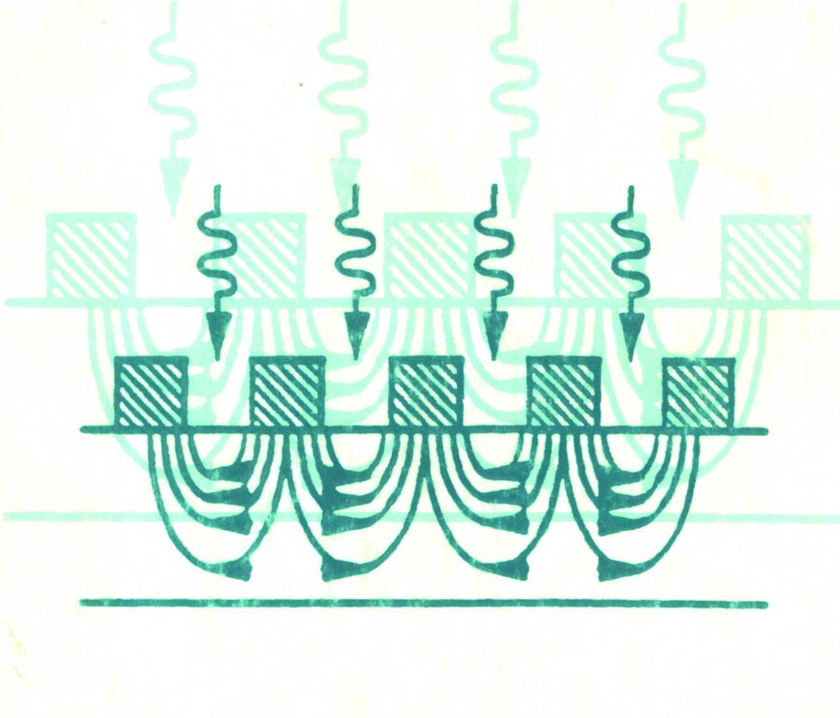
Optoelectronics: Technologies and Applications

A. Selvarajan
Krishna Shenai
Vijai K. Tripathi
Editors



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A. Selvarajan
Indian Institute of Science

Krishna Shenai
Intel Corporation

Vijai K. Tripathi
Oregon State University

Editors

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Preface

The next generation of advanced systems for terrestrial and space applications will be increasingly based on merged optoelectronic technologies to improve the overall system efficiency. For example, advanced space power systems, communication systems, information processing and computing systems, and interconnect networks are increasingly employing photonics. Revolutionary innovations in the material growth and processing technologies, devices and interconnects, and system architecture are needed to develop advanced optoelectronic systems.

This book provides an overview of some of the important technical areas that are contributing to the development of advanced optoelectronic technologies. The topics covered can be broadly classified into four major categories: optoelectronic materials, devices and integrated circuits, nonlinear optics and novel phenomena, and lightwave communication and information processing systems. A total of 14 chapters were carefully selected from among 200 papers presented at the International Conference on Emerging Optoelectronic Technologies (CEOT) held at the Indian Institute of Science, Bangalore, India, from December 16–20, 1991. The authors are internationally regarded for their contributions to the science and technology of optoelectronics and are drawn from both academia and industry. All contributions were carefully selected and revised through a peer-review process coordinated by the editors of this volume.

The first two chapters provide a broad overview of the growth of group III-V compound semiconductors based on liquid phase epitaxy (LPE) and molecular beam epitaxy (MBE). Chapter 3 is an in-depth discussion of the diagnostic techniques used for the characterization of optoelectronic materials. Chapter 4 provides an overview of the progress made in the development and application of self-electro-optic-effect devices (SEEDs). The next two chapters relate to optical fiber lasers and amplifiers. Chapter 7 provides a novel approach to the analysis of higher-order effects in laser speckles based on the method of symbolic manipulation. Chapters 8 and 9 deal with the theory and practice of integrated optical waveguides and components. Chapter 10 performs a detailed sensitivity analysis of an InGaAs/InP optoelectronic integrated receiver and provides its performance trends. The performance and application of optical interconnects are discussed in detail in Chapter 11. A detailed account of a neural net system is presented in Chapter 12. The last two chapters pertain to an integrated optic array illuminator and the general area of photonic networks, respectively. Comprehensive subject and author indexes are provided for easy reference.

