CHAPTER I

INTRODUCTION

1.1 Background

The late years of the twentieth century, years of evolution of science and technology, was filled with new things in the view point of physics and device application technology. In this event, semiconductors played as the heart of the evolution, and silicon has still remained its champion [1]. In the past and during these days, silicon technology is very influential in electronic device industry and most of the electronic devices are based on silicon. At the same time, the material and device technology has attained an amazing degree of sophistication. However, silicon's indirect bandgap nature and the poor efficiency of producing light emission are a significant difficulty for making optoelectronic devices from this material [2]. Silicon photodetectors are available in the market but they still have some disadvantages to be used at the present fiber-optic communication wavelengths [3]. There are some tremendous efforts to achieve light emission from engineered silicon structures [4]; the effective achievement is still very far from the technological point of view. It seems that the silicon technology and nowadays optoelectronic and photonic technology are not significantly matched to each other. Therefore, searching for suitable materials for optoelectronic devices became crucial in the optoelectronic technology.

Some interesting materials have been proved to be good for photonic or optoelectronic devices. Among these, GaAs and other III-V compound semiconductors, such as InAs and InP, have gained considerable attentions from the researchers due to their efficient coherent light emission property [5]. Nowadays, GaAs technology has become in full bloom and produced quite a good number of optoelectronic and electronic devices. The most important area of applications of optoelectronic devices is in fiber-optic communications, in which 1.3 μm and 1.55 μm are the chosen wavelengths [6]. In view of this, the quaternary alloy $In_{1-x}Ga_xAs_yP_{1-y}$ lattice-matched to InP [7] is applicable for making lasers, while ternary InGaAs lattice-matched to InP is employed in photodetectors [8].

The new direction for semiconductor material science and technology started from the development of MBE and MOCVD techniques [9-10]. The more popular these fabrication techniques became, the less effort the scientists and engineers spent to search for novel and suitable materials. Instead of seeking new materials for new applications and for new wavelength ranges, now one tries to use various combinations of materials, control their composition and thickness, or synthesize new materials. The word "bandgap engineering" has become crucial, and almost all modern devices are the product of this technology. Both lattice-matched and lattice-mismatched pairs are now routinely grown, and thus it is difficult to say which material combination has which specific properties and is useful for which application. After that, scaling consideration became significant in the fabrication history. Reducing the device scale into a nanometer range results in a significant progress in the device applications. Semiconductor "nanostructures" have thus become crucial in nowadays technology.

1.2 Quantum Dots: the Artificial Atoms

In the last two decades, a new direction of modern research in physics and technology, broadly defined as "nanoscale science and technology", has been developed. Doing many research and studying new things in nanotechnology has revealed the new properties of matters, from bulk to the "quantum dot", together with the contemporary development of relevant device applications. The trend of reducing the size is typical of microelectronic industry, whose target is the fabrication of devices with fast working speed, low power consumption, and reduction of the occupied volume with high efficiency.

The fabrication, characterization and manipulation of nanometre-scale devices, so-called "quantum dot (QD) structures", is based on the three-dimensional quantum confinement of semiconductors with a lower energy bandgap E_g surrounded by higher-E_g materials [11]. A pronounced property of the QD is its formation of completely discrete quantum energy levels. The achievement of this structure is a clear example of the miniaturization approach in micro- and opto-electronics. The top-down fabrication method [12] and the bottom-up fabrication approach [13] lead to an achievement of very similar nano-objects whose optical and electronic properties are determined by the same quantum mechanical laws. Three-dimensional quantum confinement in semiconductors has been deeply investigated theoretically and experimentally [14]. Due to the discretized density of states of carriers inside quantum dots, these objects are expected to bring significant progress, especially in optical and electronic device applications. The first predictions in 1982 by Arakawa and Sakaki about their application as active materials for semiconductor optical lasers and amplifiers suggested the possibility to obtain very high-gain, high-frequency operating devices with peculiar temperature stability [15]. Since then, numerous attempts have been performed in order to obtain defect-free quantum dots, whose structural, electronic, and optical properties can be technologically controlled and with which devices can be fabricated reliably and reproducibly.

