Introduction on the Semiconductor Heterostructures

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Abstract: The heterostructure physics becomes more and more important. More and more people are entering this dynamic field. This article introduces some basic concepts on the semiconductor heterostructures. And the application of the heterostructure is also presented in the end of the article.

1 Introduction

Today you can't image what the world would be if without the semiconductor heterostructures technology. And it is said that near two thirds of all research groups in the physics of semiconductors are involve in it especially double heterostructures. In 2000 one of the Physics Nobel prize owners is Professor Zhores I.Alferov whose major achievment is this field. He started to study it in the early 1930s[1]

Semiconductorsarecomposedofmorethanonematrial.Semiconductorheterostructure,whicharesimplyatomicallyabruptinterfacesbetweentwodifferentsemiconductors,canbethoughtofasbuildingblocksformoreelaboratenanostructures.Orwecansayinanotherway,semiconductorheterostructuresarecrystallinesolidscontainingoneormoreheterojunctions−−−interfacesbetweentwodifferentsemiconductors.Anabruptheterojunctioncoupleselectronicstatesfromtwodifferentmaterialswithdifferentpositionsofbandextrema(i.e.potentialenergy),ordifferenteffectivemasses,etc[2].

GaAs-$Al_xGa_{1-x}As$ is always mentioned(/studied) in this field. It is usually abbreviated simply to AlGaAs.Sometimes it is called "sandwich" because the GaAs is between two layers of $Al_xGa_{1-x}As$. The whole system acts like an elementary quantum well. It has some properties that will be introduced later.

Variations in composition can be used to control the motion of electrons and holes and further determine the properties of the heterostructure. It's important for us to know the alignment of bands at a heterojunction, where two materials meet.

2 Classical Heterostructures

2.1 General Properties of Heterostructures First of all we should use an assumptions. We treat electrons as they are free,except for an effective mass.

We like to study III-V materials and their alloys for their semiconducting properties. Minimum band gap and the lattice constant are two important properties of those materials. The following figure shows these two properties of them[3]:

From Fig 1. we can find that the lattice constants of AlAs and GaAs are very close.

So GaAs and AlAs are always been made into the alloys.

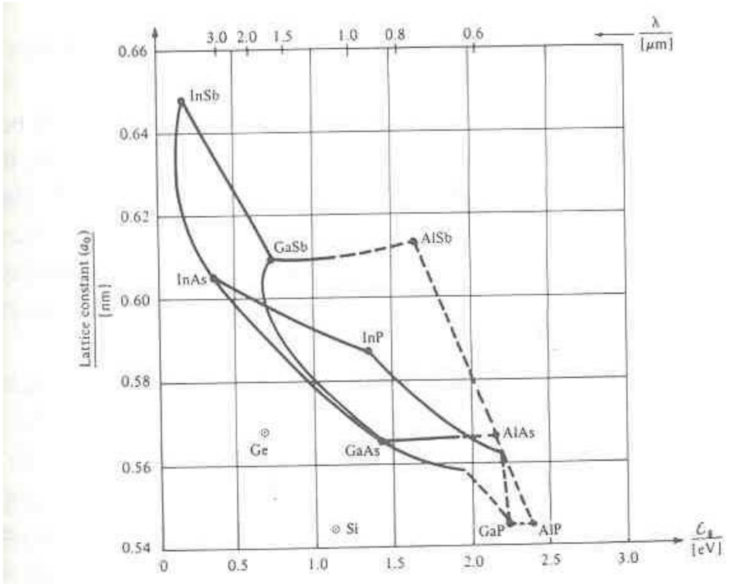


Fig 1 Plot of the lattice constant of various semiconductors against their minimum
band gap E_g.

Full Line: Direct Band Gap Dash Line: Indirect Band Gap

The active regions of heterostructures are typically at or close to interfaces. In the real life it is impossible to join the two materials in a seamless way. But for III-V heterostructures the more perfect interfaces they get, the better performance they will have. If you want to join the two materials perfectly to get a nearly 'ideal' heterostructure, you should first choose the materials that have the same crystal structures(Or at least symmetry) and the two lattice constants must be nearly identical.

The lattice constant(effective lattice constant) of $Al_xGa_{1-x}As$ is given by (ignores alloy scattering)

x a_{AlAs}+(1-x) a_{GaAs}($a_{AlAs}$is the lattice constant of AlAs) And the averaged crystal potential U(r) is:

XU_{AlAs}(r) + (1-x) U_{GaAs}(r)

So generally we can conclude at least three conditions to get an ideal heterostructure:

. The two materials' atomic structures must match.

. The interface must have high quality. Namely, it must keep clean and pure
and have perfect lattice structure.

. The layers may be thin so we are able to change the composition of successive layers very rapidly, preferably and easily.

