REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-04-

0156

1. REPORT DATE *(DD-MM-YYYY)* 05-JAN-2004	**2. REPORT TYPE** ANNUAL/FINAL REPORT	**3. DATES COVERED** *(From - To)* 15 MAR 2000 ~~30 NOV 2002~~ - ~~30 NOV 2003~~

4. TITLE AND SUBTITLE

P-N Junction Diode Ultra-VIolet Lasers with DIrectional Emission from Non-Circular Optical Cavities for Bio Sensing APplications

5a. CONTRACT NUMBER F49620-00-1-0182

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Richard K. Chang

5d. PROJECT NUMBER

5e. TASK NUMBER 2305/EV

5f. WORK UNIT NUMBER

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

Department of Applied Physics
Yale University
P.O. Box 208284
New Haven, CT 06520

8. PERFORMING ORGANIZATION REPORT NUMBER

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

Lt. Col. Todd Steiner
Optoelectronic Materials Program Manager
Physics and Electronics Directorate
Air Force Office of Scientific Research

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution Statement A: unlimited

20040315 004

13. SUPPLEMENTARY NOTES

14. ABSTRACT

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During the October 2002 site visit of Lt. Col. John Carrano of DARPA and program manager of the SUVOS program, it became apparent that the low scale collaboration between Yale and PARC was so successful and providing exciting possibilities, that Lt. Col. Carrano stepped up the funding for PARC to increase their collaboration efforts with Yale. Therefore, besides just providing samples for us in our optical pumping approach, as was the case in the past, PARC began to actively investigate the electrical pumping approach with close collaboration with the Yale group

15. SUBJECT TERMS

microcavities, spiral-shaped microcavities. AIGaN, InGaN quantum wells, electrical pumping, optical pumping

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

P-N JUNCTION DIODE ULTRA-VIOLET LASERS WITH DIRECTIONAL EMISSION FROM NON-CIRCULAR OPTICAL CAVITIES FOR BIO SENSING

ANNUAL PERFORMANCE REPORT

RICHARD K. CHANG

30-NOV-2002 – 30-NOV-2003

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

F49620-00-1-0182

YALE UNIVERSITY

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1) Overall Program Objective

The overall program objective is to develop an on-chip-emitting UV μ-laser that is able to excite optimally the fluorescence from tryptophan in bio-aerosols. This objective requires that we design different 2-d cross section for the μ-pillar (≈ 2 μm high) lasers that will have low lasing threshold and have directionality in the emission. Unlike surface emitting lasers that need distributed Bragg reflectors (DBR's) to provide the feedback and output coupling, the edge-emitting μ-pillar lasers use the sidewalls to provide feedback (via total internal reflection) and a specific location along the sidewalls for output coupling (via refraction according to Fresnal laws). For the AlGaN systems, DBR's are difficult to fabricate because these reflectors must be both electrically and optically optimized. For the task of lowering the lasing thresholds for the edge emitting μ-pillar lasers, we must investigate the optical and electrical pumping geometry that have maximum spatial overlap with modes within the μ-pillars. For the task of achieving narrow beam directionality, we must judiciously design the 2-d cross-sectional shape. The resulting non-circular shaped μ-pillar lasers necessitated that we understand some of the principles of chaos theory.

The objectives of the past 12 months has been directed toward greater understanding of the laser emission from the spiral structure and achieving for the first time, electrically pumped spiral micro-lasers. Another objective was to develop μ-amplifiers which could increase the output emission.

