"Heterojunctions"

10/11/2014 (01)

Topics: Heterojunction materials, Energy band diagrams
Two dimensional electron gas.

- A heterojunction is a junction formed between two dissimilar semiconductors (having different bandgap's, work functions and electron affinities).

- **Heterojunction materials:-**

There are four basic types of heterojunction.

→ Heterojunctions in which the dopant types changes at the junction are called "anisotype."

eg We can form nP or Np junctions, where the capital letter indicates the larger-bandgap material.

eg p-Ge, - N-GaAs (pN Ge-GaAs), n^+ - AlGaAs, p-GaAs (Np AlGaAs-GaAs)

→ In anisotype hetero-junction's, current is due minority carrier injection.

→ Heterojunctions with the same dopant-type on either side of the junction are called "isotype."

eg We can form nN and pP isotype heterojunctions.

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eg nN GaAs - AlGaAs is an isotype heterojunction.

The current flow mechanism in an isotype junction is due to majority charge carriers.

Info!

- Since the two semiconductor materials used to form a heterojunction will have different energy bandgaps, the energy band will have a discontinuity at the junction interface. (as the fermi-level line up at equilibrium) (Refer fig 1.a).

- In order to have a useful heterojunction, the lattice constants of the two materials must be well matched. (Lattice Match Requirement!)
- The Lattice match is important because any Lattice mismatch can introduce dislocations resulting in interface states.

eg. Germanium - Gallium arsenide (Ge-GaAs) have almost identical lattice constants matched to within 0.08% (5.654 °A for GaAs and 5.658 A° for Ge)

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* Energy-band Diagrams:-

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· In the formation of a heterojunction with a narrow-bandgap material and a wide-bandgap material, the alignment of the bandgap energies is important in determining the characteristics of the junction.

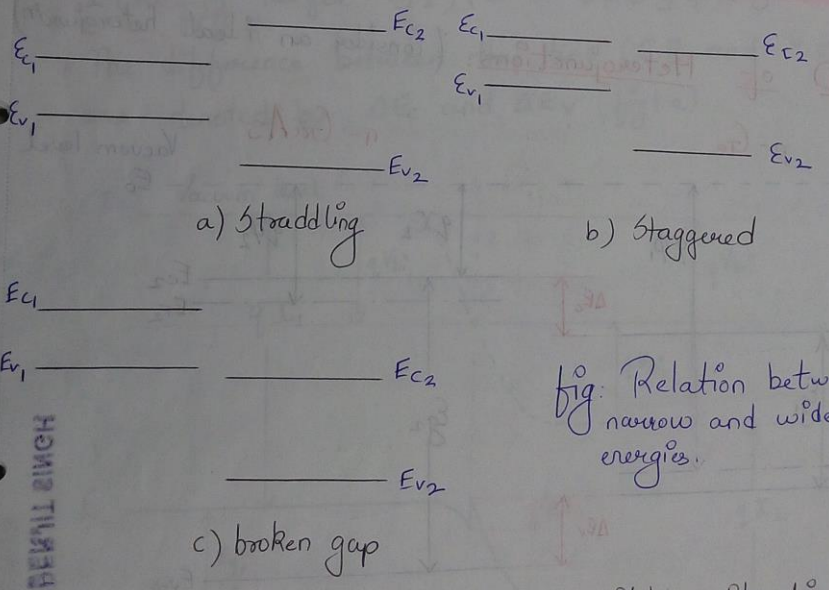

fig. Relation between narrow and wide-bandgap energies.

· Above figure show's three possible situations. In fig (a), we see the case when the forbidden bandgap of the wide-gap material completely overlaps the bandgap of the narrow-gap material. This case, called "straddling", applies to most heterojunctions.

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- The other possibilities are called "staggered" 04 where wide-band gap material's bandgap partially overlaps bandgap of narrow-bandgap material as shown in fig (b).
- In fig (c), band gap of wide-band and narrow-band material do not overlap at all. This case is called "broken gap" is shown in fig (c).

