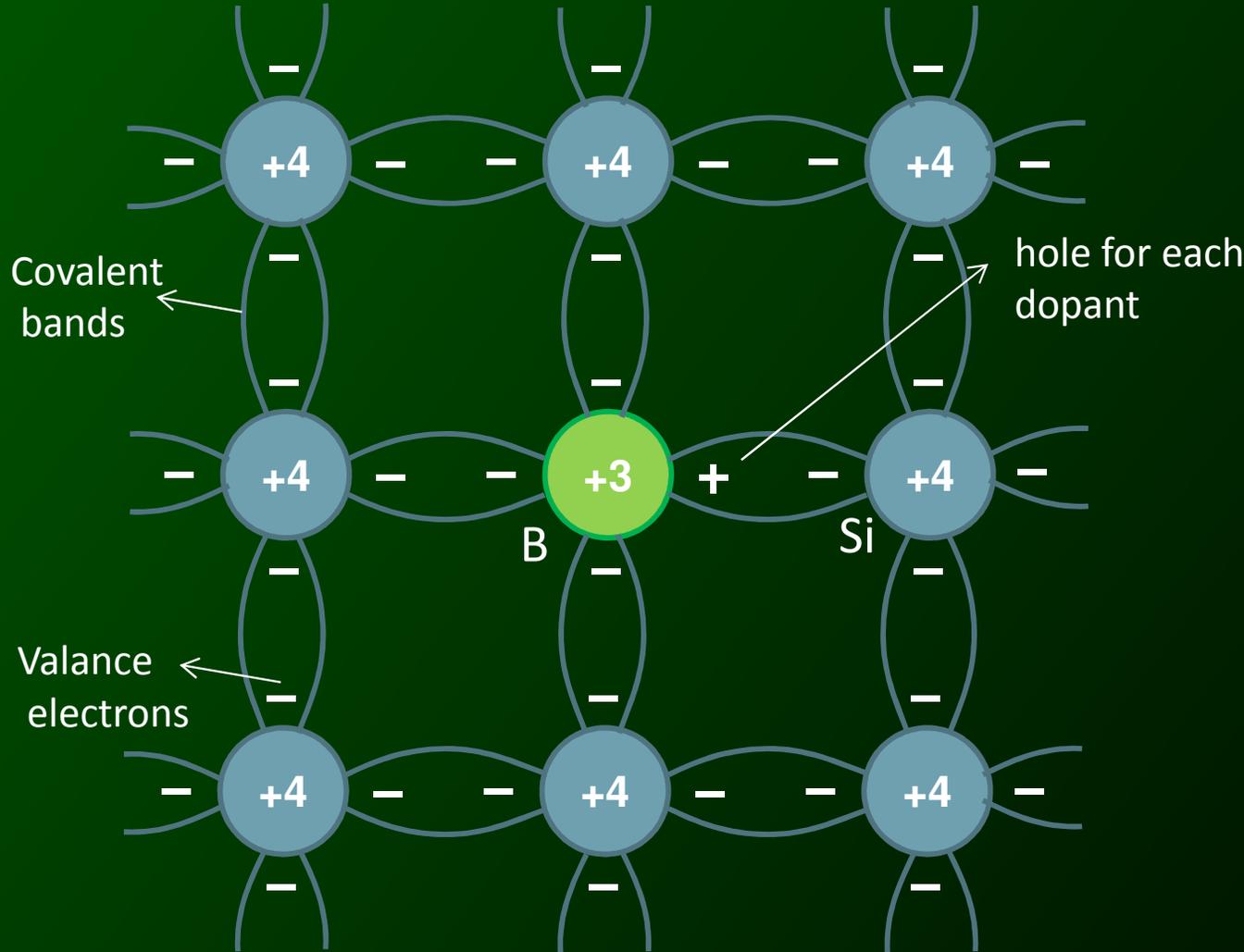
Acceptor: B , Ga , In

n_0 electron density

p_0 hole density

$$n_0 = N_A$$

$$n_0 p_0 = n_i^2$$

Covalent bands

hole for each dopant

B

Si

Valance electrons

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

☺ $n(Si) = 2 \times 10^{23} cm^{-3}$

Energy Diagrams

v

Potential Energy

Kinetic Energy

Energy Diagrams

Energy Diagrams
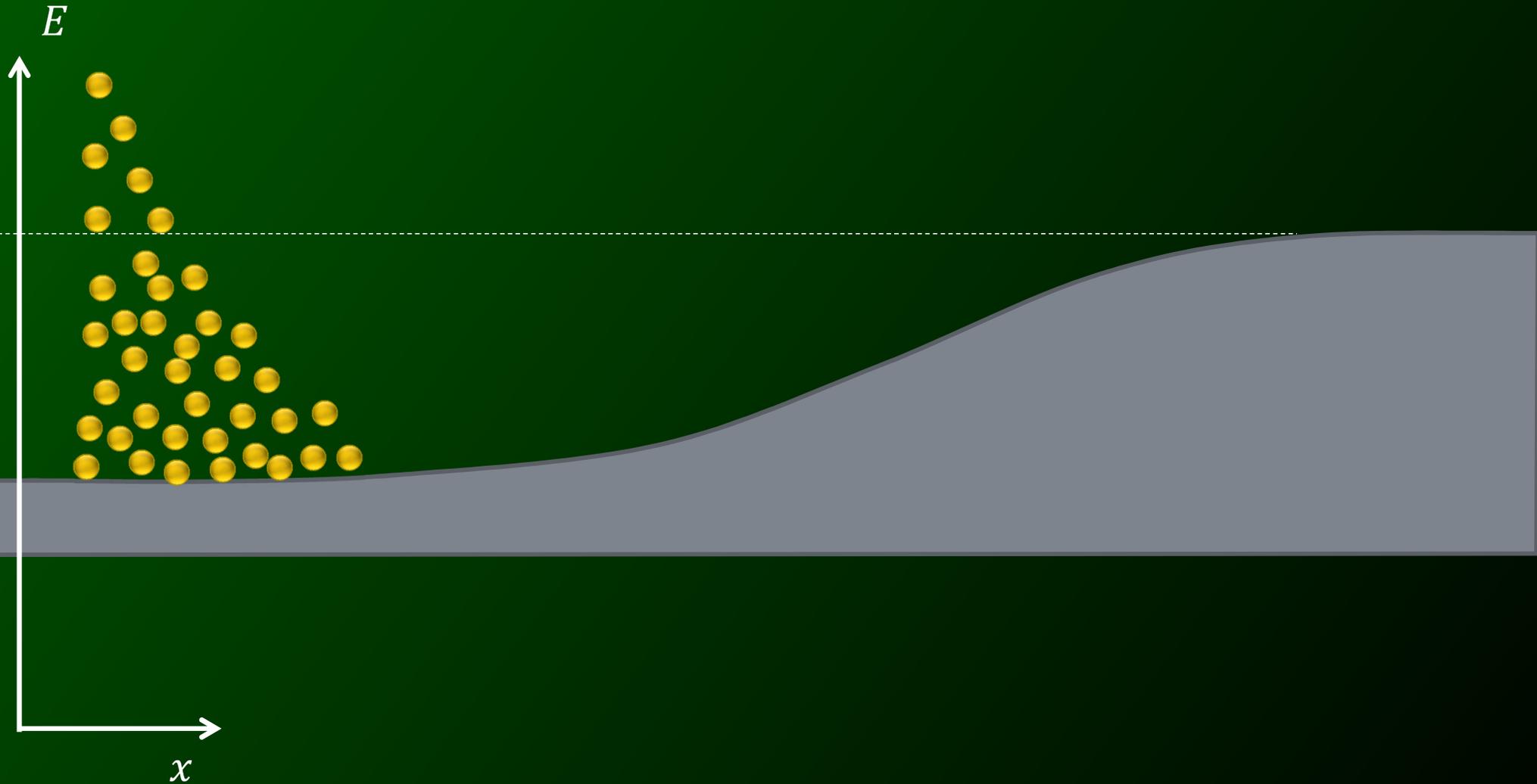
Density of States

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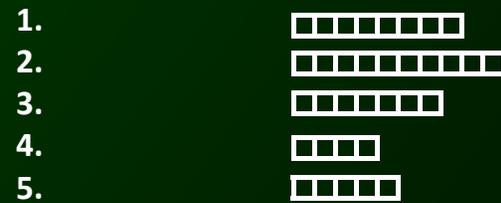
$$f(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$$

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:

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

$$f(E) \approx 1 - e^{-(E_f-E)/kT} \qquad \text{if} \qquad E - E_F \ll -kT$$
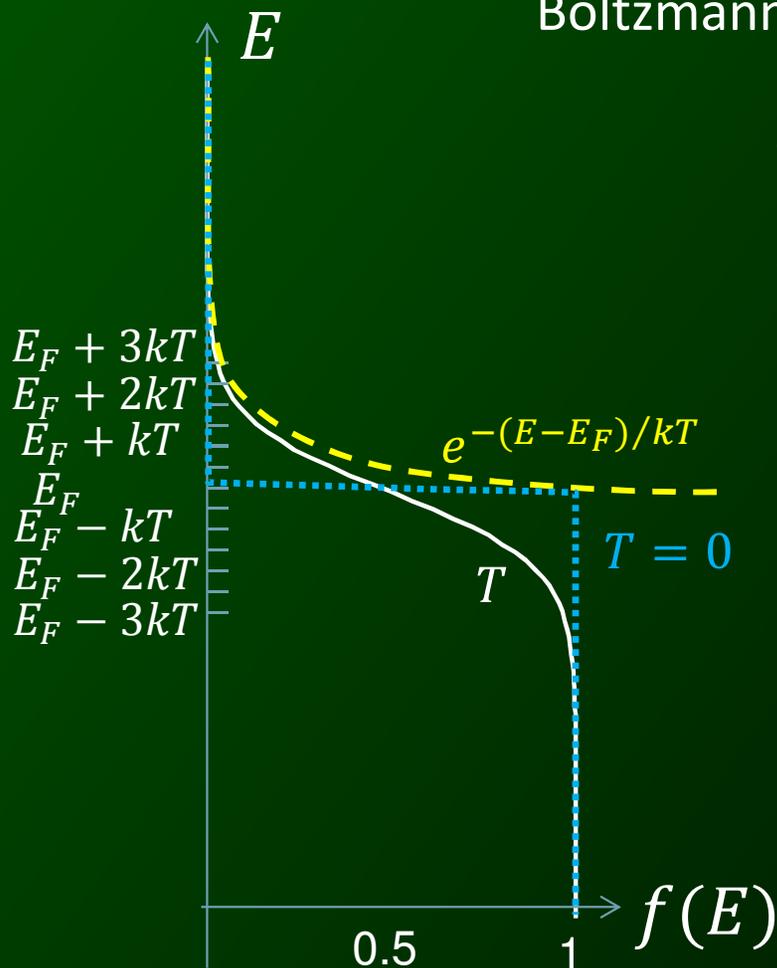
$N(E)\, f(E) =$ # of electrons at energy E

