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Semiconductor Fundamentals & PN Junction Device Physics

Reviewed 2025

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Semiconductor Fundamentals – goal and objectives

Goal

- Participants will have foundational understanding of semiconductors, PN diode device physics, and how it relates to electrical characteristics.

Objectives

- Cite basic knowledge of atomic theory and band formation, semiconductor carrier concentration, and extrinsic doping
- Illustrate the architecture and operations of PN junctions
- Able to interpret and draw basic band-diagram for different material systems and operating conditions

Target Audience

- Interns, NCGs (new college grads) and new employees in some technical roles need to understand these concepts
- Examples of critical target audience roles at Micron that utilize these concepts
  - Device Engineer
  - Process Integration Engineer
  - Process Engineer
  - Design Engineer
  - Product Engineer
  - Reliability Engineer
  - Quality Engineer
  - Yield Enhancement Engineer
  - Probe Engineer
  - Characterization Engineer
  - Test Engineer
  - Verification Engineer
  - Signal Integrity Engineer

Pro tip

Everyone interviewing at Micron can use this presentation to prepare for the interview by learning foundational information about memory. Check out the candidate guides for Engineering, Technician and Business roles.

- Micron engineering candidate guide
- Micron technician candidate guide
- Micron business candidate guide

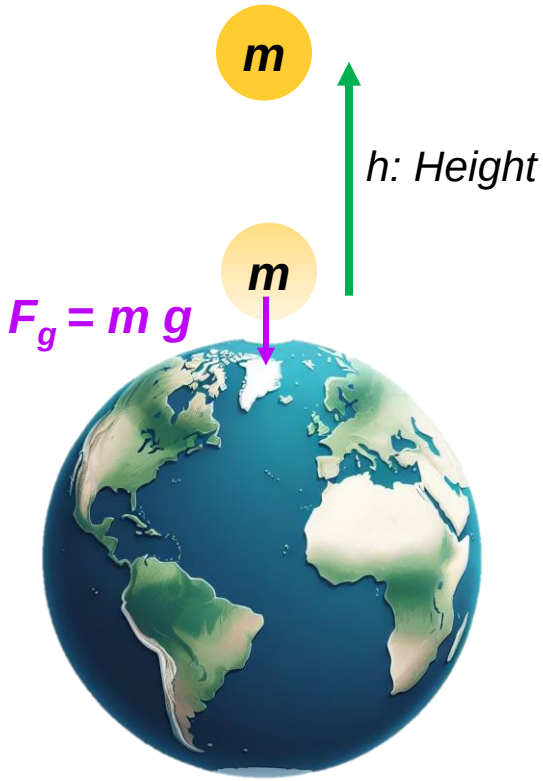
E - Potential energy
V - Electric potential
ξ - Electric field

Potential Energy

Analogy between gravitational & electrical energy

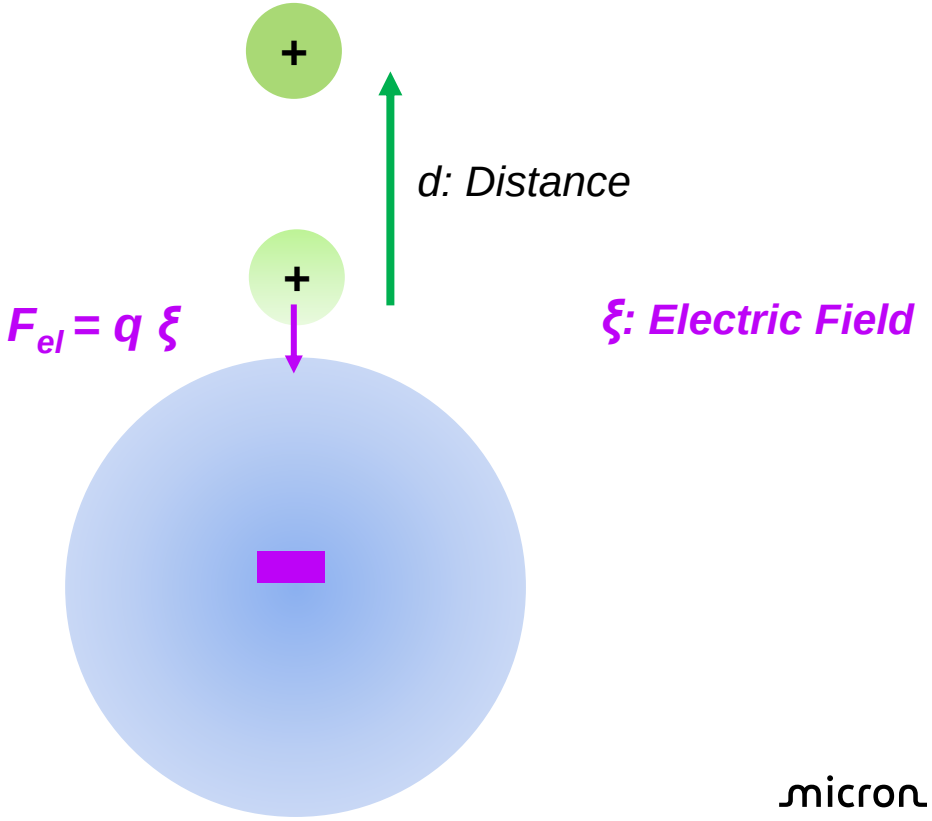
Gravitational Potential Energy, U = Work done to move an object, with mass m **against gravitational field (g)** over a height h

F = m g U = F d = m g h



Electric Potential Energy, E = Work done to move a test charge q **against an electric field (ξ)** over a distance d

F = q ξ E = F d = q ξ d



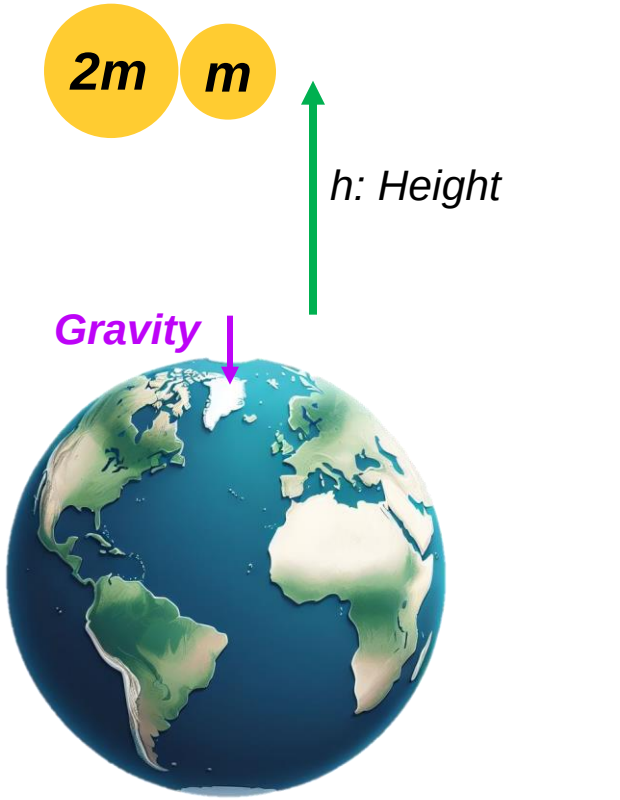
E - Potential energy
V - Electric potential
ξ - Electric field

Potential

Normalized quantity, energy per unit mass or charge

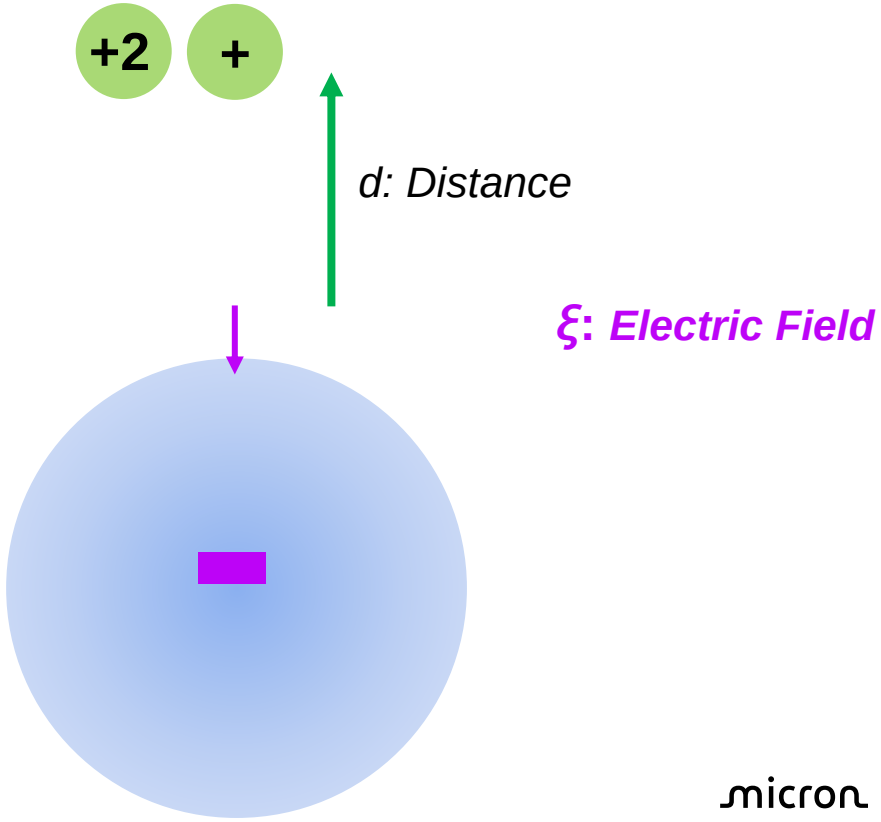
Gravitational potential is the amount of gravitational potential energy per unit mass at a specific point in a gravitational field.

Gravitational potential = m g h / m = g h



Electric potential is the amount of electric potential energy per unit charge at a specific point in an electric field.

Electric potential, V = q ξ d / q = ξ d



E - Potential energy
V - Electric potential
ξ - Electric field

Potential vs Energy

- Unit of potential is **Volt (V)** and the unit of energy is **Electron-Volt (eV)**