→ EBD of Heterojunctions: (Consider an ideal heterojunctn)

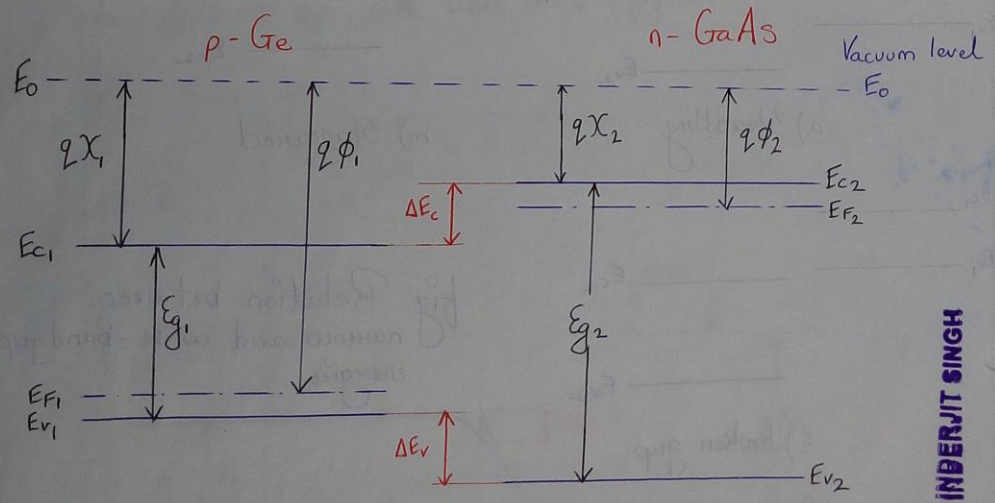

fig 1.a) EBD of a narrow bandgap (p-Ge) and a wide bandgap (n-GaAs) semiconductor before contact. (pN heterojunction)

χ → electron affinity
ϕ → Work-function differences
E_g → Energy band-gap.

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- Fig 1.a shows the EBDs of isolated p-Ge and 05 n-GaAs semiconductor's, with the vacuum level used as a reference level (ie all energy levels are measured w.r.t E_0).
- Semiconductor 1 is a ptype Ge and has a smaller E_{g_1} (narrow band-gap) but have large electron affinity than ntype GaAs ie Semiconductor 2 (having larger E_{g_2}) (wide band-gap).
- The difference between the two C.B and V.B energies are denoted by ΔE_c and ΔE_v. (fig 1.a)

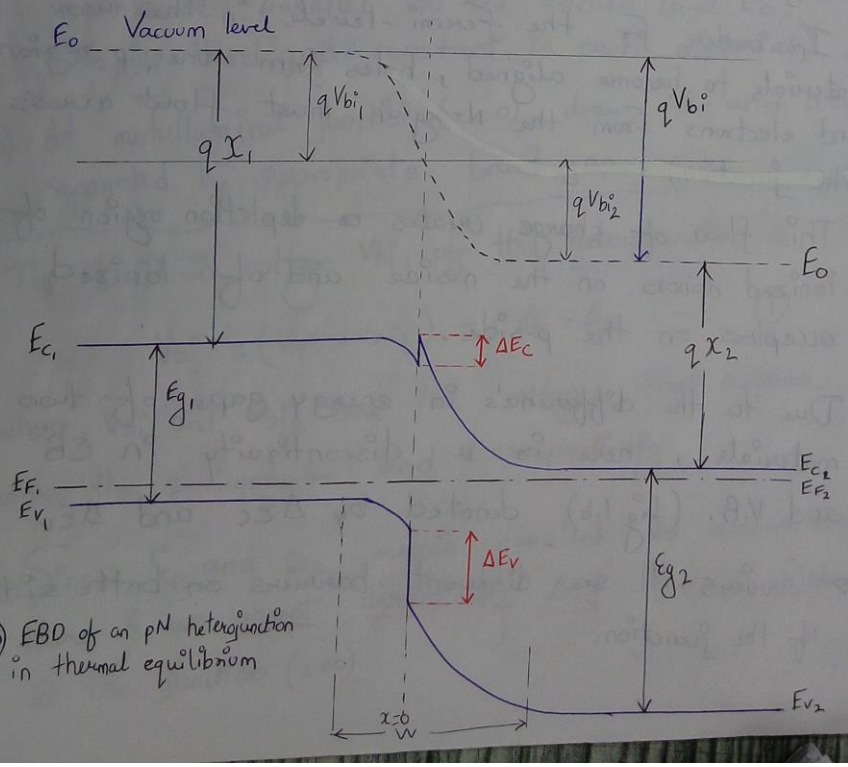

fig 1.b) EBD of an pN heterojunction in thermal equilibrium

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- In an ideal abrupt heterojunction, the vacuum level is parallel to both C.B and V.B.
- If the vacuum level is continuous, then the same ΔE_c and ΔE_v discontinuities will exist at the heterojunction interface.
- This ideal situation is known as the "electron affinity rule".

