

Junction Heating of GaAs Injection Lasers During Continuous Operation*

Abstract: The rise of the junction temperature during continuous operation of an injection laser has been measured as a function of current and is discussed for different cases. The dependence of the emitted light power on current is computed from the thermal data and compared with the experiment. The threshold current and the differential quantum efficiency for continuous operation are discussed.

Introduction

The light output from a continuously working (cw) injection laser is limited by the generation of heat in the laser diode. There are two effects responsible for diode heating: (1) the external quantum efficiency is less than unity, i.e., only a fraction of the electrical input power is converted into light, the rest is converted into heat and (2) Joule heat is developed in the series resistance. The influence of heating on the simulated light emission from cw injection lasers was discussed theoretically by R. W. Keyes¹ and by S. Mayburg.² The thermal problems of injection lasers, particularly for pulsed operation, have also been considered by Lasher and Smith,³ Burns and Nathan⁴ and Konnerth.⁵ In this paper, experimental results concerning diode heating during cw operation in a liquid nitrogen or oxygen bath will be presented and compared with the theoretical results derived in Ref. 1.

Laser fabrication

The injection lasers investigated had dimensions of about $(2.5 \times 10^{-2}) \times (0.75 \times 10^{-2}) \times 10^{-2}$ cm and were attached to a heat sink whose dimensions were very much larger than those of the diodes. The type of heat sink mount which will be referred to as "structure one" is described by J. C. Marinace,⁶ and is shown in Fig. 1a.

The laser diodes (GaAs) had Au-Sn contacts which were plated with an In layer. Two large metal plates (Cu or Mo) with an In plated surface were then pressed from two sides on the In layers of the diode. A spacer

(BeO, Pyrex glass and semi-insulating GaAs) insulated the two plates electrically.

The type referred to as "structure two"⁷ is depicted in Fig. 1b. The GaAs diodes had Au-Ni contacts and were Sn soldered to two Ni plates. Two spacers of semi-insulating GaAs (Au plated) were also Sn soldered between the Ni plates. The package, whose dimensions were about $0.5 \times 2.5 \times 0.3$ mm, was then placed on a suitable metal header.

Experimental procedure

Two methods were used to determine the junction temperature; the first was based on the temperature dependence of the threshold current. In this method, short current pulses (50 nsec duration), which did not contribute to the diode heating, were superimposed on a direct current I which raised the junction temperature by the amount ΔT over the bath temperature T_0 . The laser threshold (at the temperature $T_0 + \Delta T$) was then determined at constant direct current by varying the pulsed current. The threshold current I_t is

$$I_t = I + I_{pt},$$

if I_{pt} is the pulsed current value for reaching threshold. I_{pt} was determined through a light intensity-current plot at the laser wavelength. The threshold current depends on the temperature rise ΔT approximately in the following way:⁸

$$I_t = I_0 \exp \Delta T/T_1. \quad (1)$$

I_0 is the threshold at the bath temperature T_0 , and T_1 is an empirical parameter characteristic of the laser structure.

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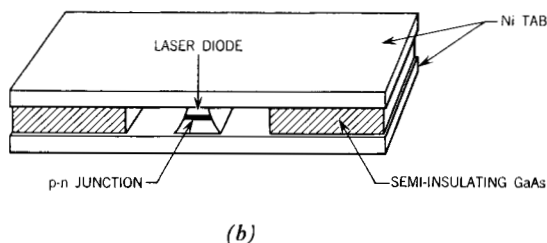
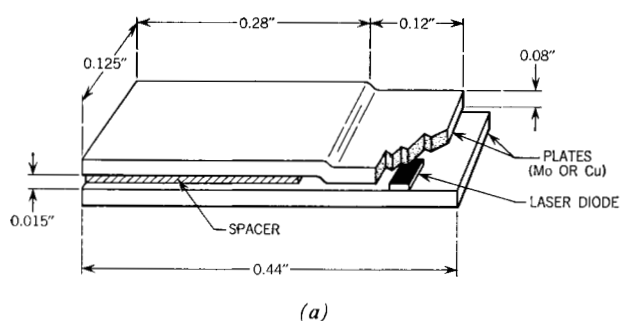
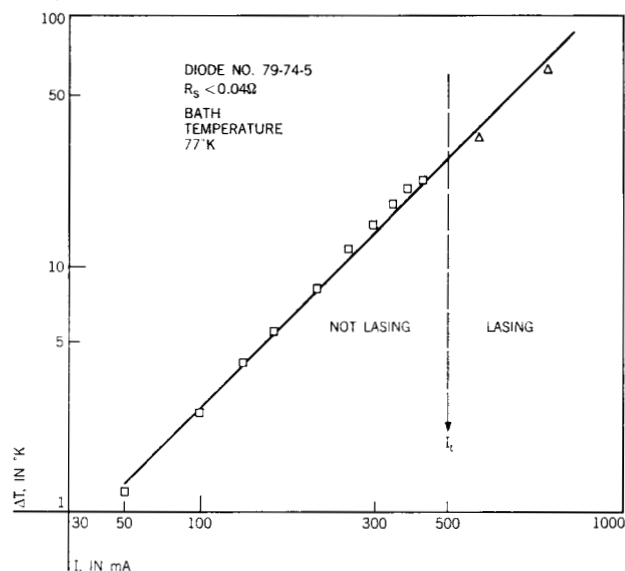


