AT&T Technical Journal
Vol. 64, No. 3, March 1985
Printed in U.S.A.

Implementation of the Proposed Reliability Assurance Strategy for an InGaAsP/InP, Planar Mesa, Buried Heterostructure Laser Operating at 1.3 μm for Use in a Submarine Cable

By F. R. NASH, W. J. SUNDBURG, R. L. HARTMAN,
J. R. PAWLIK, D. A. ACKERMAN, N. K. DUTTA, and
R. W. DIXON*

(Manuscript received March 5, 1984)

We discuss the implementation of a strategy designed to provide laser-light-emitting reliability assurance for 1.3-μm InGaAsP/InP lasers of the planar mesa, buried heterostructure type for use in a submarine cable application. The testing regimes include initial characterization (cosmetic and light-current curve inspection), passive aging (elevated temperatures [85 to 175°C] without bias, with and without humidity [≤85-percent relative humidity]), overstress active aging (high temperatures [150°C], high currents [250 mAdc]), and long-term rate-monitoring active aging (elevated temperature [60°C] burn-in [3 mW/facet]). Overstress testing is designed to compel a timely (~10^2-hour) identification of premature failures, due to modes of degradation other than the long-term ultimately controlling wear-out mode, and to stabilize transient modes. To identify premature failures of the wear-out type, survivors of overstressing are subjected to rate monitoring in which wear-out degradation rates, established in a reasonable time (~10^3 hours), may be sorted. The principal results of the important overstress aging were the detection of an initially occurring saturable degradation mode, present to some extent in most lasers, and a regimen to force its rapid stabilization, so that it would not obscure determination of the activation energy of the wear-out mode. With a credibly determined value for the latter, it was deterministically inferred from

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* Authors are employees of AT&T Bell Laboratories.

rate-monitoring results that the light-emitting reliability of the screened lasers at ocean bottom temperatures (10°C) is more than adequate to meet the system design lifetime of 25 years.

I. INTRODUCTION

One promising candidate for the lightwave submarine cable transmitter source is the InGaAsP/InP etched planar mesa, buried heterostructure laser operating at 1.3 μm.[1-4] (A light-emitting-reliability advantage in operating at 1.3 μm had previously been shown[5] by the finding that the average room temperature lifetime of Light-Emitting Diodes [LEDs] fabricated from III-V ternary alloys of the InGaAsP family increases exponentially with decreasing band gap. An LED operating at 1.3 μm would thus outlast one at 0.80 μm by a factor $\approx 10^5$. This was confirmed by the demonstration of room temperature lifetimes $\approx 10^7$ hours for AlGaAs LEDs[6] and similar lifetimes $\approx 10^{12}$ hours for InGaAsP LEDs.[7]) In this paper we discuss the *initial* (cosmetic inspection and light-current characterization), *passive aging* (elevated temperatures [85 to 175°C] without bias, with and without humidity [$\leq$85-percent relative humidity]), overstress *active aging* (high temperatures [150°C], high currents [250 mAdc]), and long-term rate-monitoring active aging (elevated temperature [60°C] burn-in [3 mW/facet]) screening tests that have been applied to lasers of this type to assure light-emitting reliability. Together, these tests constitute elements* of a reliability strategy that has been discussed.[8,9] The objectives are (1) the detection of flaws that have reliability implications and that can be corrected by timely changes in laser design or fabrication; (2) the stabilization of temporally saturable annealing and degradation mechanisms ("drift") that could prevent the reliable determination of both the thermal activation energy and the gradual degradation rates associated with the long-term ("wear-out") mode of failure of the lasers; and (3) the identification of those lasers that are likely to suffer premature failure, i.e., failure prior to the 25-year design lifetime of the subcable system operating at 10°C. Emphasis is placed on two active aging (i.e., forward bias operation) regimes. The *overstress* regime employs high temperatures (60 and 150°C) and high currents (250 mAdc) for relatively short periods of time ($\sim 10^2$ hours). The object is to compel a timely identification of those lasers likely to be premature failures due to modes of degradation other than the

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* It should be understood that this paper represents the *first* attempt at establishing a reliability strategy for one particular laser structure. The elements discussed show promise. Additional work to optimize the strategy may result in the addition, replacement, or refinement of elements.

fundamental, long-term, tolerably slow-acting wear-out mode and to stabilize transient modes. To identify those premature failures that are early wear-out failures, the survivors of the overstress tests are subjected to the *rate-monitoring* active aging regime in which are sorted the wear-out degradation rates, established in an extended duration burn-in at a lasing temperature sufficiently high so that unambiguous degradation occurs in a reasonable time ($\sim 10^3$ hours).

The principal results of the overstress testing were the detection of an initially occurring saturable degradation mode, present to some extent in most lasers, and a scheme to force its rapid stabilization. With this accomplished, credible values of the activation energy and degradation rates for the slower-acting wear-out mode can be determined. Thus, from the rate-monitoring results, it was deterministically inferred that the *light-emitting reliability* of the screened lasers is more than adequate for subcable applications. (Later studies will address the transmitter or *electro-optic reliability* [e.g., absence, with aging, of beam wander, spatial mode switching, light-current abnormalities, extinction ratio deterioration, and relative motion of the laser and optical fiber] of the transmitter.)

A word now about nomenclature. The reliability assurance results[8,9] that we propose to produce are called STP (Stabilization, Truncation, Purge). The *purge* consists of any scheme (e.g., optical inspection, light-current characterizations, overstress aging using high temperatures, currents, optical power, etc.) by which actual or potential premature non-wear-out failures are eliminated from the population. The overstress regime of the purge will also produce *stabilization* of initial saturable transient modes of degradation that appear to exist in most lasers. Rate monitoring of long-term degradation permits *truncation*, i.e., an elimination of early wear-out failures, those which would occur prior to the desired system lifetime.

II. INITIAL SCREENS (PURGE)

Initial screening involves tests that do not generally produce degradation. They may be passive (e.g., optical or Scanning Electron Microscope [SEM] examination) or active (e.g., light-current characterization).

2.1 Optical inspection

Microscopic inspection to check for missing, broken, or unattached wires; cracked, misaligned, facet-contaminated, or misbonded chips; or handling damage has obvious value. Our primary discovery was the existence of torn fragments of Au (from and still attached to the Cr-Au p-metallization and produced during facet cleaving) on the mirror

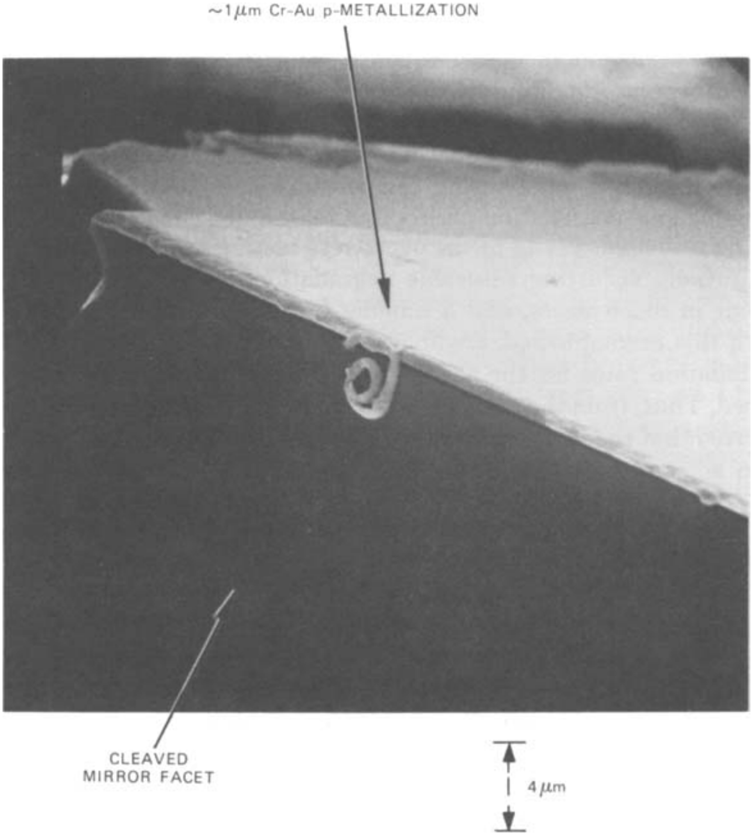

Fig. 1—SEM photograph of a fragment of Au, torn from the p-contact to which it is still attached, which lies on a cleaved facet.

surfaces, across one or more of the epilayers, and on occasion within the region of the mesa. Figure 1 is an SEM photograph of one such case.

There are three ways in which such Au fragments could be inimical to laser reliability: (1) Light blockage—in the course of system installation, long-term mechanical relaxation, or mechanical vibration tests, fragments within the mesa might move to partially obstruct the optical output. (2) Electrical shorting—the recovery of lasing operation after sudden termination, effected by mechanical removal of Au fragments from the mirror of a laser that exhibited no preceding or subsequent signs of degradation, suggested that the torn metal could externally short the p-n junction. (3) Au in-diffusion—Dark-Spot Defect (DSD) formation is a significant mechanism for degradation in InGaAsP/InP LEDs[7,10-15] and lasers,[16-18] and appears to be caused in some cases by the in-migration of Au from the p-contact.[12,13,15]

The overhanging Au problem is an example of the purge used to detect a defect that could cause premature failure and that is avoidable through a relatively simple design change (e.g., thinner or patterned Au).

2.2 L-I-V characterization at 30, 50, and 70° C, pulsed and dc

Initial pulsed (in pulsed operation the junction of the laser remains at the stud or ambient temperature) and dc electrical and optical characterization, performed at ambient temperatures of 30, 50, and 70°C, consists of plots of the following quantities as functions of current (I): light (L), dL/dI,[19] voltage (V), IdV/dI and I^2d^2V/dI^2. For purposes of clarity, we exhibit only the first two of these quantities in Fig. 2 for an acceptable laser. The sublinearity in the Continuous Wave (CW) L-I curves commences at threshold and is more pronounced than in the pulsed curves. (The implications of sublinearity will be considered in more detail in Section 4.1.) Figure 3 represents a laser with unacceptable CW L-I curves. Temperature-dependent anomalies (kinks) in the L-I curves are more apparent in the dL/dI curves. The kinks may be the result of beam wander[20] or a switch to a higher-order mode, which often results in a split mode spectrum.[21-23] Both effects can be caused by an inadvertently too large lateral active region width. Both effects can significantly reduce the power coupled into a single-mode fiber.

III. PASSIVE AGING SCREENS (PURGE)

Passive aging involves tests designed to produce degradation without current injection.

3.1 Temperature humidity

To test the integrity of the stud, standoffs, and solder, we used an 85°C 85-percent Relative Humidity (RH) ambient (the partial pressure of water vapor was 383 Torr, the volume density of water molecules was 10^{19} cm^{-3}, and the fractional concentration of water molecules was 500,000 ppm). Since the facets of the lasers were not dielectrically coated, we chose not to bias the lasers in order to avoid the risk of a lasing-induced facet degradation,[24-26] which might have masked other degradation mechanisms whose presence it would be important to detect.* It was not expected that the Pb/Sn solder used in bonding the laser (p-side up) would degrade since it appears that eutectic alloy

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* In Section 7.2 we discuss the role of facet erosion under forward bias and conclude, in accordance with Refs. 25 and 26, that it is inconsequential for InGaAsP/InP lasers operated in the environment of interest.

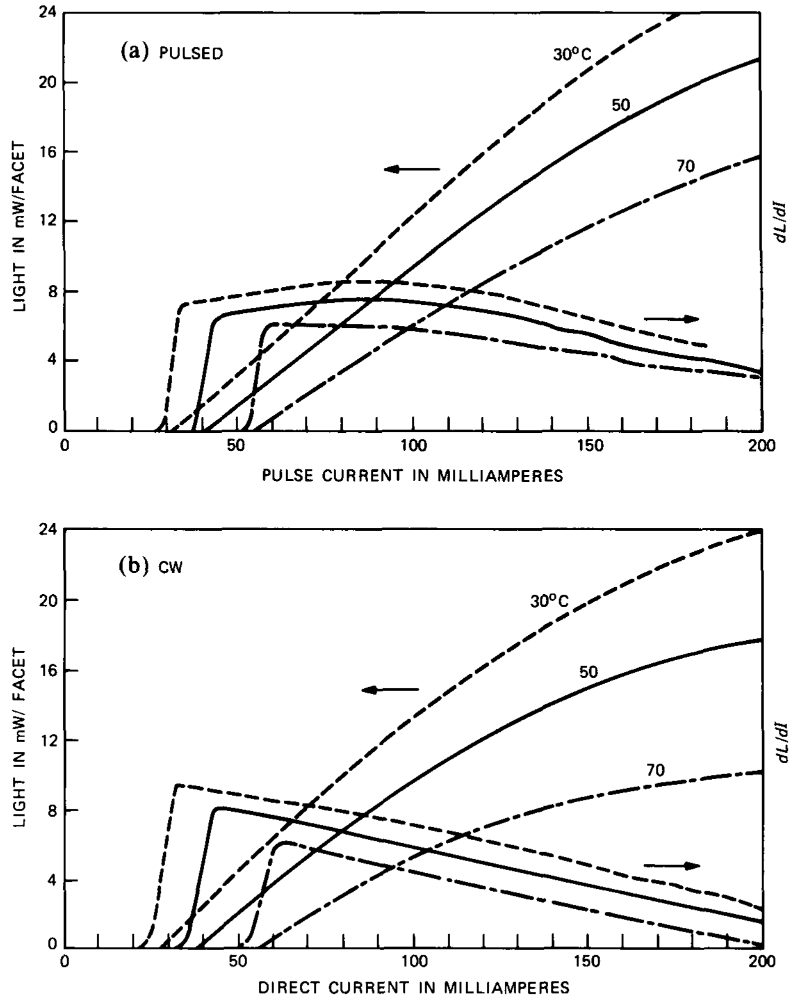

Fig. 2—*L* and *dL/dI* versus *I* as a function of temperature for a typical laser, (a) pulsed and (b) CW. The *dL/dI-I* curves in CW operation exhibit a negative slope, which reflects the rollover tendency of the corresponding *L-I* curves.

solders (e.g., Au/Sn* and Au/Ge) remain stable[28-30] for laser operation at 70°C for 10^3 to 10^4 hours, in the apparent absence of any attempt to minimize environmental humidity.

Four lasers were optically examined several times in the course of ≈2300 hours of aging without bias. Although two of the lasers operated

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* A recent study (Ref. 27), however, has revealed Sn-whisker growth at the surface of Au/Sn bonding solder.

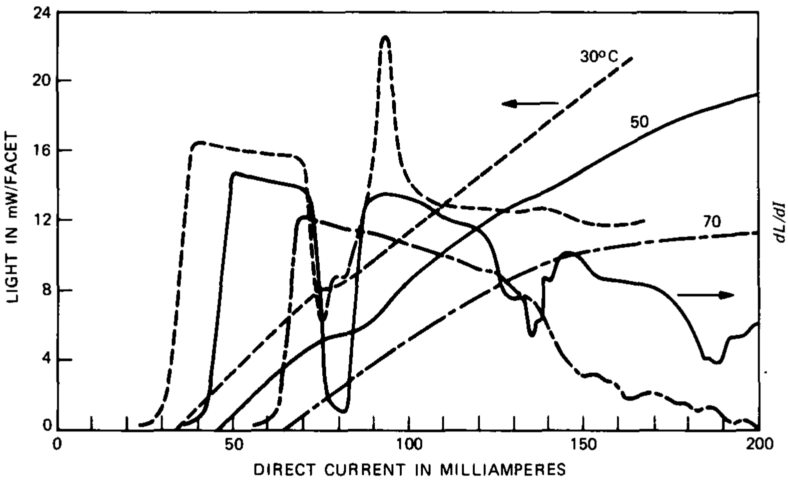

Fig. 3—*L-I* and *dL/dI-I* curves for a laser that exhibits temperature-dependent anomalies (kinks).

with only slightly altered *L-I* characteristics at the termination of aging, three corrosion products of major proportions were present on all lasers and studs. One corrosion product was present in the form of a thermally induced, nonuniform, multicolored (optically thick, ~1000-angstroms) oxide covering the laser facets; at the start of the aging, the facets had been spotlessly clean. A second corrosion product was a grayish powdery deposit on the top and sides of the standoffs, lasers, subcarriers, and studs. Using the energy dispersive X-ray attachment of an SEM,[31] it was shown that a lead oxide was predominant. A third corrosion product was associated with the presence of a steel weld ring (to which a hermetic can is eventually affixed) on the top of the bolt head part of the stud. Although the entire stud is Au-plated, the plating at the weld ring was breached. After ≈2300 hours, a red-brown iron oxide[31] (rust) was observed on top of the bolt head and on nearby surfaces of the stud remote from the ring.