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

E

$E_F + 3kT$
$E_F + 2kT$
$E_F + kT$
E_F
$E_F - kT$
$E_F - 2kT$
$E_F - 3kT$

$e^{-(E-E_F)/kT}$

$T = 0$

T

$f(E)$

0.5 1

Materials

Conductor $\qquad 10^{-2} \qquad$ Semi-conductor $\qquad 10^5 \qquad$ Insulator

$$\rho[\Omega cm]$$

N electrons

Conduction band

E_G

Valance band

2N states

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Conduction band

Valance band

2N states

E_G (SiO$_2$) = 9eV
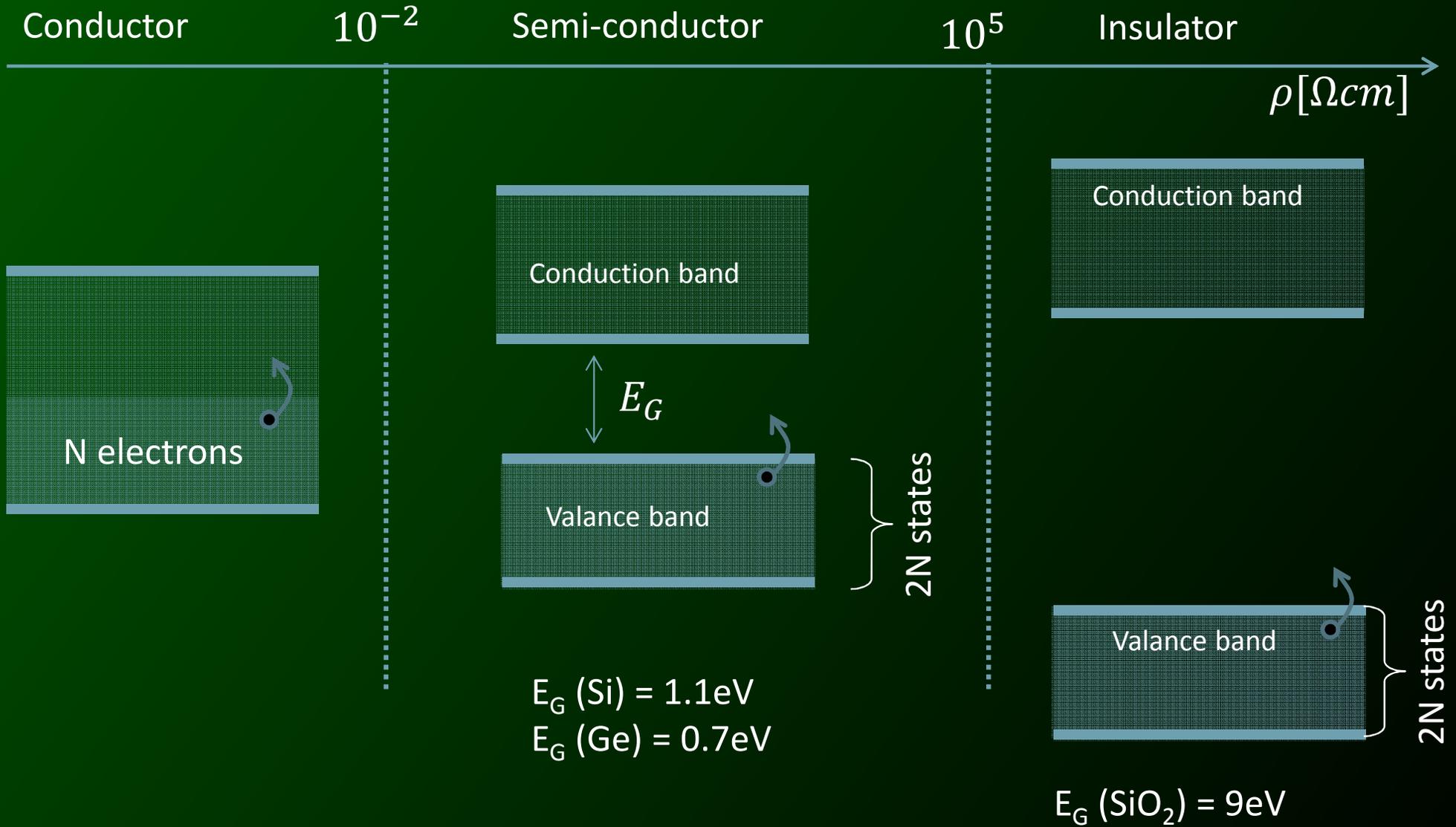
empty seat / filled seat

intrinsic

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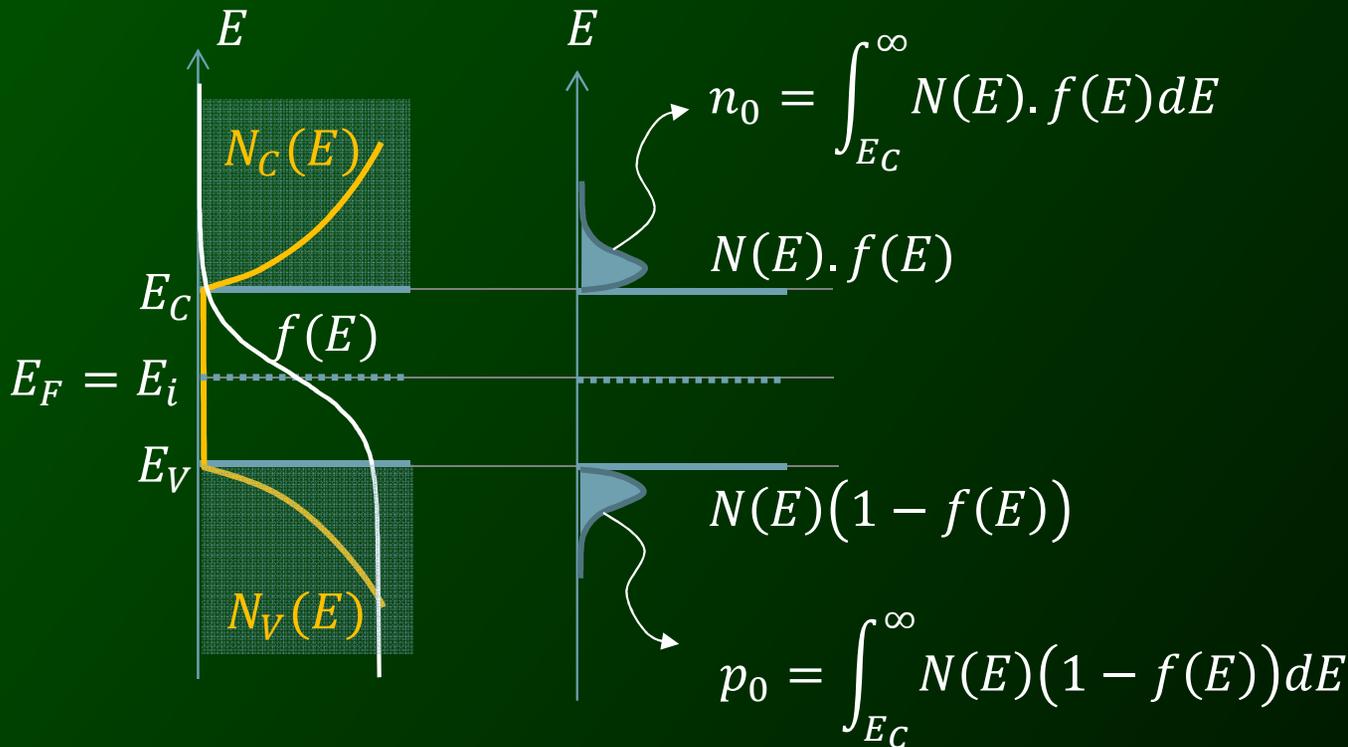
$$N(E)\big(1 - f(E)\big) = \quad \text{\# of holes at energy E}$$

