

Experimental Fabrication of One-dimensional GaAs Laser Arrays

Abstract: Arrays of GaAs injection lasers have been fabricated for use in an experimental EuO film memory system. Planar-type array structures are formed by diffusing zinc through parallel slots in a diffusion mask on a GaAs wafer. Details of fabrication are given and some initial test results on operating characteristics and life performance are reported.

Introduction

Efficient, reproducible and reliable GaAs injection lasers provide a useful source of energy for thermal writing on magnetic films. The details of a memory system based on GaAs lasers writing on EuO films have been described by Fan and Greiner[1] and Eschenfelder[2]. The results of an investigation undertaken to develop laser arrays for use in such a system are described in this paper.

The design of the laser arrays had to take into account the following general requirements and constraints of the memory system:

- 1) Because the low Curie point of the EuO film requires it to be kept at temperatures at least as low as 77 K, the lasers are operated at the same temperature. This is an advantageous feature because the performance of GaAs lasers is greatly improved by cooling.
- 2) Although writing, which requires appreciable power, is accomplished by selectively pulsing the lasers, duty cycles must be high so that essentially cw operation of the lasers is required. High-efficiency lasers are needed to supply the high writing power. The power required for reading is considerably lower.
- 3) The laser junctions have to be narrow in order to keep the bit size small and the optics should be of a simple configuration. Also, the lasers must be closely spaced.
- 4) The lasers must have long operating life.
- 5) An important requirement was that laser characteristics within the array be reasonably uniform.
- 6) A useful memory system would require a large number of lasers and the ultimate cost per laser, therefore, must be low.

Elsewhere in this Journal[3] Sprokel describes another approach to the laser array fabrication process, using a different zinc diffusant masking, and heat sink fabrication. Also, Wieder and Werlich[4] report their measurements of laser arrays produced by these processes.

General fabrication process

Of the several possible ways to fabricate lasers, including vapor-phase epitaxy[5], liquid-phase epitaxy[6,7], and zinc diffusion[8-10], the last is the simplest and probably the lowest in cost. Moreover, for operation at 77 K, lasers made by zinc diffusion are at least as good as the best produced by the other two methods. Therefore, the zinc-diffusion approach was taken.

With the zinc-diffusion process two different types of laser array structures are possible: the "mesa" type, made by etching narrow parallel mesas in a diffused wafer, and the "planar" type, made by diffusing zinc through parallel slots in a diffusion mask on a GaAs wafer. Initially, both types of structures were explored but, because the planar structure was thought to be more amenable to mass production, it was chosen to be studied and the fabrication method will be described here.

Detailed fabrication process

• GaAs material and preparation

Bridgman-grown ingots of GaAs doped with tin in the 1 to $3 \times 10^{18}/\text{cm}^3$ range are sliced into wafers with major faces in the {100} orientation. One major face of each wafer is chemically polished. Al_2O_3 films 700 to 1500 Å

thick are rf sputtered on the polished faces at about 300°C.

A small piece of the wafer is cleaved away to find and to expose a (110) plane. Standard photoresist techniques and phosphoric acid (at about 90°C), were used to etch parallel slots 0.005 mm wide into the Al_2O_3 film 0.1 mm apart, parallel or perpendicular (thus in a $\langle 110 \rangle$ direction) to the cleaved edge. The Al_2O_3 acts as a mask against the zinc diffusion[11]; the slots thus will permit the formation of p-regions of approximately semicylindrical shape in the n-type GaAs wafer.

• The diffusion step

In order to obtain the narrow junction widths required, the junctions have to be shallow. If alloyed ohmic contacts are made subsequent to the zinc diffusion, shorting through the p-region sometimes occurs. It was found that rhodium can be electroplated on the GaAs in the slots in the Al_2O_3 masking film and that the rhodium does not form a liquid with the GaAs at diffusion temperatures[12]. Moreover, the zinc diffuses readily through the rhodium. Thus, a smooth, nonshorting ohmic contact is made to the shallow p-regions. The rhodium plating thickness is estimated to be about 1000 to 2000 Å.

