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THE QUANTUM-WELL STRUCTURES OF SELF ELECTRO-OPTIC-EFFECT DEVICES AND GALLIUM-ARSENIDE

Mustafa TEMİZ
Pamukkale Üniversitesi, Mühendislik Fakültesi, Elektrik ve Elektronik Mühendisliği Bölümü, Denizli

ABSTRACT

Multiple quantum-well (MQW) electroabsorptive self electro optic-effect devices (SEEDs) are being extensively studied for use in optical switching and computing. The self electro-optic-effect devices which has quantum-well structures is a new optoelectronic technology with capability to obtain both optical inputs and outputs for Gallium-Arsenide/Aluminum Gallium-Arsenide (GaAs/AlGaAs) electronic circuits. The optical inputs and outputs are based on quantum-well absorptive properties. These quantum-well structures consist of many thin layers of semiconductors materials of GaAs/AlGaAs which have emerged some important directions recently. The most important advance in the physics of these materials since the early days has been invention of the heterojunction structures which is based at present on GaAs technology. GaAs/AlGaAs structures present some important advantages to relevant band gap and index of refraction which allow to form the quantum-well structures and also to make semiconductor lasers, dedectors and waveguide optical switches.

Key Words : Gallium-Arsenide, Band gap, Index of refraction, Semiconductor laser, Semiconductor dedector

SELF ELEKTRO-OPTİK CİHAZLARIN KUANTUM ÇUKURLU YAPILARI VE GALYUM-ARSENİT

ÖZET

Çoklu kuantum çukurlu elektroapsorptiv self elektro-optik cihazlar optik anahtarlama ve hesaplamalarında kullanılması için yoğun bir şekilde araştırılmaktadır. Kuantum çukurlu yapılara sahip self elektro-optik cihazlar, galyum-arsenit/aliminyum galyum-arsenit elektronik devrelerine ait giriş ve çıkış işaretlerinin her ikisinin birden optik olarak elde edildiği yeni bir optoelektronik teknolojidir. Optik giriş ve çıkışlar kuantum çukurlu emme özelliklerine dayanır. Bu kuantum çukurlu yapılar, günümüzde yeni boyutlar meydana getirmekte olan GaAs/AlGaAs'li yarıiletken malzemelerle yapılan pek çok ince katmanlardan meydana gelir. İlk günlerden beri bu malzemelerin fiziğinde bulunan en önemli ilerleme şu anda GaAs teknolojisinin dayandığı farklı jonksiyonlu yapıların keşfidir. GaAs/AlGaAs'li yapılar kuantum çukurlu yapıları oluşturmak ve keza yarıiletken laser, dedektör ve optik dalga klavuzlarına ilişkin anahtarlar yapmak için yasak bant ve kırılma indisi ile ilgili bazı önemli avantajlar sunar.

Anahtar Kelimeler: Galyum-Arsenit, Yasak bant, Kırılma indisi, Yarıiletken laser, Yarıiletken dedektör

1. GİRİŞ

In telecommunications switching and computing the potential use of optics has generated as a very interesting topic recently. Self electro-optic-effect devices are logic elements that are optically contolled in the digital optoelectronic logic devices family. These devices are generally referred to as SEEDs and are hybrid in the sense that they are optically controlled and but involve electronic elements in addition to optical ones.

This device is based changes in the optical absorption that can be induced by changes in an electric field perpendicular the thin semiconductor layers in quantum-well material which is usually made in GaAs/AlGaAs. This effect that provides remarkably fast and large optical modulation due to the electric field-induced shift of the sharp exciton absorption peak that is called the quantum confined Stark effect (QCSE) shifts the absorption edge of MQW to longer wavelength under applied field (Miller, 1984). When a voltage is applied across the layers, the optical transmission of the quantum wells occurs strongly, giving an optical modulator.

The schematic diagram of a SEED is shown in Figure 1. The component K may consists of a resistor, photodiode (D-SEED) , phototransistor (T-SEED), multiple quantum well (S-SEED) or a field-effect transistor (F-SEED). Light from the signal source can be used to control the pump transmission or simply to acts as a current source driving the modulator. The n-i-p device is multiple quantum-well (MQW) electro-absorption modulator.

In a given the S-SEED (Lentine, 1988), as an example for the n-i-p device, the material was grown by Molacular Beam Epitaxy (MBE) on a Si-doped n-type GaAs substrate. These devices all in general biased but only receive and transmit information through optical signals incident on or more of components making up the complete device (Temiz, 1995).