E

$N_C(E)$

E_C

$f(E)$

$E_F = E_i$

E_V

$N_V(E)$

E

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

$N(E).f(E)$

$N(E)\big(1 - f(E)\big)$

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

n-type

$$N(E)\,f(E) = \quad \text{\# of electrons at energy E}$$

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

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

$$N(E).f(E)$$

$$n_0 \gg p_0$$

$$N(E)\big(1 - f(E)\big)$$

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

E

$N_C(E)$

E_C

E_F

$f(E)$

E_V

$N_V(E)$

18

p-type

$$N(E)\,f(E) = \quad \text{\# of electrons at energy E}$$

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

E

$N_C(E)$

E_C

$f(E)$

E_F

E_V

$N_V(E)$

E

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

$N(E).f(E)$

$$p_0 \gg n_0$$

$$N(E)\big(1 - f(E)\big)$$

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

intrinsic

n-type

p-type

E

E

E

n_0

n_0

n_0

E_C

E_f

E_f

E_f

E_V

p_0

p_0

p_0

Fermi Energy

p-type   n-type

E_F————   ————E_F

p-type   n-type

————————E_F
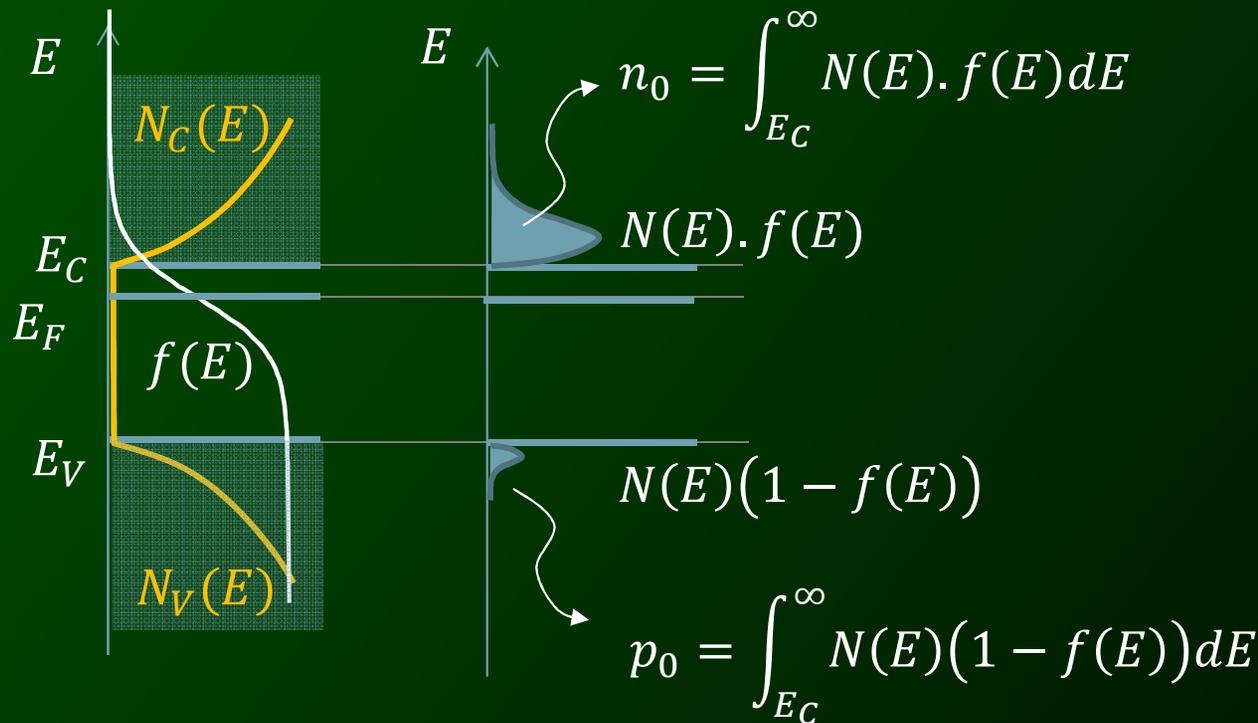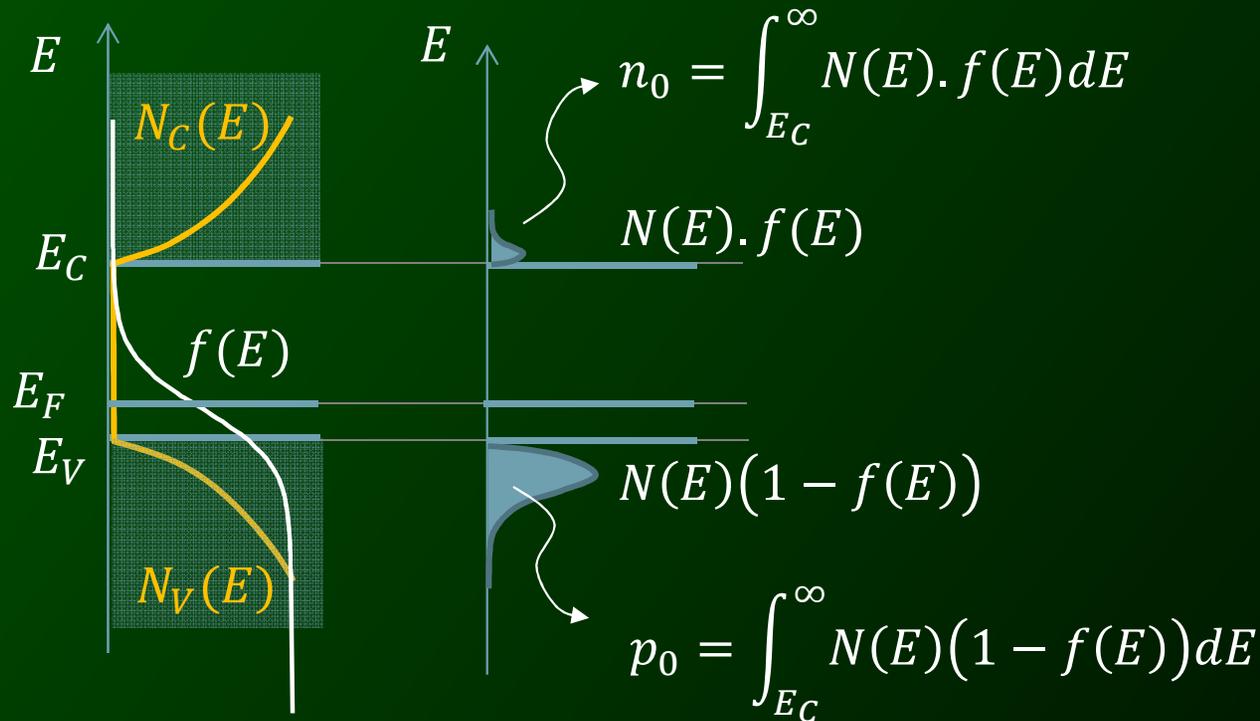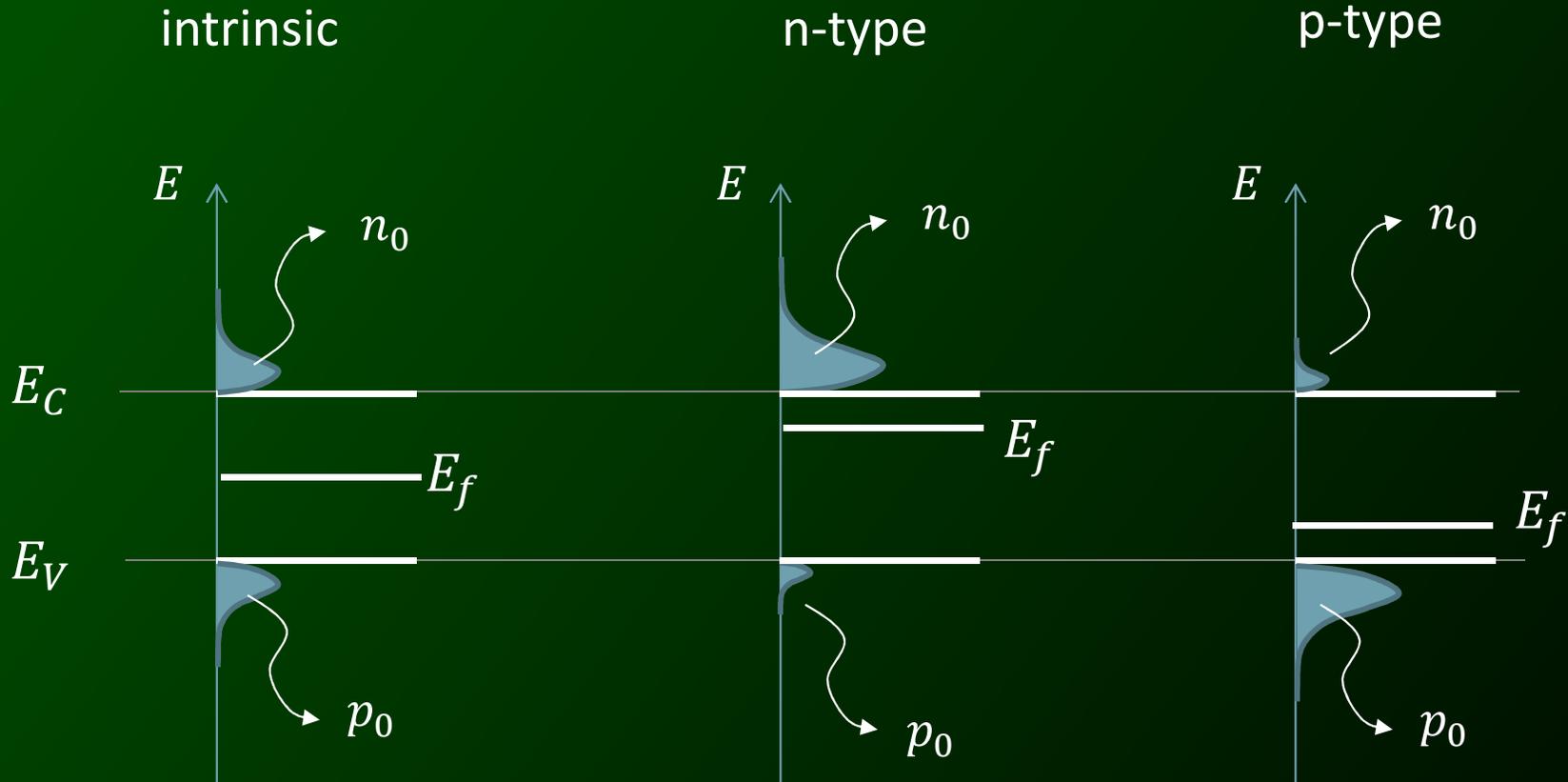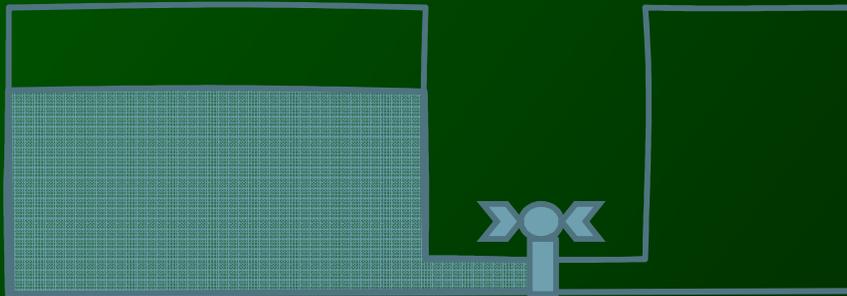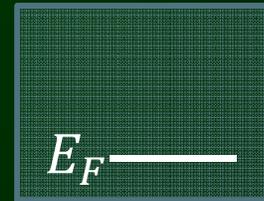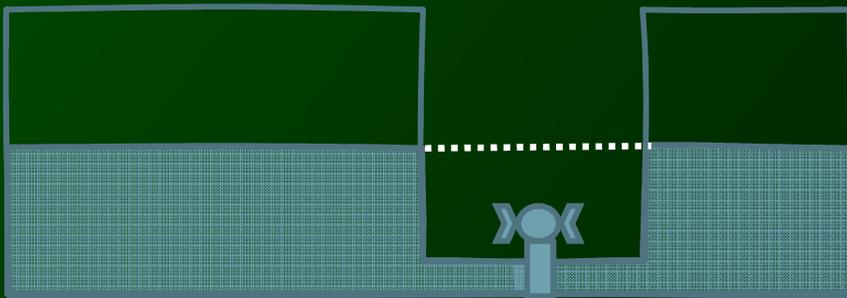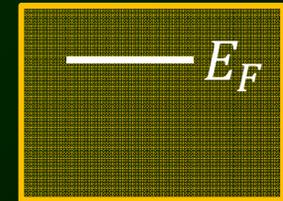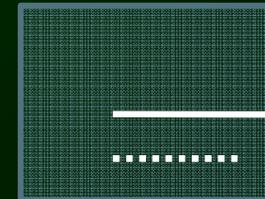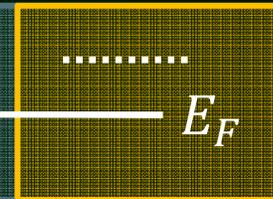
Drift
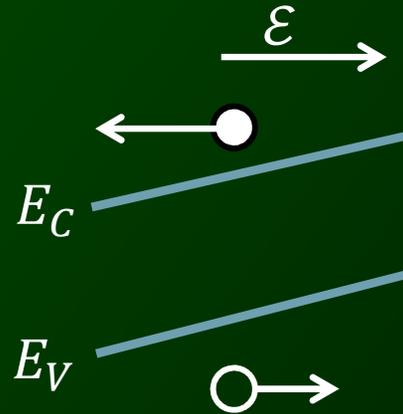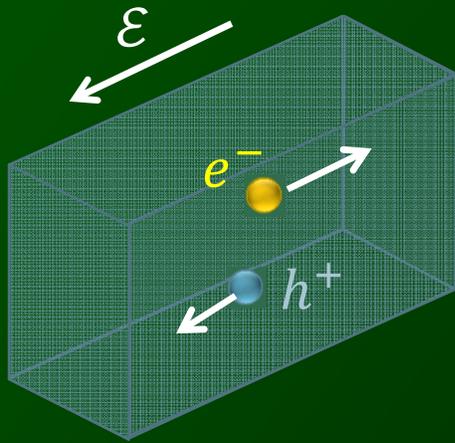
Electric field   →   gravitational field
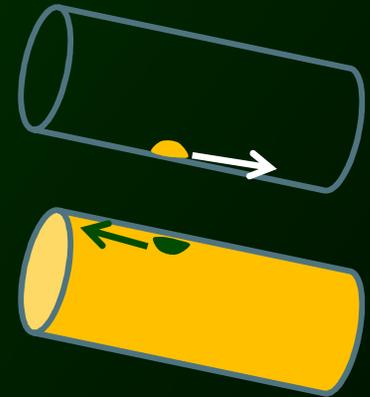
$$J \propto \mathcal{E}$$

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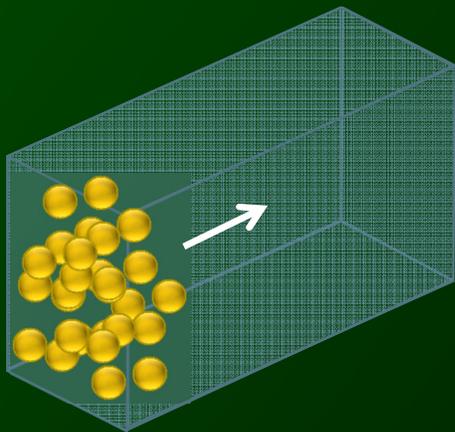
Charges move to be evenly distributed throughout space. Similar to perfume in room or heat in a solid

