Unit 25 · Solids

STUDY NOTES

WHAT NEB'S GRADE 11 EXAM ASKS

- **CDC's grid (2077):** Modern Physics (Units 24–26 together): 9 of 75 marks
- **The paper:** 11 MCQs × 1 · 8 short × 5 · 3 long × 8; 3 hours; 1 mark per expected point
- **MCQ (1 mark)**
  - n-type or p-type from the impurity (As, P, Sb; B, Al, Ga, In); majority carriers
  - an n-type sample's charge (neutral); order of band gaps
  - transformer, rectifier; barrier potential; current in reverse bias
  - impurity atoms per m^3 from one in 10^n
- **Short (5 marks, in parts)**
  - conductor, semiconductor, insulator by band theory, with a band diagram
  - holes; intrinsic vs extrinsic; doping; how p-type and n-type are made
  - why a semiconductor's resistance falls as it warms, a metal's rises
  - the depletion layer and barrier potential of a p–n junction; forward and reverse bias
  - hydrogen's energy levels; energy to free an electron

Key terms

Energy level: one of the allowed energies of an atom's electron.

Ground state: level 1, lowest. **Excited state**: any higher level (level 2 = first excited).

Ionization: electron freed, energy 0.

Energy band: very many close levels, from one atomic level in a solid.

Valence band: highest band with electrons at 0 K (bonding electrons). **Conduction band**: the next, free electrons.

Forbidden gap (band gap E_g): energies no electron can have, between the bands.

Hole: empty electron state in the valence band; acts as a + carrier.

Intrinsic semiconductor: pure; electrons = holes.

Doping: adding a tiny amount of impurity on purpose. **Extrinsic semiconductor**: doped.

Donor: pentavalent atom giving a free electron (n-type). **Acceptor**: trivalent atom making a hole (p-type).

Majority / minority carriers: the more / less numerous carriers.

Depletion layer: region at a p–n junction with no free carriers, only fixed ions.

Barrier potential: p.d. across the depletion layer (Si ≈ 0.7 V, Ge ≈ 0.3 V).

Forward / reverse bias: p side to + / to −.

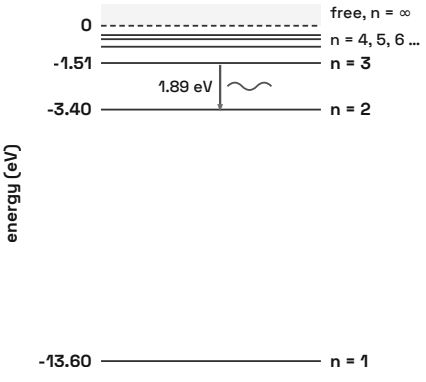
Rectifier: diodes turning a.c. into d.c. **Transformer**: changes an a.c. voltage.

Formulas

$E_n = -\frac{13.6\ \text{eV}}{n^2}$	$n = 1, 2, 3\ldots$ **Use:** hydrogen's levels
$hf = E_{upper} - E_{lower}$	h Planck's constant **Use:** photon in a jump
$\lambda_{max} = \frac{hc}{E_g}$	E_g in J **Use:** longest wavelength across a gap
$\frac{3}{2}kT \approx 0.039\ \text{eV}$	$T = 300$ K **Use:** average thermal energy

Energy levels

- electrons only at certain **discrete** energies; jump between levels, never between
- hydrogen: −13.6, −3.40, −1.51, −0.85, −0.54 eV, 0 at ∞

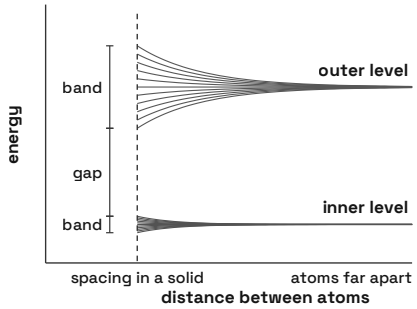


Hydrogen's levels to scale, crowding towards 0 eV; 3 → 2 gives out a 1.89 eV photon.