Individual layers may be typically 10 nm thick, with about 100 layers altogether in the device (for a total thickness of 1μm). For example, the Al mole fraction in $Al_xGa_{1-x}As$ may be 0.4 and epitaxial layer thicknesses and dopings n-GaAs (0.17μm, n= 10^{18} cm^{-3}; i-AlGaAs (1.92μm); p-superlattice SL(Baba, 1993) (250 periods of alternative 25 A^o AlGaAs and 21 A^o GaAs , p= 10^{18} cm^{-3} ; i-multiple quantum wells (MQW) (63 periods of alternative 80 A^o AlGaAs and 105 A^o GaAs layers); n-AlGaAs (0.64 μm, n= 10^{18} cm^{-3}) and n-GaAs (0.105 μm, n= 10^{18} cm^{-3}).

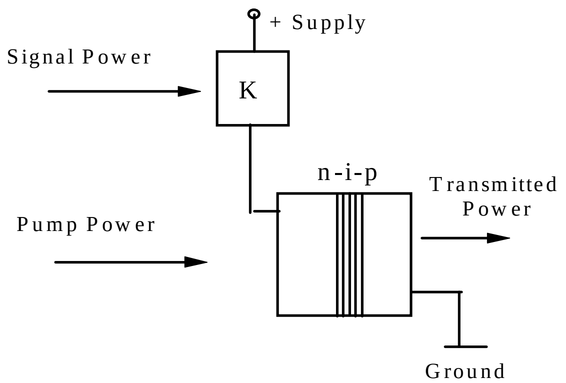


Figure 1 Schematic diagram of a SEED. The n-i-p device is MQW consists of $GaAs/Al_xGa_{1-x}As$ materials

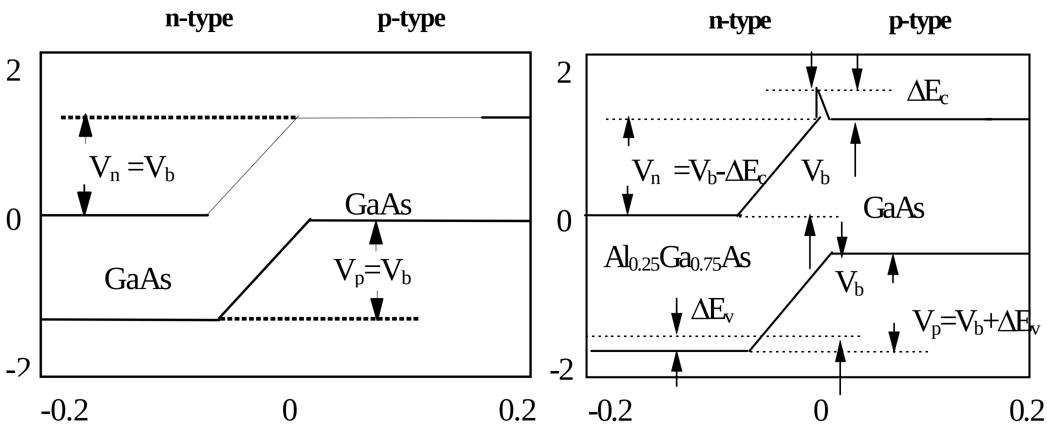
Here one studies the properties of the multiple quantum well which is an important part of the SEEDs.

2. BAND GAP AND INDEX OF REFRACTION ON HETEROSTRUCTURE FORMS

The fundamental role of the wide band gap can be understood with reference to Figure 2. Here it is compared the band diagrams for GaAs homojunction and n-$Al_{0.25}Ga_{0.75}As$ /p-GaAs heterojunction. In a conventional GaAs homojunction the potential barrier heights for electrons and holes are both equal to the junction built-in potential, V_b, because of the electrostatic potential variation due to the ionised donors and acceptors in the space-charge region of the junction contributes to the barrier height. In the n-$Al_{0.25}Ga_{0.75}As$/p-GaAs heterojunction, the variation in the band gap between homojunction and heterojunction layers makes an additional contribution to the total barrier height such that the barrier height for holes in the valance band exceeds that for electrons in the conduction band by $\Delta E_c+\Delta E_v=\Delta E_g$. The difference in the band gap between homojunction and heterojunction layers, ΔE_g, is distributed between the conduction and valance bands as ΔE_c and ΔE_v , respectively. It is seen the effect of the spike on heterojunction structure, here. But, by gradually increasing the AlAs mole fraction in the structure from x=0 at the p-n interface to x=0.25 over a sufficiently large distance (Grinberg, 1984; Chand, 1985). It is possible to complete eliminate any spike so that the bandedge varies monotonically, (Figure 2a).