This book, by no means, covers all areas of optoelectronics. However, a conscientious effort has been made to highlight the major technical areas that are contributing to the development of the next generation of optoelectronic devices and systems. The authors have made every effort to provide a detailed state-of-the-art account of their research field. From these perspectives, it is a unique collection of works reported in the general area of emerging optoelectronic technologies. It is designed for both professionals actively involved in the development and manufacturing of optoelectronic systems, and those who desire to obtain a brief account of the latest advances in each of the specific technical areas highlighted. In particular, teachers and students engaged in the research and teaching of advanced topics in optoelectronics should find this book especially useful, because it not only covers several important research topics of current interest, but also provides a detailed direction for future developments in the field.

The editors would like to thank first and foremost all the authors who responded with vigor to contribute to this collection, and who spent numerous hours compiling what appears to be an honest and detailed account of important developments in the field of optoelectronics. It has been a pleasure working with them over the past year. We are also indebted to Mr. Eric Pepper, SPIE Press Editor, for his continuous encouragement and support that made this effort worthwhile. We are grateful to all the sponsors of CEOT and the members of the CEOT organization and program committees, who spent countless hours putting together a major conference from which this book has evolved. We want to express our sincere appreciation and thanks to Ms. April Melton, who provided administrative support during most of the review process. Finally, this work would not have been possible without the constant encouragement and love that our families have provided over the past two years.

A. Selvarajan, Bangalore, India
Krishna Shenai, Aloha, Oregon
Vijai K. Tripathi, Corvallis, Oregon

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Optoelectronics: Technologies and Applications

Chapter 1
Liquid Phase Epitaxial Growth and Characterization of III-V Compound Semiconductors

B. M. Arora
Tata Institute of Fundamental Research
Homi Bhabha Road, Bombay 400005, India

1. INTRODUCTION

Historically, liquid phase epitaxy (LPE) was developed by Nelson.[1] to grow Ge for tunnel diodes. The technique proved so versatile that over the years it has been used to grow a wide variety of materials including silicon, a large number of III-V compounds, II-VI and IV-VI compounds as well as garnets.[2] As such, most of the developments in the LPE technique have been motivated largely by requirements of materials for optoelectronic devices such as lasers and detectors.[3] Thus, a range of binary, ternary and quaternary materials have been grown in multilayered structures for devices covering a wide range of wavelengths from visible to near IR.[4] The technique is particularly well suited for buried heterostructure lasers[5] which require two growth sequences: (i) one to grow the basic heterostructure and (ii) the second - a 'Regrowth' step (after etching a mesa or a grating) to provide a buried active layer with lateral electrical and optical confinement layers. For most research workers in III-V semiconductor area, LPE has been a technique of first choice for trying out growth of new materials or structures. The apparatus is relatively simple; the required starting materials may be used in elemental form with high purity; the temperature of growth is generally low, and the growth is a near equilibrium process with very small supersaturation; the resulting materials can be of very high electrical and optical quality because of fewer native defects. Apart from this materials research interest, a considerable fraction of the commercial optoelectronic devices such as LEDs, solar cells based on GaAs and semiconductor lasers is still produced by using the LPE technique. Despite these well proven capabilities, a challenge to LPE has been posed by quantum well and superlattice structures, which are now routinely used in many optoelectronic devices and for which alternative techniques such as molecular beam epitaxy (MBE) and metalorganic vapour phase epitaxy (MOVPE) are preferred. In this article, we present some aspects of the LPE growth and characterisation with special reference to AlGaAs grown on GaAs, and InGaAsP grown lattice matched to InP. We shall also briefly review the literature on the realisation of quantum well structures by LPE.

2. LPE Growth Principle

LPE is basically growth of oriented single crystal film from a liquid solution on a suitable crystalline substrate. The common substrates used for growing III-V compounds are GaAs, InP and GaSb. The solvent is generally a group III element such as Ga or In, which is one component of the material to be grown. Other components are added to make a saturated solution at a selected temperature T_{sat}. Thus, to grow an epi-layer of GaAs, a saturated solution of arsenic in gallium is prepared by adding appropriate amount of GaAs to Ga. The amount of solute required to prepare a saturated solution at T_{sat} is given by liquidus part of the phase diagram. Several liquidus curves for growing binary materials are given by Kressel and Nelson[6] and reproduced in Fig. 1.