In order to obtain shallow junctions using the desired diffusion temperatures of 750° and 850°C, a relatively low zinc vapor pressure and a moderate arsenic vapor pressure are maintained in the diffusion ampoule. These two conditions are met by the use of a new diffusion source, an InAs wafer about 0.5 mm thick which has been saturated with zinc by being sealed off in an ampoule with pure zinc and heated at 750°C for about 65 hours. Using such a source for diffusing zinc into GaAs results in a zinc concentration on the surface of the GaAs of about 2 to $4 \times 10^{19}/\text{cm}^3$. Contact resistances between the rhodium and the p-regions of the GaAs can be reduced by including a small amount of Cd_3As_2 or CdAs_2 in the diffusion ampoule. This raises the acceptor surface concentration on the GaAs to about $1 \times 10^{20}/\text{cm}^3$; because cadmium diffuses much more slowly than does zinc, the junction properties are apparently unaffected.

The actual diffusion procedure is as follows; The prepared GaAs wafers plus a zinc-saturated InAs wafer and about 1.0 mg Cd_3As_2 are sealed in a silica ampoule 11 mm i.d. and 75 mm long. The ampoule is held at 750°C for two hours and then at 850°C for one-half hour.

After diffusion, the wafers are lapped to a thickness of 0.1 mm. A cleaved and stained edge of such a wafer is shown in Fig. 1(a). The junctions shown are 3 μm deep, 14 μm wide and 100 μm apart.

A diffusion problem sometimes encountered is shown at higher magnification in Fig. 1(b). It is seen that zinc

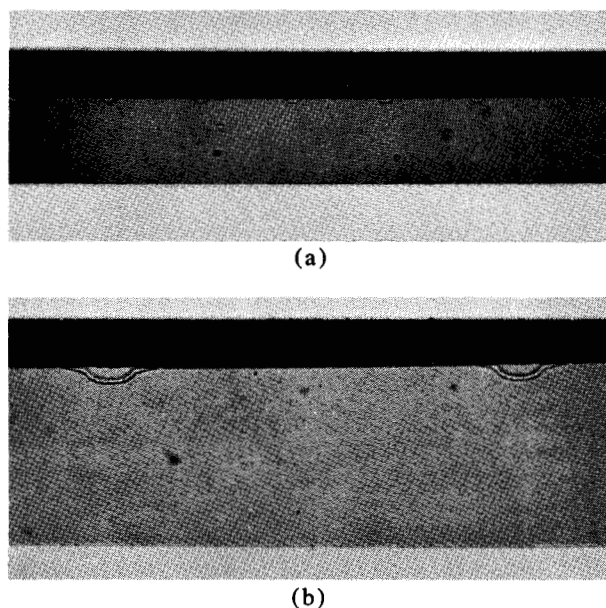


Figure 1 A cleaved and stained edge of a diffused wafer. (a) In this wafer the junction profiles are 3 μm deep, 14 μm wide and 100 μm apart. (b) Here "winging" (see Ref. 3) has occurred. The junction profiles are 4 μm deep, 28 μm wide overall and 100 μm apart.

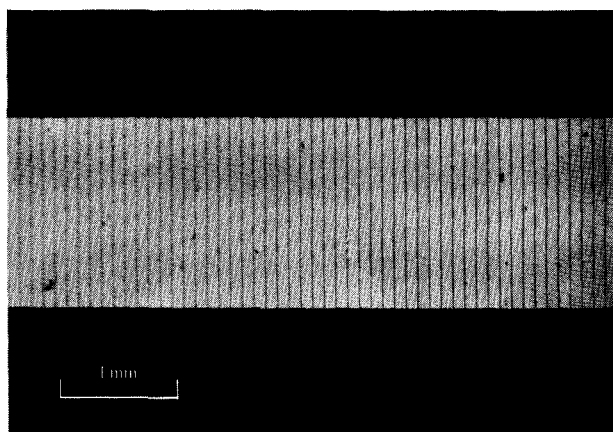
diffusion has occurred preferentially between the GaAs and the masking film. There are probably several causes for this preferential diffusion but the phenomena are not well understood. It is believed that it depends upon the adherence and quality of the Al_2O_3 masking film.