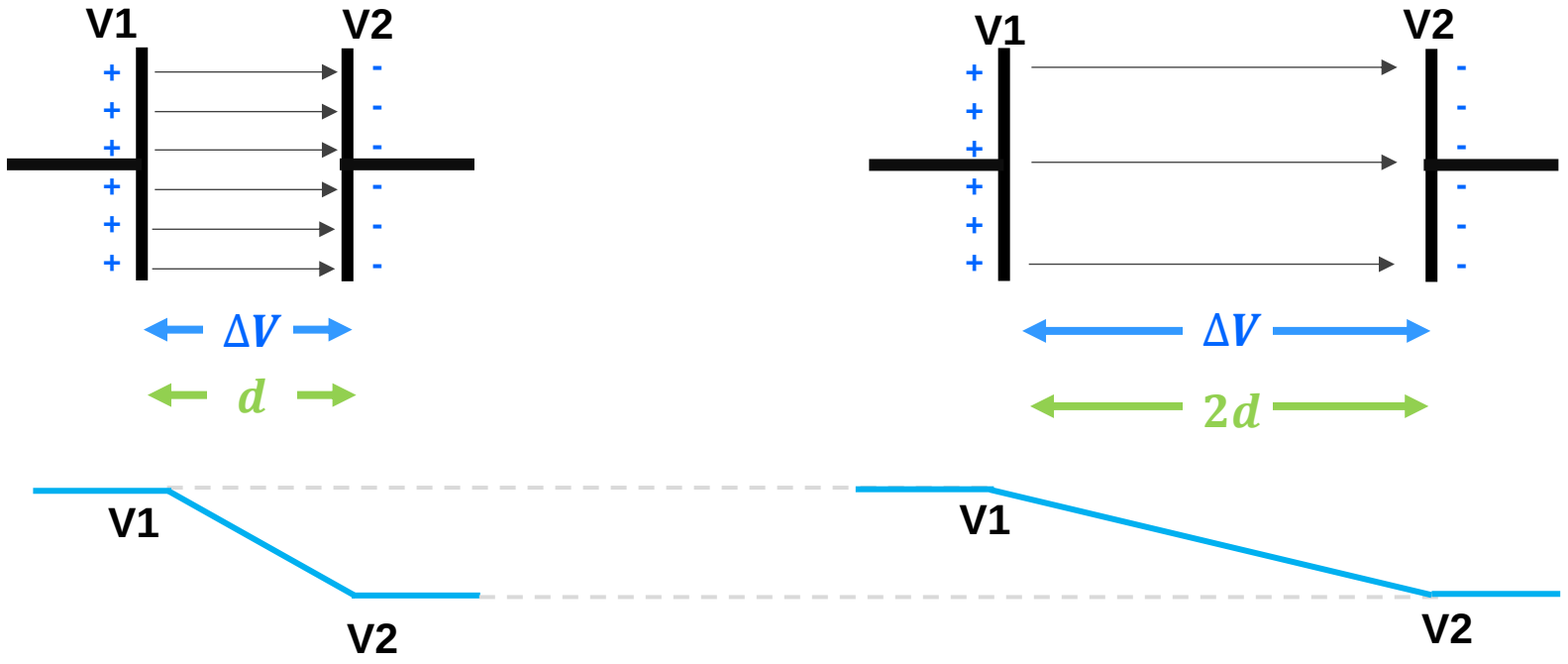
  Potential Energy, E = q ξ d

  We know potential **V = ξ d**, then **Potential Energy, E = q V**

  For electron energy, E = -e V

- 1 electric charge x 1 Volt = **1.6×10^{-19} Joules = 1eV**

Electric Field

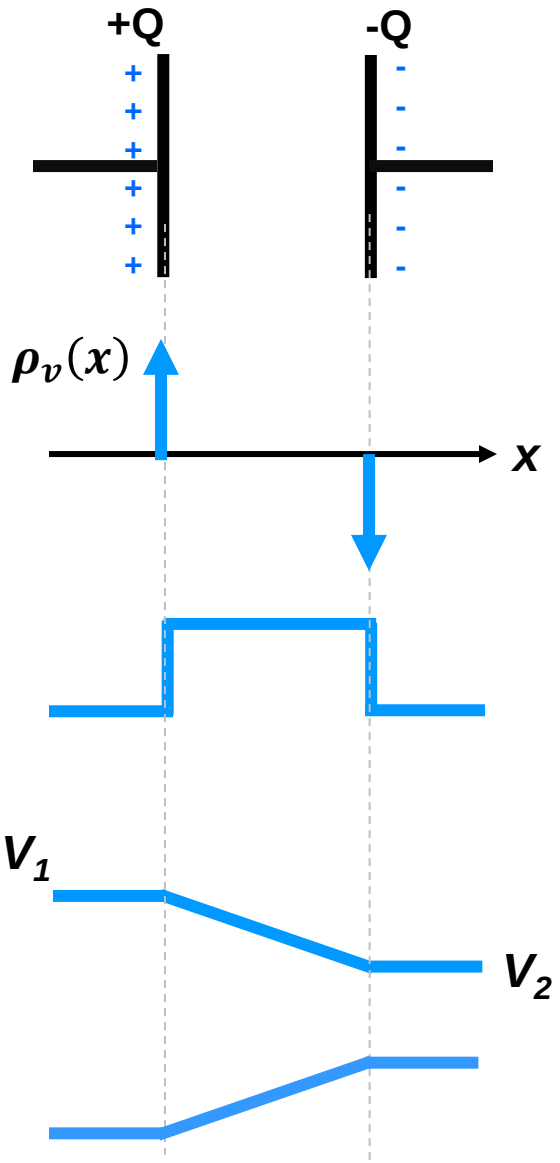


$$\xi = -\frac{dV}{dx}$$

Electric field strength reduces by half

Electric field also can be denoted by # flux lines/area

Charge, Potential, Energy and Electric Field



Gauss's Law

Charge Density, $\rho_v(x)$

$$\xi = \int \frac{\rho_v(x)}{\varepsilon} dx$$

ε : *permitivity*

ξ Electric Field,

$$\xi = -\frac{dV}{dx}$$

Potential, V, ψ

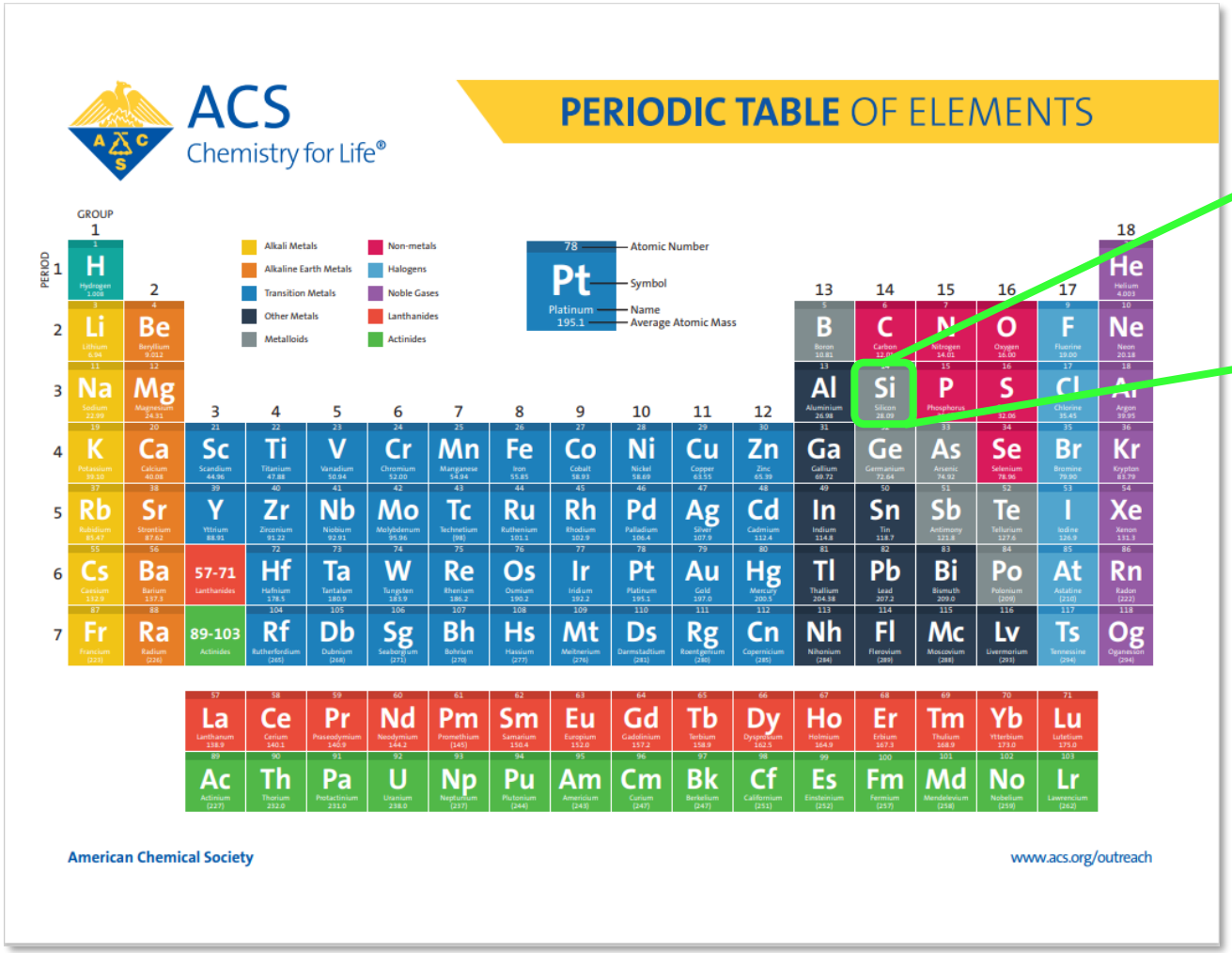
$$V = -\int \xi \, dx$$

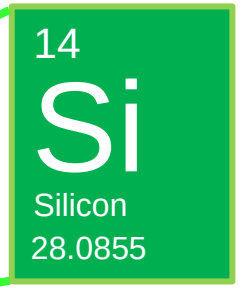
Energy (electron), E

$$E = -e.V$$

Silicon

Silicon is the most used semiconductor element in electronics world





Neutral Si atom has 14 electrons [2, 8, **4**]

Si Electronic Configuration: $1S^2\ 2S^2\ 2P^6\ 3S^2\ 3P^2$

Si has **4 valence electrons**

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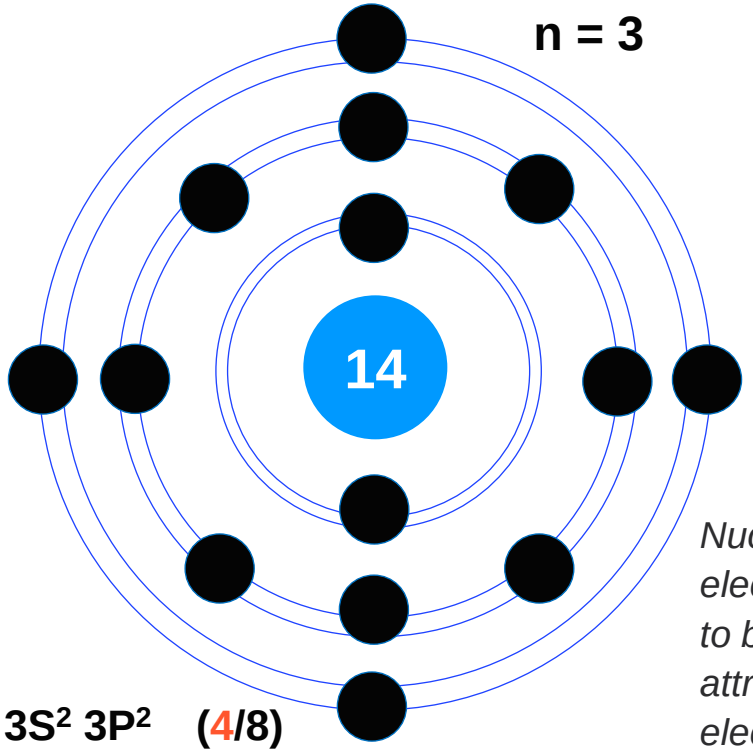
Energy Level

Si : $1S^2$ $2S^2$ $2P^6$ $3S^2$ $3P^2$

Energy levels of electrons are quantized (discrete)

Increasing Electron Potential Energy

E_0, Vacuum level

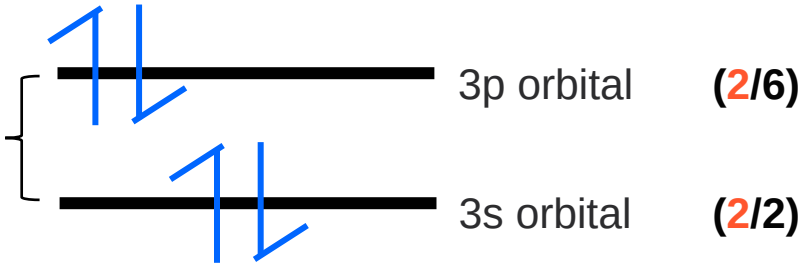


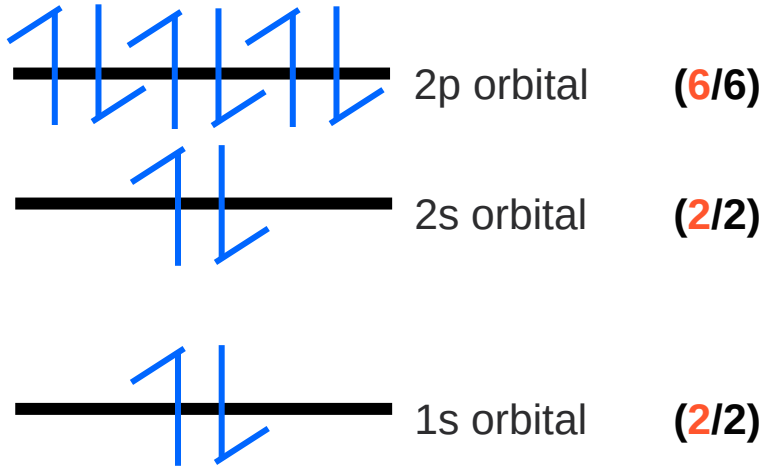
$3S^2$ $3P^2$ **(4/8)**

$2S^2$ $2P^6$ **(8/8)**

$1S^2$ **(2/2)**

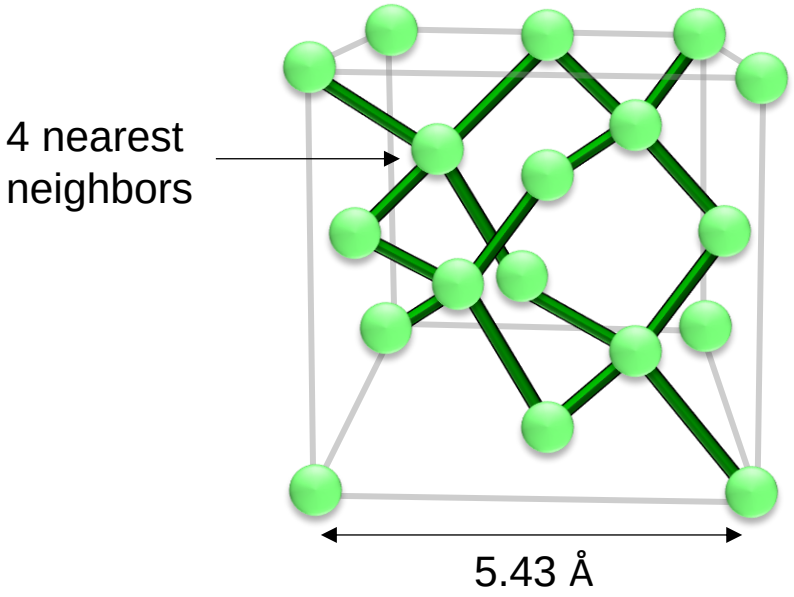
Total of **8 valence states**, **4** of them are **filled**



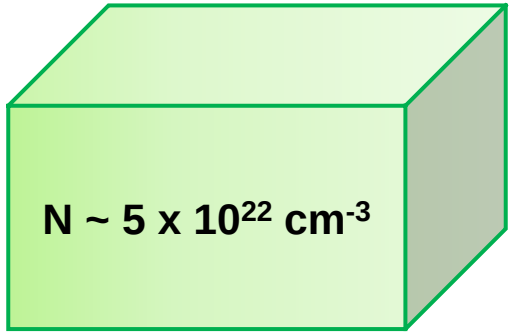


Nucleus is positively charged; inner electrons are readily attracted. Work needs to be done to separate electrons against the attraction force, thus potential energy of electron increases from inner orbitals to outer

Energy Level



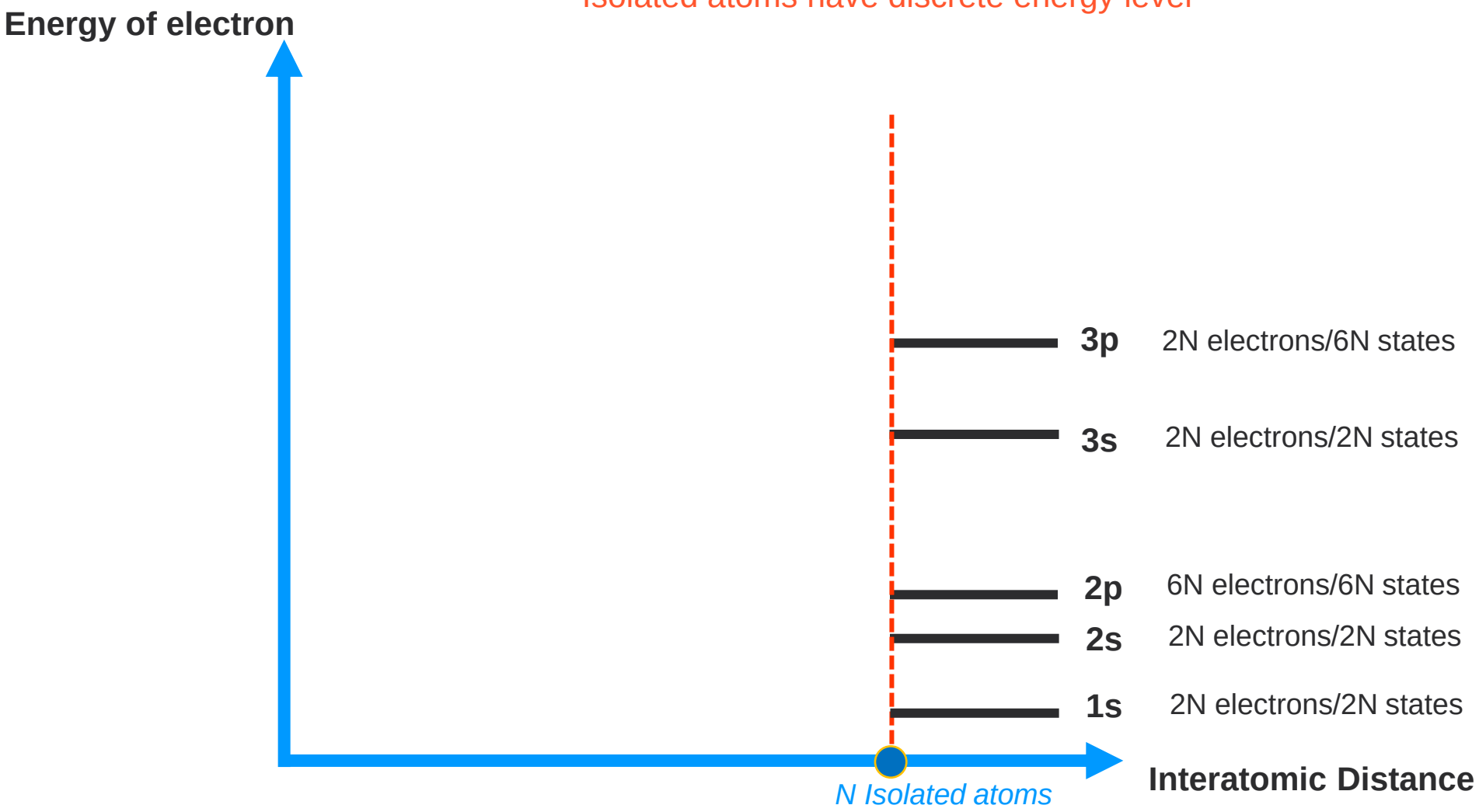
- Silicon is tetrahedrally bonded, each Si atom bonded to neighboring 4 Si atoms
- Lattice structure is like that of diamond
- Silicon has N ~ 5 x 10^{22} atoms per cm^3
- 8 valence states give rise to 8N states per cm^3



Energy Bands

Si : $1S^2$ $2S^2$ $2P^6$ $3S^2$ $3P^2$

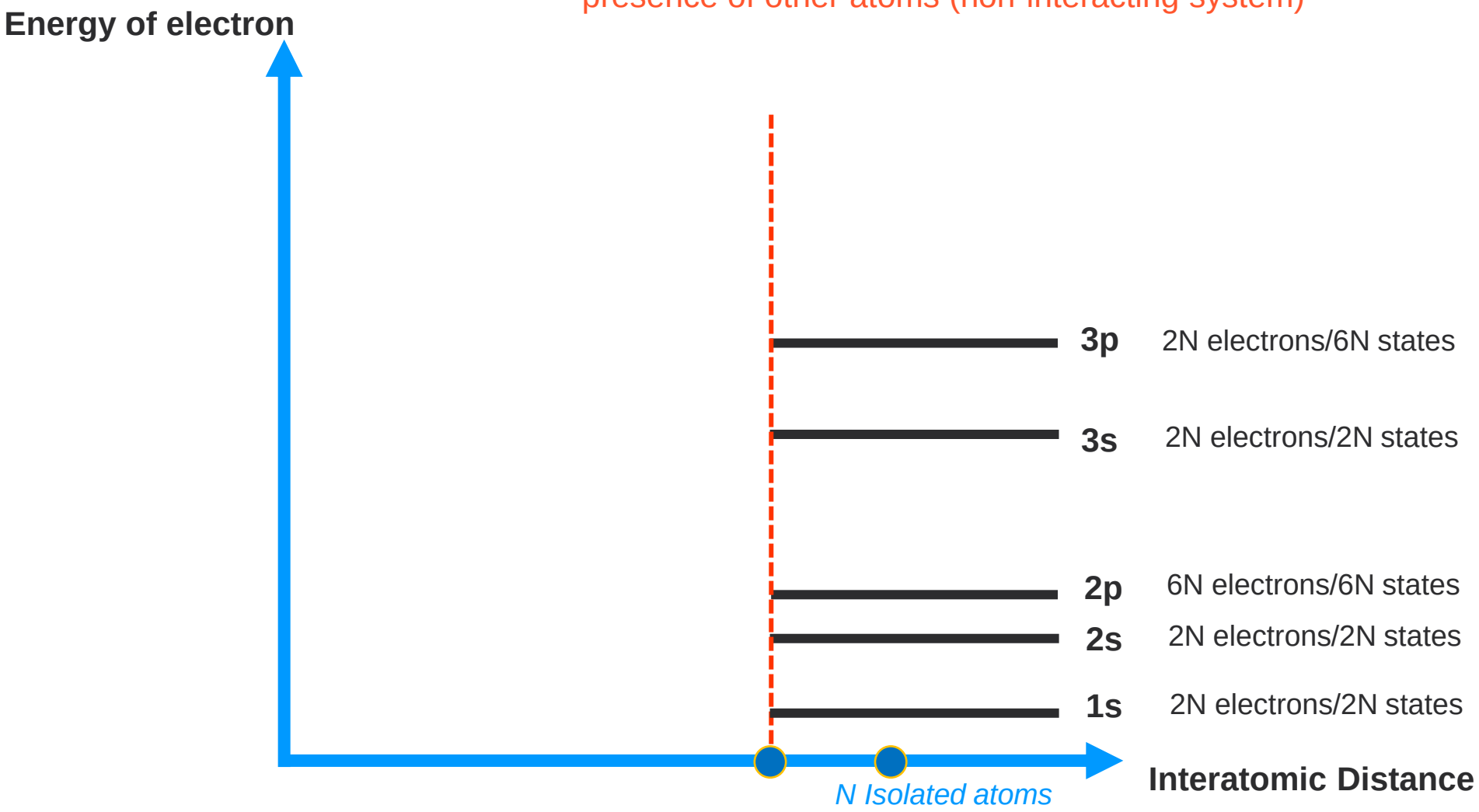
N isolated non-interacting atoms, they don't feel the presence of other atoms.
Isolated atoms have discrete energy level



