G. J. Sprokel

Fabrication and Properties of Monolithic Laser Diode Arrays

Abstract: Monolithic arrays of planar diffused GaAs injection lasers have been fabricated using diffusion masking and photolithography to delineate the junction area. After contact metallization, the arrays are soldered to a sapphire wafer which serves as a heat sink and carries the contacts for each junction. The diodes operate cw at 78 K and the threshold current density, $J_{th} = 700$ to 1100 A cm^{-2}. The dc power output is linear at least to $5 \times J_{th}$ and the power efficiency, η_P, is about 40%. Threshold and power output are quite uniform across the array but the beam polarization varies at random from one unit to the next.

Introduction

Magneto-optical memories employing single GaAs lasers and using a EuO film as the storage medium have been described by Fan and Greiner[1]. Basic requirements of arrays of such lasers in a system configuration were given by Eschenfelder[2]. The present paper deals with monolithic arrays of small injection lasers intended for use in a beam addressable memory and is limited to the fabrication and properties of these arrays. Their application is discussed in the accompanying paper by Wieder and Werlich[3]. Recently, Marinace[4] described similar arrays, differing mainly in the diffusion technique and in the method of forming contacts and heat sinks.

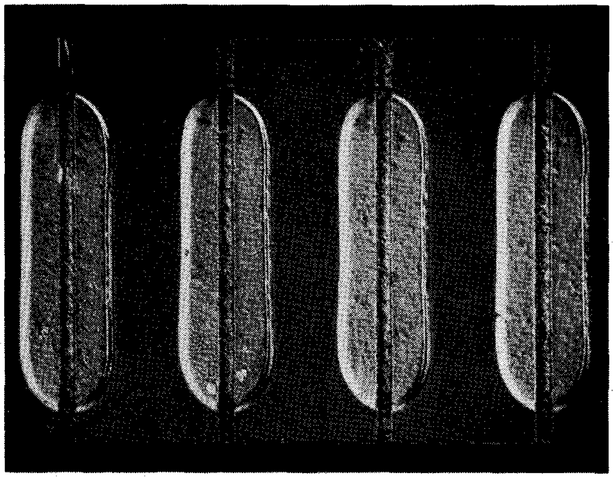
A EuO memory requires liquid-nitrogen cooling. Therefore the laser junctions can be conveniently operated at 78 K. The junctions must be small and closely spaced, and the arrays must be fabricated in monolithic form using suitable masking and photolithography. Each junction must be addressable and crosstalk between adjacent junctions must be absent. The "stripe geometry" proposed by Zachos and Ripper[5] is not suitable. The use of a monolithic structure precludes selecting devices for optimum properties and thus the uniformity of the junction properties obtained in processing is important. Uniformity across a wafer and reproducibility between runs is obtained more easily by diffusion than by liquid-phase epitaxy. Since junctions produced by either method have approximately the same threshold at 78 K (as observed by Pilkuhn and Rupprecht[6]), the diffusion process was chosen.

Customarily lasers have been mounted between two heat sinks serving as pressure contacts, and Marinace has shown that the method can be extended to arrays. However, the "flip-chip" technique developed at IBM for silicon devices[7] is better suited for mass production. A method analogous to the fabrication of the flip-chip joint has been developed in order to solder laser arrays directly to the heat sink without recourse to pressure contacts.

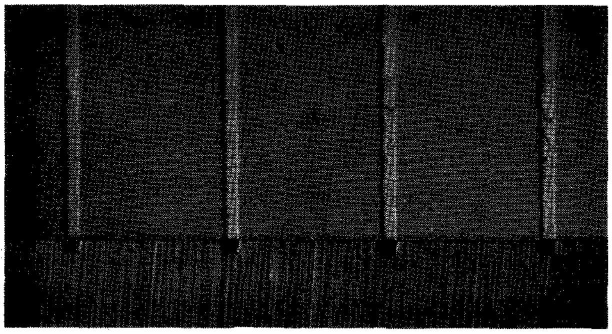
In the present paper the fabrication will be outlined briefly in the next section and details pertaining to the diffusion, junction characterization, and some optical properties will be discussed in subsequent sections.

