Lecture 6

- Doped Semiconductors
  - n-doping
  - p-doping
- Donor and Acceptor levels
- Defects - Deep Levels

The University Of Sheffield.

Periodic Table

Number of Outer Electrons

3	4	5
Group III	Group IV	Group V
5 B	6 C	7 N
13 Al	14 Si	15 P
31 Ga	32 Ge	33 As
49 In	50 Sn	51 Sb
81 Ti	82 Pb	83 Bi

- A semiconductor usually starts off as pure material (intrinsic)

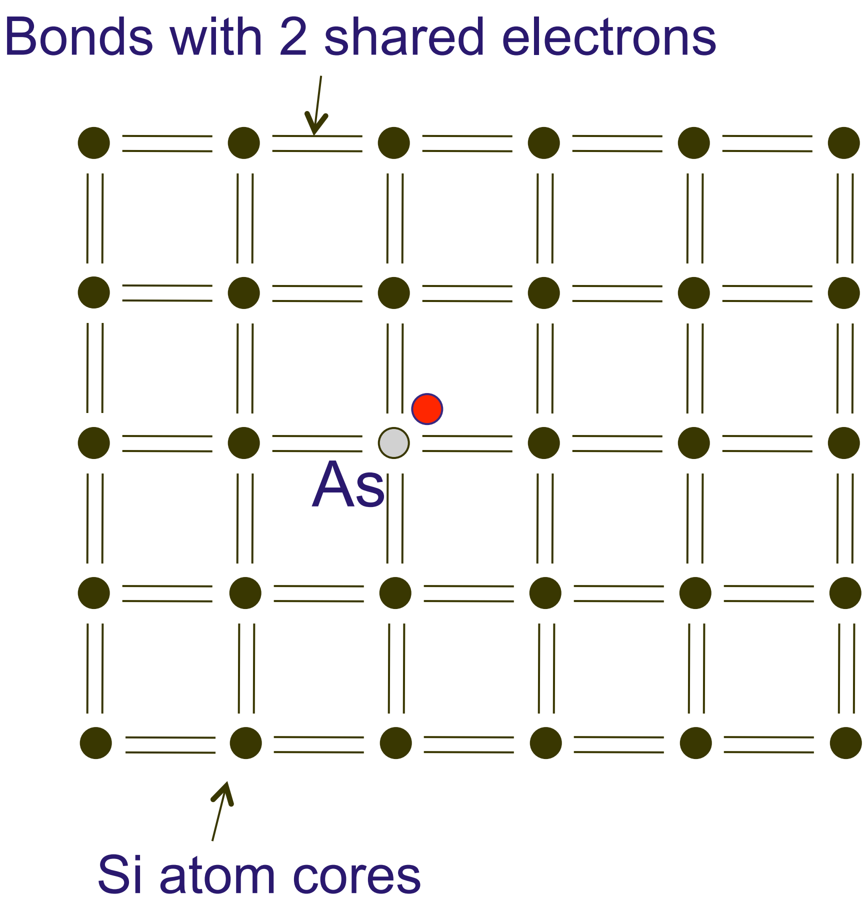
e.g. Si crystal

- In extrinsic (as opposed to intrinsic) semiconductors, they are **"doped"** with foreign atoms (an impurity) to increase the free electron or hole density

- The level of impurities is at the parts per million / parts per thousand level - i.e. very small proportion of the crystal atoms