The device-threatening formations of oxides of InP, Pb, and Fe can be substantially suppressed if the water vapor content within the hermetic can is made low. The water vapor content of the ambient outside the can should also be kept low to prevent a breach of the hermetic seal, from without, caused by an inadvertent exposure of some part of the steel ring during the welding. Operation of the lasers at ocean bottom temperatures (~10°C) will also assist in retarding oxide formation.

3.2 High temperature

This regime emphasized storage aging at 175°C, near the melting

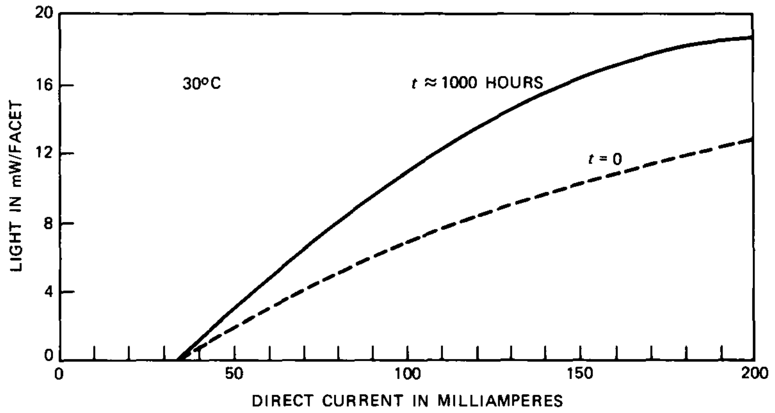

Fig. 4—Change in the 30°C CW *L-I* curve produced by unbiased storage aging at 175°C for 1 kh.

temperature (183°C)[32] of the Pb/Sn solder; the test chamber had an opening to the laboratory ambient.* It was not expected that significant deterioration of the Pb/Sn would occur because similar storage-aging experiments had apparently confirmed the stability of eutectic alloy solders for LEDs (Au/Ge, 230°C, 2000 hours)[7] and lasers (Au/Sn, 100°C, 2000 hours).[33]

No oxide growth was observed on any laser or stud that had been aged at 175°C for ≈4000 hours and periodically examined.† The lasing thresholds at room temperature remained unaltered. Several lasers exhibited increases in slope efficiency, however, as typified by Fig. 4. No change after 1000 hours was observed; it is not known when the improvement occurred prior to the first recharacterization at 1000 hours. Annealing effects similar to that shown in Fig. 4, but of smaller magnitude, were noted in the course of active aging; they occurred whenever forward bias was removed from a device at some elevated temperature (e.g., 60°C).

IV. ACTIVE AGING SCREENS (STABILIZATION, PURGE, TRUNCATION)

4.1 High-current L-I characterization—the role of shunt currents

Prior to forward bias aging at high currents, it is necessary to characterize the *L-I* curves at high currents. At elevated temperatures

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* The partial pressure of water vapor was 15.5 Torr (the same within and without the chamber); within, the relative humidity was ≈0.2 percent, the volume density of water molecules was 3.3×10^{17} cm^{-3}, and the fractional concentration of water molecules was ≈20,000 ppm. Relative to the 85°C 85-percent RH ambient, there were ≈25 times fewer water molecules.

† In Section 7.3 we shall discuss the effect of storage aging on the possible in-migration of Au from the p-contact.

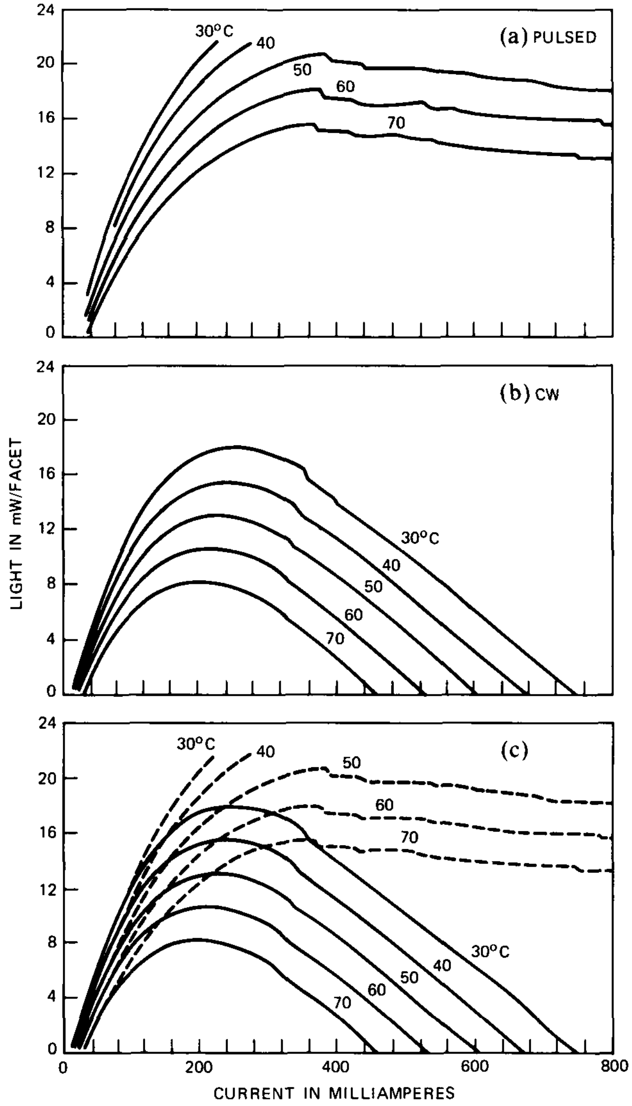

Fig. 5—(a) Pulsed, (b) CW, and (c) composite *L*-*I* curves as a function of temperature.

and/or at high currents, a major fraction of the injection current is shunted around the active region. This peculiarity of those lasers that employ reverse-biased junctions to confine current must be taken into account in the design of high stress (current, temperature, optical power) active aging screens.

A typical set of high-current *L*-*I* curves is shown in Fig. 5 for pulsed and dc operation at several different ambient temperatures. The pulsed *L-I* curves exhibit "saturation" behavior, i.e., beyond a critical current (~400 mA for the particular laser), the light output remains essentially constant. The dc *L-I* curves exhibit "rollover" behavior and an upper, as well as a lower, threshold.

The sublinearities present in the pulsed *L-I* curves are due to shunt (leakage) paths, which divert an increasingly larger fraction of the terminal current away from the lasing region, as either temperature or current is increased. In pulsed operation (no heating caused by the current), there appears to be a critical current, independent of ambient temperature, beyond which no additional current can be injected into the lasing region (see Fig. 5a). (In an ideal laser, threshold represents that current above which all additional current is converted into stimulated emission in the lasing modes. The critical current in Fig. 5a is also a threshold current, not for lasing, but for current diversion.)

To understand the rollover in the dc *L-I* curves (see Fig. 5b), it is helpful to superimpose a family of pulsed *L-I* curves (see Fig. 5c), which can be used as thermometers. The 70°C pulsed *L-I* curve crosses the 30°C dc *L-I* curve at ≈360 mA. At the crossover point, the pulsed and dc curves correspond to identical light outputs and currents, so that the active region in dc operation must be 40°C above the ambient or stud temperature. (The validity of this technique requires the assumption that the distribution of currents between the active and shunt paths in the nonheating pulsed regimes is not frequency dependent.) We may use a standard expression for the thermal impedance (R_{th}),

$$R_{\text{th}} = \Delta T[^\circ\text{C}]/VI[\text{W}], \tag{1}$$

where ΔT is the temperature rise of the active region above the stud temperature, and the voltage-current product is the electrical input power dissipation, which is responsible for ΔT. For the specific example, $\Delta T = 40^\circ\text{C}$, $V = 2.0$ volts, and $I = 0.36$ ampere, it is computed that $R_{\text{th}} = 56^\circ\text{C/W}$. This value is typical[2] for lasers of this type bonded p-up.

The 30°C, dc *L-I* curve is initially coincident with the 30°C pulsed *L-I* curve (see Fig. 5c), but as the current is increased, the active region in dc operation heats up, and the dc *L-I* curve can be seen to progressively cross the 40, 50, 60, and 70°C *L-I* curves of pulsed operation. Rollover in dc operation, caused by internal (ohmic or nonradiative) heating, is then seen as a consequence of having the operating point in the dc *L-I* space pass from one pulsed *L-I* curve to another as the current is increased. Since the maximum lasing power output in pulsed operation decreases with increasing temperature, the dc operating point will roll over and proceed toward the upper lasing threshold. For the 30°C dc *L-I* curve of Fig. 5, the upper lasing threshold occurs at $I = 0.74$ ampere, so by using (1), $R_{th} = 56°C/W$, and $V = 2.0$ volts, it is computed that $\Delta T = 83°C$. Thus, the ambient temperature at which this device could no longer be pulse-operated as a laser is $83 + 30 = 113°C$, which is in good agreement with high-temperature pulsed measurements on similar lasers. Although there is some current flowing into the active region above the upper threshold that produces ~100 μW output, the 113°C temperature is viewed as that temperature for which lasing threshold can never be attained because of the dominance of the shunt path. (A thermal runaway of threshold might be expected to occur because of the well-known empirical relationship, $I_{th} \propto \exp(T/T_0)$, where for the present lasers, $T_0 = 70K$. For three reasons, this effect is not believed to be controlling the rollover behavior in Fig. 5b: (1) According to calculations, the output power would fall precipitously beyond the point of rollover because of the exponential function, and this is not in agreement with the shape of Fig. 5b. (2) If shunting were a minor effect, there should have been significantly more spontaneous output (~3 mW) at the upper threshold (740 mA) of the 30°C dc *L-I* curve of Fig. 5b, since LED studies[14] have shown that InGaAsP does not become nonradiative at ~ 100°C; no light output in excess of ≈0.1 mW is apparent beyond the upper threshold of Fig. 5b. (3) Using a convenient relationship between the dc and pulsed thresholds, $I_{th}^{dc} = I_{th}^{pul} \exp(\Delta T/T_0)$, where ΔT is due to current heating, $I_{th}^{pul} = 35$ mA, and $\Delta T = 83°C$ in dc operation at $I = 740$ mA in a 30°C ambient, it is calculated that I_{th}^{dc} (113°C) = 114 mA; the device should have lased at a junction temperature equal to 113°C, in the absence of shunting, but it did not. Thus thermal runaway is not dominant.)

It is known[1,3,34] that leakage or shunting currents are significant in these devices. Figure 6 is a schematic of the etched mesa, buried heterostructure laser showing two possible shunting paths for the terminal current, in addition to the current through the active region. The electrical characteristics of such a laser with a diode shunt path have been calculated.[35] The *L-I* signatures for pulsed operation have been calculated for the pnpn shunt alone,[36,37] and for the pnpn and diode paths simultaneously present.[38] Using credible values of the relevant parameters, the latter study[38] permits the conclusion that the dominant shunt current is I_{pnpn}. Calculated representative pulsed *L-I* curves for several ambient temperatures are shown in Fig. 7. A "knee" is apparent, suggesting a light output saturation such as that shown in Fig. 5a. This model, however, does not show leakage at threshold, in disagreement with experiments.

In addition to the *gradual* increases in leakage current corresponding to the increasing sublinearity in the *L-I* curves of Fig. 5, there also

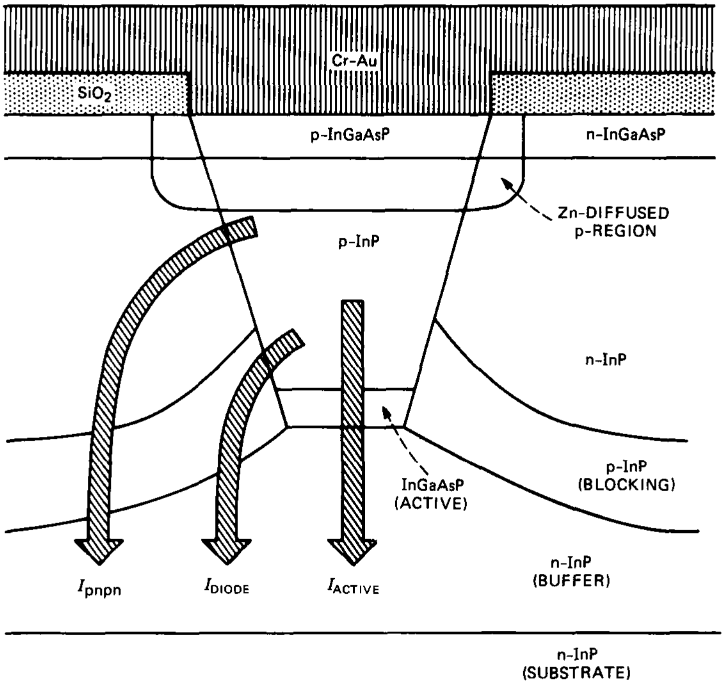

Fig. 6—Schematic cross section of the planar etched mesa, buried heterostructure laser with several current paths.

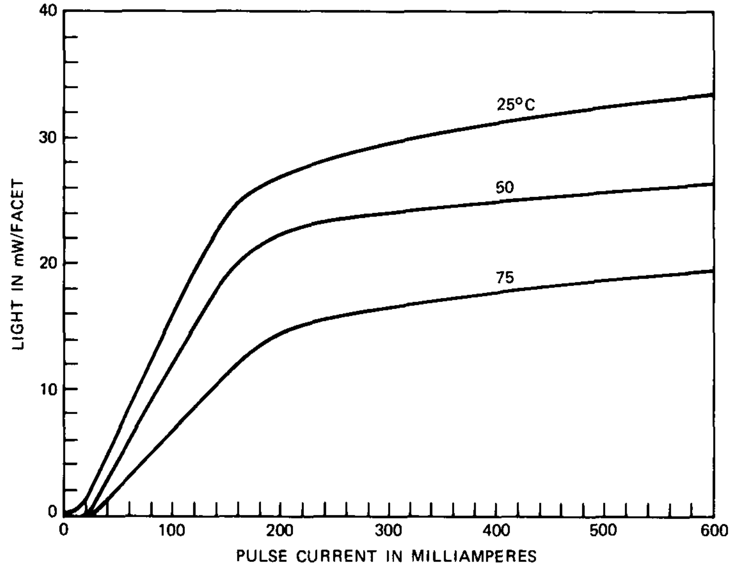

Fig. 7—Calculated pulsed *L-I* curves assuming significant shunt current flow in the pnpn path of Fig. 6.

appear *abrupt* decreases in output for small positive increments in current in both pulsed and dc operation (see Fig. 5). These sudden decreases on occasion may be large ($\Delta L \sim -10$ mW/facet); they invariably and very frequently occur beyond the critical current for output power saturation, they have been attributed[1,34] to sudden increases in I_{pnpn}, and the current at which they occur often does not decrease with accelerated aging degradation, so their existence is not automatically grounds for laser rejection.

The existence of shunt currents has been confirmed by the direct observations of spontaneous emission from lateral regions outside the active region, either from an n-side "window"[4] or facet viewing.[39] The dL/dI curves characterizing dc operation indicate that sublinearity in the L-I curves is present at lasing threshold and above (see Fig. 2b). This is true for all lasers of this type examined in the temperature range 0 to 70°C. An advantage[1] in the existence of dc-rollover (i.e., current shunting) is that catastrophic optical damage of the laser facets[40] may not occur even though the lasers are operated repeatedly up to 30 times threshold. Since unexpected current surges are a likely cause of random failures,[9] the built-in surge protection is important in a high-reliability application. *Short-duration, high-current* pulses might, however, remain a problem (e.g., compare Fig. 5a and b).