• Application of ohmic contacts

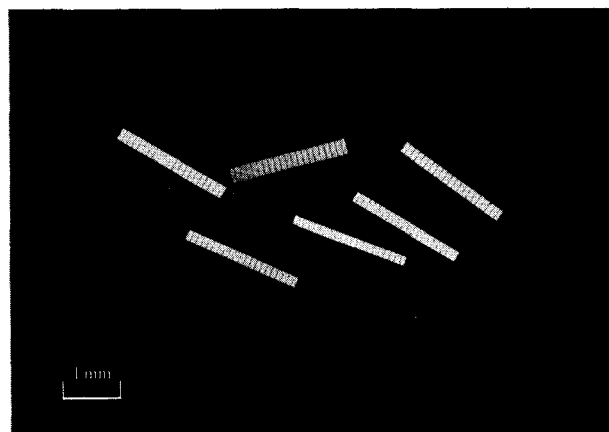
Lapping the wafer to 0.1 mm removes the zinc-diffused layer on the bottom of the wafer, and an n-type ohmic contact is required thereon. As mentioned in the previous section, ohmic contacts to the p-regions have already been made by the electroplating of rhodium on the GaAs prior to the diffusion.

That upper surface is next masked with a plating resist. The lower, lapped surface is cleaned briefly in $\text{NH}_4\text{OH}:\text{H}_2\text{O}_2::1:1$ and rinsed with water. The wafer is then immersed for about 30 secs in an electroless plating solution which deposits gold and a small amount of tin on the lapped surface. This solution is an aqueous solution of $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ to which a small amount of a tin compound has been added. In an indium fluoborate solution, about 0.5 μm of indium is electroplated over the Au:Sn.

The plating-resist mask on the upper surface is removed. The wafer is then placed on a hot stage with a forming gas atmosphere, heated rapidly to 450°C, and cooled rapidly. On both the n-type lapped surface and the rhodium stripes on the upper surface, indium is then electroplated to a thickness of 1 to 2 μm . The up-



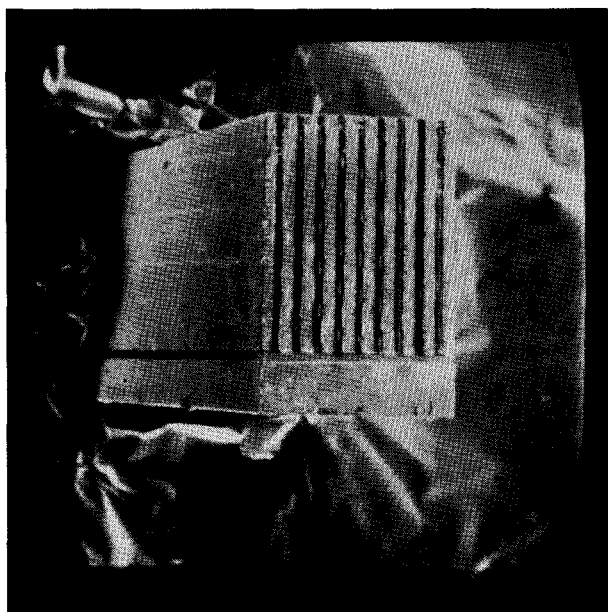
(a)



(b)

Figure 2 (a) The upper surface of a diffused wafer with the ohmic contact metallization applied. The indium-plated rhodium stripes are in a $[110]$ direction, and are $100\text{ }\mu\text{m}$ apart. (b) Cleaved laser bars 2 mm long of various widths. Each bar contains 20 lasers.

Figure 3 A scanning electron micrograph of an early laser array. The GaAs bar is 2 mm long and contains 10 lasers. The 0.625 mm thick copper bar on the bottom makes contact with the bottom of the laser bar. Each of the 10 copper plates in the upper member makes contact with a laser.



per surface of a typical wafer at this stage is shown in Fig. 2(a). The fine lines are the rhodium stripes overlaid with indium, and are 0.1 mm apart.