The top-down method is a direct extension of the already well-established quantum-well epitaxial growth technique to quantum-dot systems. QDs were generated by localizing nanometer-size regions of quantum wells either by depleting the charges into the surrounding regions with electrostatic fields or by physically removing the neighboring heterostructure with etching procedures. Although many of the predicted properties were experimentally verified, such quantum dots were not suitable for the fabrication of most optoelectronic devices due to the high density of surface states created during the lithography and etching steps [16]. A breakthrough in the field of epitaxially grown nanostructures [17] was a possibility to control the growth conditions under which defect-free islands were formed onto mismatched or strained-layers based on III–V compound semiconductors. The optical properties of "undesired" clusters of InAs located on GaAs layers showing an intense and sharp photoluminescence revealed their quantum-dot-like behavior, and at present these self-organized or self-assembled islands have become the material of choice for the realization of novel optoelectronic devices.

1.3 Ordered Quantum Dots

Ordered QDs are of considerable contemporary interest due to their potential electronic and optoelectronic device applications [18]. Vertically aligned QDs are almost perfect in the view point of fabrication technology [19-20] while lateral alignment of QDs during self-assembly process is much less pronounced. Since laterally ordered QDs have been investigated through several mechanisms by many research groups [20-22], some technical limitation due to complexity of multiple processes and crystallographic defects has caused this type of structures to have degraded optical quality, and thus there is a delay in getting the laterally aligned QDs with better optical quality. The important issue in ordered QD development is the design of the structure to produce more radiative photons even at room temperature, hence reducing the intensity loss due to non-radiative channels. The bottom-up or self-assembled approach is simple and defect-free to get good optical quality QDs. But in this method of growth on planar substrates, the QDs occur in the planar layers in a random manner. By modifying the standard growth technique, self-assembled laterally ordered QDs with high luminescence and narrow linewidth even at room temperature may be achieved. To obtain ordered quantum dots, two different methods are introduced in the fabrication technology: one is in which QDs are grown by varying growth parameters, and the other is in which QDs are grown on virtual substrates. Both of these techniques were used to grow the laterally aligned QDs investigated in this thesis work, and the detailed fabrication procedure will be discussed when relevant.

1.4 Ordered QDs for Quantum-Dot-Based Photonic Devices

Since the interest toward the three-dimensional quantum-confined semiconductor QDs was arisen from the need to improve the performance of semiconductor quantum-well lasers, most of the scientific and technological efforts in the past decades were addressed to the development of quantum-dot laser sources. In about ten years of research from the first demonstration of lasing at cryogenic temperatures, the quality of quantum-dot edge-emitting lasers has reached, and for several aspects overcome, quantum-well lasers, showing low thermal dependence of the threshold, high gain, high power emission, operation at room temperature with wavelength emission matching the critical telecommunication spectral windows around 1.3 μm and 1.55 μm [23-24]. Moreover, quantum-dot vertical cavity surface-emitting lasers (VCSELs) were also demonstrated at λ_{em} = 1.3 μm [25], owing to the possibility to grow fully epitaxial distributed Bragg reflectors exploiting alternate materials with high index contrast and low reticular mismatch (conditions not achievable with InP and InP compounds, the only materials used for emission in the second spectral window before the advent of QDs). The potential of GaAs-based quantum-dot lasers in replacing the more expensive InP-based quantum-well lasers is then clearly visible. Moreover, it is also worth mentioning different photonic devices such as surface-emitting quantum-dot inter-subband light sources and quantum-dot infrared (IR) photodetectors [26-27], which have been recently demonstrated. Although the benefits of self-assembled QDs have been demonstrated in many photonic device applications, their random sizes and distributions give some difficulties in making a better device with better performance. For many practical applications, nanometer-scale QDs should be formed with a uniform size, well-controlled position, and uniform distribution. Believed to be able to improve the performance of some photonic devices like quantum-dot lasers and quantum-dot infrared photodetectors, ordered, coupled quantum dots have nowadays become of contemporary interest. For example, employing ordered quantum dots in photonic crystals was expected to make fabrication of such light-emitting photonic devices easier than utilizing randomly distributed quantum dots, while simultaneously boosting up the device performance [28-30].

1.5 Objectives

This Ph.D. research was aimed to study certain optical properties of laterally aligned quantum dots, which are self-assembly grown by various molecular-beam-epitaxial techniques. The research work was divided into two main parts:

The first part emphasized on the optical properties of laterally aligned quantum dots from the theoretical point of view.

The second part dealt with the investigation of laterally aligned quantum dots from the experimental point of view.

