UCRL-CR-104625
P. O. B034287

NOV 01 1990

**Study and Development of Tunable,
Single Mode AlGaAs/GaAs Lasers**

P. K. L. Yu
J. C. Liu

UCRL-CR--104625

DE91 001684

September 1990

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract number W-7405-ENG-42.

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

MASTER
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Final Report on Order No. B034287

"Study and Development of Tunable, Single Mode AlGaAs/GaAs Lasers"

submitted by

P. K. L. Yu and J. C. Liu

Department of Electrical and Computer Engineering, R-007

University of California, San Diego

La Jolla, California 92093

Telephone (619) 534-6180

Table of Contents

	Page
Abstract	3
I. Introduction	4
II. Two-section single cavity tunable lasers	4
IIa. Interdigitated multi-electrode single cavity laser -- a proposal	7
III. LPE growth for GaAs/AlGaAs lasers	9
IIIa. LPE growth of the basic laser structures	9
IIIb. Issues associated with GaAs/AlGaAs regrowth	9
IV. InGaAsP/InP laser growth	12
IVa. Evanescent coupling approach	13
IVb. Direct Coupling Approach	13
V. DFB grating formed by electron beam lithography	17
VI. Tunability measurement using a CCD array	17
VII. Summary	21
References	23

Abstract

Liquid phase epitaxy has been employed in this study to fabricate two-section wavelength tunable lasers. GaAs/AlGaAs and InGaAsP/InP material systems have been used for fabricating the lasers. Both direct (butt) coupling and evanescent coupling approaches have been studied. The complications associated with the regrowth process have been responsible for poor laser performance. Some DBR gratings for three-section lasers have been made using the electron beam lithography at UCSD. A simple set up has been tested to measure the wavelength shift of GaAs/AlGaAs lasers. Also, a simple structure which avoids the regrowth process has been proposed for the two-section laser.

I. Introduction

This document summarizes the results of the work performed under order no. B034287. As stated in this contract, the goal is to fabricate tunable wavelength lasers for microwave signal recording applications. The approach pursued in this work is to employ multi-section optical cavity to tune the laser emission wavelength. In particular, two-section lasers have been investigated in this study.

Section II describes the operation principle of the two-section laser and highlights the main issues involved in the fabrication of the laser. A practical device structure to simplify the fabrication process is also proposed. Section III describes the results obtained from the liquid phase epitaxy of GaAs/AlGaAs lasers. Section IV describes the results of the InGaAsP/InP laser growths. Section V discusses the use of the electron beam lithography for fabricating the distributed Bragg reflector grating of the three-section laser. Section VI describes a scheme of viewing the wavelength tunability of a GaAs/AlGaAs laser using a silicon CCD array. Section VII gives an overall summary and suggestions for future work.

II. Two-section single cavity tunable lasers

Figure 1 shows a schematic diagram of a two-section tunable laser studied in this program. Region I contains the gain media (active layer) and region II contains the waveguide layer which has a bandgap larger than that of the active layer. A distributed Bragg reflector (DBR) grating can also be added to region II or form a separate waveguide region (region III) by itself. The same principle of wavelength tuning is used in all of these structures, namely, the index change induced by the injected carriers causes a change in the effective optical length of the optical waveguide which consequently tunes the emission wavelength. The grating region in a three-section laser serves as a narrow wavelength filter which enlarges the gain difference between the lasing mode and the neighboring modes. This mode suppression mechanism ensures a continuous tuning of the emission wavelength as the index is changed.

