AFRL-SN-RS-TR-1999-14
Final Technical Report
February 1999

MONOLITHICALLY INTEGRATED COUPLED-LASER ALL-OPTICAL SWITCHING AND ROUTING ELEMENTS AND CIRCUITS

Cornell University

F. Robert and C. L. Tang

AIR FORCE RESEARCH LABORATORY
SENSORS DIRECTORATE
ROME RESEARCH SITE
ROME, NEW YORK

This report has been reviewed by the Air Force Research Laboratory, Information Directorate, Public Affairs Office (IFOIPA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

AFRL-SN-RS-TR-1999-14 has been reviewed and is approved for publication.

APPROVED:

MICHAEL A. PARKER
Project Engineer

FOR THE DIRECTOR:

ROBERT G. POLCE, Acting Chief
Rome Operations Office
Sensors Directorate

If your address has changed or if you wish to be removed from the Air Force Research Laboratory Rome Research Site mailing list, or if the addressee is no longer employed by your organization, please notify AFRL/SNDP, 25 Electronic Parkway, Rome, NY 13441-4515. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document require that it be returned.

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 1999	Final Feb 98 - Nov 98

4. TITLE AND SUBTITLE

MONOLITHICALLY INTEGRATED COUPLED-LASER ALL-OPTICAL SWITCHING AND ROUTING ELEMENTS AND CIRCUITS

5. FUNDING NUMBERS

C - F30602-98-C-0010
PE - 62702F
PR - 4600
TA - P6
WU - PM

6. AUTHOR(S)

F. Robert and C. L. Tang

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Cornell University
Office of Sponsored Programs
120 Day Hall
Ithaca NY 14853-5401

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory/SNDP
25 Electronic Parkway
Rome NY 13441-4515

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

AFRL-SN-RS-TR-1999-14

11. SUPPLEMENTARY NOTES

Air Force Research Laboratory Project Engineer: Michael A. Parker/SNDP/(315) 330-4918

12a. DISTRIBUTION AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release; distribution unlimited.	

13. ABSTRACT *(Maximum 200 words)*

Previous work on monolithically integrated coupled-laser all-optical switching elements and circuits showed that the threshold current for the in-plane lasers fabricated from wafers designed for vertical cavity surface emitting lasers (VCSEL) were too high to permit long-term room temperature continuous wave (cw) operation. Results on experiments aimed at reducing the threshold current for the coupled in-plane lasers are reported. Two approaches were evaluated: oxidation and lattice intermixing through zinc-diffusion. No definite reduction of the threshold current for the in-plane lasers was observed, even though oxidation did lead to marked improvement in the operation characteristics of the coupled VCSELs. Emphasis of current work is on determining the switching speed of such coupled-laser switching elements and circuits.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Semiconductor Lasers, Communications, Gain Quenching, Oxide Confined Vertical Cavity Surface Emitting Lasers (VCSELs)	24
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Ackowledgments

The authors wish to acknowledge the valuable technical collaboration with Dr.Michael Parker of the Rome Laboratory Photonics Center on this research program, and technical discussions and training from D. Shire, S. Pesarcik, A. Schremer and the staff of the Cornell Nanofabrication Facility. M. H. Hong of Bell Laboratories Lucent Technologies, K. Choquette from Sandia National Laboratories and C. Lei and L. Hodge from Hewlett Packard supplied some of the epitaxial materials used in the fabrication of the devices.

Monolithically Integrated Coupled-Laser All-Optical Switching Elements and Circuits

Executive Summary

Previous work on monolithically integrated coupled-laser all-optical switching elements and circuits showed that the threshold current for the in-plane lasers fabricated from wafers designed for vertical cavity surface emitting lasers (VCSEL) were too high to permit long-term room temperature cw operation. Results on experiments aimed at reducing the threshold current for the coupled in-plane lasers are reported. Two approaches were evaluated: oxidation and lattice intermixing through zinc-diffusion. No definite reduction of the threshold current for the in-plane lasers was observed, even though oxidation did lead to marked improvement in the operation characteristics of the coupled VCSELs. Emphasis of current work is on determining the switching speed of such coupled-laser switching elements and circuits.

