122nd ASEE Annual Conference & Exposition
June 14 - 17, 2015
Seattle, WA
Making Value for Society
Paper ID #11189

The Educational Importance of Quantum Mechanics and QW Laser Diodes to Engineering Students

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Educational Importance of Quantum Mechanics and Quantum Well Laser Diodes for Electronics Engineering Students.

Abstract :

In this Research, first as an introduction , a review of present time understanding of quantum mechanics by our engineering students are summarized. Then a mini syllabus is suggested to include quantum mechanics in to our teaching physics to non- physics major students. A lesson plan that include the principals of photon emissions from semiconductor are briefly described , followed by a short discussion of P – n Junction Photo Diodes and Light Emitting Diodes , LED's. Then the band structure of quantum well layers in a P – n structures and how the Carriers are confined to these Nano layers are explained. Lastly the latest developments and progresses are summarized. with consideration of the revolutionary improvement of Nano Technology and its application of optical properties of semiconductors in the world of communication presented. The educational importance of the subject to Electronics Engineering Students is also described. At a lower scale there are potential for some of these concepts to be assigned as a research project to our undergraduate Engineering Students.

Introduction:

The Concept of Quantum Mechanics is still an scary and confusing topic to many in our Engineering Educational institutions. Most students, who are not physics majors, never have the chance to learn about the conceptual understanding of quantum mechanics. For example in Germany the first two years of College, students in Engineering, are introduced to atoms and quanta, as standard part of the curriculum[1], but are limited to photoelectric effect and Bohr atom models. In their Research, Teaching Quantum Mechanics on an Introductory Level, Rainer Muller and Hartmut Wiesner[1] concluded that the students discover from very beginning how quantum mechanics deviates from our classical everyday experiences. The results of their evaluation of the course showed that most of the students acquired appropriate quantum mechanical approach and concepts. In their method of delivering of the subject matter they have avoided many of the common confusions and misconceptions encountered in traditional instruction. However, there have been quite a few other research projects that explored reducing the challenging atmosphere of quantum mechanics and minimizing the confusion amongst undergraduate engineering students. One such research was carried out by Johan Falk[2] in his Ph.D Thesis on students' depictions of Quantum Mechanics. There he emphasized that researchers in this field feel that they are particularly making contribution to the theory of quantum mechanics, but digging into how students can comprehend the basic concepts of quantum mechanics is an important issue. Also Randal d. Knight[3] States that at the present time that nano- technology is touching multiple disciplines and understanding quantum mechanics is an essential tool for students in Electronics Engineering, especially in design of Semiconductor Devices, such as diode lasers, New classes of whole new devices called Quantum Well devices for Energy confinement and energy quantization. Another important phenomenon is Quantum Mechanical Tunneling which is a Startling Phenomenon in Electronics such as Avalanched Tunnel Diodes. As we dig more and more into literature on the developments of new devices in Electrical and Computer Engineering disciplines we find that most authors recommend that learning quantum mechanics is now becoming basic and fundamental in order for our graduates to have mastered the concepts of new technology[4]

The main goal is to address the students' critical thinking skills prior to presenting quantum mechanical approaches to the solutions of a particle motion. Because of the nature of the complexity of the subject, coupled with students' presumption of the subject being confusing and not conceivable there needs to be an approach that stimulates their curiosity and desire to learn the new subject and believe that without this new concept understanding our ever changing world is somewhat difficult. We need to give them the view of how the world is progressively changing and technology has evolved and keeps evolving. I should agree that at times this might push students beyond their cognitive limits and out of their comfort zones, but this will benefit them in acquiring the necessary skills and comprehension.

Lesson Plan and suggested teachings in all Electronics Engineering Programs:

This mini syllabus was piloted with our physics 320 class students in the College of Engineering and Information Sciences at DeVry University. The outcomes of the teaching were very positive and contrary to their expectations, all students found that the subject was not very difficult to understand. No quantitative analysis is presented here because of the small number of participating students. These results will however be presented along with another survey in our next delivery of phys320 class.