Doping

Si with Group V atoms – doping with electrons



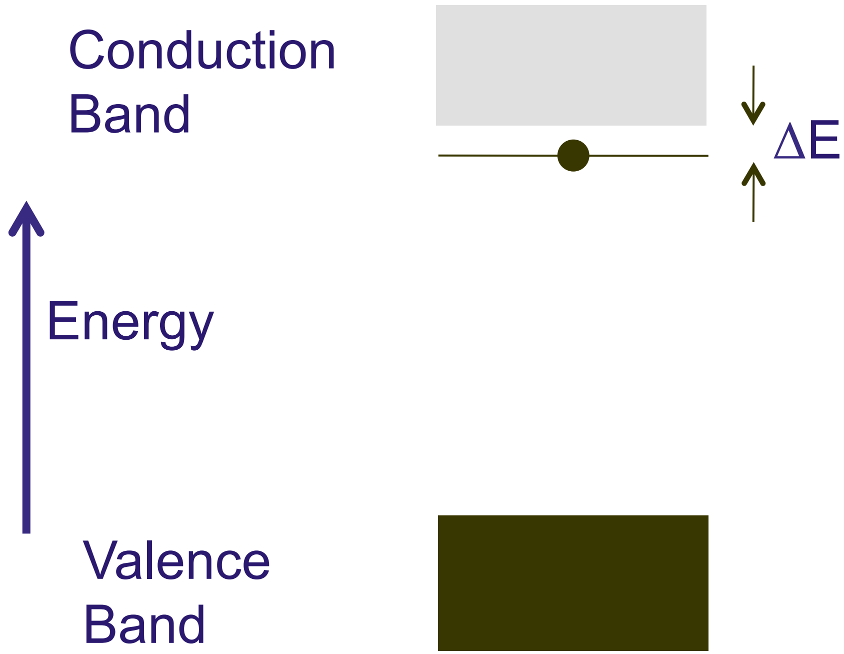
• Replace a Si atom with one from group V (Roman 5) of the periodic table which has 5 outer electrons e.g. P (phosphorus), As (arsenic), Sb (antimony) – let us consider As

• Arsenic atoms have 5 outer electrons (we can ignore the inner electrons)

• 4 of these outer electrons covalently bond with the neighbouring Si atoms - leaving an additional electron

• This additional electron is only weakly bound to the crystal

Donor Atoms (T = 0 K)

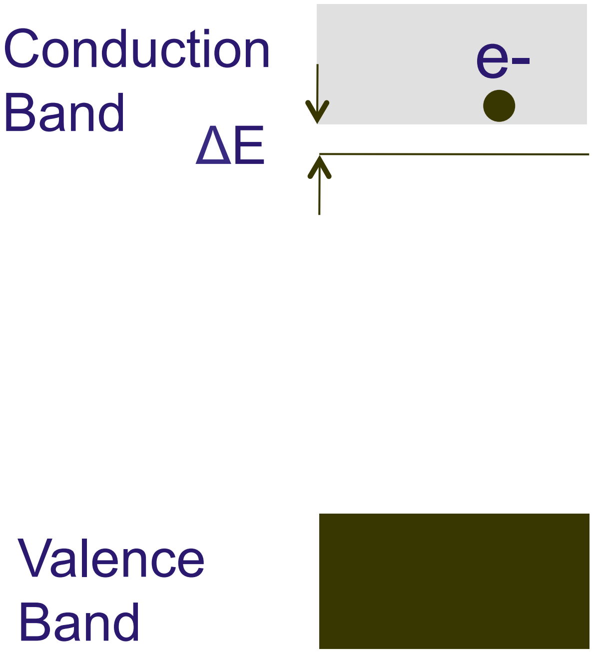


Energy diagram representation

- The additional electron of the group V impurity or dopant atom forms an electronic energy level in the band-gap sitting just below the conduction band
- This represents the fact that it is only weakly bound

- ΔE ~5 meV (5×10^{-3}eV) – small compared to 1.1 eV energy to break a bond in Si

Donor Atoms (T = 300K)



• At room temperature the average thermal energy available (the phonon energy) is ~ k_BT = 25 meV

• This energy can be given to an electron in collisions

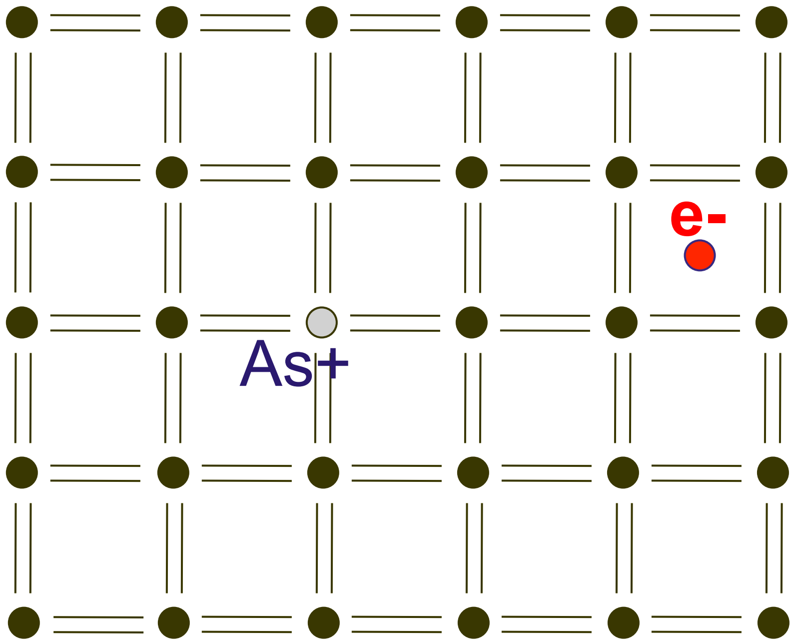
• Since $k_BT >> \Delta E$, the electron associated with the impurity atom can move up into the conduction band – i.e. break free from the impurity atom which then becomes “ionized” (in this case positively charged)