Figure 1 (a) Heat sink package of GaAs injection laser (structure one); (b) Schematic drawing of heat sink package (structure two).

Figure 2 Rise of junction temperature as a function of current for the case of negligible series resistance (structure one).



Equation (1) is a good approximation, particularly for operation in the neighborhood of 77°K. At high temperatures, the laser threshold varies mostly as T^n where n is close to 3.^{9,10}

I_0 and T_1 can be determined experimentally by a threshold measurement (with pulses) at various known temperatures. If the temperature dependence of I_t is known, ΔT can

Table 1 Experimental values for the thermal resistance, P .

Diode No.	Structure	P (°K/watt)
945	II	26
946	II	11
947	II	20
959	II	4
79-68-2	I	11.7
79-68-27	I	22
79-74-5	I	19

now be computed as a function of I . This method was employed only as long as I was smaller than the cw threshold of the laser.

The second method made use of the wavelength variation of the stimulated emission peak with temperature. It could be employed below the cw threshold (dc with superimposed pulses) and above the cw threshold (no superimposed pulses). The wavelength of the stimulated emission peak was measured as a function of the dc current, I . Independently, the wavelength of the stimulated emission was determined (with pulses) at various known temperatures. A comparison between the two measurements gives the temperature rise ΔT as a function of I . The values for ΔT obtained with these two methods agree closely.

Results and discussion

For a diode (structure one) with low series resistance (smaller than 0.04 ohm), the temperature rise ΔT has been plotted as a function of I in Fig. 2. Over a large current range (50 mA to 3 A), ΔT increases linearly with I , which is characteristic of junction heating due to the fact that the quantum efficiency is smaller than one. The squares in Fig. 2 represent values obtained with the first method (given above); the triangles refer to the second method. The temperature rise should be smaller above threshold since the quantum efficiency η of the stimulated emission is larger than that of the spontaneous emission [$\Delta T \sim IV(1 - \eta)$]. This effect, however, is small and beyond the accuracy of the experiment.

A thermal resistance P may be defined by

$$P = \Delta T / IV, \quad (2)$$

if series resistance heating is neglected and $1 - \eta \approx 1$. Several experimental values for P are listed in Table 1. P varies between 4 and 25(°K/watt) and depends on many experimental details like heat sink structure, laser geometry, laser contacts, pressure applied, series resistance, etc. It was not possible to find a reproducible quantitative relation between P and any of these parameters. Theoretically, for a junction attached to a three-dimensional

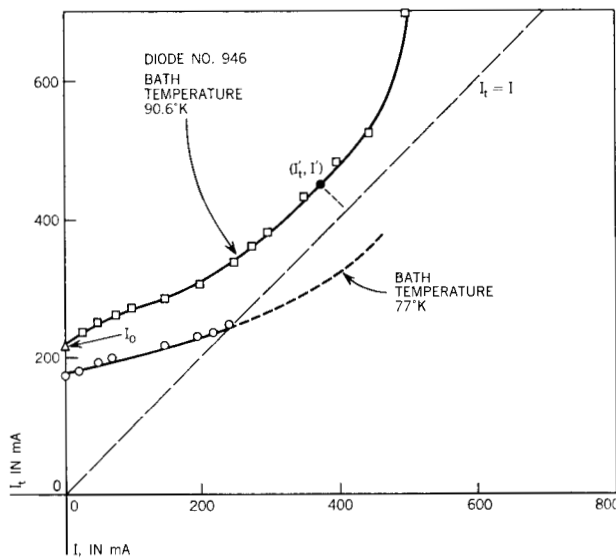


Figure 3 Dependence of threshold current on the direct current flowing through the diode (structure two). The cw threshold is reached in this case when the bath temperature is 77°K, is not reached when the bath temperature is 90.6°K.

semi-infinite heat sink, the thermal spreading resistance should be

$$P = 1/2\kappa d, \quad (3)$$

with

$$d = \frac{\sqrt{\pi} L}{K(1 - W^2/L^2)}$$

(W =laser width, L =laser length, κ =thermal conductivity, K =elliptical integral function). This relation was derived by Keyes¹ by approximating the rectangular laser by an ellipse with the same ratio W/L . For $L=2.5 \times 10^{-2}$ cm, $W=0.75 \times 10^{-2}$ cm, and $\kappa=2$ [watt/cm°K], one gets $P=13$ [°K/watt].