Heterostructures are usually formed to MQW structures and also, by the MQW, the active portion of the semiconductor laser (Knop, 1994), waveguide optical switches (Kazuhiko, 1992; Shinji, 1992) and dedectors (Liu, 1991).

These are junctions between two dissimilar materials such as GaAs and Al_x Ga_{1-x} As with x, for example as mentioned above x=0.25, being the fraction of gallium being replaced by aluminum (Figure 2(b)). GaAs and AlAs semiconductors have almost idantical lattice constants (Lattices are for GaAs 5.6533 A^o and AlAs 5.6605 A^o). So, they can be mixed and can be grown on top of each other with little strain involved and a very small density of traps at the interfaces. This metallurgical fact is critical to the success of making the junction.



(a) (b)

Figure 2 (a) Energy-band diagram for a GaAs n-p homojunction. (b) Energy-band diagram for an n-$Al_{0.25}Ga_{0.75}As$ /p-GaAs) heterojunction

Today, with MBE, it is possible to deposit perfect crystalline layers of the selected materials and to vary the composition of these layers to be stacked with outomatically perfect interfaces, giving superlattices of GaAs and Al_x Ga_{1-x} As on another substrate (Baba, 1993).

On this heterostructure as the persentage of aluminum is increased, the band gap increases and the index of refraction goes down. This fact is only God’s gifts to the optoelectronic world, especially the semiconductor laser field, for it greatly alleviates two problems. These problems are unpleasant fact that the central part of the wave may be amplified with tails and a small bit of wave guiding due to the slight decrease of refractive index on the n side (due to free electrons) and on the p side due to the small change in the band gap with acceptor doping on the homojunction structures. Figure 3 and Figure 4 illustrate the dependence of the band gap and the index of refraction on mole fraction of Al substituted for gallium respectively (Casey, 1978).

Figure 5 illustrates the heterostructure (a semiconductor laser) using a double heterostructure geometry and is shown biased in the forward direction. Figure 6 also is the variation of its refraction index. Here it is note that the variation of the index of refraction varies sharply.

It is clear that as the percentage of aluminum is increased, the band gap increases and the index of refraction goes down. The results are very important to perform multiple quantum-well structures, to guide the field in semiconductor laser and also light beam in fiber glass, respectively. A simplified rib waveguide is, (i.e), shown schematically in Figure 7.

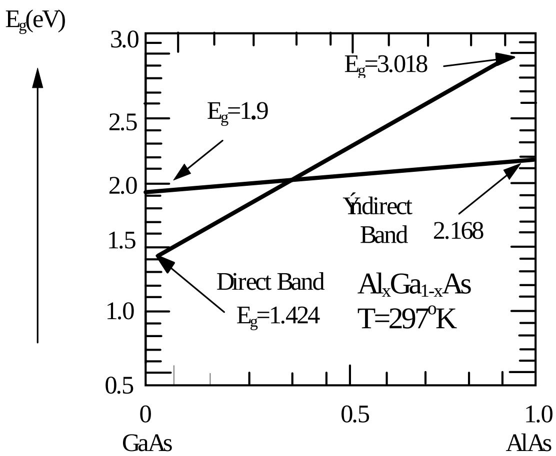


Figure 3 Mole fraction AlAs, x . Dependence of band gap

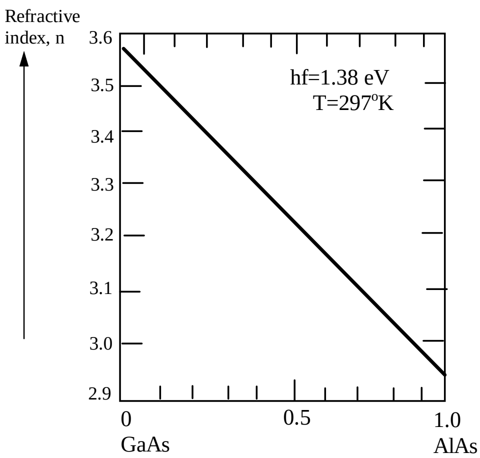


Figure 4 Mole fraction AlAs, x. dependence of index of refraction of $Al_xGa_{1-x}As$ on the amount of aluminum