Energy Bands

Si : $1S^2\ 2S^2\ 2P^6\ 3S^2\ 3P^2$

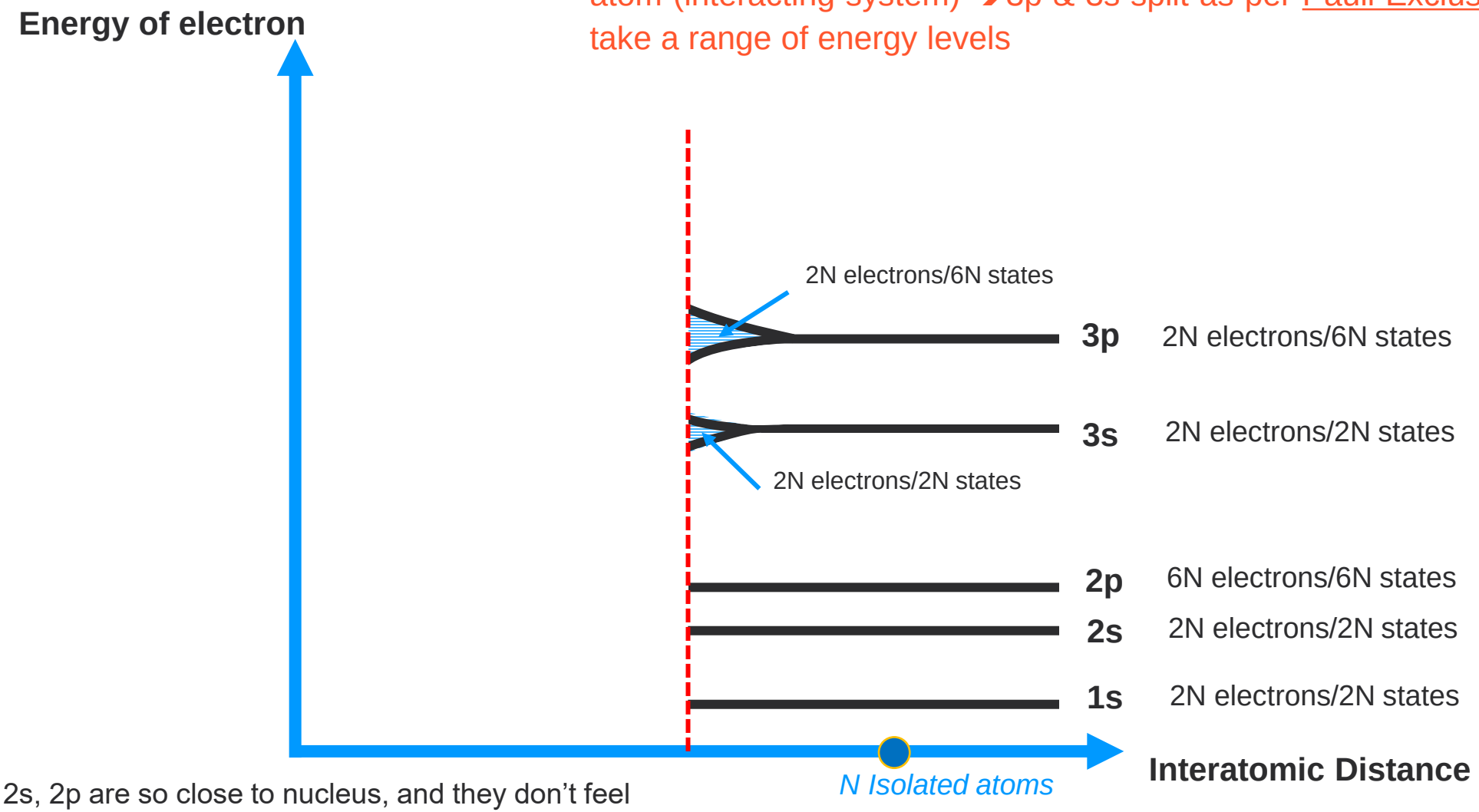
If the interatomic distance are reduced slightly, still each atom do not feel the presence of other atoms (non-interacting system)



Energy Bands

Si : $1S^2$ $2S^2$ $2P^6$ $3S^2$ $3P^2$

When atomic spacing reduced, each atom starts to feel the presence of other atom (interacting system) ➔3p & 3s split as per Pauli Exclusion principle. It will take a range of energy levels



1s, 2s, 2p are so close to nucleus, and they don't feel presence of other atoms disturbing their energy levels

Interacting system

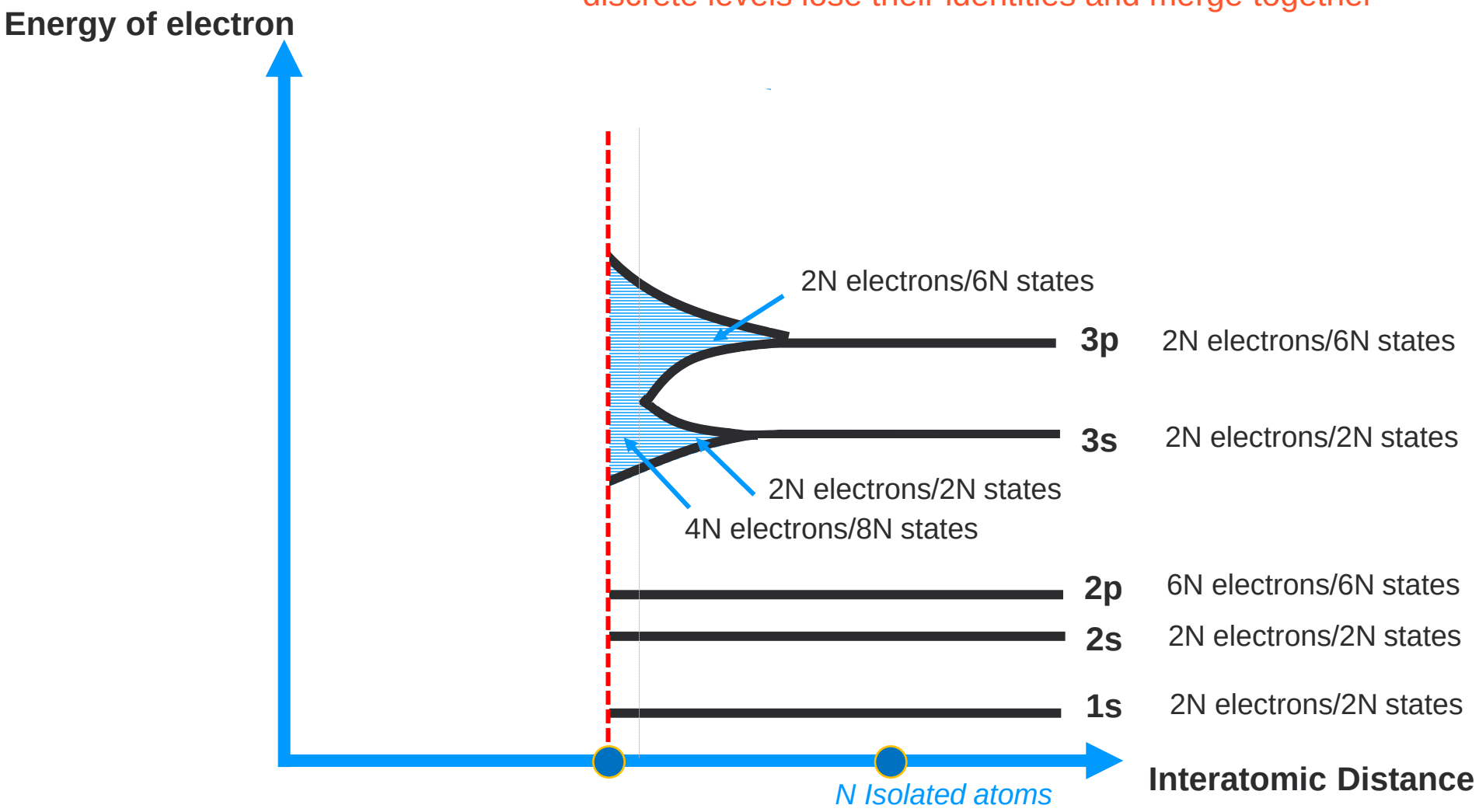
No two electrons with same state

1. **PAULI'S exclusion principle** states that **no two electrons** which interact with each other can have the **same quantum state**
2. When interatomic distance is very large the electrons in orbital will not influenced/disturbed by neighboring atom. The energy levels are discrete
3. When the interatomic distance is small, the electrons sitting in orbitals will be disturbed, resulting in energy level splitting. Impact is worse for higher orbitals
4. **In interacting system, Pauli exclusion principle comes in place**

Energy Bands

Si : $1S^2\ 2S^2\ 2P^6\ 3S^2\ 3P^2$

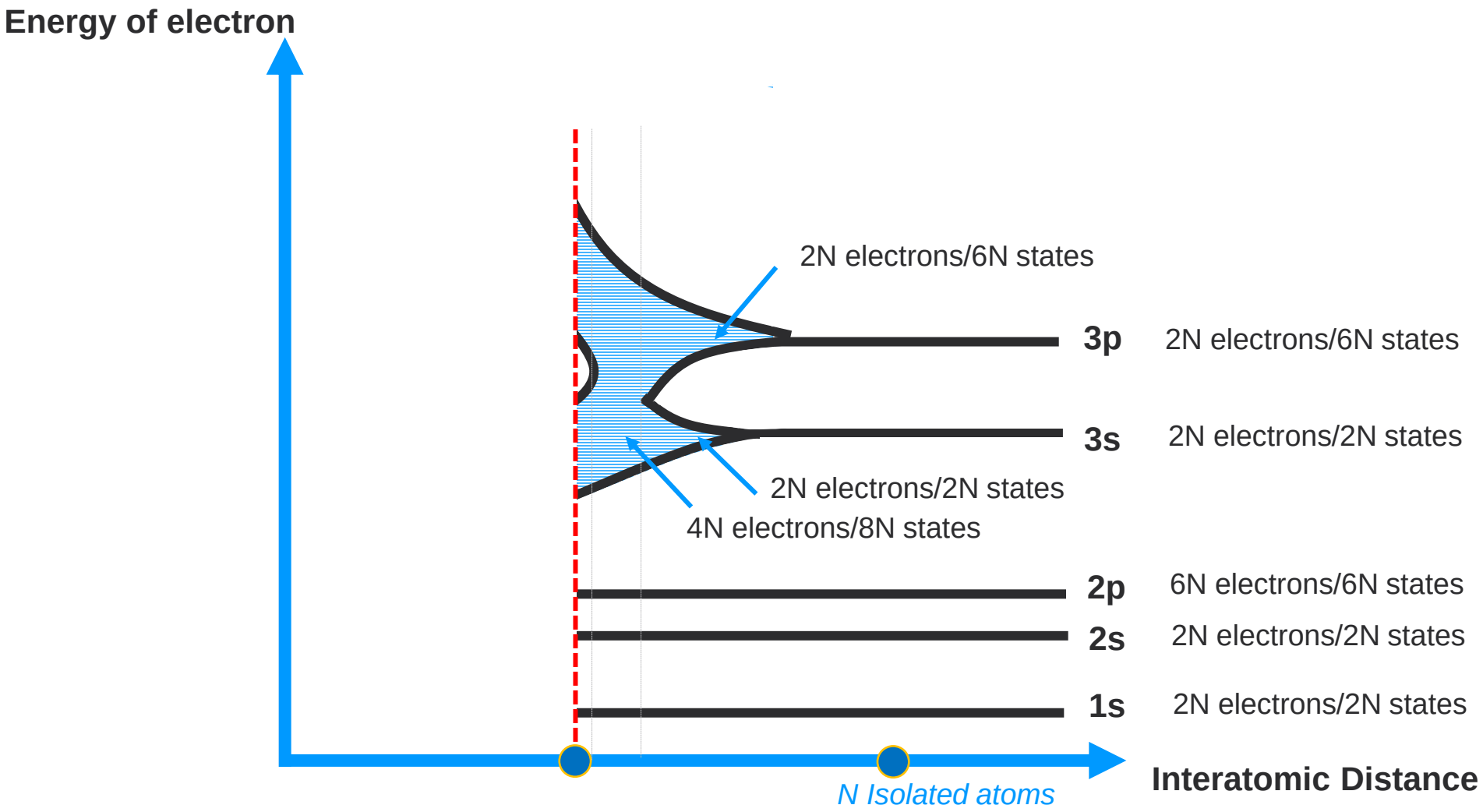
When atomic spacing further reduced, bands originating from different discrete levels lose their identities and merge together