→ When the two dissimilar materials are brought into intimate contact, e^--hole flow occurs across the junction until thermal-equilibrium is reached.

(ie In order for the Fermi-levels in the two materials to become aligned, holes from the p-region and electrons from the N-region must flow across the junction)

- This flow of charge creates a depletion region of ionized donors on the n-side and of ionized acceptors on the p-side.
- Due to the differences in energy gaps of two materials, there is a discontinuity in CB and V.B. (fig 1.b) denoted by ΔE_c and ΔE_v.

→ Carriers will see different barriers on both sides of the junction.

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Reference: (Steps to draw EBD for a heterojunction) 07

1) Draw a common fermi-level E_F
2) Locate the positions of respective band edges and the vacuum level relative to E_F in the neutral n and p-regions
3) In the junction depletion region, the vacuum level from semiconductor 2 is made to gradually approach that of semiconductor 1.
4) Finally, the band edges $\mathcal{E}_{c_1}$, $\mathcal{E}_{c_2}$, $\mathcal{E}_{v_1}$ and $\mathcal{E}_{v_2}$ are located parallel to the vacuum level E_0. (Keeping band gap constant in each material).
5) At metallurgical junction ($x=0$), draw $\Delta\mathcal{E}_v$ and $\Delta\mathcal{E}_c$ separated by appropriate band gap.

- The built-in voltage V_{bi} of this heterojunction is

$$V_{bi} = (V_{bi_1} + V_{bi_2}) = \phi_1 - \phi_2 \quad \text{— (1)}$$

where, V_{bi_1} and V_{bi_2} are the voltages that appear across the semiconductor 1 and 2 respectively.

- Since $\mathcal{E}_{c_1}$ and $\mathcal{E}_{c_2}$ remain parallel to vacuum level, there is an abrupt discontinuity "$\Delta\mathcal{E}_c$" in the CB edge at the junction ($x=0$).

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In ideal case, from fig(1.b), it is seen that

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$$\Delta E_c = q(\chi_2 - \chi_1) \quad \text{— (2)}$$

- Similarly, the abrupt discontinuity ΔE_v in the V.B edge is given by.

$$\Delta E_v = q\chi_2 + \mathcal{E}_{g2} - (q\chi_1 + \mathcal{E}_{g1})$$

$$\Delta E_v = q(\chi_2 - \chi_1) + (E_{g2} - E_{g1}) \quad \text{— (3)}$$

From (2) and (3), we obtain

$$\boxed{\begin{aligned} \Delta E_c + \Delta E_v &= E_{g2} - E_{g1} \\ \Delta E_c + \Delta E_v &= \Delta E_g \end{aligned}} \quad \text{— (4)}$$

Ideal situatn represented by eqn (4) is called Electron affinity rule

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Current transport for (1.b) heterojunction.

- Under ideal conditions, the main current component in a forward biased pn heterojunction is caused by the minority carrier injection over the barrier.
- From fig (1.b), it is evident that the electrons in the wide band gap (n type) semiconductor see a much lower barrier than the holes in the narrow band gap semiconductor (p type).

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• Thus the wide-band semiconductor injects more minority carrier across the junction than the narrow band gap semiconductor. 09

Note: (Interesting Fact in HeteroJ^ns)
The current flows because of minority carrier injection from wide-bandgap semiconductor in to the narrow bandgap semiconductor, (even when dopant concentration in wide band-gap SC is lower than that in narrow band gap SC.

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→ This offers a potential advantage of using heterojunction in some devices such as BJTs and Lasers.

Applications: (Heterojunctions) !!