Fig. 1 Cross section view along the cavity direction for a two-section single cavity laser with different bandgap materials

Fig.2 Cross section view along the cavity direction for a two-section single cavity laser with the same material structure

From the requirement that the round trip phase of the photon field is an integral multiple of 2π , for the two-section laser shown in Figure 1, we obtain,

$$n_1 l_1 + n_2 l_2 = \frac{\lambda}{2} \quad (1)$$

and

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta n_1}{n_1} \left[1 + \frac{n_2 l_2}{n_1 l_1} \right]^{-1} + \frac{\Delta n_2}{n_2} \left[1 + \frac{n_1 l_1}{n_2 l_2} \right]^{-1} - \frac{\Delta n_2}{n_2} \left[1 + \frac{n_1 l_1}{n_2 l_2} \right]^{-1} \quad (2)$$

The wavelength change is mainly resulted from the index change at region II since the carrier density in region I is clamped at a constant value as lasing commences. This index change is usually accompanied by an increase of material absorption which either increases the threshold current or increases the optical attenuation in region II. To minimize the overall loss and to maximize the useful wavelength tuning range, it is necessary that a high coupling efficiency exists between the different regions. This is especially true for three-section lasers where the coupling between the DBR region and the other regions needs to be high for effective wavelength tuning.

In Figure 1, the different bandgap of regions I and II can be obtained by a regrowth process. As pointed out in Section III, the regrowth process is to be avoided if possible in the laser fabrication process due to the fact that in between growth runs the wafer can be exposed to contaminants in the ambient. As an alternative, Figure 2 shows a schematic diagram of two-section single cavity semiconductor laser in which both regions I and II have the same material structure. It has been demonstrated theoretically^[1] and experimentally^[2] that this structure can offer a tuning range of several angstroms. Its limited tuning range can be explained by the fact that the (control) region II is very lossy during operation since it absorbs strongly at the lasing wavelength of (gain) region I. It is thus necessary to bias region II to a level slightly below threshold to partially overcome the transparency condition so that lasing is achieved with reasonable current injected into region I. However, once threshold is reached, the total carrier density in the cavity is clamped. Further current injected to the control region will not

appreciably change the carrier density and hence little index change will occur. In order to minimize the absorption loss in region II, the length ratio of region II to region I is kept small which further reduces the effective tuning range (see Eq. 2).

For this structure, the tuning efficiency (defined as the tuning range per unit injection current at the control region) increases as the bandgap of the waveguiding layer in region II approaches, but slightly higher than, that of the active region. This is related to the fact the spectral distribution of the index change peaks near the bandgap of waveguiding layer of region II, so for a given amount of injection current, the wavelength tuning range is also maximized there. For instance, Imai et al.^[3] has showed that the tuning efficiency was greatly increased when the waveguide composition is changed from $1.2\ \mu\text{m}$ to $1.38\ \mu\text{m}$ for a $1.55\ \mu\text{m}$ active region. However the absorption loss also increases rapidly around the bandgap energy, thus it is difficult to maintain the same output power over the entire tuning range.

IIa. Interdigitated multi-electrode single cavity laser -- a proposal

Because of the above difficulties with the two-section laser in which the same material structure is employed for both sections, we propose an interdigitated multielectrode single cavity laser structure shown in Figure 3 for tunable wavelength laser application. This structure makes use of the leakage carriers which diffuses^[4] from the driving region to the control region so that little bias is required at the control electrode. Its tuning range is expected to be limited due to the same reason discussed earlier. However, by adopting a multiple quantum well structure in the active layer and by using the impurity induced disordering or ion beam mixing, the bandgap of the waveguide in the control region can be slightly enlarged. The resultant emission energy shift is expected to be as large as a few hundred meV's and the absorption loss in the control region can be overcome by the gain generated from carriers diffused from the pumped section. This concept is currently being investigated in a follow-on of this contract (B108444).

Fig.3 Interdigitated multi-electrode single cavity laser

III LPE growth for GaAs/AlGaAs lasers

IIIa. LPE growth of the basic laser structures

Before fabricating the two-section lasers, convention three layer stripe geometry GaAs/AlGaAs lasers are first fabricated and evaluated. Figure 4 shows a photomicrograph of the as-grown layers. Both oxide stripe and ridge waveguide lasers are made from these materials with a $6\text{ }\mu\text{m}$ stripe (or ridge) width for the lasers. The respective threshold current are 180 mA and 120 mA for $300\text{ }\mu\text{m}$ long devices. The high threshold current of the ridge waveguide lasers is attributed to the fact that the structural parameters have not been optimized, namely the current spreading under the stripe must be reduced and that the stripe width adjacent to the active region must be made narrower. In addition, the control of the active layer thickness is also important in the reduction of threshold current. We have not optimized these parameters as we had engaged much of the time in taking care of issues such as the regrowth and the completion of the device for measurement.

