General Notes On Semiconductor Physics

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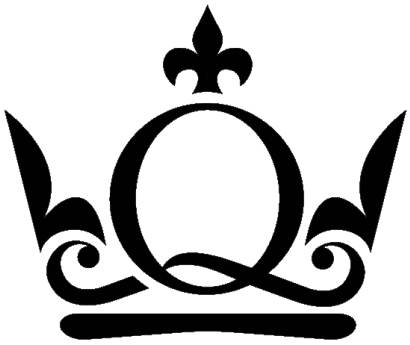

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In this article, brief summary and fundamental understanding of some basic notations in semiconductor physics will be given. Hopefully the summary given in this article will server as a good starting point for further learning and understanding of certain topics in semiconductor physics.

- Direct and Indirect Bandgap

The bandgap is a quite important notation for semiconductor physics, and the value and property of the bandgap determines the optical properties of the semiconductor materials, such as the photoluminescence behaviour and photon absorption. Here the the importance of the value of bandgap is straitforward to configure – the larger the gap is, the higher photon energy it is correlated to. Then what about the 'properties' of the bandgap? Well, given specific value of the bandgap, different types of bandgap may respond to the photons in quite distinct way. The direct and indirect bandgap are just two typical types of bandgap, which interacts with photon in completely different way.

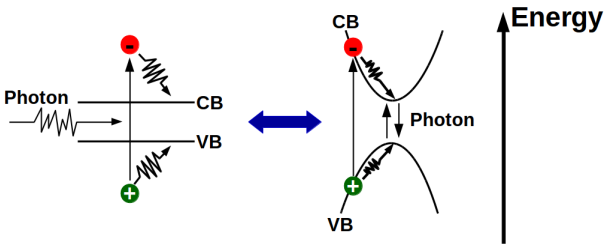

Figure 1: Illustration for photon absorption/emission in direct bandgap semiconductor.

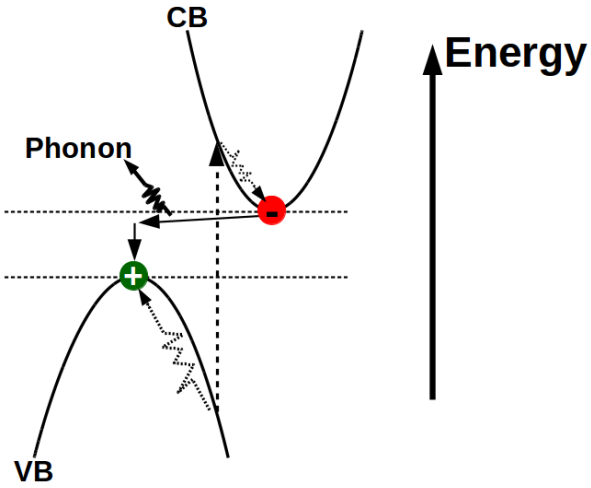

Figure 2: Illustration for indirect bandgap.

The direct bandgap refers to the band structure where both the bottom of conduction band and the top of the valence band are at the $k = 0$ point. Therefore it meets the requirement that the transition between the conduction band bottom (CBB) and valence band top (VBT) should emit/absorb photons with approximately zero momentum. However, there may be a question that why the transition always happen between CBB and VBT? Actually, electrons/holes tend to move towards the energy minium in the energy diagram. CBB and VBT are just those minima, so if the energy of incoming photons is

higher than the gap, the excess energy will be wasted as heat while the electrons and holes move to their minima in the energy diagram. Another question may be that why CBB and VBT happens to be located at $k = 0$ point (Γ point). This is actually the result of Bloch theorem, which tells that the band structure in k space is periodic and therefore all the energy band can be moved to the first Brillouin zone. The result of such shifting considering the periodic condition of the band structure will create CBB and VBT at $k = 0$ point – the Γ point. The above discussion is illustrated in Fig. 1.

As shown in Fig. 2, the CBB and VBT of indirect bandgap are not located at the same position on the momentum axis. Therefore if the exciton is going to recombine to emit photons (or the photons are going to be absorbed to create exciton pair), phonons have to be involved in the process, which ism usually more difficult than the direct transition as in direct bandgap materials. And this is why usually the quantum yield of indirect bandgap materials is lower than that of direct bandgap materials. Moreover, if similar process happens as for direct bandgap, where the transition does not happen the the band edge, for indirect semiconductor as well, the momentum of the exciton will be then non-conservative, which again, needs the assistance from phonons.

- Bohr Exciton radius

The exciton is defined as the composed of the interacting electrons in the conduction band and the holes in the valence band. In the simplest model, the energy of an exciton is composed of two parts – the motion of the center of mass and the relative motion between electrons and holes. The first part actually behaves like the free electron, and the second part behaves like a hydrogen atom, where the hole acts the role of a positron to form a 'electron-positron' pair. This can be imagined as the electron moving around the nucleus and accordingly, we may have similar definitions as it is for hydrogen system. In analogue to Bohr radius definition, the exciton radius is given as:

$$a_{Be} = \frac{m_e}{m^*}\epsilon_r a_B \tag{1}$$

where m_e is the electron mass, m^* the reduced mass of the exciton given by $m^* = \frac{m_e^* m_h^*}{m_e^* + m_h^*}$ with m_h^* and m_E^* the effective mass of holes and electrons. The parameter a_B is the Bohr radius given as:

$$a_B = \frac{4\pi\hbar^2\epsilon_0}{m_e e^2} \tag{2}$$

Detailed discussion about the exciton can be found in the following two materials: Click Me, and Click Me.

- About Brillouin zone folding

Sometimes when the nanoparticle size becomes very small (e.g. 10 nm, or even comparable to the lattice constant), a superlattice structure may be formed, which can then reduce the size of Brillouin zone. Then according to the Bloch theorem, it is possible that the conduction band minimum in the indirect band gap material folds into the Γ point, resulting in a direct gap material. Sucn effect is called the Brillouin zone folding effect.

The discussion given here is based on the following materials:

1. Visible photoluminescence from Ge quantum dots –

doi:10.1016/j.physe.2005.05.063

2. M. Kumagai, T. Takagahara, E. Hanamura, Phys. Rev. B 37 (1988) 898.

3. T. P. Pearsall, J. Bevk, L. C. Feldman, J. M. Bonar, J. P. Mannaerts, A. Ourmazd, Phys. Rev. Lett. 58 (1987) 729.