Figure 3 shows the increase of the threshold current as a function of direct current passing through the diode (structure two). For the lower curve (bath temperature 77°K), the cw threshold is reached when the line $I_t = I$ is crossed at 240 mA. For the upper curve, cw operation is not reached (bath temperature 90.6°K). At an intermediate bath temperature, the case exists where cw operation is just reached at one point. For this case, the following condition is valid:

$$(\partial I_t(I)/\partial I)_{I=I_t} = 1.$$

Using the combined equations (1) and (2), that is, $I_t = I_0 e^{PIV/T_1}$, we get:

$$\frac{\partial I_t}{\partial I} = \frac{PV}{T_1} I_t = 1 \quad \text{and} \quad \frac{I_t}{I_0} = e. \quad (4)$$

This means that the cw threshold can be larger than the pulsed threshold by a factor of e at the most. (Series resistance effects have been neglected in this derivation).

Experimentally it is difficult to reach exactly this particular case. However, it is easy to test the corresponding relation for the upper curve in Fig. 3. For that point of the curve (I'_t, I') which is closest to cw operation (closest to the line $I_t = I$) the relation

$$\frac{I'_t}{I_0} = e^{I'/I'_t} \quad (4a)$$

follows from Eqs. (1) and (2). For the point $I'_t = 450$ mA, $I' = 370$ mA in Fig. 3, condition (4a) is approximately fulfilled (with $I_0 = 210$ mA).

The case of diode heating with the presence of a large series resistance is shown in Fig. 4 (structure one). ΔT varies linearly with I at low currents and with I^2 at high currents. The thermal resistance P is approximately the same for both cases in Fig. 4:

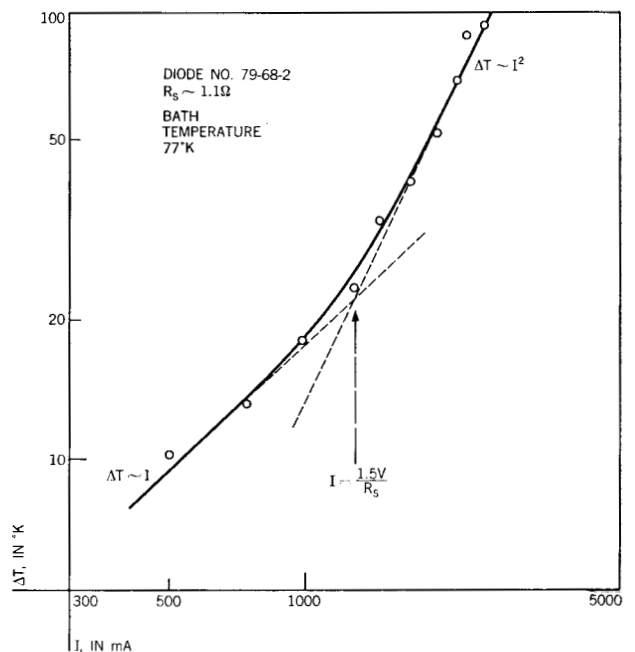
$$\Delta T = PI(V + IR_s) \quad (5)$$

(R_s = series resistance, $I - \eta \approx 1$).

The change from a linear to a square dependence occurs where IR_s becomes equal to the junction voltage V (~ 1.5 volts), as indicated in Fig. 4.

The total light emission W of the same diode was measured with an integrating sphere type of apparatus¹¹

Figure 4 Effect of the series resistance on the rise of the junction temperature as a function of current (structure one).