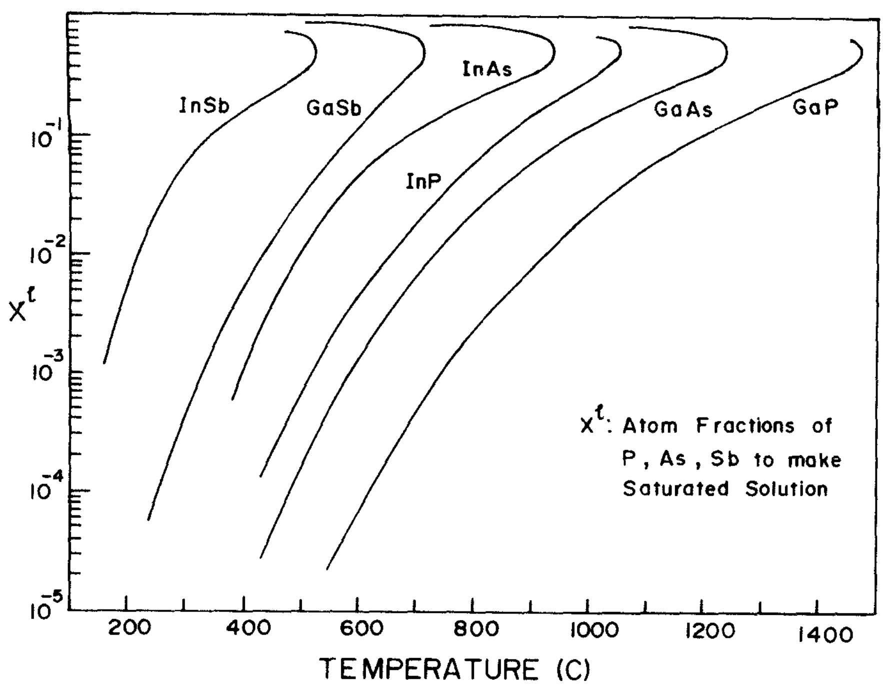

Fig. 1 Atom fraction x^{l} required to saturate liquid Ga or In versus temperature from Ref.6

At the low temperatures used for LPE growth, the solution is dilute and mole fraction of the solute x^l required for saturation of the solution increases with temperature with an activation energy ΔH (heat of dissolution)

$$x^l \sim \exp\left(-\frac{\Delta H}{RT}\right) \quad (1)$$

where R is the gas constant. The corresponding mole fraction x^s in a binary solid is 0.5 which does not change when the saturated solution is cooled during growth. The growth process of multicomponent systems $Al_xGa_{1-x}As$ and $In_{1-x}Ga_xAs_yP_{1-y}$ is considerably more complex. To grow a solid of composition such as $Al_{0.3}Ga_{0.7}As$, there is a specific solution composition (x^l_{Ga}, x^l_{Al}, x^l_{As}) required at a growth temperature T_G. If the growth temperature decreases, the proportion of components in the solution to get the same epi composition changes. Alternatively, if the solution composition is kept the same as in most of the actual growth conditions, the epi-composition will change. Therefore, the growth of nearly uniform composition layers is restricted to a narrow range of temperatures. The liquidus and solidus of several specific ternary and quaternary alloy compositions have been determined by experiments at specific temperatures.[3,7-12] In addition, there are several theoretical model calculations which extend the range of phase diagrams over other compositions and temperatures.[13-18]

To carry out epi-layer growth, the saturated solution is brought into contact with the seed substrate and cooled below the saturation temperature T_{sat}. Figure 2 shows a typical growth sequence. Growth occurs because of supersaturation of solution by supercooling over a temperature $\Delta T = T_{sat} - T_G$. At the solution-substrate interface, the supersaturation is relieved by precipitation and deposition of the excess material on the substrate. Away from the interface, the solution remains supersaturated and a concentration profile $x^l(Z,t) \cong x^l - \Delta x^l \operatorname{erfc} Z/2\sqrt{Dt}$ is set up assuming a semi-infinite solution and a planar interface with no compositional inhomogeneities or gradients. This causes a diffusive flux [$\approx \sqrt{D/\pi t}\,(\Delta x^{l})$] of the solute to the interface where $\Delta x^{l} = x^{l} - x^{l}(o,t)$. If we assume that there is no

