A Review of Semiconductor Quantum Well Devices

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Abstract

Quantum well devices feature very thin epitaxial layers of heterostructure III-V and II-VI semiconductor materials that are grown using Molecular Beam Epitaxy (MBE) and Metal-Organic Chemical Vapour Deposition (MOCVD) growth techniques. These devices are monolithically integrated with various optoelectronic devices to provide photonic integrated circuit with increased functionality .The quantum well structure can be realized with GaAs as wells and AlGaAs as barriers for wavelength about 0.8 µm and InGaAsP/InP offering longer wavelengths (0.9-1.6 µm). Quantum well devices find their applications in quantum well lasers or improved lasers, photodetectors, modulators and switches. These devices operate much faster, more economically and have led to a million increases in speed, a point of enormous importance to the telecommunication and computer industry.

Keywords: Quantum well, Semiconductor, Heterostructures, Lasers, Detectors, Modulators.

1. Introduction

Quantum well (QW) devices are devices that use quantum well effects. The basic concept of a quantum well is illustrated in Fig.1. The basis of a quantum well device is a situation where a thin semiconductor layer of lower band gap material is sandwiched between two thick semiconductor layers of larger band gap. These devices are currently replacing all conventional electronic components in many electronic devices. Since the width of the semiconductor material is comparable to the de Broglie wavelength, size quantization will result and electrons and holes will be confined in the small band gap semiconductors, where their potential energies are lowest. Most often the thickness of the small band gap material is about 100 Å or less. At such thickness, a smaller drive current will lead to population inversion and lasing a phenomenon generally observed in quantum well lasers.

In a quantum well, carriers are restricted in the growth direction (z-direction) i.e. direction perpendicular to the growth axis and free to move in the other directions. Since motion is restricted in the z-direction and free in the other directions, these devices are also described as two dimensional structures. Attempt is being made to realize quantum well device with size quantization in two or all the three dimensions. It is envisaged that this low dimensional structures will yield better and efficient devices. These devices are using the same basic principles as the corresponding bulk material devices. Quantum well devices feature heterostructures of very thin epitaxial layers of group III-V, and II-VI semiconductor material grown using MBE and MOCVD (Meenakshi *et al.*, 2010). This technique is capable of depositing single layers of atoms and it is possible to grow structures with physical confinement of the order of the de Broglie wavelength of electrons. It is also capable of growing heterostructures of any composition with crystalline perfection at the interfaces, good enough for quantum well devices (Nag, 2002). QW devices are realized by using type I, heterostructures either as lattice matched or strained-layered system. Not many type-II or type-III structures are used.

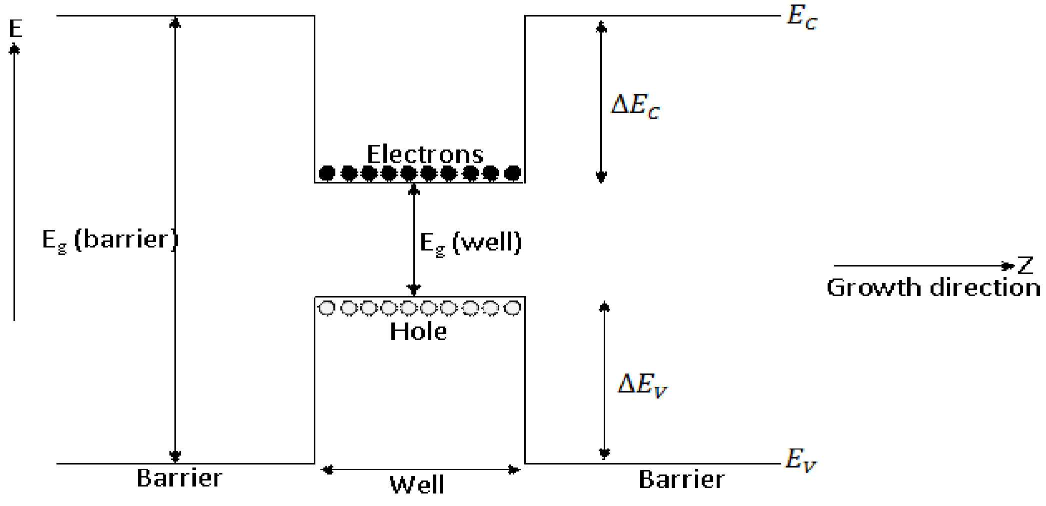

Fig. 1. Schematic of a quantum well as function of distance in the growth direction Z.