IIIb. Issues associated with GaAs/AlGaAs regrowth

We have encountered some difficulties in the regrowth process of GaAs/AlGaAs materials. These have to do with (a) regrowth of GaAs on an exposed AlGaAs surface (b) selective etching properties of GaAs versus AlGaAs, (c) enhanced growth rate at the terrace boundary region created by etching, (d) the fact that the GaAs material is highly absorptive at the lasing wavelength.

Regrowth on exposed AlGaAs surface has been a problem for us since the exposed AlGaAs surface is covered with a native oxide layer which prohibits GaAs from growing on top. On the other hand, a good regrowth on GaAs surface is much easier to achieve. However, extreme care in wafer cleaning is still needed to avoid spotty and irregular growth pattern.

The selective etching of GaAs grown on AlGaAs and AlGaAs grown on GaAs is very important for an efficient evanescent coupling (Fig 5) between regions I and II of a two-section

Fig.4 Cross section photomicrograph of the as-grown GaAs/AlGaAs wafer

Fig.5 Cross section view along the cavity direction for an evanescent-coupled GaAs/AlGaAs two-section laser

Fig. 6 Cross section view along the cavity direction for a direct-coupled GaAs/AlGaAs two-section laser

Regrown region

laser. Ideally, we like to selectively remove the first LPE at region II and stop the etching at the AlGaAs waveguide layer before regrowth. However, the selectivity is found to be drastically reduced when the aluminum mole fraction is below 22 %.^[5] It is thus concluded that the evanescent coupling approach is difficult to achieve in this material system.

Alternatively, the direct coupling approach shown in Fig 6 has been studied. In this approach, one can etch selectively the grown substrate until the GaAs substrate is reached. Regrowth is much easier to achieve on GaAs surface. However, the exact lining-up of the waveguide layer in region II to the active layer in region I is difficult to achieve. Furthermore, it is found that the growth rate tends to increase near sharp corners due to surface kinetics.^[6] Consequently, curved layer growth is observed near the etched steps making it difficult to butt-couple the two regions.

Because the substrate (GaAs) bandgap is smaller than (or equal to) the bandgap of the active region, it is very absorptive at the lasing wavelength. Consequently, the cladding n-AlGaAs layer must be thick enough to prevent the substrate absorption. For this reason, the DBR grating cannot be made directly on GaAs substrate. One alternative is to form the grating at the top p-AlGaAs cladding layer. Another approach is to design a material structure that emits at wavelengths longer than that of the GaAs. For instance, with a strained quantum well laser structure which consists of GaAs/ $\text{In}_x\text{Ga}_{1-x}\text{As}$ /GaAs layers, the lasing wavelength is longer than $0.9\text{ }\mu\text{m}$ which is transparent in the GaAs materials.

IV. InGaAsP/InP laser growth

Tunable wavelength lasers for use in the $1.3\text{ }\mu\text{m}$ wavelength have also been investigated in this study. The materials for device are LPE grown InGaAsP and InP. Both basic laser and two-section laser structures have been studied in this work.

IVa. Evanescent coupling approach

Figures 7, 8 show the schematic diagrams of the cross section view of the wafer after the first LPE and the second LPE growth. Five layers were grown on a (100) n-InP substrate as shown in Figure 7. In this case, the evanescent coupling scheme is employed for light coupling between the two regions, a thin layer of InP is intentionally grown between the active quaternary layer and the waveguiding quaternary layer for selective etching purposes. After selectively etched the p-InP layer and the active layer at region II, the sample was loaded back into the LPE system for the growth of the p-InP cladding layer and p⁺-InGaAsP contact layer, as shown in Figure 8. However, the InP layer sandwiched between the quaternary layers is too thick that a poor optical coupling of the quaternary layer is observed. Attempts have been made to reduce the thickness of this InP layer by shortening the growth time. The lasers tested so far still show poor emission characteristics. Further growth optimization is required for this approach.