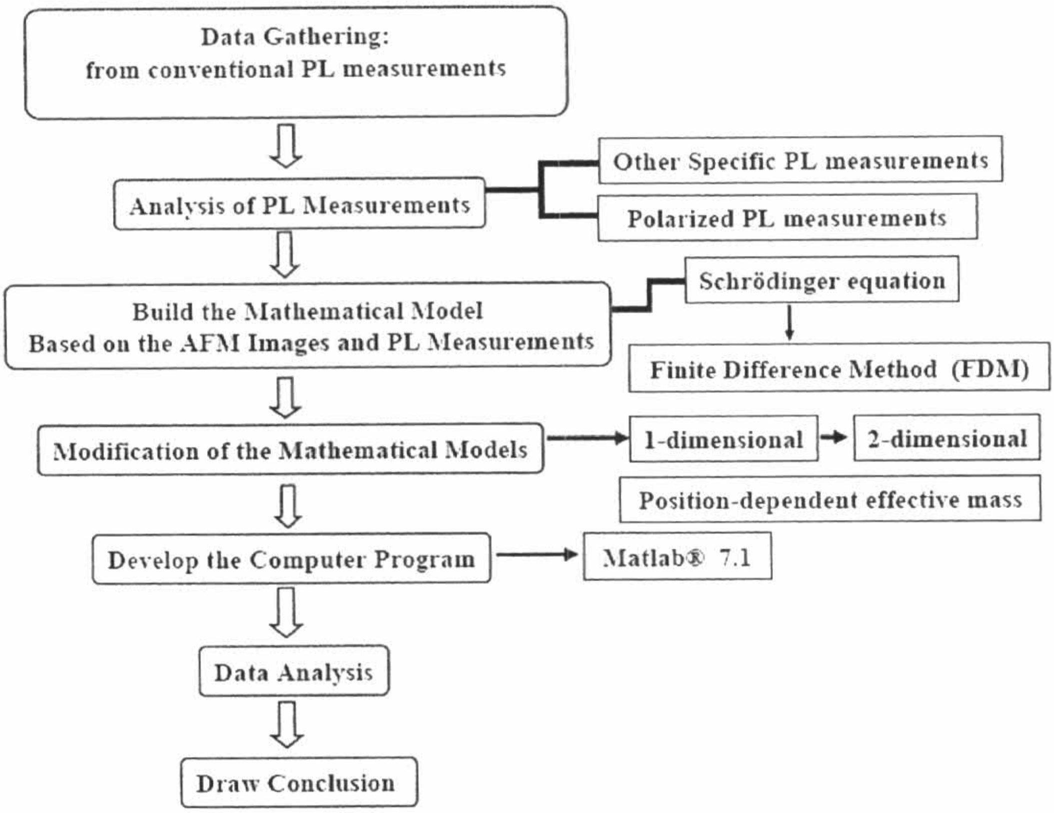
1.6 Scope of Work

To achieve the objectives mentioned above, first, the mathematical model of laterally aligned quantum-dot system was built up to be used in solving the Schrödinger equation and then specific computer programs were developed to solve such equation.

Experimental measurements were performed to obtain some optical properties, focusing on the linear polarization property, of photoluminescence (PL) from the laterally aligned quantum dots and then the experimental results were compared with theoretical ones.

This research also covered a study of the ground-state energy splitting of laterally aligned QDs which was the starting point of the polarization behavior.

1.7 Research Methodology



1.8 Significance of the Research

This research work investigated optical properties, focusing on the linear polarization property of laterally aligned quantum dots which is important for the polarization-sensitive photonic devices based on III-V semiconductor quantum dots.

1.9 Work Presented in This Thesis

In this thesis, the theoretical and experimental characterizations of laterally aligned QDs epitaxially grown by molecular-beam epitaxy (MBE) are presented. The polarization property of various laterally aligned quantum dot structures was investigated. This work proposed an idea of utilizing the polarization property of laterally aligned quantum dots for photonic device applications and proved that the polarization property and optical properties of the aligned quantum dots may be enhanced by optimizing the design and fabrication method.

In Chapter II, an overview of the physical properties of quantum dots is presented. In particular, the main characteristics and drawbacks of QDs grown by epitaxial techniques and their optical properties are highlighted. Chapter III concerns with theoretical calculations in which the finite-difference method is described and later on is used to solve the Schrödinger equation to eventually obtain the polarization characteristics of laterally aligned QDs. The theoretical characteristics of these quantum-dot systems are also discussed in detail. Chapter IV focuses on the spectroscopy and the associated macro-photoluminescence and micro-photoluminescence setups. The influence of the temperature, the excitation power and the structural effect on the optical properties of QDs are especially emphasized in that chapter. In Chapter V, the results obtained from optical characterization of various QD structures are presented. Such characterization is necessary and gives very useful information for future device designs and applications. The conclusion of this thesis work is given in Chapter VI. Finally, the Appendix will deal with the main Matlab® program that was written and used in the theoretical part of this thesis work.