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

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

p

n
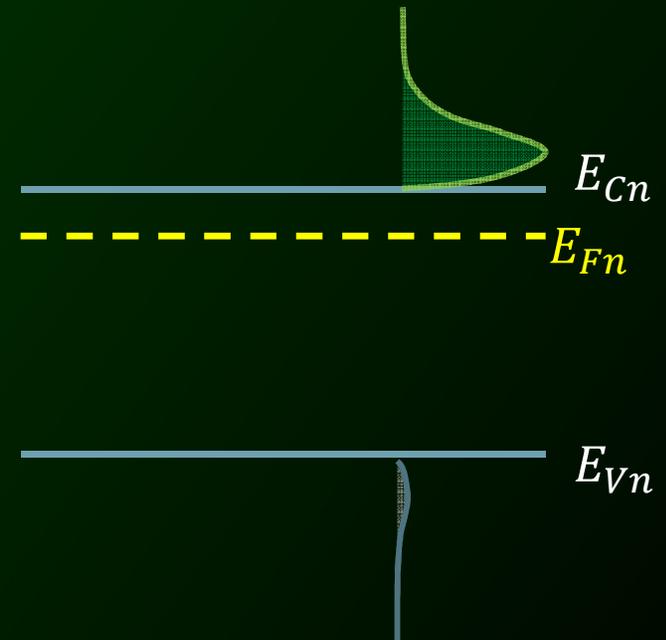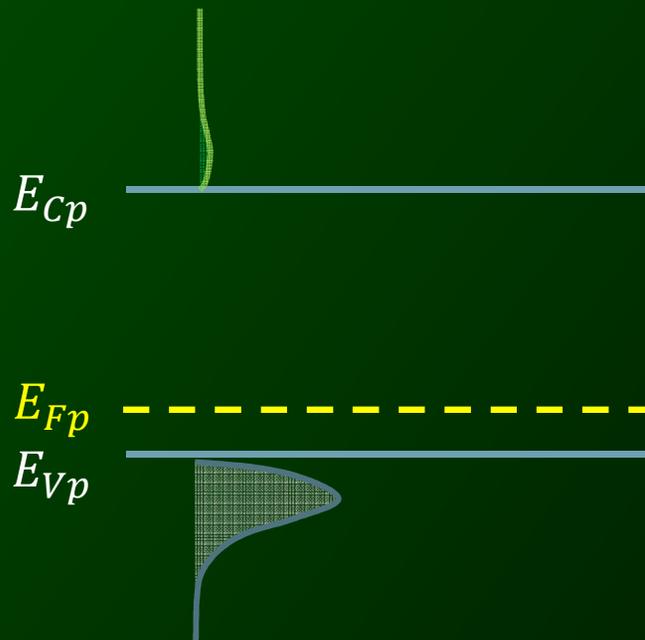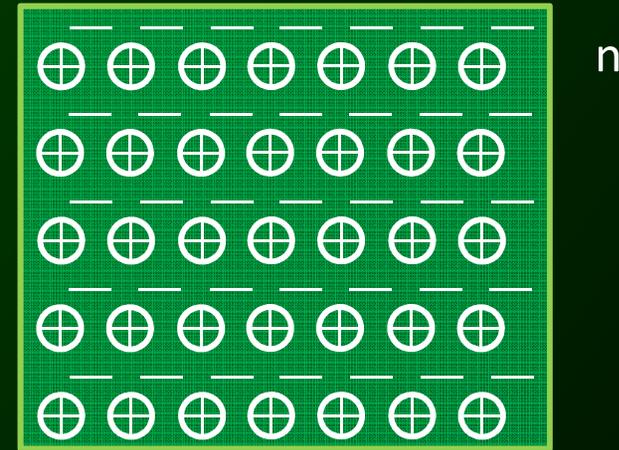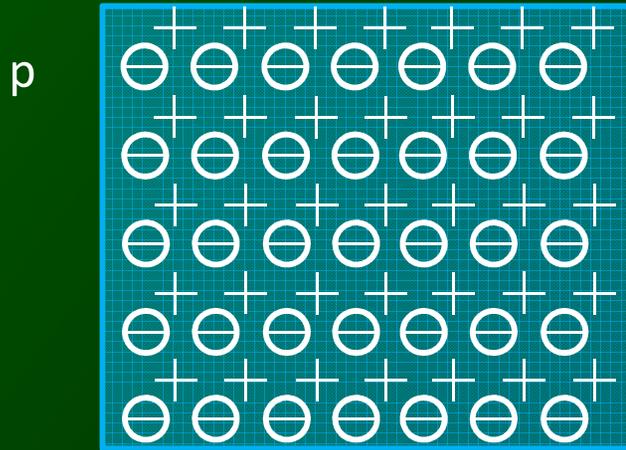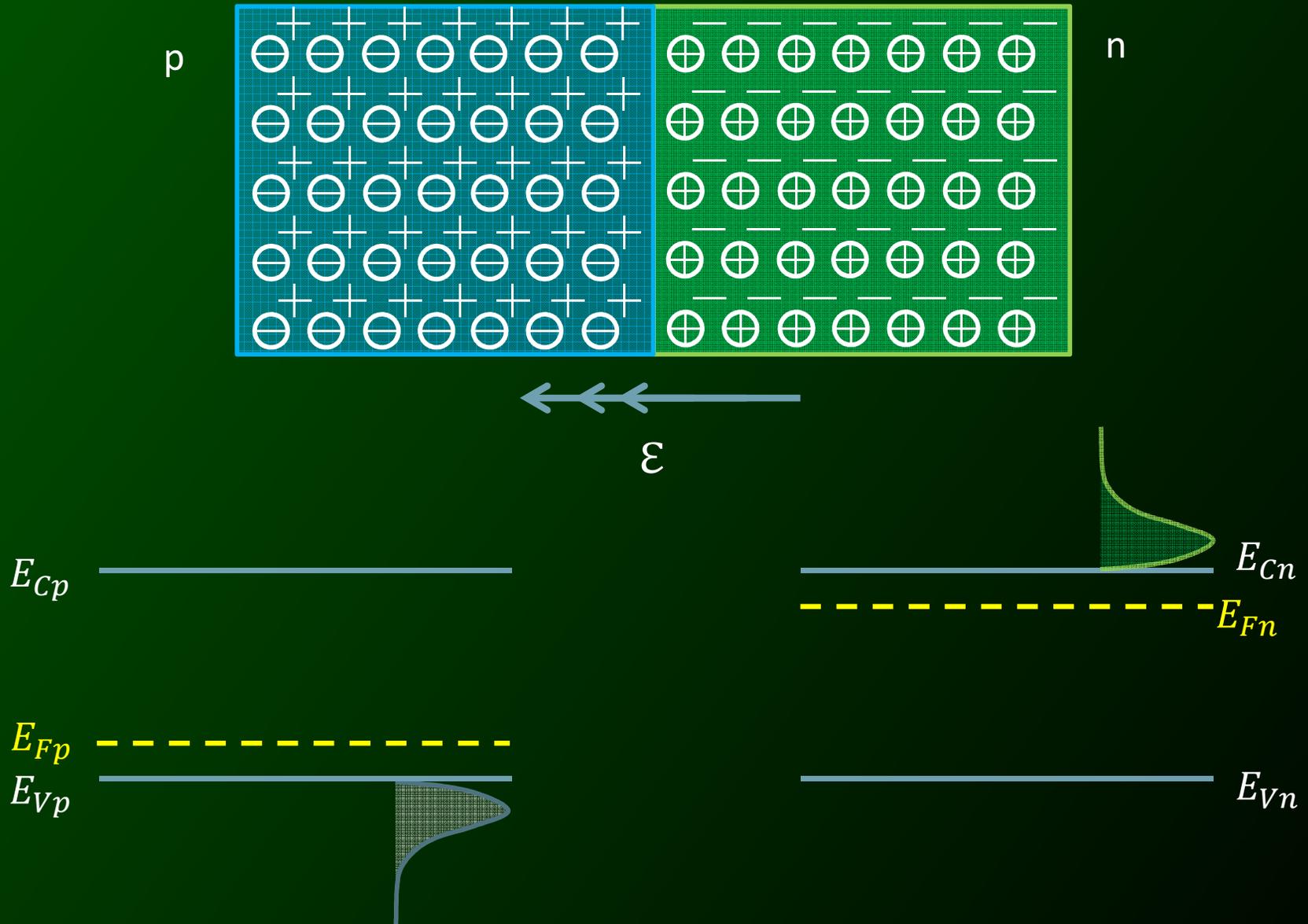
E_{Cp}