• Cleaving and sawing of laser bars

In order to facilitate cleavage of the laser bars in the proper direction, the GaAs wafers should have their major surfaces in a (100) plane. Thus, if the slots in the Al_2O_3 masking film are aligned in one of the $\langle 110 \rangle$ di-

rections, the laser bars can be cleaved in the other $\langle 110 \rangle$ direction perpendicular to the slots. Bars are usually cleaved 0.15 to 0.30 mm wide. This is the length of the individual lasers in the bar and the smooth cleaved edges of the bars comprise the partially reflecting mirrors required for the laser cavities.

As stated earlier, the total number of lasers required for a system would be very large and would require that the arrays be of modular arrangement. It was decided somewhat arbitrarily to put 20 lasers in each array module; this number could be increased or decreased later, depending upon yield and other considerations. Consequently, because laser spacing in the present design is 0.1 mm , the cleaved bars are cut into lengths of 2 mm . Figure 2(b) shows some typical laser bars of various widths.

Bars on which the edges were mechanically polished to provide the laser mirrors do not show any improvement in laser characteristics over lasers with cleaved edges. Moreover, polished bars require additional processing steps.

• Heat-sink mounting of laser bars

The general scheme of mounting the laser bars follows that of heat-sink mounting of individual lasers[13] in that indium-to-indium cold welded contacts are used. Indium-plated regions of the laser bar are pressed at room temperature against mating indium-plated regions of the heat-sink package. Such a system yields good electrical and thermal contacts.

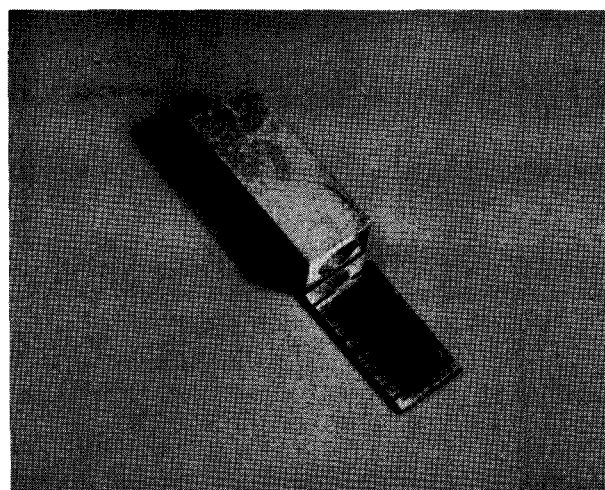
An array package fabricated early in the development work is shown in Fig. 3. This consisted of a 2 mm bar with 10 lasers in it positioned between a 0.625 mm copper bar on the bottom and a laminated bar on the top. The laminated bar was cut from a larger laminated plate

made up of 10 sheets of copper 0.15 mm thick, insulated from one another by 0.05 mm of fiberglass-epoxy. Each copper laminate rested on an indium-plated stripe of the p-region of a laser. The purpose of the relatively massive laminates was to provide adequate heat-sinking for cw operation. Behind the laser bar there was a fiberglass-epoxy spacer ≈ 0.09 mm thick; the spacer, the upper laminated bar, and the lower copper bar were bonded together with epoxy.