In the past emphasis was laid on lattice-matched heterostructures, but presently a lot of materials are being grown with lattice-mismatch strained layers of various compositions offering better characteristic performance (Nag, 2002). These devices include: quantum well lasers, avalanche photodiodes, modulators and switches. Quantum well structures have been used to fabricate tunable mid infrared photo detectors (Das *et al*, 2013), phase modulators, electro absorption modulators and optical switches in the mid infrared spectral range. They are the main components today in electronic equipment particularly in optical fiber communication. These devices are even integrated with other optical and electronic devices to produce optical and optoelectronic integrated circuit.

Harris (1990) reported the recent development of internal integration of a modulator with a photodiode to produce a photonic switch. These devices are all high speed much higher than with the conventional ones (Morkoc *et al*, 1991). In the next section, we will briefly look at each of these devices.

2. Quantum Well Lasers (QWL)

It is also known as semiconductor lasers or improved lasers (Sze, 1985; Meenakshi *et al.,* 2010). QWL operate on the same basic principle as a laser diode. Heterostructures are the main components of this device. L. Esaki and R. Tsu (Esaki and Tsu, 1969, 1970) reported quantum well devices in heterostructure of alternating nanothin layers with two semiconductors of different band gap. This device feature novel and unique properties with sharper junctions and size comparable to the de Broglie wavelength of the electrons. After understanding the principle of operation of a laser, Alferov (1998) proposed a double heterostructure (DHS) laser that could better trap charge carriers. In a DHS laser, two heterojunctions are used to sandwich a layer of material with narrow band gap between the materials of wide band gap. The slight energy difference between the band gaps of the two semiconductors set up a potential barrier that serves to confine the charge carriers in the narrow region near the junction.

The semiconductor material with the lower band gap will have a higher refractive index while the larger band gap material will have lower refractive index. The change in the refractive index at the heterointerface between the large band gap and low band gap material provides a wave guide effect which confines light (Kirti *et al.*, 2010). In addition to the carrier confinement in the lower band gap material, the DHS laser provides optical confinement of the emitted light from the lower band gap material. This confinement enhances stimulated emission and substantially reduces the threshold current density, J_{th} for DHS lasers to as low as 12 A/mm^2 or less at 300 K and so continuous room temperature operation has been achieved. However, QWL was first obtained by Van de Ziel *et al.* (1975) in GaAs/GaAlAs, but this device lasing parameters failed short of the DHS laser. Meenakshi *et al* (2010) exploiting the quantum size effect in reduced dimensions reported a continuous wave room temperature QWL with improved output characteristics.

An interesting aspect of a QWL is the narrow nature of the well. In this small volume of space, carrier concentration is the highest and consequently recombination of electron-hole pairs is very much enhanced, strong population inversion will occur in this well region where excess electron-hole pairs recombine to emit the laser light. Similarly, carrier confinement and optical confinement all hold in the well region. One of the most important aspects of QWL is the fact that some of the lowest threshold current has been measured in them (Kirti *et al*, 2010). Currents in the order of tens of milli-amps and emission wavelength between 695 nm and 820 nm have been measured in AlGaAs/GaAs quantum wells. The threshold current density and the laser temperature are related by the expression (Bhattacharya, 2002)

$$J_{th} = J_0 \exp\,[T/T_0] \qquad (1)$$

where T is the device temperature, T_0 is the threshold temperature coefficient and J_0 is the initial injected current.