Energy Bands

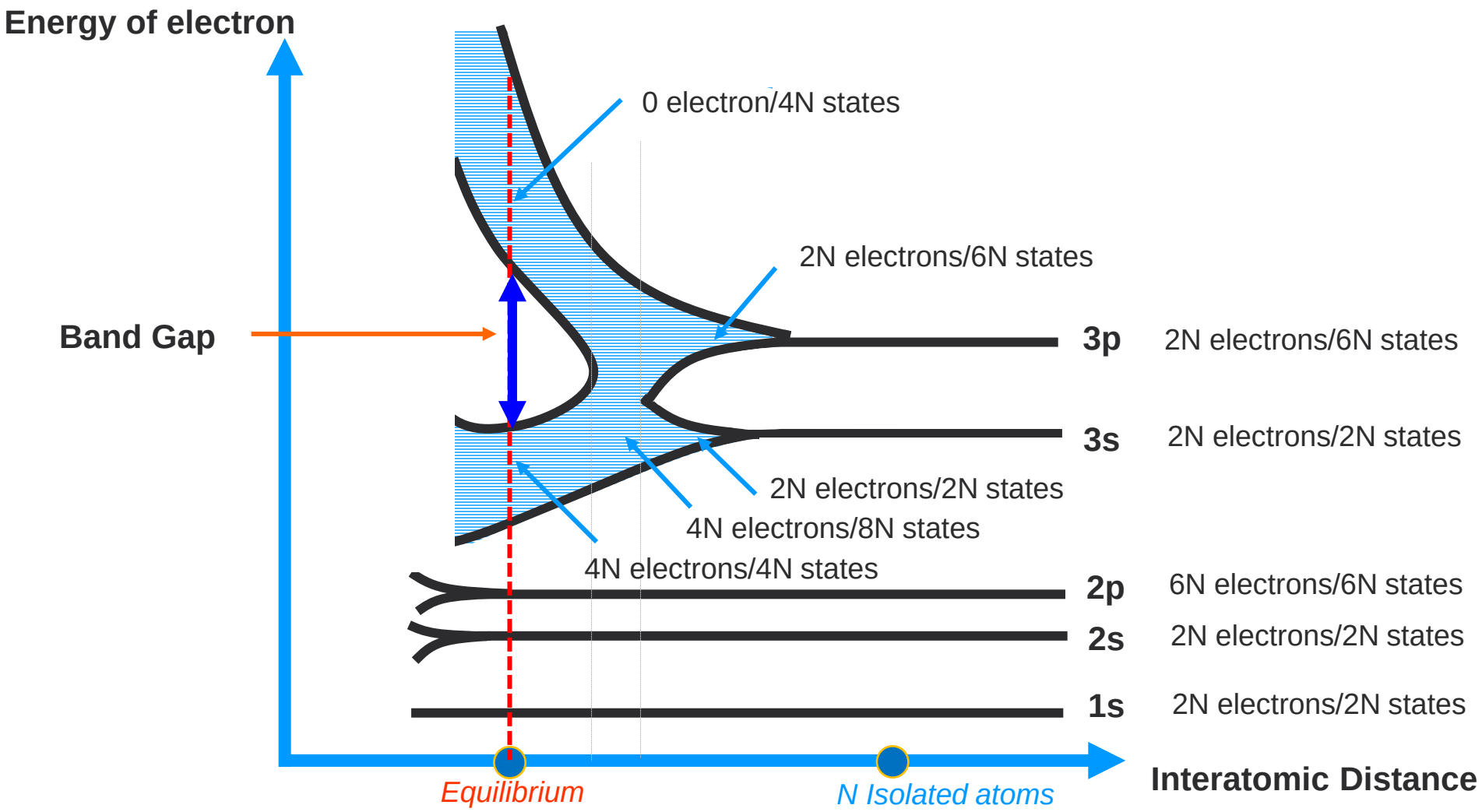
Si : $1S^2$ $2S^2$ $2P^6$ $3S^2$ $3P^2$

Bands will split again into two different bands



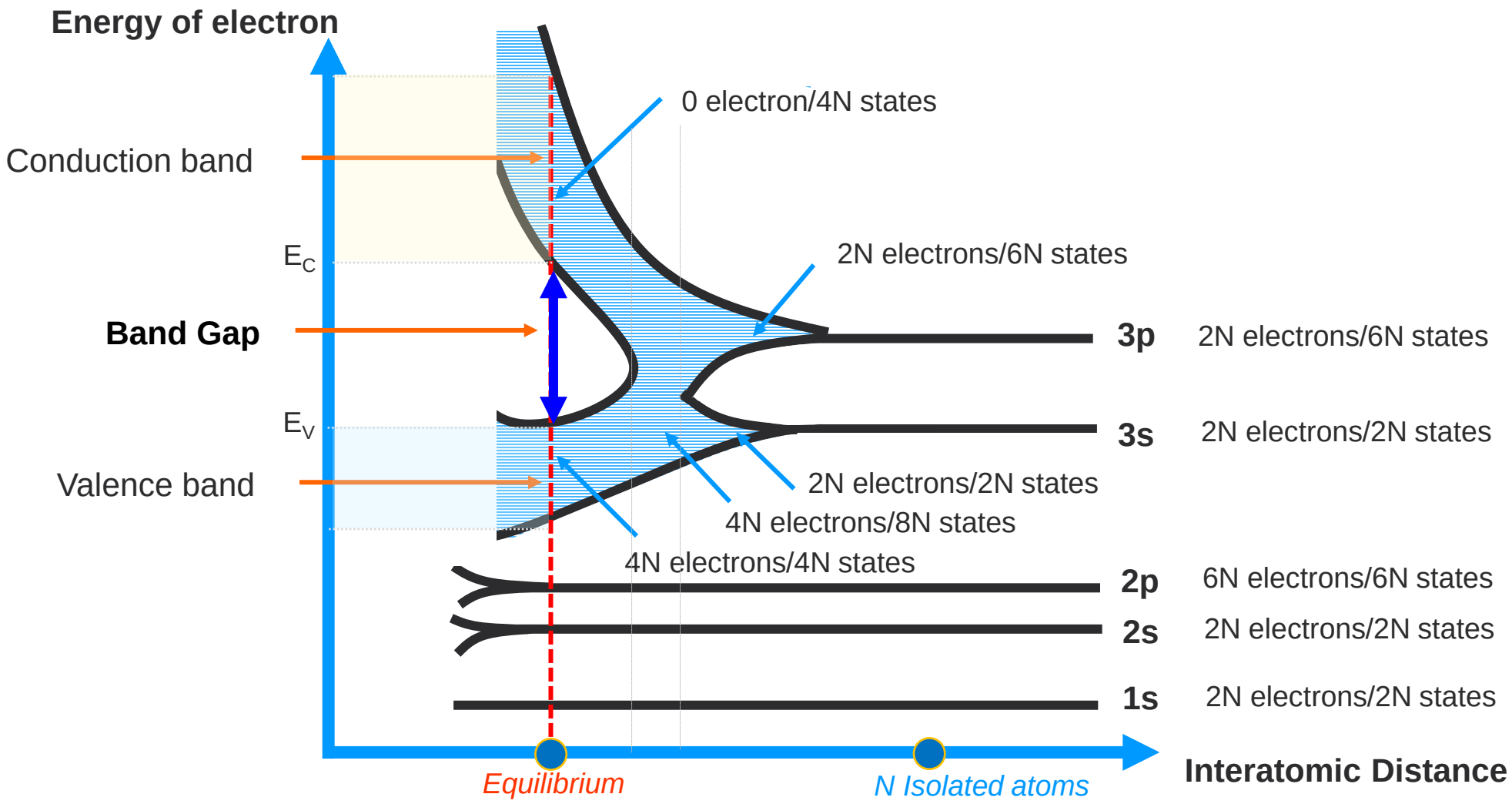
Energy Bands

Si : $1S^2\ 2S^2\ 2P^6\ 3S^2\ 3P^2$



Si : $1S^2\ 2S^2\ 2P^6\ 3S^2\ 3P^2$

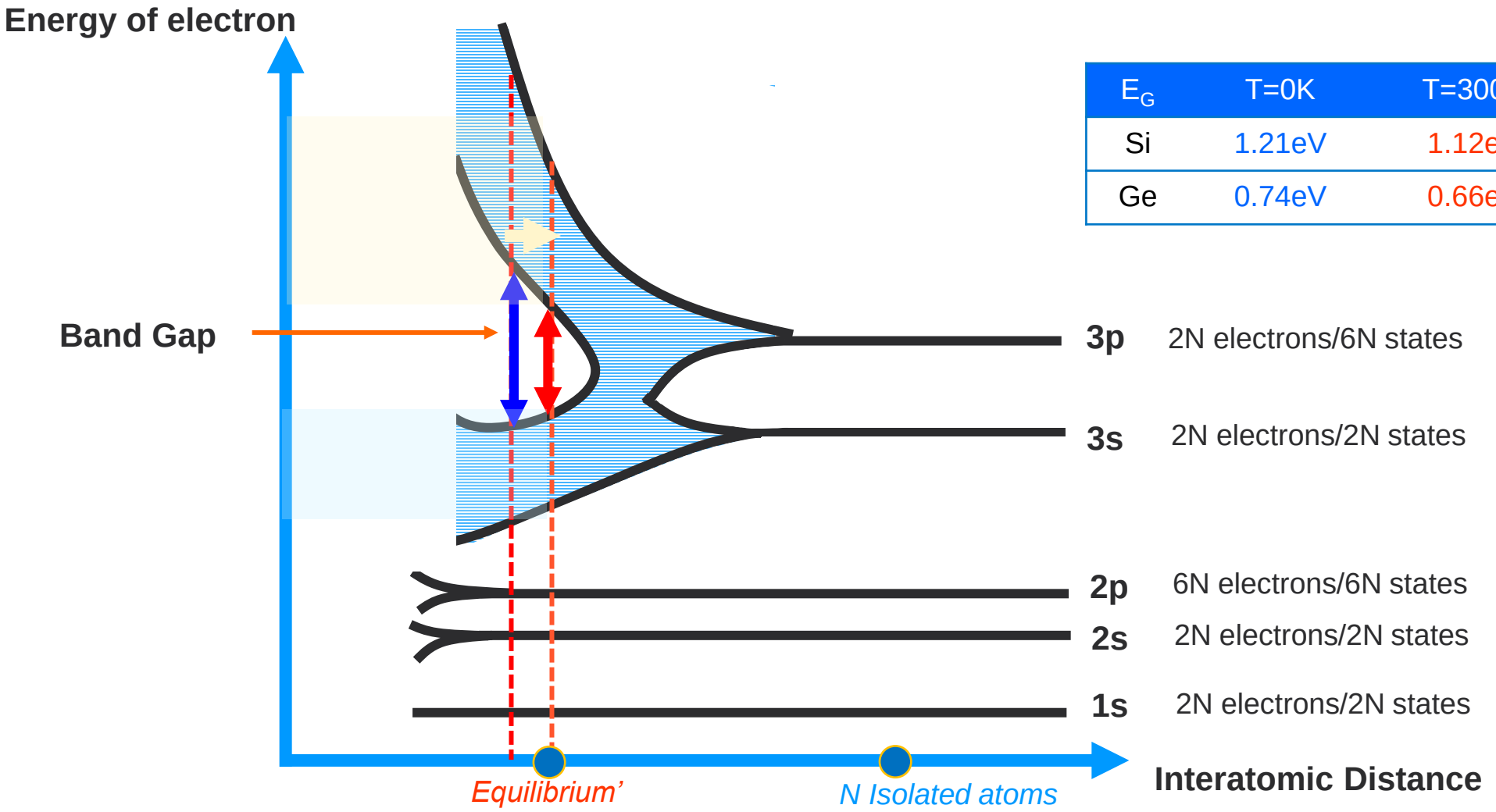
Energy Bands



Energy Bands

Si : $1S^2\ 2S^2\ 2P^6\ 3S^2\ 3P^2$

As temperature increases, the interatomic distance increases (material expands) and hence bandgap reduces

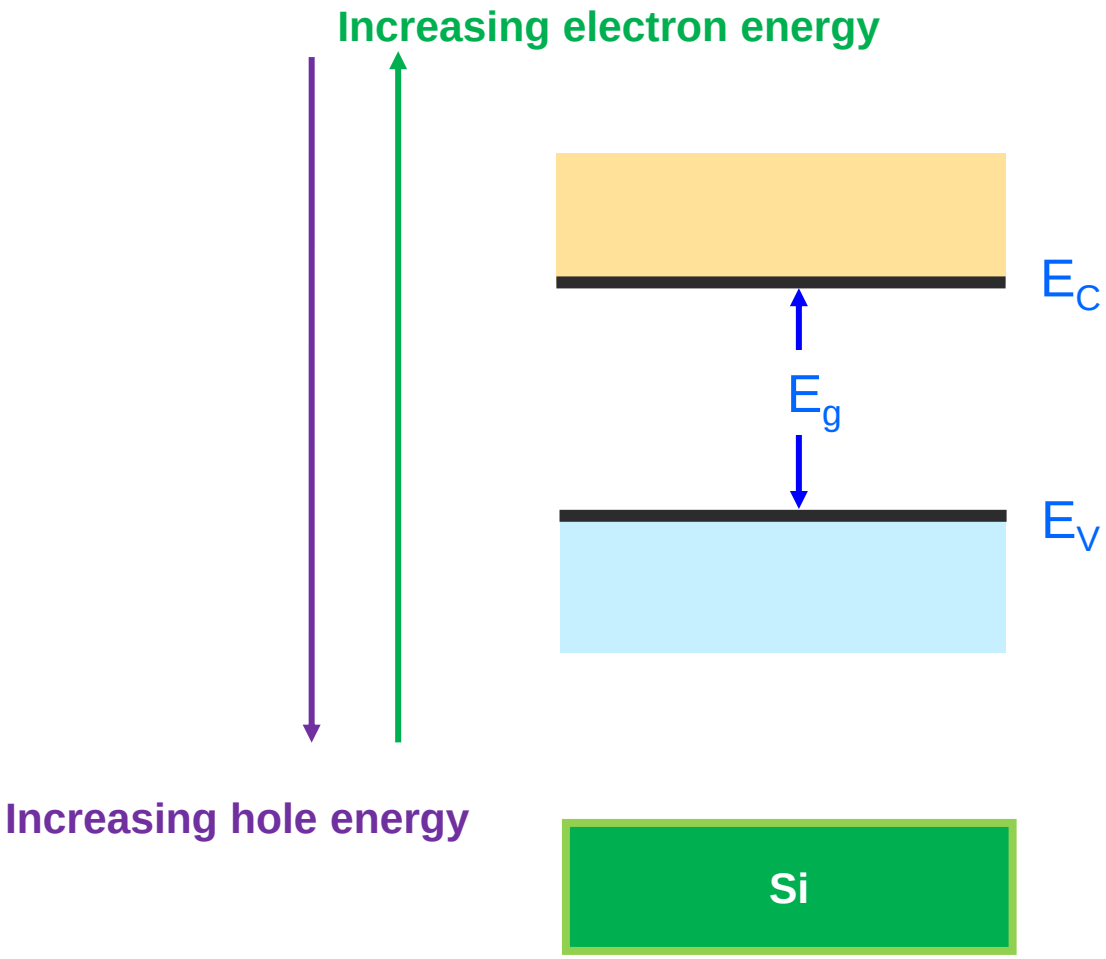


E_G	T=0K	T=300K
Si	1.21eV	1.12eV
Ge	0.74eV	0.66eV

Group 14

Energy Bands

Simplified View of Band Model



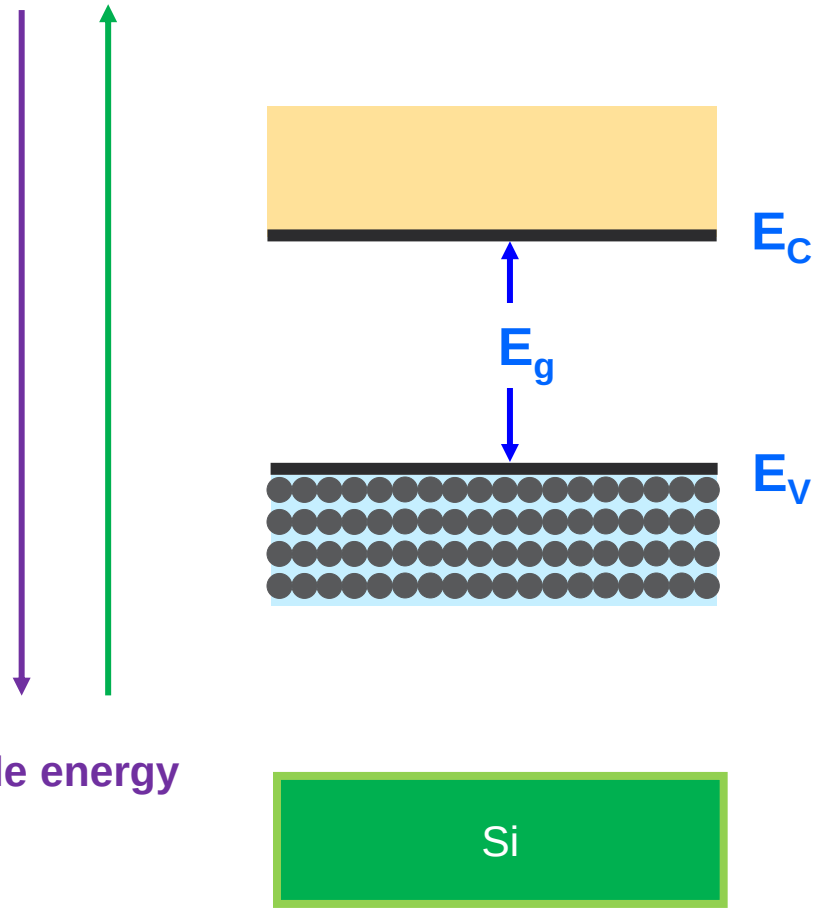
Energy band diagram is drawn with respect to electron energy