E_{Cn}

E_{Fn}

E_{Fp}

E_{Vp}

E_{Vn}

p

n

ε

E_{Cp}

E_{Cn}

E_{Fn}

E_{Fp}

E_{Vp}

E_{Vn}

p

n

Depletion region

E_{Cp}

qV_{bi}

E_{Cn}

E_{Fp} — — — — — — — — — — — — — E_{Fn}

E_{Vp}

E_{Vn}

depletion region

E_{Cp}

$J_{n_{drift}}$

$J_{n_{diff}}$

qV_{bi}

E_{Cn}

E_{Fp}

E_{Fn}

E_{Vp}

E_{Vn}

$J_{p_{diff}}$

$J_{p_{drift}}$

V_R

p
n

depletion region

$J_{n_{drift}}$

$J_{n_{diff}}$

I

V

E_{Fp}

qV_R

E_{Fn}

$J_{p_{diff}}$

$J_{p_{drift}}$
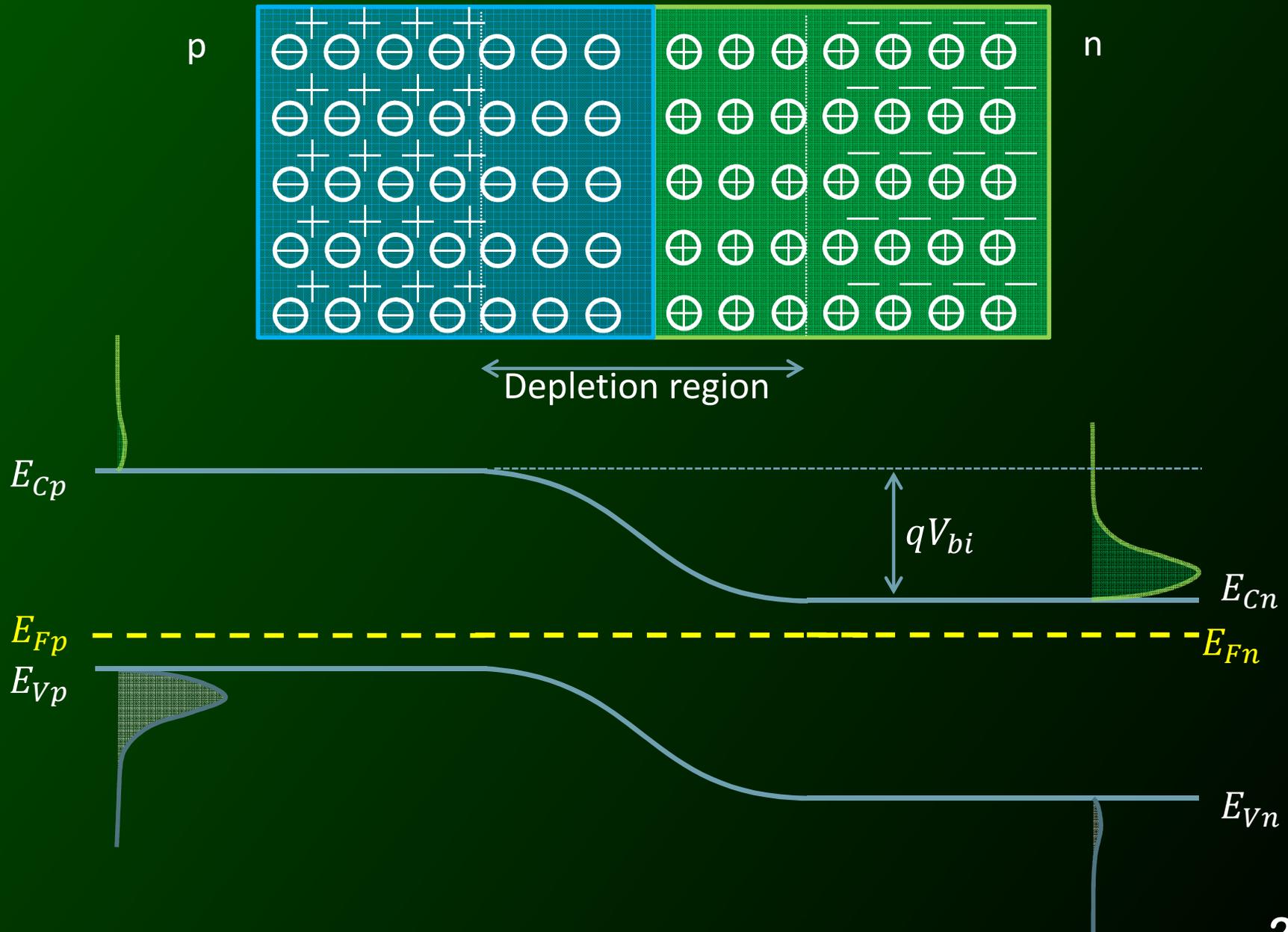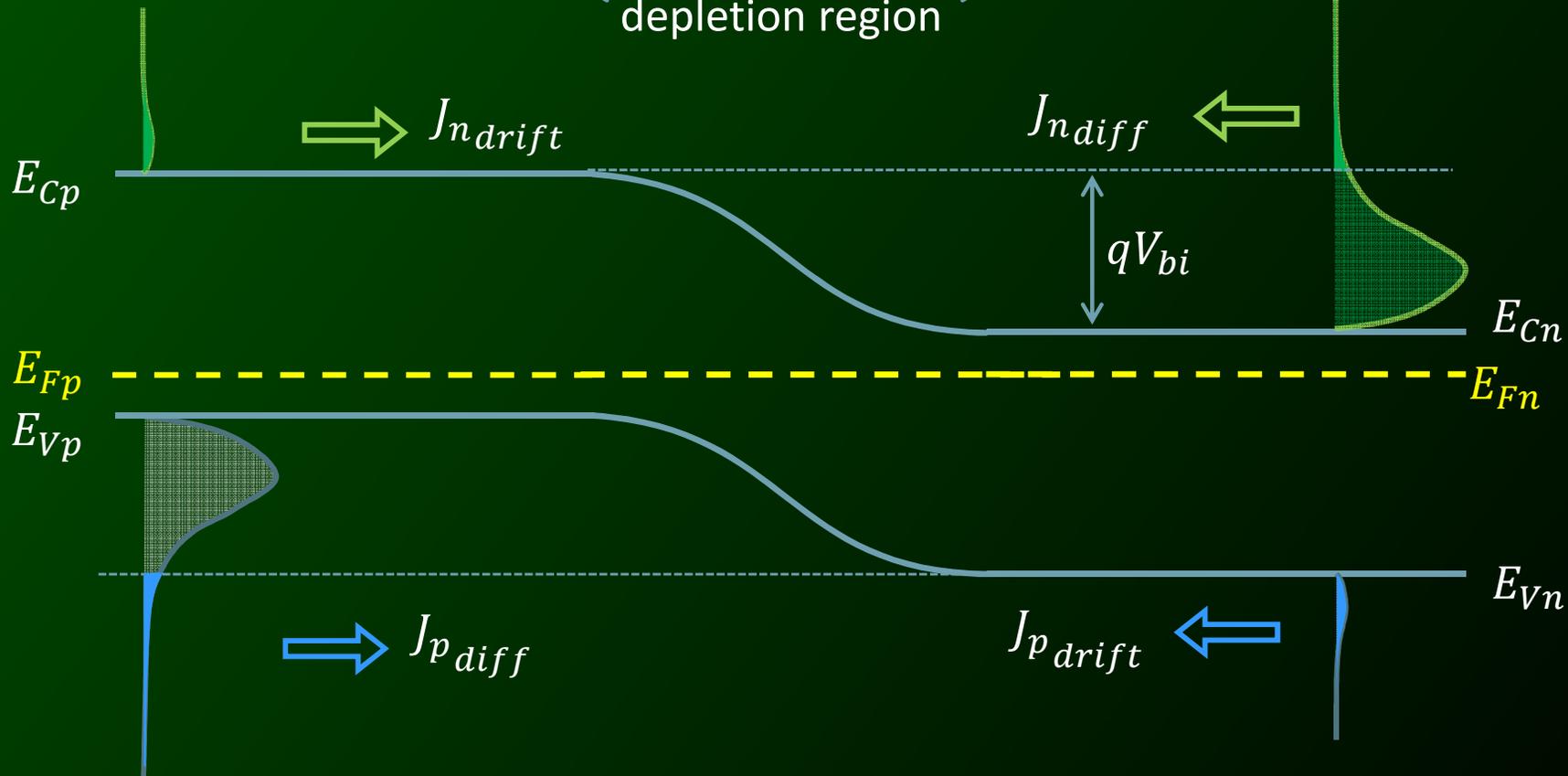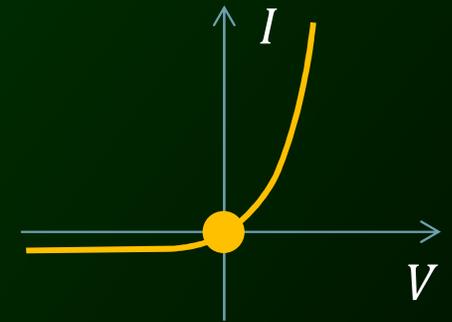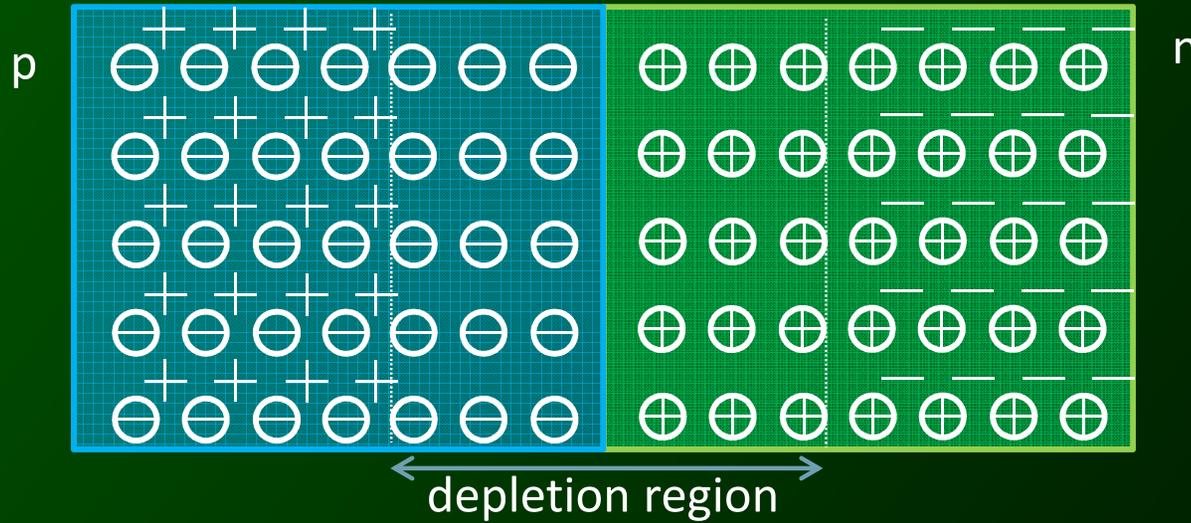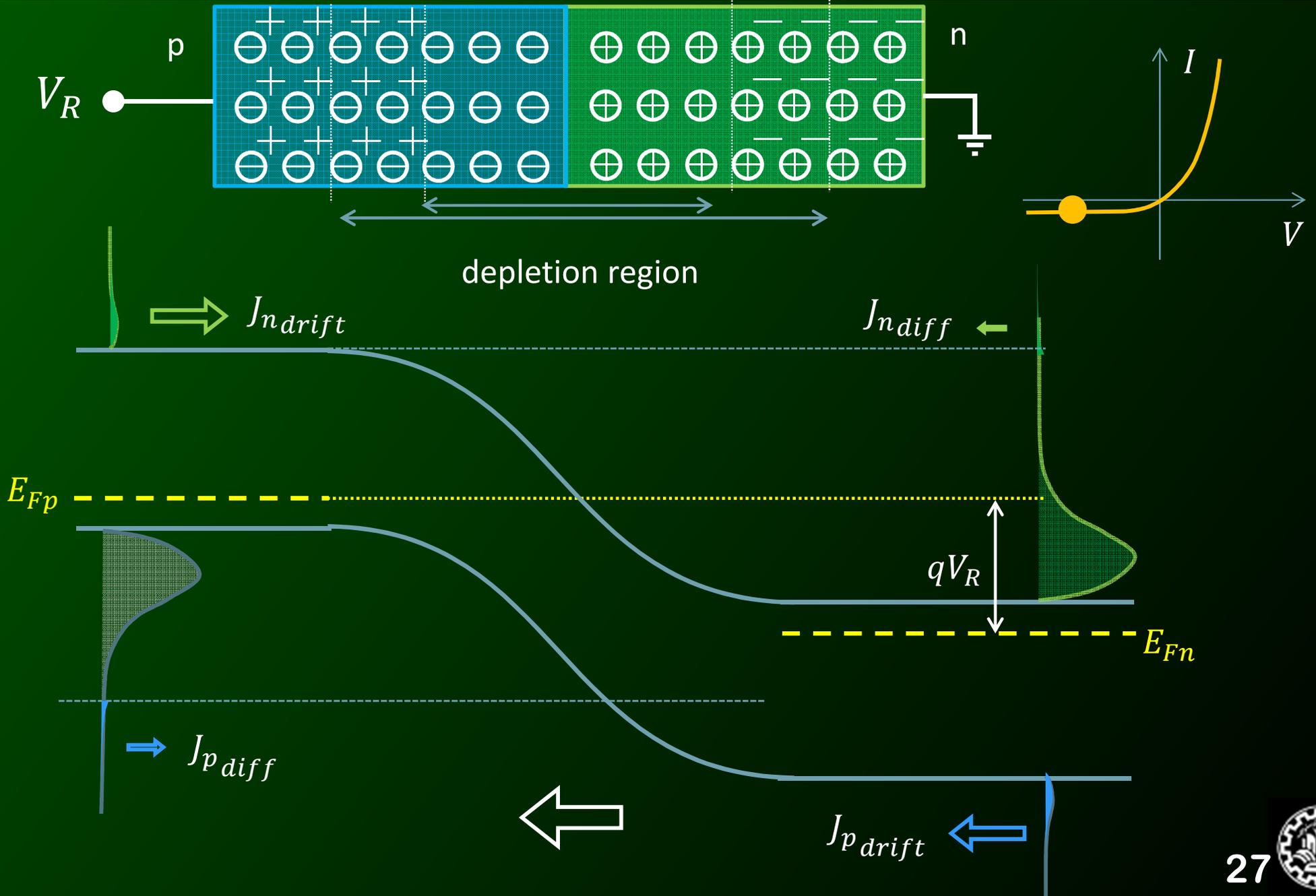
PN junctions , Forward Biased
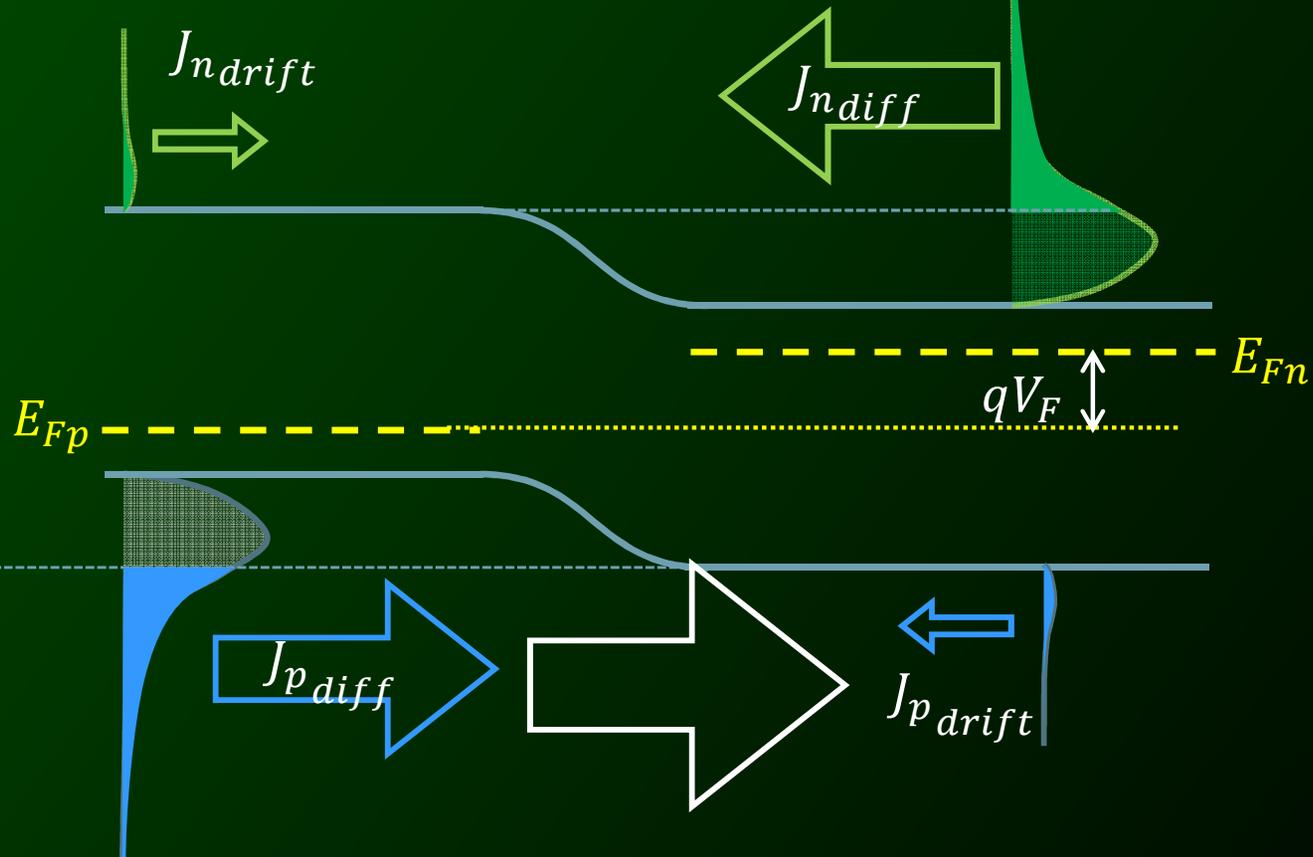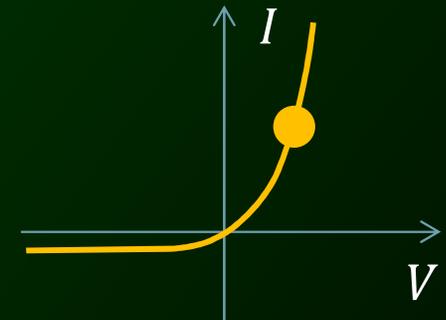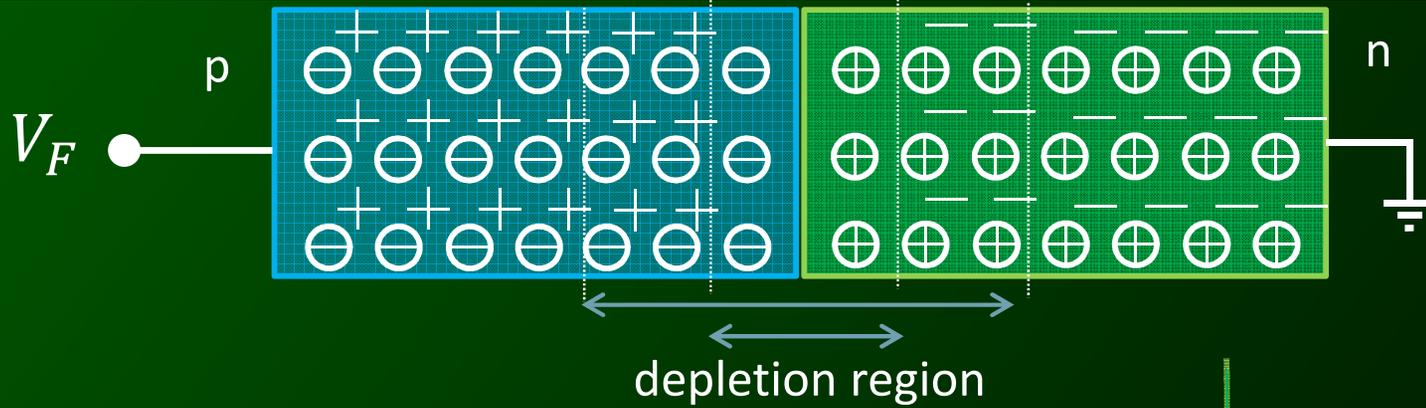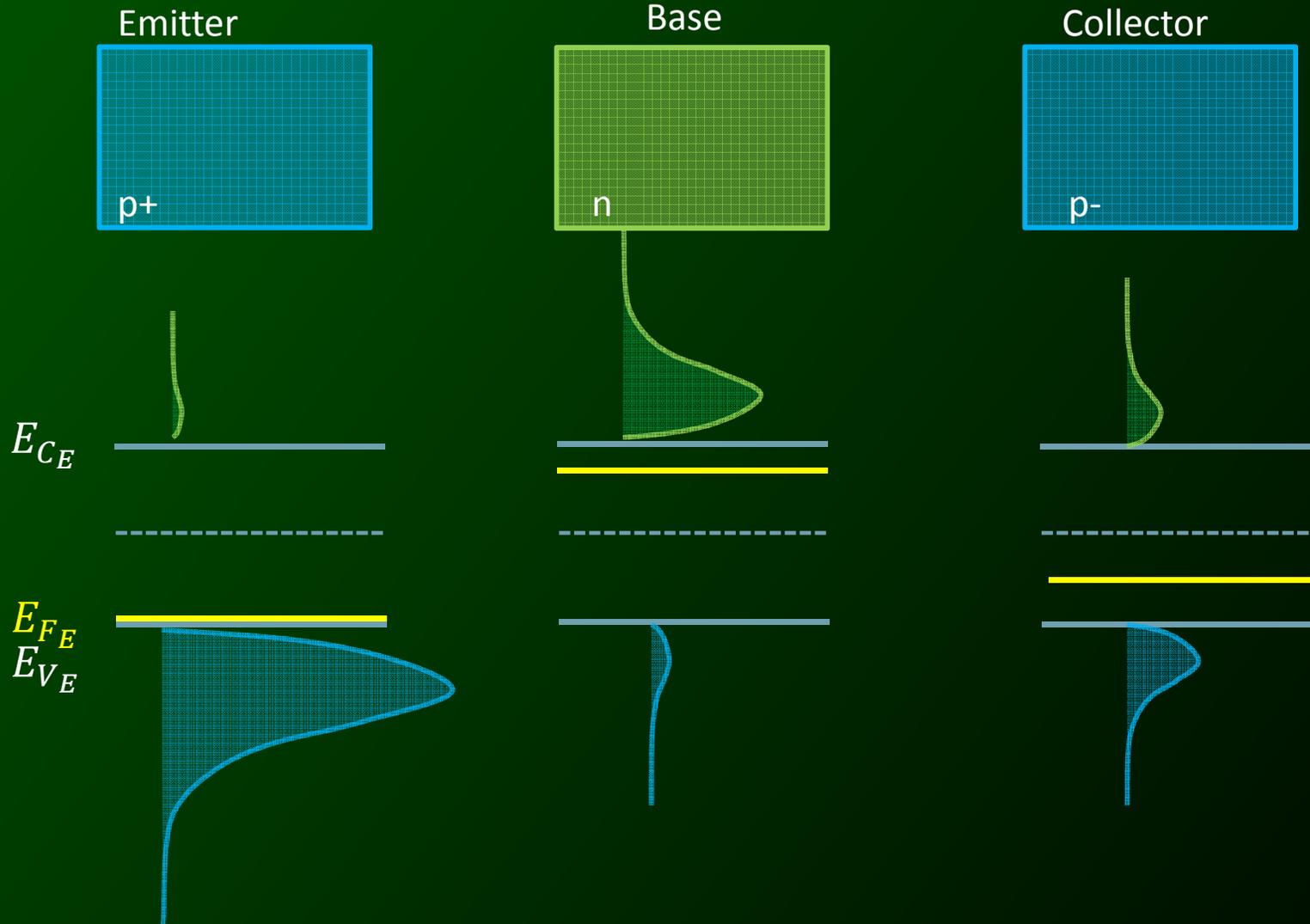
V_F