4.2 Initial elevated temperature burn-in

All of the lasers used in our tests were the survivors of two elevated temperature burn-in tests conducted prior to our receipt of the devices: (1) 60°C, 5 mW/facet, 24 hours, $\Delta I_{\text{op}}/I_{\text{op}} \leq 1.5$ percent; and (2) 60°C, 5 mW/facet, 100 hours, $\Delta I_{\text{op}}/I_{\text{op}} \leq 5$ percent, where ΔI_{op} and I_{op} are the increase in operating current and initial value of operating current to produce a given output. Burn-in tests (operation at normal outputs and elevated temperatures for a short duration, $\sim 10^2$ hours) are useful for eliminating some so-called infant failures. Potential low thermal activation energy modes of failure may not, however, be identified in this kind of screening test.[8,9] We shall show that due to the existence of an initially occurring saturable mode of degradation, which exists in some degree in virtually all lasers, and which typically can escape detection in burn-in tests because it has an incubation period, the conventional elevated temperature burn-in was found to be inadequate to assure reliability of its survivors. The purge (understood, hereinafter, to mean the overstress regimes) that was imposed on the burn-in survivors was essential to the success of the undertaking.

4.3 Degradation accelerants and driving mechanisms

Discussions of screening strategies[8,9] have emphasized the concepts of the *harshness*, *selectivity*, and *tailoring* of the accelerants used to detect the presence of premature non-wear-out failure and transient modes. Initial device characterization and an understanding of how the device operates is crucial in giving specificity to these concepts. The laser is a forward bias device. Potential accelerants for the light-emitting degradation of lasers under forward bias are temperature, injection current, optical power, and humidity.

In the absence of forward bias, *humidity* is both a driving mechanism for, and an accelerant of, degradation; it is not, however, selective, because it treats all lasers alike (see Section 3.1). For a laser operated in forward bias without protective facet coatings, humidity in the testing ambient will also nonselectively promote and accelerate degradation due to the formation of an oxide on the emissive portion of the mirrors.[24,25,41] The degradation may take many forms (e.g., reduce the output at a fixed current, redirect the output beam, promote electro-optic deficiencies such as pulsations and light jumps),[41] but it should have approximately the same effect on all lasers, i.e., it makes no distinction between lasers that are inherently reliable and those that are not. The lasers used in our tests had uncoated facets. Our initial test results showed that no light-emitting degradation that we detected was due to facet oxidation (see Section 7.2). This is in accord with recent studies[25,26,31] that have concluded that InGaAsP/InP lasers of the etched mesa, buried heterostructure type can operate at elevated temperatures (~70°C), in laboratory ambients (~30-percent RH), with outputs ≈5 mW/facet, without any appreciable degradation due to lasing-induced facet erosion for times that are more than an order of magnitude larger than the design lifetime (2×10^5 hours) of the subcable lightwave system. Thus, uncoated lasers can be used to find which of the other possible accelerants might be made selective in detecting premature failures, without having our results significantly affected by facet effects due to the presence of humidity in the testing ambient.

Temperature alone is not a driving mechanism for degradation in our lasers, and hence acting alone it is not an accelerant. Elevated temperature shelf lives are very long. In the presence of forward bias, under which optical power and/or injection current are driving mechanisms, temperature is an accelerant. The melting temperature (183°C) of the Pb/Sn solder is the approximate upper limit on the harshness of the ambient temperature. For purposes of stressing the active region in CW lasing operation, a more important upper limit on the ambient temperature is the temperature (~100°C) at which most of the injected current flows into a shunt path.

To the extent to which optical power, as distinct from current, is both a driving mechanism for, and an accelerant of, degradation, it is typically limited to a maximum of ~20 mW/facet at room temperature (see Fig. 5). It is inconvenient to lower the temperature in order to produce larger maximum CW outputs, and it is somewhat unwise, as well, because the deceleration of degradation due to a lowered temperature could offset the acceleration of degradation due to the increased optical power.

We shall show that direct current, as distinct from optical power, is a driving mechanism for the most significant degradation that we observe. If the direct current is too large, it will flow predominantly into a shunt path, resulting in nonlasing and hence no stressing of the active region (see Section 4.1 and Fig. 5). An upper limit on the current stressing of the shunt path will be related to the melting temperature of the solder. Thus, it is clear that temperature, optical power, and current either cannot or should not be elevated indiscriminately if a proper attempt at reliability assurance screening is to be made.

4.4 Optical power-current (P/I) overstress regime

To stress the active region, current must pass through that region. A lasing output is the best evidence of this. Since substantial currents are required to get substantial output powers at room temperature, the tailored stressing of the active region requires the simultaneous use of optical power and current as accelerants. If P_p is the peak available output power, i.e., the power at which rollover (see Fig. 5) occurs in CW operation, and I_p is the corresponding direct current, then, e.g., in a 30°C ambient, P_p may be as large as 25 mW/facet, and I_p is typically 180 to 250 mA, which is 5 to 15 times the threshold current (I_{th}) at 30°C. Since many of the lasers had P_p (30°C) $\approx$ 25 mW/facet, it was possible to select a group for constant optical power aging at $\approx$20 mW/facet; this level was chosen to be below P_p to allow for some decrease in P_p with aging. The operating current to maintain an output $\approx$20 mW/facet was continually monitored. This P/I regime was characterized by the following constant stress conditions: $P \approx 20$ mW/facet, $T_{\text{amb}} = 30°\text{C}$, uncoated facets, and laboratory ambient ($\approx$50-percent RH).

Plots of operating current (I_{op}) versus time are given in Fig. 8. The bimodality in degradation behavior is only apparent; a variety of degradation rates are actually present. The initial values of I_{op}, which are $\approx$5 times I_{th}, are, on average, lower in the group showing marked degradation than in the group showing little or no degradation; $I_{\text{op}}(0)$ is not indicative of degradation potential. Judging from the sublinearity present in the dc L-I curves, i.e., the substantial departure of P_p from the power output that would have been expected from a straight line extrapolation of the initial value of the L-I slope up to a current I_p, the P/I regime is unavoidably stressing both the active region and

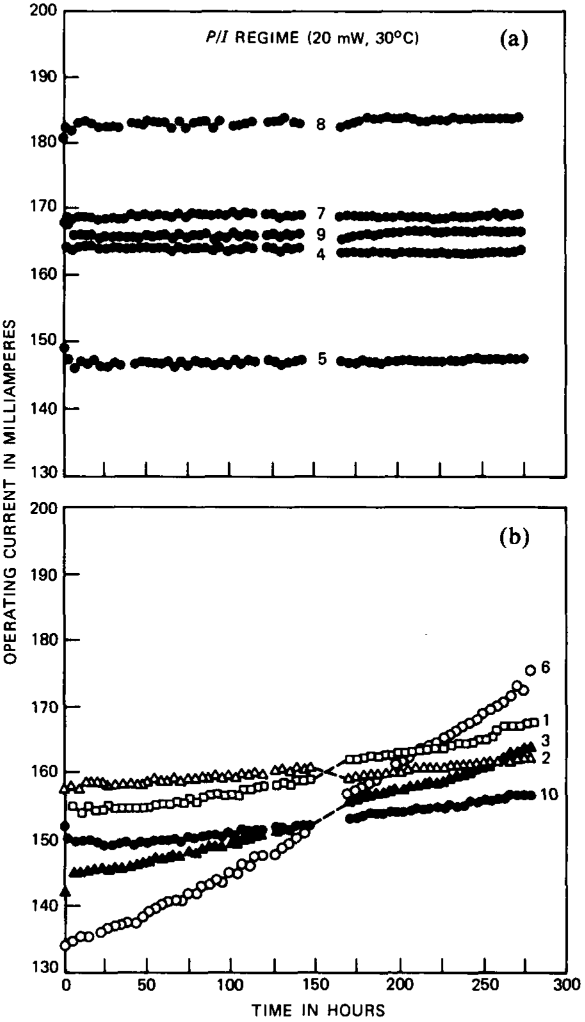

Fig. 8—Plots of operating current (to maintain 20 mW/facet in a 30°C ambient) versus time for ten lasers that had previously only experienced a burn-in (5 mW/facet) at 60°C for 100 hours, and had shown $\Delta I_{op}/I_{op}(0) \leq 5$ percent.

shunt current paths. Although there is some sign of an initial incubation period present in the degradation behavior of some lasers, no stabilization occurs in 275 hours. Even if power, as distinct from current, is an important accelerant, its usefulness is limited not only by the fact that P_p rarely exceeds 25 mW/facet, but as well by the substantial downward spread in actual values of P_p in a given population (see Fig. 9). Henceforth, in attempts to stress the active region, current will be emphasized as the practically important accelerant.

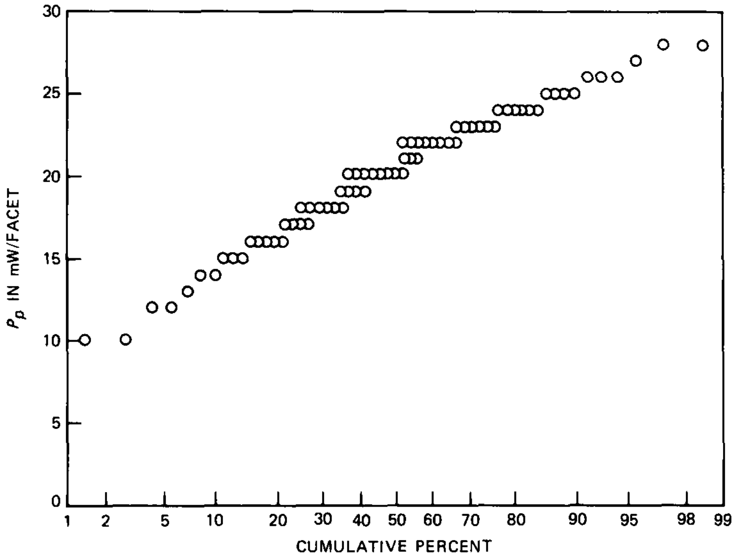

Fig. 9—Normal plot of the peak or rollover CW power (P_p) at 30°C for 70 lasers that had been subjected to only a burn-in (see caption of Fig. 8).

4.5 Temperature-current (T/I) overstress regime

High temperatures and currents will exclusively stress the shunt path. The sublinearity present in the dc *L-I* curves at threshold indicates that some current is always flowing into the shunt path, regardless of the temperature and output power at which the laser is operated. To stress the shunt path alone, the ten lasers aged previously in the *P/I* regime (see Fig. 8) were subjected to the *T/I* regime characterized by the following constant stress conditions: $I(\approx I_p) =$ 250 mA; $T_{\text{amb}} =$ 100°C; uncoated facets; and laboratory ambient. Periodically, the ambient temperature was lowered to 60°C, and the operating current to yield 3 mW/facet was recorded (see Fig. 10).

The most important discovery in the degradation patterns of these lasers is the stabilization effect that occurs within ≲20 hours. The lasers (numbers 3 and 6) that exhibited the largest change in Fig. 8 failed to emit 3 mW/facet at 60°C and consequently are not represented in Fig. 10. Lasers (numbers 1, 2, and 10) that exhibited intermediate changes in Fig. 8 exhibited in Fig. 10 increases that were similar to one another. The lasers (numbers 4, 5, 7, 8, and 9) that exhibited the smallest changes in Fig. 8 continued to exhibit relatively small or no changes in Fig. 10. (We shall subsequently present data that show that virtually all lasers exhibit an initial transient mode of degradation, which can be compelled to stabilize rapidly [~a few hours] in a high temperature-high current stress regime; after stabilization,

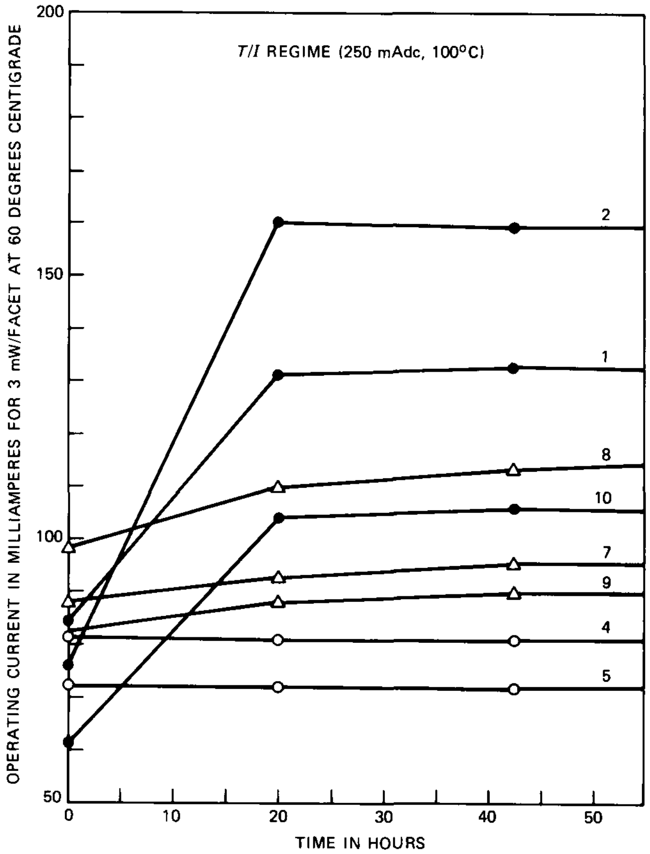

Fig. 10—Plots of operating current (to maintain 3 mW/facet in a 60°C ambient) versus the time that the lasers were subjected to overstressing in a nonlasing regime (100°C, 250 mAdc); the lasers used had previously been subjected to a power-current overstressing (see Fig. 8).

the degradation rates of all surviving lasers are substantially lower and very similar to one another, despite the larger rate differences in the prestabilization time period.) Since the *P/I* regime stresses the active region and shunt current paths simultaneously, and since the *T/I* regime almost exclusively stresses the shunt path, the correlation between Figs. 8 and 10 suggests that the prestabilization increases in operating current occur because of some mechanism related to the shunt path. This is important because the shunt path is always operative, even at threshold.

4.6 *Effect of T/I and P/I overstress regimes on the initial saturable degradation*

To confirm the conclusion that the prestabilization degradation is largely a shunt path phenomenon, the order in which the *P*/*I* and *T*/*I* stress regimes had previously been imposed was reversed, and more comprehensive monitoring was done by periodically generating *L*-*I* curves. For a second set of lasers the *T*/*I* regime was characterized by $T^{\dagger}_{\mathrm{amb}} = 150°\mathrm{C}$, $I = 250$ mAdc, time = 10 hours, uncoated facets, and laboratory ambient. An *L*-*I* curve was generated at a test ambient temperature of 60°C, at the start and finish of this regime. Immediately thereafter, we imposed a *P*/*I* regime whose characteristics were $T^{\dagger}_{\mathrm{amb}} = 60°\mathrm{C}$, $I^{\ddagger} = 200$ mAdc; time ≈ 200 to 300 hours. *L*-*I* curves were generated periodically at 60°C. The results of the two sequential regimes are shown for one laser in Fig. 11. The important change occurred in the *T*/*I* regime, in which the terminal current was diverted almost entirely into the shunt path. Much less significant changes were observed during the *P*/*I* regime, in which the active region path and shunt path were comparably and simultaneously stressed. This suggests that stabilization had been completed for this laser within 10 hours, since further stressing of the shunt path produced no comparably dramatic effect. Another example of degradation during the *T*/*I* and *P*/*I* regimes is shown in Fig. 12. Note that after the *T*/*I* regime, it was not possible to get 3 mW/facet at 60°C at any value of current. A similar large decrease in P_p is the likely explanation for why devices numbers 3 and 6 of Fig. 8, which had exhibited the largest degradation, were unable to emit 3 mW/facet at 60°C and hence were not represented in Fig. 10. The laser of Fig. 12 continued to exhibit marked degradation in the *P*/*I* regime; this may have been due to degradation of the active region path as distinct from the shunt path, or it may reflect an additional nonsaturable, or not yet saturated, degradation of the shunt path.

To demonstrate the time evolution of the stabilization of the initial transient mode, another group of lasers were *T*/*I* stressed at $T_{\mathrm{amb}} = 135°\mathrm{C}$ and $I = 250$ mAdc. The rollover power, P_p, at 60°C was recorded at various times throughout the stress duration of 200 hours (see Fig. 13a). This experiment was repeated with another set of lasers stressed

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[†] The temperature was chosen so that with $I = 250$ mA, the junction temperature would remain below the melting point (183°C) of the Pb/Sn solder.

[‡] This value of current was chosen because $I_p \approx 180$ to 250 mAdc, i.e., the current (I_p) at which the peak output occurs (independent of ambient temperature) is, on average, ≈200 mAdc. The emphasis for this version of the *P*/*I* regime was not on optical power output as an accelerant, even though $P_p \approx 10$ mW/facet at 60°C. Rather, it was, in part, upon maximizing the current through the active region, whose stressing we desired. More of the injected current (200 mA) would have flown through the active region at a lower temperature (e.g., 30°C), but we also wanted to maintain some thermal acceleration, as well as current acceleration, of the active region path, so 60°C was chosen as the ambient temperature. Temperatures below 60°C are difficult to obtain, even if desirable, because of the current heating of the laser bar holder.

