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Current Directions in GaAs Laser Device Development

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Double heterostructure (Al,Ga)As injection lasers are efficient, easily modulated emitters of light in the wavelength range $0.8 < \lambda < 0.9\ \mu m$. They are being widely applied as sources, especially in various fiber-optic communications applications. This paper describes several of the most important directions of current applied research and development on these devices with emphasis on reliability, optical linearity, and temporal stability.

I. INTRODUCTION

Lightwave communications systems, which send information by encoding it onto light beams propagating in hair-thin glass fibers, are now undergoing rapid development throughout the world. These systems, which, it may be no exaggeration to say, will revolutionize terrestrial communications techniques, have been made possible mainly by two technological achievements. The first is the development of glass optical fibers with small optical attenuations (less than about 50 percent per kilometer). The second is the development of semiconductor light sources for efficiently producing the light which is transmitted in these fibers.

The purpose of this paper is to describe several of the recent trends and problems in the development of (Al,Ga)As injection lasers which, together with light-emitting diodes made from the same materials, are the principal light sources of this lightwave revolution. A comprehensive treatment of the subject of injection lasers is not intended. The size of the field and the rapid pace of its progress make this difficult.

Rather, the attempt is made to define problem areas and to report on recent developments which the author believes are particularly significant. Only discrete devices are considered. Sufficient references are included to permit easy access to the literature. Early work in this field has been extensively reviewed in two recent books.[1,2]

The advantages of injection lasers are well known. They are among the most efficient of light sources; they may be modulated to gigahertz rates by simply varying the current in their driving circuits; they are physically small, intrinsically inexpensive, etc. The emphasis here, however, is on areas where improvements are desirable or have recently occurred. The pedagogy of the discussion is aided by Fig. 1, where the four regions schematically represent the major areas of laser deficiency which will be discussed in this paper. Many other areas, the attainment of spectral purity, a discussion of system noise performance, or the attainment of the lowest possible lasing threshold, for example, which are deemed to be of lesser overall importance, have been purposely omitted.

The first circle in Fig. 1 represents the goal of high reliability, which these devices have not historically possessed to an adequate degree, but in which very significant improvements have occurred in the last few years. The second circle represents the goal of optical linearity, which has also been inadequate for many applications. The lasers tend to exhibit, at least in the simpler structures, what we have called "kinks."[3] The third circle, temporal stability, refers to the fact that these devices, even when driven with constant current amplitude, sometimes produce a nonconstant light output. This may take the form of short optical pulses at one extreme, or of a low-modulation-index, high-frequency optical perturbation of the dc output at the

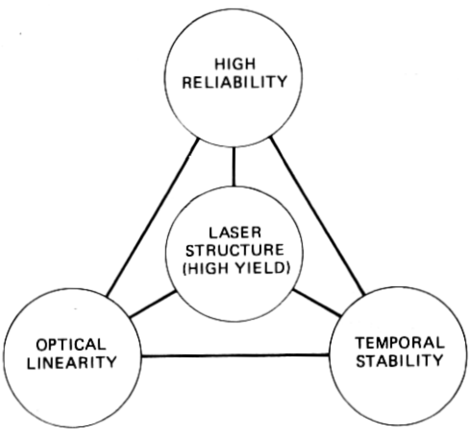


Fig. 1—For purposes of discussion in the text, the challenges of injection laser device development are conceived of as comprising four major interactive areas.

other. The fourth circle of Fig. 1, laser structure, has at least two important subcategories. The first relates to the problems of crystal growth inherent in fabricating such complex devices. It includes questions such as the optimum trade-offs among liquid phase epitaxy, vapor phase epitaxy, organometallic vapor phase epitaxy, molecular beam epitaxy, etc. It also includes materials preparation questions such as purity, cleanliness, defect nucleation and propagation, thermal geometry, and dynamics. While these questions are absolutely critical to successful laser device development, they are considered outside the scope of the present paper. The simpler laser-structure subcategory, which contains subjects related to the optimum physical parameters of lasers, is touched on below. This area includes optimization of layer thicknesses and doping, identification of structural designs for eliminating kinks and pulsations, etc.

Viewed appropriately, the elements of Fig. 1 form a tetrahedron. While this is an accident of the illustrative process, it should perhaps be used to emphasize an important discipline of the subject of laser device development. Lasers must be fabricated which *simultaneously* possess all the good features mentioned above, and the fabrication must be via a high-yield reproducible process. If this is accomplished, the tetrahedron is an extremely stable structure, but if a single bond fails, it collapses ignominiously.

1.1 Fiber loss and dispersion

Before discussing each area of Fig. 1 in more detail, let us consider briefly the situation that exists with respect to the properties of fibers. Figure 2 shows a recent fiber-loss curve for an uncabled fiber.[4] By varying the aluminum concentration, the (Al,Ga)As-laser system can span a wavelength region from about 0.8 to 0.9 μm, corresponding to a loss per kilometer of about 2 or 3 dB. With GaAs laser sources coupling 1 or 2 mW of optical output into them and with modern silicon detectors, such fibers can be used for communications purposes with repeater spacings of roughly 10 to 20 km.

It has been less well appreciated that optical fibers can also be used to transmit power (as contrasted with information). Thus, for example, it has been possible to remotely operate an optical telephone, including the alerting function, over more than 1 km of optical fiber.[5] This experiment shows more generally that injection-laser sources are capable of remotely powering a number of integrated circuits and/or other electronic devices over a long fiber. The author has no doubt that this capability will come to be widely utilized.

The low material dispersion of fibers[6] combined with the lower fiber loss makes it desirable that long, high-data-rate systems operate near 1.3 or 1.5 μm. The considerable efforts currently being expended

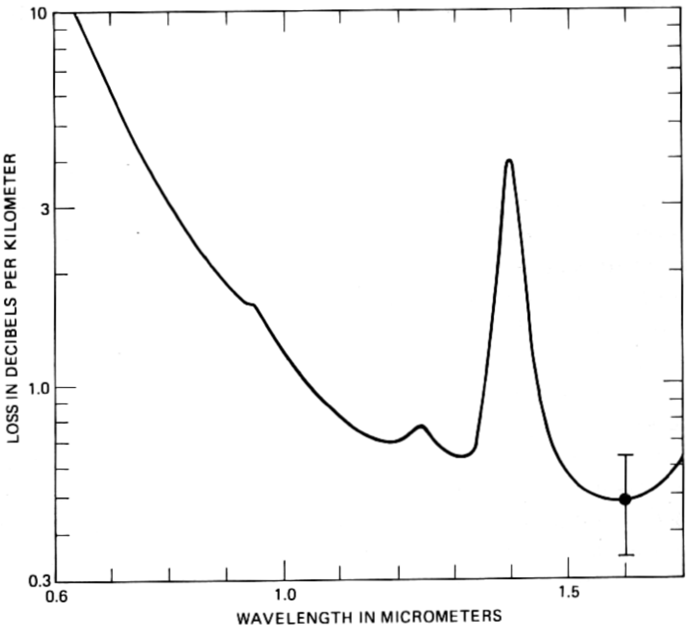


Fig. 2—Approximate loss spectrum of a modern optical fiber (see Ref. 4). The wavelength region from about 0.8 to 0.9 μm is accessible by varying the aluminum concentration in the active volume of an (Al, Ga)As double heterostructure laser.

throughout the world to develop sources at these wavelengths are not reviewed here. However, many GaAs laser concepts have close analogs in these longer wavelength devices.

1.2 The basic stripe-geometry lasers

To introduce the GaAs injection laser, consider Fig. 3, which depicts a standard proton-bombardment-delineated laser structure of a type which we have widely used.[7,8] Such a laser consists of a substrate of GaAs about 100-μm thick, on which four layers have been grown by liquid phase epitaxy. The first layer is $Al_{0.35}Ga_{0.65}As$ about 2-μm thick, the second is the critical active layer of approximate composition $Al_{0.08}Ga_{0.92}As$ and is about 0.15-μm thick, the third layer is again $Al_{0.35}Ga_{0.65}As$ about 2-μm thick, and the final layer of GaAs is fabricated on the structure to improve the contacting. The conductivity types of the various layers are indicated in the figure.

In this structure, current isolation is achieved by means of proton bombardment.[7] That is, all the volume of the laser within about 2 to 3 μm of the surface, with the exception of that portion above the volume from which light is to be generated, is proton-bombarded, rendering it highly resistive. The current supplied to the device then efficiently produces spontaneous emission in an active volume sufficiently narrow that only a single lateral spatial mode of the laser cavity is excited. The cleaved GaAs facets reflect about 32 percent of normally incident light and act as the mirrors of this cavity. This reflectivity is more than adequate to provide the necessary feedback for this very efficient, high-gain injection laser.

The typical active volume widths in these devices are 5 to 12 μm, and a typical length is 380 μm. The lasing threshold is about 100 mA (2.2 kA/cm^2).[9] The optical emission from this type of laser is not, however, particularly well collimated. It has about 20 degrees (full-width, half-power) beam divergence in the plane parallel to the p-n junction and about 50 degrees divergence in the perpendicular plane.[10] Nevertheless, the angular divergences are small enough that a large fraction of the light output ($\lesssim$50 percent) may be easily coupled into standard multimode fibers of about 50-μm core diameter and 0.2 numerical aperture. In theory, utilizing optical coupling schemes, this fraction may approach unity.[11]

II. RELIABILITY

As initially fabricated in about 1970, cw injection lasers[12] had typical lifetimes of perhaps as much as a few hours at room temperature. In

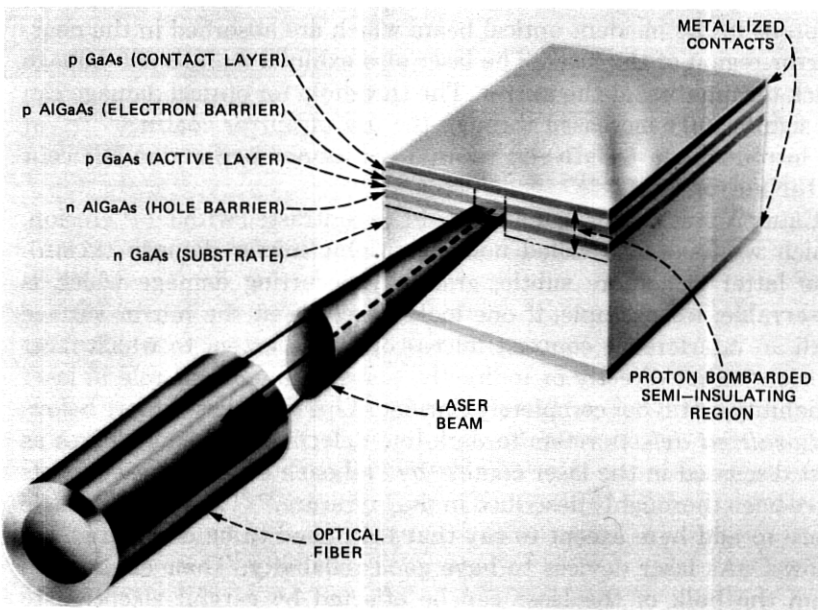


Fig. 3—A schematic drawing of a proton-bombardment delineated stripe-geometry double-heterostructure GaAs laser.

a sense, this is not surprising because the internal power densities of such devices are large, and it is well known that the optical intensities at the mirrors, for example, can approach megawatts per square centimeter. Nevertheless, they are semiconductor devices, their intrinsic internal efficiencies can be nearly 100 percent, and there was no known reason why their reliability could not be as good as that of other solid-state devices. Thus, at Bell Laboratories a program was undertaken to define the causes of these lifetime limitations and to improve them to the extent possible. The results of this and the similar programs of other laboratories are briefly summarized below.

2.1 Categories of degradation

The area in which reliability improvement and understanding have increased can be roughly divided into four categories: (*i*) catastrophic mirror damage, (*ii*) localized interior defects, (*iii*) uniform mode of degradation, and (*iv*) gradually occurring facet-related degradation.