TABLE OF CONTENTS

A. Introduction

Previous work on this project has demonstrated the effectiveness of coupled in-plane and vertical cavity lasers (coupled IPL and VCSEL) to perform basic optical logic operations for the purpose of switching and route such signals[1-2]. The basic idea is to monolithically integrate on the same chip different lasers with coupled gain sections. The feasibility of the basic device concept was demonstrated. The lifetime of the fabricated devices in CW operation at room temperature was, however, relatively short and the basic question of switching speed was not resolved.

The short lifetime of the coupled devices was short primarily because the threshold current for the in-plane laser part of the device was unacceptably high. Improved CW characteristics for the coupled devices require an improvement of the in-plane lasers. This is particularly difficult to achieve, because the epitaxial materials we are using for this work are standard wafers from Hewlett Packard or Sandia National Laboratory. They are mainly designed for improved VCSELs characteristics. Indeed we could achieve good operation of the VCSELs, with low threshold current on the order of few mA and reasonable output power in the range of few mW. But the epi structure was not designed for low-threshold in-plane laser operation. Moderate mode confinement and relatively high resistance of the structure tend to contribute to a high threshold current density and, therefore, to a short lifetime of the in-plane lasers under CW condition due to heating.

To alleviate this problem, we first tried to exploit oxidation confinement in the in-plane lasers. We first characterized this process and studied its influence on the IPL characteristics. Unfortunately, no improvements were obtained. We also investigated the possibility to reduce the overall resistance of the devices through a zinc diffusion. A weak improvement of the CW performance was obtained this way. This effort was discontinued for the moment. Our main effort at the present time is to determine the switching speed of the devices using femtosecond pulse injection.

In this report, we report preliminary results on the effects of oxidation and zinc diffusion on reducing the threshold current of in-plane lasers fabricated from Lucent/Bell Labs and Hewlett Packard VCSEL materials.

B. Oxidation

Ion implantation has been widely used for confinement of the injected carriers in semiconductors. For the last few years, selective wet oxidation of AlGaAs has also been successfully employed in the fabrication of efficient, low threshold current VCSELs [3]. The exposed layer then turns to a native oxide suitable for current and optical confinement.

Oxidation was conducted on both etched and cleaved samples. The samples were placed in the center of a furnace heated quartz tube. Because of the strong dependence of the depth of oxidation upon temperature, a great deal of attention was paid to minimizing all the heat losses in the line and to stabilizing the temperature. Water vapor was supplied to the tube by flowing nitrogen (at a constant flow of 4 SCFH) through heated water at 85^{o} C. The temperature inside the tube was monitored by a thermocouple close to the sample holder. The oxidation depth was determined using a Normaski microscope within a accuracy of 0.5 micron. It was measured as a function of time for a constant temperature of 410^{o} C.

In addition to the temperature dependence, the oxidation process is strongly dependent upon the Al content of the epi material. The estimated ratio of oxidation for pure GaAs and pure AlAs is on the order of 1:100. For current confinement, practical VCSEL wafers generally contain only one layer, with an Al content greater than 0.95, for a subsequent oxidation. The Bell Labs and Hewlett Packard wafers available to us for experimentation, unfortunately, did not have this special oxidation layer. Oxidation in the samples we tested involve oxidation of the all Al-containing layers in the mirror stacks.

We performed oxidation tests on two kinds of wafers, respectively from Bell Labs and Hewlett Packard. The DBR mirrors in both were of the same kind, consisting of alternating AlAs and low Al content layers (0.2 and 0.15, respectively, for Bell Labs and Hewlett Packard wafers) separated by graded interfaces. The oxidation rate was of 1.1 micron per minute for the Hewlett Packard material and 1.8 micron per minute for the Bell Labs wafer with an accuracy of 10%. A cross section examination of the samples revealed a strain induced delamination for the Bell Labs sample, while the Hewlett Packard one exhibited a clean oxidation front. Lasers fabricated from the Bell Labs sample never oscillated, as expected.

Unfortunately, it turned out that, while the oxidation led to improved characteristics of the VCSEL, it seemed to have deleterious effects on in-plane lasers obtained from the Hewlett Packard wafer, while lased, also did not exhibit good characteristics. The current threshold of oxide confined in-plane lasers was generally twice that obtained with ridge waveguide lasers processed in a previous run. They did not oscillate under CW condition, while the VCSELs worked perfectly.