Fabrication

Substrate wafers are ⟨100⟩ slices of Sn-doped GaAs ($N = 2$ to 3×10^{18} cm^{-3}) free of dislocations as indicated by x-ray topography. The diffusion mask is a film of rf sputtered Al_2O_3 about 1500 Å thick. Parallel stripes 0.5 mil wide are etched in the [100] direction. The junction is formed at 2 μm depth by capsule diffusion using a Zn-doped GaAs powder source. The wafer is lapped to about 4 mils and polished. On the p-side Au or Ag/Zn is plated or evaporated onto the stripes. Then Cr/Ni/Ag solder lands are evaporated through a metal mask. The n-contacts are made by evaporating Au followed by Cr/Ni/Ag for the solder contact. The contacts are alloyed to the substrate by heating at 450°C for about 1 minute as outlined by Dobson[8]. Bars are cleaved and sawed to the desired length.



(a)



(b)

Figure 1 (a) P-side of an array after diffusion and metallization. The diodes are 0.5 × 15.3 mils on 6-mil centers. The Cr/Ni/Ag solder pad is 3 × 12 mils. (b) Bevel lapped and etched cross section. Lapping angle is 5°. $x_j = 1.3\ \mu m$.

Figure 1(a) shows part of the p-side of an array. The alloyed contacts extend over the full length of the cavity but the solder pads are made slightly shorter to prevent solder from flowing to the end of the cavity and possibly blocking the beam.

Heat sinks are prepared by evaporating a Cr/Cu/Cr land pattern on a sapphire wafer. Solder is plated at the ends of the lands to match the solder pads on the array and the arrays are then soldered down. The early arrays had a common n-contact consisting of a wire strap connecting the substrate to a land on the heat sink. Later the strap was eliminated and p- and n-contacts were made on one side of the array, thus greatly simplifying the soldering operation.

• *Diffusion masking*

A film of rf sputtered Al_2O_3, 1000–1500 Å thick, is deposited to block Zn diffusion. (Electron beam evaporated Al_2O_3 does not block Zn diffusion even after densification at 850°C.) The film can be etched in dilute H_3PO_4 at 65°C using AZ1350 photoresist without apparent damage to the exposed GaAs surface. Satisfactory films are obtained at 200-W rf input power, 10 μm Ar pressure and 250°C substrate temperature, but these parameters may vary somewhat for other rf sputtering systems. The surfaces are sputter-cleaned prior to the deposition cycle.

It is well known[9] that SiO_2 by itself cannot be used as a diffusion mask. Other films such as phosphosilicate glass[10] deposited over SiO_2 have been used successfully as the masking layer. But unless the area to be diffused is protected by an additional film of SiO_2, severe lateral diffusion occurs along the interface of the substrate and mask. This lateral diffusion, colloquially called "winging," is nearly absent in Al_2O_3 films even though the GaAs surface is exposed. Figure 1(b) shows the beveled and etched cross section of an array made with a satisfactory Al_2O_3 film. The phenomenon is not well understood. It depends on the properties of the masking film and on the diffusion conditions. A moderate amount of winging has little effect on the threshold current but the near-field patterns of such laser junctions then no longer resemble straight lines.

• *Diffusion*

Efficient heat removal from the junction area is important. The diffusion must produce shallow junctions, but the surface concentration must be high enough so that the desired concentration gradient is attained at the junction. In addition, for low contact resistance the surface must still be specular after the diffusion. High-C_0 diffusions ($1 \times 10^{20}\ cm^{-3}$) tend to produce local alloying and pitting caused by loss of As from the substrate surface and formation of a Ga-rich melt. If As is added to the capsule, an As-rich film is often formed, causing high contact resistance. For deep junctions, surface defects can be removed by etching. For shallow, planar diffused junctions, defect removal is not possible.