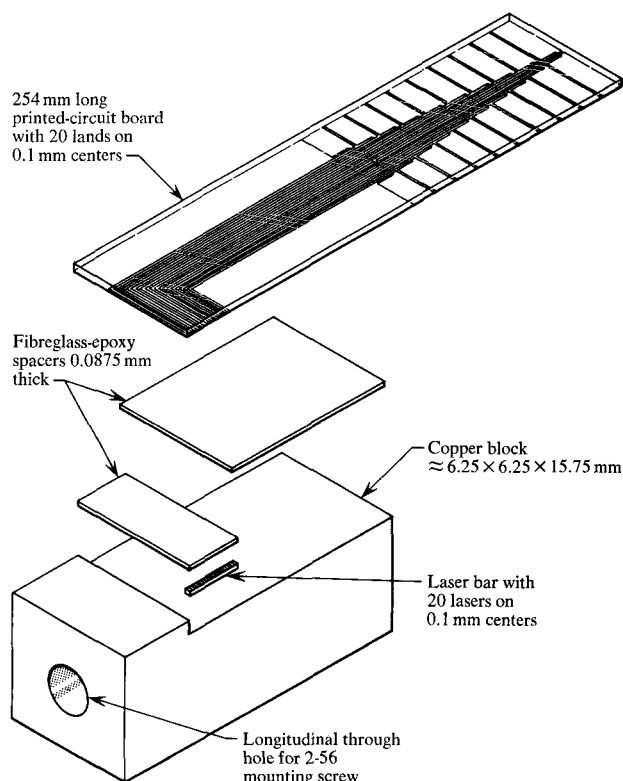
The packaging described above worked well, but it was superseded by another design when it was found that only a small amount of copper was actually needed in contact with the p-region to provide cw operation. This design simplified the processing considerably because the less expensive conventional printed-circuit board could then be used as the upper member of the assembly. Also, the new array package would be more compact, which is advantageous for the memory system design.

Figure 4(a) is a photograph of a mounted laser array of the present design. Figure 4(b) is an exploded view of the mount. A method of assembly is to hold the copper block in a small vise with Teflon jaws and to position the laser bar near the step in the copper block. A small amount of uncured liquid epoxy is dabbed on the copper block under the insulating spacers and the spacers are placed on the copper block. The spacers are used to push the laser bar against the step in the copper block and against the adjacent Teflon jaw. A small amount of uncured liquid epoxy is dabbed on the upper surfaces of the insulating spacer, and the printed-circuit board is positioned on top. The printed-circuit board is cut with sufficient precision to put each land over one laser in the laser bar when the printed-circuit board is pushed against the step in the copper block and against the Teflon jaw of the vise adjacent to the laser bar. A spring-loaded probe is then brought to bear on the printed-circuit board while the epoxy cures. Mechanical failures of these mountings have been rare, even though they are cycled many times between 77 K and room temperature. Epoxy has sometimes been used to encapsulate the region surrounding the laser bar and, although this is beneficial in some respects, especially since it affords protection during handling, the epoxy tends to smear out the laser beams and is now used only in special cases.

Shelf aging of unencapsulated unprotected laser arrays varies considerably from one array to another and is not well understood. The laser characteristics of some arrays degrade after several days or weeks on the shelf, while in many other cases laser characteristics change only slightly after several months on the shelf. As a general precautionary rule, however, laser arrays are stored in a vacuum desiccator or in an evacuated polyethylene ampoule. This kind of storage has been found to prevent



(a)



(b)

Figure 4 (a) A mounted laser array of the present design. (b) An exploded sketch of the laser array shown in (a).

shelf aging. Also, it was found to be important to remove with a warm gas stream any moisture that might have condensed on a laser array after testing in a non-vacuum atmosphere. If the moisture is not eliminated degradation often occurs.