This test allowed us to develop the control procedure for the oxidation process with good accuracy. It also showed that, with the design structure of the wafers used, the best performance of the in-plane lasers were from the ridge waveguide in-plane lasers. As a consequence, it was necessary to find a new way to improve the electrical characteristics of the devices. A zinc diffusion method was evaluated and the results of this attempt are given in the next paragraph.

C. Zinc Diffusion

In an attempt to modify the undoped AlGaAs supperlattices, Laidig et al discovered accidentally that the layers of a superlattice are unstable against zinc diffusion and intermix, thus yielding bulk, undamaged, homogeneous material of an Al composition average to that of the original structure[4]. From then, Impurity-induced layer disordering appeared very appealing to alter selectively desired regions in effective energy gap and refractive index, allowing the fabrication of heterojunctions perpendicular to the epitaxial layers. Three-dimensional structures can be realized leading to carrier and optical confinement.

Zn diffuses through the vacancies and leads to the intermixing of layers of different compositions to a layer of average composition[5]. It can be performed in limited areas using a suitable mask and, therefore, can be exploited to selectively intermix the top DBR mirror in VCSEL wafers. This should provide two advantages for in-plane laser operation: removing the multiple interfaces reduces the resistance, and the higher p-doping cause by the zinc improves the electrical contact at the metal-semiconductor interface. Zinc diffusion and its effect in our VCSEL wafer were evaluated.

Efficient Zinc diffusion requires high temperatures (higher than 600^0 C) and a suitable mask. We tested both silicon dioxide and silicon nitride masks deposited by PECVD. We found that a SiO_2 mask deposited at a temperature of 400^0 C and subsequently annealed by RTA at 450^0 C for 1 minute has good stability in the zinc diffusion process.

The SiO_2 mask was patterned using a standard lithography process. Zinc diffusion was then performed using the sealed ampoule technique[6]. The sample was loaded with a small amount of source $ZnAs_2$, Zn_3As_2 or a mixture of the two (25 mg) in an quartz ampoule of approximately 15 cm^3 volume. The ampoule was then evacuated to $2x10^{-5}$ Torr prior to sealing. The samples were loaded into the diffusion furnace which was preheated at 650^0 C. The furnace temperature was controlled to within 5^0 C. We performed tests with different diffusion time. Thermal decomposition of the source provided the necessary As overpressure to avoid any surface damage to the samples.

After the diffusion, the samples were cleaved and then inspected using either angle-lapping or a scanning electron microscope to measure the depth of diffusion. Both methods gave a accurate measurements of the depth of diffusion. Figure 1 shows the cross section of a VCSEL wafer which was zinc diffused through a SiO_2 mask for 1 hour at 650^0 C. The diffusion penetrated through the upper p-DBR stacks. Under the exposed areas, the supperlattice is totally intermixed right under the surface. The disordering is not complete in the deeper stacks. The diffusion process also appears isotropic: the areas protected by the SiO_2 mask are also intermixed close to the edge of the features.

The dependence of the diffusion depth versus time was investigated subsequently. An example of the results is presented in Figure 2. Two VCSEL samples were investigated, both from Hewlett Packard (E71-021-B6 and E71-204-B6). A bulk GaAs wafer was loaded in the same ampoule with each sample as a monitor sample. We first verified that the diffusion depth obeys a Fick's law, i.e., the diffusion depth depends directly on the square root of time. We also found that the diffusion process is much faster in the AlGaAs epi material than in bulk gallium arsenide. In the latter material, the diffusion depth was approximately 3 times smaller. The depth of the superlattice intermixing in the VCSEL wafers was approximately 2/3 than the depth of the zinc diffusion.

For our purpose, the diffusion should stop above the active region (clearly visible in the Figure 1), because zinc diffusion into the active layer would lead to a shift of the bandgap and a lower differential gain coefficient of the lasers because of the p-doping.

In-plane Laser Tests

To check the effect of zinc diffusion on the in-plane laser performance, in-plane lasers with and without zinc diffusion were fabricated in the sample of VCSEL wafer.

The design includes ridge waveguide lasers with lengths ranging from 200 to 600 microns and widths of 5, 7, 12 and 22 microns. The lasers were etched by Chemical Assisted Ion Beam Etching, with a Cr film as a mask. The facets of the lasers were either defined by the etching process, or by cleaving the wafer after processing.

