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Optimization of Growth Process and Structural Characterization of Nanoscale Compound Semiconductor Heterostructures

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***Abstract*— *This study focuses on optimizing the process sequence for fabricating a double quantum well structure composed of the compound materials AlAsSb/InGaAs/GaAsSb. The selection of optimized sequence parameters is guided by an extensive literature review on material properties, nanoscale engineering considerations, and molecular beam epitaxy (MBE) growth conditions. A key advantage of using heterostructures is the precise control over the thickness of individual material layers, which is crucial for device fabrication. To ensure uniform epitaxial growth of the ternary compounds AlAsSb, InGaAs, and GaAsSb, a slow deposition rate of 0.5 micrometers per hour is maintained during the MBE process.*

Keywords*— *MBE, Quantum well, Heterostructure, Compound Semiconductor.

INTRODUCTION

Optoelectronic devices like light-emitting diodes (LEDs), laser diodes (LDs), Photodetectors (PDs) and optical waveguides are widely utilized in the field of optical fiber communication, medical science, automobile industries and spectroscopy for pollution monitoring and food control. This growth of the semiconductor optoelectronic components industry is mainly expected by the increased use of visible range and infrared components due to the long life, cheap and low power consumption demand. Nanoscale heterostructures, new materials and improved fabrication techniques have led to improvement in the performance of optoelectronic devices [1-4]. The heterostructure is the interface of two dissimilar materials with different bandgap energy. Nanoscale heterostructures involve quantum confinement so that it gives diverse electronic and optical properties which are useful for device development. The simulation work of the structure $AlAsSb/In_{0.59}Ga_{0.41}As/GaAs_{0.53}Sb_{0.47}$ is already simulated and discussed by the authors of this paper [5]. Heterostructure manufacturing generally requires the use of molecular beam epitaxy (MBE) and chemical vapor deposition (CVD) technology for the deposition of compound material layers. But at the nanoscale and for mass production, MBE provides more precise control over the thickness during the deposition process and creates a cleanly lattice match abrupt interface [6-9]. MBE is the process in which thin crystal layers are deposited on a substrate using an atomic or molecular beam in a high vacuum chamber. The major benefit of quantum well structure from the perspective of device fabrication is that we can regulate the thickness of the material layer during the film deposition. In this process optimization, the MBE process is proposed for the thin film deposition of nanoscale thickness because it precisely controls the thickness due to low deposition rate.

Structural Information and Process Sequence Optimization:

A schematic cross-section of the structure is shown in fig 1, where an AlAsSb (10 nm thick) confinement layer is proposed to grow on the GaAs substrate. Then P-doped InGaAs (mole fraction x=0.59) of 2 nm thick followed by the 4 nm GaAsSb (mole fraction x =0.53) material layer. After it again InGaAs and AsAsSb (10 nm) is proposed for deposition.

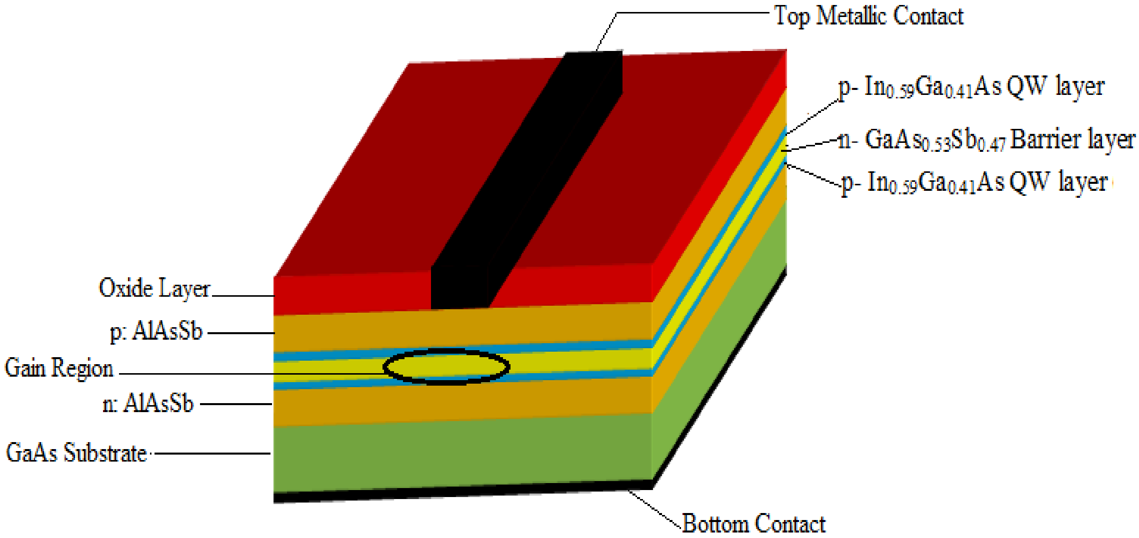

Fig.1. A schematic cross-section of the proposed structure for process sequence optimization