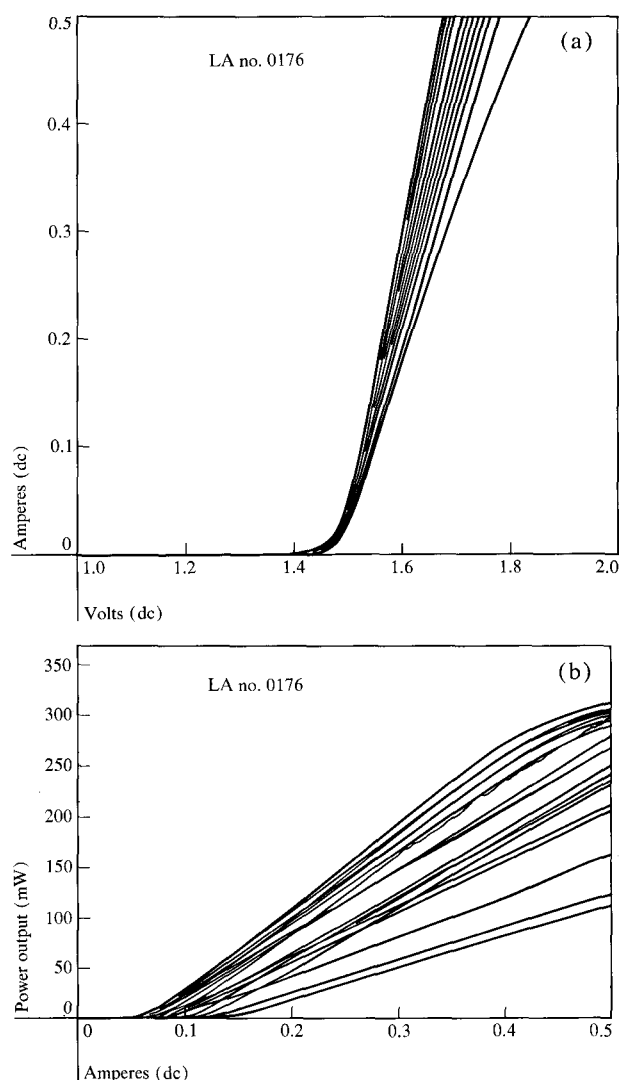


Figure 5 (a) Current-voltage characteristics of lasers in an array. (b) The cw light-power output vs current input of the lasers in (a).

The array configuration shown in Figs. 4(a) and 4(b) is made at present in this laboratory and properties of such arrays are studied in the San Jose Research Laboratory. Other configurations are made from time to time, but all employ printed-circuit boards for making contact to the p-regions of the laser bars.

Laser characteristics

The laser characteristics of a typical "good" array are shown in Figs. 5(a) and 5(b). This array had 20 functioning cw lasers, as do 10 percent of the arrays assembled. The junctions in this particular array are $5\text{ }\mu\text{m}$ deep, $22\text{ }\mu\text{m}$ wide and $200\text{ }\mu\text{m}$ long. Lasers with junction depths as shallow as $1.5\text{ }\mu\text{m}$ have also been made. Figure 5(a)

displays the current-voltage characteristics. From these data it can be seen that the total series resistance of a laser is about $0.5\text{ }\Omega$, an estimated $0.2\text{ }\Omega$ of which is in the printed-circuit land and leads.

The light-power output as a function of input current is shown in Fig. 5(b). The laser exhibiting the erratic power output had open-circuited subsequent to its measurement. A spread in this output characteristic is generally observed at the present state of the art, but a few arrays have shown much better uniformity. Power was measured by allowing the light to fall on a silicon solar cell which is positioned 3 or 4 mm from the lasers and is at or only slightly below room temperature[14]. It is assumed that the solar cell is 70 percent efficient. The falling off of the power output curves of the more efficient lasers in Fig. 5(b) is believed to be due to saturation of the solar cell and not to heating of the lasers, because the more efficient lasers should be cooler than less efficient lasers at the same input powers.

Life-test results

Several dozen lasers in a number of arrays have been life-tested under vacuum at -77 K . The laser arrays were life-tested in the same dewar apparatus used for the power and current-voltage measurements. Two arrays were mounted in opposite sides of the cold finger, each with its own solar cell. At first, a mechanical pump was used to maintain a vacuum of about 10^{-2} mm of Hg in the chamber. However, the mechanical pump, despite the use of traps, allowed oil to back-stream onto the lasers. The laser power output would then follow a damped sinusoidal oscillation as the oil film passed through reflecting and antireflecting thicknesses[15]. The mechanical pump was replaced by a sorption pump and a Vac-Ion type 911-0001 (Varian) pump. This combination eliminated the oil problem.

The data of Fig. 6(a) can be considered typical of the lasers that were life-tested for periods of several hundred hours or more. It may be a coincidence that after the first of two temporary losses of vacuum, slow degradation started. Or, because the low temperature was maintained, some moisture might have condensed on the lasers. No change was observed at the second temporary loss of vacuum.

Figure 6(b) shows the effect of step-stressing by increasing the dc input to the laser. A similar laser at 0.9 A dc input operated for about the same elapsed time and then started to degrade rapidly.