- Introduction to quantum mechanics and its evolution to the present time.
- Introducing the Schrodinger Equation as a substitute for Classical Newton' Law of Motion.
- Solving the one dimensional solutions of the Schrodinger Equation.
- Including an Active Physics Tutorial video if we can incorporate. (Particle confined in a Box)[5]
- Demonstrate Energy Levels in Potential Well, which is the solution of the Equation.
- Relate Carrier Concentrations In Potential Well.
- Excitations of Carriers in Potential Well
- Semiconductor's p – n Junctions and Optical Properties
- Emission of Photon and Recombination of Carries
- Structure of thin Semiconductor Quantum Well Layers
- Process of Lasing and Population inversion in Semiconductors
- Wavelength dependence of Semiconductor forbidden Ban Gap
- Classification of Low and High band gaps Semiconductors
- Processes of light emitting from These Layers and amplifications (QW lasers)

Introducing Quantum Mechanics and its evolution to present time. :

Quantum Mechanics is based on the principal Equation given by Erwin Schrodinger which is derived from the fact that Particles are presented by their Wave Function , $\Psi(x)$ instead of X(t) in Classical mechanics. The whole equation is really making a good use of De Broglie theorem that for every moving particle with momentum P, there must be a propagating wave $\Psi(x)$ with Wavelength λ , $\lambda = h/p$ with h being the Plank's constant , $6.63*10^{-34}$ j.s. The following could be shown as a very simple proof of Schrodinger equation :

From the very basic classical mechanics, General Physics I Class students already know the Work – Kinetic Energy Theory :

$$W = \Delta k = -\Delta U \qquad (1)$$

and at the same time for all conservative Forces we have :

$$F = -\frac{\partial u}{dx} \qquad (2)$$

Where ΔU is change in Potential Energy

Now Newton's second Law states that: $$\frac{\partial^2 x}{dt^2} = \frac{F}{m} \qquad (3)$$

So combining the 2 formulas: we have

$$\frac{\partial^2 x}{dt^2} = \frac{F}{m} = -\frac{1}{m}\frac{\partial u}{dx} \qquad (4)$$

This is the basis of Schrodinger Equation where Erwin Schrodinger made use of De Broglie Principal to obtain his equation. He took faith in De Broglie Theorem[6] and considered the motion of the particles to be shown by a sine wave, or what we call a harmonic wave with wavelength defined by De Broglie:

$$\psi(x) = A\, Sin\, \frac{2\pi}{\lambda} x \qquad (5)$$

And when taking the 2nd derivative of the above equation:

$$\frac{\partial^2 \psi}{dx^2} = -\frac{4\pi^2}{\lambda^2}\,\psi(x) \qquad (6)$$

But by introducing $\hbar = \frac{h}{2\pi}$ and reminding De Broglie Wavelength[6] $\lambda = \frac{h}{mv}$

Then, $\hbar^2 = h^2/4\pi^2$ and at the same time $\lambda^2 = \frac{h^2}{(mv)^2}$ and $\frac{4\pi^2}{\lambda^2} = \frac{2km}{\hbar^2}$

Easily we found that Schrodinger Equation is obtained which is:

$$\frac{\partial^2\psi}{dx^2} = -\ \frac{2m}{\hbar^2}\ (K - V)\psi(x) \qquad (7)$$

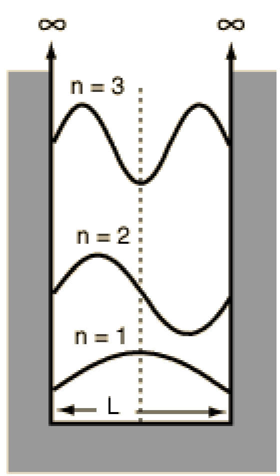
The right hand side is the total energy of the particle and the left hand side is the 2nd derivative of the wave function with respect to space. The interesting point is that Newton's 2nd law(4) also involves the 2nd derivative of the position of the particle but with respect to time. The right hand side in Newton's 2nd law is the gradient of potential energy and the right hand side of Schrodinger equation is the total mechanical energy, potential and kinetic.