Catastrophic mirror damage may usually be thought of as a threshold effect that occurs when high optical intensities exceed the breakdown strength at the mirrors of the laser. The precise reasons for the initiation of catastrophic mirror damage remain unclear, but its other general features are now well understood.[13,14] The damage is thought to be intimately associated with melting, with the energy coming from photons in the incident optical beam which are absorbed in the near-mirror region of the laser. The laser also exhibits an internal damage track terminating at the mirror. The threshold for optical damage can be significantly increased through the use of mirror coatings[15,16,29] or by introducing a (relatively) transparent, unpumped region adjacent to the mirror facet.[62,89,94]

Catastrophic mirror damage should be contrasted with facet erosion, which we have also called noncatastrophic mirror damage (NCMD). The latter is a more subtle, gradually occurring damage which is observable, for example, if one looks carefully at the mirror surface with an interference contrast microscope. The extent to which facet erosion, either directly or indirectly, plays an important role in laser reliability is still not completely clarified. This is discussed more below.

Localized defects refers to dark-line defects and their relatives as first discussed in the laser context by DeLoach et al.[17] These defects have been thoroughly described in the literature,[18–21] and we have little more to add here except to say that they need to be eliminated[22] to allow GaAs laser devices to have good reliability. Their elimination from the bulk of the laser can be effected by careful attention to substrate quality (including dislocation density), strain, growth, and processing variables in the fabrication of the lasers. Dark-line defects can occur at the mirrors and are still an important degradation mechanism in very long-lived lasers.[23]

Uniform mode of degradation is a somewhat ambiguous term that is defined operationally by the fact that in good lasers the spontaneous emission viewed, for example, through a window in the n-metallization[23] is seen to decrease relatively uniformly as the device degrades (the device threshold increases). This terminology, while often useful, does not distinguish well among more microscopic origins of degradation. Thus, this type of degradation may be due to an increase in bulk nonradiative carrier recombination, such as would be caused by increasing trap densities or shorter carrier recombination time constants in the active volume, but it may also be caused by nonradiative shunt paths such as those which can occur near the mirrors or stripe edges. Defects coming from nearby interfaces and surfaces, for example, under the influence of recombination-aided defect diffusion,[24,25] may also manifest themselves this way, as may an increased optical absorption, either distributed throughout the active volume or concentrated near the mirrors. This "uniform mode" should be distinguished from dark-line-defect degradation in which the spontaneous luminescence from the active volume decays quite *non*-uniformly. We see later that annealing can affect the reliability of devices through this uniform mode and that the interaction of processing parameters and materials growth parameters with the uniform mode of degradation is one of the important current areas of investigation aimed at further improvements in the reliability of GaAs lasers.

The category of *gradually occurring facet-related degradation* is one in which a great deal of recent work has occurred and in which the final word has probably not been written. The author and his colleagues[26–28] have taken the view that facet-related degradation of lasers aged at moderate power levels in clean ambients undoubtedly exists in very long-lived lasers but has not been convincingly proven to limit laser life by the results usually quoted.[29–32] We are particularly unable to reconcile the claims made for mirror coatings with our own rather considerable experience.[27] Good evidence does exist that coatings can protect the facets from contamination, heavy metal ions, and water vapor, for example (see below), but at least in the regime of aging for several thousands of hours at 70°C we have no evidence that coatings improve the lifetimes of lasers aged in clean ambients. In this sense, they do not improve the "intrinsic" laser lifetime, which is the lifetime of interest in the typical encapsulated application. Carefully fabricated coatings on freshly cleaved facets can act to inhibit a short-term (~50-hr at 70°C), saturable mode of degradation.[112] This is probably the same degradation mode previously reported by others,[29,30] although it has strangely sometimes been called "long-term" degradation.[29] This may be partly due to its relatively increased importance in shorter lasers. In our lasers, however, the elimination of this saturable mode seems to have little effect on ultimate device lifetime.[27] On the other hand, other investigators feel quite strongly that their coatings do possess the capability for extending this "clean-ambient" device lifetime.[31,32] These points are discussed more fully below.

2.2 Lifetime Improvements

Above, we mentioned windows[23] in the n-side metallizations of GaAs lasers. Figure 4 shows views of the stripes of several GaAs lasers photographed through such windows as well as several of the kinds of defects which such photographs can reveal. In the upper left is a normal laser. One sees the 12-μm-wide, 380-μm-long stripe relatively uniformly illuminated by the spontaneous emission. A standard dark-line defect is shown in the upper right, and various other defects appear in the other four photomicrographs. The use of windows has provided an important advantage in the development of high-quality lasers because imperfections like dark-line defects and active-layer-thickness variations[33,34] can be seen easily in as-fabricated devices and the mysteries of adverse device performance associated with them can be quickly eliminated. Since lasers with n-side windows are as long-lived as lasers without such windows,[23] they can be employed in practical applications where they are advantageous in diagnosing laser failures.

Beginning with the discovery of the existence and importance of the dark-line defect in about 1973,[17] the reliability of GaAs laser devices has improved steadily. It is now obvious that this progress must be documented and treated using relatively large numbers of devices and that a statistical treatment is therefore necessary. Figure 5 shows several of the milestones that were reached during the first several years of the reliability improvement program. The curve on the lower right shows the first comprehensive accelerated aging data obtained for GaAs lasers.[35] These lasers, which were selected from sequentially grown slices, were operated at about 3 mW of optical output per mirror face in a dry nitrogen ambient at an ambient temperature of 70°C, and the times at which they would no longer emit 1 mW of stimulated emission were plotted in this probability plot. The devices were always aged in a lasing condition at the elevated temperatures so that the results might exhibit the full adverse impact of any stimulated-emission-related degradation processes. It is apparent that this plot in Fig. 5 is approximately log normal. The dashed line drawn through the data is a log normal distribution. It is characterized by a median life of 750 hours at 70°C and by a standard deviation in the log of the

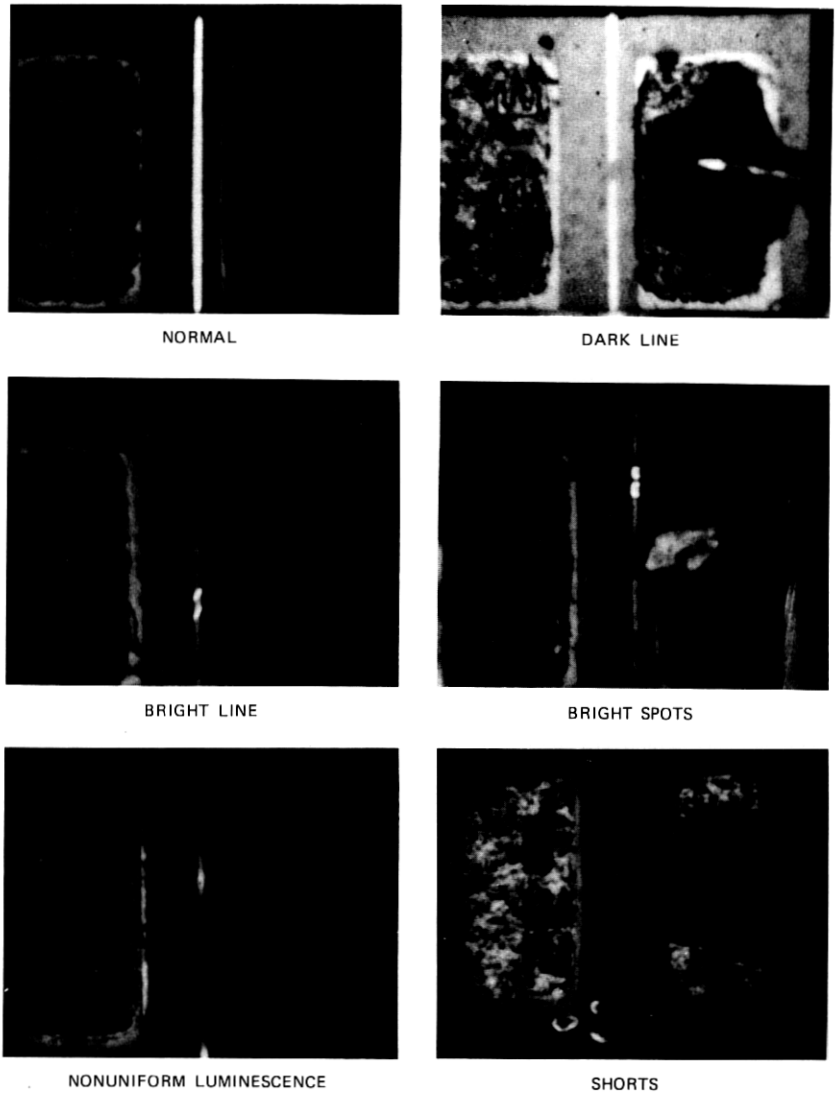


Fig. 4—Several types of defects observable through a window in the n-metallization of a GaAs laser (see Ref. 23).

lifetimes of 1.1.[35] If one assumes that the degradation process is thermally activated, with an extrapolation energy of 0.7 eV,[3] this 750-hr median life corresponds to about 50,000 hours in an ambient environment at 22°C. This acceleration factor has been directly confirmed by the operation of similar devices in 30°C ambients.[36]

Lasers of the type depicted in this curve were the first to have reliabilities that were adequate for telecommunications applications,

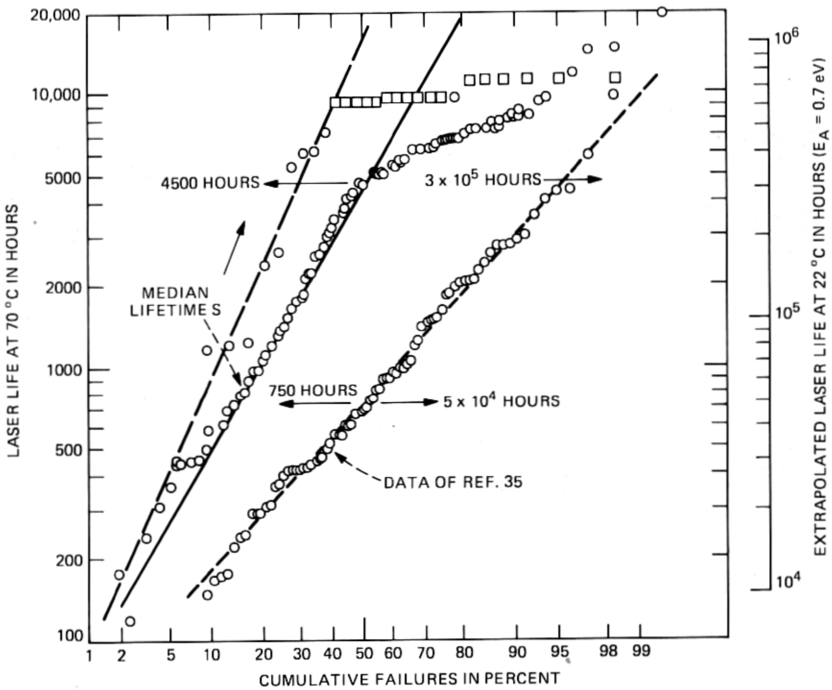


Fig. 5—Several measured lifetime distributions for lasers aged in a 70°C dry-nitrogen ambient. Extrapolated room temperature lifetimes assume a 0.7 eV extrapolation energy. The two better lifetime distributions possess extrapolated room temperature, continuously lasing, mean lifetimes of more than a million hours (~100 yr) (see Refs. 35 and 39).

and indeed similar lasers have been used quite successfully in the Bell System's Atlanta and Chicago lightwave experiments.[37,38] The data rate in these experiments was approximately 45 Mb/s.

