Compliant Substrate Strain Modulated Epitaxy for WDM Laser Arrays
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Introduction

The market surge in wavelength division multiplexing (WDM) systems has focused research upon new methods for producing WDM laser arrays. Previous efforts toward realizing multiple wavelength laser arrays for WDM systems include changing the growth rate by varying the wafer surface temperature in a molecular beam epitaxy (MBE) system, resulting in multiple wavelength vertical cavity surface emitting laser (VCSEL) arrays with a large lasing wavelength span and highly uniform threshold currents [1]. Using chemical beam epitaxy, selective-area growth has produced wavelength peaks in the photoluminescence spectrum which are a function of the width of the SiO2 mask opening [2]. In this paper, we propose a new method of making a multiple-wavelength laser array by using strain modulated epitaxy. This growth process, which enables growth on a smooth substrate surface while enabling three-dimensional bandstructure engineering, uses a bottom-patterned compliant substrate to modulate the strain variation on the epitaxial layer grown on the compliant substrate.

To achieve this strain variation as a function of lateral position on the grown sample, a bottom patterned compliant substrate is used to vary the strain. The strain partitioning calculation, applicable to ideal compliant substrates with large patterns (>10 μm), is used to calculate the strain, which gives the new strain in the epitaxial layer on the compliant substrate as approximately [3]

\[ \varepsilon_f = \frac{h_f}{h_f + h_s} \varepsilon_0 \]  

(1)

where \( \varepsilon_f \) is the partitioned strain in the epitaxial film, \( \varepsilon_0 \) is the total misfit strain, and \( h_s \) and \( h_f \) are the thickness of the substrate and the film, respectively. Since the compliant substrate, which is usually below 1 μm, is much thinner than the conventional substrate, the strain \( \varepsilon_f \) in the epilayer can be controlled by varying the compliant substrate thickness. Furthermore, the bandgap in the epilayer can be modified to achieve multiple wavelength laser arrays grown simultaneously on a smooth substrate surface.

Theoretical discussion

InAsP/InP strained quantum wells will be examined herein for the WDM laser application. In InAsP/InP strained quantum wells, the hydrostatic component of the strain changes the conduction band of InAsP_{1-x} given by [4]

\[ \Delta E_n(x) = 2a(x)\left\{\frac{C_{11}(x) - C_{12}(x)}{C_{11}(x)}\right\} \varepsilon \]  

(2)

And the shear component of the strain induced energy changes of the heavy-hole valence band is given by [4]

\[ \Delta E_{hh}(x) = b(x)\left\{\frac{C_{11}(x) + 2C_{12}(x)}{C_{11}(x)}\right\} \varepsilon \]  

(3)

The band gap for strain-free InAsP_{1-x} alloy depending on the As composition is given by [4]

\[ E_g^0(x) = 1.351 - 1.315x + 0.32x^2 \]  

(4)

In a simple InAsP/InP quantum well, we can calculate the As compositions for 1.3 μm and 1.55 μm lasers using equations (2), (3), and (4). But when the bottom-patterned compliant substrates are used to provide more strain variation in the epilayer, strain partitioning must be taken into account. The strain \( \varepsilon \) in equations (2) and (3) will be replaced by \( \varepsilon_f \) from equation (1). The strain in the epilayer can be changed by different thickness of compliant substrate, thus the energy band gap in the strained InAsP will be different. A multiple wavelength laser array is therefore possible by patterning the backside of the compliant substrate to make the thickness
vary across the entire compliant substrate. Fig. 1 shows the structure of this multiple wavelength laser array created using compliant substrates.

Using this model, which assumes an ideal compliant substrate, we assume the maximum compliant substrate thickness to be 1μm to realize multiple lasers in our model. 100Å is assumed to be a reasonable thickness difference of compliant substrate between two adjacent lasers, given etching processing limits. The wavelength difference between adjacent lasers is 2 nm, centered around 1.55 μm. Fig. 2 shows the results of this model. Under three different As compositions, with the same thickness of epilayer, three curves were obtained for comparison, each with an epilayer thickness of 120Å. The results show that the curve shifts considerably under even a 1% As composition difference. A 1% compositional uniformity is attainable over a 2" substrate [5]. When the As compositions of InAsP is 67%, 68%, and 69%, 13 lasers spaced by 2 nm were obtained in each case.

**Processing Approach**

Toward the realization of these WDM arrays, compliant substrates can be fabricated by a bonded substrate removal process (although non-ideal), as shown in Fig. 3, which is a GaAs-based substrate. For both the InP and GaAs-based compliant substrates, the bottom patterns can be made by etching the thin layer side nonlinearly to achieve different thickness in the compliant substrates. In order to achieve such a small thickness difference (100 Å) between two adjacent lasers, slow etching is necessary. The samples are then bonded to the host substrate using a glass bond. The bulk of the substrate is then removed from the samples using selective etching.

**Conclusion**

Our model theoretically predicts realization of a multiple wavelength laser array using bottom patterned compliant substrates. Higher As composition and thicker InAsP epilayers produce larger laser array sizes, and increase the wavelength span. A 67% As composition of InAsP is the best result for WDM arrays centered near 1.55 μm.

Fig. 1. Structure of bottom-patterned compliant substrate with epilayer. The thickness t varies across the substrate.

Fig. 2. The model result at 67%, 68%, 69% As composition of InAsP. Each one has 13 lasers (points on the curve). The thickness is t in Fig. 1.


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