It was found that the use of Zn-doped GaAs as a diffusion source alleviates these problems. The source material is prepared by diffusing Zn into GaAs wafers until saturation. The alloyed surface layer is lapped off and the remaining part is then ground to about 1 micrometer particle size. The Zn concentration in the source is determined only by the source diffusion temperature. Alternatively, source material can be prepared from Czochralski-pulled, Zn-doped GaAs but the desired Zn concentration is not readily available.

During device diffusion the Zn vapor pressure in the capsule is determined by the Zn concentration of the source and is quite independent of the amount of source material. Figure 2 shows the relation between junction depth x_j and source concentration for typical laser diffusions.

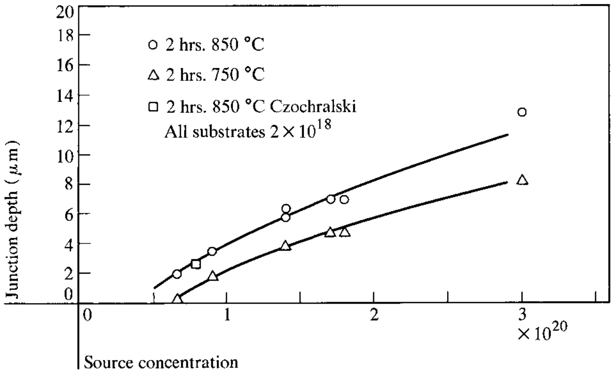


Figure 2 Junction depth vs source concentration for typical laser diffusion parameters.

Junction parameters

• *Junction depth, x_j*

The junction can be clearly defined by bevel lapping and etching. The surface concentration, C_0, is obtained by plasma resonance; for a typical laser diffusion, $C_0 = 0.8$ to 1×10^{20} (according to Philbrick et al.[11]). Details of the Zn impurity profile for shallow junctions are as yet unknown. Attempts have been made to obtain the profile by spreading-resistance measurements. The experiments yield $R(x)$, the resistance of a thin layer at distance, x, from the surface. It has not been possible to reduce the data unambiguously to the impurity profile and thus only qualitative information is available. For deep junctions, ($x_j > 5\ \mu$m) the $R(x)$ curve is essentially flat near the surface and shows a pronounced knee starting about 1 μm from the junction. For shallow junctions the knee is absent, although C_0 is about the same.

• *I-V characteristics*

Figure 3 shows *I-V* characteristics for an array of lasers soldered to a sapphire heat sink. The assembly is clamped to a flat-bottom dewar and operated in vacuum. The data are the average for ten diodes; individual diodes differ usually by about 2%. The data are corrected for the external resistance (mainly the heat sink metallization) but not for the resistance of the substrate or that of the contact. These corrections are negligible up to currents of about 50 mA.

At room temperature the *I-V* relation has the form

$$J = J_0 \exp\ (\mathrm{eV}/nkT). \qquad (1)$$

For this array $n = 2.1$.

At liquid-nitrogen temperatures the exponential law does not hold very well; n decreases from $n = 6$ at $J = 10^{-3}$ A cm^{-2} to $n = 3$ at $J = 1$ A cm^{-2}.