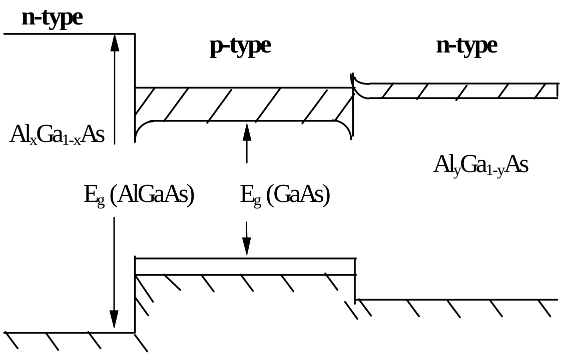


Figure 5 The band diagram for a forward-biased heterostructure

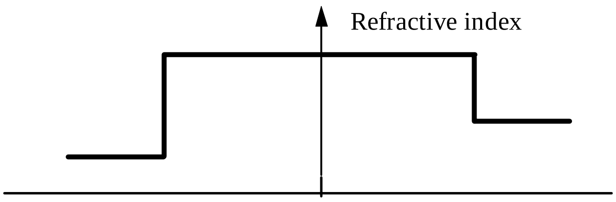


Figure 6 The refractive index of in Figure 5

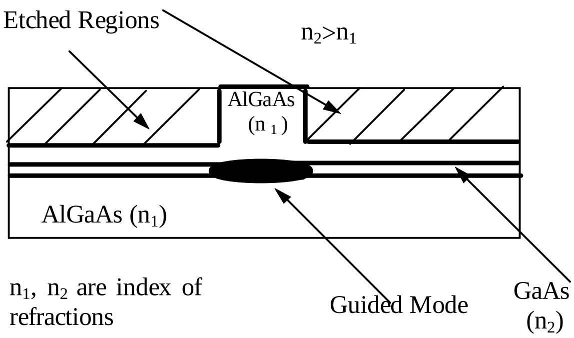


Figure 7 Schematic of the rib waveguide structure. The GaAs active region is sandwiched by AlGaAs cladding layers.

3. BAND STRUCTURE OF QUANTUM WELLS

An electronic carrier in a semiconductor heterostructure layer of dimension L_x , L_y and L_z can be considered to be a particle confined to a three-dimensional infinite potential well. The energy eigenstates for such a carrier are

$$E = \frac{h}{8\pi^2 m}(k_x^{\ 2} + k_y^{\ 2} + k_z^{\ 2})$$

where $k_i = n\pi/L_i$ are the wave vector components, i=x, y, z; n=1, 2, 3..., and h is Planck constant.

If one takes $L_z \ll L_y$, L_z for the case of very thin, planar film, and $L_z=\lambda$ where λ is the Broglie Wavelength as

$$\lambda = \frac{h}{\sqrt{2Em^*}}$$

and m* is the effective carrier mass, then particle motion in the z-direction is quantized. This gives rise to a discrete term in the energy of particle.

$$E = E_n + \frac{h}{8\pi^2 m^*}(k_x^{\ 2} + k_y^{\ 2})$$

$$E_n = \frac{h}{8\pi^2 m^*}\left\{\frac{n\pi}{L_z}\right\}^2$$

This modification of the energy eigenstates dramatically changes the properties of the layer and is the origin of the quantum size effects (QSE).

The density of states in energy interval dE is

$$\rho(E)dE = \frac{1}{2\pi^2}\left\{\frac{2m^*}{\hbar^2}\right\}\left(\frac{\pi}{L_z}\right)dE , \qquad E>E_1$$

$$E \rangle E_1 = \frac{\left[\hbar(\pi / L_z)\right]^2}{2m^*}$$

which is a constant independent of energy provided E is larger than the first allowed state E_1 . Whereas in both conduction and valance band the density of states was

$$\rho(E)dE = \frac{1}{2\pi^2}\left\{\frac{2m^*}{\hbar^2}\right\}^{3/2} E^{1/2} dE$$

which is dependent of energy. Here E is measured from the band edge (Figure 8).

By choosing the dimension L_z, one can design the energy state and thus engineer the band gap. This requires repeating the prior development with idantical results except that it defines another

$$E = E_2 = \frac{\left[\hbar(2\pi / L_z)\right]^2}{2m^*}$$

subband that starts and proceeds upward at a constant value. By restricting the number of states as a function of energy until E> E_1 , a larger number of electrons can have a same energy within the band

and thus these inverted electrons can be stimulated much more effectively by an electromagnetic wave for semiconductor laser. In Figure 8 it is emphasised that for the first allowed band the (n=1) wave is just that of a simple standing wave, going to zero at the boundaries and for n=2 and the second mode, the wave function is antisymmetric and corresponds to fitting a full wavelength of electron wave function between the boundaries (Verdeyen, 1989).

QSE modifies the band structure of carriers in the GaAs well from its bulk nature. A series of subbands are formed for both electrons and holes, (Figure 9).

The density of states diagram for electrons (E_n) and holes (E_h) in a GaA/AlGaAs quantum well is shown in Figure 10 where the parabolic lines originating at the conduction band edge E_c and valance band edge E_v indicate the density of states for a bulk Crystal.