IVb. Direct Coupling Approach

Figures 9 and 10 show two different ways of implementing this approach. In the first way, as shown in Figure 9a, four layer structure is grown, then a layer of silicon nitride is deposited at region I as the etching mask for selectively removing the p⁺ InGaAsP contact layer, the p-InP cladding layer and the InGaAsP active layer at region II. The same nitride layer also serves as a growth mask. An undoped InGaAsP waveguide layer, a p-InP cladding layer and p⁺-InGaAsP contact layer are grown at region II in the regrowth step (see Figure 9b). In the second way, as shown in Figure 10a, three layers are grown in the first LPE step. The p-InP and InGaAsP active layers are removed selectively in region II. During the regrowth, p⁻-InGaAsP waveguide layer, p-InP layer and p⁺-InGaAsP contact layers are grown on both regions (see Figure 10b).

In the first way, with nitride as growth mask, we observed an overgrowth at the terrace boundary between the regions I and II. The thickness there is about four to five times that of the flat region. This feature is not desirable for effective coupling of the two regions. In the second way, although the overgrowth at the boundary is reduced, the growth rate around the boundary is

Fig.7 Cross section view along the cavity direction after the first LPE growth for an evanescent-coupled InGaAsP/InP two-section laser

Fig. 8 Cross section view along the cavity direction after the second LPE growth for an evanescent-coupled InGaAsP/InP two-section laser

Fig.9a Cross section view along the cavity direction after the first LPE growth for an evanescent-coupled InGaAsP/InP two-section laser

To be etched off selectively

Fig.9b Cross section view along the cavity direction after the second LPE growth for a direct-coupled InGaAsP/InP two-section laser

Regrown region

Fig.10a Cross section view along the cavity direction after the first LPE growth for a direct-coupled InGaAsP/InP two-section laser

To be etched off selectively

Fig.10b Cross section view after the second LPE growth for for direct-coupled InGaAsP/InP two-section laser

Regrown region

still larger than the rest. This behavior is similar to that of the GaAs/AlGaAs regrowths. By reducing the growth time, and by increasing the etched step, the growth characteristics at the boundary can be improved, as shown in Figure 11.

V. DFB grating formed by electron beam lithography

Distributed corrugated grating fabricated by electron-beam lithography can achieve a higher degree of uniformity^[7] and flexibility than those made by convention holographic techniques. For example, it is possible to vary the mark/space ratio (defined as the ratio of the exposed width to the width of one period) of E-beam exposed gratings so as to produce a maximized coupling strength (κ) for a given grating profile and Bragg order used.

A 1000 Å wide opening on 1.5 μm period has been made on a resist-coated GaAs substrate using E-beam lithography at UCSD. A scanning electron microscope photograph is shown in Figure 12. With E-beam, the backscattering of electrons from the substrate is the major factor which limits the grating resolution.^[8] Mark/space ratio can be adjusted by varying the overall dose. However, as the grating period reduces, the backscattered electrons can expose the region next to the mark region and widens the mark region. This affects both the uniformity and the control of the mark/space ratio of the grating. In order to achieve an acceptable DBR grating with E-beam, more calibration is needed on processing parameters such as electron energy, overall exposure dose, and the exposure time.