The other two statistical distributions in Fig. 5, which show median lifetimes at 70°C of about 4500 and 14,000 hours, were obtained in lasers fabricated from selected wafers in which the material growth and processing had been improved. Both these distributions possess extrapolated room temperature mean lifetimes in excess of a million hours, or about a hundred years.[39] The ability to make lasers of this type, which involved improvement of laser lifetime since 1970 by about a factor of 10^6, represented an important achievement because it showed the feasibility of applying these devices in real systems. The proposition[3] that degradation in high-quality lasers is thermally activated has now become generally acknowledged,[40–42] although it is easily possible to measure low rates of thermal activation when, for example, contact-related degradation is not adequately inhibited.[26] Greatly improved lifetimes have also been achieved in several other laboratories using several different device structures.[40–47]

This is not to say, however, that further lifetime improvements are not desirable. Because of the statistical nature of the lifetime distributions, it is important for the most critical applications (e.g., in telecommunications) to achieve another factor of 10 or 100 increase in lifetime and to decrease the standard deviation to the extent possible. These improvements remain goals of the ongoing reliability programs. Several aspects of these programs relate more specifically to the physics of degradation, which contains many not-fully-understood areas, a few of which will now be mentioned.

2.3 Unfinished business—possible areas for further lifetime improvements

2.3.1 Aluminum in the active layer

Consider first the question of the importance of aluminum in the active layer. Figure 6 shows recent laser aging results in which a serious penalty caused by the absence of aluminum in the active layer is convincingly indicated.[45] These data should be viewed in the following context. In the past, it had been thought to be important to have several percent aluminum in the active region of GaAlAs lasers so that the emission wavelength of these devices could be more accurately tuned to the minimum loss of the fibers. With fiber improvements, resulting in fibers with loss characteristics of the type previously shown in Fig. 2, it is now clear that the optimum wavelength of GaAlAs devices is near 0.9 μm (the longest wavelength obtainable in this material system). Thus the growth of lasers with little or no aluminum in the active region becomes important. The conventional explanation of the degradation-related action of aluminum in the active region is that it getters inadvertently present oxygen,[48]* which is detrimental to the lifetime of the devices. If this is true, it may be possible to obtain the long lifetime associated with aluminum and yet avoid the aluminum wavelength shift by using very clean oxygen-free crystal growth techniques,[49] by adding a nearly imperceptible amount of aluminum to the active layer melt, or by using other gettering methods. For the present, the questions remain to be clarified of how much aluminum is needed to improve the lifetime and of how fundamental is the addition of aluminum.

2.3.2 More accurate specification of the origins of degradation: facet coatings

Another important area that requires further work is the improvement of the precision with which the microscopic origins of degradation are identified. The possible dependence of degradation rate on the

* Active layer Al may also reduce strain to some extent.

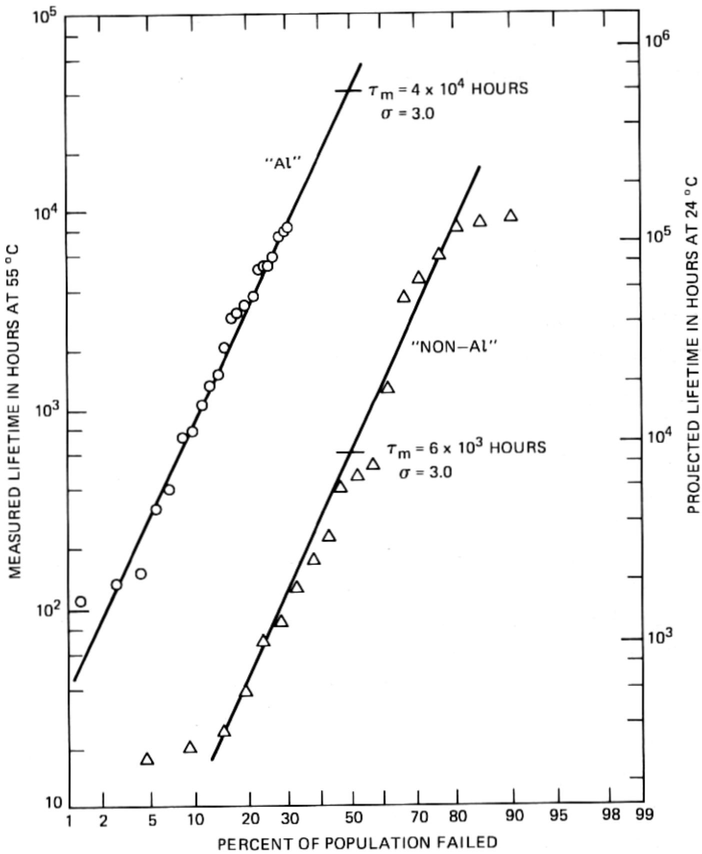


Fig. 6—Measured lifetime distributions for two groups of lasers aged in a 55°C ambient; those having no intentional aluminum in the active layer and those having approximately 6 percent aluminum in the active layer (see Ref. 45).

presence, or intensity, of stimulated emission is also of interest. Results of a statistical aging experiment done by Dixon and Hartman[26] and relevant to the latter question are presented in Fig. 7 (see also Ref. 42). In this experiment, two kinds of lasers were aged at 70°C until failure. The lasers were selected from the same slice. One group was aged as lasers emitting about 3 mW of optical output per mirror face. The other group was aged with approximately the same current density but with the current adjusted to below laser threshold. Thus, effectively, there was no stimulated emission in these devices and the devices were operated as light-emitting diodes.

A comparison of the two statistical aging distributions in Fig. 7 does not indicate any serious difference between the lifetimes of lasers aged in these two ways. It is therefore consistent with the conclusion that the stimulated emission did not adversely affect the device lifetimes for devices with lifetimes of a few thousand hours at 70°C. Higher optical intensities do, however, impact the device lifetime,[27,50] although the origins of this impact remain to be clarified. We believe they may involve the saturable, mirror-related mode of degradation mentioned below. Since the devices aged as light-emitting diodes in Fig. 7 did *not* show facet erosion, these results argue that facet erosion, defined as something observable when the laser mirrors are examined in interference-contrast microscopy, did not cause the device degradation. [Facet

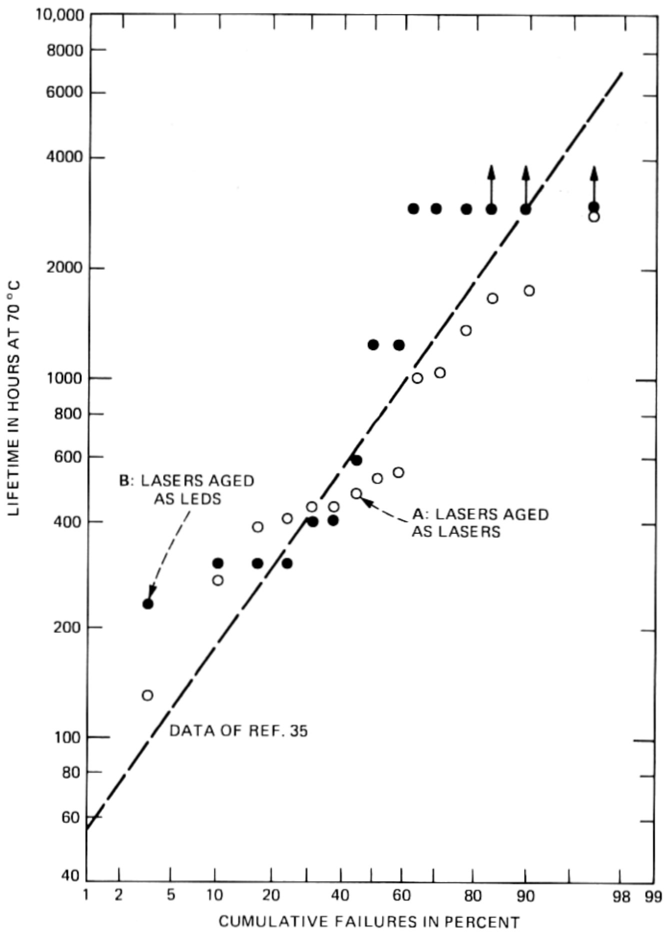


Fig. 7—Similar distributions of lifetimes of lasers aged as lasers (A) and of lasers aged as light-emitting-diodes (LEDs) (B). A 3-dB decrease in spontaneous emission intensity from the mirrors of these devices was correlated with their inability to operate as lasers, independent of the mode of aging. These observations are consistent with a degradation mechanism which is not lasing related (see Ref. 26).

erosion, or noncatastrophic mirror damage (NCMD) is probably due to a photochemically formed oxide.[51]]

To make this point slightly differently, consider the data shown in Fig. 8.[52] These data are from two lasers emitting approximately 4 to 6 mW per mirror face, respectively, as they were aged at *constant current* and 70°C in a clean dry ambient. The point is that facet erosion was clearly visible in these devices within 200 hours of the beginning of accelerated aging but, as can be seen, the light output from these devices was not seriously affected.

Consider now the results[27] shown in Fig. 9. This figure shows statistical aging results at 70°C for lasers which were coated with electron-beam-deposited half-wavelength coatings of aluminum oxide prior to aging. Two different types of lasers were selected for these experiments. The data in the lower part of the figure were from a type that had poor 70°C lifetimes with a median around 100 hours. These lasers are thought to have died from internal dark-line defects. The data in the upper part of the figure were from better devices with a median lifetime at 70°C of about 2000 hours. As can be seen by the comparison of the aging characteristics of the coated and uncoated devices, there is no meaningful distinction between these two sets of devices. It is important to note, however, that the coatings did keep facet erosion from occurring on these devices (which were aged in a dry nitrogen ambient).[27] One cannot conclude from these data that

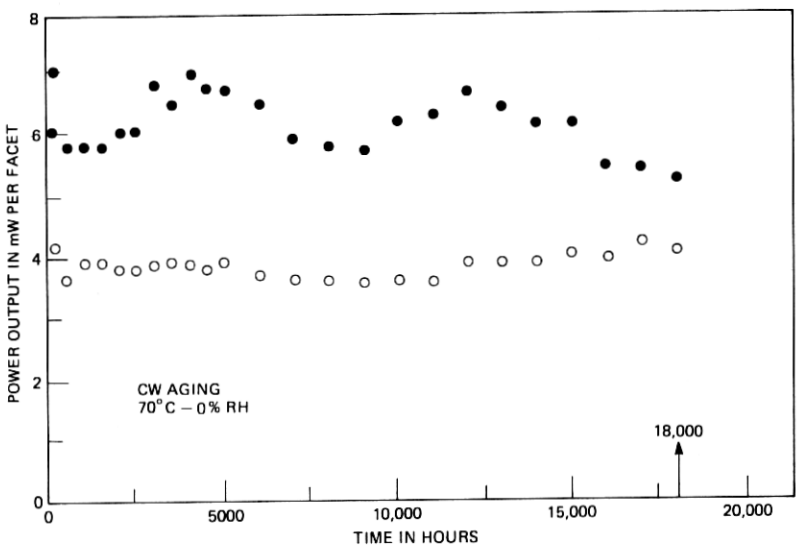


Fig. 8—Lasing emission vs time for two uncoated lasers aged at *constant current* in a 70°C dry-nitrogen ambient. The outputs were not substantially affected by the facet erosion which existed (see Ref. 52).