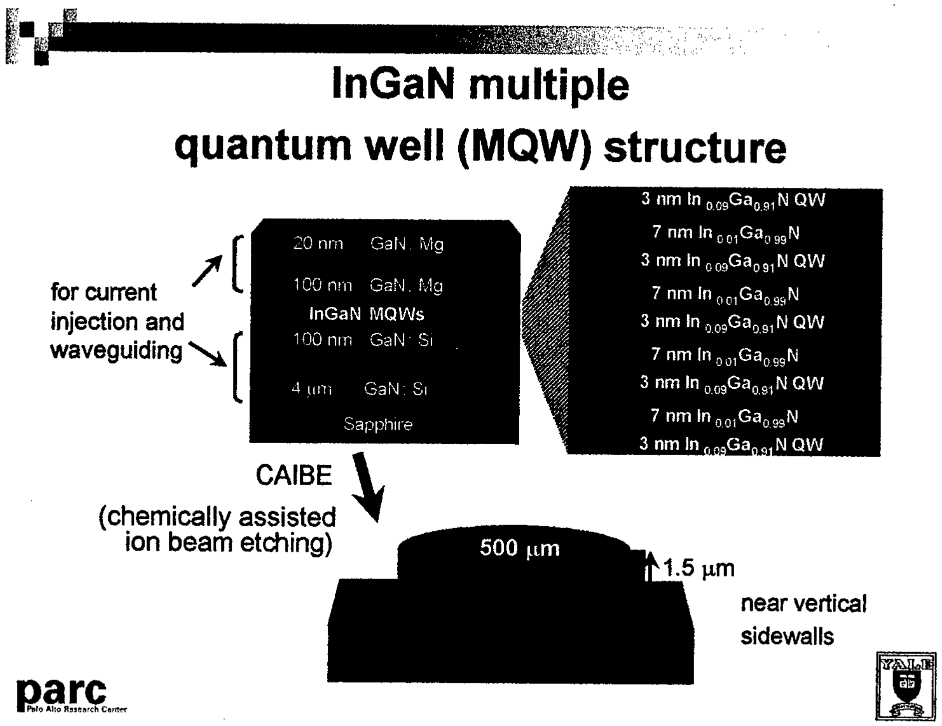
During the October 2002 site visit of Lt. Col. John Carrano of DARPA and program manager of the SUVOS program, it became apparent that the low scale collaboration between Yale and PARC was so successful and providing exciting possibilities, that Lt. Col. Carrano stepped up the funding for PARC to increase their collaboration efforts with Yale. Therefore, besides just providing samples for us in our optical pumping approach, as was the case in the past, PARC began to actively investigate the electrical pumping approach with close collaboration with the Yale group.

2) Significant Accomplishments

a) Electrical Pumping

We have optically pumped a laser structure designed specifically for electrical pumping. In the figure below (Fig.1) the details of the electrically pumped μ-lasers with spiral shaped cross-sections are shown. Note particularly the five layers of quantum wells of GaInN and the separate layers of AlGaN for confinement of the internal radiation. These quantum wells emitted at 407 nm.

PARC designed the geometry of the electrodes for electrical pumping based on the Yale group's work on selective optical pumping where the pumped area should correspond to the region where the optical modes are confined within the μ-cavity. The metallic electrodes could be placed on the top face of the μ-pillar without being concerned of the mask-obscuration effect since the light is not coming out from the top face. PARC found that all 3 electrode geometries (circular, spiral and combination) could be used for lasing. These geometries could be seen in Fig. 2. Note that the electrode geometry follows the perimeter of the spiral structure at the lowest threshold and that the "combination geometry" in Fig. 2 has the lowest threshold.



InGaN multiple
quantum well (MQW) structure

20 nm GaN: Mg
100 nm GaN: Mg
InGaN MQWs
100 nm GaN: Si
4 µm GaN: Si
Sapphire

for current
injection and
waveguiding

3 nm $In_{0.09}Ga_{0.91}N$ QW
7 nm $In_{0.01}Ga_{0.99}N$
3 nm $In_{0.09}Ga_{0.91}N$ QW
7 nm $In_{0.01}Ga_{0.99}N$
3 nm $In_{0.09}Ga_{0.91}N$ QW
7 nm $In_{0.01}Ga_{0.99}N$
3 nm $In_{0.09}Ga_{0.91}N$ QW
7 nm $In_{0.01}Ga_{0.99}N$
3 nm $In_{0.09}Ga_{0.91}N$ QW

CAIBE
(chemically assisted
ion beam etching)

500 µm
1.5 µm
near vertical
sidewalls

Fig. 1. This hetero-junction MOCVD µ-pillar is specifically designed for electrical pumping and the cross-section of the µ-pillar is of spiral shape. The emission of the 5 InGaN MQWs is at 407 nm and the uni-directional emission emerges from the notch of the spiral shaped cavity. The radiation is guided from escaping from the top and the bottom faces by 2 separate layers of AlGaN.