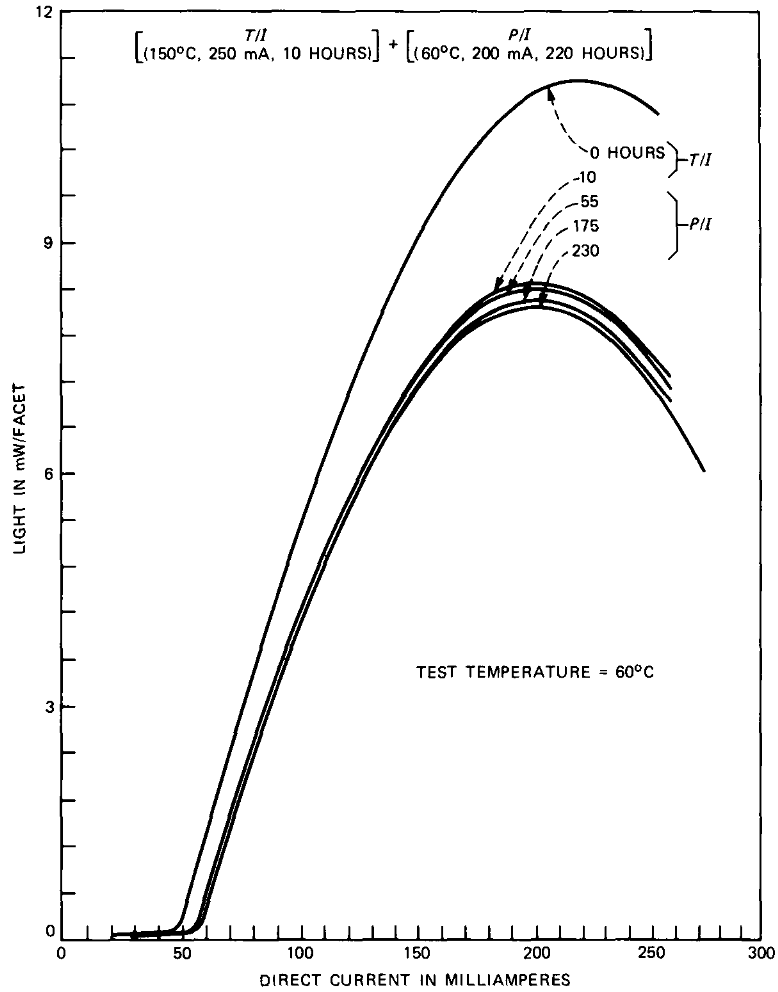

Fig. 11—The effects on the 60°C CW *L-I* curve of a purge, i.e., a sequential temperature-current and power-current overstressing for the time durations shown.

at $T_{\text{amb}} = 150°\text{C}$ and $I = 250$ mAdc (see Fig. 13b). Stabilization, in the contexts of Fig. 13a and b, means that an initially large rate of degradation of P_p decreases with time until it becomes constant. The current was constant (250 mAdc) in both T/I regimes, and in both cases it flowed exclusively in a shunt path. The optical output was also constant in each case, i.e., very small, because no current went into the active region.

4.7 Activation energy of the saturable initially occurring mode of degradation

Many degradation mechanisms involve the diffusion of atoms and

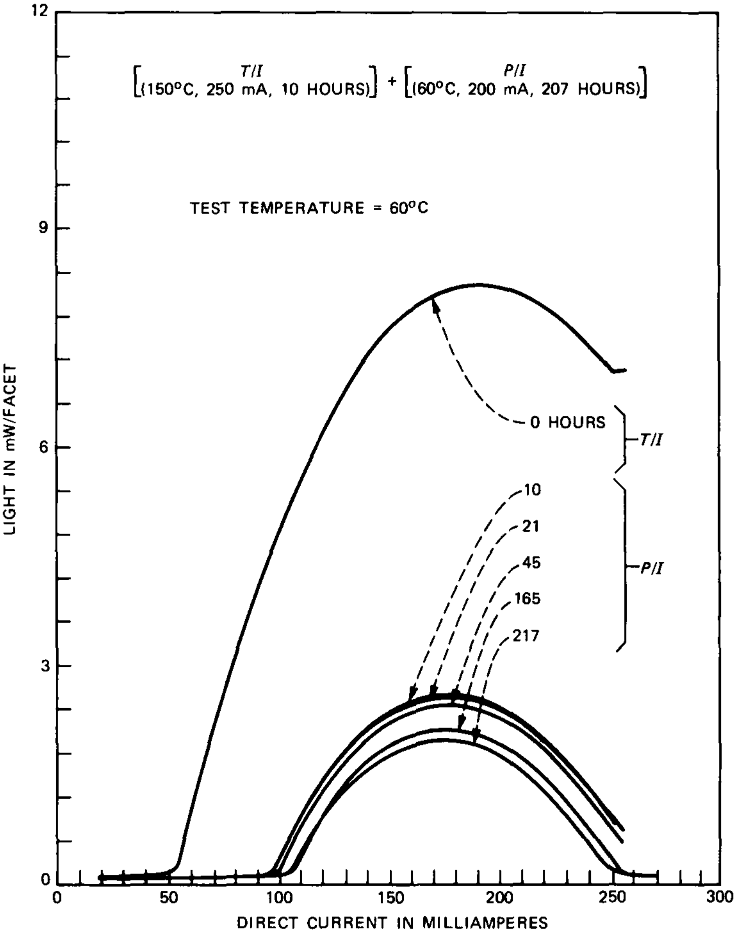

Fig. 12—The effects of sequential overstressing (purging) on another laser; regimes are similar to those of Fig. 11.

hence possess an Arrhenius time-temperature dependence, i.e., a reaction rate given by

$$R \propto \exp\left[-\frac{E_a}{kT}\right], \tag{2}$$

where k is Boltzmann's constant, T is the absolute temperature, and E_a is the activation energy. More complicated temperature-dependent reaction rates might be used, e.g., the Eyring equation.[42] Since there is no physical basis for making a rational choice, the simplest, (2), will be used. We shall follow the approach of Joyce et al.[43,44] R is understood to be the rate of degradation of some parameter that occurs at an

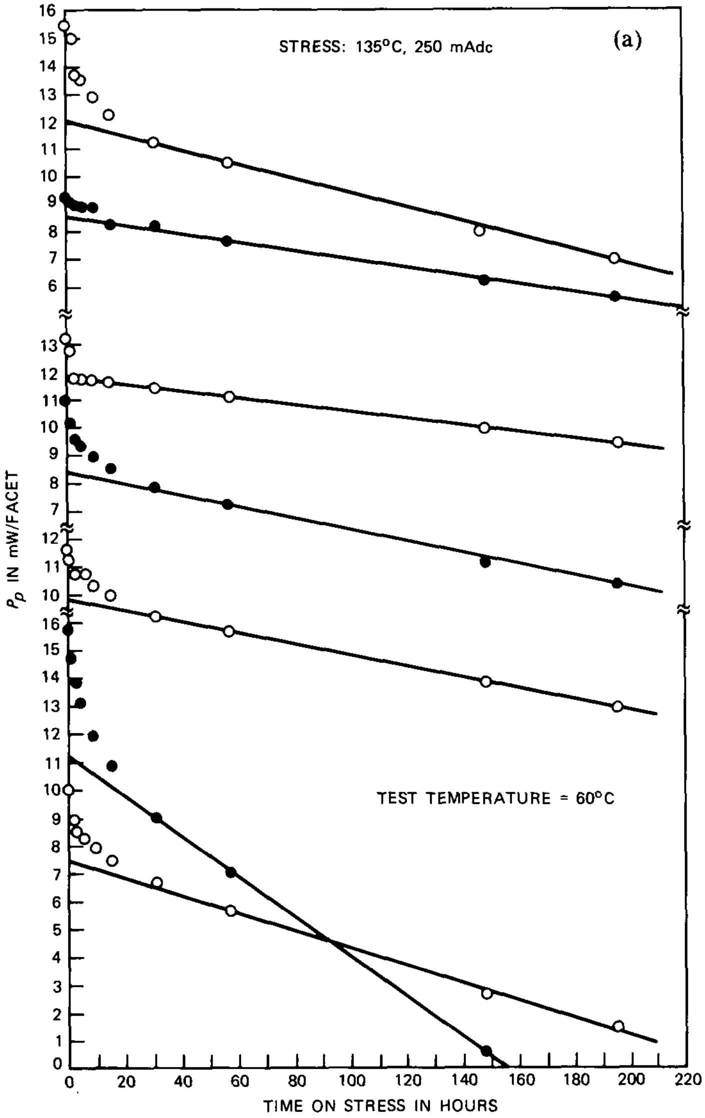

Fig. 13—Peak CW power (P_p) versus time for seven lasers; (a) the stress condition was 135°C and 250 mAdc and the L-I curve monitoring of the effects was done at 60°C. (Cont.)

elevated accelerated aging temperature, T, as measured at some lower reference temperature. This is the activation energy approach.[44] Since no rates of degradation are monitored at the accelerating temperature(s), this approach is suitable for the case of Fig. 13, where the accelerating temperatures exceed that at which lasing occurs. With T_1

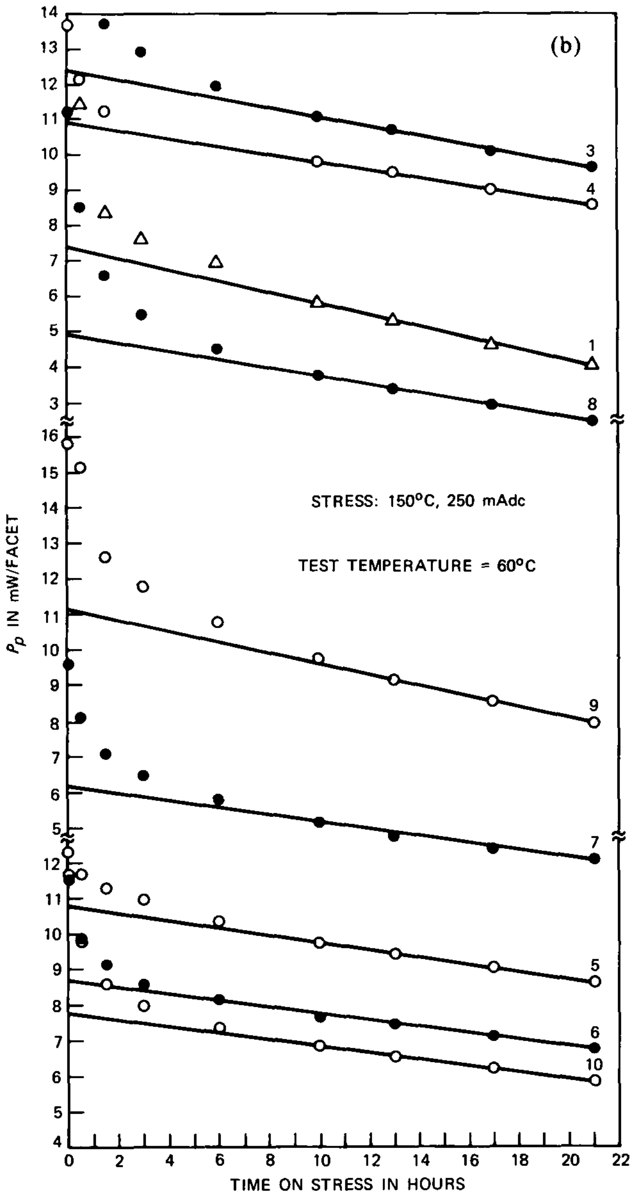

Fig. 13—(b) Same as Fig. 13a except that the overstress temperature is 150°C.

and T_2 as the two accelerating temperatures, E_a may be calculated from

$$E_a = k\left[\frac{1}{T_1} - \frac{1}{T_2}\right]^{-1} \ln\left[\frac{R_2}{R_1}\right], \tag{3}$$

an expression that is independent of the reference temperature. No explicit current density dependence of the rate of degradation was included in (2) because the current was the same in the thermal regimes (see Fig. 13) to be compared and such dependence would be expected to cancel out in forming the ratio, which is (3).

Adding a current-induced temperature increase (25°C) to the ambient temperatures of 135 and 150°C enables us to compute that $(E_a)_i \approx 1.5$ eV for the initial mode, using the median decreases in rollover power in the first hour, $R(150°\text{C}) = 1.9$ mW/h, and $R(135°\text{C}) = 0.48$ mW/h, as obtained from Fig. 13. Alternatively, one might suppose that the time duration (τ) required for stabilization also obeys an Arrhenius equation like (2), so that with $R(150)/R(135)$ replaced by $\tau(135)/\tau(150)$, it is calculated that $(E_a)_i \approx 1.2$ eV, using $\tau_{\text{av}}(135°\text{C}) \approx 24$ hours and $\tau_{\text{av}}(150°\text{C}) \approx 8$ hours. There is no a priori reason that both calculations should have given equal answers, even apart from uncertainty in the data. For lasing operation in the ambient temperature range 40 to 70°C, it has been found[23] that $(E_a)_i = 0.54$ eV. All estimates of $(E_a)_i$ have been made by comparing degradation properties among groups of lasers that are isothermally aged at different temperatures.

It may always be speculated that the large difference between the 0.54 and 1.5 eV values is due to the presence of two different modes of degradation. A more likely explanation[23] for at least some of the discrepancy is related to the fact that the comparisons leading to estimates of $(E_a)_i$ are being made between *statistically inequivalent*-populations that are isothermally aged; considerable variations in rates of degradation and stabilization times can exist within a population at a fixed temperature. Step temperature stressing on individual lasers is preferred[23] as a method for avoiding the large within-population variations, but this scheme is impractical to employ when the rates of degradation are changing significantly throughout the test period. From a practical standpoint, however, knowledge of $(E_a)_i$ is much less important than the knowledge about how to compel a timely stabilization of the initial mode.

4.8 Conclusions about prestabilization degradation

The important result of the two active aging overstress stages of the purge, which were intended to use temperature and current as accelerants for the degradation of both the active region and shunt paths, is that virtually all lasers exhibit an initially occurring transient mode of degradation. Further on, it will be shown that this mode may require 300 to 1000 hours to stabilize in an elevated temperature (60°C) burn-in (3 mW/facet). The rates of degradation associated with this mode are considerably larger than the rates associated with the mode that controls the long-term behavior.

The stabilization of the initial saturable or transient mode is associated with considerable degradation,* as might be monitored by an increase in operating current to maintain a constant optical output. The prestabilization degradation produced during the 10 hours of *T/I* overstressing (150°C, 250 mAdc) will be shown to be substantially in excess of the additional degradation subsequently experienced by the same laser during an entire subcable system lifetime (2.2×10^5 hours) at 10°C.

The prestabilization degradation produced during the purge overstressing is caused by current (not by optical power, which is negligibly small in the *T/I* regime) flowing exclusively in a shunt path (very little current flows simultaneously in the active region path). Current is the crucial stabilizing accelerant.

To determine the rates of degradation and activation energy for the long-term wear-out mode, the initial mode must be stabilized. It is unsatisfactory to produce stabilization solely by means of an elevated temperature burn-in because, as will be shown, it can require $>10^3$ hours of aging to make certain that stabilization has actually been achieved. Since the times-to-stabilization and the extent of the stabilization (increase in current to maintain a fixed optical output) are variable, any attempt to determine activation energies and degradation rates, which are expected to accurately characterize the bases for long-term lifetime predictions, while stabilization is still in progress, will introduce considerable uncertainty† into these predictions. Activation energies and degradation rates that include variable amounts of pre- and poststabilization modes of degradation can lead to either overly optimistic lifetime predictions or to unduly pessimistic predictions requiring expensive redundancy in laser installation. Having recognized the existence of an initially occurring mode that eventually saturates or stabilizes, it is imperative that the stabilization process be temporally accelerated to facilitate a timely access to the longer-term ultimately controlling mode.

The overstress regimes of the purge serve *sorting*, and *filtering*, as well as *stabilization*, purposes. Surviving lasers may be sorted according to the increase in operating current (to maintain a constant output) produced during the *T/I* regime; all else being equal, the lower the operating current, the better, since current is certainly a candidate for

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* Speculations about possible specific mechanisms will be reserved until Section VII.