• Heterojunctions have shown great promise in a number of devices such as LEDs, semiconductors lasers, solar cells, photo-detectors and BJTs.

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• EBD of an nP heterojunction :

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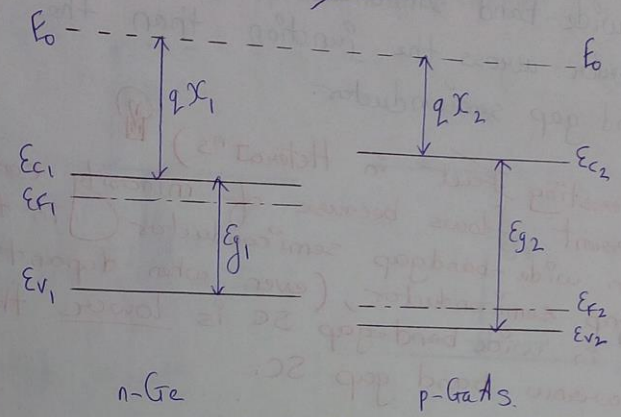

fig 2 a) EBD of nP heterojunction before contact.

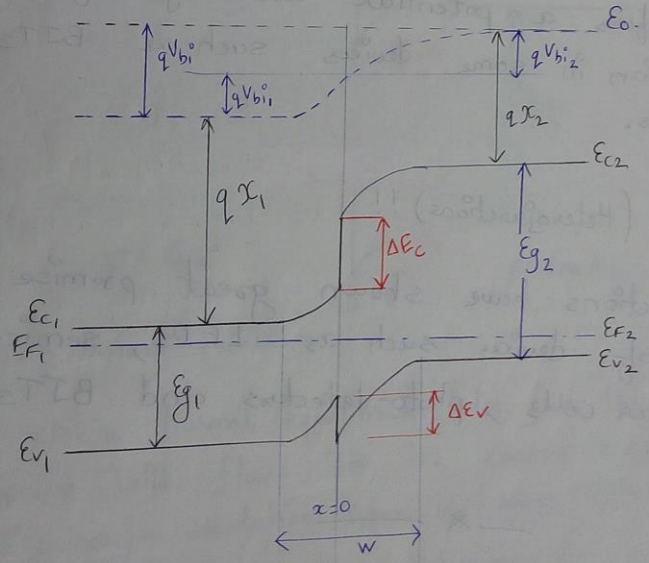

fig 2 b) EBD of an nP heterojunction in thermal equilibrium

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EBD of a pP isotype heterojunction.

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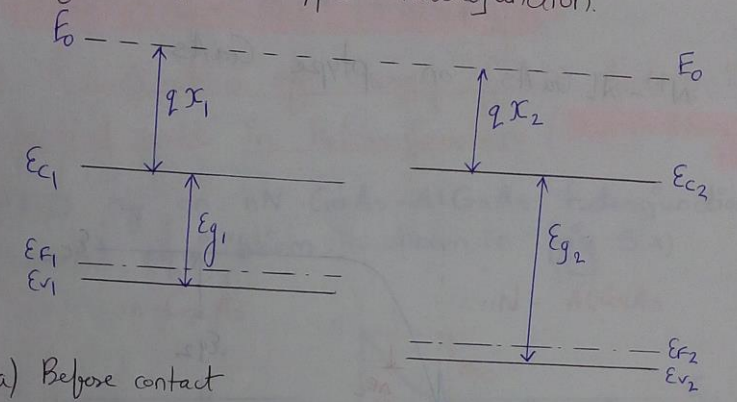

fig 3 a) Before contact

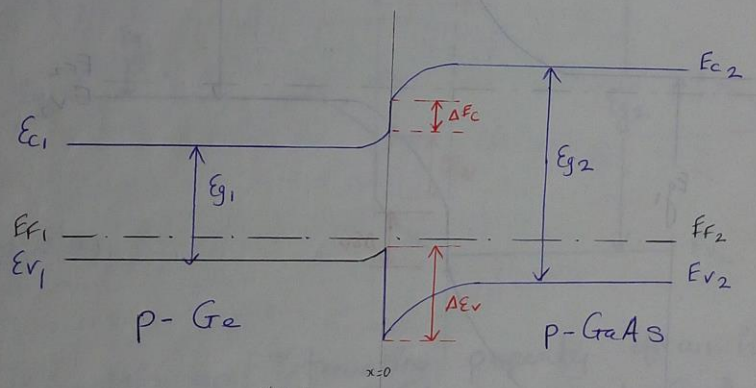

fig 3 b) In Thermal equilibrium.