Lasers potted in epoxy were more erratic. Usually they degraded rapidly from the beginning of the test. A few lasted longer, and at least one held up in about the same manner as did those in Fig. 6(a). The epoxy was cured with an amine type of hardener. Epoxies using amine type hardeners are known to have electrical char-

acteristics inferior to those using anhydride type hardeners. Although several kinds of anhydride type hardeners have been tried, none has yet met all the needs of laser potting.

Of the several dozen unpotted lasers in arrays put on life test, none showed rapid degradation. It must be pointed out, however, that the lasers chosen for life-testing were the better lasers of an array, but nevertheless characteristic of those necessary to meet memory specifications. The rationale for choosing the better lasers for life-testing is that if and when an actual memory system is built, laser technology would have to advance to the point where all the lasers will be as good as the better present-day lasers.

Some life-testing at 77 K under pulsed conditions was carried out. Although a more detailed study needs to be made, the present tentative conclusion is that cw life-test data can be extrapolated to pulsed conditions.

Discussion

The description of this experimental fabrication process for laser arrays brings out several significant features:

- 1) Sputtered Al_2O_3 films are suitable masks against zinc diffusion.
- 2) Low zinc vapor pressure and a moderate arsenic vapor pressure for diffusion can be attained by including a zinc-saturated wafer of InAs in the diffusion ampoule.
- 3) Smooth, low-resistance contacts can be made to p-regions by diffusing zinc through electroplated films of rhodium.
- 4) Heat-sinking adequate for cw operation at 77 K can be achieved by positioning the bottom of the laser bar on a relatively massive piece of copper and by positioning only a printed-circuit board on the top of the bar.
- 5) The experimental fabrication process requires only one diffusion-masking step, one photoresist step, and one diffusion step.

Further, it has been demonstrated[4] that the laser arrays produced by this process can be used to write and read information on EuO films, and that the lasers are long-lived at input currents of 0.5 A dc.

On the other hand, while characteristics from laser to laser are sometimes encouragingly uniform, many times they are not, as Fig. 5(b) indicates. This non-uniformity will of course, require, better GaAs material and more refined processing procedures. For example, at the present time GaAs ingot specifications are not sufficient; specifying doping level, dislocation density, growth direction, etc., does not insure that the ingot will produce good lasers. However, when one laser processing group finds that a particular section of a particular ingot produces good lasers, other processing groups using that material generally find the same result. It could be spec-

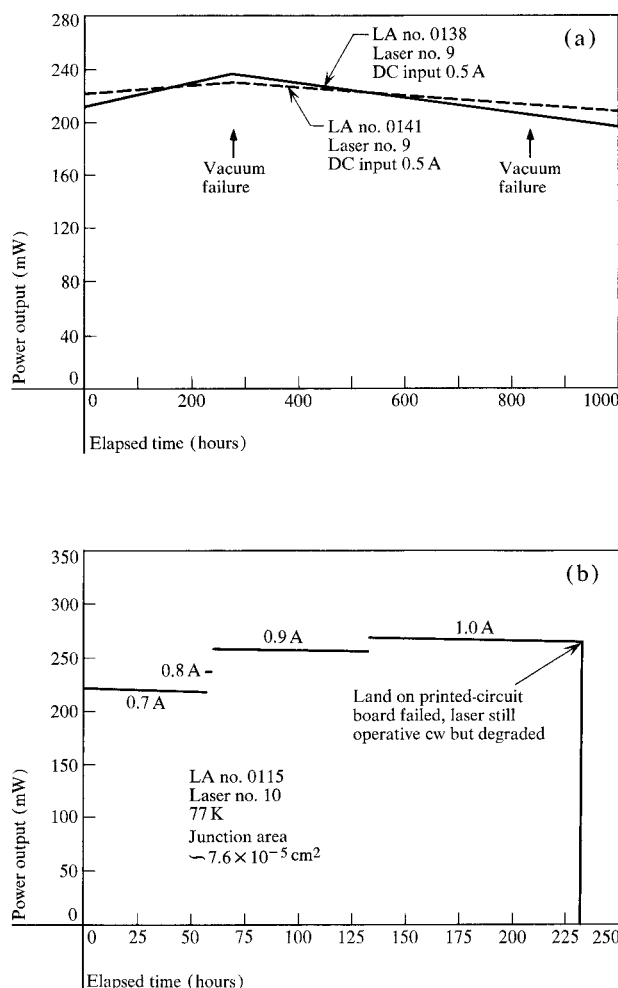


Figure 6 The cw light-power output (a) 0.5 A dc input as a function of time for two lasers from different arrays being life tested simultaneously in the same dewar. Vacuum was lost temporarily in the test chamber at the times indicated. (b) The cw light-power output with increasing dc input as a function of time for one laser of an array.