QWL with one active region (well) is called single QW (SQW) lasers and that with multiple active regions is known as multi-quantum well (MQW) laser (Govind and Dutta, 1993). The structure is optimized by choosing the proper dimension of the active layer quantum well and the number of wells. Usually, single quantum well lasers pose a problem of poor optical confinement due to size. For a large number of wells, confinement will greatly increase. An optimized multi-QWL with four 120 Å wells and 280 μm lengths is reported to have threshold current density, J_{th} of 250 A/cm^2. The value of J_{th} of a single QW laser is also reduced to 160 A/cm^2 by using a 1125 μm long cavity. The lowering of threshold current due to quantum size effects is largely offset by the small width of the gain region in a SQW laser which causes the optical confinement to be poor. The problem can be solved by using separate confinement heterostructure (SCH) to enhance the optical confinement factor. In particular, graded refractive index-separate confinement hererostructure (GRIN-SCH) structures have resulted in the lowest threshold current densities. The GRIN-SCH not only improves the optical confinement efficiency but also improves the carrier collecting efficiency. Greater optical confinement is realized by using the GRIN-SCH structures (Nag, 2002). Fuji *et al.* (1984) reported a very low threshold current density as low as 175 A/cm^2 with 480μm cavity length in a GaAs/AlGaAs GRIN-SCH SQW laser.

Most common QWL are fabricated from GaAs/AlGaAs and InGaAsP/InP structures. AlGaAs QWL exhibit lower threshold current and higher differential quantum efficiency as compared to regular DHS laser (Kirti *et al.*, 2010). InGaAsP QWL is based on MQW and a 1.5 μm QWL. Using this material it has J_{th} of 170 A/cm^2 at threshold temperature of 45 K (Nag, 2002).

Similarly, MQW lasers have been reported in GaInN/GaN and operate at 450 nm with a J_{th} of 1.4 KA/cm^2 and a threshold voltage 25 V (Kirti *et al*, 2010). There is a considerable amount of research which effectively deals with the strain on the band structure. The deformation potential calculation has shown that there is dramatic change of the optical properties. These changes may be used in designing better lasers. For example, InGaAs based strain QWL; the wells consist of compressively strained $In_xGa_{1-x}As$. The barriers are usually GaAs or $In_xGa_{1-x}As$. Depending on the value of x, the well region can be under compressive or tensile strain. Semiconductor diode lasers have become the most widely available and important lasers in our daily life (Kirti *et al*, 2010).

3. Quantum Well Detectors

An avalanche photodiode (APD) is used to detect optical signal from the visible to the far-infrared of the optical spectrum. This device is grown by epitaxial techniques MBE or MOCVD. It operates on the basis of a reverse biased P-N junction with a relatively large voltage kept substantially below the avalanche breakdown voltage (Bhattacharya, 2002). The large reverse bias voltage lowers the carrier transit time through the depletion region of the semiconductor as well as its capacitance. The APD is a homogeneous slab of semiconductor material with separate absorbing and multiplication regions. A suitable bias voltage is applied across the contact to collect the electron-hole pair that is generated.

When light is incident on the semiconductor material with sufficient energy, photons are absorbed and electron-hole pair are created. The electron-hole pair produced within the diffusion length of the depletion region is accelerated to the multiplication region by the bias. In the presence of the field the electron and hole will acquire enough energy and ionizing collision with the lattice can occur (Bhattacharya, 2002). A necessary field to produce an ionizing collision is about (10^4-10^5) V/cm depending on the type of material. The charge carriers created will accelerate into the multiplication region where each electron or hole will produce additional electron-hole pair as a result of collision. This will continue as each carrier produced will accelerate in opposite direction under the influence of the field, suffering more ionizing collision and creating more electron-hole pairs. The process continue to repeat and the photocurrent will increase and the photodiode finally breakdown at a particular breakdown voltage. This voltage can be calculated using Poison's equation and expressed as (Bhattacharya, 2002)

$$V = \frac{\varepsilon_r \varepsilon_0 E_M^2}{2qN_D} \qquad (2)$$

where E_m is the maximum field, q is the electronic charge, N_D is the donor doping density on the n-side, while ε_r and ε_0 are the relative permittivity of the doping material and permittivity of free space respectively. Breakdown occurs when every carrier has one ionizing collision. Therefore, breakdown and avalanching process depends on the carrier population and collision rate in the depletion region and not on the carrier type that initiates the avalanche process. This is called impact ionization which leads to carrier multiplication and gain. The multiplication factor or avalanche gain is dependent on the impact ionization coefficient ratio α_e/α_h of electrons to holes. This impact ionization coefficients α_e and α_h define the number of ionizing collision per unit length. Very large values of the gain are obtained in APD biased near the breakdown voltage. Depending on the semiconductor material available and device design, very large avalanche gain of over 200 or more is obtained. APD have been produced in many semiconductors including Ge, Si, III-V compounds and their alloys (Tyagi, 1991).