By solving this differential equation (7) we will find the solutions of the wave function whose squared value , $|\psi|^2$ would show the probability of the position of the particle at position x. We already know that classical mechanics would give the location and well defined position of the particles.

One dimensional solution of the Schrodinger Equation:

This solution would give wave packets that would show different energy levels in a given potential energy well with defined potential barriers at either side[5]. Giving an active physics tutorial like the one noted in Ref.5 is a very useful and important part of the delivery which is recommended.

By clicking the link in Ref.5 the active tutorial would load and the instructor can describe to students the process as just like a standing wave in a closed tube or a wave travelling along a string. The concept of quantization is already very familiar with harmonics of a sound wave in a tube. How the closed tube can play only the odd harmonics, but an open tube can play odd and even harmonics should be reviewed[6].



x = 0 at left wall of box.

Fig. 1 A particle in a Potential Well

Here we visually see how the wavelength take only defined energy levels (energy quanta) and that the amplitude of the waves can also be indicative of their density, numbers/unit volume (or the intensity of light , when photons are concerned)

Concentration of charged carriers, Electrons and holes in a Quantum well :

A quantum well, QW, consists of a thin (~100Å) semiconductor layer sandwiched between two semiconductor layers with larger band gaps. In the one dimensional case this gives rise to discrete energy levels above the conduction band and below the valence band in which the well serves as a trap for EHP's (Electron Hole Pairs) and when EHP recombines in a direct band semiconductor, a photon is emitted.
This trapping effect increases the probability of an electron hole pair recombining between these new energy levels compared to the bulk semiconductor. This leads to more efficient laser emission due to the fact that the energy spread of the photons generated is tighter than that compared to bulk material[7]. The concentration of particles is governed by the Fermi Level.

The Fermi Level :

The probability of a state being filled with an electron is *F(E)*, and is given by :

$$F(E) = \frac{1}{1+e^{(E_c - E_f)/KT}} \qquad (8)$$

Where T is the temperature in Degree Kelvin Scale and K is the Boltzman Constant : $K_B = 1.38 * 10^{-23}$ J/K , Reminding students that when the Fermi level is at the middle of the band gap then the $F_E = ½$ or 50% that means the probability of an electron in conduction band becomes the same as probability of a hole in the valance band. The concentration of Electrons in conduction band of a semiconductor is then given by the product of available states by the Fermi level.

Semiconductor's P – n Junctions and Optical Properties:

Students in Electronics Engineering and closely related disciplines already know the Characteristics of a p – n Junction but very little about the Energy Band diagram. It is very beneficial to relate the above said quantum mechanical approach to charge carriers and the formation of p – n Junction and point out the optical properties of these junctions. The following figure shows a typical p – n Junction Energy Bands with the Fermi Level constant through the p and the n layers.

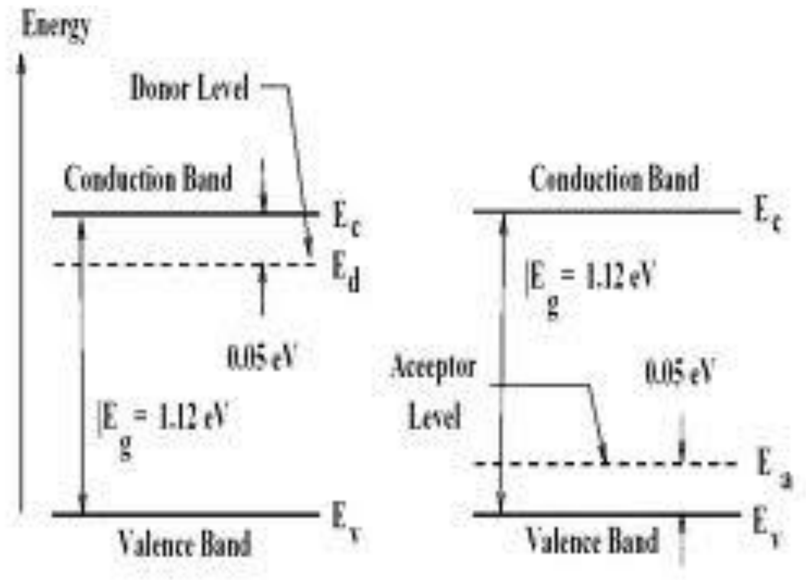


Fig.2 The Fermi level moves close to Conduction Bad in n – Type and close to Valance Band in P – type Semiconductor.

