CHAPTER I

INTRODUCTION

Semiconductor technology has been continuously developed since the invention of bipolar transistor in 1947, metal-oxide-semiconductor field-effect-transistor (MOSFET) in 1960 and nonvolatile semiconductor memory in 1967. These three classes of device have been used widely and are important devices for integrated circuits (ICs). The semiconductor materials that make up these devices can be grown by various epitaxial techniques that include vapor phase epitaxy (VPE) and liquid phase epitaxy (LPE). However, these growth techniques have some limitations. For examples, VPE requires high temperatures which enhance bulk diffusion and LPE does not produce films of uniform thickness. Film deposition by molecular beam technique was initiated by Cho in 1971 (Cho, 1971). Since then, the evolution of the molecular beam epitaxial (MBE) technique resulted in various modifications that improve upon the purification and perfection of semiconductor crystals.

Epitaxial growth is one of several techniques used to grow an oriented single crystal layer on a wafer substrate. During the last decade, *heteroepitaxy* has emerged to improve the properties of many devices. Heteroepitaxy is a topic of great fundamental and technological interest, since epitaxial layers can be produced with electrical properties different from those of the substrate, with variations on the type and concentration of electrically active impurities. Associated with heteroepitaxy are energy band offsets that can be used to confine charge carriers and refractive index profile that can be used to confine photons in one or more directions. Lasers fabricated from heterostructures exhibit low threshold current due to charge carrier and optical confinement in the active region.

One significant epitaxial technique that is the main focus of this work is heteroepitaxial growth of strained structures which offers the possibility to reproduce nanoscale islands with high crystalline quality. Under proper conditions, nucleation of 3-dimensional (3D) islands via Stranski-Krastanow (SK) growth mode yields a nanostructure called quantum dots (QDs) (Stranski et al., 1938). Various SK QDs have been formed from several material systems; for examples, $Ge_{1-x}Si_x/Si$ (Mo et al., 1990), InAs/GaAs (Joyce et al., 1998), $In_xGa_{1-x}As/GaAs$ (Moison et al., 1994) and $Ga_xIn_{1-x}P/InP$ (Carlsson et al., 1994). These self-assembled nanoscale islands led to QD-based devices that include lasers (Huffaker et al., 1998; Tachibana, 1999; Krishna, 2000) and detectors (Xu, et al., 1998; Astafiev, et al., 2002). Of particular importance, due to their relevancy to the work in this thesis, are high-performance $In_xGa_{1-x}As/GaAs$ QD lasers that have been demonstrated by several research groups (Eliseev et al., 2001; Grundman et al., 2000; Kovsh et al., 2003; Xu, et al., 2004). The long emission wavelengths in the 1.3-1.55 μm region are important for optical communication systems.

Although the benefits of self-assembled SK QDs have been demonstrated in lasers, their random sizes and distributions result in poor qualities for other electronic and optical devices. For many practical applications, nanometer-scale quantum dots should be formed with well-controlled, uniform size and position distribution. Ordered QDs are necessary for many QD-based devices such as integrated circuits based on single-electron transistors (Li et al., 2004; Osborn et al., 2004) and quantum dot cellular automata (Lent et al., 1993; Timler et al., 2002).

There are various templating techniques that can be used to form laterally- and vertically-ordered QDs; for examples, high-index substrates (Nötzel et al., 1996), substrate with insulated mask or anodic porous alumina mask (Hahn et al., 1998; Liang et al., 2002), multilayer vertical stacking (Nötzel et al., 2001; Ma et al., 2001; Vurgaftman, et al., 2001; Sanguinetti et al., 1999; Dai et al., 1997; Lobo et al., 1999), multi-layered high-stepped (Kitamura et al., 1995), vicinal substrate (Zhu et al., 1998) and strained layer growth on patterned substrate (Mui et al., 1995; Konkar et al., 1998; Seifert et al., 1996, Lee et al., 2000).

For vertically-aligned QDs, strain fields form the underlying buried islands influence island nucleation in the growing layer, resulting in vertically-aligned and closely stacked QDs (Ledenstov et al., 1996; Heidemeyer et al., 2002). For laterally-aligned QDs, several useful growth techniques include pre-patterned substrates (Jin et al., 1997) and self-assembled growths (Lee et al., 2000). Recently, thin-capping and-regrowth process has been shown to be able to also achieve laterally-aligned QDs (Suraprapapich et al., 2004). In such process, repeating the capping, regrowth and annealing steps for multiple cycles can turn a GaAs flat substrate into a template with stripes in the $[1\bar{1}0]$ direction due to anistropic strain of adatoms in the [1-10] direction (Shiraishi et al., 1992). Regrowth of QDs on this template gives rise to QDs which are well aligned. Another recent technique that can achieve laterally-aligned QDs involves the growth of SK QDs on surface undulations or cross-hatch surfaces (Kim et al., 2004; Zhang et al., 2005; Akiyama et al., 2006).

Despite the frequent observation of cross-hatch morphology, its origin remains controversial and unresolved (Andrews et al., 2002). Therefore, better understanding of the evolution of cross hatch is an essential issue and constitutes one main part of this research. Studies on QDs ordering on cross-hatch patterns give rise to the understanding of the growth mechanism of SK QDs on surface undulation. These insights may ultimately yield novel materials for future electronic and photonic devices.

The objectives of this work can be divided into two main parts. The first part is to investigate the growth of InGaAs/GaAs cross-hatch pattern with a view to developing a qualitative model to explain the structural evolution of the cross hatch. The second part is to develop MBE growth techniques and to characterize, by means of surface morphology and photoluminescence, laterally-ordered InAs QD grown on InGaAs cross hatch surfaces.

The structure of the dissertation is as follows: Chapter 2 explains about the experimental details which focus mainly on the MBE systems and important characterization techniques. Chapter 3 reviews and illustrates the fundamental concepts of self-assembled nanostructures. Chapter 4 reports the main results of the growth and characterisation of InAs QDs on InGaAs cross-hatch virtual substrates. Finally, Chapter 5 concludes and suggests further work.