† See Section 4.9 for a specific discussion of how the initial transient mode can distort determinations of the degradation rates and the activation energy for the long-term mode.

being an accelerant of wear-out. Some filtering (identification and elimination of infant failures) may have been accomplished during preliminary prior-to-receipt burn-in (see Section 4.2). Additional filtering results from the imposition of the T/I regime. Subsequently conducted long-term rate monitoring (see Section 4.9) requires measurable degradation to occur during an elevated temperature (60°C) burn-in (3 to 5 mW/facet) for a laboratory experiment convenient time period (~1 kh). If the degradation that occurs for a laser during the T/I regime is so potent that it is not possible to then get 3 to 5 mW/facet at 60°C for any value of operating current, then that laser is rejected because it is *practically* untestable, even though it might be capable of quite stable long-term operation at lower burn-in temperatures. Thus, if a laser achieves stabilization and is able to emit 3 to 5 mW/facet at 60°C, with some margin, it is a survivor. On the other hand, if a laser loses the capability of emitting 3 to 5 mW/facet at 60°C, whether or not it has stabilized, then it is rejected.

4.9 Long-term rates of degradation—Elevated temperature burn-in rate-monitoring regime

To this point, we have examined the harsher shorter-term components (T/I and P/I regimes) of the active aging portion of the purge. Yet to be considered is the longer-term elevated temperature burn-in of the truncation active aging regime on devices that have passed through (or survived) the earlier imposed harsher stress regimes of the purge. The general intent of the burn-in testing is to detect the early failure fraction of the wear-out population.[9] Specifically, the elevated temperature burn-in stage may be used to do the following: (1) to establish a "fan" in the distribution of the long-term degradation rates to permit a deterministic selection of the least rapidly changing devices for subcable applications; (2) to determine whether the harsher prior stages of the purge actually performed their intended function, i.e., to stabilize an initially occurring transient mode of degradation;* and (3) to demonstrate, by comparison with the burn-in of lasers that had not been exposed to the T/I and P/I regimes, that these purge regimes do not introduce degradation that would not otherwise have been present.

Forty lasers were divided into two equal groups. Each group had an equal number of representatives from each of 11 wafers. One group, but not the other, was exposed in sequence to a T/I regime (T_{amb} = 150°C, I = 250 mAdc, laboratory ambient, and time = 10 hours) and

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* If stabilization has not been achieved, as might be detected in the first ~100 hours of the burn-in, the relevant lasers could be recycled through the prior harsher stages. Those devices which remained unstabilized would be discarded after another elevated temperature burn-in.

then a P/I regime ($T_{amb} = 60°C$, $I = 200$ mAdc,[†] laboratory ambient, and time = 350 hours). Both classes were then subjected to an elevated temperature (60°C) burn-in (3 mW/facet) for 1000 hours. An ambient temperature equal to 60°C is approximately the lowest temperature at which unambiguous degradation is likely to be seen in a convenient time period (~1 kh). The 3 mW/facet level was chosen so as not to eliminate from the burn-in test any laser that might not have been able to produce a higher output (e.g., 5 mW/facet), but that would otherwise have exhibited tolerably slow degradation. Figure 14a displays the smoothed aging behavior for the group that was not exposed to the overstress regimes (T/I and P/I). Figure 14b is the smoothed behavior for the group that had previously been overstressed. Of the 20 overstressed lasers, two were not admitted to the burn-in test because they could not emit 3 mW/facet, at any current, at 60°C; this is the result of L-I degradation similar to that shown in Fig. 12. Three of the overstressed lasers had operating currents >120 mA and were omitted from Fig. 14b; 15 lasers are represented in Fig. 14b. A number of conclusions about Fig. 14 can be made.

The previously overstressed population of Fig. 14b exhibited low rates of degradation in contrast to the previously unstressed group of Fig. 14a, which exhibited a variety of much larger rates of degradation. Despite the variety, all of the degradation patterns of Fig. 14a are caused by an initially occurring saturable (in different times, 300 to 1000 hours) mode of degradation that can be compelled to stabilize in ~10 hours during a T/I overstress regime. Although the overstress regimes caused an increase in operating current (I_{op}) to maintain a constant output, the subsequent degradation rates during burn-in are largely immeasurably low in the 1-kh time period. If the presence of the initially occurring transient mode is not recognized as being controlling for virtually all of the lasers of Fig. 14a, then the aging behavior during a conventional 3-mW/facet, 60°C, 100-hour burn-in, without prior overstressing, can give misleading indications about long-term reliability.

Prior to any attempt to measure E_a for the long-term mode of degradation, it is crucial to stabilize the initially occurring transient mode. To see why, consider the laser represented by the uppermost curve in Fig. 14a, which exhibited stabilization in ~400 hours. Imagine that a step temperature stress procedure[23,45-47] employing measured

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[†] Since the P/I regime is designed to overstress the active region current path, the stressing current was lowered from the 250 mAdc of the T/I regime to 200 mAdc in order to avoid the sudden pnpn switching effects (e.g., Fig. 5b) that can divert significant additional current into the shunt path. These sudden switching effects invariably occur above $I_p \approx 200$ mAdc.

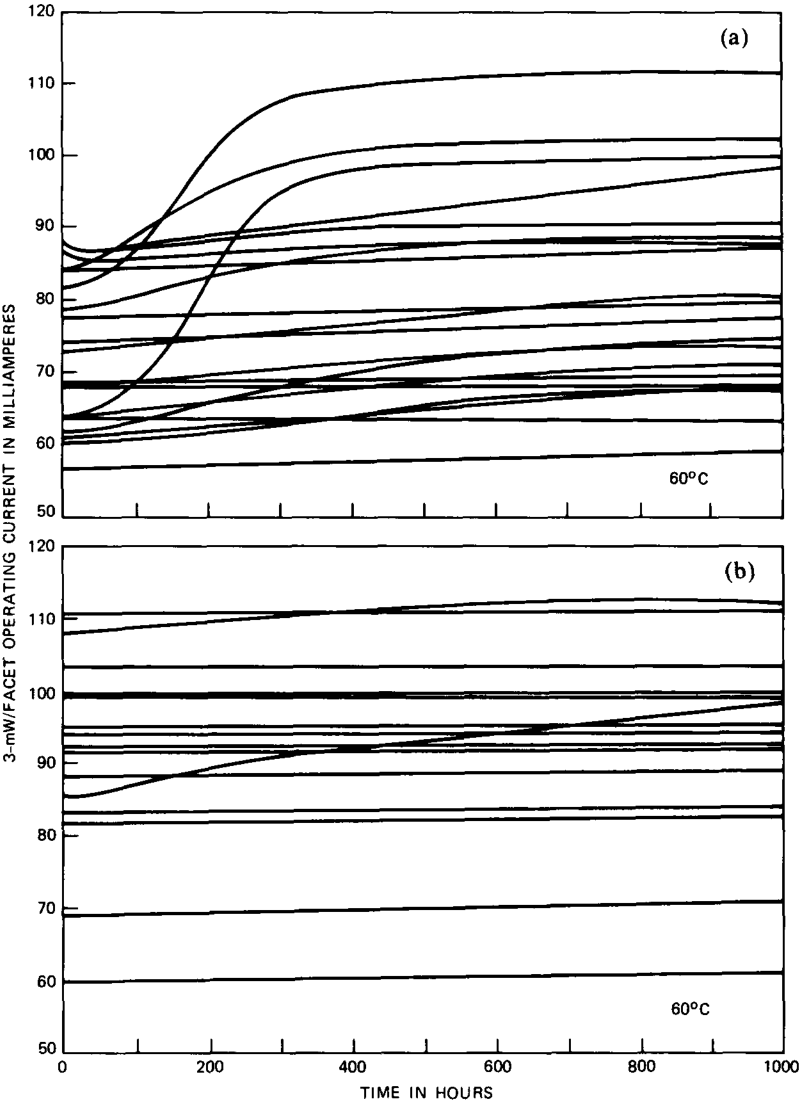

Fig. 14—Comparison plots of aging behavior (operating current to maintain 3 mW/facet) at 60°C for companion groups of lasers which (a) had not, and (b) had been previously overstressed (purged).

rates of degradation has been used to determine the E_a for this laser, which had not passed through the *T*/*I* and *P*/*I* overstress regimes. Suppose that after testing at 60°C for 200 hours, the ambient temperature had, for example, been increased to 70°C; the degradation rate would naturally be expected to increase. Since, however, the rate at 60°C would have undergone a significant reduction in the 200- to 400-

hour period had aging been continued at 60°C, the rate at 70°C would actually be less than it might have been if the initial (0- to 200-hour) rate at 60°C had persisted. Consequently, this particular step stress direction (an increase in ambient temperature, 60 to 70°C) would yield a value for E_a that was too small. Similar reasoning shows that if the step stress direction had been reversed (a decrease in ambient temperature, e.g., 60 to 50°C), E_a would have appeared too large.

For another example, if sublinear behavior is detected for a given laser, then any temporal extrapolation based upon fitting the degradation data to a sublinear time dependence may give greatly overestimated laser lifetimes, if the time dependence of the degradation were to become linear after the initially occurring mode has stabilized. Alternatively, if the degradation time dependence were to be *incorrectly perceived* as linear during an initial burn-in ($\sim 10^2$ hours), an unduly pessimistic lifetime prediction might be made upon the incorrect assumption that a large degradation rate remained uniform in time well beyond the burn-in period.

From a comparison of Fig. 14a and b, it is seen that the increases in $I_{\rm op}$ caused by the overstress regimes are comparable to those that occur in the absence of any prior overstressing.* The overstress regimes compelled the stabilization to occur quickly and caused the elimination of 5/20 lasers, which were viewed as having incurred too much degradation.† The overstress regimes did not appear to cause any degradation that, but for the overstress, would not otherwise have been present.

Figure 15 exhibits the normalized operating currents for 14/15 of the lasers of Fig. 14b for ≈7000 hours of a 60°C, 3-mW/facet burn-in. The largest increase in $I_{\rm op}/I_{\rm op}(0)$ was ≈22 percent in ≈7000 hours. The purge regimes that preceded the extended duration burn-in at 60°C did not consume intolerable fractions of useful operating lifetimes, nor were they inherently destructive of good lasers. The previously unstressed lasers (Fig. 14a) also exhibit very low rates of degradation at 60°C beyond 1 kh, which are comparable to those of Fig. 15. Thus,

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* Because of this, it cannot be argued that the initial increase in current during the 150°C T/I purge regime is caused by changes in the Pb/Sn solder, since similar increases occur at 60°C, over much longer periods of time.

† Continuous operation of a laser at any current less than, but near, I_p (the current corresponding to the peak power output, P_p, of the rolled-over dc L-I curve, e.g., see Fig. 12), where the slope efficiency is low, will be likely to lead to a sudden failure. Even a minor increment in degradation, which has the effect of shrinking the L-I curve in the manner of Fig. 12, can cause a substantial increase in current to maintain a constant output. When the operating current equals I_p, any further degradation causes the current to increase rapidly to the limit of the power supply, since at no value of current is it any longer possible to obtain the desired output; P_p is now less than the desired output. The time dependence of this degradation would be superlinear in operating current.

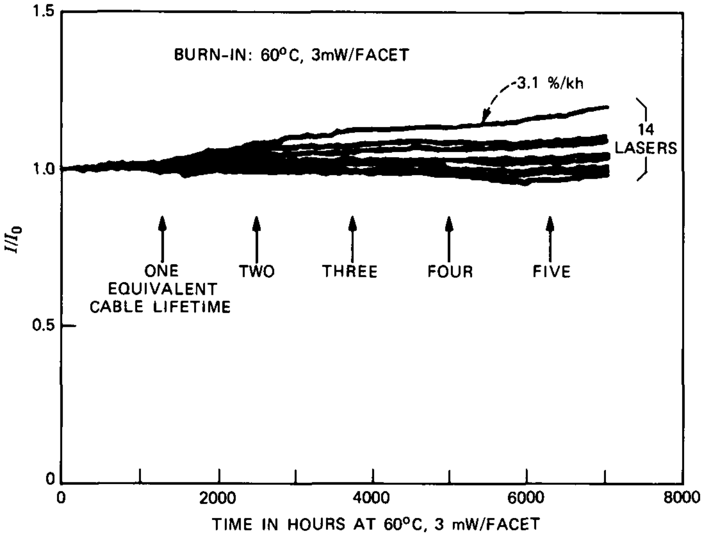

Fig. 15—Elevated temperature (60°C) burn-in (3 mW/facet) for 7 kh of a group of 14 purged lasers.

stabilization of the initially occurring transient mode will eventually take place without the necessity for overstressing; the penalty exacted is ~1 kh of aging at 60°C before it is reasonably certain that a long-term mode of degradation has become controlling. No correlation was found between the purge-induced initially occurring decrease in P_p (Figs. 11 through 13) and the long-term wear-out degradation rate.

To test whether the long-term degradation rates were increased at higher output power levels, another batch of lasers was purged and burned-in at 60°C for 2000 hours, with half aged at 5 mW/facet and half at 3 mW/facet. The Normalized Degradation Rates (NDR) are shown in Fig. 16. It is uncertain from these data that there exists any significant dependence upon level of operation. Other workers,[23,31] however, using a larger range of outputs (1 to 7 mW/facet) and step-stress aging, were able to show that operation at higher outputs produced larger degradation rates. These findings[23,31] are expected since the unbiased shelf life of these devices is long; current and/or optical power are certain to be long-term degradation driving mechanisms and accelerants. Our inability to perceive a significant difference in degradation behavior between two levels of operation (3 and 5 mW/facet), by comparing the widely varying NDR of two separate groups of lasers (see Fig. 16), emphasizes the benefit of the step-stress aging technique.[23,31]

Two points may be made about the dependence[23,31] of the long-term NDR upon the output power level of operation. The first is that, at

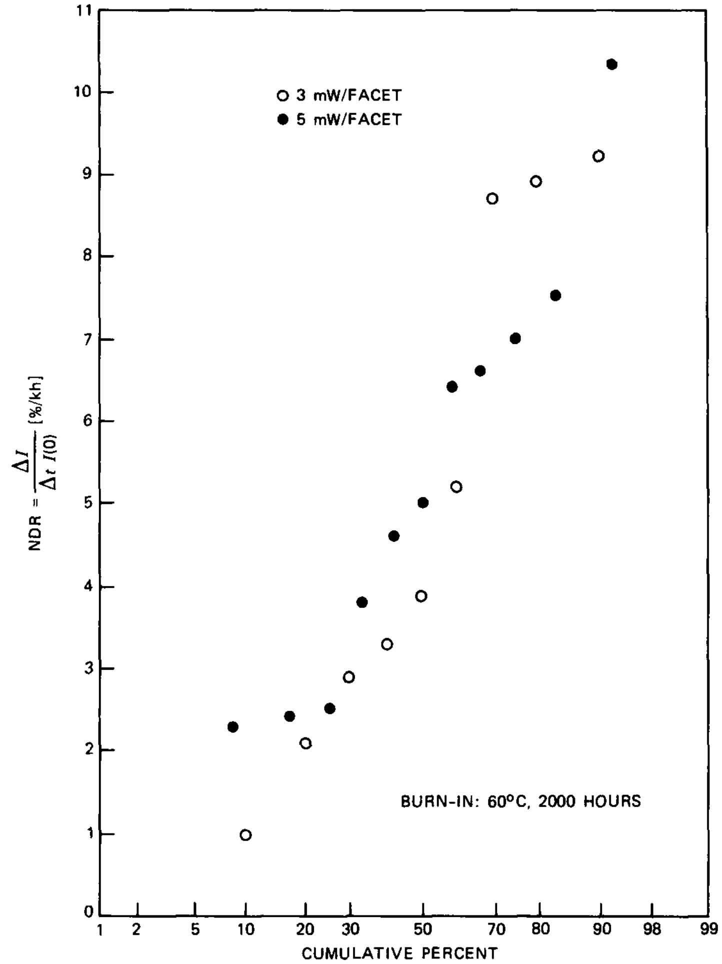

Fig. 16—Normalized degradation rates for two different groups of purged lasers operated at 60°C at 5 and 3 mW/facet for 2000 hours.

least for subcable use, the NDR are so small that demands for larger (than 5 mW/facet) laser transmitter output powers could be satisfied. The second relates to whether the driving mechanism for long-term degradation is optical power or current. To get a higher output power at some temperature, the current must be increased. As the current is increased, the fraction of that current diverted into a shunt path is also increased; this is a nonlinear effect (see Fig. 5b). In our view it has not yet been conclusively established whether, e.g., it is the optical power[23] within the active region or the current in some shunt path (which is activated even at threshold) that is responsible for long-term degradation.