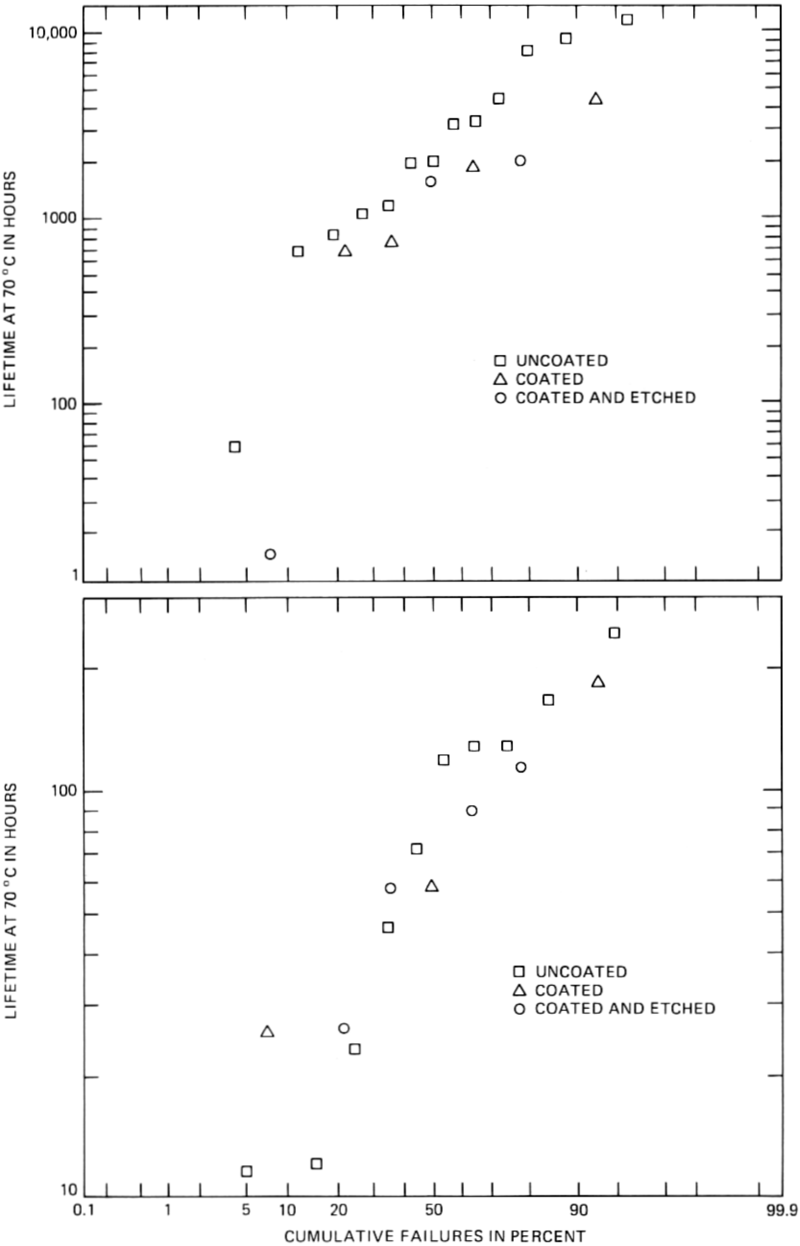


Fig. 9—Measured 70°C lifetime distributions of devices from a slice with a 1975-hr median lifetime (upper) and from a slice with a 95-hr median lifetime (lower). The *E*-beam deposited half-wavelength Al_2O_3 coatings did not significantly affect the aging distributions (see Ref. 27).

coatings can never improve intrinsic laser lifetime, but it is true that no such improvement is evident here. One can say that the elimination of facet erosion did not eliminate the degradation.

This is not to suggest, however, that the above coatings are completely ineffective. As one can see from the data shown in Fig. 10, which was also taken with devices which possessed similar $\lambda/2$ Al_2O_3 coatings, the coatings can perform an important protective function if needed. The two groups of lasers tested in this experiment[53] differed in that one set was simply aged at 70°C in a clean nitrogen ambient, but the other set was purposely contaminated with copper on the mirrors prior to a similar aging. As can be seen, the set containing copper degraded much more rapidly than the set which was not contaminated. The important result is that Al_2O_3 mirror coatings can protect the

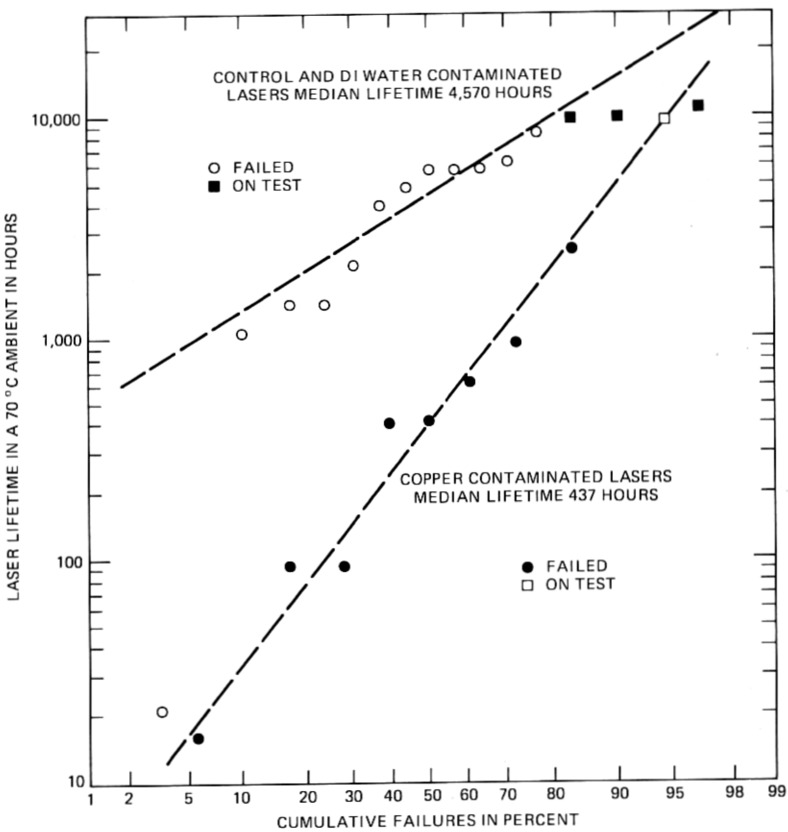


Fig. 10—Measured 70°C lifetime distributions for lasers from the same slice but randomly divided into two classes. One class was aged normally as lasers and a 4570-hr median lifetime was obtained for it (upper curve). The other class was purposely contaminated with copper prior to similar aging and exhibited a median lasing lifetime of only 437 hr (see Ref. 53).

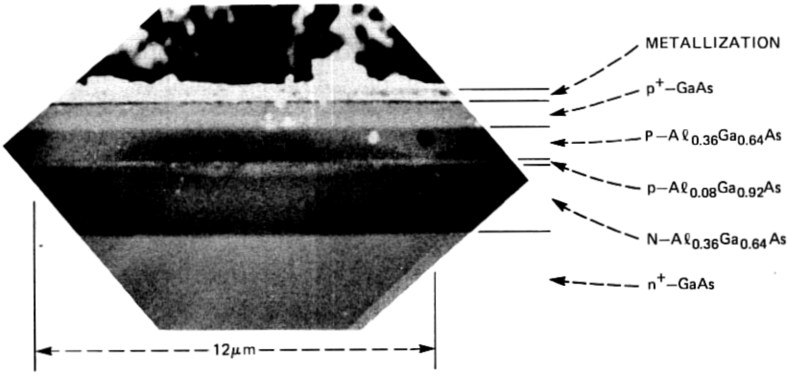


Fig. 11—A scanning electron photomicrograph of facet erosion as seen on a laser which had been operated for 18,273 hr in a 70°C dry-nitrogen ambient (see Ref. 27).

laser from copper-induced degradation and, by inference, from other ambient contamination as well. Thus one important conclusion with respect to the effect of mirror coatings on laser lifetime is that the testing environment for comparative studies must be carefully stipulated. This has probably not been adequately done in the past. For example, some workers have used room ambients for reliability investigations. It should also be reiterated that coatings on freshly cleaved facets can suppress the initial saturable mode of degradation[112] (see Fig. 34) and, as we shall see later, also stabilize the development of pulsations. The suppression of this initial facet-related saturable mode would be expected to be a relatively more important effect in lasers with shorter optical cavities.

2.3.3 Facet erosion and mirror darkening

Let us turn now to the question of what the uncoated mirrors look like in lasers that have been aged in clean ambients for relatively long periods of time and then try to distinguish mirror-related degradation from the appearance of the mirrors. Figure 11 shows a scanning electron microphotograph of noncatastrophic mirror damage on the facet of a laser which had operated continuously at 70°C for more than 18,000 hr.[52] The oval discoloration in the vicinity of the active area is clear, but its association with any deterioration of reliability is not apparent. It is possible to say that this and similar devices can live for several years at the accelerated aging temperature of 70°C.[52]

The appearance of facet erosion should, however, be distinguished from a darkening behind the mirror[23,27] such as that shown in Fig. 12. Figure 12 is a photograph taken through the n-side metallization window of a laser, first when it was unaged and again after 2,000 hours of aging at 70°C. Two things are noteworthy about these photographs.

The first is that mirror darkening has appeared within about 20 μm of the mirror surface after the aging of this device. It appears that this mirror darkening can adversely impact device reliability[23,27] and that it can occur where no facet erosion is present.[27]

The second important point is that the photograph after 2,000 hours of aging was taken with the same current but a longer exposure time than the photograph at time zero, and this again illustrates the more-or-less uniform decrease in spontaneous emission. This could be due, for example, to either a uniform bulk degradation process, or to the shunting of current around the bulk region of the device by regions near the mirrors. The dark region behind the mirrors may also have increased optical loss associated with it. In any case, it is important to distinguish between facet erosion, which may be largely a cosmetic effect in lasers aged in clean ambients at power levels of a few milliwatts,[26] and darkening behind the mirrors,[23,27] which may be the signature of a more serious degradation process. These two effects are not equivalent.[27] Either can occur without the other being present.

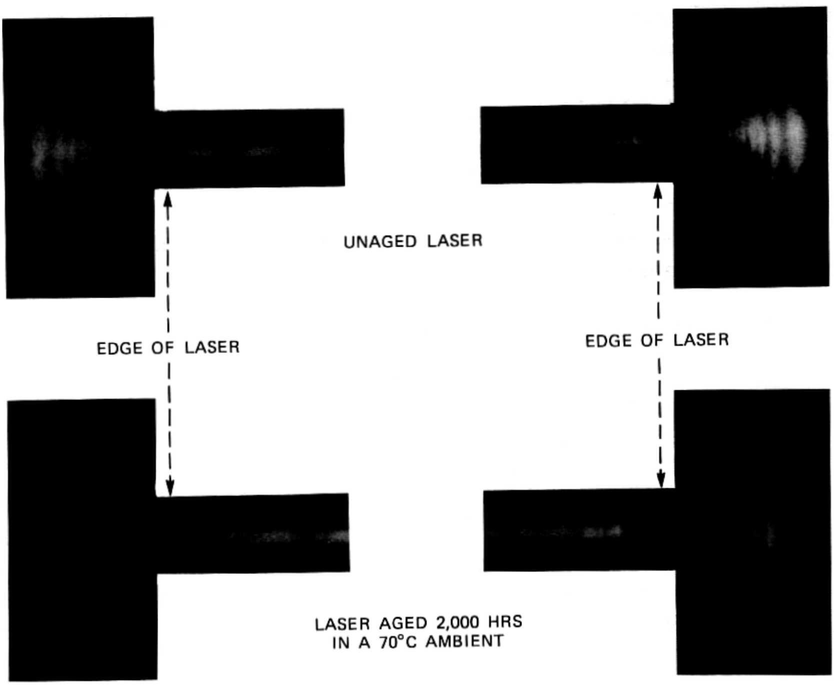


Fig. 12—Photographs of the spontaneous luminescence, observed through an n-side window, from the stripe region of a laser before and after 200 hours of accelerated aging in a 70°C dry-nitrogen ambient. The photographs were taken at the same below-threshold injection current, but the exposure time in the lower photograph was substantially increased, thus exhibiting the uniform mode of degradation. The darkening at the mirrors is seen clearly in the lower photograph (see Ref. 27).

2.3.4 Humidity

To better understand the properties of the gradually occurring mode of facet degradation, a series of experiments were conducted in a higher-temperature, humid atmosphere where it was hoped to accelerate the degradation.[52] In the extreme cases, this work showed that rather dramatic oxide growth on the mirror surfaces is possible. An example is shown in Fig. 13. This laser was aged at 70°C in an 85-percent humidity atmosphere for 3000 hours. Note the considerable distortion from planarity, whch has occurred in the vicinity of the active region (which in this case contained 8-percent Al). A similar bulge is also visible in the P-GaAs region near the contact. It is believed that these are regions of photon-activated oxide growth[51] in this relatively strongly oxidizing environment. It should be emphasized, however, that the device still lases, even with these large distortions of the mirror surface. The most important detrimental influences of the oxides result from (nonuniform) reflectivity changes. These can increase the mirror transmissivity and/or cause the beam position on the facet to move. In some devices, dark-line defects were also initiated at the mirrors and this then becomes an important degradation mechanism.[23]

2.3.5 Reliability-related modifications of device processing

Consider next two procedures that show promise for decreasing the degradation rate of GaAs lasers. Both of these relate to processing changes* for which detailed mechanisms are not completely understood. In Fig. 14, statistical aging data of lasers taken from one slice are shown. These data refer to two different groups of lasers. One group came from a portion of the slice that was processed in a normal way. The other group was fabricated from a portion of the slice on the p-surface of which an anodic oxide had been grown and removed just prior to the deposition of the titantium-platinum-gold metallization.[54] It has been known for some years that the quality of the metal-semiconductor interface at the p-contact is critically important to the fabrication of long-lived GaAs lasers.[39,55] Data such as those shown in Fig. 14 illustrate that careful control of the device processing just prior to the deposition of p-metals can be critically important in producing high-quality devices. Uniform current density and a clean stoichiometric surface are both thought to be important in attaining this surface-related reliability improvement.