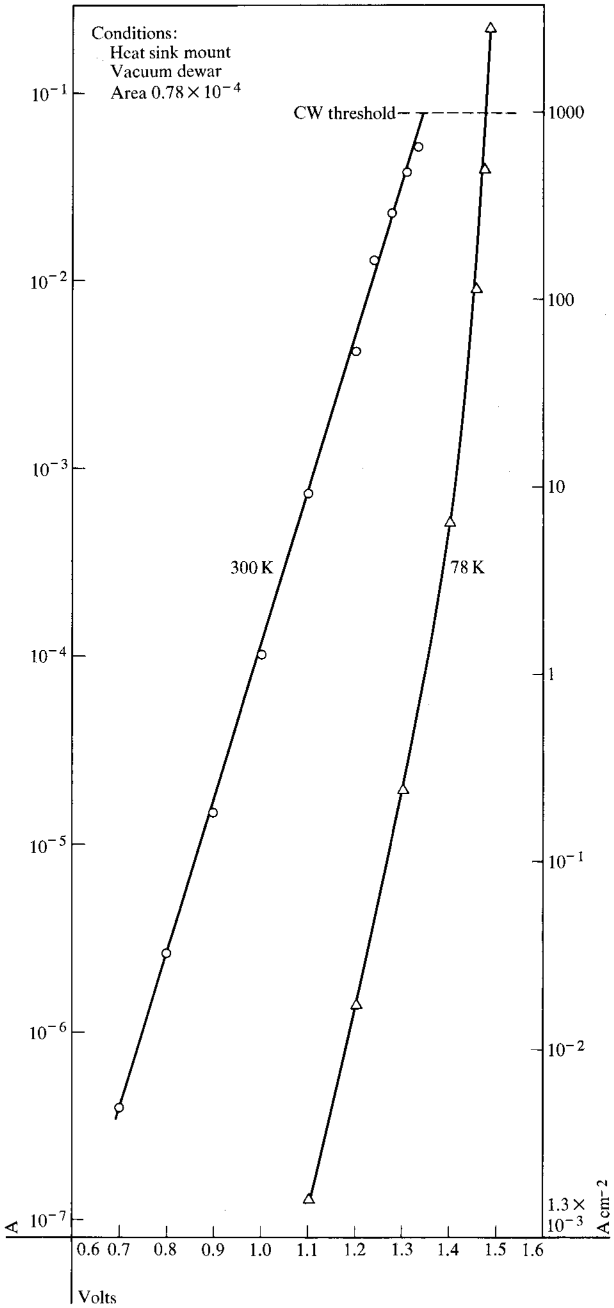


Figure 3 *I-V* characteristics at 300 K and 78 K. Data are average of ten diodes in a no. L184 array.

Data on *I-V* were reported by Dumin and Pearson[12], and by Pilkuhn and Rupprecht[6]. Their devices were made by blanket diffusion and thus the entire circumference of the junction is exposed. In the planar diffused diodes used in this paper, only 3% of the junction (the laser facets) is exposed. At low forward bias the observed current density is smaller by an order of magnitude, which seems to indicate that the Al_2O_3 film reduces surface leakage.

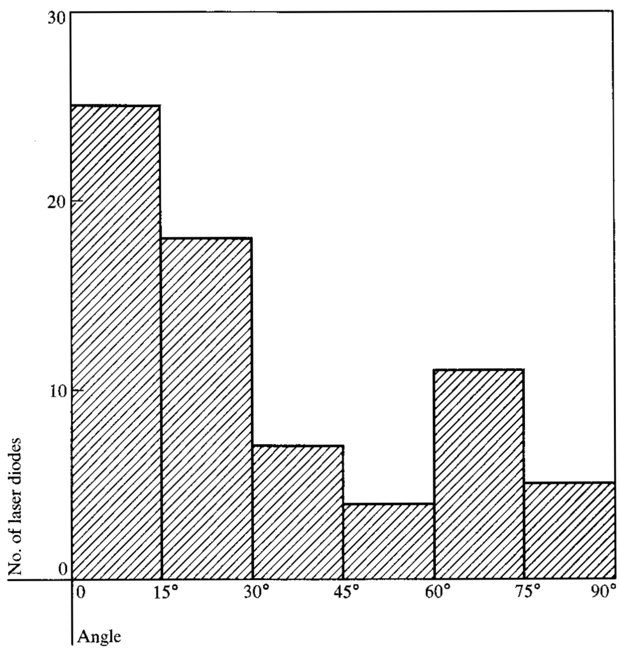
Table 1 Carrier concentration, concentration gradient and reverse breakdown voltage obtained from C-V data.