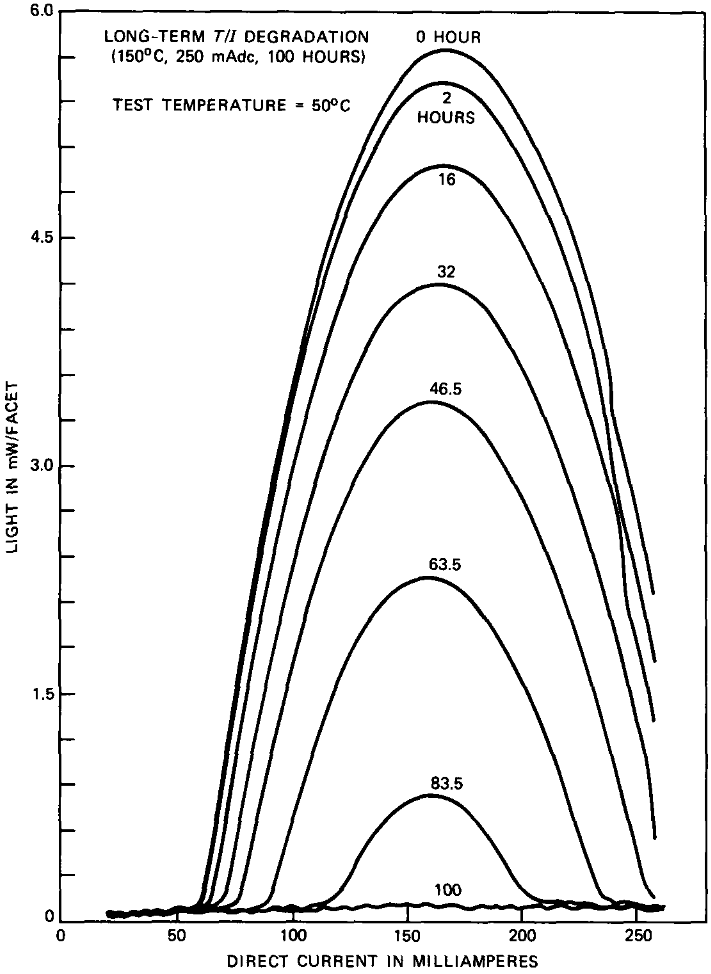

Fig. 17—The effect on the 50°C CW *L-I* curve of a laser as it is aged to complete failure in a 150°C, 250-mAdc, 100-hour regime.

V. ACTIVATION ENERGY OF A LONG-TERM NONLASING SHUNT PATH MODE OF DEGRADATION

Figure 13 shows that beyond the time of stabilization in a T/I purge regime, there is a longer term mode of degradation present. An example of complete degradation due to long-term *T/I* aging, as monitored by the lasing output at 50°C, is shown in Fig. 17. We wish to determine the activation energy for the long-term *T/I* mode, because, if too high a purge ambient temperature is chosen, it is possible that a significant fraction of the useful lifetime of a "good" device would be consumed if the duration of the *T/I* regime were excessive. It is also desirable to know the activation energy for this shunt path mode, because the shunt path is activated even at the lower temperatures and currents associated with normal laser operation.

The process of using a T/I regime to stabilize the initial transient mode in a timely fashion and then using a T/I regime to produce long-term degradation, with the eventual purpose of determining some upper limit on T, has a distinct bootstrap appearance. We were, however, aided by our initial observation (see Fig. 10) that stress temperatures $\approx$100°C were not significantly deleterious, and by a practical upper limit that was the melting temperature (183°C) of the Pb/Sn solder. Using our previous determination (see Section 4.1) that the thermal impedance $R_{th} \approx 50°\text{C}/W$ and that $V = 2$ volts when $I = 0.25\text{A}$, the use of (1) yields $\Delta T = 25°\text{C}$. An upper limit on the ambient temperature is given by subtracting the incremental junction heating (25°C), which occurs during the T/I overstress, from 183°C. For safety we picked $T_{amb} \leq 150°\text{C}$. (Extra margin is derived from the p-up bonding. Even if the active region reached 183°C, it is unlikely that this temperature would be felt at the n-side, Pb/Sn solder interface.)

For purposes of transient mode stabilization, a first T/I regime was imposed and characterized by $T_{amb} = 125°\text{C}$, $I = 250$ mAdc, and $\Delta t = 150$ hours. Next the two accelerating T/I regimes were imposed: $T_{amb} = 100°\text{C}$, $I = 250$ mAdc, $\Delta t \approx 200$ hours; and then $T_{amb} = 150°\text{C}$, $I = 250$ mAdc, and $\Delta t = 100$ hours. Optical power was not a significant accelerant in either of these regimes, since the power outputs were low and similar (<0.1 mW). The stressing current, $I = 250$ mAdc, was kept constant.* Periodic monitoring was performed at 50°C where a dc L-I curve was generated each time.

A number of different parameters may be used to record the rate of degradation, e.g., the threshold current (I_{th}), the current required to produce a 3-mW/facet output (I_3), $I_5 \cdots$ or P_p. Since I_{th} is somewhat ambiguous in view of an increasing "softness" in the turn on with increasing time, since a variety of kinks appeared in some of the curves at 3 and 5 mW, and since some curves had no output at 5 mW at 50°C, we restricted our attention to the increases in $I_{1.5}$ and the decreases in P_p. Correcting the ambient temperatures (100 and 150°C) by the current-induced junction heating (+25°C), which is the same for both regimes, the rates of degradation of $I_{1.5}$ and P_p and use of (3) lead to the values of $(E_a)_{sh}$ for the long-term shunt path mode shown in Table I for seven lasers. $I_{1.5}$ as a function of time is shown in Fig.

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* If the stressing current had been different in the two accelerating regimes, then deriving a value for E_a based upon a ratio of the degradation rates at the two temperatures would impute solely to temperature an effect which may actually have been a function of both temperature and current.

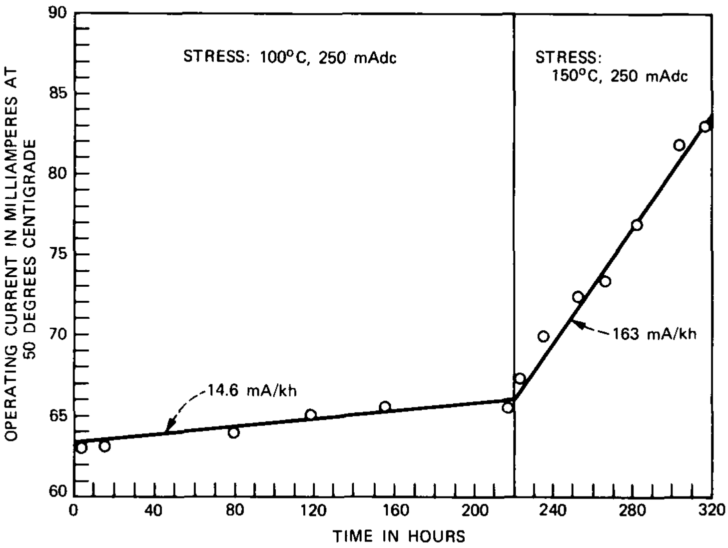

Fig. 18—Plots of the 50°C values of the operating current ($I_{1.5}$) to produce 1.5 mW/facet in the course of stressing at 250 mAdc, first in a 100°C and then in a 150°C ambient. Previously, overstressing was used to stabilize an initial transient mode.

18 for laser number 3 and P_p as a function of time is shown in Fig. 19 for laser number 4. Since step-stress aging was used, a value of $(E_a)_{sh}$ for each laser could be determined.

From the apparent linear degradation* with time after stabilization (Figs. 13, 18, and 19) it is reasonable to assume that there exists a single dominant mode of degradation that is responsible for the changes in both $I_{1.5}$ and P_p. Consequently, the values determined from these two indicia might be expected to be the same. The device-to-device differences in $(E_a)_{sh}$ are not considered meaningful. We shall use $(E_a)_{sh} \approx 0.85 \pm 0.1$ eV as a common population descriptor[23,44] of thermal aging in the nonlasing T/I regime.

It is of interest to compare our findings with the activation energies determined by others for operation in the light-emitting regime. Step stressing was used to determine[23] an activation energy, in long-term lasing operation, equal to 1.05 ± 0.15 eV in the ambient temperature range 40 to 80°C. In the course of lasing operation, both the active region and shunt paths may be simultaneously degrading, since both

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* For the reason given in Section 4.9, the rate of increase of $I_{1.5}$ will tend to become superlinear as P_p degrades downward toward 1.5 mW; as P_p reaches $\lesssim$1.5 mW, I_p will tend toward infinity, which in a practical case is the maximum current available. The linear rates observed in Fig. 18 are expected to hold provided that P_p does not approach too closely the desired constant output power.

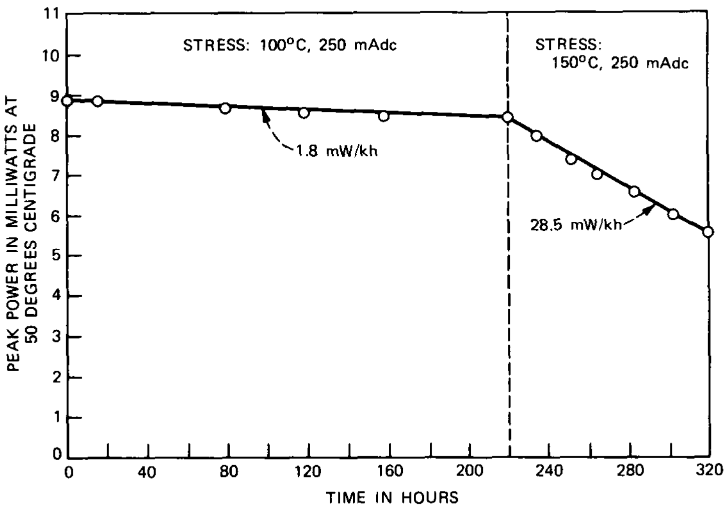

Fig. 19—Same as Fig. 18 except that the monitored parameter is the peak CW power (P_p) for another laser.

Table I—Experimentally determined activation energies using step temperature aging

Laser Number	$I_{1.5}$ (eV)	P_p (eV)	Average E_a (eV)	Measurement Error (eV)
1	0.86	0.80	0.83	±0.03
2	0.85	—	—	—
3	0.74	0.94	0.84	±0.10
4	0.94	0.85	0.90	±0.05
5	0.81	0.77	0.79	±0.02
6	0.86	0.74	0.80	±0.06
7	0.99	0.82	0.91	±0.08
Average	0.86	0.82	0.85	±0.06
Standard Deviation	±0.08	±0.07		

are being stressed. Isothermal aging of lasers, of exactly the same structure and composition, in the ambient temperature range 50 to 70°C, yielded[4] an extrapolation energy[43,44] $E_e \approx 0.9$ eV. For the temperatures of interest it may be computed (see Ref. 44, eq. [33]) that $E_e = E_a + 0.14$ eV, so that $E_a \approx 0.76$ eV. This measurement also presumptively involved degradation of either one or both of the active region and shunt paths. In an LED configuration (no shunt path), the activation energy in the ambient temperature range 170 to 250°C for the thermally induced degradation of the active region path, as measured at room temperature, was found[7] to be $E_a \approx 1.0$ eV.

Considering the experimental uncertainties (step-stress versus isothermal* aging), and the differences in operating conditions (lasing measurements[4,23] were for constant optical power, while the LED measurements[7] were at constant current), the above values of E_a, including ours for the shunt path, are not viewed as significantly different. This does not mean, however, that for our lasers the shunt path mode of degradation is controlling during low temperature lasing operation; we have not shown that the shunt path has an $(E_a)_{sh} = 0.85$ eV at low temperatures. The similarities in the above values of E_a only suggest that if there is an active region mode of degradation that is different from a simultaneously present shunt path mode, then they may have nearly the same values for the long-term E_a.

VI. LONG-TERM LIFETIMES

This paper is concerned exclusively with light-emitting reliability, and not with any lifetime limitation imposed by kinks in the L-I characteristic, beam wander, mode hopping, etc. Figures 8 and 10 through 19 indicate that all degradation of our lasers is characterized by both increased operating current (I_{op}) and decreased rollover or peak power (P_p). The system-imposed lifetime limitation on P_p is $P_p \geq 5$ mW/facet, and the limitation on I_{op} is $I_{op} \leq I_m$, where I_m is the maximum available current from the transmitter compensating circuit. If $I_p (= 175$ to 250 mAdc) is the current at which P_p generally occurs, we shall assume that $I_m < I_p$, so that the lifetime will be current- and not power-limited.

For the purpose of making plausible lifetime estimates, we shall assume that the operating current (I_{op}) to produce a constant optical output is linearly dependent upon time. If I_f is the value of I_{op} at failure ($t = \tau$), then the lifetime (τ) is given by

$$\tau = \frac{\dfrac{I_f}{I_{op}(0)} - 1}{\text{NDR}}, \tag{4}$$

where the Normalized Degradation Rate (NDR) is given by

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* Batch isothermal aging to deduce activation energies can be meaningful only if the populations are large and statistically equivalent. Our step-stress aging measurements yielded $(E_a)_{sh} = 0.85$ eV. In contrast, if $(E_a)_{sh}$ had been determined from the isothermal poststabilization data of Fig. 13, it would have been found that $(E_a)_{sh} \approx 1.9$ eV. The discrepancy is believed to be due to the effect produced by large variations in degradation rates among devices at a fixed temperature. Another example of what might be the same problem comes from isothermal measurements made on another structure, the double-channel planar BH laser operating at 1.3 μm. The E_a for the long-term mode appears to fall in the range of a few tenths to 0.4 eV (see Refs. 48 and 49), which is considerably below the step-stress values that we and others[23] have found for our structure.

$$\mathrm{NDR} = \frac{1}{I_{\mathrm{op}}(0)} \frac{dI_{\mathrm{op}}}{dt}. \tag{5}$$

An upper limit which always exists on I_f is the value I_m. It may be desirable, however, to allow for the imposition of a stricter requirement upon I_f, so that one may write

$$I_f = \text{lesser of } [\beta I_{\mathrm{op}}(0) \text{ or } I_m]. \tag{6}$$

The rationale for choosing a small value of $(\beta - 1)$ is that if I_{op} is not permitted to change by much within a subcable system lifetime, then very likely no other property will change much either. This can provide added confidence that a variety of electro-optic deficiencies will not occur within the system lifetime. A small value of $(\beta - 1)$ also tends to validate the assumption that I_{op} is increasing uniformly with time.

As an example, it appears possible to choose $\beta = 1.05$, which permits only a 5-percent increase in I_{op} in a system lifetime. Assuming that $I_{\mathrm{op}}(0) \leq 0.95\, I_m$, then from (4) and (6) one gets

$$[\tau][\mathrm{NDR}] = \text{constant} = 0.05. \tag{7}$$

This will be true at all temperatures. With a very large yield, it appears that postpurge aging at 60°C, 5 mW/facet produces NDR (60°C) $\leq$ 5 percent/kh. Consequently, from (7) it is computed that $\tau(60°\mathrm{C}) = 1$ kh. Assuming that τ scales with temperature by a factor

$$\gamma = \exp\left[\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right], \tag{8}$$

then with $T_1 = 10°\mathrm{C} = 283\mathrm{K}$, $T_2 = 60°\mathrm{C} = 333\mathrm{K}$, and $E_a = 1.0$ eV,[23] it is computed that $\gamma = 469$ so that $\tau(10°\mathrm{C}) = 469$ kh, which is twice the required subcable system lifetime (25 yr = 220 kh) at 10°C. Thus, by the use of the best estimate[23] of the value of E_a for long-term degradation and an exceptionally strict definition of lifetime, the lasers appear more than adequate for the needs of the system.

Alternatively, one may ask about the consequences of using a lower, and hence more conservative, value of the activation energy. If, for example, $E_a = 0.85$ eV, the low end of the measured[23] range, then $\gamma = 186$, and thus a $\tau(10°\mathrm{C}) = 220$ kh has a 60°C equivalent lifetime of $\tau(60°\mathrm{C}) = 220/186 = 1.2$ kh. In this instance, the 14 lasers of Fig. 15 have lived more than five cable lifetimes, and in that period the largest increase in the operating current has been $\approx$22 percent, an increase easily accommodated by a feedback compensating circuit.