$E_g = E_C - E_V$

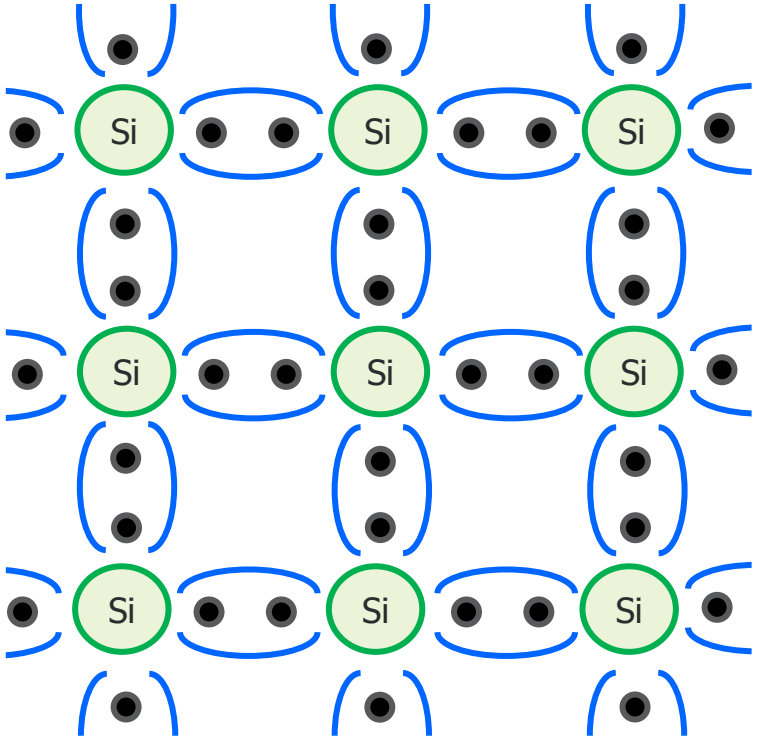
Intrinsic Semiconductor

Intrinsic: no foreign atoms/undoped, pure crystal

T=0K



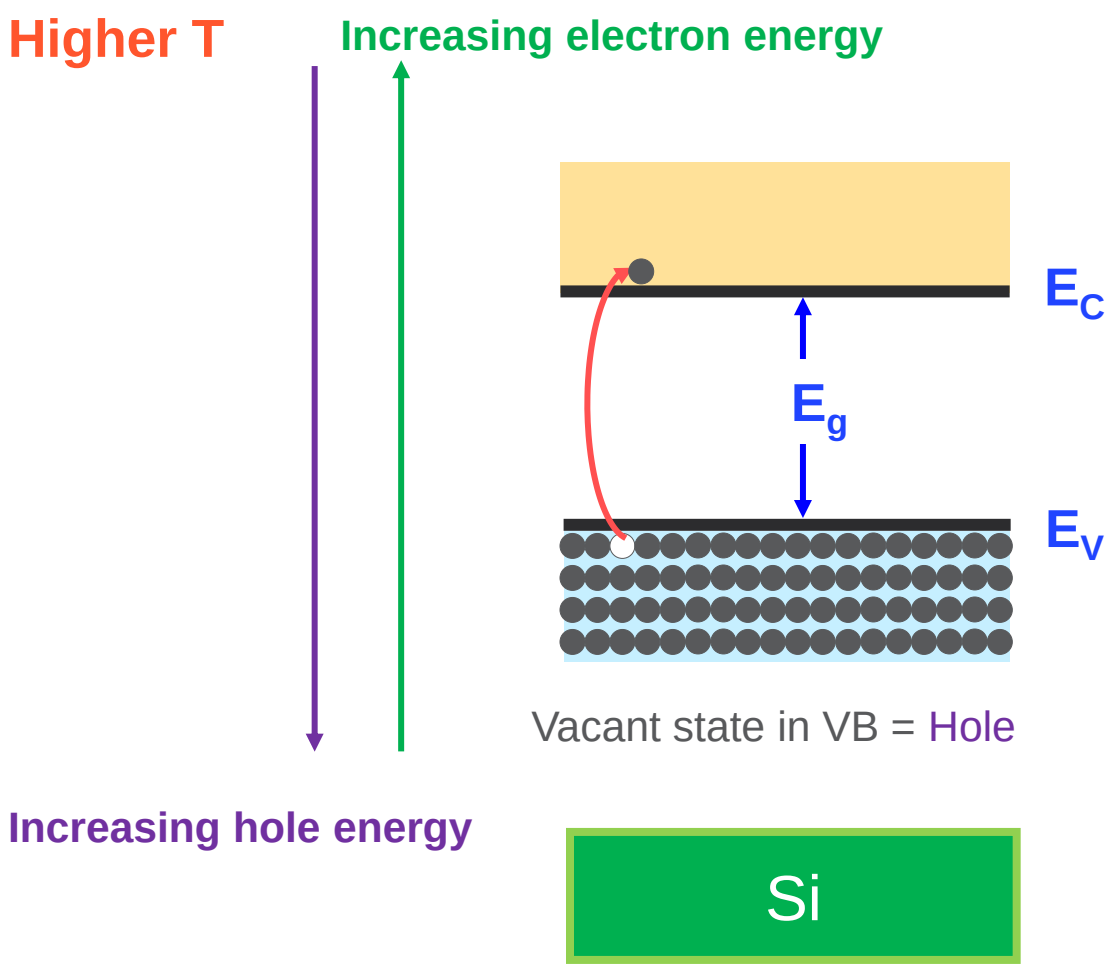
Increasing hole energy



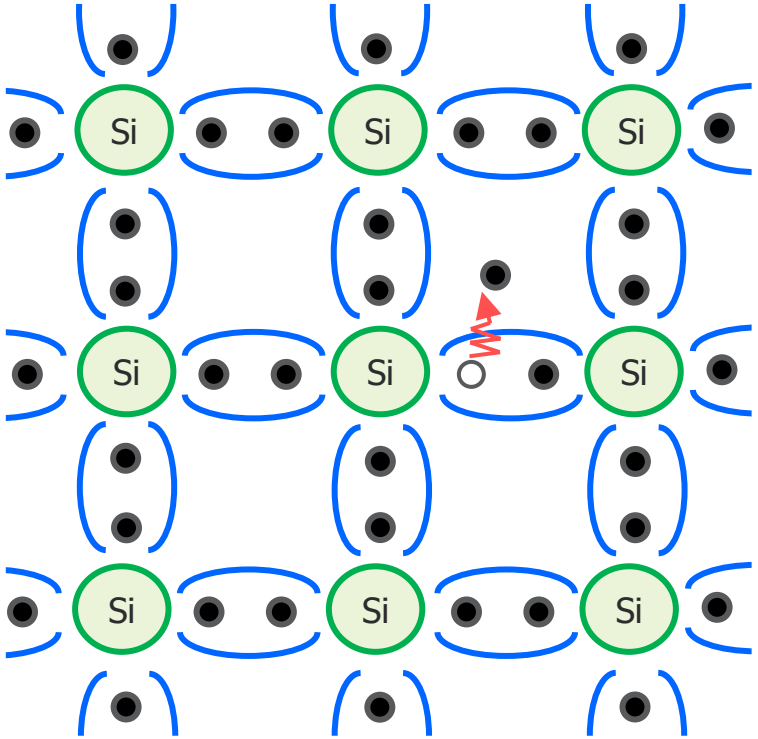
At T=0K , no electrical conduction will take place (no electrons in CB & no space for electrons to move in VB)

Intrinsic Semiconductor

Intrinsic: no foreign atoms/undoped, pure crystal



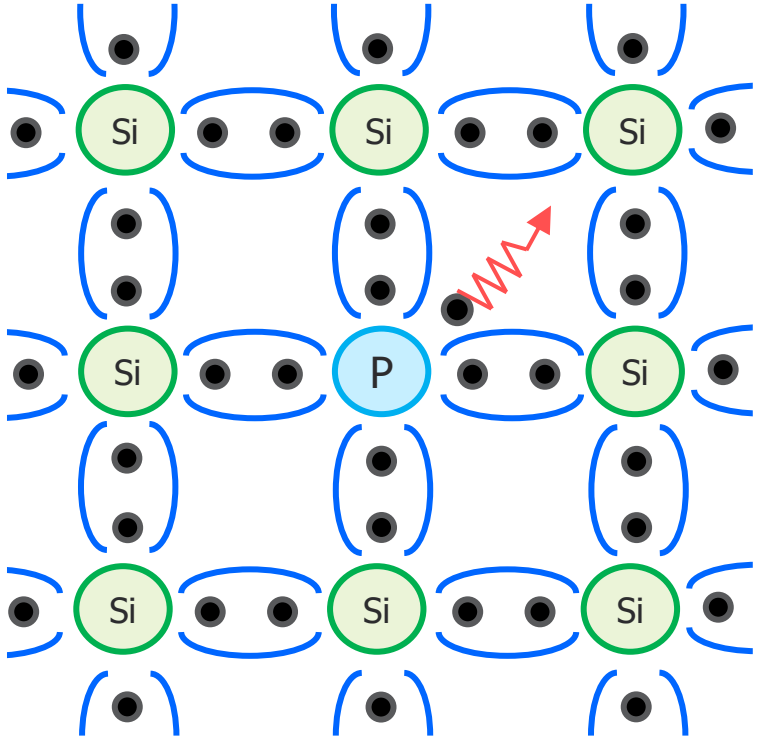
$For\ Si,\ n_i = 1.5 \times 10^{10}\ cm^{-3}$



As T ↑, atoms vibrates which potentially break Si-Si bond and create a free electron and simultaneously it creates a vacant state (hole) ➔ $n=p=n_i$, measured in # cm^{-3}

Extrinsic Semiconductor

Doping with Group 5 elements (Pentavalent/Donors)

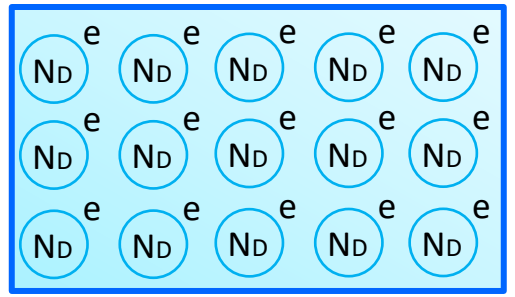


Group 5 elements have one extra electron which is weakly bounded to nucleus and at room temperature is readily freed ("donated") to wander around the lattice and hence become a carrier

When the Si is doped with donor (N_D), we called it as n-type Si

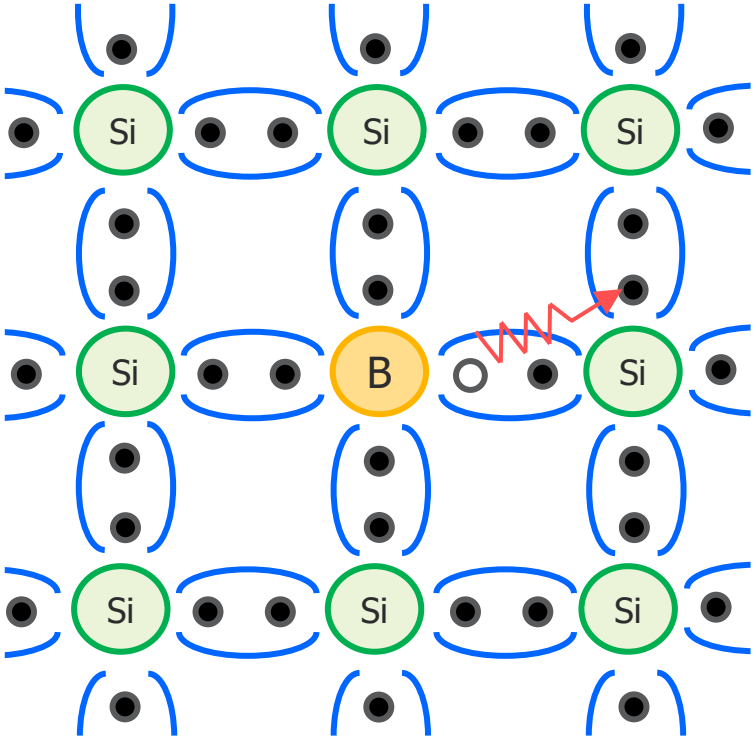
Electrons are majority carrier and holes are minority carrier

N-type material is as whole it is charge neutral



Extrinsic Semiconductor

Doping with Group 3 elements (Trivalent/Acceptors)

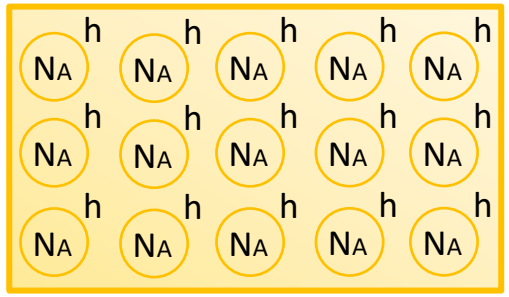


Group 3 elements have 3 valence electrons and cannot complete semiconductor bonds when substituted for Si atoms, however it readily “accepts” an electron from nearby Si-Si bond

When the Si is doped with acceptors (N_A), we called it as p-type Si

Holes are majority carrier and electrons are minority carrier

P-type material is as whole it is charge neutral



Fermi-Dirac Distribution

$f(E)$ gives probability of electron filling an energy level

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

E_f = Fermi Level

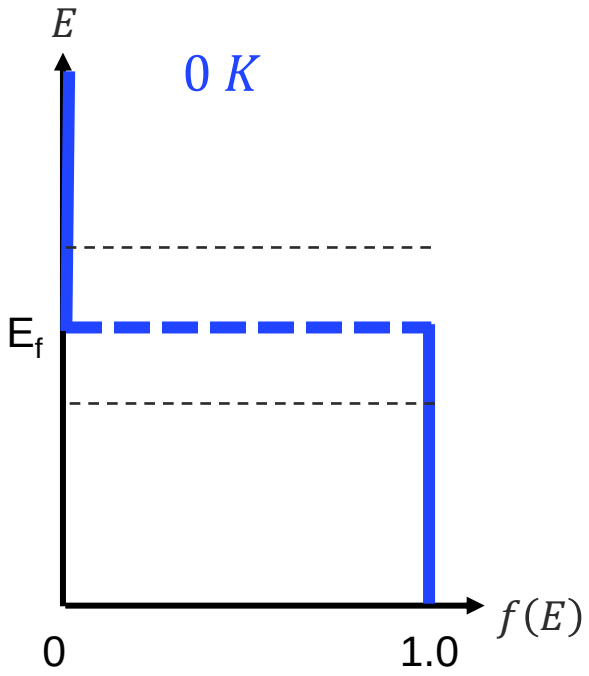
1-$f(E)$ gives probability of <u>hole</u> filling an energy level

$$0 \leq f(E) \leq 1$$

$$T = 0\ K$$

$$E > E_f \quad f(E) = \frac{1}{1 + e^{\frac{(+ve)}{0}}} = 0$$

$$E < E_f \quad f(E) = \frac{1}{1 + e^{\frac{(-ve)}{0}}} = 1$$

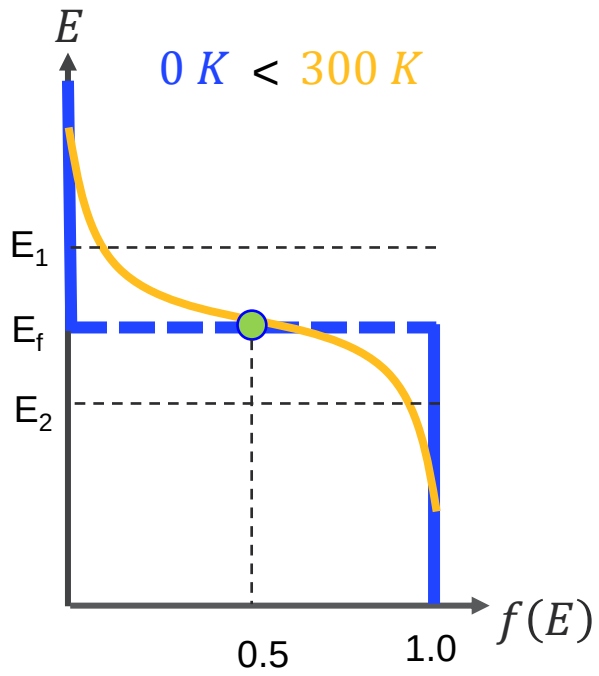


Fermi-Dirac Distribution

$f(E)$ gives probability of electron filling an energy level

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

$$0 \leq f(E) \leq 1$$



- As **T increases**, Si bond will break and there will be more electrons in higher energy levels (i.e: conduction band)
- Hence, the probability of finding an electron in higher energy levels will increase with T. So as probability of finding a hole in lower energy levels

Fermi-Dirac Distribution

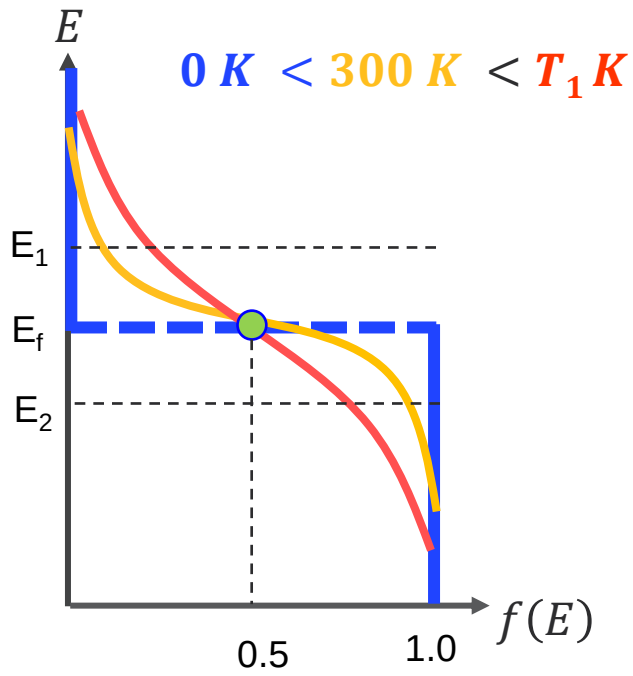
Definition of Fermi Level

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

$$0 \leq f(E) \leq 1$$

For any T

$$E = E_f \quad f(E) = \frac{1}{1 + e^{\frac{0}{kT}}} = 1/2$$

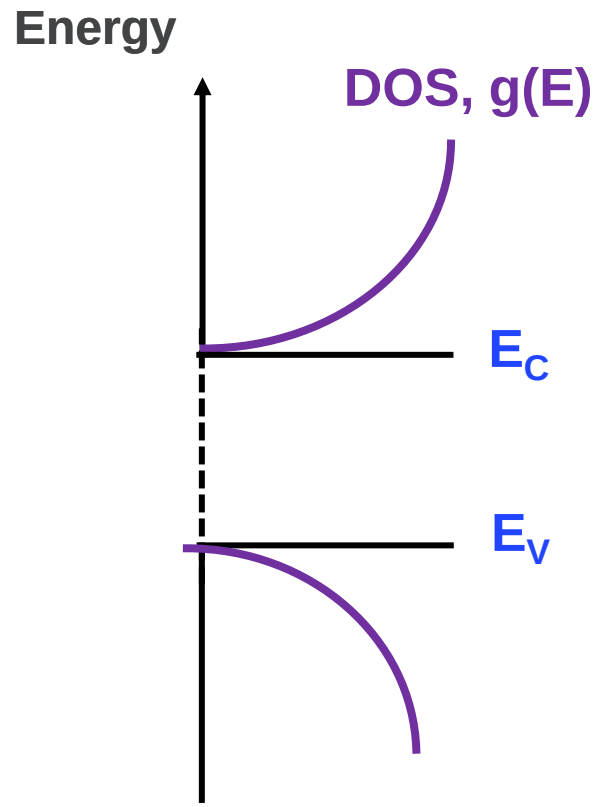


- As **T increases**, Si bond will break and there will be more electrons in higher energy levels (i.e: conduction band)
- Hence, the probability of finding an electron in higher energy levels will increase with T. So as probability of finding a hole in lower energy levels
- Fermi Level = Probability of finding an electron (or hole) is ½

Density of States (DOS)

DOS: Number of electron (hole) **states per unit energy** per unit **volume**

Derived from solution of Schrödinger equation (gives dispersion relation) and Heisenberg's uncertainty principle (defines volume element)



Carrier Concentration

DOS : **How energy states are distributed**

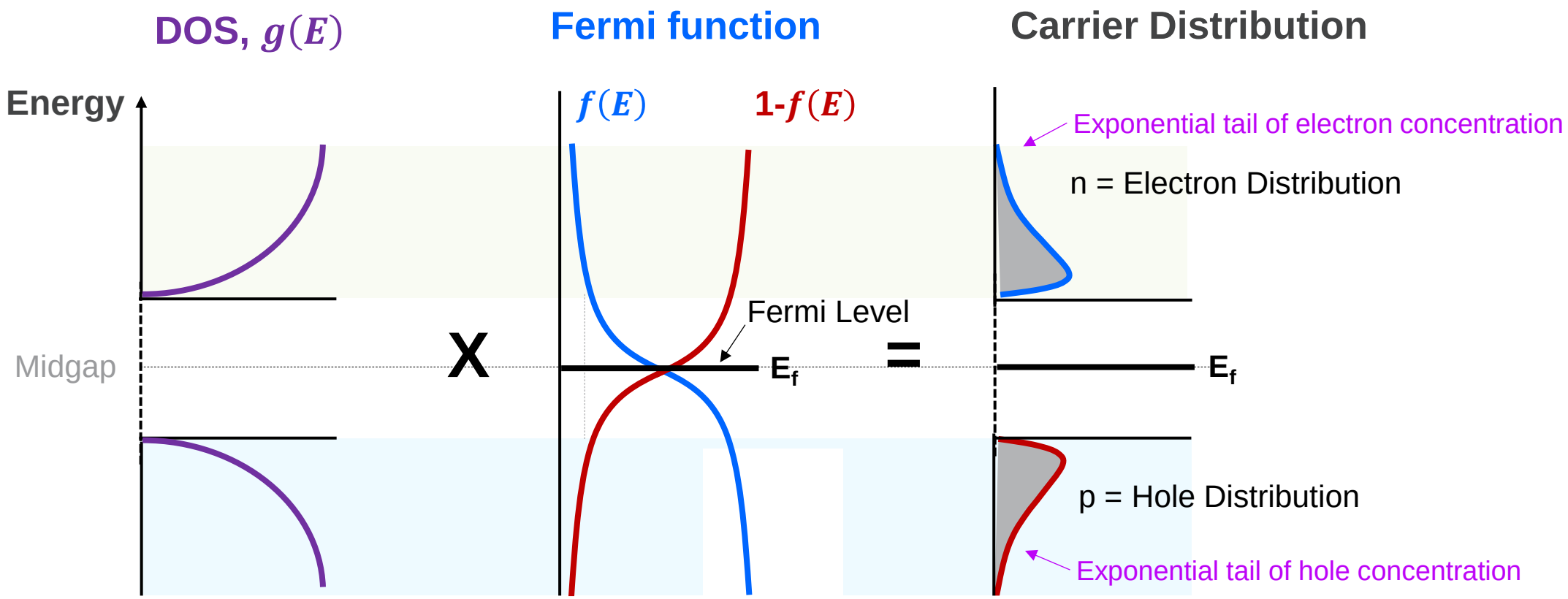
Fermi-Dirac : **How carriers are distributed within the energy**