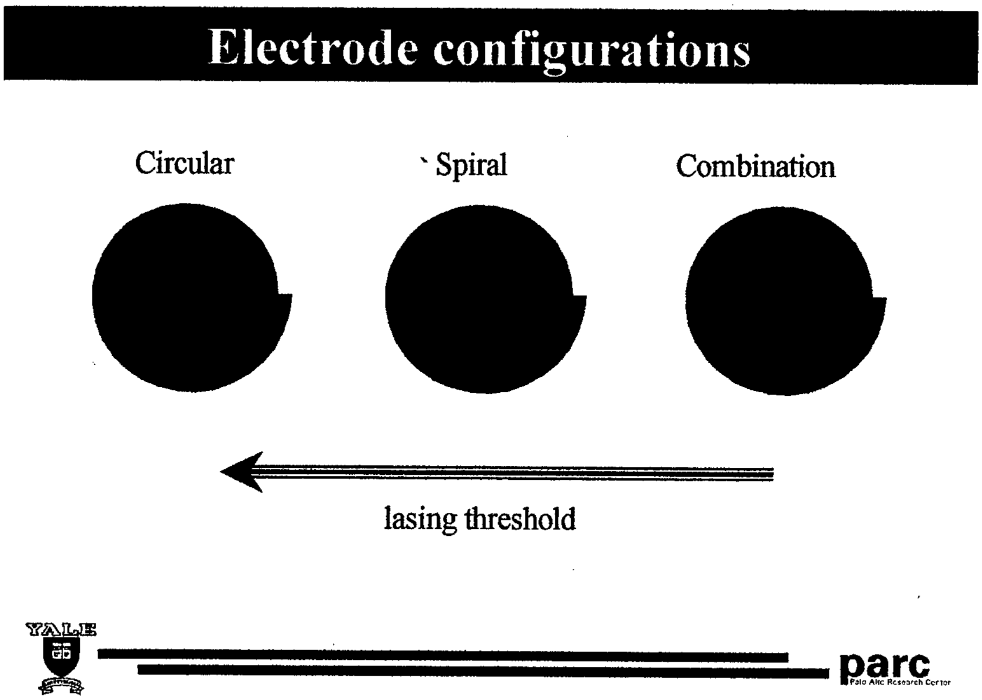


Fig. 2. The 3 electrode geometries for electrically pumping the top face of the μ-pillars are shown here. The combination has the lowest lasing threshold. The electrodes that are coated along the perimeter of the spiral shaped μ-cavity has slightly higher lasing threshold. The spiral shaped in a circular ring fashion has the highest threshold, implying that the lasing modes are not in the form of a circle.

Three criteria were used to determine that the electrically pumped μ-structure was indeed lasing. They are: 1) spectral narrowing of the output emission as the pumping current increased; 2) the output intensity versus pumped current exhibits the spontaneous fluorescence region, amplified spontaneous emission (ASE) region and finally, the saturation region is reached as the pumped current reached the maximum allowed by heating considerations; and 3) the emission is omni-directional before reaching the lasing threshold when it becomes unidirectional. All the work has been done with a pulsed electrical pumping approach.

b) Preliminary Theory of Spiral Shaped μ-Cavity

For μ-cavity with circular cross-section, the counterclockwise wave (CCW) and the clockwise wave (CW) are degenerate and form a standing wave. However, for the spiral geometry, chirality exists. The CCW and the CW are no longer equal (Fig.3). The CCW encounters the notch and with a high Fresnel transmission escapes from the cavity. The CW is diffracted and thereby converting a small part of the CW to CCW. Furthermore, the surface wave associated with the internal CW gets reflected at the notch and becomes a part of the output wave. The theory developed by Hakan Tureci of Professor Douglas Stone's group at Yale, is not sophisticated enough to provide a Q value of the CCW and CW. Nor is the theory ready to calculate the outward coupling coefficient.