p

n

depletion region

I

V

$J_{n_{drift}}$

$J_{n_{diff}}$

E_{Fn}

qV_F

E_{Fp}

$J_{p_{diff}}$

$J_{p_{drift}}$

BJT Electrostatics

pnp

Emitter

Base

Collector

p+

n

p-

E_{C_E}

E_{F_E}
E_{V_E}

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

BJT Electrostatics
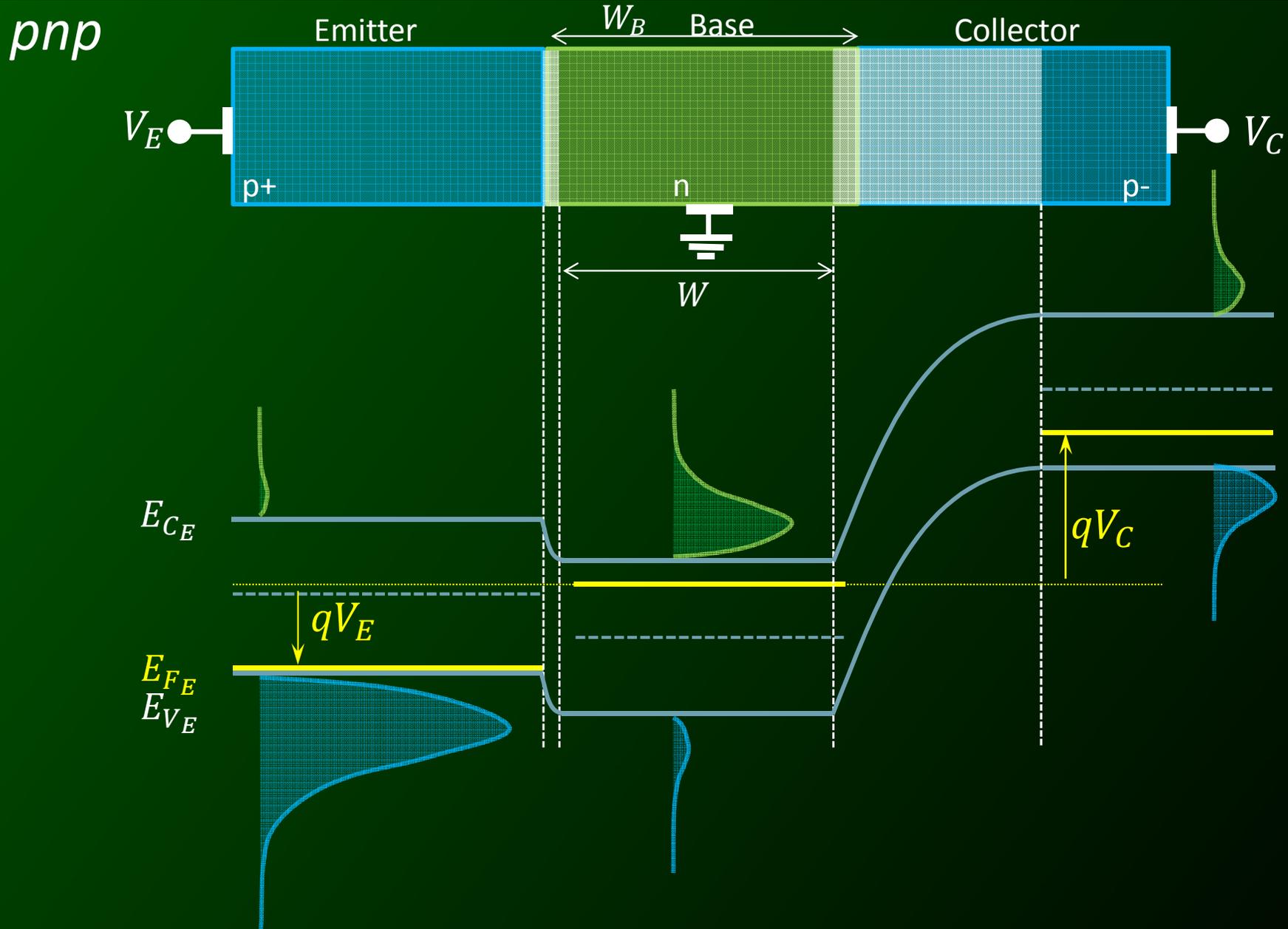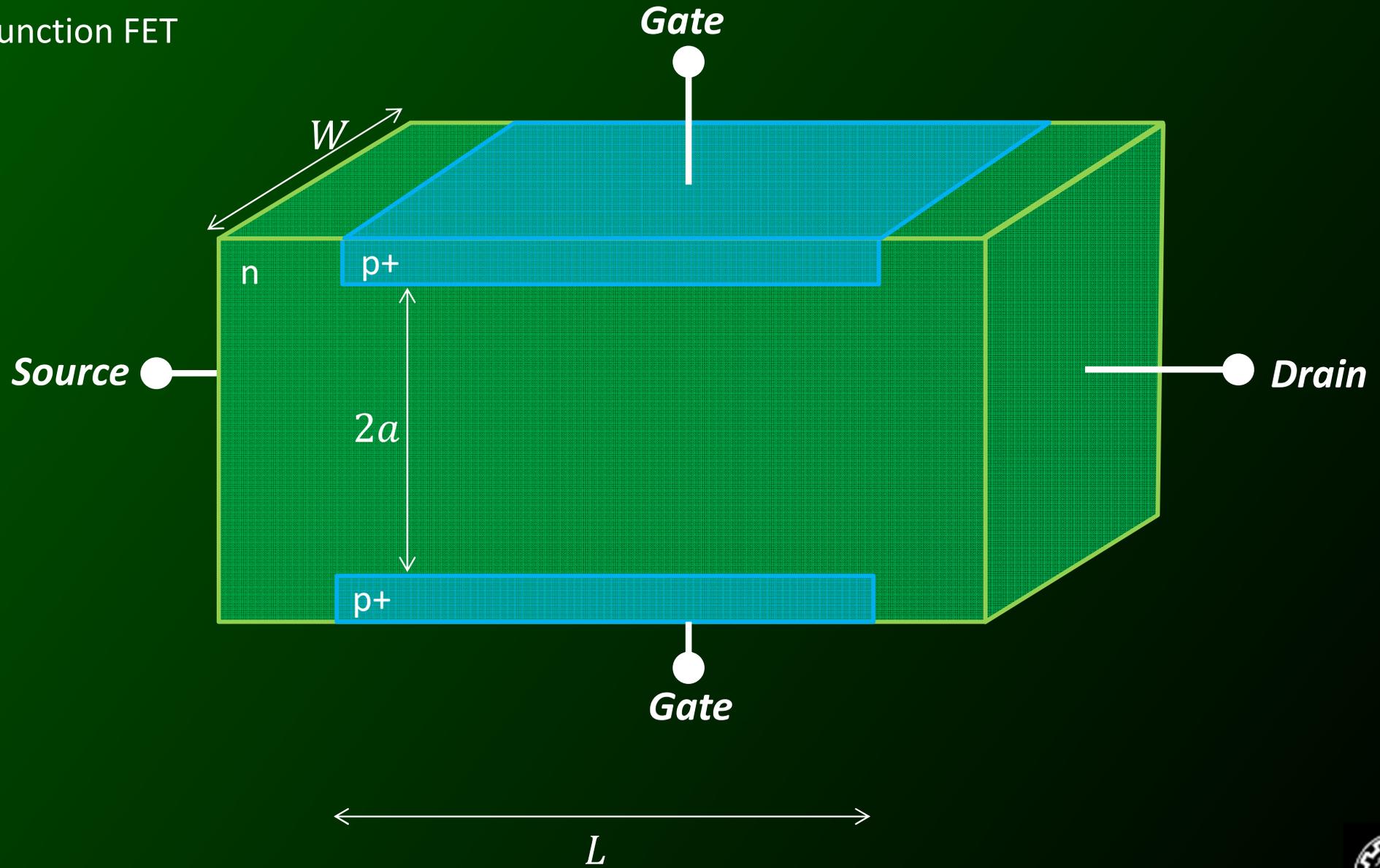
pnp