A similar situation exists with respect to the processing variation behind the aging results depicted in Fig. 15. In this case, one portion of the wafer was annealed at a temperature of approximately 450°C

* Another fabrication-related degradation mechanism is described in Ref. 79.

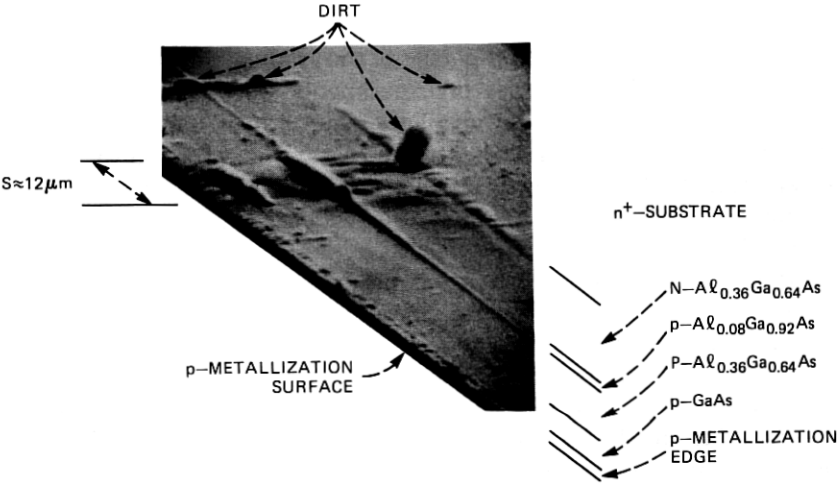


Fig. 13—An oblique scanning electron microscope view of the facet of an uncoated laser which had been aged for 3000 hr at 3 mW/mirror face optical output in a 70°C-85-percent relative humidity ambient. Note the facet nonuniformities, which are presumed due to oxide growth. The photograph is consistent with a photo-induced oxide growth which is inhibited by the presence of aluminum, but which requires minority carriers for its growth (see Refs. 51 and 52).

for several days following the deposition of p-metals, while a control portion of the same wafer was not annealed but was otherwise processed similarly.[54] As can be seen from the aging data, the annealed devices appear to be substantially better than the unannealed devices.

Even when lifetime improvements are not as easily documented as in cases described by Figs. 14 and 15, proper processing can significantly improve the uniformity of devices. Figure 16 illustrates such a case. Here, one portion of the slice was anodized as in Fig. 14, while the other portion of the slice was not. In this case, however, the device aging distributions were rather similar, at least for times below the approximately 1000-hour 70°C median. As can be seen from Fig. 16, however, the current increases required to maintain 3 mW of optical output per mirror face are significantly more erratic in the unanodized than in the anodized portion of the sample.

From the examples of Figs. 14 to 16, it should be obvious that another active direction in injection laser-applied research concerns processing modifications like annealing and the anodization of the p-surface of the semiconductor. The attempt is to find fabrication methods which result in significant reliability or uniformity improvements. A more fundamental study of the origins of these reliability improvements has yet to be done.

Another possibly related technique by which the degradation behavior of a laser can be substantially modified is through the growth of a laser in which the junction is placed slightly outside the active volume (the remote-junction laser[56]). This remote junction placement has been shown to significantly improve the rate of deterioration of the threshold of the laser with time. The technique would appear to be a method for utilizing the inherently low nonradiative recombination associated with isotype heterojunctions[57] in a laser structure. It is also plausibly a way to separately study degradation of junction-related and bulk-luminescence-related degradation processes.

2.4 Reliability summary and the problem of testing

The present status of GaAs laser reliability can be summarized in the following way. First, the achievement of a million hours extrapolated mean-time-to-failure is an enormously important achievement,

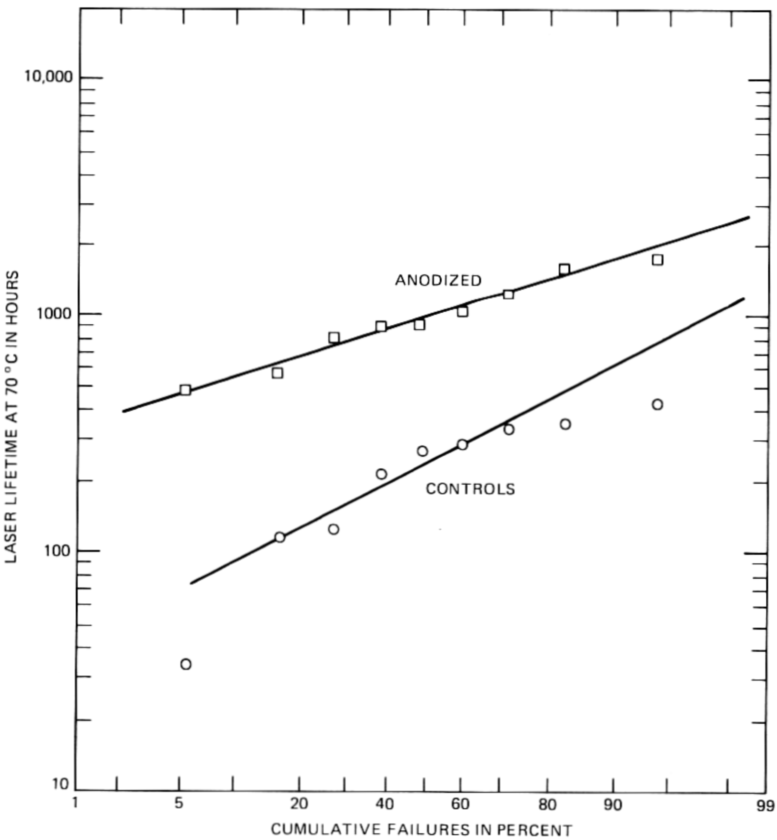


Fig. 14—Dry-nitrogen ambient 70°C lasing lifetime distributions of a set of normally processed devices (lower curve) and of a set of devices in which an oxide was anodically grown and then chemically removed from the p-surface of the wafer after the zinc contact diffusion was performed (see Ref. 54).

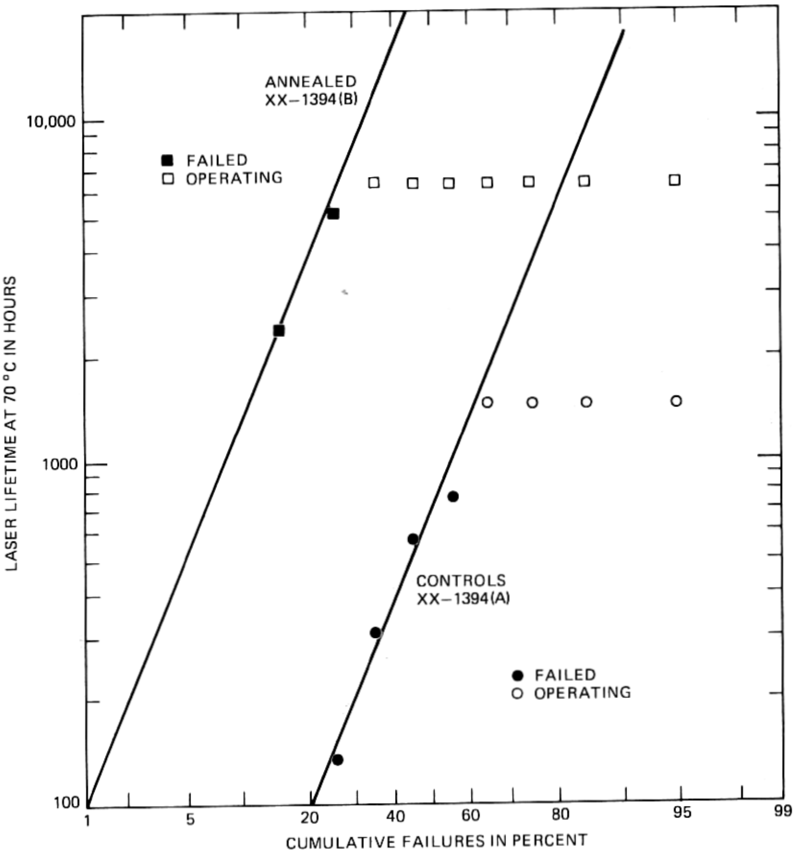


Fig. 15—Results of a dry-nitrogen ambient 70°C comparison aging experiment in which one portion of a wafer was processed normally (A) and the other (B) received a 72-hr annealing at 450°C after the p-metals were deposited. The straight lines are log-normal distribution functions. Open symbols indicate devices which are still operating (see Ref. 54).

in the sense that it qualifies these devices to be seriously considered as optical sources in a wide variety of applications. As has been stated, the reliability has improved by about a factor of 1 million since cw operation was attained. This is not to say, however, that the reliability is perfect or adequate at the present time. Some critical applications, such as those in which devices will operate in remote locations (such as in undersea cables) or at higher temperatures, require further improvements in the average reliability. Also, it is fair to say that a high yield of long-lived lasers has been and still is an elusive problem. One would like to learn how to fabricate lasers which have uniformly high yield and where the standard deviation from the median life is as small as possible.

In this regard, it may be relevant to mention lasers fabricated by molecular beam epitaxy (MBE). Several years ago, high yield and uniformity were achieved in cw room-temperature lasers using molecular beam epitaxy techniques,[58] but their thresholds were higher and their reliability poorer than for devices grown by good LPE (liquid

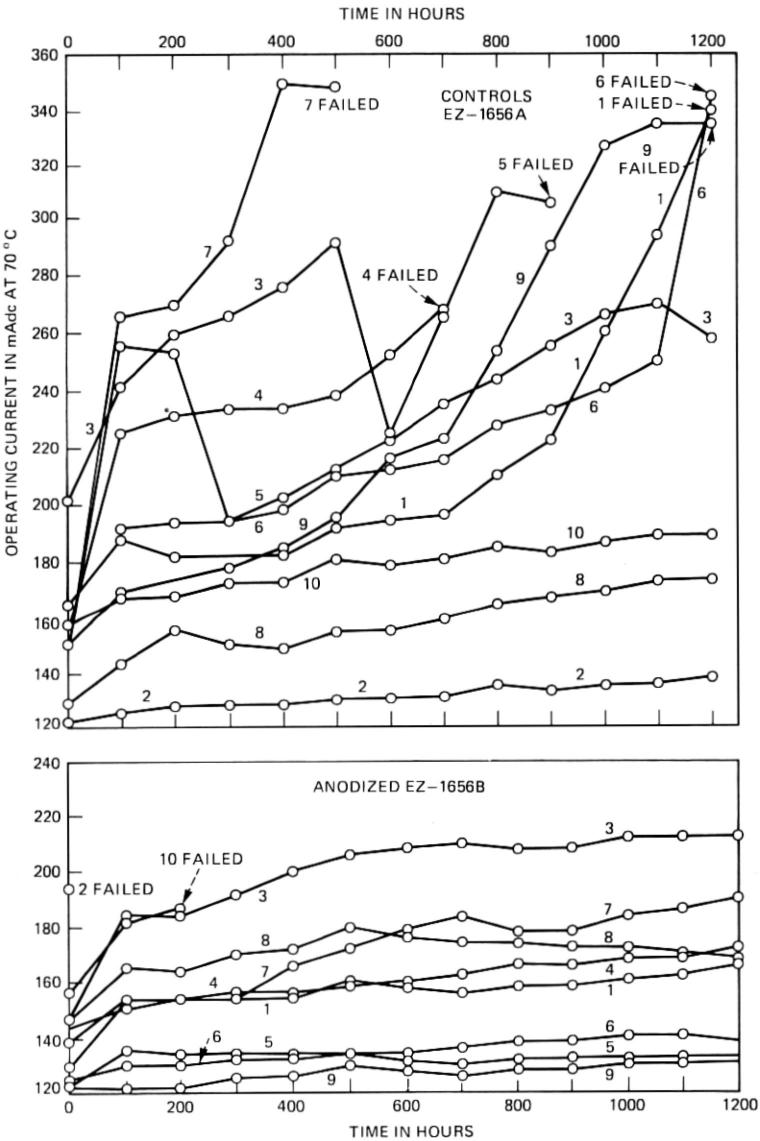


Fig. 16—Operating currents required to maintain 3 mW/mirror facet from 20 lasers obtained from the same wafer. Half the lasers (upper figure) were from a control portion of the wafer while the other half (lower portion) were from a portion on which an oxide had been anodically grown and chemically removed following zinc diffusion. These results illustrate the extreme importance of p-side processing (Refs. 54 and 55).