A third alternative view emerges from answering the following question. Assuming that the correct value of E_a is lower than has been measured,[4,23] how low could it be before the subcable system would become unfeasible? Suppose that the transmitter compensating circuits can accommodate a 50-percent increase in I_{op}, then $\beta = 1.5$ in (6), so that from (4) it is calculated that

$$[\tau][\text{NDR}] = \text{constant} = 0.5. \tag{9}$$

Given that NDR (60°C) = 5 percent/kh, an upper limit on observed rates, it follows that $\tau(60°\text{C}) = 10$ kh. Since $\tau(10°\text{C}) = 220$ kh, it also follows that $\gamma = 220/10 = 22$, so that from (8) it is calculated that $(E_a)_{\min} \approx 0.5$ eV. It should be noted, however, that after several thousand hours of a postpurge 60°C, 5 mW/facet burn-in, it is found[50] with a high yield that NDR (60°C) ≤ 1 percent/kh, so that on this basis, $\tau(60°\text{C}) = 50$ kh and $(E_a)_{\min} = 0.24$ eV. (The decrease in NDR is due to a sublinear time dependence.)

This leads to a fourth alternative framework for viewing the adequacy of the lasers. If it can be shown that the lasers will live adequately long (220 kh) at 60°C, then regardless of the activation energy, they will be adequate, a fortiori, at 10°C. Substituting $\tau(60°\text{C}) = 220$ kh into (9) yields $[\text{NDR } (60°\text{C})]_{\max} = 0.23$ percent/kh. There are lasers which satisfy this condition, but more work is required to produce a reliable yield estimate.

All of our concern up to this point has been with the question, will the lasers last as long as the system? We have not made any serious attempt to answer the question, how long can the lasers live? The sublinear behavior[50] in postpurge burn-in tests offers the hope that the lasers have the potential for long life. An upper bound may be the estimated[7] 60°C lifetimes of LEDs that are $\approx 10^9$ hours. This is, however, probably too optimistic; measured[7] lifetimes of LEDs in a 170°C ambient are $\approx 10^5$ hours, while the lifetimes of our lasers in a 150°C ambient are orders of magnitude shorter (see Figs. 13b and 17 through 19). If LED lifetimes are assumed to reveal a "material" limit upon light-emitting lifetimes, then our lasers may have a "structure"- or "processing"-induced limit.

VII. CONSIDERATION OF POSSIBLE ORIGINS OF THE INITIAL SATURABLE MODE OF DEGRADATION

In this section we shall consider three possible specific explanations for the origin of the initial transient mode, which stabilizes after some aging: (1) an increase in temperature sensitivity, e.g., thermal impedance (R_{th}); (2) lasing-induced facet oxidation; and (3) the formation of precipitate-like defects caused by the in-migration of Au from the p-contact. The literature of reliability shows that each has been associated with an initially occurring temporally saturable mode of degradation. Existing evidence can be used to rule out the significance of (1) and (2); existing evidence tends to favor (3) or something similar to (3).

7.1 Possible increase in temperature sensitivity of pulsed and dc thresholds

7.1.1 Increase in pulsed threshold due to a possible decrease in T_0

The empirical expression universally used[51] to relate the threshold current of a laser to the temperature of the active region is given by

$$I_{th}(T) = C \exp\left[\frac{T}{T_0}\right], \tag{10}$$

where C and T_0 are empirical constants, the latter being so only for a restricted temperature range. In low duty cycle pulsed operation, the temperature of the active region is just the ambient or stud temperature. To detect changes in T_0, we compared ratios of pulsed thresholds at different ambient temperatures before and after aging. Using (10), T_0 is calculated to be

$$T_0[\mathrm{K}] = \frac{40}{\ln[I_{th}^{pul}(70^\circ\mathrm{C})/I_{th}^{pul}(30^\circ\mathrm{C})]}. \tag{11}$$

Before aging, $[I_{th}^{pul}(70^\circ\mathrm{C})/I_{th}^{pul}(30^\circ\mathrm{C})]_{t=0} = 58.9\ \mathrm{mA}/35.6\ \mathrm{mA} = 1.65$, and hence $T_0 = 79.9\mathrm{K}$, for a particular laser. After a T/I stressing at 125°C, 250 mAdc for 20 hours in order to stabilize the initial transient mode of degradation, the thresholds had increased approximately 50 percent, $[I_{th}^{pul}(70^\circ\mathrm{C})/I_{th}^{pul}(30^\circ\mathrm{C})]_{t=20\ \mathrm{hours}} = 86.1\ \mathrm{mA}/51.8\ \mathrm{mA} = 1.66$ and $T_0 = 78.9\mathrm{K}$, a value essentially unchanged because of the initial degradation. Alternatively expressed, if a decrease in T_0 were responsible for causing an increase in I_{th}^{pul} (70°C) from 58.9 to 86.1 mA, then it is calculated that $(\Delta T_0)_{cal} = -6.5\mathrm{K}$; from above it is seen that $(\Delta T_0)_{exp} = -1.0\mathrm{K}$. Thus, the observed initially occurring stabilizable degradation appears unrelated to T_0, which remained unchanged.

Similar comparisons of experimentally determined values of T_0, before and after a much more significant stressing (30°C, 20 mW/facet, 280 hours, followed by 100 to 125°C, 250 mAdc, 250 hours) were made on ten lasers. Although most of the lasers exhibited an apparent decrease in T_0 of ≤ 6 percent, this is not viewed as being outside experimental error,* which when taken into account permits the conclusion that T_0 does not decrease significantly in the course of degradation. This agrees with other work.[23] At least with regard to pulsed threshold increases, in the course of aging, the degradation must affect the prefactor C in (8), rather than T_0.

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* The algorithm for determining I_{th} depended on the shape of the pulsed L-I curve in the vicinity of threshold. Prior to aging, the 30°C L-I curve is slightly concave upward, which leads to an overestimate of I_{th}. After aging, the 30°C L-I curve is slightly concave downward, which underestimates I_{th}. These deviations from ideality tend to make T_0 appear lower after aging. Additionally, two lasers that suffered virtually no degradation showed $\Delta T_0 \approx -2$ percent, while another laser that showed substantial degradation had a $\Delta T_0 = +1$ percent.

7.1.2 Increase in dc threshold due to a possible increase in thermal impedance (R_{th})

(GaAl)As lasers bonded p-side down with In solder have a well-documented history of reliability problems associated with temporally occurring metallurgical interactions between In and Au. Thus, it was found that voids could form in the mixed In-Au layer[52,53] during device operation, that voids can also form[52] during 1000 hours of unbiased storage aging at 70 to 100°C, that the bonds of life-tested devices exhibit poor adhesion,[54] that aged chips can often be easily pulled off their studs,[53] and that the thermal impedance increases during device operation[46,53,54] so as to exhibit what appears to be a saturable mode of degradation,[53,54] reminiscent of the knee-like effects shown in Figs. 10, 13a and b, and 14a. We thought it was important to consider a possible instability of the Pb/Sn bond despite the demonstrated stabilities of other eutectic alloy solders.[7,27-29,33]

The dc threshold may be written in terms of the pulsed threshold as

$$I_{\mathrm{th}}^{\mathrm{dc}} = I_{\mathrm{th}}^{\mathrm{pul}} \exp\left[\frac{R_{\mathrm{th}} V I_{\mathrm{th}}^{\mathrm{dc}}}{T_0}\right]. \tag{12}$$

The incremental temperature increase of the active region above the ambient temperature, due to injection current heating, equals $R_{\mathrm{th}} V I_{\mathrm{th}}^{\mathrm{dc}}$, where, as in (1), R_{th} is the thermal impedance and $V I_{\mathrm{th}}^{\mathrm{dc}}$ is the input power dissipation at threshold. Consequently,

$$R_{\mathrm{th}} = \frac{T_0}{V I_{\mathrm{th}}^{\mathrm{dc}}} \ln\left(\frac{I_{\mathrm{th}}^{\mathrm{dc}}}{I_{\mathrm{th}}^{\mathrm{pul}}}\right), \tag{13}$$

$$\approx \frac{T_0}{V I_{\mathrm{th}}^{\mathrm{dc}}}\left[\frac{I_{\mathrm{th}}^{\mathrm{dc}}}{I_{\mathrm{th}}^{\mathrm{pul}}} - 1\right], \tag{14}$$

since to a sufficient approximation, the exponential in (10) may be expanded as $e^x = 1 + x$. In general, we do not know the dc and pulsed thresholds with enough accuracy to use (11) or (12) credibly. For example, because of the opposite concavity of the dc and pulsed *L-I* curves near threshold (see previous footnote), it is often found that $I_{\mathrm{th}}^{\mathrm{dc}}/I_{\mathrm{th}}^{\mathrm{pul}} \lesssim 1$, a physically unreasonable result. When it is found that $I_{\mathrm{th}}^{\mathrm{dc}}/I_{\mathrm{th}}^{\mathrm{pul}} \gtrsim 1$, calculations using (11) or (12) sometimes show that R_{th} has decreased with degradation, while in other cases apparent increases are computed. The calculational uncertainty occurs because $I_{\mathrm{th}}^{\mathrm{dc}}/I_{\mathrm{th}}^{\mathrm{pul}}$ exceeds unity by only a few percent; thus, an error of only a few percent in this ratio can easily alter the calculated value of R_{th} by a factor of two.

To more persuasively address the question of whether R_{th} decreases and causes threshold degradation, we employed the crossing technique, discussed in Section 4.1, which we view as a substantially more error-free and credible approach for examining the behavior of R_{th} before and after aging. Prior to aging a particular laser, whose $P_p = 18$ mW in dc operation at 30°C, it was found that the 70°C pulsed L-I curve crossed the 30°C dc L-I curve at $I = 0.37$ ampere and $V = 1.9$ volts and crossed the 50°C dc L-I curve at $I = 0.22$ ampere and $V = 1.7$ volts. Using (1), it was computed that at these two crossings $R_{th} = 57$ and 53°C/W, respectively. After thoroughly degrading the laser so that P_p at 30°C was reduced a factor of 300, the above crossings occurred at $I = 0.365$ ampere and $V = 2.0$ volts, and $I = 0.228$ ampere and $V = 1.8$ volts. The after-aging values were determined to be 55 and 49°C/W, respectively. The reasonable conclusion is that R_{th} was unaffected by the degradation. In any case, the indicated decrease in R_{th}, if real, would have an annealing rather than a degrading effect upon threshold or operating current.

7.2 Lasing-induced facet oxidation (erosion)

A lasing (forward bias)-induced facet erosion (oxidation) exhibits itself on (Al,Ga)As lasers, in its early stages, as an initial saturable mode of degradation.[41,55-58] The oxidation that occurs on the emissive portion of a laser facet can be suppressed if a dielectric (half-wavelength) film is deposited on the facet soon (~1 h) after cleaving.[41,58] If the film deposition is deferred for several days, the facet erosion is only mildly retarded.[41] The proposed explanation[41] for this inadequacy is related to the existence of a natural oxide (thickness ≈30 angstroms), which forms with a logarithmic time dependence[59,60] on the entire facet after cleaving. The oxide film, probably spongy, sandwiched between the GaAs and the dielectric coating is a likely conduit for the transportation of ambient oxidants to the emissive portion of a laser facet. If the coating is applied soon after cleaving, the natural oxide will be only ≈10 angstroms thick and a less permissive conduit. The rate of formation of the natural oxide on InP is the same as that for GaAs.[61] Therefore, if the lasing-induced oxidation were the same for InP as for GaAs, then quickly deposited coatings would be essential. Our present purge studies have been performed on uncoated lasers, hence our concern about this mechanism. For the following reasons, we believe that the initial saturable mode is not caused by facet erosion.

1. The initial saturable mode in the etched mesa BH lasers is extremely variable[4] in its potency and duration (e.g., see Figs. 8 and 10 through 14). A notable feature of degradation caused by facet erosion in (Al,Ga)As lasers is that for fixed powers and temperatures, the magnitude of the increases in operating current and the period of stabilization were approximately the same for all lasers.[41] The varia-

tions which we and others[4] observed are inconsistent with expectations about the operation of facet erosion based upon commonality of the following conditions for the aged lasers—same wafer, percent relative humidity, temperature, operating current, material composition, etc.

2. The initial saturable mode is also seen[23] to a comparable extent for packaged lasers that are in a hermetic can containing significantly less water vapor than a laboratory ambient.

3. Although preliminary experiments[4] with sputtered coatings indicated an apparent effectiveness in the suppression of the initial saturable mode, recent work[31] has shown that coatings are actually ineffective.

4. A recent study,[33] using an etched mesa laser structure very similar to ours, concluded that for operation at 30 mW/facet in a 25°C, room temperature ambient, an uncoated laser will suffer substantial degradation, $\Delta I_{op}/I_{op}(0) \geq 20$ percent in 250 hours; the cause was alleged to be facet erosion.[33] Since it has been shown[26] that the thickness of the lasing-induced oxidation $d \propto P$ (optical power), we might have expected to see operating currents increase by $\gtrsim$13 percent in Fig. 8, where similar high power operation was monitored. Instead, none of the lasers in Fig. 8a show any credible increase at all in 250 hours, and only 1/5 lasers in Fig. 8b fulfills this expectation. Our explanation for the reported[33] degradation when $P = 30$ mW/facet, which takes into account the runaway or catastrophic appearance of end-of-life,[33] is that operation was too close to P_p, the rollover power (see Fig. 9), and any slight degradation (e.g., our initial saturable mode) caused P_p to fall toward and then drop below 30 mW/facet, at which point the current supply limit of 250 milliamperes[33] is rapidly attained.

Not only are we convinced that the initial saturable mode is not induced by facet erosion, but we are also persuaded that within the system lifetime (2.2×10^5 hours at 10°C), lasing-induced facet oxidation will very likely never promote degradation that is significant enough to cause premature failure; thus, uncoated lasers may be used even in high-reliability applications. The reasons are the following:

1. Uncoated lasers and Al_2O_3-sputtered coated lasers of a structure identical to ours were aged at 15 mW/facet and 25°C for 4000 hours in a laboratory ambient (<30-percent RH) and a dry nitrogen ambient; there were no significant differences in aging behavior.[26]

2. The thickness of the lasing-induced facet oxidation is proportional to the logarithm of time,[26] unlike the square-root time dependence found for AlGaAs/GaAs, so that in a 25°C, 30-percent RH ambient, operation at 5 mW/facet will produce only ~70 angstroms of oxide in 2×10^5 hours, a thickness insufficient to promote degradation related to optical scattering, reduced facet reflectivity, or surface current leakage.

3. This is supported by the observation[31] that an uncoated laser aged at 50°C and 5 mW/facet for 6000 hours showed only a native oxide layer ($\approx$30 angstroms) at the emissive portion of the facets.

4. In another study,[25] it was determined that the time for $I_{th}^{pul}/I_{th}^{pul}(0)$ to reach 1.5, because of facet erosion, was $\approx 10^7$ hours for an InGaAsP/InP laser operating in a 70°C, 1 to 10-percent RH ambient at a power output ~5 mW/facet. In a hermetic can with reduced water vapor at 10°C, this time would be considerably longer.

7.3 Dark-spot defects and gold in-migration

A predominant mode of degradation in InGaAsP/InP DH LEDs[7,10-15] and lasers[16-18] is related to the formation of Dark-Spot Defects (DSD), although instances of Dark-Line Defect (DLD) formation have been reported.[10,16-18,62] The early manifestation of the degradation associated with the nonradiative DSD and DLD appears as an initial saturable mode in lasers.[16-18,62] The crystalline defects connected with DSD are precipitate-like[7,10,13,63] and recently were found[12,13,15] to contain gold (Au), which had migrated into the vicinity of the active region from the p-metal contact.