The carriers have different effects on the conduction and valance bands. Since it has both light and heavy holes the positions of the subbands are different. The transitions can occur between an electron state in the conduction band to either a light hole (lh) or a heavy hole (hh) state in a valance band.

The beginning and terminating layers affect the wave function of electrons in the confining structure somewhat. These confining layers create a potential barrier to the wave function of the electron (or hole) trapped in the GaAs well.

For multiple quantum-well structure Figure 11 (Coleman, 1987) is one example of what has been done and points out the combination is an artificial with applications limited only by the imagination.

An example of the use of aluminium concentration effects (Baba, 1993 Coleman, 1987) in a junction laser made in GaAs/AlGaAs for use (Figure 12).

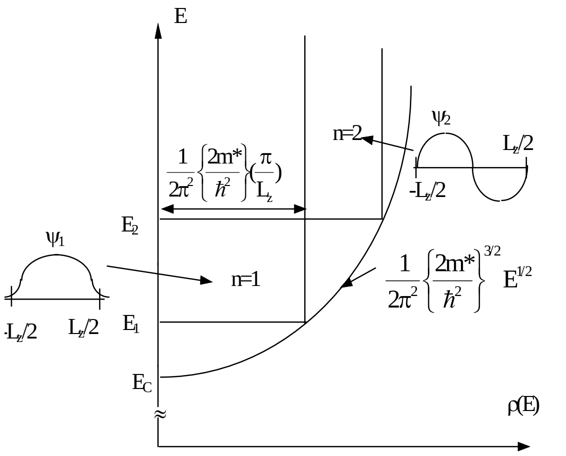


Figure 8 Density of states in a quantum well of thickness L_z

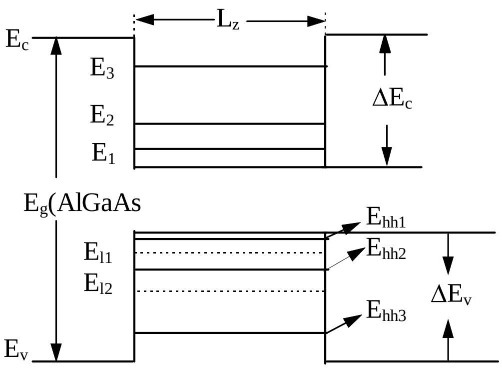


Figure 9 Energy-band structure for a GaAs/AlGaAs heterostructure single quantum well

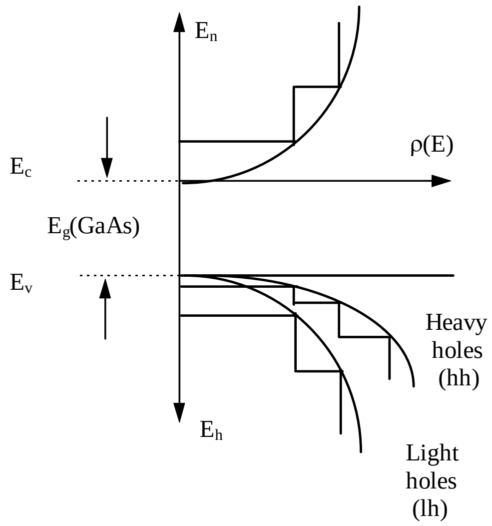


Figure 10 Energy-band structure of GaAs/AlGaAs quantum well

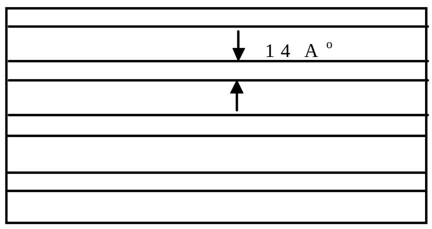
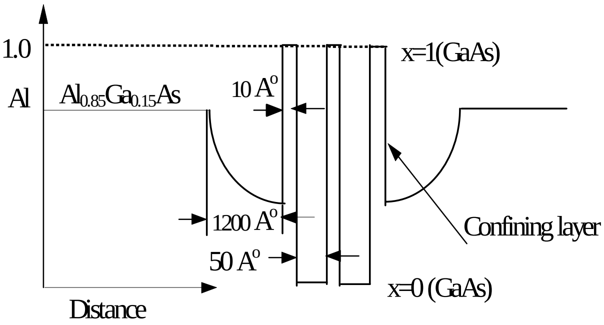
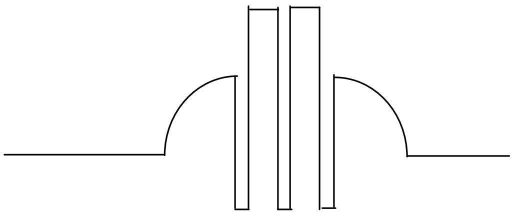


