Donor and Acceptor Levels in Semiconductors

Summary Note for Semiconductor Physics

1. Intrinsic Semiconductor Baseline

In a pure (intrinsic) semiconductor such as silicon:

- The valence band is completely filled with electrons.
- The conduction band is empty at 0 K.
- The bandgap $E_g = E_c - E_v \approx 1.1\,\text{eV}$.

Electrons must be thermally excited across this gap to contribute to conduction, which is inefficient at low temperature. Doping introduces shallow energy levels to make this process easier.

2. Donor Levels (n-Type Doping)

When a donor atom such as phosphorus is introduced into silicon:

- Phosphorus has five valence electrons; four form covalent bonds, leaving one extra electron.
- This extra electron is weakly bound to the donor atom, creating a discrete energy level slightly below the conduction band edge E_c.
- This state, called the **donor level** E_d, is where the donor electron **sits before ionization**.
- The **donor ionization energy** is the small energy needed to free that electron into the conduction band:
$$E_c - E_d \approx 50\,\text{meV}.$$

At room temperature, $kT \approx 25\,\text{meV}$, so most donor electrons are thermally ionized, producing free conduction electrons and resulting in **n-type conductivity**.

3. Acceptor Levels (p-Type Doping)

When an acceptor atom such as boron is introduced:

- Boron has only three valence electrons and can accept one electron from a neighboring Si bond.

- This creates a **hole** in the valence band and an **acceptor level** E_a just above the valence band edge E_v.
- The **acceptor level** represents the energy state the captured electron occupies **before ionization**, i.e., before the hole is freed into the valence band.
- The **acceptor ionization energy** is the energy required to excite a valence electron into the acceptor level:

$$E_a - E_v \approx 50\,\text{meV}.$$

This process generates holes in the valence band, giving the material **p-type conductivity**.

4. Energy-Level Diagram

Figure 1 illustrates these energy levels schematically.

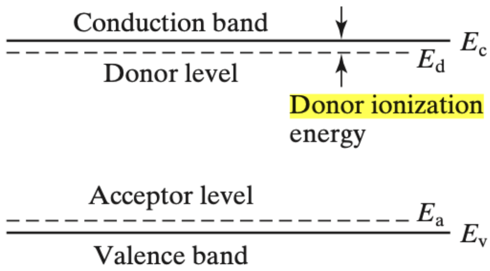

FIGURE 1–12 Energy levels of donors and acceptors.

Figure 1: Energy levels of donors and acceptors (adapted from Chenming Hu). The donor electron initially occupies the donor level E_d, located just below the conduction band edge E_c. Ionizing the donor requires an energy $E_c - E_d$ to lift this electron into the conduction band. Similarly, an acceptor level E_a lies just above the valence band E_v; before ionization, it can capture an electron from the valence band, leaving behind a mobile hole.

5. Where Conduction Occurs

A key distinction between n-type and p-type semiconductors is **which band** supports carrier motion:

- In **n-type** material, conduction occurs in the **conduction band**.
  Donor electrons are easily excited from E_d to E_c, where they move freely as conduction-band electrons.

- In **p-type** material, conduction occurs in the **valence band**.
  When an acceptor captures an electron from the valence band, it leaves a hole behind. That hole can move through the valence band as neighboring electrons fill it—the holes are the actual mobile charge carriers.

Type	Dopant Atom	Energy Level	Carrier Type	Conduction Band
n-type	Donor (e.g., P, As)	E_d just below E_c	Electrons	Conduction band
p-type	Acceptor (e.g., B, Al)	E_a just above E_v	Holes	Valence band

Table 1: Comparison of n-type and p-type conduction mechanisms.

6. Summary

- **Donor level:** Shallow energy level introduced by a donor atom, typically $E_d \approx 50\,\text{meV}$ below E_c. The donor electron resides here *before ionization.*
- **Acceptor level:** Shallow energy level introduced by an acceptor atom, typically $E_a \approx 50\,\text{meV}$ above E_v. It represents the bound state of the captured electron before the hole is freed.
- In n-type semiconductors, conduction occurs through electrons in the conduction band.
- In p-type semiconductors, conduction occurs through holes in the valence band.

In one sentence: Dopant atoms create shallow electronic states within the bandgap—just below E_c for donors or just above E_v for acceptors—and the small ionization energy ($\sim 50\,\text{meV}$) frees carriers into their respective bands: electrons into the conduction band (n-type) and holes into the valence band (p-type).