Two wafers were processed. The first VCSEL wafer (E71-204-B6) had been optimized to define VCSELs through oxidation, while the second sample (E71-021-B6) had been optimized for ion-implantation. There are significant differences between the two wafers, mainly in the epi structure of the active layer. They were both designed with the same Quantum Wells (GaAs with $Al_{0.3}Ga_{0.7}As$ barriers) but embedded in different materials. The epi structure of E71-021-B6 emphasizes vertical mode confinement for the in-plane lasers, while the corresponding mode confinement from the E71-204-B6 wafer is expected to be poor.

The depth of the zinc diffusion, measured from a cleaved facet, reached the target value of 2.8 microns, while the depth of the active layer was 3 microns.

Threshold density:

The threshold density dependence versus the width of the ridge clearly shows that the devices suffer from carrier leakage. The measurements were performed under pulsed condition (1 microsecond pulse duration, 1 kHz repetition rate). Broad area lasers (22 microns wide) exhibit a threshold density of 1 kA/cm^2 but the narrowest ones up to 6 kA/cm^2.

The Zinc-diffused lasers generally present a higher threshold density than the non-diffused ones. The main reason for this behavior could be the increased free carrier absorption due to higher doping of the mode tail outside of the active layer.

Almost no lasing effect was obtained from the devices in the E71-204-B6 wafer, probably due to the poor vertical confinement of the optical mode mentioned above.

As expected, the threshold voltage of the zinc-diffused lasers is considerably lower than the non diffused ones (3 V versus 3.5 V).

The ultimate test to check the lifetime was performed with the lasers biased at twice the threshold current under CW condition. The output power generally dropped dramatically down within few minutes for both kind of lasers. Some Zn diffused devices exhibited a longer life time. We are presently evaluating whether the small improvement of the CW performance is sufficient to justify the additional processing step required to perform the zinc diffusion.

D. Conclusions and Future Work

Despite the efforts to improve the characteristics of the IPL, no definite improvements were obtained. We think that to achieve a significant improvement, a specifically designed epitaxial material is necessary to better fulfill the requirements for both in-plane lasers and VCSELs.

Our present goal is the study of the dynamical response of the gain quenching effect. This important characteristic has not been investigated up to now. We will first focus on the dynamical response of a VCSEL output to an injected optical pulse from a Ti:Sapphire mode-locked femtosecond laser. Depending on these results, the dynamical response of coupled devices will be studied.

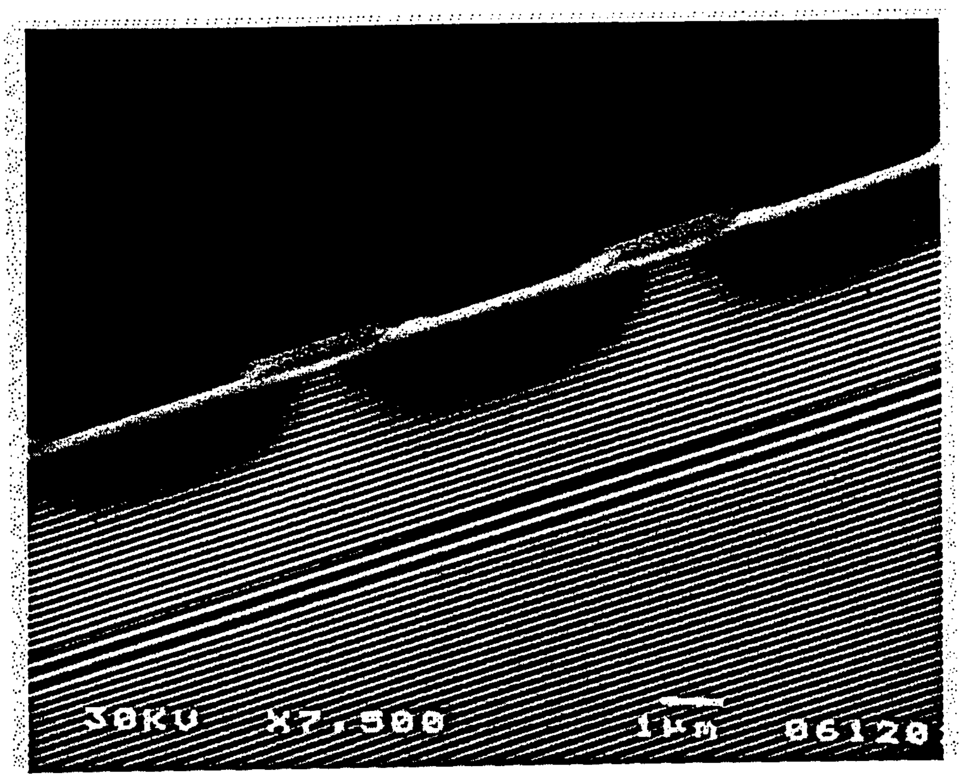

Figure 1: Zinc Diffusion through a VCSEL wafer E71-021 -B6. The diffusion takes place through the openings in a Silicon dioxide mask.