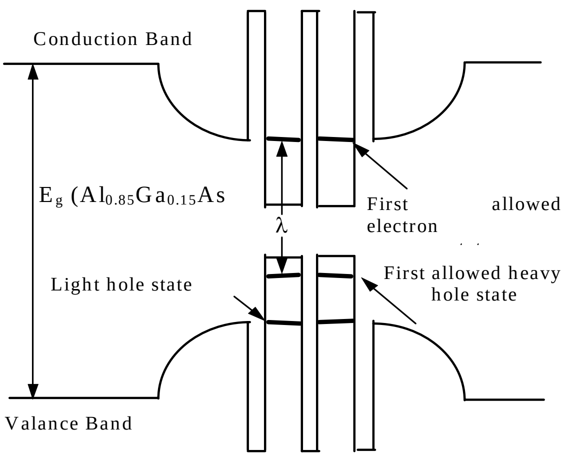
Figure 11 A Multiple quantum-well structure. This is a transmission electron microscope (TEM) display owing alternating layers of GaAs/AlGaAs materials The aluminum concetration is slowly graded over much larger distances to aid in the trapping of injected carriers in the central region where the recombination takes place by transition between allowed states in quantum wells formed by sandwiching thin layers of GaAs between thinner layers of AlAs.



(a) Aluminium concentration at the junction

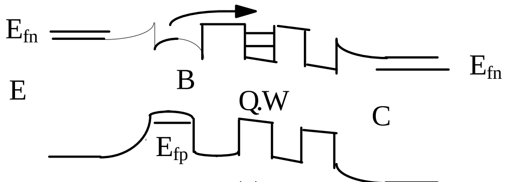


(b) Variation of the Index of Refraction

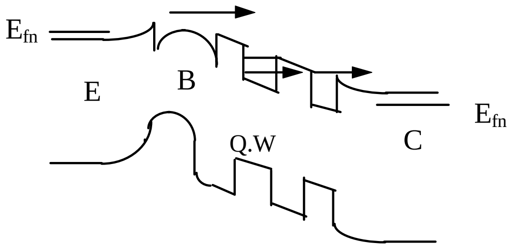


(c) Band diagram

Figure 12 (a) Aluminium concentration as a function of depth in the junction, (b) and (c) the effect of aluminium concentration on the index of refraction and the band gap



(a)



(b)

Figure 13 The Energy-band diagrams of the transistor at (a) High-voltage low-current OFF state, (b) Low-voltage high-current ON state

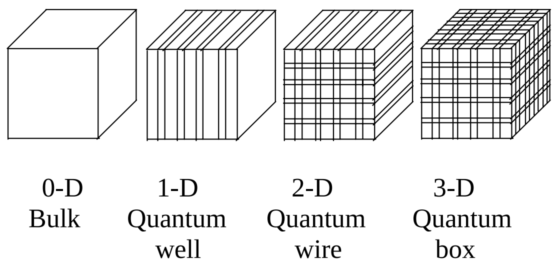


Figure 14 The material structure for bulk, quantum well, quantum wire, quantum box layers

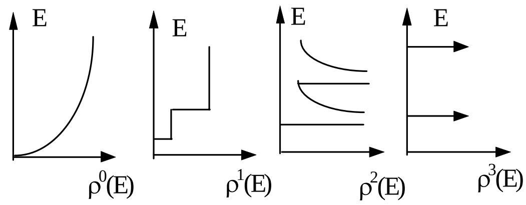


Figure 15 Density of state $\rho^i(E)$, for electrons with i-dimensional confinement

4. HIGHER DIMENSIONAL CONFINEMENT

In a quantum well the possibility of confining carrier motion in a more than one dimension gives even better (laser) performance. Confinement in 2 or 3 dimensions forms in a quantum wires and quantum box, and their density of states, respectively in Figure 14, and Figure 15.

Figure 13 Shows the energy-band diagram of quantum- well heterojunction bipolar transistor at low bias voltage (Tseng, 1991).

Laser with high dimensional confinement have been shown. Predictions of performance of quantum box lasers are noted here. For cube-shaped GaAs/$Al_{0.2}Ga_{0.8}As$ quantum boxes 100 A° on a side, Asade (Asade, 1986) calculate a threshold current density of 45 A/cm^2 and gain ten times higher than the bulk. To day the patterning layers is dominated by the move towards finer dimensions so that all three dimensions are under the control of the process engineer with an unprecedented degree of resolution.