2.2 The Bond Diagram

Most heterostructures are formed by heterojunctions. The heterojunctions are either flat or have very low curvature on the atomic scale. So we can just study the planar heterojunctions. Their properties depend only on one longitudinal coordinate(e.g. assume it is the z axis). With this assumption, the structures then can be classified in terms of band diagrams.

Consider a semiconducting alloy of the type A_xB_{1-x}.Here the A and B are two different semiconductor materials(including alloy respectively). Let's focus on a heterojunction between two materials A and B. E_g^A¡ E_g^B

Some notations:

E_c : Energy of Conduction Bands E_v : Energy of Valence Bands

E_c : Difference between the energies of the conduction band extreme in the two
materials. $E_{c\equiv}$ E_c^B- E_c^A= χ^A-χ^B

E_v : Difference between the energies of the valence band extreme in the two
materials. $E_{v\equiv}$ E_v^B- E_v^A

$ThepositionsofE_c$ and E_v are determined by the chemical bonding of the atoms and can be measure or calculated by solving Schrodinger's equation. These energy levels must be measured relative to some reference level. We choose one energy reference level(vacuum levels aligned in Fig 2[3] —- Or label it as E_0). χ is the electron affinity, the energy needed to remove from the semiconductor of an electron located at E_c and make it a free electron.

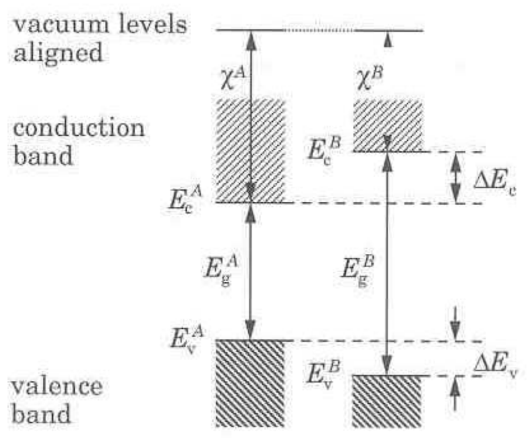


Fig 2 Alignment of the bands at a heterojunction between materials

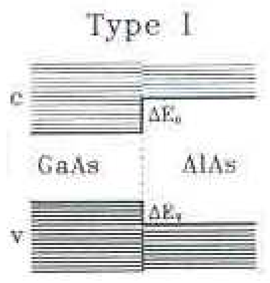
A(left) and B(right) (Note: From Anderson's Rule: The Vacuum levels of the two materials of one heterostruction
should be lined up)

If the components are two different semiconductors, the band diagram can also be constructed from the each known band structure. The relative postion of the bands can be determined from the electron affinity.

2.3 Four Types of Heterostructure

2.3.1 Type I (Or Straddling Alignment) Heterostructure

As the Fig 3[2][4] shows:



(a) (b)

Fig 3 (a) Type I structures have band offsets of opposite sign

(b) Observed band alignments for $Al_{0.3}Ga_{0.7}As$

The narrower band gap is enclosed within the wider band gap(as the Fig3a shows). In this case, the signs of band offsets for the two bands are opposite. This is the case for such systems as GaAs/AlGaAs, GaSb/AlSb,GaAs/GaP. From Fig3-b, We can find for $Al_{0.3}Ga_{0.7}As$-GaAs system: E_c=0.23 ev, E_v= -0.15ev. The offset in valence bands is to be about 40% of the difference in band gaps. For this material pair, the conduction and valence bands of the smaller bandgap semiconductor lie completely within the bandgap of the wider bandgap semiconductor.

2.3.2 Type II(Staggered) Heterostructure and Type III(Broken-gap) Heterostructure

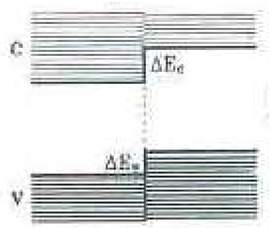


Fig 4[2] Type II. The band offsets have the same sign

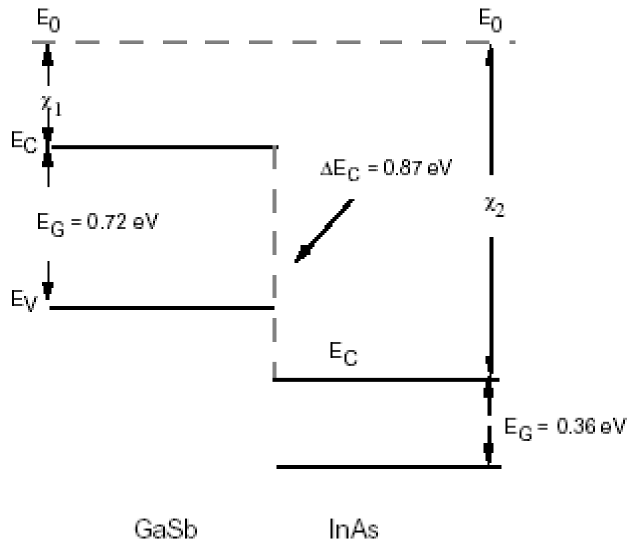
For Type II heterostructures, the band offsets have the same sign. The examples are InP/$Al_{0.48}In_{0.52}P$, $In_xGa_{1-x}As/Ga_x Sb_{1-x}$ As and $Al_x In_{1-x}As$/InP systems.