ulated that the stoichiometry of the GaAs is important and that the arsenic pressure during ingot growth has to be very closely controlled. The significance of dislocation density is questionable at this time; some of the best laser arrays have been made on material of very low dislocation density and also on material with dislocation densities as high as $4 \times 10^4/\text{cm}^2$.

Acknowledgments

The writer is grateful to A. R. Benoric, R. C. McGibbon, J. C. Topalian and E. L. Wilkie for their cooperation in carrying out the work described in this article and to G. Y. Fan, H. Wieder, G. J. Sprokel, and R. F. Rutz for many helpful discussions.

References and notes

1. G. Fan and J. H. Greiner, "Low-Temperature Storage Using GaAs Lasers and EuO as Storage Medium," *J. Appl. Phys.* **41**, 3, 1401 (1970).
2. A. H. Eschenfelder, "Promise of Magneto-Optic Storage Systems Compared to Conventional Magnetic Technology," *J. Appl. Phys.* **41**, 3, 1372 (1970).
3. G. J. Sprokel, "Fabrication and Properties of Shallow Diffused Laser Diode Arrays," *IBM J. Res. Develop.* **15**, 265 (1971, this issue).
4. H. Wieder and H. Werlich, "Use of GaAs Laser Arrays for Beam Addressable Memories," *IBM J. Res. Develop.* **15**, 272 (1971, this issue).
5. M. Pilkuhn and H. Rupprecht, "Spontaneous and Stimulated Emission From GaAs Diodes with Three-Layer Structures," *J. Appl. Phys.* **37**, 3621 (1966).
6. H. Nelson, "Epitaxial Growth from the Liquid State and Its Application to the Fabrication of Tunnel and Laser Diodes," *RCA Rev.* **XXIV**, 603 (1963).
7. I. Hayashi, et al., "Junction Lasers Which Operate Continuously at Room Temperature," *Appl. Phys. Letters* **17**, 3, 109 (1970).
8. R. N. Hall, et al., "Coherent Light Emission from GaAs Junctions," *Phys. Rev. Letters* **9**, 366 (1962).
9. T. M. Quist, et al., "Semiconductor Maser of GaAs," *Appl. Phys. Letters* **1**, 91 (1962).
10. M. I. Nathan, et al., "Stimulated Emission of Radiation from GaAs p-n Junctions," *Appl. Phys. Letters* **1**, 62 (1962).
11. Pyrolytic Al_2O_3 films and electron-beam evaporated Al_2O_3 had been found unsatisfactory as a mask material against zinc diffusion. The use of rf sputtered Al_2O_3 films was suggested by Jan Hoekstra of this laboratory.
12. J. C. Marinace, "Diffusion of Zinc Through Films of Refractory Metals in GaAs," *J. Electrochem. Soc.* **117**, 1, 145 (1970). This reference describes the use of tungsten and molybdenum as contact materials.
13. J. C. Marinace, "High Power CW Operation of GaAs Injection Lasers at 77 K," *IBM J. Res. Develop.* **8**, 5, 543 (1964).
14. K. L. Konnerth and J. C. Marinace, "Non-Catastrophic Degradation of GaAs Lasers under CW Operation," *J. Quant. Electron.* **QE-4**, 4, 173 (1968).
15. E. J. Walker and A. E. Michel, "Modification of the Threshold Current and Near-Field Pattern of a GaAs Laser by an Adsorbed Dielectric Layer," *J. Appl. Phys.* **35**, 2285 (1964).

Received February 9, 1971

The author is located at the IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598.