• The electron is “donated” to the conduction band and in this case the impurity atom is called a **“donor atom”** or just **“donor”**

• Dopant (impurity) atom density = majority of the free electron density at room temperature

• This process is also termed **“n-type doping”** or **“n-doping”** since it provides extra <u>n</u>egative electrons

Ionized Donor



• Freeing up the weakly bound electron leaves a positively charged (ionized) donor atom (As)

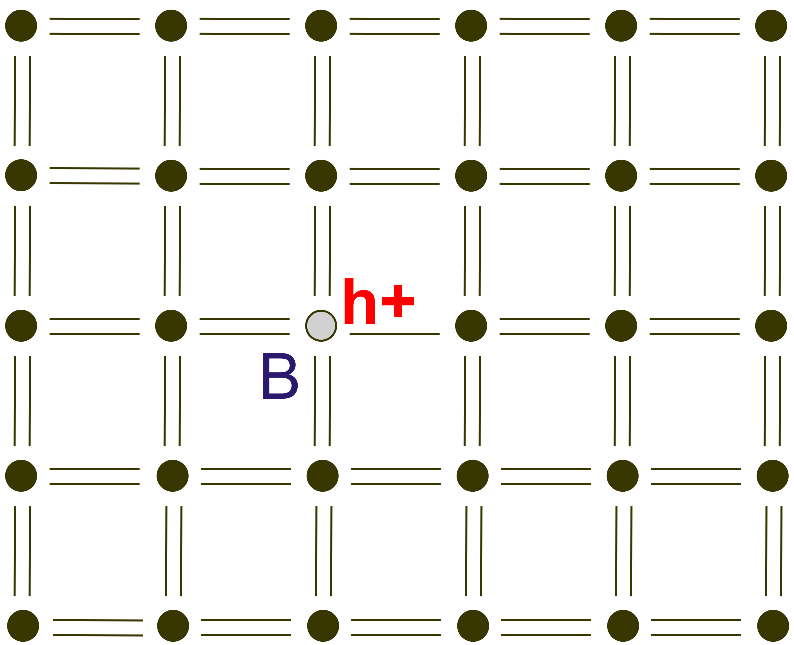
• If the concentration of donor atoms is relatively high the electrons are the majority carriers whereas the holes (thermally generated) are minority carriers

• The donor impurity atom is bound into the crystal. **It *cannot* move and therefore doesn't contribute to conduction – *it is not a hole***

• The ionized impurity is a scattering centre. Hence increased ionized impurity density tends to decrease the scattering time, τ, decrease v_d and decrease μ

Doping

Si with Group III (B) atoms – doping with holes



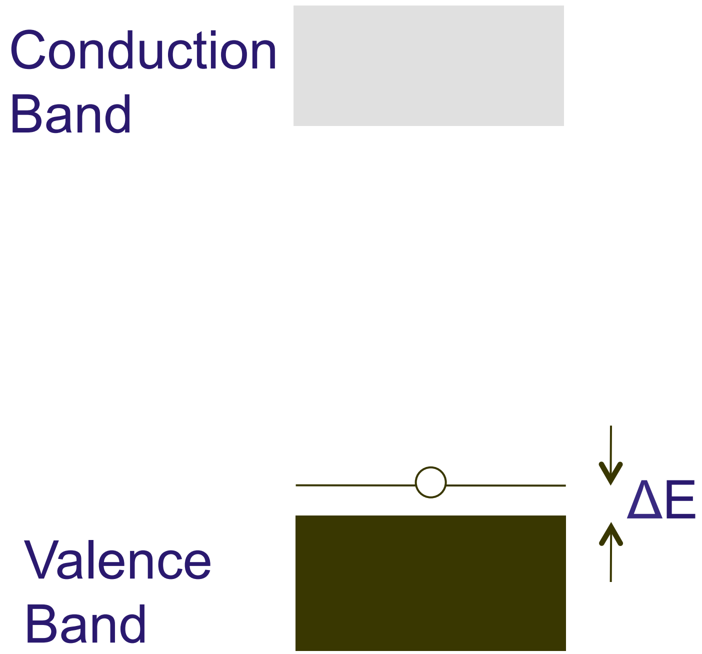
- This time replace a Si atom with one from group III of the periodic table, e.g. Ga (gallium), B (boron) – consider B (it is used in practice)