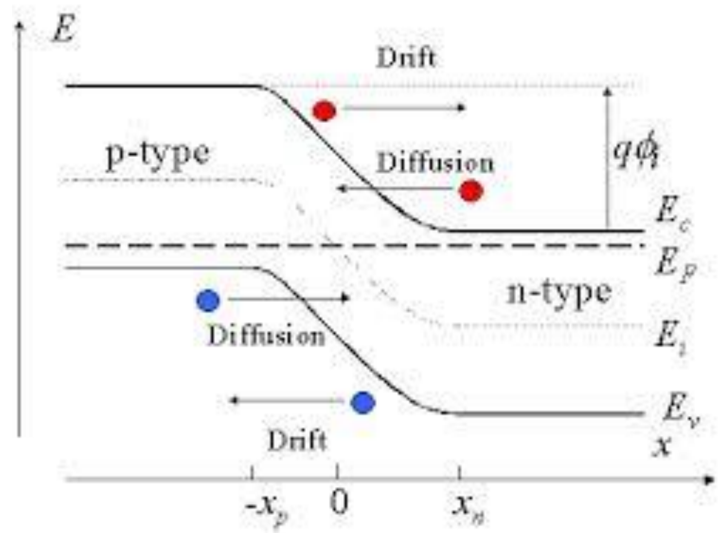


Fig.3 When these 2 types get attached to each other the Fermi level needs to stay constant throughout the device. This a zero bias p –n Junction energy band diagram.

Excitation of carriers in a potential well :

Shown in Fig.4 are, carriers generate photons by recombination from conduction band to valance band. Some times this recombination takes place via an impurity level within the band gap[8] in QW active layer.