- negative: zero is the electron free and at rest; bound → less energy

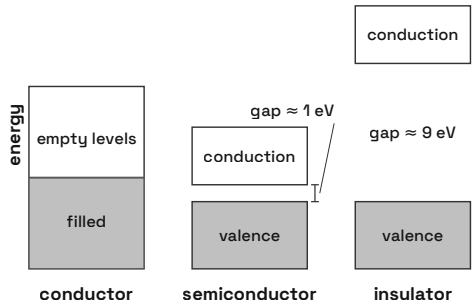
- ground state needs 13.6 eV to ionize; second excited state (level 3): 1.51 eV

Band theory



Far apart: sharp levels; at the solid's spacing each spreads into a band; gaps between.

- two atoms → each level splits in two; N atoms → N levels ($\approx 10^{20}$ in a grain) → band
- current needs empty levels just above: a **full** band carries none



Conductor: top band partly full or bands overlapping. Semiconductor: full valence band, gap ≈ 1 eV. Insulator: gap 5–10 eV.

- **conductor**: top band partly filled, or bands overlap → plenty of empty levels
- **insulator**: valence full, conduction empty, gap 5–10 eV (diamond 5.5, glass ≈ 9); thermal 0.039 eV can't cross
- **semiconductor**: gap ≈ 1 eV (Si 1.12, Ge 0.67): a few electrons cross at room temperature
- "a few" is a lot: Si $\approx 10^{16}$ per m^3 (of 10^{29} in bonds), Ge 2×10^{19}, diamond < 1
- gaps in order: Ge < Si < diamond

Holes

- electron to the conduction band leaves a hole; valence electrons hop into holes → holes drift towards −
- **both** carry current: electrons (conduction band), holes (valence band)
- intrinsic: number densities equal (each jump makes one of each)

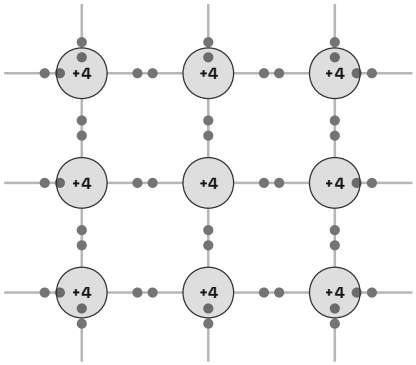
Temperature

- semiconductor: more carriers, far outweighing more vibration → R **falls** (thermistor)
- metal: no more carriers, more scattering → R **rises**
- 20 → 50 °C: copper +12%; silicon falls to ≈ a tenth
- intrinsic conductivity low: gap ≈ 25 × thermal energy, ≈ 1 bond in 10^{13} broken

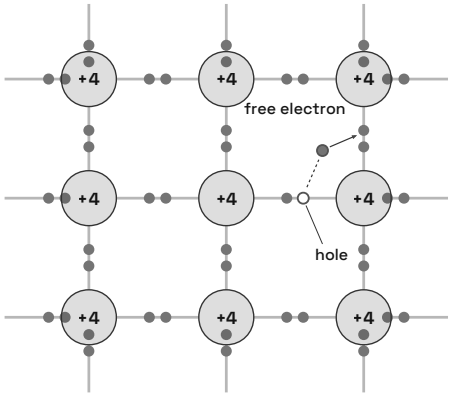
Light-dependent resistor

- photon with $hf \geq E_g$ lifts an electron → brighter, more carriers, lower R
- cadmium sulphide 2.4 eV → $\lambda_{max} = 520$ nm (green and shorter); red doesn't work
- ≈ 1 MΩ dark, a few hundred Ω in sunlight; silicon 1.12 eV → 1100 nm (infrared)

Silicon crystal and doping

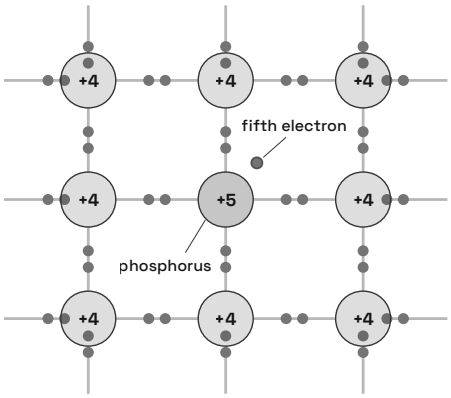


Each Si (+4) shares its four outer electrons with four neighbors: covalent bonds.