DOS x Fermi Dirac : **Distributions of carriers with respect to energy**

Carrier Concentration

Area under the curve ➔ $n = \int_{E_C}^{\infty} g(E) f(E) dE$

Scenario 1, n=p



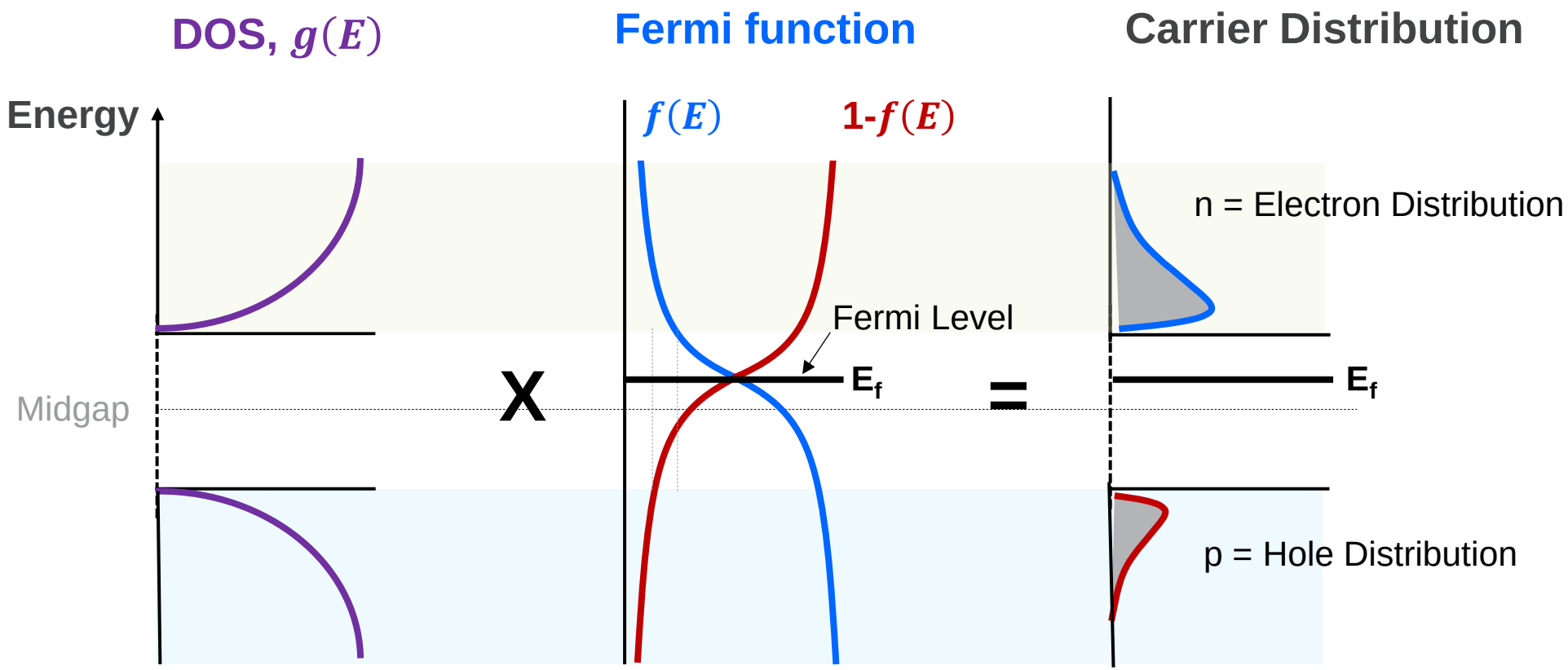
Electron Distribution = DOS x Probability of finding an electron

Hole Distribution = DOS x Probability of finding a hole (1- Fermi function)

Carrier Concentration

Area under the curve ➔ $n = \int_{E_C}^{\infty} g(E)f(E)dE$

Scenario 2, n>p



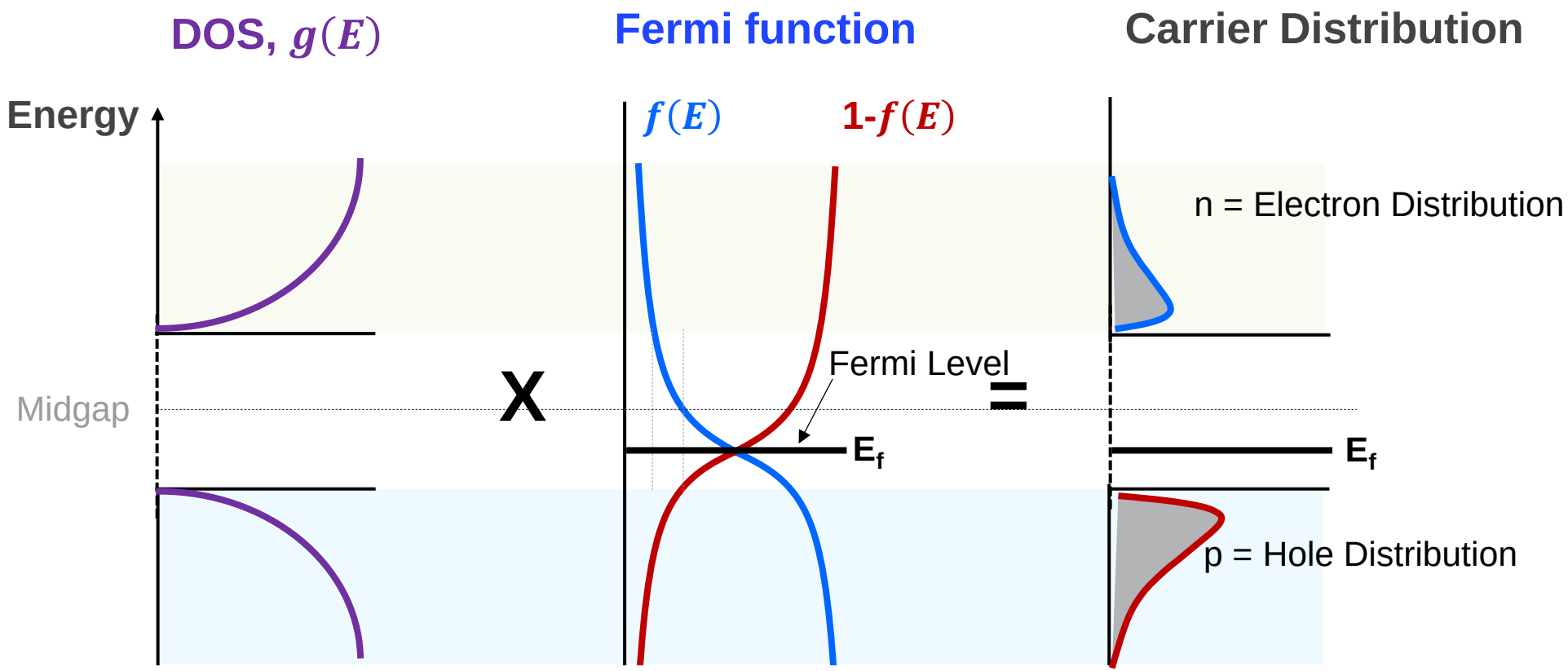
Electron Distribution = DOS x Probability of finding an electron

Hole Distribution = DOS x Probability of finding a hole (1- Fermi function)

Carrier Concentration

Area under the curve ➔ $n = \int_{E_C}^{\infty} g(E)f(E)dE$

Scenario 3, n<p



Electron Distribution = DOS x Probability of finding an electron

Hole Distribution = DOS x Probability of finding a hole (1- Fermi function)

Energy Bands

Basics

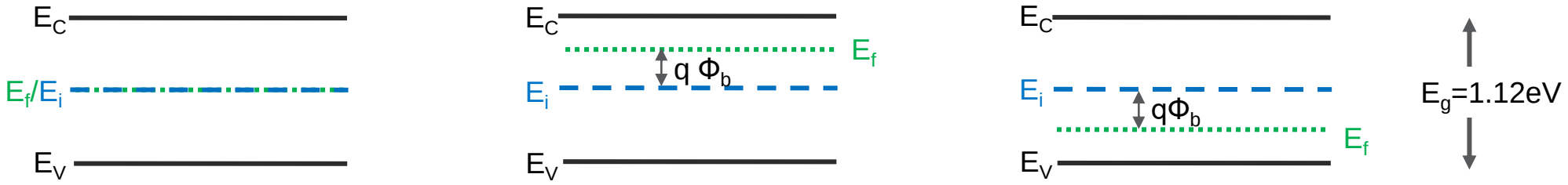
E_f = Fermi level

E_i = Intrinsic Fermi level

E_C = Conduction band edge

E_V = Valence band edge

E_g = Band gap



Undoped Si

N-Type Si

P-Type Si

$n=p=n_i$

$n >> p$

$n << p$

$| E_f - E_i | = q \Phi_b$ is known as Fermi potential (bulk potential), measure the doping strength

For Si, $n_i = 1.5 \times 10^{10}$ cm^{-3}

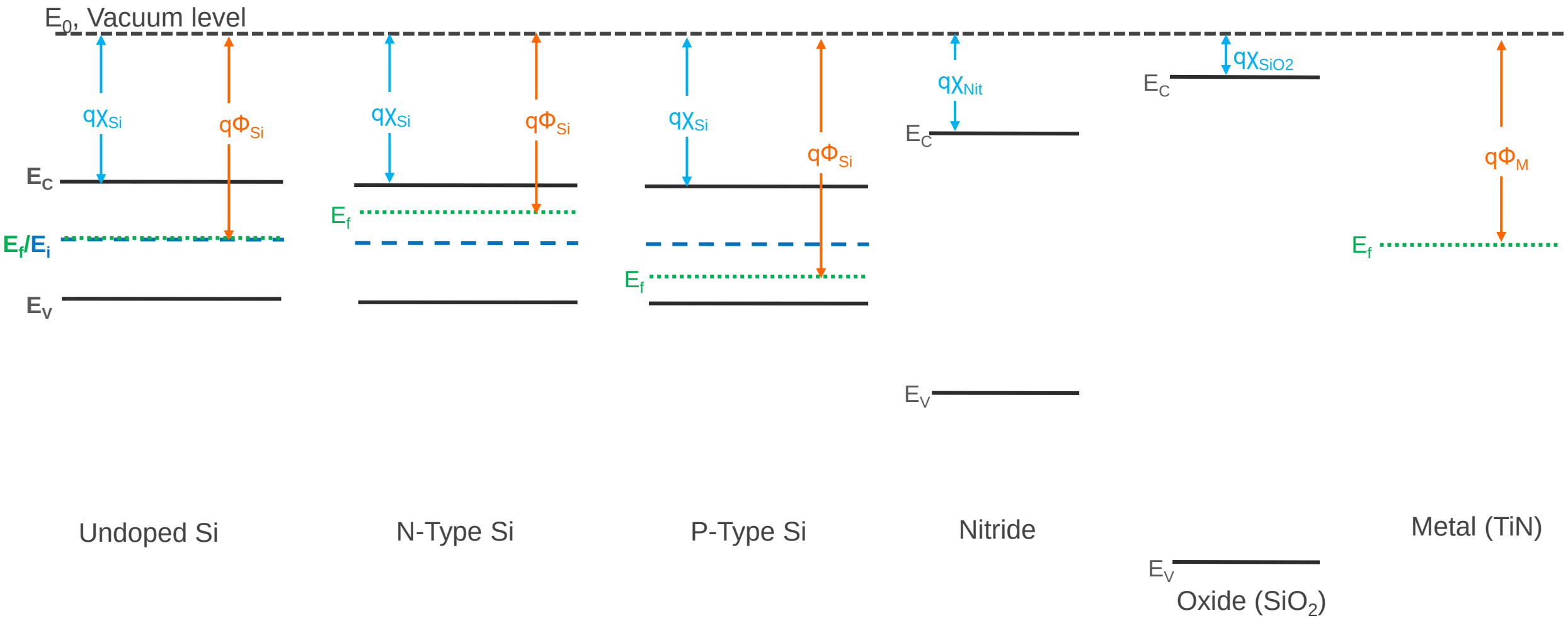
$$n = n_i \, e^{\frac{(E_f - E_i)}{kT}} = n_i e^{\frac{q \Phi_b}{kT}}$$

$$p = n_i e^{\frac{(E_i - E_f)}{kT}} = n_i \, e^{\frac{q \Phi_b}{kT}}$$

Energy Bands

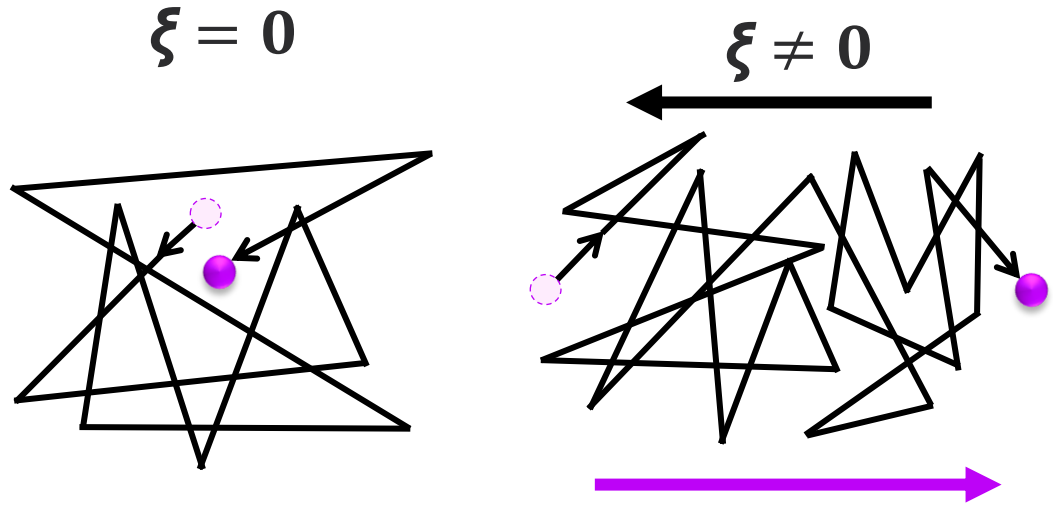
Silicon, Oxide, Nitride, Metal

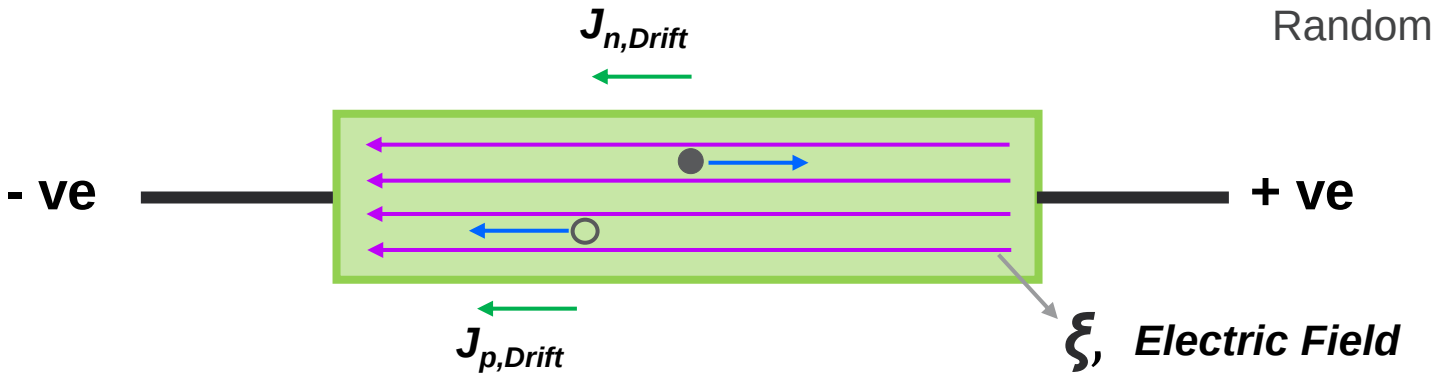
- E_0, Vacuum energy level is a common reference level which is defined as the energy level at which the electron is free, i.e: no longer bonded to the lattice
- $q\Phi_{M/Si}$, Energy difference between vacuum level and Fermi level, E_f (workfunction)
- $q\chi_{SiO2/Si}$, Energy difference between vacuum level and conduction band edge, Ec (electron affinity)
- **Φ** and **χ** are **invariant material property**, i.e: does not change with bias condition