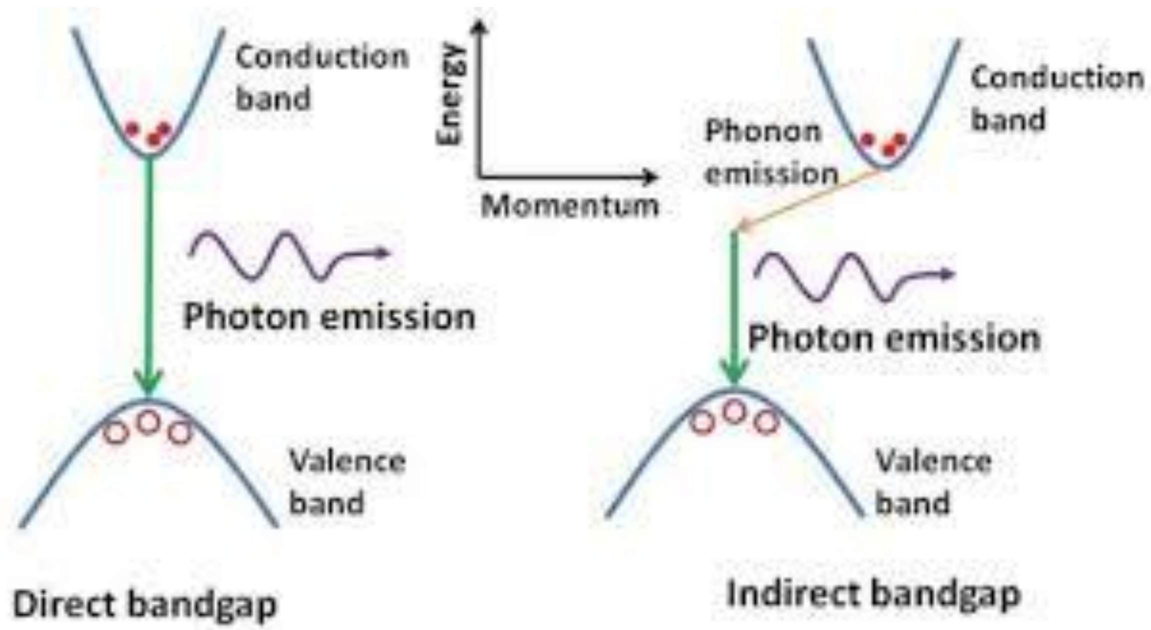


Fig. 4 Illustration of Recombination process and Photon Emission in a) Direct band gap and

b) in an indirect band gap semiconductor.[9]

The QW layers can be constructed to enhance the concentration of carriers and hence a larger yield of recombination to emit larger quantities of photons. Fig. 5 shows a typical quantum well structure[10.] As an example a structure consisting of a 10 nm wide GaAs quantum well embedded between two $Al_{0.1}Ga_{0.9}As$ barriers are shown. The conduction band offset is assumed to be 0.3 eV, the effective mass is assumed to be the mass of GaAs (0.067 m_0) in both materials. The grid resolution is 0.5 nm.

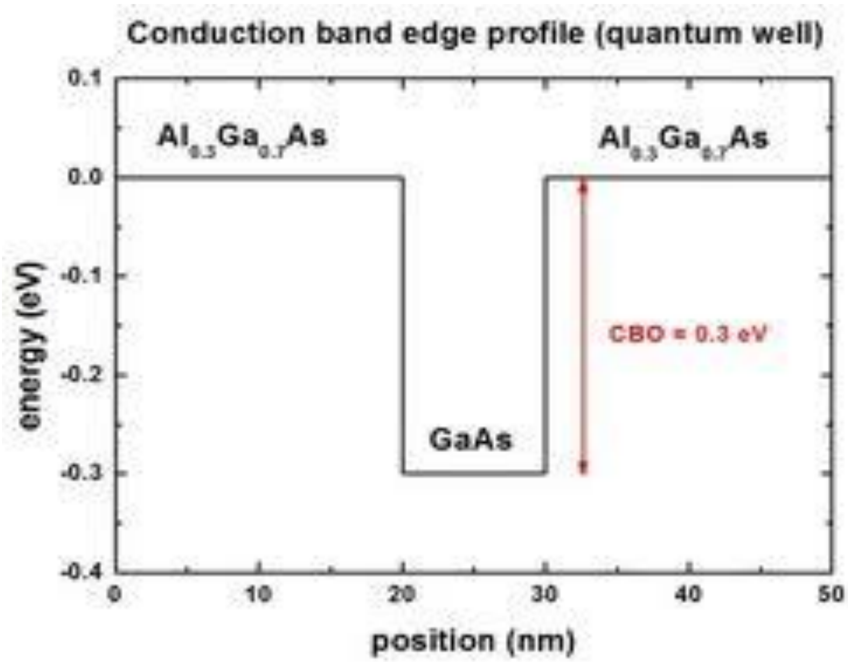


Fig.5 Illustration of a Conduction Band Quantum Well Structure.

With consideration of Valance band Structure the single quantum well structure would look like fig.6 below:

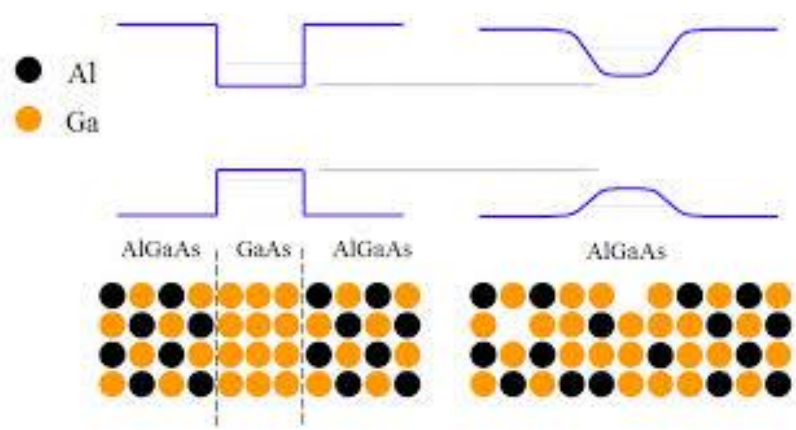


Fig. 6 : Structure of Band Diagrams in a single quantum well structure of

AlGaAs/GaAs/AlGaAs including lower Valance Band.

Process of Lasing and population inversion in semiconductors:

When the injection of minority carriers across a thin barrier is strong enough to tesult in a higher population of excited states, this strong carrier injection can lead to population inversion. Now if a cavity is designed in the end layers of this structure, a Stimulated Emission similar to lasing will occur in the active layer of the junction. Also, In addition to the requirement for an optical cavity in one direction at end points, an optical confinement perpendicular to this cavity is helpful to keep the photons that are achieved within the cavity. At the same time change in the index of Refraction of the adjacent layers, where The active layers normally have a little higher index of refraction, so that the total internal reflection takes place similar to that in an optical fiber[11] is an important design in the growth of these QW laser diodes.

Wavelength dependence of Semiconductor forbidden band gap:

The relationship between band gap and the wavelength is given by Einstein Equation[12]

$$E = \frac{hC}{\lambda} = \frac{1.24eV}{\lambda(\mu m)} \qquad (9)$$

The Table below is a summary of present popular semiconductor's band gap and their corresponding wavelength, used in nano technology research and industry. As it can be seen from the values of the band gap and the wavelength, some of these semiconductors are classified as narrow band gap semiconductors,($E < 1$ eV) which would have the application of being used as an infrared detector. The mid band gaps which are classified as visible light emitting semiconductors (1.8 eV $< E <$ 2.8 eV) are used in construction of visible LED's. The wider band gap semiconductors are emitting light at far blue and ultra- violets have recently been under extreme attention by researchers for producing bright white light LED,s such as GaN. The latter semiconductor was the subject of the 2014 Nobel Price award won by Isamu Akasaki et al[13].

Classification of Low and High band gaps Semiconductors :

Semiconductor	Band Gap (eV)	Wavelength (µm)	Symbole
Indium Antimonide	0.17	7.29	InSb
Indium Arsenide	0.36	3.44	InAs
Germanium	0.67	1.85	Ge
Indium Nitride	0.70	1.77	InN
Iron Sulfied	0.95	1.31	FeS_2
Silicon	1.12	1.11	Si
Indium Phosphide	1.35	0.92	InP
Gallium Arsenide	1.43	0.87	GaAs
Cadmium Telluride	1.49	0.83	CdTe
Cadmium Selenide	1.74	0.71	CdSe
Cupper Oxide	2.10	0.59	Cu_2O
Gallium Phosphide	2.26	0.55	GaP
Silicon Carbide	2.30	0.54	SiC
Cadmium Selenide	2.42	0.51	CdS
Zinc Selenide	2.69	0.46	ZnS
Zinc Oxide	3.37	0.37	ZnO
Gallium Nitride	3.40	0.36	GaN
Zinc Sulfied	3.54	0.35	ZnS
Diamond	5.54	0.22	C
Aluminum Gallium Nitride	3.44 - 6.38	0.36 - 0.19	$Al_x Ga_{1-x} N$

The Last Semiconductor , Aluminum Gallium Nitride is from the ternary semiconductor family that can be designed to have tunable band gap which can be adjusted depending the value of the x[14] : $0 < x < 1$

The application of the mentioned ternary semiconductor can be in blue laser diodes, ultraviolet LEDs (down to 250 nm), and AlGaN/GaN high electron mobility transistors, HEMT's can be grown on sapphire[15] and used in heterojunctions with AlN and GaN[15].

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