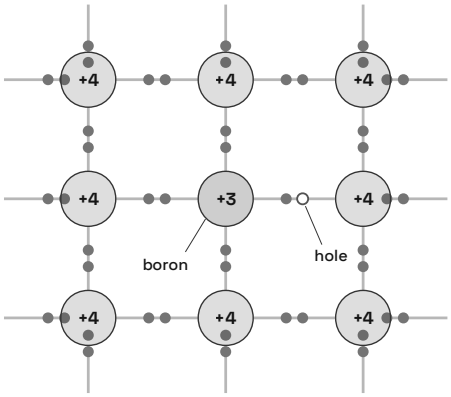


A vibration frees an electron from a bond, leaving a hole.

- best conductors 1 outer electron; Si, Ge 4
- pairs made by heat, others **recombine**; lifetime ns to ms

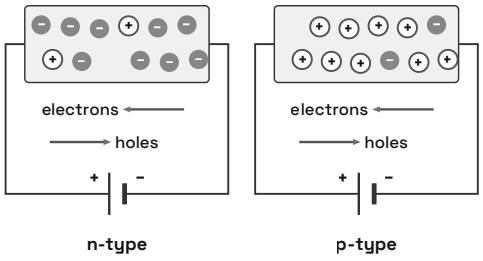


Phosphorus (+5): four bonds; the fifth electron loosely held, soon free.



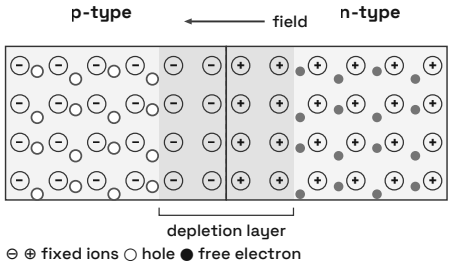
Boron (+3): three bonds; the fourth short of an electron, a hole.

- **n-type**: pentavalent donors **P, As, Sb**; electrons majority, holes minority
- **p-type**: trivalent acceptors **B, Al, Ga, In**; holes majority, electrons minority
- doped crystal still **neutral**: donors left as + ions, acceptors − ions
- conductivity rises with doping; lightly or heavily doped
- e.g. B 1 in 10^7, 5×10^{28} atoms/m^3 → 5×10^{21} holes/m^3, $5 \times 10^5 \times$ pure Si's 10^{16}
- In 1 in 10^8 → 5×10^{20} per m^3, acceptor



n-type and p-type across a battery: electrons drift to +, holes to −; the wires carry electrons.

p–n junction



Electrons and holes cross and recombine: depletion layer of + donor ions (n side) and − acceptor ions (p side); field n → p.

1. electrons diffuse n → p, holes p → n; recombine near the junction
2. fixed ions left: + on the n side, − on the p side → **depletion layer**
3. their field (n → p) pushes back further carriers → diffusion stops
4. p.d. across it = **barrier potential**

- **forward** (p to +): barrier opposed, layer narrows; above ≈ 0.7 V, large current
- **reverse** (p to −): layer widens; tiny minority current (< 1 μA)
- one-way: a **diode**
- charger: **transformer** steps 230 V a.c. (50 Hz) down; **rectifier** (one, two or four diodes in a bridge) → d.c.
- transformer works only with a.c.; generator: mechanical → electrical

COMMON MISTAKES

✗ electron energies can take any value
✓ only **discrete** levels.

✗ second excited state is level 2
✓ level **3**.

✗ semiconductor's *R* rises with temperature like a metal's
✓ **falls**: more carriers.

✗ holes are positive particles
✓ empty states that behave as + carriers.

✗ n-type is negatively charged
✓ **neutral**; "n" names the majority carriers.

✗ arsenic gives p-type
✓ **n-type** (pentavalent donor).

✗ reverse bias conducts
✓ only a tiny minority current.

✗ transformer turns a.c. into d.c.
✓ that's a **rectifier**.