Width of the Ridge Waveguide (microns)	Non Zinc Diffused Lasers Threshold Current Density (kA/cm^2)	Zinc Diffused Lasers Threshold Current Density (kA/cm^2)
5	4.4	6
7	3.4	3.2
12	1.5	2
22	1	1.7

Table 1: threshold current density of 400 microns long In Plane Lasers of different widths, Zinc and non Zinc-Diffused.

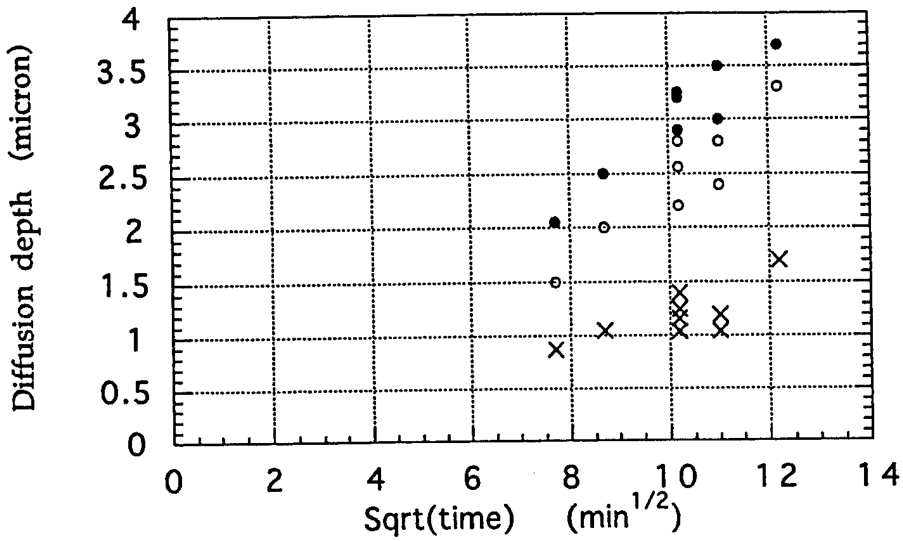

Figure 2: Zinc diffusion results in the E71-204-B6 VCSEL wafer at 650^0 C

Solid circles: depth of the zinc diffusion

Open circles: depth of the superlattice intermixing

Crosses: depth of the zinc diffusion in the bulk GaAs reference sample

References

[1] D.B. Shire, M.A. Parker, P.D. Swanson, J.S. Kimmet and C.L. Tang, "Multiple-Input Optical Control of Vertical Cavity Surface Emitting Lasers Using Intracavity-Coupled In-Plane Lasers", IEEE Photonics Technology Letters, vol.8. no 2, pp 188-190, 1996.

[2] D.B. Shire, C.L. Tang, M. Hong and J.D. Wynn, "Coupled In-Plane and Vertical -Cavity Lasers 1xN routing Switches", IEEE Photonics Technology Letters, vol.8. no 11 pp 1537-1539, 1996.

[3] "Advances in Vertical Cavity Surface Emitting Lasers", OSA trends in Optics and Photonics Series, Series Editor Tingye Li, AT&T Labs, 1997.

[4] W.D. Laidig, N. Holonyak, Jr, M.D. Camras, K. Hess, J.J. Coleman, P.D. Dapkus and J. Bardeen, Applied physics Letters, 38, 776, 1981.

[5] D.G. Deppe and N. Holonyak, Jr, "Atom diffusion and impurity-induced layer disordering in quantum well III-V semiconductor heterostructures", Journal of Applied Physics, 64, 12,15 dec. 1988, R 93-113.

[6] V. Quintana, J.J. Clemencon and A.K. Chin, " Sealed-ampoule diffusion of zinc into $GA_{1-x}Al_xAs$ at 650 C", Journal of Applied Physics, 63, 7, 1 April, 1988.