A lot of improved new APD structures have been made of recent with improved performance characteristics by simply artificially increasing the ratio of the ionization coefficient of electrons to holes (α_e/α_h). In this structure, the absorption and multiplication regions of APD is replaced with either multi-quantum well (MQW) or superlattice structure having varying sizes of wells and barriers. The multilayered superlattice structure is incorporated in the multiplication region of the semiconductor materials, see figure 2. The electron acquires more energy than holes as they drop into GaAs well because of the large band gap discontinuity in CB edge than VB edge. The superlattice (SL) is composed of AlGaAs thin layer.

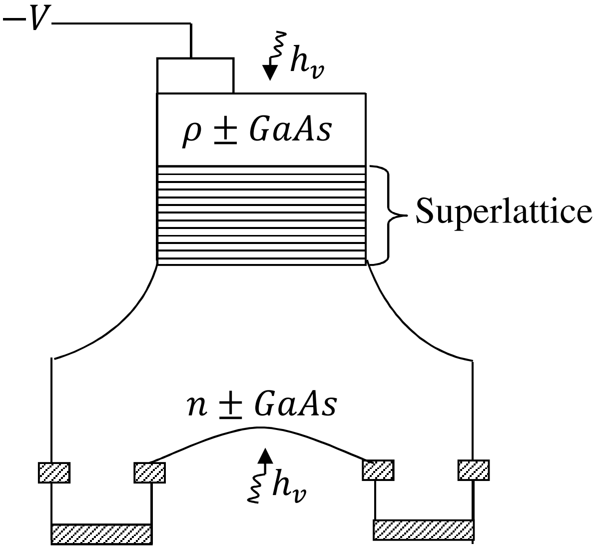

Fig. 2: Superlattice APD (Sze, 1990).

This will act as the avalanche region, the staircase superlattice structure. The purpose of the multilayered structure is to increase the ratio α_e/α_h, the ionization coefficient of electron to holes (Sze, 1990). Once the avalanche process is initiated by a carrier (electron) as it accelerates under the influence of the field and bias, it will gain energy at each step of the staircase structure, enhancing more ionizing collision and creating more electron-hole pairs. The process will yield a large multiplication of the number of electrons meanwhile the number of holes has not encountered such a large potential step and their multiplication remain constant. Consequently, the ratio α_e/α_h is enhanced. The process of preferential multiplication of one type of charge carrier particularly electrons is of interest since more frequent ionizing collisions occur with electrons than holes. In the case of QW structures, where well and barrier sizes become smaller (i.e. about 100 Å or less) enhancement in the multiplication factor and in the value of α_e/α_h is still obtained. Furthermore, the difference between the conduction and valence band discontinuities enhances the electron ionization rate relative to that of holes (Sze, 1990). Superlattice APD has large avalanche gain and reduces noise, thus very useful in device application. Superlattice structure of InGaAs is used for APD. This structure improves the speed and sensitivity of InGaAs APD.

However, there are detectors (Nag, 2002) that are using light absorption phenomenon in QW. These detectors are posing a strong challenging alternative to superlattice APD for some of the applications. This photodetector depend on electron transition between subband energy levels in a QW. Since the energy difference between subband levels is small, of the order of 100 meV, such devices are used for far-infrared detection. Quantum well infrared photodetector (QWIP) is using this principle and design such that the energy separation between the ground state and the second quantized level of the well is equal to the photon energy of the infrared radiation. The width of the well and the composition of the barrier materials are so chosen for a QW intersubband detectors that the well have two energy levels separated by the energy of a photon to be detected. The incident radiation excites an electron from the lower ground state to the upper level and the electron so excited are transported out of the well freely or by tunneling due to the applied field to produce current. A number of structures have been realized with these phenomena such as intersubband absorption in $GaAs/Ga_xAl_{1-x}As$, $InGaAs/Al_xGa_{1-x}As$ and Si_xGe_{1-x}/Si MQW systems, interband absorption in $InAs/Ga_{1-x}In_xSb$ and HgTe/CdTe superlattice (Nag, 2002).