Drift Current

Electric current due to presence of electric field





$$J_{n,Drift} \propto env$$

$$J_{n,Drift} = en\mu_e\xi$$

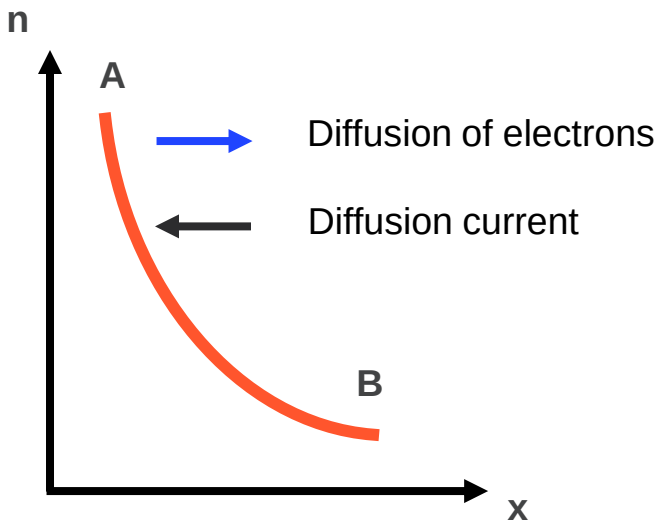
$$v = \mu_e\xi$$

$$\mu_e = \frac{q\tau}{m_e^*}$$

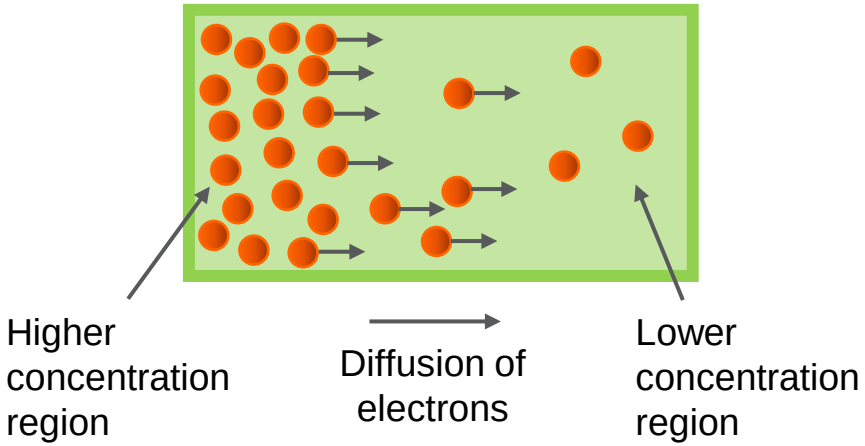
v : velocity
μ_e : mobility
m_e^* : effective mass of electron
τ : mean free time (average time between collisions)
e : electric charge

Diffusion Current

Electric current due to concentration gradients of carriers



N type

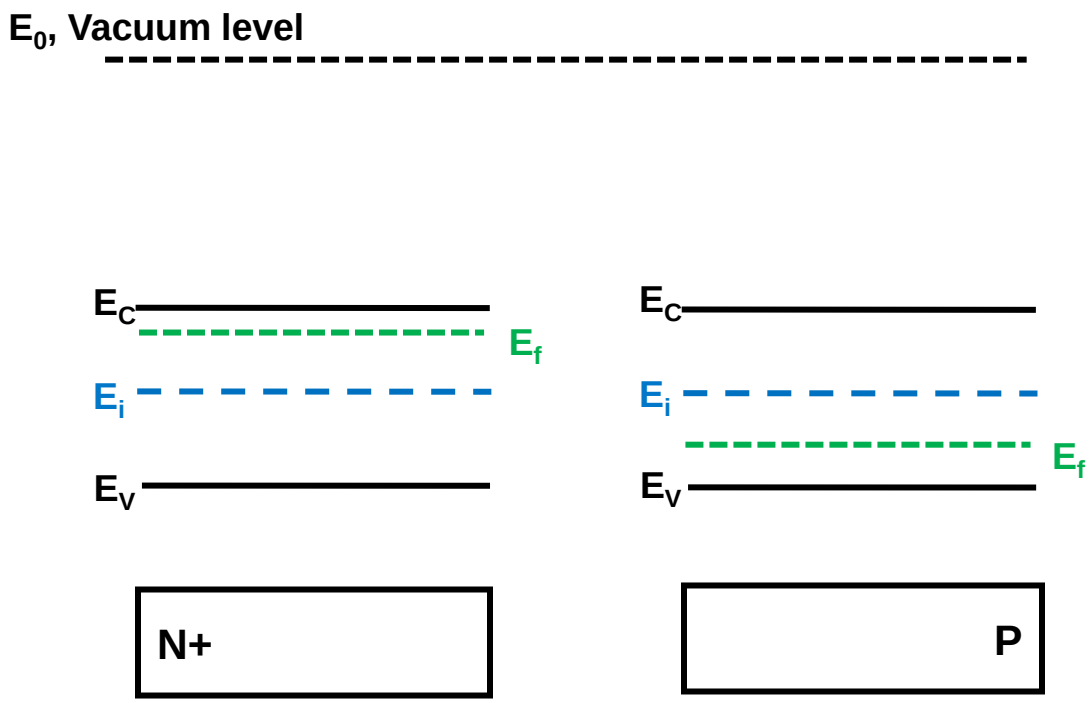


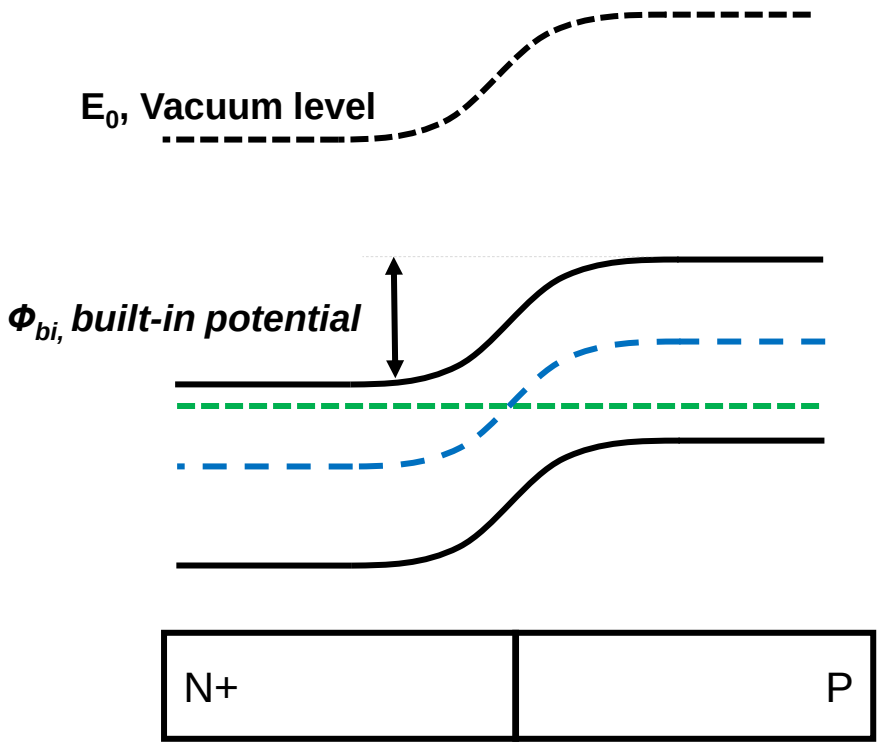
$$J_{n,Diff} \propto \frac{dn}{dx}$$

$$J_{n,Diff} = eD_n \frac{dn}{dx}$$

D_n : *Diffusion coefficient*

PN Junction

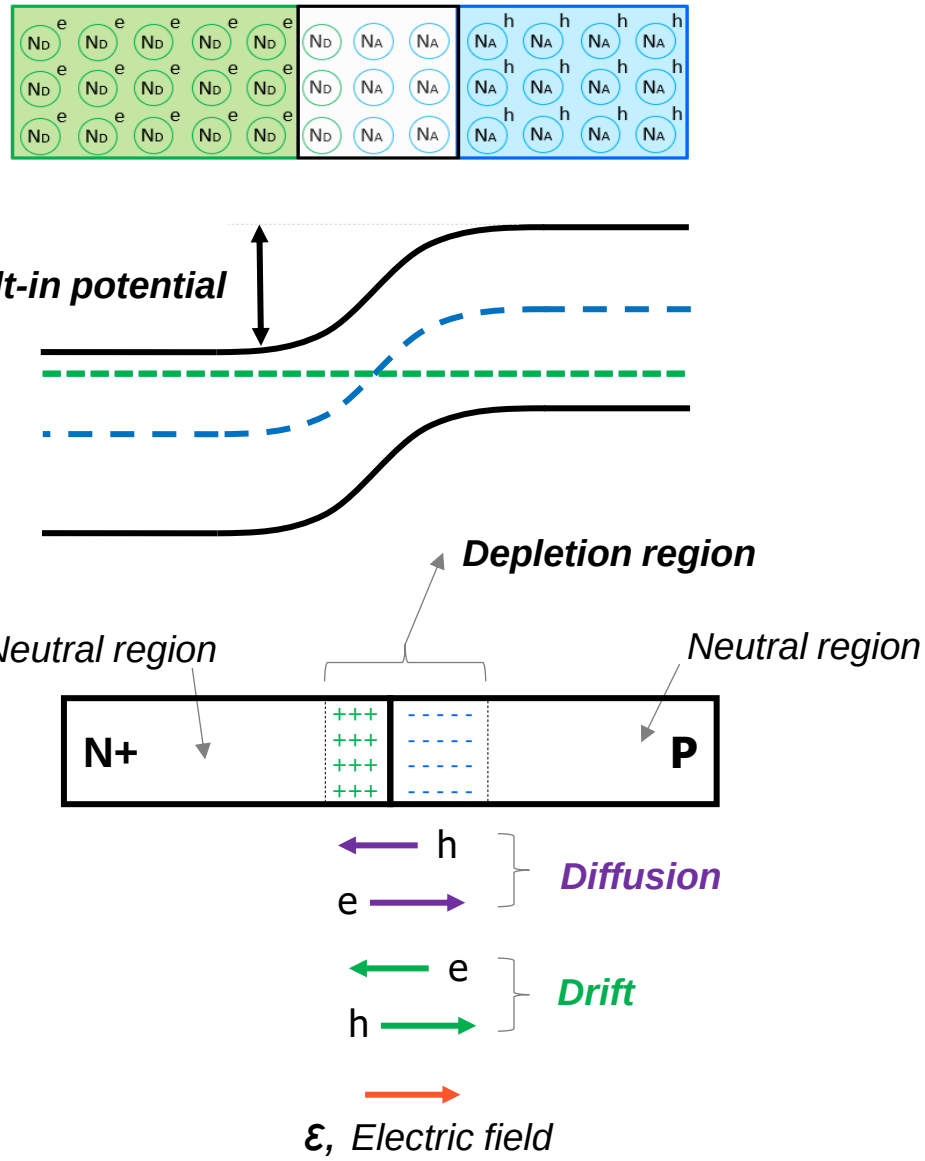




Thermal Equilibrium

- No external bias/excitations
- Reaches steady state/invariant of time
- No net current flow
- Fermi level needs to be constant/aligned

PN Junction



Summary of equilibrium process

1. Large concentration gradient of electrons and holes at the junction causes diffusion current
2. Recombination of electron and holes will take place, exposing ionized donors and acceptors
3. Depletion region causes electric field and hence drift current
4. Drift current increases until it is equal and opposite to diffusion current. No net current flow at steady state

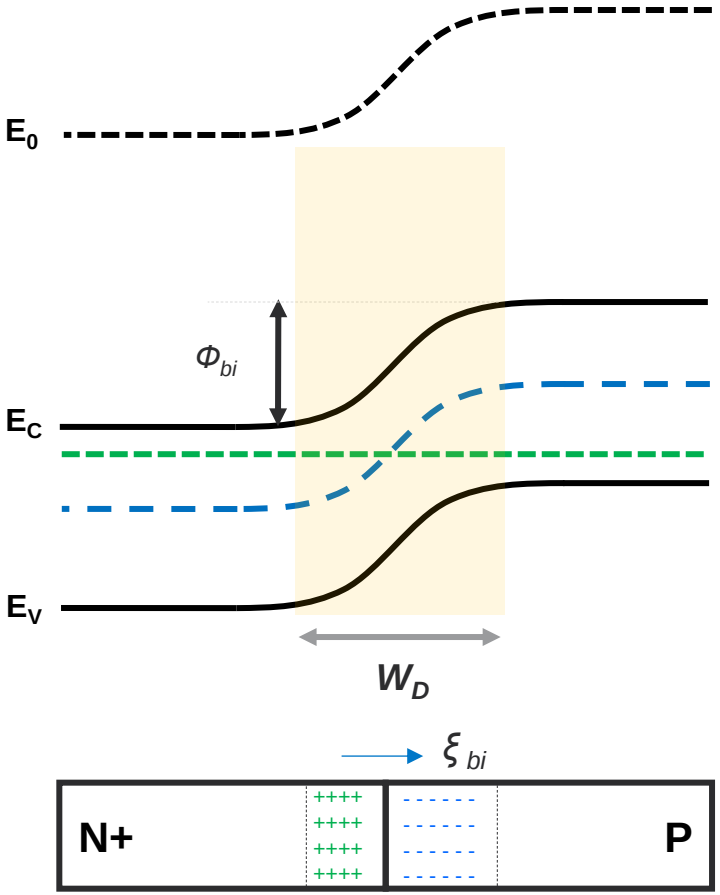
Depletion region

- Depleted of carriers
- Consists of exposed acceptors/donors
- Immobile & Resistive