Type III also has the band offsets of the same sign, but the offsets are so large that the gaps in the two materials do not overlap(Fig 5[2][4]). The example is InAs/GaSb.

(a) (b)

(c)

Fig 5 (a) Band diagram of Type III Heterostructure (b) The valence electrons from the right material can penetrate the conduction band of the left material and form a double layer of electrons and holes at the interface. (c) Band alignments for GaSb and InAs.



2.3.3. Difference between Types II and III

Type III heterostructures are sometimes called "Type II with nonoverlapping gaps" or "Type II misaligned Heterostructure". But there is an important physical difference between the two types: The Type III components will equalize the Fermi levels and leads to large bending (Fig 5b) to get a equilibrium point.

The band diagrams ignore electrostatic potentials. Near the junction the mobile rearrange after the semiconductors are placed in contact. when placed in contact, electrons move from the semiconductor with the higher Fermi-level to the one with lower direction. Then the process will produce an electric field to balance this transfer.

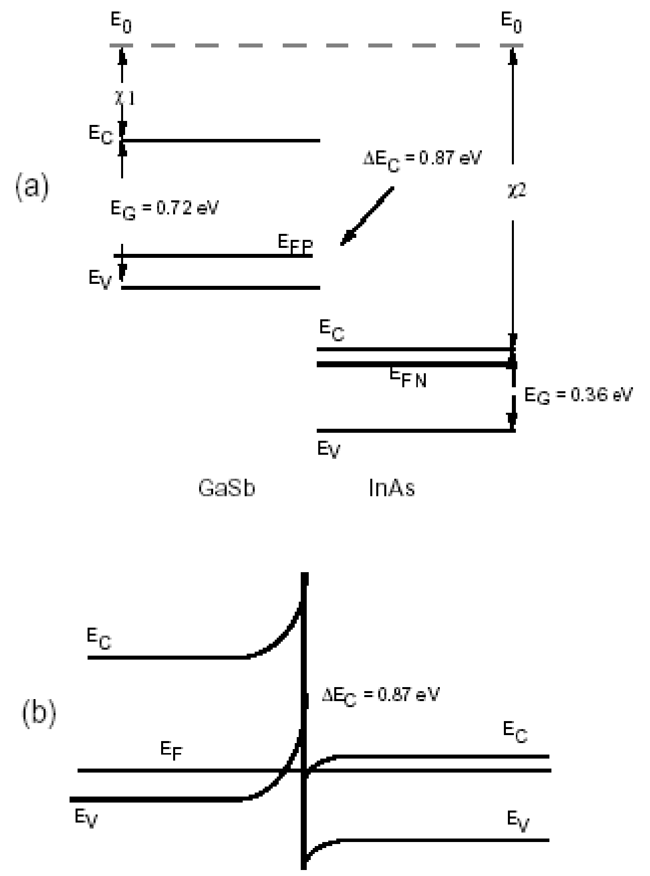
As the Fig. 6[4] or Fig 5b shows.

Fig 6 GaSb:InAs/P-n Heterojunction (a) before contact (b) after contact

Where $E_F$is the Fermi Level. Before they are in contract, there are separate Fermi levels for the n-type(E_{FN}) and p-type (E_{FP})semiconductors. But after they are put in contact, the energy bands adjust to align the Fermi Levels.

3 Important Applications in Electronics[5]

As we have mentioned in the first two paragraphs, heterostructure productshave been widely used in the industry and research field. You also can find its applications in your life.


(a)
E0
E0
χ1
EC
ΔEC = 0.87 eV
χ2
EG = 0.72 eV
EFP
EV
EC
EFN
EG = 0.36 eV
EV
GaSb
InAs
(b)
EC
ΔEC = 0.87 eV
EC
EF
EV
EV

. Semiconductor lasers (Used in Compact Disk—CD player)

. High-efficiently LED's(heterostructure light-emitting diodes) and low-noise,
high-electron-mobility transistors(HEMTs) used in high-frequency devices

. Solar cells and photodetectors,based on wide-gap window effect.

. Bipolar wide-gap transistors

. High-power diodes and thyristors

. Infrared to visible converters

Conclusion:

We introduced some basic concepts on the semiconductor heterostructure. Although only a few properties are provided in this presentation, Some other important properties are almost based on the lattice structure of heterostructures included in this article. And some interesting theoretic properties and useful industrial technology are not covered because of the limit of time and the space. With the basic concepts it is not difficult for you to find out why and how the heterostructures are widely used near you.

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