4. Quantum Well Modulators

Quantum well modulators (Nag, 2002) are realized using the field dependence of excitonic absorption in QWs. An exciton is a hydrogen-like bound state of electron-hole pair in semiconductor materials (Manijeh, 1995). It is being considered as an individual entity or pseudo particle. Its energy spectrum consists of a discrete set of energies given by

$$E_n = E_g - \frac{R_y^*}{n^2} \qquad (3)$$

where n is the order of the exciton (n = 1, 2, 3…), E_g is the energy gap, R_y^* is the exciton Rydberg energy of the material. The absorption occurs at energies below the fundamental band gap.

In bulk semiconductor material excitons will appear as a series of sharp peaks at the low energy side of the band edge in the absorption spectra of direct band gap semiconductor (Bhattacharya, 2002). It is however, formed in indirect band gap semiconductor with the absorption or emission of a phonon.

However, in bulk materials and in the presence of an applied electric field, excitons will drastically alter its absorption features. The bound electron and hole exist in a coulombic potential that is tilted by the field. Recall that the transition rate of an electron from an initial state in the valence band to a final state in the conduction band is determined by the overlap wave function. The eigen functions are shifted laterally by the electrostatics potential and Bloch waves are no longer described by the stationary states of the crystal. The tails of both wave functions now penetrate the previously forbidden region which allows partial overlap of electron and hole wave functions. This in turn allows absorption of photons with energy below the band gap as shown in Figure 3(a). Above the band gap oscillations are superimposed on the absorption due to the increasing lateral shift of the wave function when performing the overlap integrals for increasing energies.

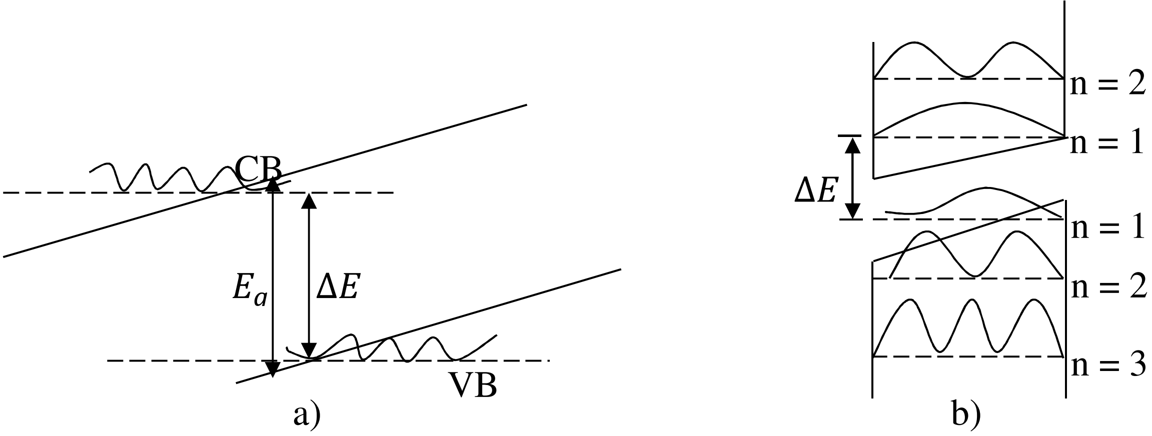

Fig 3 (a): Franz-Keldysh effect for bulk direct band gap semiconductor for absorption between eigenstates (b) The Quantum Confined Stark Effect (QCSE) showing the spatial separation of the electron and hole wave function (Mallins, 2007).

This has the effect of red-shifting the absorption band edge. The shift of the absorption edge in bulk semiconductors due to an electric field is known as Franz-Keldysh effect (Nag, 2000). Though this effect is used successfully in electro-optic waveguide modulators, yet it is not strong enough to be used for contrast modulator when light is applied perpendicular to the layers. As such, excitons in bulk material are weak. Similarly, excitonic effects are less significant in bulk semiconductors at room temperature due to ionization.