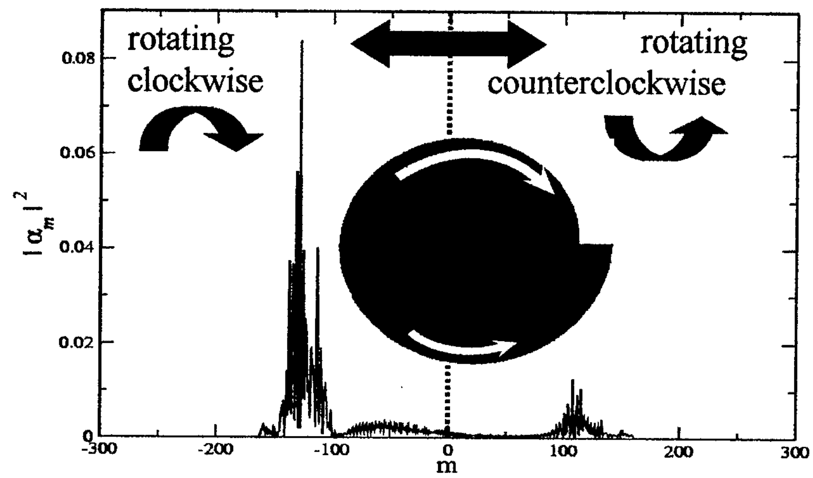


Fig. 3. This figure depicts the internal fields of a spiral shaped μ-cavity. The outward coupling for the counterclockwise wave (CCW) is through Fresnel transmission. The output coupling for the clockwise wave (CW) is partial conversion of the CW determined by the 90° corner of the notch and the diffraction by the notch of the surface wave associated with the CW.

The preliminary theoretical analysis of the internal and external fields in terms of cylindrical Bessel functions can be seen in Fig. 4. The false color plot depicts the internal and external intensities. This particular theoretical plot made the cover of Applied Physics Letters (September 2003) and was picked up by Nature's News and Views section. Figure 4 also shows the far-field intensity in a polar plot. Note that the polar plot shows the output lobe to be tilted from the normal to the notch. Whether this tilt is power dependent remains to be observed. The theory has not been worked out yet.

4) Interaction with Other Institutions

We continue to have strong interactions with Professor Joseph Zyss' group in Ecole Normale Superieure in Cachan, France. All of our dye-doped PMMA μ-pillars were grown and etched by this group, much to our appreciation. One of Prof. Zyss's student Tahar Ben Messaoud , came to work in our laboratory for over 5 months. Partially based on the work done here at Yale, he will be defending his Ph.D. thesis on December 5, 2003 and I have been asked to be one of the four examiners.

We also have a strong interaction with Professor Jean-Pierre Wolf's group in the University of Lyon, Lyon, France. They have started studying the dynamics of the 100 femtosecond laser pulses of a spiral-shaped InGaN μ-pillars. With the permission of PARC, we have been sending them our extra wafers with various cross-sectional shaped μ-pillars.

There is strong collaboration with Drs. Steven Hill and Ronald Pinnick of the U.S. Army Research Laboratory, Adelphi, Maryland. This collaboration has enabled them to set up a dispersed fluorescence instrument capable of measuring the fluorescence of individual ambient aerosols. In addition, this collaboration has enabled us to work as a team on three other projects supported by DARPA, U.S. Air Force Research Laboratory.

The close collaboration with PARC has been presented throughout this report.