phase epitaxy) techniques. Recent improvements in MBE procedures suggest that it may be possible to overcome these liabilities.[59] If so, this would be a very exciting development. Organometallic vapor phase deposition is another interesting technique, and lasers with quite reasonable initial properties have been fabricated using this method.[60] Initial reliability results on these lasers are encouraging.[61]

Other present laser improvement efforts involve the facets; certainly, mirror coating and its relationship to mirror darkening and nonradiative carrier recombination near the mirrors is an important area of current investigation. Probably it will be possible to inhibit facet-related degradation processes, either through appropriate passivation techniques, including coatings, or by making the active volume remote from the surface.[62,89,94] Similarly, the importance of the interfaces and their impact on reiability continue to be studied. These studies emphasize the contact-semiconductor boundaries, but also include the proton bombardment edges, Zn diffusion fronts, active layer-cladding interfaces, etc. Processing changes such as sample annealing and the anodization of the p-surface prior to metallization show promise for achieving more uniform and more reliable devices. Finally, the explanation of the various empirical observations in terms of more fundamental degradation mechanisms remains an interesting, if difficult, area. For example, the impact of recombination-aided defect motion in these devices seems certain to command more attention in the coming years.[25,63] It should perhaps be said that no *fundamental* limitation on the quality of these devices has yet been found.

A reliability-related area that is becoming more and more serious, however, is the area of testing. The problem can be illustrated by the following question. If one were *given* devices which were known to have greatly improved reliability, how would one test them to confirm this fact? Operating the devices as lasers at increased accelerated aging temperatures is difficult because of the temperature dependences of the gain mechanisms in these devices.[3] Present devices will not lase consistently at temperatures much above 110°C. Possibly this limit can be improved by better design, bonding, etc. If not, LED types of testing at higher temperatures will be necessary to infer lasing lifetimes at lower temperatures. High temperature lasing controls, as in the experiments of Dixon and Hartman,[26] would not be available. These experiments would yield an upper bound on the lifetime, but not the more useful lower bound. Alternatively, one might try to infer the failure distribution by testing at temperatures where the devices will lase, for times which are necessarily much less than the mean lifetimes. This is often the case with high-quality silicon devices.[64] Extrapolation to the median or mean lifetimes from several standard deviations away would be required. Those who have worked long with semiconductor lasers are generally hesitant to recommend such an extrapolation procedure at present. There are too many ways for infant mortality and unknown defects in the testing techniques to affect the results. The problem will be solved only when the degradation mechanisms and their various parameter dependences are better understood.

III. OPTICAL LINEARITY

Figure 17 shows a typical nonlinearity in the optical output of a GaAs laser.[3] Some years ago, the term "kink" was coined[3] to describe this nonlinearity, and that nomenclature has been widely adopted. As Fig. 17 shows, the kink is not terribly temperature-dependent, but it does occur in the middle of the desirable optical output power range. It has an adverse influence in many applications where more linear output would be desirable. Efforts to understand the origins and to eliminate kinks are worldwide.

3.1 Mode motion, stripe width, and optical linearity

A most important step toward understanding this phenomenon occurred in connection with the experimental result shown in Fig. 18. This experiment showed that proton-bombarded lasers in which the stripe width was reduced to 8 μm from the normal 12 μm had considerably improved optical linearity.[65] The experiment also identified the near- field motion[65,66] of the optical intensity distribution with the

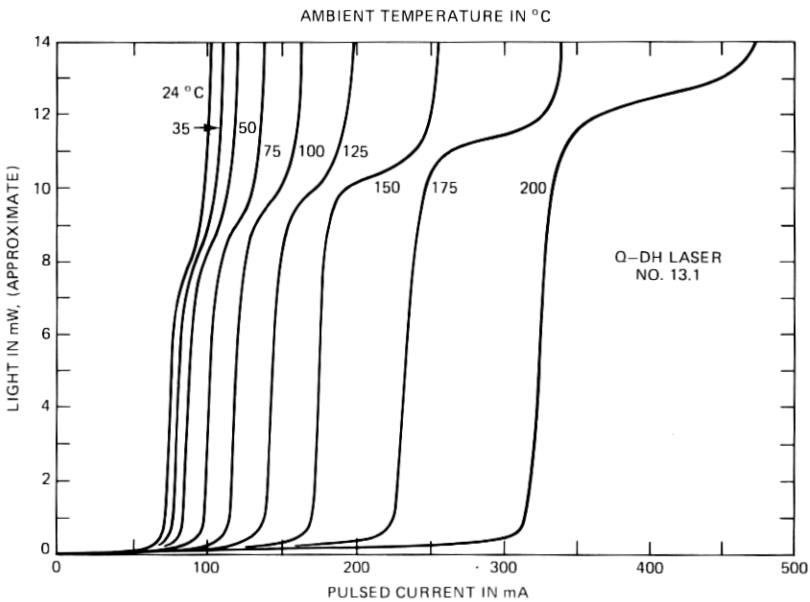


Fig. 17—Light output versus current curves, at several ambient temperatures between 20 and 200°C, showing the kinks which are often observed in lasers without lateral mode control (see Ref. 3).

kink, with beam steering, etc. Elimination of the mode motion resulted in a much more linear optical output. Of course, 8-μm-wide stripe lasers still have serious carrier diffusion losses at the edges of the active volume,[67,68] but, as Fig. 18 shows, their linearity is much improved over devices with wider active volumes.

For many optical communications applications, the linearity of these 8-μm lasers is quite satisfactory. One should note that narrowing the stripe does not eliminate the kink, but simply moves it to higher output powers.[65] As indicated below, the simplest explanation of this effect is that narrowing the stripe increases the curvature of the gain distribution and thus increases the gain guiding available to the mode. (The increased loss at the stripe edges may also be important.) This increases the optical intensity[69] which can be present in the laser before the refractive index perturbations caused by carrier depletion result in a kink. Similar relationships between stripe widths and linearity have also been shown to exist in other types of lasers.[70,71] The Zn-diffused stripe laser, for example, has been extensively studied,[71] as has the PpnN laser intended for high-power, pulsed applications.[72]

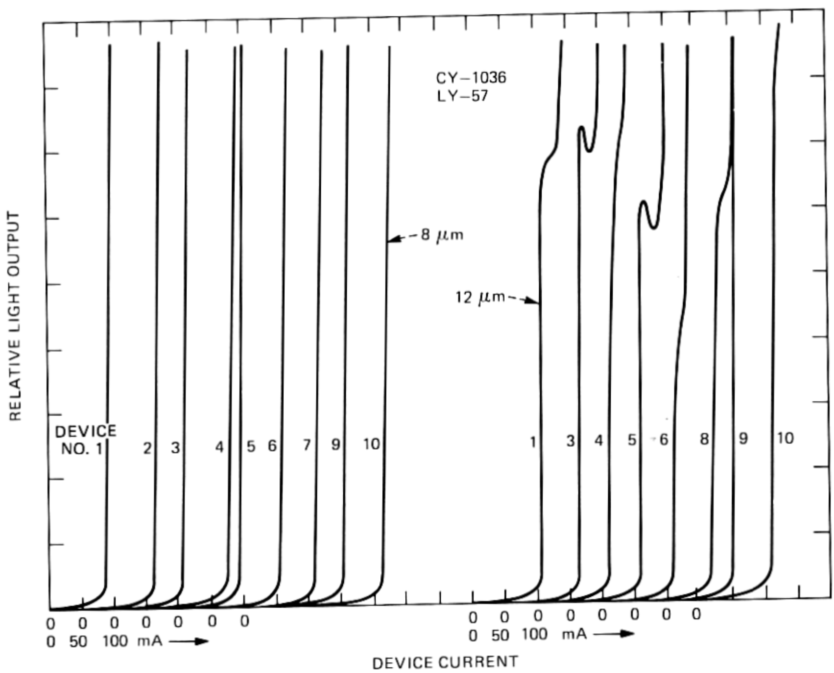


Fig. 18—Comparison of light output vs current characteristics among devices with 8- and 12-μm-wide proton bombardment delineated stripes fabricated from interleaved regions of the same slice. Near-field observations in the kink region showed changes in the spatial position of maximum lasing intensity due to small changes in current and asymmetries in the optical output between the mirrors of a given laser. Spectral broadening was also typically associated with the kink region. Full-scale optical output is about 3.5 mW per mirror face (see Ref. 65).

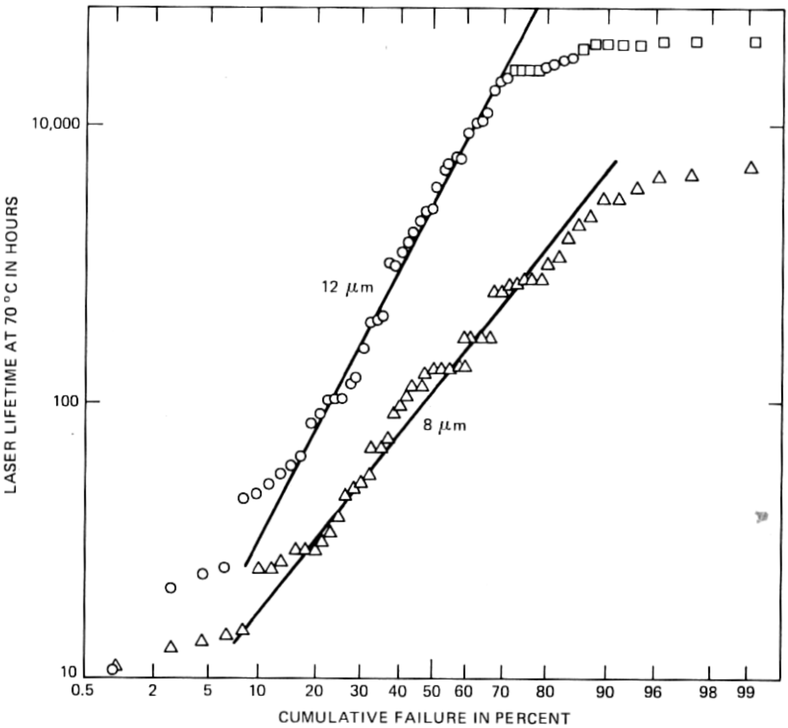


Fig. 19—Lifetimes of 8- and 12-μm-wide stripe lasers fabricated from the same wafer and aged in a 70°C dry-nitrogen ambient. The nominal factor-of-four superiority of the devices with wider stripes occurs in devices with median lifetimes greater than about 1000 hours. Note the 6000-hr median life of the 12-μm lasers in this figure. The squares represent devices which have not failed (Ref. 73).