In a QW structure, carrier motion in the growth direction (z-direction) is restricted and free carrier motion is in the other direction. Due to the size of the well, the electron and hole produced when a photon is absorbed, coulombic interaction couples the electron-hole pair in the growth direction and in the perpendicular plane. The bound pair is referred as exciton and confinement of exciton will occur in the growth direction (Nag, 2002). The energy level is discrete and located below the conduction band edge. Inside the well, exciton is compressed since the well width (i.e about 100 Å) is generally smaller than the calculated diameter of the exciton (i.e. it is ≥ 300 Å). Thus, the exciton binding energy is greatly increased and the exciton is stable at room temperature unlike the bulk materials that are not. Consequently, the absorption spectra of QW shows exciton peaks at room temperature that occurs at energies below the step, such spectra have indeed been observed by many workers (Dingle *et al*, 1974 and 1975).

In a quantum well modulator, the electric field is applied perpendicular to the well layers (Meenakshi *et al*, 2010). Whilst the electron and hole of the exciton is pulled to opposite sides of the well this does not ionize the bound system due to confinement, though the coulombic attraction of the pair is reduced. The effect of the electric field will appear as a shift in the discrete energy levels of the excitons and also of free carriers and as a result, the excitonic peaks as well as the absorption edge shift to lower energies including heavy and light hole peaks. The electric field applied to the well increases, the absorption peaks shift toward lower energy. The contribution to the total reduction in the absorption edge energy is only an additional few meV, consequently excitonic peaks is red-shifted.

The shift in energy level due to an electric field is referred to as Quantum Confined Stark Effect (QCSE). This effect is a kind of electro-absorption which is change in the optical absorption when electric field is applied perpendicular to QW layers. The field at which significant electro-absorption is observed ranges from 10^4-10^5 V/cm. If the field is applied parallel to the QWs the excitons can readily be ionized by the field which gives rise to a broadening in the band edge much like in the bulk case.

QCSE based devices are faster, operate in excess of 40 Gb/s and modulate light strongly even with only 1µm of material (Meenakshi *et al*, 2010). Multiquantum well electro-absorption waveguide modulators operating near 1.5µm wavelength have been demonstrated using InGaAs/InP, InGaAs/InAlAs, InGaAsP/InP and GaSb/AlGaDb materials (Midwinter and Guo, 1992).

Self-Electro-optic Effect Devices (SEED) combines a photo-detector with one or more QW modulators possibly with some intervening circuitry, to give a device with optical inputs and output (Miller, 1990). Only a series resistor (R) and a constant voltage bias supply is added to the p-n diode to make the optically bistable device. To make the device switch, the incident light wavelength is chosen to be near the exciton resonance position for zero voltage across the diode. With low optical power, nearly all the supply voltage is dropped across the diode because there is little photocurrent. This voltage shifts the exciton absorption to longer wavelengths (lower energies) and the optical absorption is relatively low. Increasing the optical power increases the photocurrent, reducing the voltage across the diode. However, this reduced voltage gives increased absorption as the exciton resonances move back, resulting in further increased photocurrent and consequently leading under the right conditions to representative feedback and switching. It operates over a broad range of conditions readily compatible with semiconductor light sources; it shows inverting logic operations and smaller scaled devices offer the possibility of attractively low switching energies. They can combine in simple circuits to perform usable functions. To be most useful this device can be integrated into electronic systems. For example, field-effect transistor SEED (F-SEED) integrates field effect transistor (FETs) with quantum well modulator by making the FETs directly in the top layer of the modulator diode (Miller 1990). The same diode layers can also be used as photodetectors to give optical inputs as well.

Another useful device in quantum well is Quantum Well Charge-Coupled Devices (QWCCD) which are obtained from packets of electrons clocked through a quantum well channel with a series of charge controlling gates. These devices have one common feature, that is, the ability to move packets of electrons from one position to another in an epitaxial layer without losing any electron. QWCCDs are useful as images, for dynamic storage and as control elements

5. Conclusion

In this article, we have discussed the basic physical phenomena of quantum well and quantum well device engineering. Different examples of devices that utilized optical and transport properties of quantum wells have been explained. It is revealed that an optimized use of quantum well structures can lead to substantial improvement in most of the important properties of these devices. More importantly, the understanding of quantum well behaviour can lead to important information about the properties of electrons in crystalline semiconductor materials.

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