A qualitative description of the Au in-diffusion and degradation has been given[13,15] as follows. During the p-contact alloying procedure, nonuniformities in the alloyed region are formed, which can have a spikelike appearance.[64] Under forward bias, the current density is larger in these regions in which the contact metals, especially Au, have preferentially penetrated. Electromigration and thermomigration (promoted by local ohmic heating) cause even deeper local penetration of Au. DSD, formed when the Au reaches the active region, can act as optical and current (nonradiative recombination) losses.[13,15,18] Local heating has been observed at DSD in the active regions of lasers.[17] Outside the active region,* in the nearby shunt paths of an etched mesa BH laser, the presence of Au may also cause local heating, ohmic and nonradiative; electrical shorting of the blocking junctions, which promote increased shunt current flow independent of heating, is also possible. Any increase in local temperature, at a fixed terminal current, whether the defect site is inside or just outside the active region, will promote an increase in shunt current (by virtue of Fig. 5a), i.e., degradation, since the terminal current must be increased to preserve the intended optical output. Consistent with our view that laser-

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* Within the active region, the precipitate-like defects, caused by local Au deposits, are manifested as DSD in an electroluminescent view of that region; equivalent deposits outside the active region, i.e., in the shunt path that borders the active region, do not have such a visible manifestation and so cannot be called DSD. Our discussions use the term DSD because that describes how the defects are seen when they are within a strongly luminescing region.

degradation-promoting defects exist in the shunt path and can be caused by exclusive shunt path operation are the observations[31,33] that initial degradation in lasers of our structure is not necessarily accompanied by any darkening of the active region.

The existence of random local invasions of Au from the p-contact is consistent with the observations of DSD made by others. After an initial period, the number of DSD in laser operation remained fixed, if they occurred at all, and this number-saturation coincided with the knee-formation or degradation stabilization process.[18] In LEDs, it has been reported that both the number and size of DSD increased with time.[11,13] Evidence of a darkening of a portion of the active region in etched mesa BH lasers has been associated[4] with degradation in laser performance. The time for the first appearance of a DSD is strongly current density dependent.[10,18]

A certain number of observations about the initial transient mode and its stabilization are consistent with the idea of randomly located spikelike regions in which remotely situated nonradiative centers can electromigrate to the vicinity of the active region. The following are some examples: (1) On occasion double knees may occur in the course of *T/I* stressing, which could correspond to the sequential establishment of two distinct and locally separate diffusion fronts. (2) Some lasers exhibit no evidence of an initial saturable mode, and for those that do, the manifestations are quite varied, i.e., both the increases in operating current required for stabilization and the times-of-stabilization can span a range of values. (3) Figure 14a displays "incubation" periods prior to the occurrence of the initial saturable mode of degradation, which strongly suggests that little or no degradation can take place until some in-migrating degradation-causing centers reach the active region,* or its vicinity, and that once there, the deposited centers promote a locally confined degradation (increase in nonradiative current), which becomes self-limiting, because each center can cause only so much additional current loss. (4) After substantial degradation (induced by extensive *T/I* and *P/I* stressing), a laser may operate pulsed but not CW at, e.g., 70°C; since an increase in thermal impedance seems ruled out (see Section 7.1.2), local heating, produced by defects that did not exist prior to aging and that cause substantial current shunting in dc operation, seems a likely explanation. (5) To support this contention of additional heating at the same value of terminal current after aging, the crossing point method (see Section 4.1) was used to show that, e.g., the 70°C pulsed *L-I* curve always crossed the 50°C dc *L-I* curve at a lower value of current after degrada-

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* The existence of the incubation period explains why all of the lasers of Fig. 14a passed the initial burn-in tests (see Section 4.2).

tion had occurred. (6) In several instances a thermal annealing effect, which is present in the absence of forward bias, has been observed (e.g., Section 3.2), and in one case the threshold of a degraded laser was decreased by ~10 mA after storage aging at 175°C for 60 hours; annealing is consistent with a movement or homogenization of a degrading species.

Still another point of comparison is the activation energy for the initial saturable mode. We have determined (see Section 4.7) that $(E_a)_i = 1.2\text{–}1.5$ eV for the initial mode, while others[23] have found $(E_a)_i = 0.54$ eV. In an LED study,[10] the activation energy associated with the first appearance of a DSD was found to be $(E_a)_{\mathrm{DSD}} = 1.2$ eV, while a laser study[18] found $(E_a)_{\mathrm{DSD}} = 0.16$ eV. The substantial variations, due perhaps to the uncertainties caused by using the isothermal aging comparison technique, prevent any credible conclusion.

Another area of apparent concern is why elevated temperatures alone, without forward bias, do not produce degradation, when diffusion calculations indicate that they should. For the interstitial diffusion of Au in InP, the distance traveled is related to the diffusion constant and time by

$$x = \sqrt{Dt}, \tag{15}$$

where[65]

$$D = 1.32 \times 10^{-5}\mathrm{cm}^2\mathrm{s}^{-1} \exp\left[-\frac{0.48 \text{ eV}}{kT}\right]. \tag{16}$$

Since the p-contact annealing (350°C for 10 minutes) is known to cause Au to penetrate the Cr barrier layer,[66] our storage aging (no bias, 175°C for 4000 hours) (see Section 3.2) should have allowed Au to penetrate a distance $x = 280$ μm, more than enough to cause degradation of the active region. No degradation occurred, however, which is in accord with storage aging experiments on quaternary LEDs (230°C for 2000 hours)[7] and lasers (100°C for 2000 hours).[33] Assuming that the constants of (16), which were determined at 600 to 820°C, are validly extrapolated to lower temperatures, it would appear that Au probably does diffuse large distances, however, in concentrations so low[65] ($\sim 10^{15}$ cm^{-3}) that no degradation is produced. With the application of forward bias, however, many orders of magnitude larger concentrations of Au are found[12,13,15] to have diffused inward, perhaps into vacancies created during annealing; this may correspond to the more shallow diffusion and distinctly different process for the migration of Au into InP, which was not characterized, but found.[65] (When Au/Ge contacts on GaAs are annealed with constant current, filaments of the contact material are found in the substrate. Annealing under identical circumstances without current flowing does not produce contact penetration.[67])

In conclusion, we view the in-migration of Au (or perhaps some other contact element) from the p-contact region as the explanation, which best fits our observations and those of others,[23] for the initial saturable mode.

VIII. CONCLUSION

The results of our experimental study of the degradation characteristics of the 1.3-μm etched mesa BH laser may be summarized as follows.

1. Virtually all unscreened lasers possess to some degree an initially occurring mode of degradation that stabilizes with aging, i.e., the observed rate of degradation decreases in some time period from an initially high value to a constant lower value.

2. At all temperatures of interest, the CW light-current (*L-I*) curves are sublinear starting at threshold. As the terminal current is increased, an increasing fraction of that current is diverted into a shunt path around the active region; two current paths are always operative under lasing conditions. The CW *L-I* curves show rollover behavior, i.e., at a fixed ambient temperature, an increase in the direct current produces a sublinear increase in output power until a maximum (rollover) power is reached, and for still larger currents the output power decreases until lasing is extinguished at some upper threshold current (~1 Adc). Above this point all injected current goes into a shunt path. If the injection current is held constant, then an increasing ambient temperature will cause an increasing fraction of this current to flow into a shunt path. At a high enough temperature ($\gtrsim$100°C) all current will flow into the shunt path.

3. In a long-duration (~3 kh), elevated temperature (60°C) burn-in (3 mW/facet), the initial mode will stabilize in 0.3 to 1 kh; in any lasing regime, some fraction of the terminal current will always flow in a shunt path. The initial mode will, however, stabilize more rapidly (~10 hours) (as observed by periodic monitoring at a temperature at which lasing occurs) in a high-temperature (150°C), high-current (250 mAdc) purge regime in which the current flows exclusively in a shunt path; there is no optical output in this regime. Thus, it is reasonable to conclude that the initial mode stabilization, which is often accompanied by a considerable fixed degree of degradation in laser performance, is caused by current flowing in a shunt path around the active region, whether or not the device is operated as a laser.

4. If, instead, it were concluded[23] that during *initial lasing* operation, prestabilization degradation occurred in the active region, while in an *initially* imposed *T*/*I* regime, the prestabilization degradation occurred

in the shunt path, then it would be prudent to refrain from any lasing operation until T/I purging compelled stabilization; it might prove beneficial to long-term aging if the relatively large prestabilization degradation were forced to occur outside the active region, rather than within. If it were shown to be beneficial, then the purge would actually produce a better laser than would an elevated temperature burn-in.

5. If the high-current, high-temperature purge regime is continued beyond the point of stabilization, then there is a long-term temporally linear degradation of the shunt path, which has a thermal activation energy, $(E_a)_{sh} \approx 0.85$ eV. The current is the driving mechanism for the degradation, and the degradation appears to be associated with a shunt path.

6. Thus, it is possible that when a purged (stabilized) device is operated as a laser, the always-existing shunt path fraction of the terminal current is the (or at least one of the) long-term wear-out degradation driving forces.

7. The degradation that occurs during the purge overstress aging may be considerably in excess of any subsequent degradation that would be experienced in the course of the system lifetime (25 years) of a laser operating at ocean bottom temperature. Alternately put, most of the degradation that would occur in an *unscreened*, *unpurged* laser during a system lifetime is compelled to occur "up front" by the purge.

8. Because the initial saturable mode has an incubation period, unscreened lasers can easily "pass the test" ($\Delta I/I \leq 5$ percent) of a conventional short-duration (10^2-hour), elevated temperature (60°C) burn-in (5 mW/facet). Thereafter, as we have witnessed, the degradation of a laser that is purge-induced, and which would occur eventually no matter how the device was operated, can be large enough to force a rejection of that laser as a subcable candidate. It is also possible that such a routine burn-in would cause a rejection of a laser that actually might have been a suitable subcable candidate, once stabilization had occurred. However rational short-duration burn-in aging might appear as a screening procedure to assure long-term reliability, it proved to be inadequate.

9. The unrecognized (by a conventional burn-in screen) existence of the initial saturable mode of degradation might have doomed the lightwave subcable project, either because of a significant number of postinstallation failures or because of the chaos and delay that its variable effects would have produced in making reliable lifetime predictions. Particular adverse consequences of using *unstabilized* lasers, i.e., survivors of a conventional burn-in, are:

a. As long as the initial mode, which exists in varying degrees in all lasers, is controlling, it is impossible to determine credible rates of degradation at any elevated lasing temperature for the long-term, wear-out mode.

b. As a result, no reliable estimate of activation energy for the wear-out mode may be made.

c. Consequently, lifetime predictions for lower use temperatures are impossible.

d. If the initial mode is mistaken for the long-term mode, the actual superlinear followed by sublinear increases in current as a function of time will result in an enormous spread in activation energies as determined by step temperature aging of individual lasers; whether the activation energy is large or small will depend upon the direction of the step, i.e., higher to lower temperatures, or the reverse.

e. A mistaken identification of modes, coupled with too small an apparent activation energy, would doom a potential system because of the excessive costs connected with redundancy and/or anticipated replacement. Similarly, the use of an erroneously large activation energy would doom a system after installation because the devices could fail substantially prior to the system lifetime.

f. A mistaken identification of modes might also reject perfectly good lasers, indeed doom a system, because the perceived rates of degradation would be too large; appearances might have been deceiving because the initial rapid rates would eventually stabilize at some lower entirely acceptable values.

g. A failure to detect the initial saturable mode might also cause excessive field failures because an initially occurring 50-percent increase in operation current, followed by another 50-percent wear-out increase over much longer times, could exceed the capacity of the transmitter compensator circuit. Such would not have been true, e.g., if a purge strategy were used to compel a timely stabilization that was accompanied by the initial 50-percent increase, because this would have occurred before the transmitter parameters were set up.

10. The purge compelled a timely (~10-hour) stabilization of the initial mode of degradation; thereafter, access to the long-term mode permitted its activation energy and temperature-activated degradation rates to be credibly determined so that reliable lifetime estimates could be made.

11. The long-term degradation rates have been found to be so low that, with some confidence, a subcable lightwave system using these lasers may be contemplated with either an extremely conservative definition for device failure or with a considerably smaller activation energy than has actually been measured.

12. The best guess about the origin of the initial saturable mode of degradation relates to the in-migration of Au, or some other p-contact metal or impurity.

IX. ACKNOWLEDGMENTS

We are obliged to P. A. Barnes, A. K. Chin, E. I. Gordon, B. W. Hakki, W. B. Joyce, P. R. Skeath, and C. L. Zipfel for very useful conversations and comments on the manuscript. The technical assistance of R. M. Camarda is gratefully acknowledged.

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AUTHORS

David A. Ackerman, A.B. (Physics), 1976, Cornell University; M.S. and Ph.D. (Physics), University of Illinois at Urbana-Champaign, in 1978 and 1982, respectively; AT&T Bell Laboratories, 1982—. Since 1982 Mr. Ackerman has been working at AT&T Bell Laboratories in the area of semiconductor lasers. Member, APS, Sigma Xi.

Richard W. Dixon, A.B. (Engineering and Applied Physics), 1958, Harvard College; M.S. and Ph.D. (Engineering and Applied Physics), Harvard University, in 1960 and 1964, respectively; AT&T Bell Laboratories, 1965—. Mr. Dixon is currently the Director of the Lightwave Devices Laboratory of AT&T Bell Laboratories.

Niloy K. Dutta, B.Sc. (Physics, Honours), 1972, and M.Sc. (Physics), 1974, St. Stephen's College, New Delhi, India; Ph.D. (Physics), 1978, Cornell University, Ithaca, NY; AT&T Bell Laboratories, 1979—. Mr. Dutta had a

Postdoctoral Associate at Cornell University for one and a half years. During his doctoral and postdoctoral work at Cornell, he worked on spin-flip Raman lasers, infrared spectroscopy, soft x-ray lasers, and nonlinear optics with nonmonochromatic waves. Since 1979 he has been a Member of Technical Staff at AT&T Bell Laboratories, where he has contributed extensively to the research and development of InGaAsP semiconductor lasers. He has authored or coauthored more than 60 publications on his work. Member, IEEE, American Physical Society, Optical Society of America.

Robert L. Hartman, B.A. (Mathematics), 1958, Columbia College; B.S. (Engineering Physics), M.S. and Ph.D (Physics), Columbia University, in 1959, 1961, and 1968, respectively; AT&T Bell Laboratories, 1968—. At AT&T Bell Laboratories, Mr. Hartman is presently engaged in studying the physics of III-V compound semiconductor devices, particularly InGaAsP/InP and (Al,Ga)As-GaAs double-heterostructure injection lasers. He has contributed extensively to the understanding of the degradation mechanisms in these devices and authored or coauthored several key papers in this field, especially those involving the discovery and analysis of dark-line defects; the discovery of strain effects upon laser reliability; the attainment of long operating lifetimes in LEDs and injection lasers; the first measurement of the thermal acceleration of injection laser operating lifetime; and effects of surfaces on LED and laser reliability. In 1980 Mr. Hartman was appointed Supervisor of the Semiconductor Lightwave Lasers Group. Member, Sigma Xi, American Physical Society.

Franklin R. Nash, B.S. (Physics), 1955, Polytechnic Institute of New York; Ph.D. (Physics), 1962, Columbia University; AT&T Bell Laboratories, 1963—. At AT&T Bell Laboratories, Mr. Nash has been involved in research on gas lasers (modulation and mode locking), detection of subnanosecond pulses using photodiodes, nonlinear optical materials, parametric oscillators, neoclassical theory of radiation, and semiconductor lasers (mode guidance, material defects, electro-optic anomalies, and degradation mechanisms). Currently, he is engaged in the reliability assessment of long-wavelength semiconductor lasers. Member, American Physical Society, IEEE.

Jonathan R. Pawlik, B.S.E. (Engineering Physics) and M.S. (Physics), University of Michigan, in 1969 and 1971, respectively; Ph.D. (Applied Physics), Harvard University; AT&T Bell Laboratories, 1979—. While at Harvard University, Mr. Pawlik studied the infrared and magnetic properties of hydrogenated amorphous silicon and germanium. As a Member of Technical Staff at AT&T Bell Laboratories, he has been involved in InGaAsP and GaAlAs injection laser characterization.

William J. Sundburg, B.S.E.E., 1968, Newark College of Engineering; M.S.E.E., 1972, Rutgers University; AT&T Bell Laboratories, 1959—. From 1959 to 1965, Mr. Sundburg participated in experiments studying surface phenomena of semiconductors materials. From 1965 to 1969, Mr. Sundburg studied oxide growth on single crystal metals. From 1969 to 1972, he established processing techniques for fabricating single cell MOS nonvolatile memories. He designed integrated memory circuits utilizing nonvolatile memory cells from 1972 to 1977. Mr. Sundburg worked on the design of custom logic large-scale integrated circuits from 1977 to 1981. Since 1981 he has worked in the laser reliability group studying modes of degradation of semiconductor lasers.