5. INTRINSIC MULTIPLE QUANTUM WELL

Typical structure of a MQW transmission modulator (Temiz, 1995) is shown in Figure 16. The MQW consists of a large number (typically about 50) of layers of GaAs and AlGaAs grown epitaxially by MBE or Metallo-Organic Chemical Vapour Deposition (MOCVD). Reverse biasing the p-i-n structure provides a high electric field across the well for modulation. The GaAs substrate has to be removed in the case of the transmission modulator because it is absorbing at the operating wavelength.

We would prefer for the carriers to be generated where field is large, so that the charge transport, such as velocity, is due to the fast drift rather than the slow diffusion in conventional p-n junction. This accomplished by adding an intrinsic region between p and n layers. As shown in Figure 16, thus, the quantum wells are located in the intrinsic region of a p-i-n structure so a large electric field can be applied using a low voltage reverse bias. The absorption edge of gallium-arsenide quantum wells is dominated by a sharp excitonic absoption which gives a significantly larger absorption change than

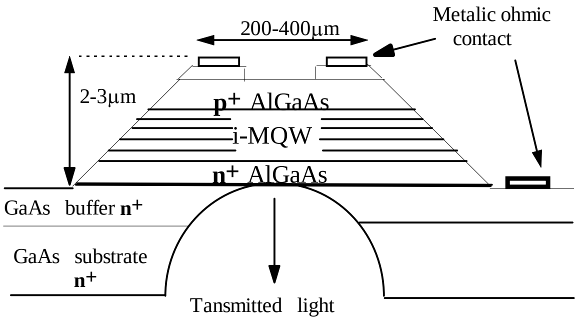


Figure 16 Typical structure of a MQW transmission modulator

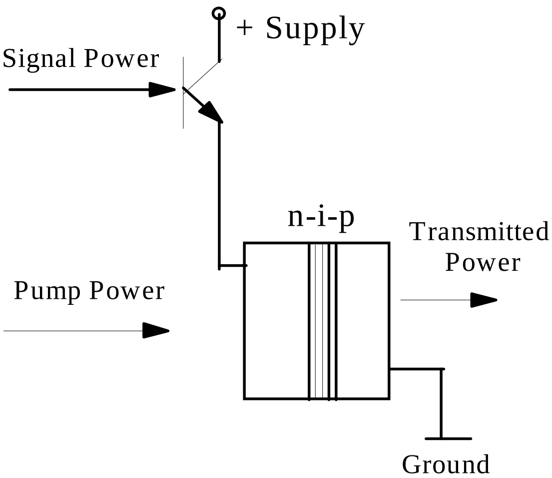


Figure 17 The T-SEED

could be achieved in bulk material. Both the mechanism responsible for the shift of the absorption edge and the presence of strong exciton absorption at room temperature are associated with the quantum confinement in the well (Miller, 1985).

It is clear that the narrower well sample show a clearer shift of the absorption edge but the wider well sample a similar transmission change at a lower operating voltage. Because the devices are a simple p-i-n structure they may be small in size and so it may operate at high frequencies.

6. TRANSISTOR SEEDs

Here one studies, as an example, the T-SEED (Wheatley, 1987) which is connected in series with the n-i-p as showing in Figure 17.

As a three port device with the optical beam incident on the phototransistor is used to control the tansmission through the modulator. The interaction between the current generated in the transistor and the current generated in the modulator is crucial in determining the characteristic of the T-SEED. When the optical power on the phototransistor is low so that the current results in biasing ratio such that the full voltage appears across the phototransistor, the modulator is in its maximum transmission state.

The optical power on the phototransistor results in a photocurrent which varies linearly with the optical power incident and results in a corresponding linear change in the intensity of light transmitted through the modulator. In this case the bias across the modulator varies with the current on the phototransistor resulting in the change in transmission observed.

The optical power on the phototransistor is such that at peak quantum efficiency the transistor would generate too much current for the modulator to match. Consequently, the balance of voltage bias is set so that the full voltage appears across the modulator. The output is changed to a low transmission because of the modulator switches to an absorption state due to QCSE (Chikara, 1991).

7. RESULTS

SEED is a new technology which has capability to obtain both optical inputs and outputs for GaAs - based devices, but it does offer the hope of large-scale connectivity. Its potential strengths possess the ability to obtain lower signal energy and power dissipation for a chip per connection, lower crosstalk between connections, lower interconnection skew, higher connection density, and huge parallelism. Therefore, it is especially emphasized the basic conceptions of MQW structures which is one of main elements of the SEED.