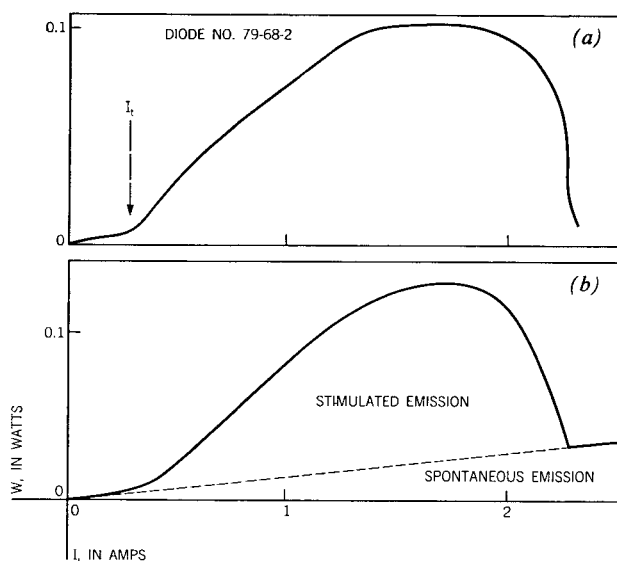


Figure 5 Power output of a cw laser (structure one) as a function of current: (a) measured; (b) computed.

and is shown in Fig. 5a. W depends on the diode current in the following manner:

$$W = V[\eta_{st}(I - I_t) + \eta_{sp}I_t], \quad I > I_t. \quad (6)$$

η_{st} , η_{sp} are, respectively, external quantum efficiencies of the stimulated and the spontaneous emission. Assuming that the quantum efficiencies are temperature independent in the first approximation, one can calculate W as a function of I using Eqs. (6), (5) and (1) and the experimentally determined values $I_0 = 0.33$ A; $T_1 = 38^\circ\text{K}$; $P = 11.7$ (°K/watt); $R_s = 1.1$ ohm; $\eta_{sp} = 0.01$; $\eta_{st} = 0.11$. Figure 5b shows W computed in this manner, and there is reasonable agreement with the experimental curve in Fig. 5a. The small difference between the two curves is due to the decrease of η_{st} and η_{sp} with increasing I .

We will now discuss the external quantum efficiencies for the case where the current is not much higher than the threshold current, and series resistance effects shall be neglected. It was found that the differential quantum efficiency of the stimulated emission, η_{st} , was generally higher under pulsed conditions than for cw operation. In some cases this difference could be up to a factor of 2. The spontaneous quantum efficiencies η_{sp} are identical within the limits of error.

In Table 2, differential efficiencies measured under pulsed conditions at 77°K and 90°K are compared with those obtained under cw conditions for a typical diode (structure two). One can see that the differential stimulated efficiencies hardly vary with temperature between 77°K and 90°K (as determined by pulsed operation).

The lower value for η_{st} under cw conditions can be explained by the continuous rise of the junction tempera-

Table 2 Quantum efficiencies: pulsed and cw operation

	77°K		90°K	
	η_{sp}	η_{st}	η_{sp}	η_{st}
pulsed	2.02%	25.4%	1.56%	24%
c. w.	2%	13.3%		

ture with increasing current and the simultaneous increase of the threshold current density. The highest apparent differential quantum efficiency η_{eff} observed was 33% for cw operation at 77°K. Using Eqs. (1), (2) and (6), the following expression for η_{eff} can be derived:

$$\eta_{eff} = \eta_{st} - (\eta_{st} - \eta_{sp})(PVI_0/T_1)e^{PVI/T_1}. \quad (7)$$

The quantities which are most easily determined experimentally are the cw threshold $I_{t,dc}$ and the pulsed threshold I_0 . Now, η_{eff} is determined by these two parameters in the following manner:

$$\eta_{eff} = \eta_{st} - (\eta_{st} - \eta_{sp})\gamma^{I/I_{t,dc}-1} \ln \gamma, \quad (8)$$

with

$$\gamma = I_{t,dc}/I_0.$$

As long as series resistance heating is negligible, i.e. for not too high currents, the experimentally observed dependence of η_{eff} on I agrees approximately with Equations (7) or (8).

Conclusions

The rise of the junction temperature ΔT is linear with direct current as long as the product of current and series resistance is smaller than the bandgap. If the product is larger than the bandgap, ΔT increases quadratically with the current. The experimental values for thermal resistance vary from diode to diode, but they are generally of the same order as the theoretically derived spreading resistance. In the presence of junction heating, the cw laser threshold is larger than the pulsed threshold. The two thresholds can differ by as much as a factor of e which characterizes the limiting case where continuous operation is just reached at one point. The dependence of the total light emission on the direct current can be computed from the thermal data, the external quantum efficiencies and the temperature dependence of the threshold; good agreement is obtained with the experimental curves. The same applies to the cw differential quantum efficiency of the stimulated emission which is smaller for continuous than for pulsed operation.

Finally, we wish to note that the diodes used in our experiments were selected in order to demonstrate the effects of heating. The absolute laser data quoted are therefore not representative of the best values obtained so

far. For instance, we have also achieved cw operation at bath temperatures of 90°K. Values of up to 2 watts for the total power output during continuous operation at 77°K have been reported earlier by J. C. Marinace.⁶

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