Emitter | Base | Collector

p+ | n | p-

E_{C_E}

E_{F_E}
E_{V_E}

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

pnp

Emitter

W_B Base

Collector

V_E

V_C

p+

n

p-

W

E_{C_E}

qV_C

qV_E

E_{F_E}
E_{V_E}

Junction FET

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

$V_D \sim 0$

W

L

p+

n

$2a$

x

V_D

p+

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

I_D

$V_D > 0$

V_{DS}

W

L

n

p+

$2a$

x

p+

V_D

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

I_D

$V_D \sim 0$

V_{DS}

W

L

n

p+

$2a$

x

p+

V_D

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

I_D

$V_D \sim 0$

V_{DS}

$$W$$

$$V_G = -2$$

$$L$$

n

p+

$$2a$$

$$x$$

$$V_D$$

$$V_G = -2$$

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

$$I_D$$

$$V_G = 0$$

$$V_G = -2$$

$$V_{DS}$$
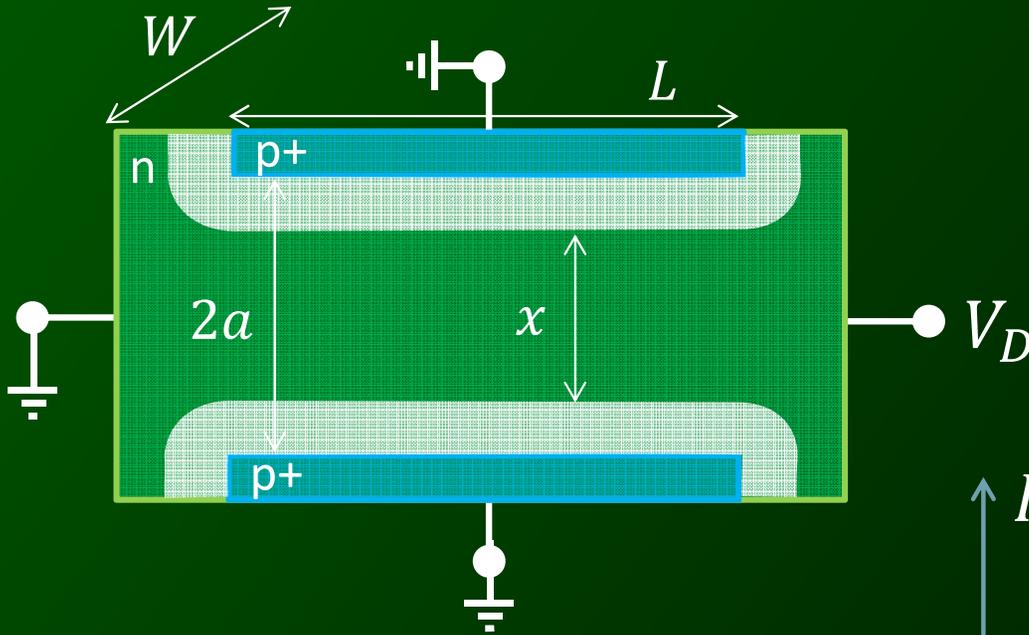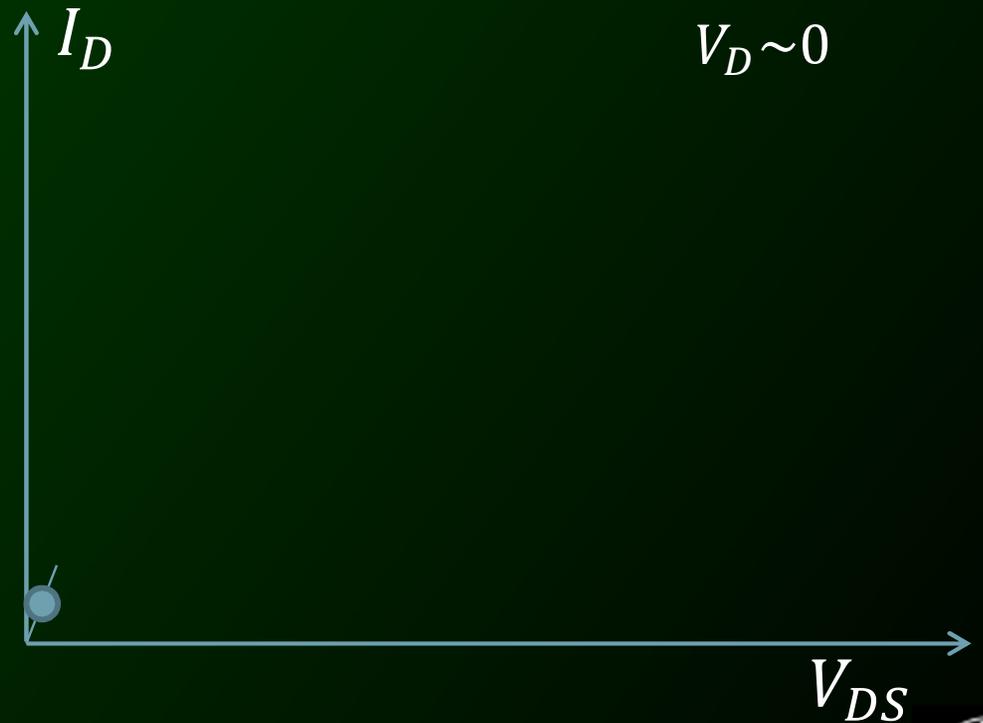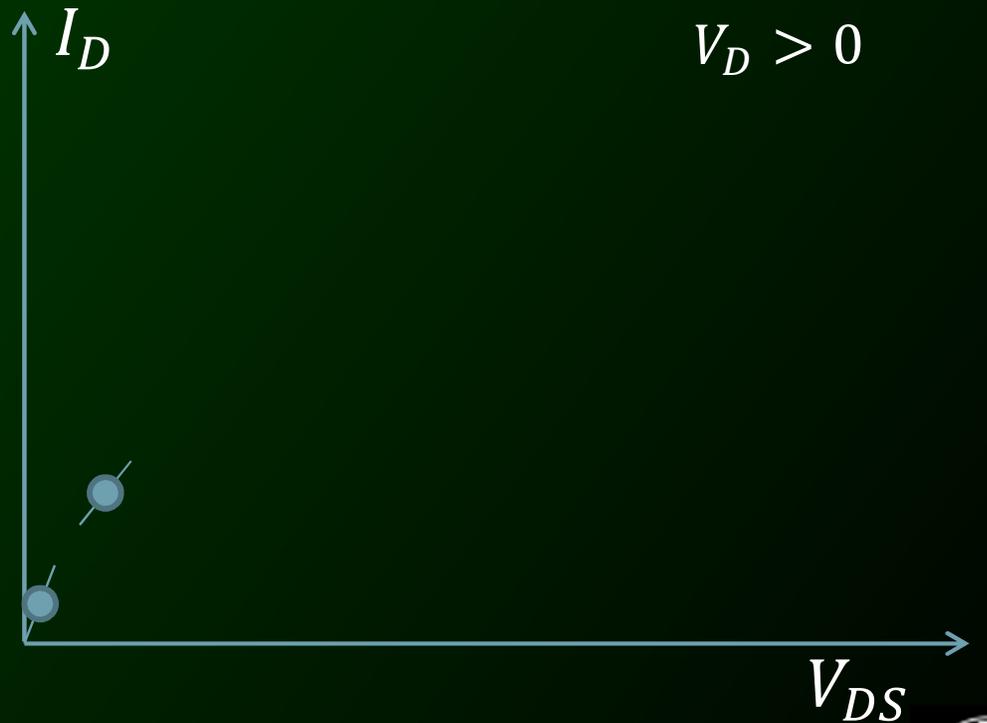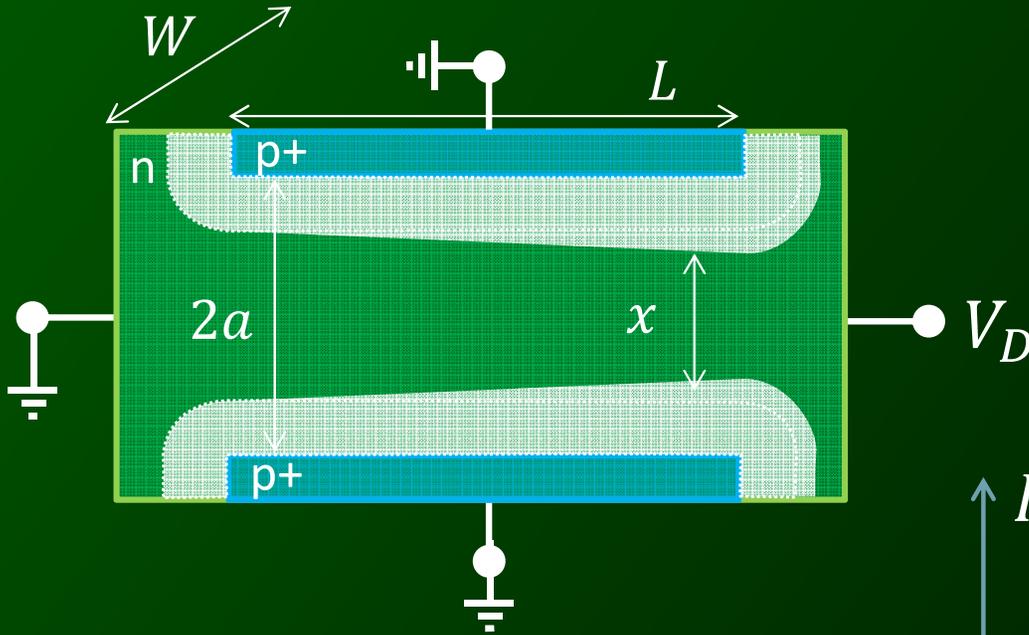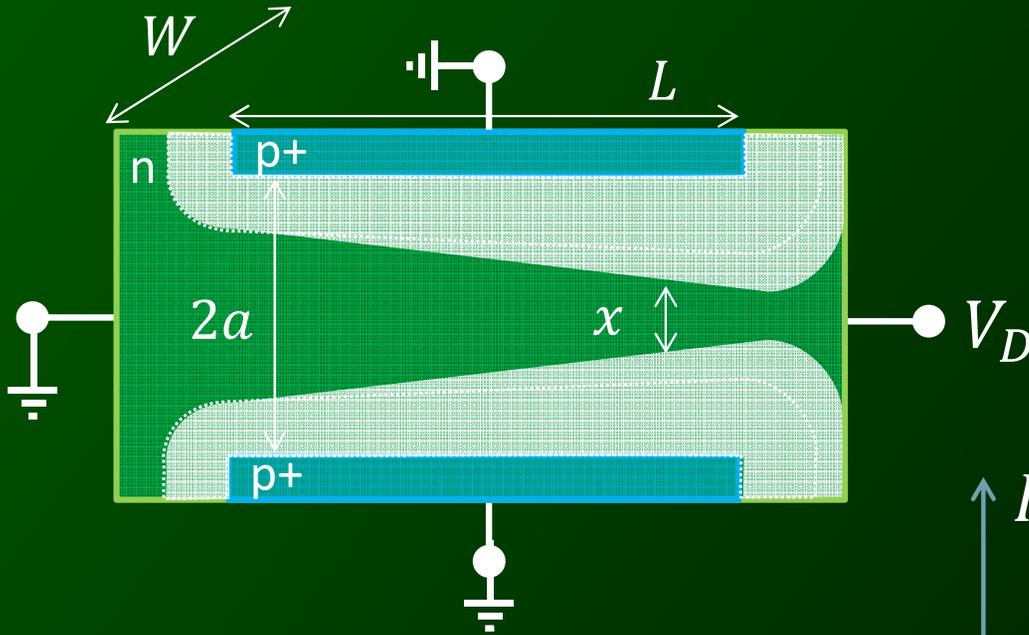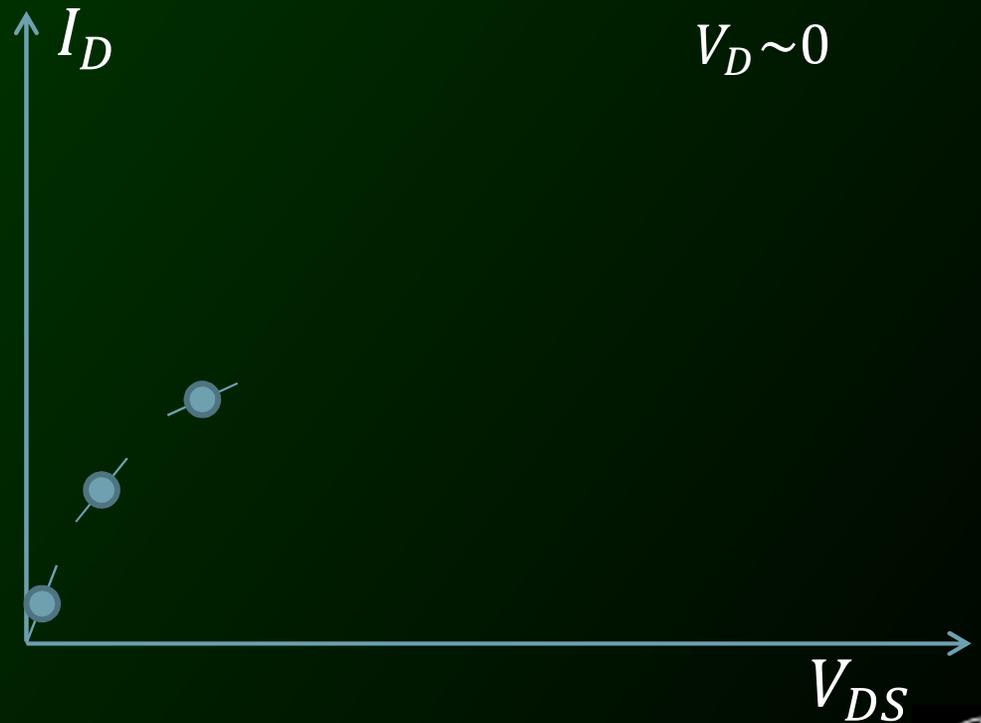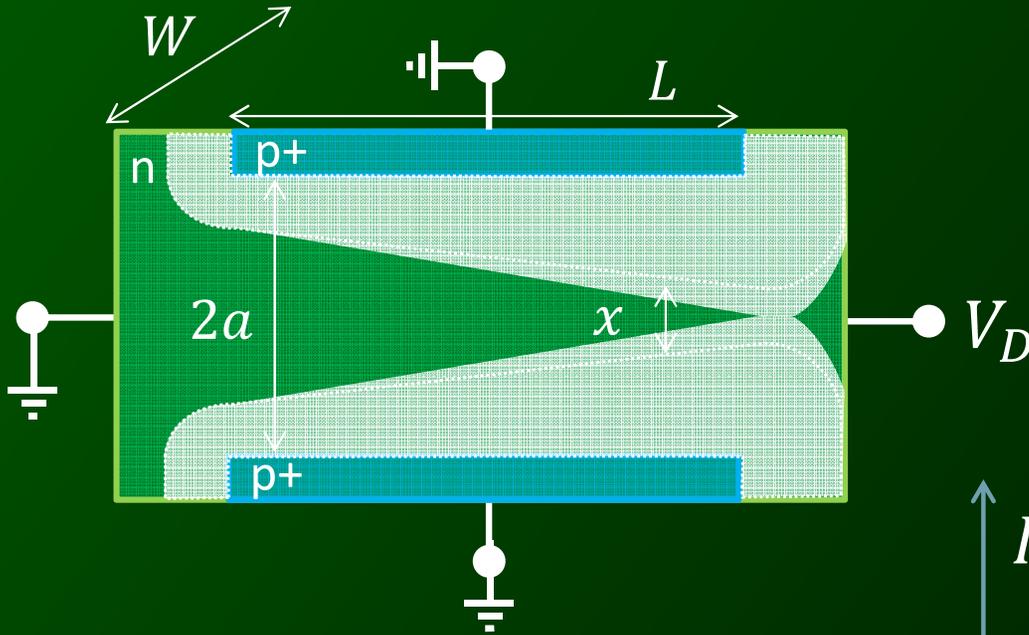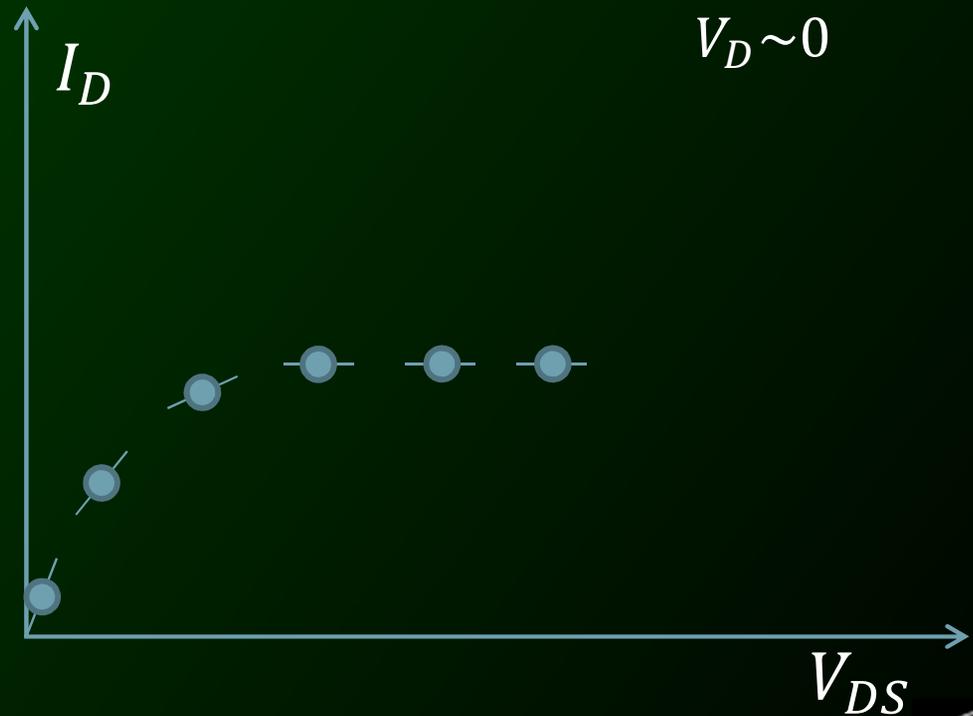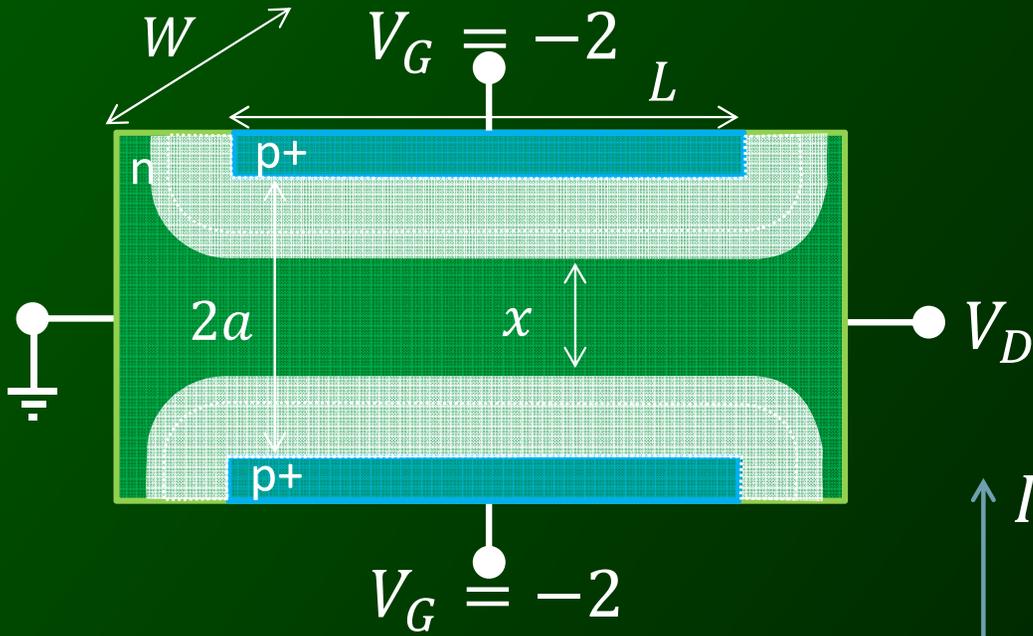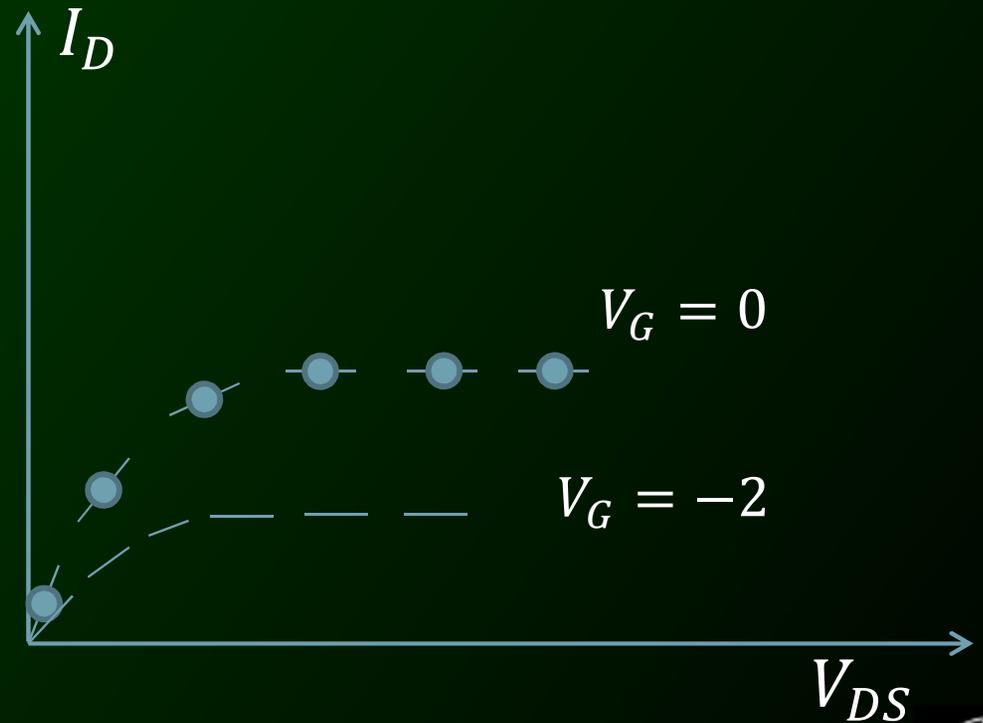
Qualitative Theory of the NMOSFET

Gate

Source

Drain

A SiO2 A'

n+   n+

p

$V_G = 0$

$V_G > 0$

$V_G = V_T$

E_C
E_F

Source

Drain

E_V

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

$V_{GS} > V_T$

S D

n+   n+

$V_{DS} \approx 0$

p

I_D

$V_{GS} > V_T$

S D

n+ $0 \longmapsto y$ $V(y)$ n+

$V_{DS} > 0$

p

V_{DS}

$V_{GS} > V_T$

S D

n+   n+

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

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

p

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