- B atoms have 3 outer electrons causing a missing electron in the bond next to the B atom (need 4 in total for Si lattice)

- Before, we saw that the absence of an electron from the bond equates to a hole

- In this case the hole is weakly bound to the impurity

Acceptor Atoms (T = 0 K)



Energy diagram representation

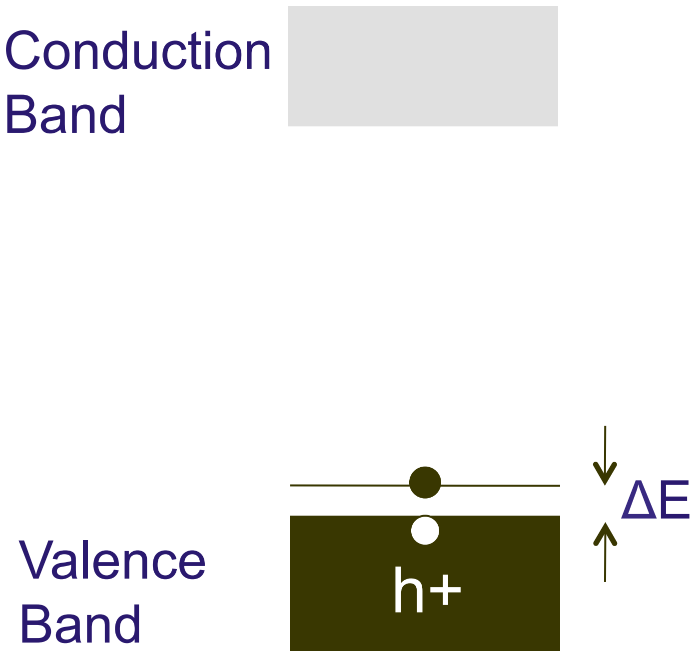
- The additional electronic energy level of the group III impurity dopant atom forms in the band-gap sitting just above the valence band

- ΔE ~ 5meV for B in Si

- B and other group III impurities are referred to as "**acceptor atoms"** or "**acceptors**" because they can "accept" an electron from the valence band

- This can be confusing – they *donate* a hole into the valance band for conduction, but we reserve the term 'donor' for electron donation

Acceptor Atoms (T = 300K)



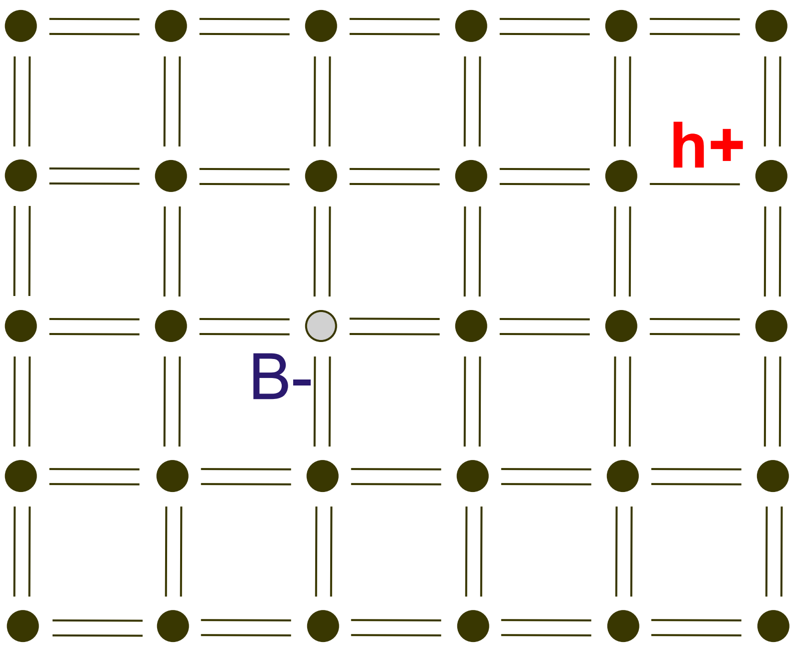
- At room temperature the average thermal energy = k_BT = 25meV