For epitaxial growth of these III-V compound semiconductor layers, GaAs substrate is usually utilized. So first we will take the standard p-type GaAs substrate and cleaned it with the standard process before going to molecular beam epitaxy. Pre-cleaning of the substrate is important because it removes the hydrocarbons, water molecules and other particles from a substrate. For effective results, the GaAs wafer cleaning includes the acid cleaning step in acetone solution for approximately 45 seconds, deionized water cleaning to remove the deposited cleaning solutions and a rotary drying process to dry the GaAs wafer. Rotary dryers work by tumbling material in a rotating drum in the presence of drying air. The substrate cleaning using these three steps provides the cleaned GaAs wafer without precipitate particles. After the substrate cleaning, the GaAs wafer is fixed on the MBE substrate heating holder for the epitaxial growth of the material layers. The optimized parameters of the sequences are selected based on the literature study of the materials properties, nanoscale engineering and MBE growth parameters [10-18].

Table 1: Quantum well structure with fabrication techniques

QW structure (Substrate- GaAs) with parameters	Design/ Fabrication technique	Emission wavelength (μm)
GaSb/AlGaSb	Molecular beam epitaxy (MBE)	1.65
GaInAs/GaAsSb	Metalorganic vapour-phase epitaxy (MOVPE)	1.2 - 1.47
GaInAs/GaAsSb	Metalorganic vapour-phase epitaxy (MOVPE)	1.2
GaAsSb/lnGaAs	Molecular beam epitaxy (MBE)	1.38, 1.43
GaAsSb/lnGaAs	Metalorganic chemical vapor deposition (MOCVD)	1.022, 1.075

For the deposition process, the materials (Al, Ga As, In, Sb and dopants) put in the MBE effusion cell. These cells provide highly efficient and controllable vapor deposition. The close-coupled thermocouple in the radiatively heated crucible ensures stability and reproducibility, not found in conventional evaporation sources. All the cells are heated using the heating coil and maintained temperature for vaporization. All the effusion cells have the shutter, so once the deposition is done for the required time, we close the shutter and no excess amount of material will be deposited that is why it is a very precise kind of method. For the designed heterostructure, Boron can be utilized for the p-type dopant and phosphor for the n-type dopant. The doping concentrations and the mole fractions are selected based on the atomic weight percentage and atomic mass of the materials. To find the mass percent of any element in the compound semiconductor, we divide the mass of the element in 1 mole of the compound by the compound's molar mass and multiply the result by 100. In general, the mole fraction and chemical composition can be determined using Augur spectroscopy. The substrate GaAs is fixed on the heating substrate holder and it is rotated, so that uniformity can be obtained in the deposition. The substrate temperature can be chosen at 200 °C. This high temperature of the substrate facilitates mobility and lesser defects. During the deposition process, we should be assured that atoms will not collide with any ambient atmosphere that is left in the chamber. For this purpose, the MBE base chamber pressure can be taken of the order of 10^{-9} Torr. The deposition pressure is of the order of 10^{-5} torr. This low pressure of the chamber is required so that the atoms can travel to the substrate without colliding with each other and a mean free path of around 10 meters with the ambient atmosphere. To attain this low pressure for the MBE chamber, we can use a rotary pump (up to 10^{-3} torr), diffusion pump (up to 10^{-6} torr) and turbomolecular pump (up to 10^{-9} torr). After making the high vacuum or low pressure inside the chamber the deposition process takes place. In order for uniform epitaxial growth of ternary material AlAsSb, InGaAs and GaAsSb, the deposition time is chosen very slow i.e. 0.5 micrometers per hour during the process in the MBE and layers are deposited as per the required thickness of the layer i.e. for the thickness of layer 10 nm the deposition time is taken 72 seconds for optimum growth. The deposition thickness can be determined by the use of a reflection high-energy electron diffraction (RHEED) gun, where the electrons are incident on the film, so we can control the thickness of the film more precisely. The top and bottom contacts for the characterization can be formed with the use of the thermal evaporation method.

CONCLUSION

In this research work, the process sequence optimization for the nanoscale heterostructures based on the ternary compounds is investigated for the NIR and visible range applications. The applications of the heterostructure depend on the emission wavelength. The choice of the materials and thickness of the material's layers are the critical parameters for the design of the heterostructures for an application. In the heterostructure, the thickness of the well layer or active layer is in our control. This is an important advantage of the heterostructures for device fabrication. So this research gives the choice of alternate materials for the development of optical sources for the NIR and visible range applications. The heterostructure designed in this work is of nanoscale and can be fabricated for device development. After the device fabrication, we can apply pn junction engineering to study the electro-photoluminescence (PL) spectra under the forward voltage, reverse voltage conditions and in open circuit conditions in order to know the internal quantum efficiency or emission property. It is expected that the heterostructures will give emission as proposed in the simulation work and these can be utilized for optoelectronic devices development.

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