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**III-V HETEROJUNCTION STRUCTURES FOR
LONG-WAVELENGTH INJECTION LASER**

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TABLE OF CONTENTS

Section	Page
I. OBJECTIVE	1
II. PROGRESS	2
A. 1.4- μ m Wavelength Lasers	2
B. 1.1- μ m Wavelength Lasers	5
III. PLANS FOR NEXT QUARTER	7
IV. FINANCIAL STATUS	8
V. DISTRIBUTION	9

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SECTION I

OBJECTIVE

The long-term objective of our research program is to develop high-quality heterojunction lasers (pulsed and cw) and photodiodes capable of operating at any desired wavelength primarily between 0.92 and at least 1.7 μm , although wavelengths in excess of 2.0 μm should be feasible. In this second phase of our program, the use of vapor-grown quaternary alloys will be evaluated in heteroepitaxial device structures. These structures are comprised of (In, Ga) (As,P) and InP layers deposited primarily onto InP substrates.

SECTION II

PROGRESS

In the first quarter of our quaternary InGaAsP program, we calibrated and optimized the various flow parameters essential to the vapor deposition of this material; we also characterized InP substrates presently available, and established a reasonable chemical polishing technique for preparing substrates for subsequent vapor deposition. Details of these efforts were reported in Quarterly Report No. 4.

In the present quarter, we began the preparation of double-heterojunction laser structures of InGaAsP/InP. Two different reactors were employed for these devices: one for structures with emission wavelengths between 1.1 and 1.2 μm , and the other for structures with wavelengths near 1.4 μm . Progress with both structures has been very rapid; room-temperature pulsed lasers have been consistently obtained, with threshold currents as low as 2400 A/cm² at 1.38 μm , and 3830 A/cm² at 1.12 μm . Details of these structures are given below.

A. 1.4- μm WAVELENGTH LASERS

The InGaAsP alloys prepared for heterojunction structures at 1.4 μm have an energy bandgap of approximately 0.83 eV. The composition used to achieve this value, while matching the InP lattice parameter (5.869 Å), is about $\text{In}_{0.69}\text{Ga}_{0.31}\text{As}_{0.71}\text{P}_{0.29}$. Comparison of measurements for energy bandgap (by optical absorption), alloy composition (by electron microprobe analysis), and lattice parameter (by x-ray diffraction) established the general validity of the previously-published set of curves relating E_g , x , and a_0 for the regime around 0.8 eV. Furthermore, the reproducibility of vapor-grown alloy composition (within about 1%) was established by the virtual agreement of E_g , x , and a_0 on two successive runs.

Next, a series of double-heterojunction lasers was prepared consisting of a homoepitaxial vapor-grown layer of n-type InP on the n-type InP substrate, followed by an n-type $\text{In}_{0.69}\text{Ga}_{0.31}\text{As}_{0.71}\text{P}_{0.29}$ active layer, a p-type InP confining layer and a p-type $\text{In}_{0.69}\text{Ga}_{0.31}\text{As}_{0.71}\text{P}_{0.29}$ capping layer to facilitate contacting. The electrical properties, as determined from Hall-effect measurement, of these layers are given in Table I.

TABLE I. ELECTRICAL PROPERTIES OF LAYERS IN LONG-WAVELENGTH LASER STRUCTURES

<u>Layer</u>	<u>Alloy Composition</u>	<u>Doping Type</u>	<u>Carrier Concentration (cm⁻³)</u>	<u>Mobility (cm²/V-s)</u>
1	InP	n (S)	1.6×10^{17}	2,770
2	InGaAsP	n (S)	4.4×10^{17}	3,180
3	InP	p (Zn)	1.1×10^{18}	57
4	InGaAsP	p (Zn)	6.1×10^{18}	49

The preliminary characteristics of lasers fabricated from these double-heterojunction structures are summarized in Table II. Here, room-temperature threshold current density values for six of our last seven runs are seen to be below 7000 A/cm^2 with a minimum value of 2400 A/cm^2 . These current densities are nearly low enough to achieve cw operation at room temperature.

A plot of the threshold current densities in Table II versus the laser cavity thickness (for those samples where the thickness has thus far been determined) shows that J_{th} decreases monotonically with cavity thickness. Accordingly, future samples will be prepared with cavity thickness near or below $0.12 \mu\text{m}$, so that still lower threshold currents can be obtained. We also should add that the differential quantum efficiency value measured on a few of these lasers is on the order of 30%, which is typical of that obtained from our ternary InGaAs/InGaP lasers developed earlier in this program. Measurement of the emission wavelength has been initiated, and for sample 2306 - 1.5" it is $1.38 \mu\text{m}$. The other samples are expected to be close to this value.