VI. Tunability measurement using a CCD array

We have designed and tested a simple, inexpensive set up to assess the wavelength tunability of GaAs/AlGaAs lasers. This set up involves a monochromator and a silicon CCD array. Figure 13 depicts the measurement set up. The exit slit of the monochromator is left widely open so that radiation within a wide range of wavelength can exit the slit at different angles. The output of the monochromator is imaged to a CCD array which is connected to a

Fig.11 Cross section photomicrograph of the as-grown InGaAsP/InP laser along the cavity direction after the second LPE growth. The corresponding schematic cross section view is shown in fig.10b

Fig.12 A scanning electron microscope photomicrograph of 1000Å openings on 1.5μm spacing made on a resist-coated GaAs substrate by using E-beam lithography

Fig. 13 Schematic set up for spectral viewing of the laser wavelength shift using a silicon CCD array

storage oscilloscope. The wavelength shift is observed as a shift of the detected spot on the CCD array. In this set up, the relative shift can be measured by first narrowing the slit and calibrates the correspondence between the wavelength and the position on the oscilloscope trace. The extent of the spectral window measured is primarily limited by the reciprocal dispersion of the monochromator, the slit width and the CCD array width. For our set up, the spectral window is about 100 Å (see Figure 14), while the resolution is limited by the grating resolution of the monochromator and the pixel size of the array element.

VII. Summary

In summary, we have studied the two-section lasers in this work using LPE grown GaAs/AlGaAs materials and InGaAsP/InP materials. Both evanescent coupling and direct coupling approaches have been studied in these material systems. The progress of the work was hindered by complications associated with regrowth in both cases. More control of the growth and processing parameters is required to achieve high performance devices. Some efforts to fabricate DBR grating using electron beam lithography have been initiated and the results obtained have been very encouraging. A measurement scheme to view simultaneously the different wavelengths emitted by GaAs/AlGaAs lasers has been achieved. Finally, we have also proposed a simplified approach to make a two-section laser which can avoid some of the regrowth issues. The proposed structure, with a multiple quantum well incorporated and lattice disordering selectively employed to induce a bandgap shift at the control region, has the potential to achieve a large wavelength tuning range.

Fig.14 Storage scope trace of six different wavelengths emitted by a Mitsubishi laser. This spectral window range is around 100Å.(7740Å-7840Å)

References

1. R. F. O'Dowd, M. G. Davis, "Theoretical study of a two-section single-cavity semiconductor laser use as a wavelength-tunable source". *Optical and Quantum Electronic* 20, 383-393 (1988).
2. S. W. Coizine, L. A. Coldren, C. A. Burrus, and T. L. Koch, "Continuous tunability in the three-terminal coupled-cavity lasers". *Appl. Phys. Lett.* 48(18), 1190-1192, (1986)
3. H. Imai, Y. Kotaki, M. Matsuda, Y. Kuwahara, H. Ishikawa, "Wavelength tunable laser with wide tuning range". *CLEO MBI* 1988.
4. Tribhawan Kumar, Richard R. Ormondroyd, and T. E. Rozzi, "Numerical Solution of Lateral Current Spreading and Diffusion in Near-Threshold DH Twin-Stripe Lasers". *IEEE Journal of Quantum Electronics*, Vol QE-21, 421-433 (1985).
5. C. M. Knoedler and T. F. Kuech, "Selective GaAs/Al_xGa_{1-x}As reactive ion etching using Cl₂F₂. *J. Vac. Sci. Technol.* 4(5), 1235-1236 (1986).
6. M. G. Astles, H. Hill and V. W. Steward, "An experimental investigation of edge-growth effects in the LPE growth of GaAs and GaAlAs". *Journal of Crystal Growth* 62, 61-66 (1983).
7. L. D. Westbrook, A. W. Nelson and C. Dix. "High-quality InP surface corrugations in 1.55 μ m InGaAsP DFB Lasers Fabricated using Electron-Beam Lithography". *Electronics Letters* 18(20), 863-865 (1982).
8. P. G. Floyin, C. Dix and M. E. Jones, "Fabrication of devices for optical communication systems by electron beam lithography". *Br. Telecom. Technol. J.* 1(1) 43-50 (1983).
8. Semiconductors and semimetals Vol. 22 Part B pp 210-212 editor W. T. Tsang.
9. IF. Fiedler and A. Schlachetzki, "Selective epitaxy from the liquid phase on InP", *Journal of Crystal Growth* 53 623-626 (1987).

END

DATE FILMED

11 / 26 / 90