Parameter	Array number L184	L187	L195
N_{Hall} cm^{-3} at 300 K	2.3×10^{18}	2.6×10^{18}	1.5×10^{18}
X_j, μm	3.5	1.3	1.6
a cm^{-4} at 300 K	2.2×10^{24}	5.6×10^{24}	9.2×10^{24}
a cm^{-4} 78 K	1.4×10^{24}	3.7×10^{24}	6×10^{24}
N_D cm^{-3} at 300 K	2.1×10^{18}	1.5×10^{18}	2.2×10^{18}
N_D cm^{-3} at 78 K	1.6×10^{18}	1.1×10^{18}	1.7×10^{18}
V_B at 10 μA at 300 K	3.5	3	2
V_B at 10 μA at 78 K	4	3.8	3

Table 2 Threshold current, power output and polarization of a ten-diode array (L184 series) at 78 K.

Diode no.	I_{th}(mA)	P_{out} (mW 0.5 A)	Slope (mW/A)	Power efficiency (mW$_{out}$/mW$_{in}$)	Polarization max.	f_{pol}
1	80	77	183	26%	−80°	0.94
2	75	93	220	31	−56	.86
3	70	122	286	41	−65	.89
4	70	129	300	43	−74	.60
5	70	116	270	39	−70	.88
6	70	126	293	42	−39	.72
7	75	136	320	45	−11	.45
8	70	112	260	37	+9	.44
9	70	94	218	31	+6	.52
10	65	132	304	44	+10	.80

Figure 4 Distribution of angle between plane of polarization and junction plane for a group of 71 diodes at input current of 0.2 A.



At the substrate doping levels used for these devices ($Sn = 2 \times 10^{18}$) there is no evidence of a tunneling current at low forward bias. This agrees with the findings of Dumin and Pearson.

• *C-V measurements*

Capacitance-voltage measurements were made on mounted arrays, rather than on specially constructed diodes, in an effort to correlate these results with laser threshold current. However, the heat sink introduces stray capacitance that cannot be compensated accurately. Therefore the data are plotted as

$$C = \left(\frac{q\epsilon^2}{12}\right)^{1/3} a^{1/3} (V_{bi} + V)^{-1/3} \qquad (2)$$

for the linearly graded junction approximation, or as

$$C = \left(\frac{q\epsilon}{2}\right)^{1/2} N_D^{1/2} (V_{bi} + V)^{-1/2} \qquad (3)$$

in the abrupt junction approximation. Since the stray capacitance enters linearly, it does not affect the calculation of a or N_D.

The symbols have the usual meaning; C is the capacitance in Farad cm^{-2}, q is the electron charge, ϵ is the dielectric constant, V is the bias voltage, V_{bi} is the built in potential, a is the concentration gradient in cm^{-4}, N_D is the substrate dopant concentration in cm^{-3}. Values for V_{bi} are taken from Sze[13].

Experimental C-V data fit both equations equally well. The concentration gradient calculated from (2) is of the order of 10^{24} cm^{-4} as is expected, since C_0 is of the order of 10^{20} cm^{-3} and x_j is of the order of 10^{-4} cm. From the abrupt approximation, N_D is found to be of the order of 2×10^{18} cm^{-3}, in good agreement with Hall measurements on the substrates. Table 1 lists results for some representative arrays. Low-temperature measurements were made following a suggestion by C. T. Sah[14]. For the abrupt junction approximation, it is seen that in all cases the apparent donor concentration is decreased at 78 K. The difference, ΔN_T, is interpreted as the concentration of acceptor type recombination centers. It is seen that ΔN_T is of the order of 10^{17} cm^{-3}. Its exact value is somewhat uncertain since it is affected by the choice of V_{bi}. Support for this contention was obtained by diffusing Au into the junction. The difference ΔN_T increases to 10^{18} cm^{-3} and these units can no longer be operated cw; the pulsed threshold increases about threefold.

Also listed in Table 1 are the reverse bias voltages at 10 μA reverse current. V_B decreases as the concentration gradient increases. Comparison with published data for GaAs shows good agreement (see, for example, Sze[13], p. 116).

Optical characterization

• *Beam power output*

The parameter of interest is the power available in a narrow beam. The output from one facet of one diode is collected with an $f/2$ 50-mm lens and focused onto a photodiode through an absorber made from a 50 ohm-cm, p-type Si wafer. A 10-mm aperture Glan-Thompson polarizer can be placed in the beam to determine its polarization

Table 2 lists the threshold current, beam power output at 0.5 A dc and the slope efficiency for an array of ten diodes. The power efficiency is calculated with the assumption that the power output is equal on both sides of the laser.