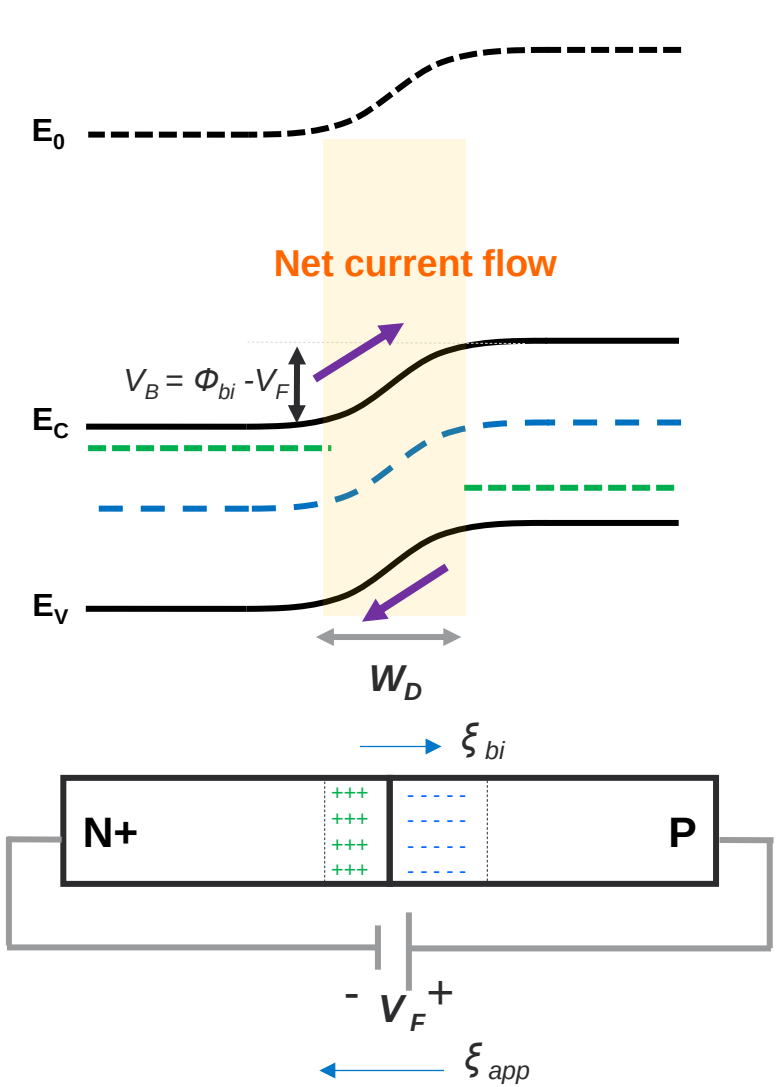
PN Junction

PN Junction Diode ➔ Current flows in one direction only

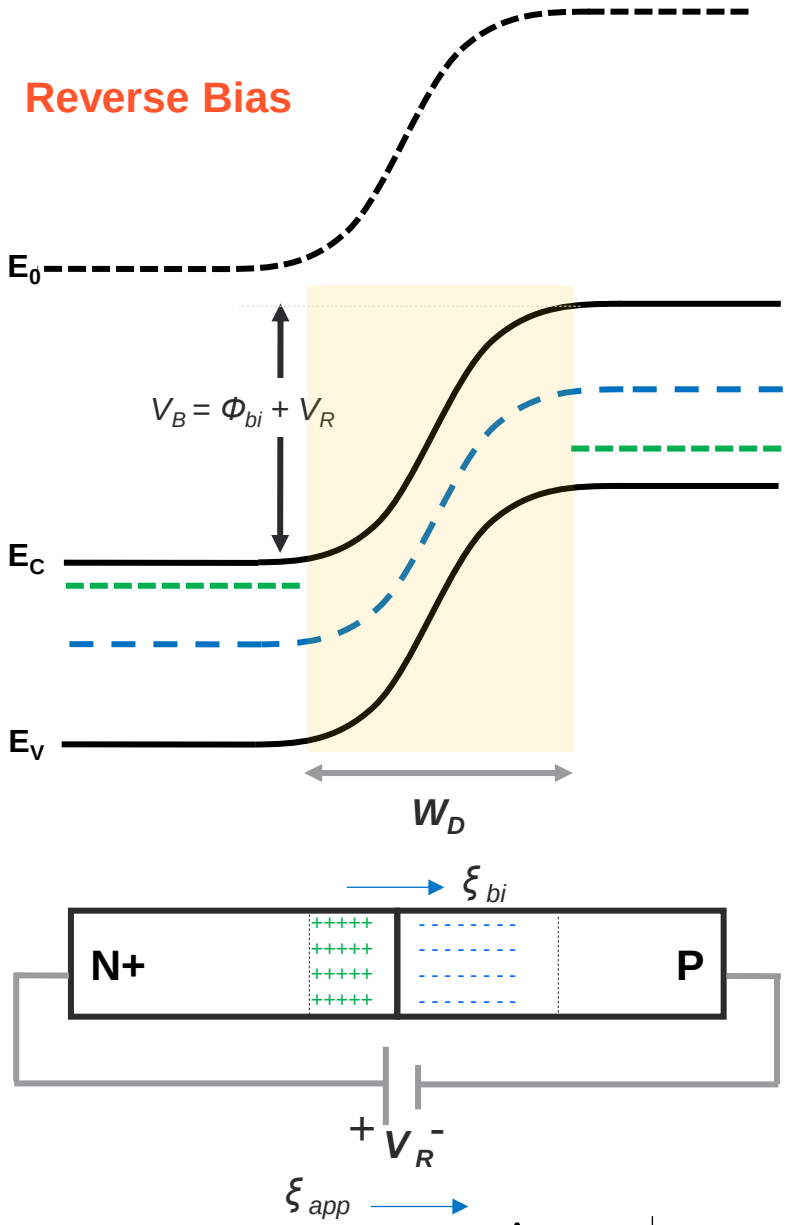
Equilibrium



Forward Bias

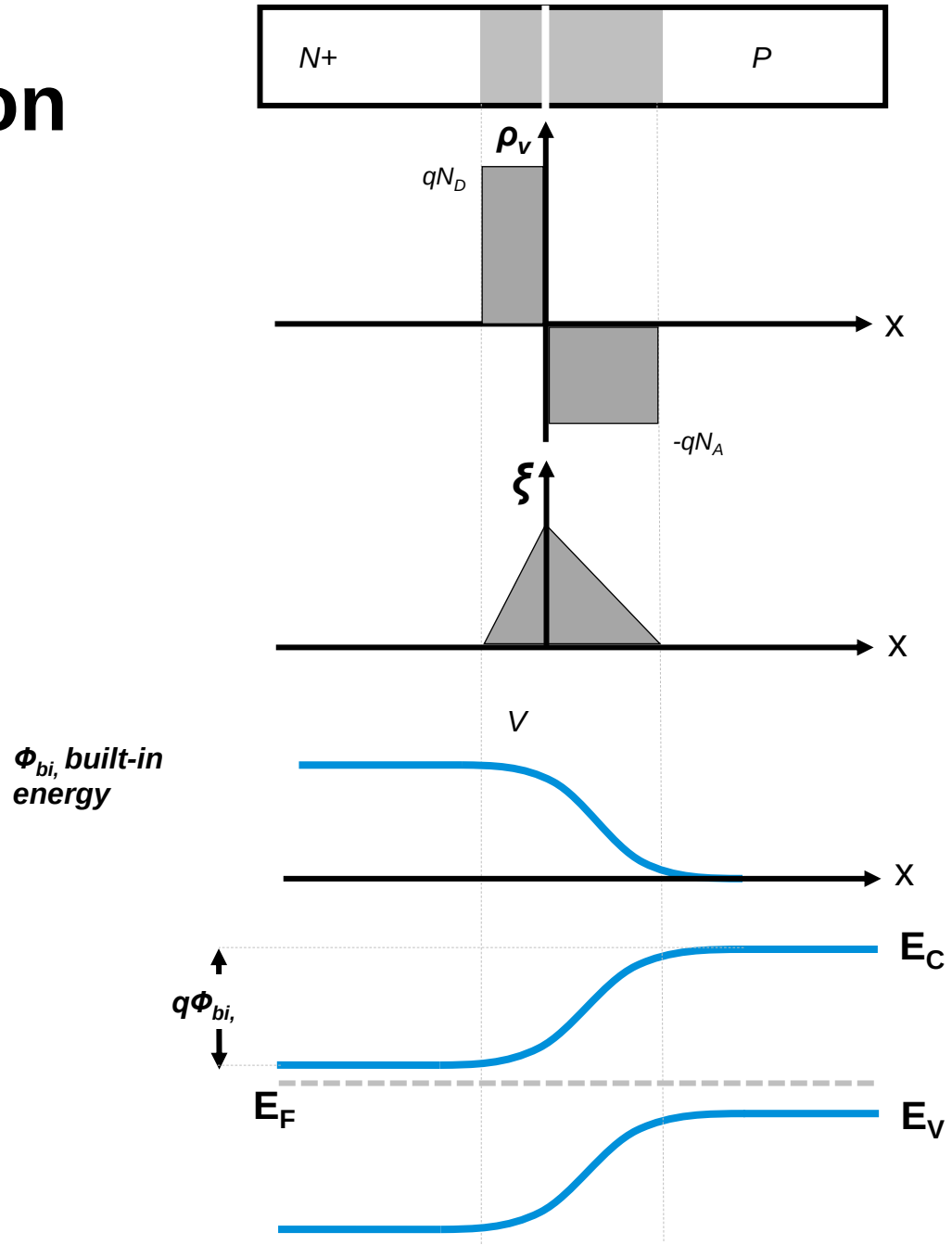


Reverse Bias



PN Junction

Equilibrium



$$\xi = \int \frac{\rho_v(x)}{\varepsilon_o} dx$$

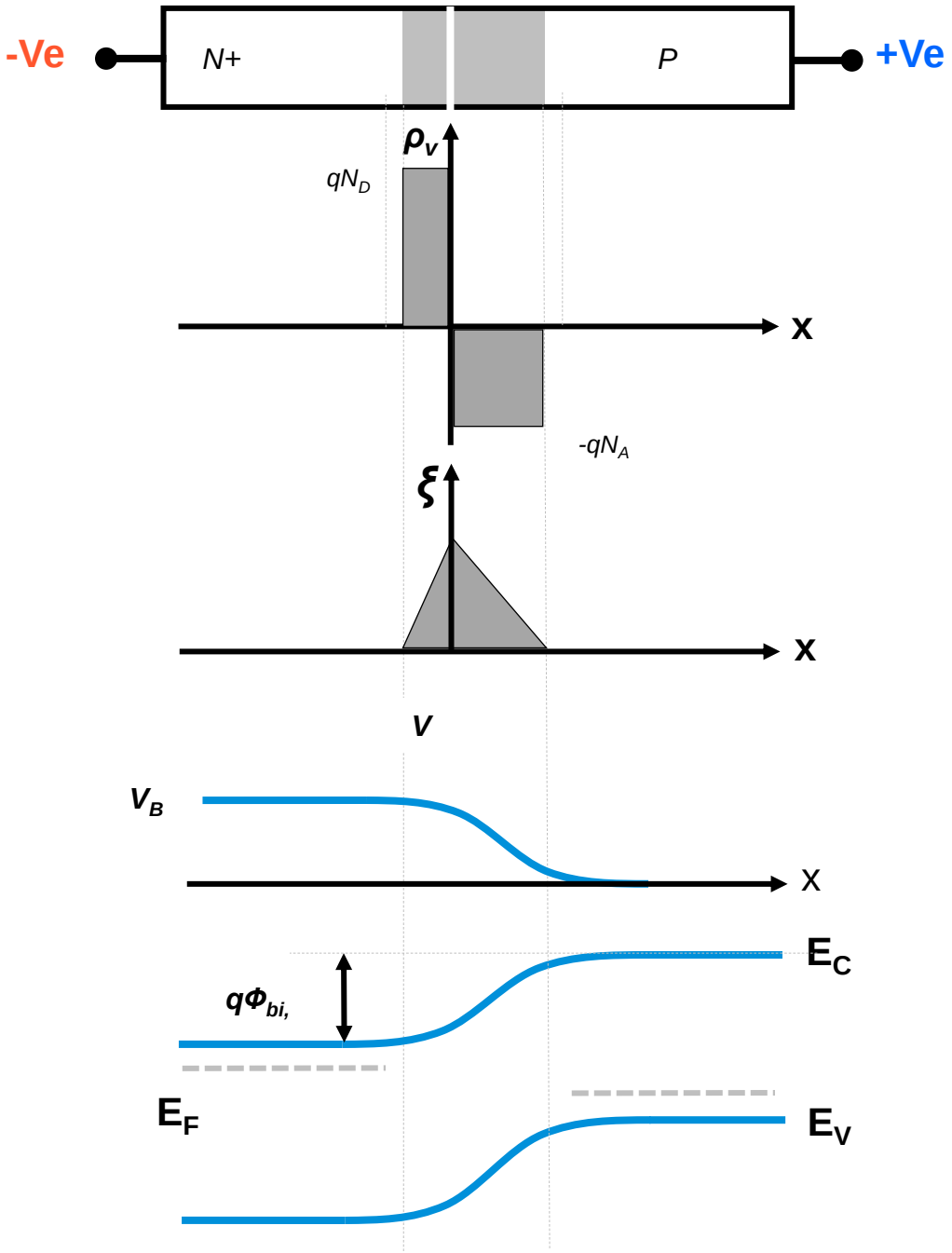
$$\xi = -\frac{dV}{dx}$$

$$V = -\int \xi \, dx$$

$$E = -e.V$$

PN Junction

Forward Bias



$$\xi = \int \frac{\rho_v(x)}{\varepsilon_o} dx$$

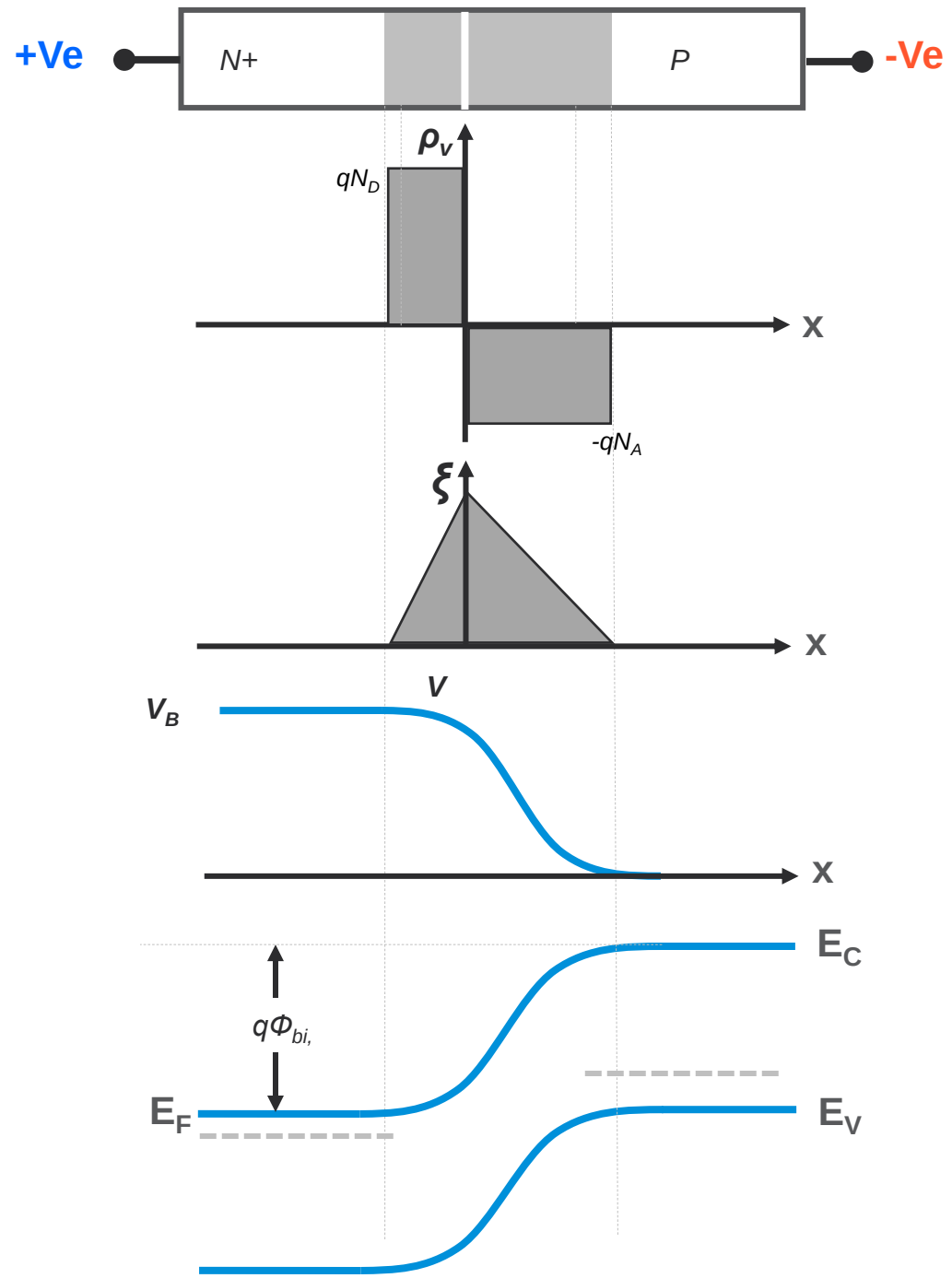
$$\xi = -\frac{dV}{dx}$$

$$V = -\int \xi \, dx$$

$$E = -e.V$$

PN Junction

Reverse Bias



$$\xi = \int \frac{\rho_v(x)}{\varepsilon_o} dx$$

$$\xi = -\frac{dV}{dx}$$

$$V = -\int \xi \, dx$$

$$E = -e.V$$

Glossary

Term or acronym	Definition/description
Bandgap	The energy difference between the conduction band edge (E_C) and the valence band edge (E_V) in a material. It determines the electrical conductivity of a material as it represents the minimum energy required to excite an electron up to a state in the conduction band.
Built-in Potential	The electric potential difference across a PN junction in thermal equilibrium and without external applied voltage, caused by the diffusion of carriers
Carrier Concentration	The number of charge carriers per volume.
Carrier Distribution	The distribution of electrons and holes within the energy states of a semiconductor, influenced by the density of states and the Fermi-Dirac distribution
Density of States (DOS)	The number of electron or hole states per unit energy per unit volume, derived from the Schrödinger equation and Heisenberg's uncertainty principle. The DOS function describes the number of states available in a system. It is used to determine the carrier concentrations and energy distributions of carriers in a semiconductor.
Diffusion Current	The electric current caused by the movement of charge carriers from a region of high carrier concentration to a region of low carrier concentration. The direction of the diffusion current depends on the gradient of the carrier concentration.
Doping	The process of adding impurities to a semiconductor to change its electrical properties. Doping can create n-type or p-type semiconductors.
Drift Current	The electric current caused by the movement of particles due to an electric field. The direction of the drift current is always in the direction of the electric field.
Electric Potential Energy	The work done to move an electric charge q against an electric field (ξ) over a distance d.
Energy Bands	The range of energy levels that electrons can occupy in a solid. Energy bands are formed due to the interaction of atomic orbitals in a crystal lattice.
Extrinsic Semiconductor	A semiconductor that has been doped with impurities or dopants to modify its electrical properties. Examples include n-type and p-type semiconductors.
Fermi Level	The energy level at which the probability of finding an electron is 50%. It is a crucial concept in understanding the electrical properties of semiconductors.

Glossary

Term or acronym	Definition/description
Fermi-Dirac Distribution	A statistical distribution that describes the probability of an electron occupying a specific energy level at a given temperature.
Forward Bias	A condition in which the positive terminal of a power supply is connected to the p-type material and the negative terminal to the n-type material of a PN junction, allowing current to flow
Gravitational Potential Energy	The work done to move an object with mass m against a gravitational field (g) over a height h
Intrinsic Semiconductor	A pure semiconductor with no foreign atoms or doping, where electrical conduction occurs due to thermally generated electrons.
Pauli's Exclusion Principle	A quantum mechanical principle stating that no two electrons which interact with each other can have the same quantum state simultaneously.
PN Junction	The combination of a p-type semiconductor and an n-type semiconductor. At the interface or junction between the two a depletion region is created as the free electrons from the n-type fill the available holes from the p-type. A PN junction represents the most basic semiconductor electronic device known as a diode.
Reverse Bias	A condition in which the positive terminal of a power supply is connected to the n-type material and the negative terminal to the p-type material of a PN junction, preventing current flow
Work Function	The minimum energy required to remove an electron from a solid to a point in the vacuum immediately outside the solid surface.

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