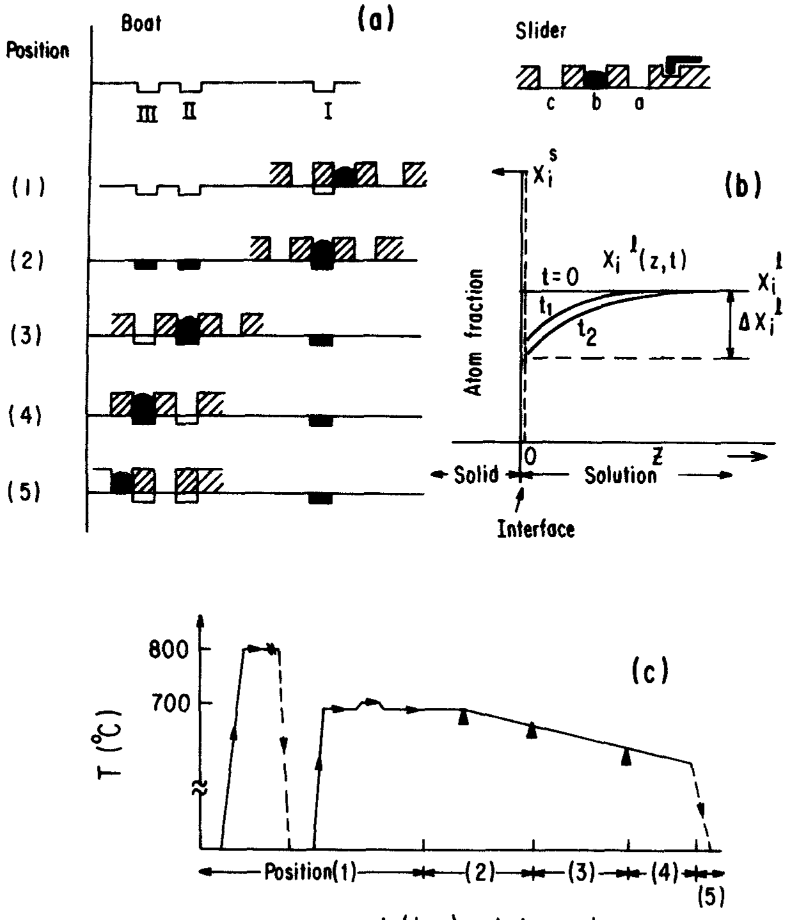

Fig. 2. a) Relative positions of boat and slider (1-5) used in the growth of AlGaAs. b) Profiles of solute concentration distribution in the solution at various times after contact between solution and substrate. c) Temperature cycle during growth.

convection or mixing in the solution, then the growth rate depends directly on the diffusive flux. If the growth time is limited, such that $\sqrt{Dt} < h$ (the height of the solution) then the epi-layer thickness can be estimated from the amount of supercooling and the duration of growth. There are essentially three schemes used for cooling the solution.

(i) Step Cooling: The solution is cooled to a temperature T_G, a few degrees ($\Delta T \sim$ 5-10^oC) below T_{sat} before making contact with the substrate. The growth occurs isothermally at T_G. For the binary case, the supersaturation Δx^l can be expressed in terms of supercooling ΔT and slope

of the liquidus $\left(\Delta T = \frac{\Delta x^l}{dx^l/dT}\right)$ such that the growth velocity and thickness d of the growing layer are given by

$$v = \frac{a}{2\sqrt{t}}$$

$$d = at^{1/2}$$

$$\text{where} \quad a = 2\theta \sqrt{\frac{D}{\pi}} \quad \frac{1}{mx^s} \Delta T , \tag{2}$$

θ = ratio of atomic density in the liquid to atomic density in the solid

$x^s = 0.5$ and $\frac{1}{m} = \frac{dx^l}{dT}$ is slope of the liquidus

In the multicomponent case, different solute components diffuse towards the interface and get incorporated into the growing solid. Since there is one common growth rate, the diffusion of different components (D_i, D_j) towards the solution-solid interface and the compositions of different solute components at the boundary (x_i^l, x_j^l) are connected. Assuming that interaction between the solute elements in the solution can be neglected, it is possible to show that at the interface.[17]

$$\frac{x_i^l - x_i^l(o,t)}{x_j^l - x_j^l(o,t)} \quad \frac{\sqrt{D_i}}{\sqrt{D_j}} = \frac{x_i^s - x_i^l(o,t)}{x_j^s - x_j^l(o,t)} \tag{3}$$

If the thickness of the solution is sufficient, then the composition of the growing solid (x_i^s, x_j^s) will be constant in a growth run depending on the supercooling ΔT which fixes the values of $x_i^l(o,t)$, $x_j^l(o,t)$ at the interface. In this case, the layer thickness is still given as in equation (2) with the following modification

$$d = At^{1/2}$$

$$\text{where } A = \frac{2\theta}{\sqrt{\pi}} \frac{1}{\sum_{i=1}^{n} \frac{x_i^s}{\sqrt{D_i}} m_i} \Delta T \qquad (4)$$

θ = ratio of atomic density in the liquid to atomic density in the solid.