The dc laser threshold current for 0.5-mil diodes is typically 50 to 90 mA (700 to 1100 A cm^{-2}). The output power increases quite linearly with the current beyond threshold at a rate of 200 to 300 mW/A. The devices are routinely dc tested up to 0.5 A; most can withstand 0.8 A.

• *Polarization of laser beams*

Polarization of laser beams has not been fully understood, although the effect was noted in the first papers dealing with these devices[15,16]. The fraction of polarization (f_{pol} in Table 2) and the direction of the plane of polarization vary from diode to diode in the same array. (Direction is defined as the angle between the plane of the **E** vector and the junction plane.) In Table 2, the data on array no. L184 exhibits a gradual variation from **E** perpendicular to the junction plane (diode 1) to **E** parallel with the junction plane (diode 10). This gradual variation has been observed on other arrays but it is not a general rule; often there is a random variation. The histogram in Fig. 4 shows data for about 70 diodes, and the number of diodes in a 15° interval is plotted. There is some preference for the plane of polarization to align with the junction plane; about 60% of devices tested have an angle less than 30° with the junction plane.

• *Polarization of spectral lines*

Spectra are obtained by focusing the beam onto the entrance slit of a Spex 1702 grating spectrometer. Figure 5 illustrates a line spectrum of an almost completely polarized beam. Spectra are shown at 60°, 15° and −30° (where the junction plane is 0°). The diode is operated at 200 mA dc, about $2.5 \times J_{th}$. It is seen that all modes are linearly polarized at 60°, while the intensity at −30° is practically zero. The modes show the typical Gaussian distribution, and the mode spacing can be accounted for by the longitudinal modes of the laser cavity. Most spectra are not as simple as the example chosen here. It is more common to find two or more sets of modes polarized in independent directions. In general, near the threshold one mode will dominate and the beam will be strongly polarized. As the current is increased, new spectral lines appear which may be polarized quite differently.