- Since $k_BT >> \Delta E$ for B in Si, the energy level of the impurity “accepts” an electron from the valence band - creating a hole (broken bond) in the valence band

- The acceptor dopant atom density = free hole density (if $k_BT >> \Delta E$)

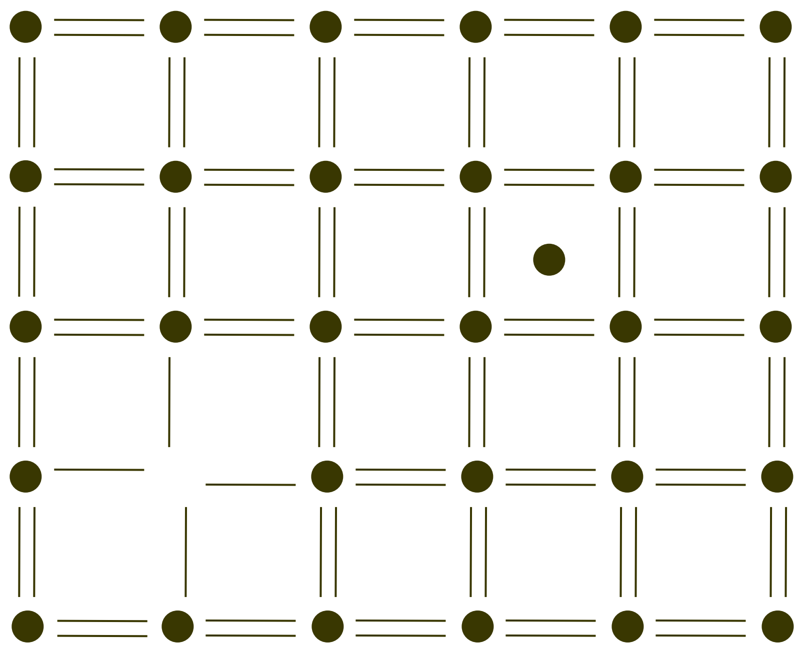
- This is termed **“p-type doping”** or **“p-doping”** from the positive holes produced

Ionized Acceptor



- The weakly bound hole is easily freed from the acceptor atom due to thermal energy
- If concentration of acceptors is relatively high – holes are the majority carriers, electrons are the minority carriers
- Leaving behind a negatively charged ionized acceptor
- Again – like ionized donors, these act as scattering centres

Defect States



- Other atoms may be present in the semiconductor, or atoms may not sit on a lattice site and are not involved in bonding ('interstitials'), or atoms may be missing (vacancies)

- These form states in the semiconductor called 'defects' with energy usually in the middle of the bandgap

- Such states are not useful electronically and serve only to trap and scatter charge carriers – tending to decrease τ, decrease v_d, decrease μ

Summary

- A pure semiconductor is termed intrinsic – which means that at room temperature there are a relatively small number of electrons and holes (from thermally broken bonds)
- It is possible to increase the density of electrons or holes by doping the semiconductor with different atoms – here we consider Si
- Since we can control how many atoms are added to the crystal we can control the electronic properties this way
- For Si, adding atoms from Group V, where there are 5 outer electrons, results in the "donation" of a free electron and an ionized atom ("donor"). At room temperature nearly all donors are ionized. This is termed n-type doping or n-doping as the charge carriers are negatively charged.

Summary (2)

- Adding atoms to Si from Group III, where there are 3 outer electrons, results in the atom "accepting" an electron from the valence band resulting in the creation of a free hole and an ionized atom ("acceptor"). At room temperature nearly all acceptors are ionized. This is termed p-type doping or p-doping as the charge carriers are positively charged.
- The dopant atoms have electronic energy levels close to the conduction (donors) and valence band (acceptors)
- Ionized impurities act to scatter electrons and holes, reducing their mobility
- Other impurities and defects can form levels close to the middle of the band-gap which interfere with charge transport