- To achieve thermal equilibrium, holes from the wide-bandgap material will flow into the narrow-bandgap material, creating an accumulation layer of holes in the narrow-bandgap material at the interface.

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Reference:

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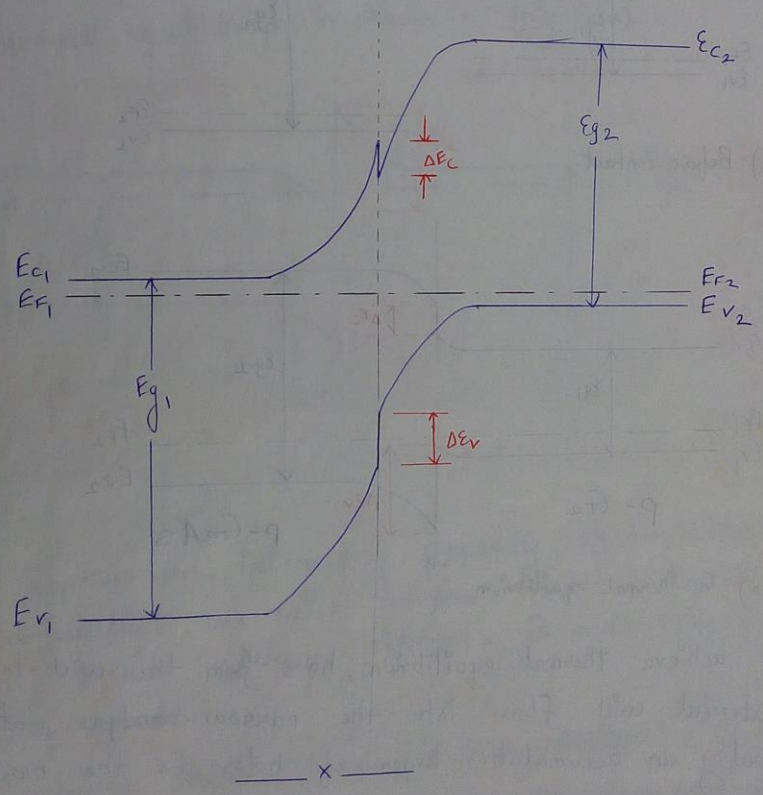
EBD of N^+ - AlGaAs on ptype GaAs



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* Two-dimensional Electron gas:

OR Quantization of energy of an electron in a potential well in hetero-junction: (Explain either (a) case or (b))

a) EBD of an nN GaAs-AlGaAs heterojunction in thermal equilibrium in shown in fig 5.a)

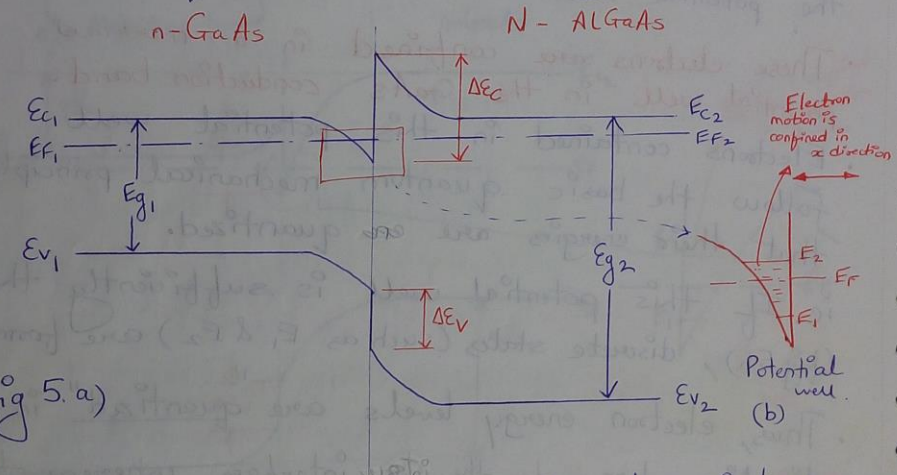

fig 5. a)