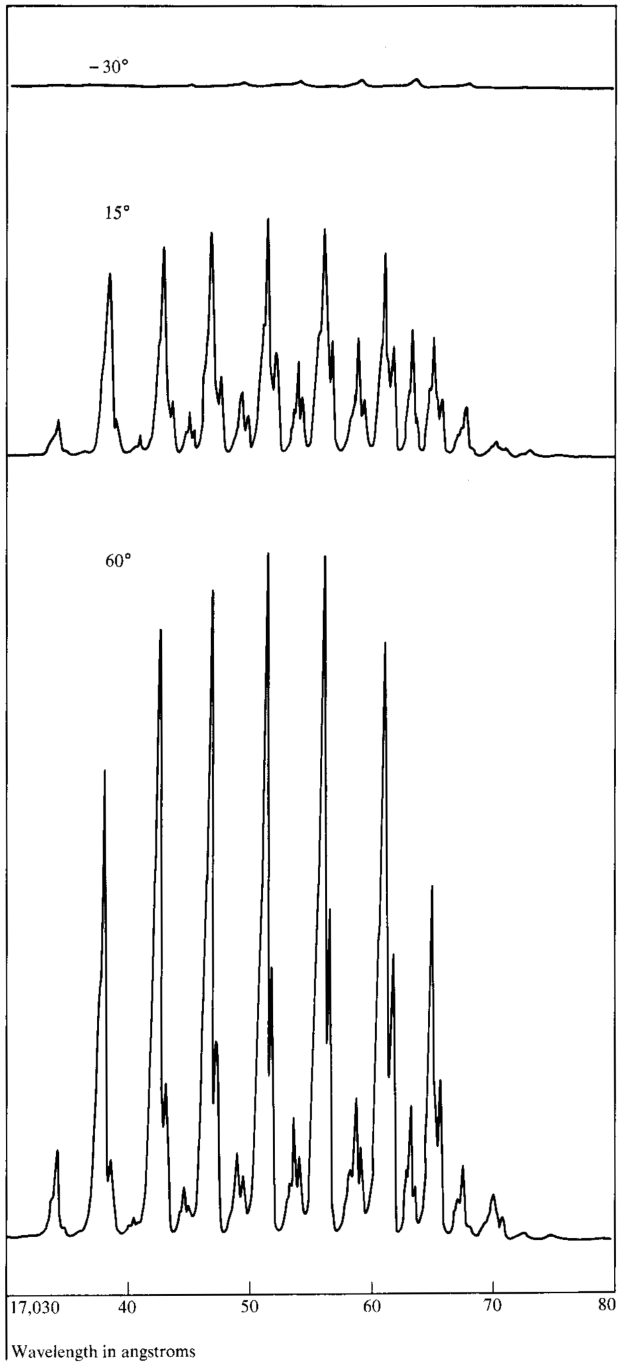
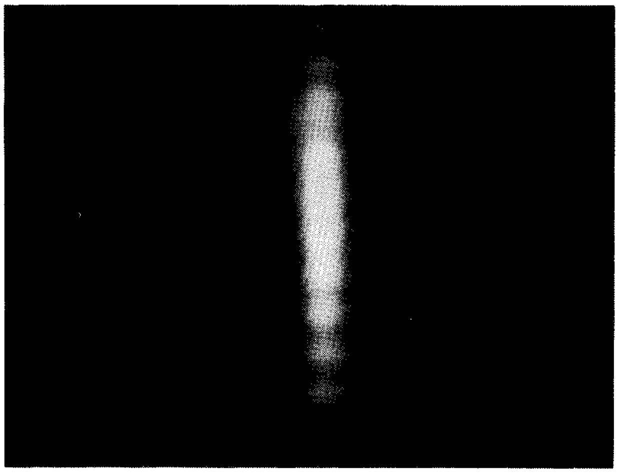


Figure 5 Spectra of array no. L184−8−1 at 3 settings of the polarizer, 60°, 15° and −30°, with respect to the junction plane. Diode current 200 mA dc; $f/5.6$; 8 μm slits 1200 V, 10 kΩ load resistor, 0.2 V/in, vertical deflection.

(a)



(b)

Figure 6 Far-field pattern of array no. L184-8-1 at (a) 100 mA and (b) 122 mA. The photographic film was 3 in. from the laser diode and exposed for 10 μsec. Junction plane is horizontal.

• *Far-field pattern*

Figure 6 shows the far-field pattern of the device used in Fig. 5. The photographic film was 3 in. from the laser facet and exposed for 10 μsec at 125 mA diode current. The beam angle in the junction plane is 7°, and in the perpendicular direction the beam angle is 40°. Again, far-field patterns are often more complicated than this; it is more common to find two different patterns side by side.

Heat sink evaluation

It can be shown that for highly asymmetrical structures, where the junction is very close to one surface, the effect of a heat sink at the opposite surface is small. The model used for these calculations is that of a continuous line source at $x_j = 0.02\ d$, where d is the thickness of the substrate wafer. Using the method of images[17] to introduce the boundary conditions, one calculates that for 1 W dissipated in one junction the temperature rise in the neighboring junction is approximately 5°C without a heat sink and about 2°C with heat sink on the n-side. The model is too crude to represent an actual array. Nevertheless it indicates that the effect of a top heat sink would be too small to justify the added complexity and cost of the package. Experimental evidence proves this concept to be correct. As shown in Table 2, these laser diodes, soldered to a sapphire heat sink, can be operated continuously at seven times threshold. The data, however, refer to only one device operating at a time. To estimate the effect of one diode on another, the threshold of a given diode was determined as a function of the current through another diode. The array used for this experiment had eight laser diodes rather than the customary ten; two diode positions were used to provide the n-contacts. Diode no. 4 of the array ($I_{th} = 90$ mA) is approximately in the center, and this diode was biased respectively at 0, 50, 100, 150 and 200 mA. The dc threshold currents of the other diodes were determined as a function of the current in diode no. 4, I_4; the slit system of the spectrometer was used to prevent the beam of diode 4 from reaching the detector. Table 3 lists the results. For all diodes the threshold increases nearly proportionally with the current through diode 4. The pairs 3 and 5, 2 and 6, and 1 and 7, arranged symmetrically around 4, show about the same increase. Assuming that the change in threshold reflects the increase in local temperature, we have, to the first approximation[18],

$$\frac{\Delta T}{T} \approx \frac{1}{3}\frac{\Delta I_{th}}{I_{th}}. \qquad (4)$$