Our investigation of InP polishing etches has continued. In the previous report, results using a bromine-methanol solution were given. This solution is rapid and effectively removes work damage, however the resulting surface is not quite as smooth as desired. Accordingly, bromine-methanol solutions containing phosphoric acid have been recently investigated. The results for this etchant are given in Table III. Solutions (3) and (5) appear to yield very good surfaces, although the polishing rate is somewhat slower than that of

TABLE II. PROPERTIES OF InGaAsP/InP 1.4- μ m DH LASERS

<u>Sample</u>	<u>t_{cav} (μm)*</u>	<u>J_{th} (A/cm²)</u>
2292 - 2"	-	2385
-1.5"	0.15	2630
2298 - 2"	0.25	5810
-1.5"	-	6590
2299 - 2"	-	6460
-1.5"	0.17	7675
2300	NO LASING, BAD In	
2340 - 2"	0.27	6235
-1.5"	-	4310
2306 - 2"	-	4170
-1.5"	0.20	3230
2307 - 2"	0.22	4030
-1.5:	0.12	2390

*From SEM

TABLE III. ETCHING CHARACTERISTICS OF BROMINE-METHANOL-PHOSPHORIC SOLUTIONS ON InP

<u>No.</u>	<u>Bromine, Phosphoric Acid Concentrations in 100 ml of Methanol</u>			<u>Etching Rate (μm/min)</u>	<u>Surface Appearance</u>
	<u>Br</u>	<u>-</u>	<u>H₃PO₄</u>		
(1)	1 ml		40 ml	0.44	Good
(2)	2 ml		80 ml	0.25	Good (sol. loses Br upon standing)
(3)	2 ml		40 ml	0.69	Very Good
(4)	3 ml		40 ml	2.17	Large Surface Defects
(5)	3 ml		60 ml	0.95	Very Good

the standard 1% bromine-methanol solution. It also appears that different solutions might be required for InP substrates originating from different vendors, so our work on polishing techniques is expected to continue.

B. 1.1- μm WAVELENGTH LASERS

For this wavelength range, the desired lattice-matching quaternary alloy is $\text{In}_{0.84}\text{Ga}_{0.16}\text{As}_{0.31}\text{P}_{0.69}$. During the past quarter, double-heterojunction lasers of InGaAsP/InP have been grown for emission near 1.1 μm . To date, several of these structures have been found to be capable of room-temperature lasing, with the lowest threshold current density from them being 3800 A/cm². Differential quantum efficiencies of a few of these samples are about 30%, like those of our long-wavelength quaternary lasers described above. For one double-heterojunction structure, a portion of the wafer was fabricated into oxide-defined stripe-contact lasers, which were found to have threshold currents as low as 375 mA at room temperature (See Fig. 1). Devices of this type are presently being evaluated for the purpose of attaining cw operation near room temperature.

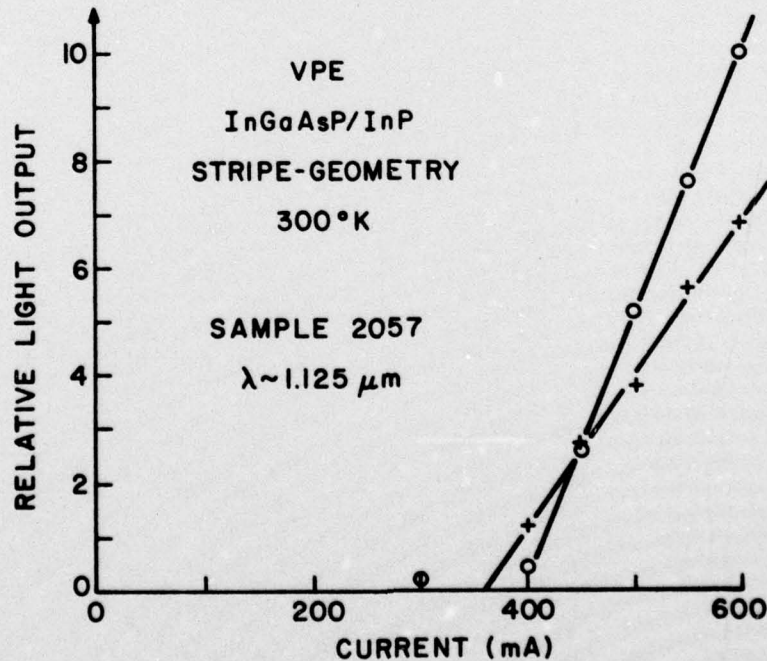


Figure 1. Relative light output vs input current for a stripe-contacted 1.1- μm DH laser.

We should note that our photoluminescence facility has recently been modified to allow its use to wavelengths as long as 1.8 μm . This required the addition of a high-power argon laser (2-W cw maximum) and a Ge photodiode. Photoluminescence evaluation of the InGaAsP layers is used daily as a means of providing information on alloy composition (from the photoluminescence wavelength coupled with x-ray measurements of the lattice constant) and on crystal quality (from the relative photoluminescence intensity under standardized measurement conditions).

SECTION III

PLANS FOR NEXT QUARTER

1. Double-heterojunction laser structures of InGaAsP/InP will continue to be grown for emission near 1.1 μm and 1.4 μm at room temperature. Emphasis will be on reducing the laser threshold further to allow the devices to reach cw operation at room temperature.
2. A study of photodiode structures at both wavelengths will begin after cw operation is attained.

SECTION IV
FINANCIAL STATUS

As of 30 Nov. 1977, \$229,000 has been charged to this ARPA contract in support of our heterojunction program.