There is, however, a serious problem with the 8-μm-wide stripe lasers, and that is depicted in Fig. 19. This figure is a comparison in the lifetimes at 70°C of 12- and 8-μm lasers.[23] Seven slices were used for this comparison, and pieces of each slice were fabricated into 8- and 12-μm lasers. One can see an approximate factor-of-4 decrease in the median lifetime results for the 8-μm lasers. This decrease has been seen in many slices and is believed to be statistically meaningful. To expand on this a bit, it appears that, in devices which have median lifetimes of about 1000 hours or less at 70°C, the lifetime distribution of 8- and 12-μm lasers are quite similar. But from slices yielding longer life devices, the 12-μm devices clearly outlive the 8-μm devices. It is important to try and eliminate this lifetime difference for two reasons. First, this would allow the more widespread use of 8-μm lasers with their improved optical linearity. The 8-μm devices are otherwise quite satisfactory lasers.[73] Second, such understanding could presumably be used to further improve the lifetimes of both the 8- and 12-μm devices. Thus, for example, the effect of the annealing and anodization steps mentioned earlier on the properties of 8-μm laser lifetimes is an area of active investigation.

3.2 The physical origins of kinks

Before continuing with the discussion of other laser structures, it seems appropriate to digress enough to describe what the author believes to be the fundamental origin of kinks. Figure 20 is an aid in doing this. Figure 20a depicts a gain profile such as that which exists in the active volume of a normal stripe geometry laser where carrier diffusion from the sides produces a more or less parabolic transverse gain profile. From the work of Nash,[74] it is known that a slight positive dielectric constant perturbation and a concomitant optical modal

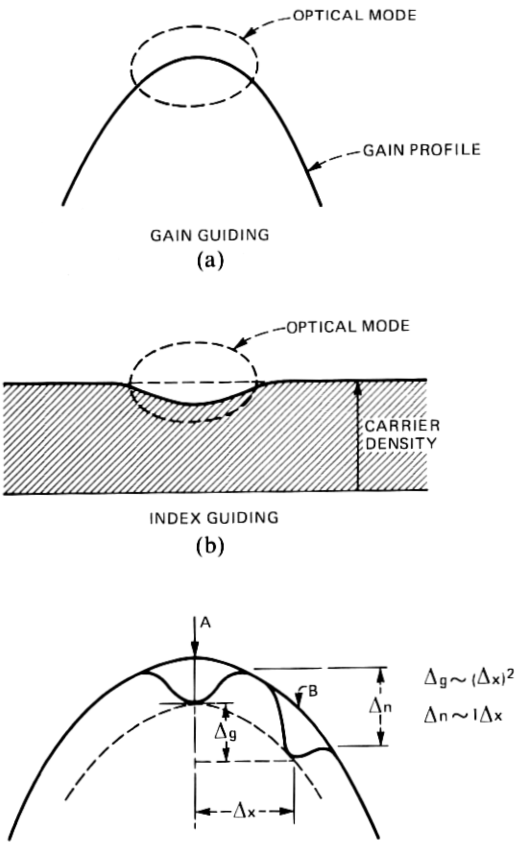


Fig. 20—(a) Illustrates the gain guiding present in devices with a lateral carrier profile (see Ref. 93). (b) Illustrates the index guiding caused by carrier depletion which is thought to contribute to lasing filament formation in broad area lasers (see Ref. 75). (c) Illustrates how the two effects can be combined in such a manner as to produce a kink in the light output of a laser.

confinement effect should be associated with this profile. This explains, for example, why a low intensity optical mode is symmetrically located in the middle of the 12-μm-wide stripe of a normal proton-bombarded laser.

Figure 20b schematically shows a different effect which is thought to occur in so-called broad area lasers; that is, lasers without a narrow stripe. It is a well-known property of these lasers that they tend to emit light in filaments. That is to say, the near field of such devices is composed of separated bright spots each several microns wide. Thus the optical emission is very nonuniform across the aperture of such devices. It is believed[75] that the tendency to filament is caused by the effect depicted in Fig. 20b. Through an electron-hole plasma interaction, the carrier density that exists in the active volume produces a slight negative change in the effective refractive index. Then, as the device starts to lase, the stimulated emission causes excess carrier recombination in the vicinity of the optical mode. The resulting carrier depression results in a small relative *increase* in the refractive index at the position of the optical mode. Thus, the mode tends to be confined to regions where the carrier density is being depressed, at least until the carrier density is suppressed so much that the gain will no longer support lasing. Filaments are thus unstable in position when the drive current is changed. They are also easily influenced by slight gain or loss inhomogeneities, defects, etc.

In a simple physical sense, the author believes, following Thompson et al,[76] that the initiation of a kink in a GaAs stripe geometry laser can be understood as a combination of these two effects. Figure 20c illustrates the reasoning. Position A depicts a lasing mode which is symmetric with respect to the gain profile. Gain guiding is dominant. One imagines, however, that this mode is capable of eating a spatial hole in the profile. It was thought initially by some that a kink was caused simply by the fact that the resulting carrier and gain depressions implied, following this spatial hole-burning, that there existed a region to the right or left of the symmetric mode position where the gain was higher, and that the lasing mode would therefore move over into this region of higher gain. Unfortunately, this argument cannot be carried much further. It should be realized that the optical mode would depress the gain profile in its new position and that the mode would then move back toward the symmetric position of the gain profile. In this case, no kink in fact results. On the other hand, it is possible to argue that a roughly constant amount of mode guiding exists near the top of this parabolic profile independent of the precise position of the lasing mode. (That is, the loss of gain Δg from displacement Δx is an even function of Δx and hence has no linear term in Δx.) The dashed curve in Fig. 20c is an attempt to depict this concept.

Now consider a mode that exists at position B in Fig. 20c and imagine that its stimulated emission also causes a decrease in the carrier density, and hence in the gain available, at this mode position. A new effect is now available to perturb the mode guiding. This is caused by the fact that, toward the center of the gain distribution (toward A) from position B, the number density and the gain are higher than they are on the opposite side away from the center of the gain distribution. This results in a refractive index perturbation Δn with a sign such that the farther the mode is from the center of the initially symmetric gain profile the higher the refractive index difference becomes. The mode experiences a force that tends to move it toward the edge of the gain profile. Note also that this force is asymmetric with respect to the gain profile and thus that the tendency of the index guiding effect is always to move the mode away from the center position to an asymmetric position. (Thus Δn is odd in Δx and can have a linear term in Δx). Since this force is roughly proportional to the optical intensity (see Fig. 20c), one now has the primary ingredients for producing a kink. Gain guiding exists because of the parabolic property (curvature) of the gain profile, and its magnitude is relatively independent of the precise position or intensity of the filament $[\Delta g \sim -(\Delta x)^2]$. On the other hand, one has a destabilizing force caused by index guiding, which is proportional to the optical intensity($\Delta n \sim I\Delta x$). At small optical intensity, the mode is guided near the middle of the gain profile but, as the optical intensity increases, the filament moves significantly toward the side of the distribution. Detailed calculations of this effect are, of course, very complicated. But the important features for kink initiation seem to be available from this simple physical picture.* There is no doubt, for example, that the origins of kinks are electronic rather than (say) thermal, and that they are an intrinsic property of a well-fabricated structure. They are not caused by inadvertently present pumping nonuniformities, etc. Lasers even operate for a short period of time following the initiation of stimulated emission, and before spatial hole-burning can occur, in a symmetrically placed transverse mode.[106] This results in a leading edge "spike" in the optical output.[106] The mode distortion[65,66,70,72] related to kinks takes on the order of one nanosecond to occur.[106]

3.3 Structural variations to eliminate kinks

Qualitatively, it is important to understand that the dielectric constant perturbations caused by gain or index guiding are very small.[74] Thus, if one can produce a dielectric constant perturbation with a sign

* Discussions of these points with W. B. Joyce have been helpful and are gratefully acknowledged.

appropriate to guide the mode toward the center of the gain profile, this purposely introduced perturbation does not have to be very large to be effective. Many structures which accomplish such an increase in local dielectric constant have now appeared in the literature, and Fig. 21 is an aid for discussing several interesting examples. These examples have been chosen to allow illustration of the excellent electro-optic properties which good GaAs lasers possess as well as to show some different growth and fabrication techniques that are now available.

Figure 21a depicts a proton-bombarded-stripe laser, of which the oxide-stripe[77] and planar-stripe[78] lasers are close relatives. These relatively simple structures are fabricated in many laboratories throughout the world. They suffer dramatically from kinks, although possibly the proton-bombarded laser is more affected than the oxide-stripe laser. This has recently been attributed[79] to the strain fields inadvertently present when the window is opened in the oxide mask. The small strain present, by means of the photoelastic effect,[80] produces a real refractive index perturbation which is adequate to produce considerable mode guiding. Unfortunately, the strain field is also adequate to cause degradation problems in these devices, so that the use of the strain associated with oxide windows appears not to be an appropriate method for controlling the optical linearity.[79] As noted earlier, narrow-

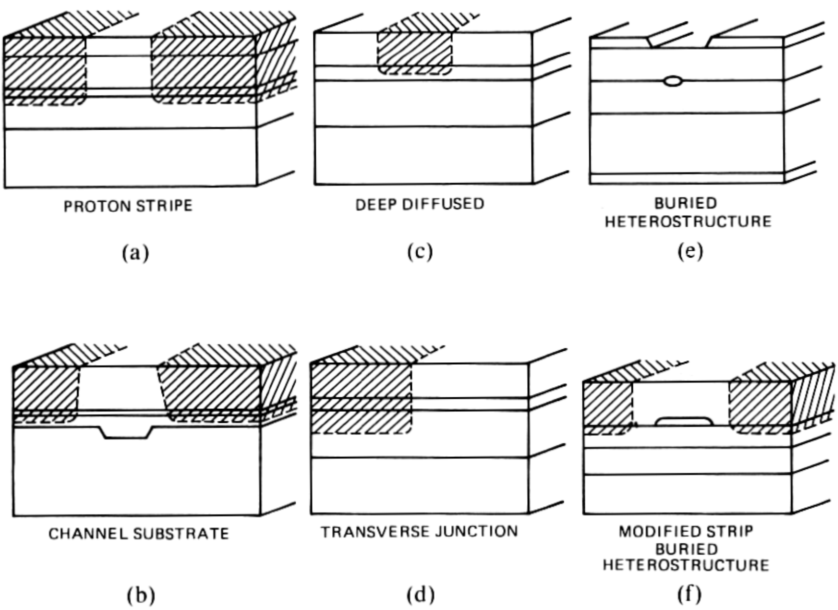


Fig. 21—Several double-heterostructure (DH) laser structures selected to illustrate the range of techniques available for controlling the lateral mode position, and thus for improving the above-threshold optical linearity, of lasers.

ing the stripe widths of these simple structures does force the kinks to occur at higher output power levels.[65] Thus appropriate adjustment of the gain or loss profiles can result in significantly more linear lasers. This is still an important concept because of the relative fabrication simplicity of these devices.

The channel substrate laser (Fig. 21b) is a structure[81] in which the average N-ternary layer thickness has been made thin enough that the fringing fields of the optical modes encounter the high loss of the substrate. Thus, when a channel is etched in the substrate and filled with wider bandgap ternary material, the optical mode occupies the channel preferentially. This laser has much improved linearity compared with structures which do not possess the channel and is also capable of optical output powers very much like the ordinary stripe geometry lasers. Since the channel in the substrate can be prepared ahead of time, this structure allows the epitaxial layers to be fabricated in one normal growth cycle. Etching and regrowth of the epitaxial layers are not necessary. A closely related structure, the terraced substrate laser, has been recently reported.[82]

Still another important structure (Fig. 21c) may be achieved by forming the stripe and p-n junction by acceptor diffusion (e.g., Zn) into n-type material which contains suitable heteroboundaries. This technique makes use of the slight refractive index increase due to the bandgap depression of the diffused material.[83] The depth and profile of the Zn-diffusion must be carefully controlled, but the structure has the advantage that the epitaxial layers may be grown in normal sequence.

Figure 21d illustrates the interesting and novel transverse-junction-stripe (TJS) laser.[84] This is a *homo*-junction laser in which the (Al,Ga)As heteroboundaries confine the current flow into a channel parallel to the junction plane. This has the advantage of automatically resulting in a small pumped active volume. Consequently, good mode control and low current thresholds result. The structure may also be produced in a junction-up planar configuration which lends itself to integration with other components on the same substrate,[85] which may be insulating if desired. The lifetimes recently reported in this structure[43] confirm that zinc diffusion is viable for long-lived-laser junction formation.