Also, for i=1,2,3, the step-like behaviour of the the i-dimensionally confined density of states greatly improves the characteristics of quantum well lasers and related to another devices. Since the carriers are distributed over a smaller range of energy states, quantum well lasers require less pumping to achieve population inversion (Bernard, 1961) and exhibit grater gain. However, such as the confinement in 2 and 3 dimensions in quantum wires and quantum boxes, possibility of confining carrier motion than one dimension offers even better laser performance than that in quantum wells.

Thus, not only does MQW structures offer the SEED-based devices, but it gives to form the semiconductor laser by guiding the field and to get enhancement of the laser gain in addition to form dedectors and waveguide optical switches. So, multiple quantum wells are very attractive for constructing all-optical signal processing and computing circuits.

8. REFERENCES

Asade, M., Miyamoto Y., Suematsu Y., 1961. Gain and the Threshold of Three-Dimensional Quantum-Box Lasers, IEEE, J. Quantum Electron. QE-22, 1915-1986..

Baba A.N., 1993. Annealing-induced Dislocation Loops in Si-doped GaAs-AlAs Superlattices, Journal of Materials in Electronics 4, 29-37.

Bernard, M.G., Duraffourg, G., 1961. Laser Conditions in the Semiconductors, Phys. Status Solidi 1, 699.

Casey, H.C., Panish, M. P., 1978. Heterostructure Lasers, Academic Press, Inc., New York.

Chand, N., et al., 1985. IEEE Trans. Electronic Devices ED-32, 1061.

Chikara, A., Matsuo, S., Kurokawa T. 1991. Novel Photonic Switch Arrays Consisting of Vertically Integrated Multiple-Quantum-Well Reflection Modulators and Phototransistors: Exciton Absorptive Reflection Switch, IEEE Photonics Technology Letters, 3 (8).

Coleman, J.J., Emanuel, M.A., 1987. Optimization and Characterisation of Index-guided Visible AlGaAs/GaAs Graded Barrier Quantum Well Laser Diodes, IEEE J. Quant Electronic. QE-21,QE-23, (6).

Grinberg, A. A., et al., 1984 . IEEE Trans. Electronic Devices ED-31, 1061, 1758.

Kazuhiko, A., et al., 1992. Low-Drive Voltage Intersectional Waveguide Optical Switch Using GaInAs/InP MQW Structure, IEEE Photonics Technology Letters, 4 (4).

Knop, W., et al., 1994. Compound Cavity Gain Tandem-Electrode Multiple Quantum-Well AlGaAs Laser Diodes, IEEE Photonics Technology Letters, 6(3).

Lentine, A.L. and Hinton, H.S. 1988. Symmetric Self-Electro-Optic Effect Device: Optical Set-Reset Latch, Appl. Phys. Lett. 52 (17).

Liu, Y., Forrest, G.L., Tangonan, R.A., Jullens, R.Y., Loo, V.L., Jones, D., Persechini, D., Pikulski, J.L., Johnson, M.M., 1992. Very-High-Band $In_{0.53}Ga_{0.47}As$ p-i-n Dedectors Arrays, IEEE Photonics Technology Letters, 3 (10).

Miller, D.A.B., et al., 1984. Phys. Rev. Lett. 53, 2173.

Miller, D.A.B. et al., 1985. Electric Field of Absorption Near the Band Gap of Quantum Well Structures, Phys. Rev. B 32, 1043.

Shinji, M., Kurokawa, T., Tsuda, H., Amono, C., 1992. All-Optical Bit-Pattern Matching with Photonic Switching Arrays, IEEE Photonics Technology Letters, 4 (3).

Temiz, M., 1995. GaAs Teknolojisi, Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi, 1(2-3).

Temiz, M. ve Sayın A.R., 1993. Geleceğin Yarıiletkeni GaAs, 5. Denizli Malzeme Sempozyumu, Bildiriler, 286, 7-8-9 Nisan 1993, Denizli.

Tseng, H.C., Sheng, S. L., 1991. Regenerative Switching Characteristics of a Novel Electrical or Optical Base-Controlled AlGaAs/GaAs Quantum-Well Heterojunction Bipolar Transistor, IEEE Electron Device Letters, 12 (10).

Verdeyen, J.T., 1989. Laser Electronics, 622p, Prentice Hall, Englewood Cliffs, New Jersey.

Wheatley, P.J., Bradley, M., Whitehead, G., Parry. J.E., Midwinter, P., Mistry, M. P., Robert, S., 1987. Novel Nonresonant Optoelectronic Logic Device, Elect. Lett.,23 (92).