- To explain an interesting property of an isotype hetero-junction, we will assume that GaAs is lightly doped, whereas AlGaAs is moderately to heavily doped.
- To achieve thermal equilibrium, electron flow from the wide-band-gap material into the low-band gap GaAs.
- This leads to the formation of an accumulation layer

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of electrons in the potential well adjacent to the interface. 14

- Thus the discontinuity in the conduction band (C.B) allows electrons to spill over from the ALGaAs into the GaAs, where they become trapped in the potential well.
- These electrons are confined in a narrow potential well in the GaAs conduction band.
- Electrons contained in this potential well follow the basic quantum mechanical principle that their energies are quantized.

ie If this potential well is sufficiently thin (fig 5b), discrete states (such as E_1 & E_2) are formed.

- Thus, electron energy levels are "quantized" in a direction $\perp r$ to the interface, whereas the electron's are free to move in the other two spatial directions.
- Such a behavior of electrons is referred to as "two-dimensional electron gas" or "2DEG"
- Electron conduction in such a potential well can result in very high mobility which is due to fact that the e^-s in this well come from ALGaAs, and not from doping in the GaAs.

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- This property of isotype heterojunction can be used to alter the relative injection of electrons and holes.

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b) 2D Electron gas concept can also be explained by considering n^+ - AlGaAs & n - GaAs

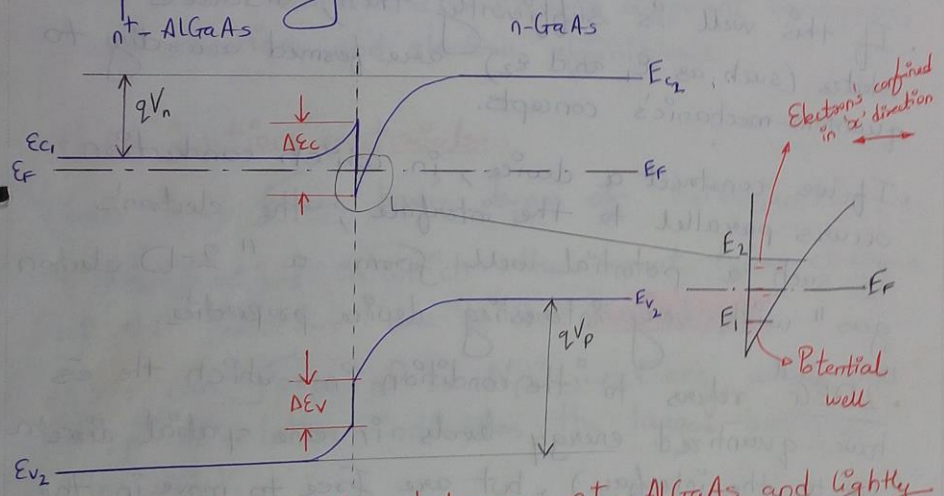

fig 6: A heterojunction between n^+ - AlGaAs and lightly doped GaAs, illustrating the potential well for e^-s formed in the GaAs's C.B.

- In this case, heavily doped ntype AlGaAs is grown on lightly doped GaAs.
- In this example, the discontinuity in the C.B allows electrons to spill over from the n^+-AlGaAs into the GaAs, where they become trapped in the potential well.

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- As a result, electrons collect on the GaAs side of the heterojunction and move the Fermi-level above the C.B in the GaAs near the interface.
- These electrons are confined in a narrow potential well in the GaAs CB.
- If this well is sufficiently thin, discrete states (such as E_1 and E_2) are formed according to quantum-mechanic's concepts.
- If we construct a device, in which conduction occurs parallel to the interface, the electron's in such a potential well form a "2-D electron gas" with very interesting device properties.
- "2DEG" refers to the condition in which the e's have quantized energy levels in one spatial directn (⊥r to the interface), but are free to move in the other two spatial directions.

Electron conduction in such a potential well can result in a very high mobility (which is due to the fact that the e's in this well come from the AlGaAs and not from doping in the GaAs.

→ This property of isotype heterojunctions can be used to alter the relative injection of e's and holes

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