For example, at $I_4 = 200$ mA, the temperature increase at the diode locations 3, 2 and 1 is respectively 4, 3 and 2°C. One cannot conclude that all of the heat is generated at diode location 4. Part of the temperature rise could be caused by Joule heating of the substrate. The question could be settled only through numerical solution of the heat equation for this complicated system of sources and sinks. It has been shown here that, for practical purposes, soldering arrays to a single sapphire heat sink is simple and adequate even if two adjacent devices are turned on simultaneously.

Summary

One aspect of this work was to determine optimum diffusion conditions for laser fabrication. Table 4 lists data for some representative laser arrays and it is seen that large variations are possible. By matching source concentration and the diffusion time and temperature cycle, junctions were obtained between 1.5 and 3.5 μm that

Table 3 DC threshold currents of diodes 1, 2, 3, 5, 6, 7 and 8 in an array as function of the current through diode No. 4.

I_4	I_{th} (1)	I_{th} (2)	I_{th} (3)	I_{th} (5)	I_{th} (6)	I_{th} (7)	I_{th} (8)
0	92	86	90	90	94	97	93
50	94	88	93	93	96	100	95
100	96	91	97	98	100	102	99
150	98	92	99	100	102	104	100
200	99	95	101	102	104	106	102

Table 4 Comparison of laser arrays

	L140	*L152*	*L184*
Substrate, Sn	$2-3 \times 10^{18}$	1.8×10^{18}	2×10^{18}
Source conc., Zn	9×10^{19}	1×10^{20}	1.3×10^{20}
Source prep. method	Czochralski	diffusion	diffusion
Diffusion	2 hrs./850°	2 hrs./750° 1 hr./850°	2 hrs./750° 1 hr./850°
x_j, μm	1.3	3	3.5
a, cm^{-4}	3×10^{25}	5×10^{24}	2×10^{24}
Average I_{th} mA at 78 K	83	84	71
No. of acceptable devices*	6	9	10
Average output in mW at 0.5A at 78 K	140	150	280
Contacts	Ag/Zn, Ag/Te	Ge/Au/Ni	Au, Au/Sn

*Defined as $I_{th} \leq 100$ mA and $P_{out} \geq 100$ mW at 0.5A.

had essentially the same threshold current. The concentration gradient of such shallow junctions is in excess of 10^{24} cm^{-4} and the junctions may be considered "abrupt." From *C-V* data at 300 K and 78 K, the concentration of trapping centers in the junction region was found to be of the order of 10^{17} cm^{-3}. If diodes in one array are compared, uncertainties in parameters such as junction area and V_{bi} become less important. However, small differences in *C-V* characteristics between the diodes in one array do not correlate with the laser thresholds.

Soldering arrays to a metal land pattern on a sapphire wafer acting as the heat sink is quite adequate to achieve cw operation at 78 K. The method is suited to mass production; contacts are self-aligning and jigs are not required. The truly metallurgical bond is more rigid than pressure contacts but flexible enough to permit temperature cycling.

The laser beams are polarized; the polarization generally decreases as the diode current is increased. The direction of the plane of polarization varies at random from one diode to the next in one array. On the average, most beams will be polarized within 30° of the junction plane.

The beam power output of these devices is sufficient to store and read bits in an EuO film, as discussed in the accompanying paper by Wieder and Werlich[3].

Acknowledgments

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The author is located at the IBM Components Division Laboratory in East Fishkill, New York 12533.