$m = \dfrac{\partial T}{\partial x_i^l}$ is obtained from partial derivative of the liquidus for each component

(ii) Equilibrium Cooling: The solution is brought into contact with the substrate at the temperature T_{sat} and then cooled at a linear rate α (~ 0.1 to 1.0°C/min). In the binary case, thickness of the layer is given by

$$d = bt^{3/2}$$

$$\text{where } b = \frac{4\theta}{3} \sqrt{D/\pi} \frac{1}{mx^s} \alpha \qquad (5a)$$

In the multicomponent case, thickness can still be given as

$$d = Bt^{3/2}$$

where $$B \approx \frac{4}{3\sqrt{\pi}} \frac{1}{\sum_{i=1}^{n} \frac{x_i^s}{\sqrt{D_i}} m_i} \alpha \qquad (5b)$$

However, the composition of the growing solid is not constant since the composition of the liquid at the interface keeps varying with time.

(iii) Supercooling: This scheme combines (i) and (ii). Cooling the solution is started before making contact with the substrate. After cooling the solution by ΔT below T_{sat}, the solution is contacted with the substrate and the cooling is continued.

The thickness of the grown layer is given by superposition

$$d = at^{1/2} + bt^{3/2}$$

A structure consisting of several layers can be grown by bringing in succession appropriate saturated solutions into contact with the growth substrate and cooling by a specific amount for the desired thickness. For binary and some ternary compounds (e.g. AlGaAs), it is possible to ensure saturation by keeping the solution in touch with a saturating substrate (GaAs for GaAs and AlGaAs) at the growth temperature. However, for several ternary and quaternary materials such as InGaAs and InGaAsP, there is no saturating substrate, and accurate weighing of the solution components is necessary.

The growth considerations outlined above apply to planar substrates. If, however, the substrate is patterned as in the case of heterostructure lasers, distributed feedback lasers, and integrated optics (Fig.3) the solution-substrate interface is not planar. In such cases, the growth is strongly affected by topological features such as channels and terraces.[18-21] Thus, within a single growth run, the grown layer is (i) thicker than normal in the concave portions, (ii) thinner than normal in the convex portions and (iii) there may even be a melt back instead of growth on the convex corners depending on the degree of supersaturation of the solution. The effect is extensively used in the device fabrication during the 'regrowth step' after patterning to planarise the structure and is considered a very attractive aspect of

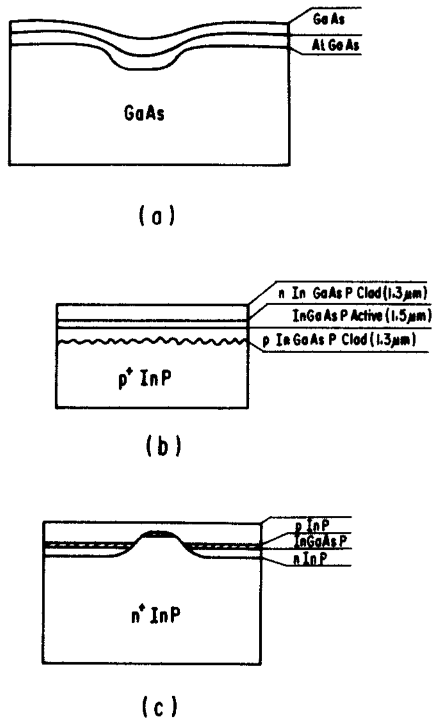

Fig. 3. Schematics diagarams of various regrown structures: a) Channel waveguid Ref.18 b) InGaAsP DFB laser structure over a first order grating Ref. 5 c) Laser structure with buried active layer grown by a single step LPE Ref.5.

of the LPE growth. The effect itself has been attributed[21] to variation of the chemical potential of the solution with change in the curvature of the interface. Thus, a homogeneous melt in equilibrium (i.e. just saturated) with planar portions of a substrate behaves as if it is undersaturated with respect to a convex surface and supersaturated with respect to a concave surface.

Apart from the general principles outlined above, there are many other considerations for achieving good quality growth. Quality itself may involve smooth surface morphology, defects and dislocations, interface abruptness, uniformity of thickness and composition, background concentration and mobility, photoluminescence etc. There are several reviews[6,22] which deal with the growth issues involved in the synthesis of high quality LPE layers and structures.