Another excellent technique for controlling the position of the lasing mode is, of course, the buried heterostructure (BH).[86] In this device (Fig. 21e), the cross-sectional area of the active volume is made small and is surrounded by GaAlAs. Since the refractive index of the active volume is substantially higher than the refractive index of the surrounding (Al,Ga)As, the optical mode is confined quite well. The troubles with this elegant structure are that it is difficult to fabricate and that its output power levels are low (about 1 mW/mirror face).

These difficulties arise from the necessity to avoid higher order lateral modes. Because of the large refractive index difference between the active volume and the surrounding cladding layers, the active volume must be made ~1 to 2 μm wide. This presents considerable technological challenge both in etching the narrow stripe and in regrowing the ternary layer over it. Because of the small area of the active-volume cross section, this laser structure inherently possesses low output power capability. For the same reason, however, and because lateral carrier diffusion losses are eliminated, it can make very efficient use of the injected carriers. Thus, lasers of this type have been made with room temperature thresholds below 10 mA, the lowest values yet achieved.

An important modification of the buried heterostructure is shown in Fig. 21f. It is related to the strip-buried-heterostructure,[87,88] and is called the modified-strip-buried heterostructure (MSBH).[89] It differs from the BH laser most fundamentally in that a higher refractive index guiding layer has been added below the active volume in this device.[87-89] The active volume is still made in such a way that it confines carriers laterally, but the optical field is allowed to leak substantially into this guiding layer, analogously to a strip-loaded waveguide. This is important because it relaxes the tolerances on the lateral dimension of the active volume compared to the BH laser. It, in fact, allows an active volume lateral dimension of the order of 4 or 5 μm while still maintaining lowest-order, transverse, optical-mode operation.

Figure 22 schematically shows the MSBH crystal growth structure as well as a scanning electron micrograph of a cleaved mirror facet of such a laser. As indicated, the difference in aluminum concentration between the active volume and the guiding layer is about 12 percent (there is 3 percent aluminum in the active volume). Figure 23 shows the dc optical output as a function of current from each mirror of a typical MSBH laser and illustrates the fact that the optical outputs of the two mirrors are virtually indistinguishable. The first and second voltage derivatives with respect to current are also shown in Fig. 23. Such derivative techniques[90,91] have been very useful in understanding the properties of GaAs lasers. The first voltage derivative of this device shows very good voltage saturation at threshold. The second derivative, the dashed line, shows the strong peak which is characteristic of the transition region between the spontaneous-emission-dominated regime below threshold and the stimulated-emission-dominated regime above threshold. This may be thought of as a phase transition if one wishes.[90] It is worth emphasizing that with voltage derivative techniques one has the ability to sense, via measurements made only at the external circuit terminals, the internal lasing properties of the device. Measurements of lasing threshold, of high current device

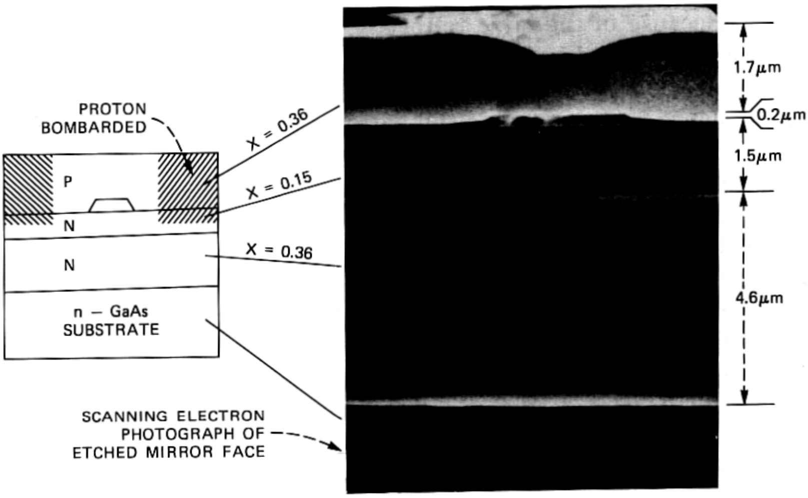


Fig. 22—Schematic diagram of a modified-stripe buried heterostructure (MSBH) laser (left) and a scanning electron photomicrograph of the mirror face of an actual MSBH laser (right). The active volume of this device contained about 3 percent aluminum (see Ref. 89).

impedance, and of the loss of saturation associated with kinks, for example, are easily made using these techniques.[90,91] In Fig. 23 it is noteworthy that above threshold the second derivative is essentially constant. This is indicative of a more uniform saturation and pinning of the quasi-Fermi levels than exists in normal proton-delineated lasers.[92] We see later that pulsations in these lasers may also be sensed from this second derivative.

The MSBH lasers not only possess good optical linearity, but because of the relatively large cross-sectional area occupied by the optical fields it can also deliver several tens of milliwatts of cw power from each facet. Usually the optical emission is predominately confined to a single longitudinal mode, although proportionately more optical power is found in adjacent modes near threshold. The fact that these lasers have relatively narrow angular intensity distributions and do not possess the astigmatism[93] characteristic of the standard proton-bombarded and oxide-stripe lasers is also important. Thus MSBH optical beams may be focused to the diffraction limit with ordinary spherical optics. These lasers are therefore preferred not only where fiber-coupling efficiency is important but also where small focused spots are desired; for example, in micrographics and video disk information, recording, and retrieval systems.[72]

Another property of the MSBH laser is illustrated in Fig. 24, namely, the ability to produce a passive mirror modification of the structure.[89] Here the growth of the active volume has been segmented in such a way that the active volume does not intersect the surface of the semiconductor. Thus, the darkening near the mirrors of the photographs shown in Fig. 24 is not caused by nonradiative recombination within the active volume but rather by the fact that the region between the bright spontaneous emission and the mirror is occupied by transparent AlGaAs. It is presumed that the influence of the surface and interactions of the photon field with the surface can be greatly diminished in such a device. It should thus be of interest in reliability studies. An analogous structure has been fabricated using the deep, diffused technology previously mentioned, although its threshold current densities were quite high.[94]

3.4 Summary of optical linearity discussion

A summary of the present status of research into the problems of optical nonlinearities in GaAs lasers follows. First, it appears that the physical stabilization of the lowest-order lasing mode in the cavity is the key concept, and that once this is accomplished the laser will be significantly more linear. Second, the fundamental origins of kinks are now reasonably well understood although detailed calculations in each of the several structures are difficult and remain to be carried out.

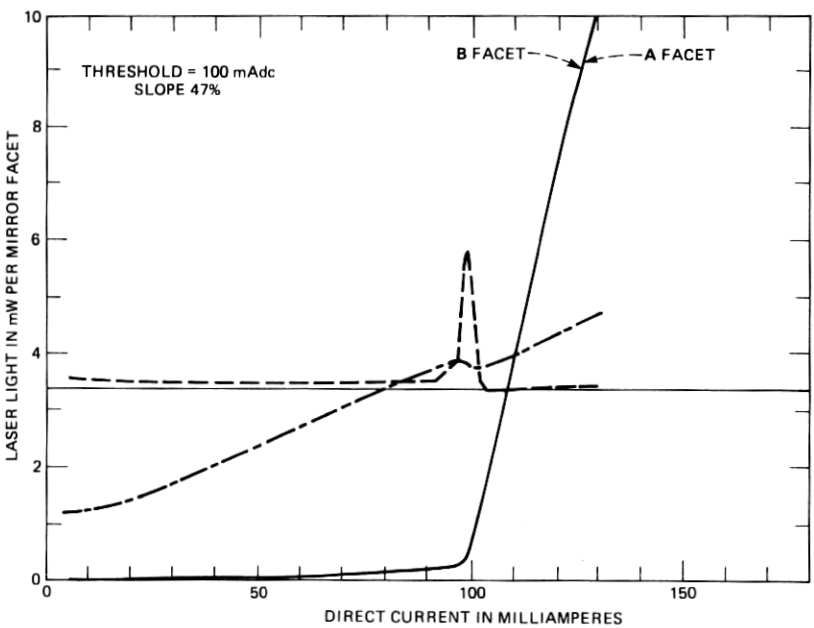


Fig. 23—Typical light-current-voltage characteristics of an MSBH laser. Note the linear, symmetric light output above threshold. Note also the nearly ideal first (dot-dashed) and second (dashed) voltage derivatives with respect to current (Refs. 90 and 91). See Ref. 89.

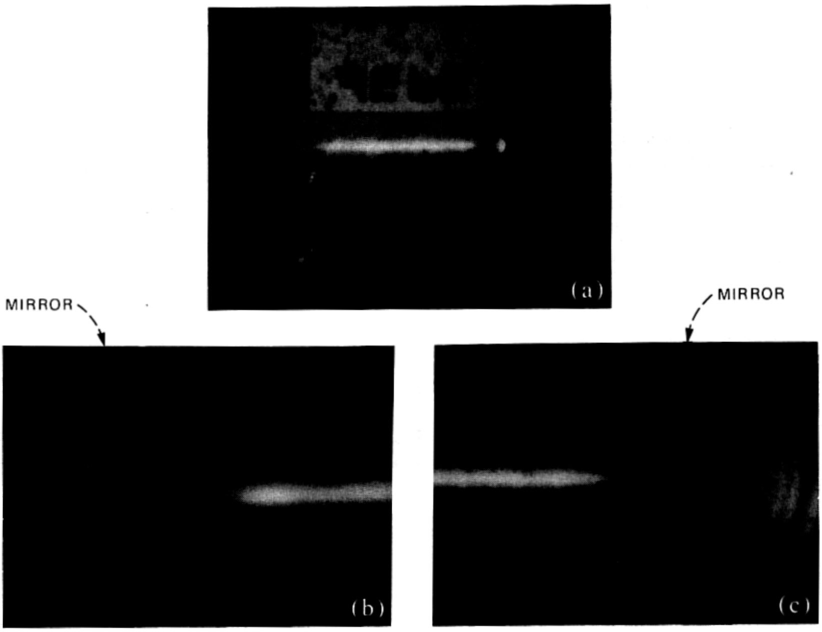


Fig. 24—Photographs of a passive-mirror MSBH laser. The active volume of these lasers does not extend to the mirror surfaces.

Third, many mode-guiding structures exist which control the position of the mode adequately. Thus, the problem is not necessarily to invent a structure which will control the mode but rather to produce a mode-controlling structure which can be made easily. That is to say, all the structures with which the author is familiar are difficult to make well; thus there remains the challenge of producing lasers with good optical linearity compatibly with high fabrication yield, long life, etc.

IV. TEMPORAL STABILITY

The final injection laser problem area (see Fig. 1) discussed in this paper concerns the well-known tendency of these devices to produce nonconstant-amplitude steady-state optical outputs, even when the device current is not purposely modulated. The author feels that significantly increased understanding of this previously very puzzling phenomenon has been recently achieved, and that its fundamental causes are now rapidly emerging.

The optical output of a self-oscillating laser may be nominally constant, but with a small-amplitude high-frequency component, or the pulsations may be "well-developed." In Fig. 25c, for example, the latter case is illustrated for the output of a proton-stripe laser. The pulse repetition frequency in this example is about 500 MHz, although values between 200 and 2000 MHz are typical. The particular pulse sequence shown consists of pulses with instrument limited rise times of less than 200 ps (Fig. 25d). Pulses as short as 5 ps have been measured in similar lasers using other techniques.[95]

A considerable complication in the study of the pulsation phenomenon results from the fact that self-induced pulsations in these lasers can become apparent after relatively small amounts of aging even though the devices originally did not self-oscillate.[96–98] Figures 25a and 25b show an example before and after only 50 hours of 70°C accelerated aging.[98] Thus, it is not sufficient to produce a structure or a laser which is pulsation-free as tested initially. It is also important to understand the influences which can initiate self-oscillation after operation but produce relatively little change in the other properties of the device.

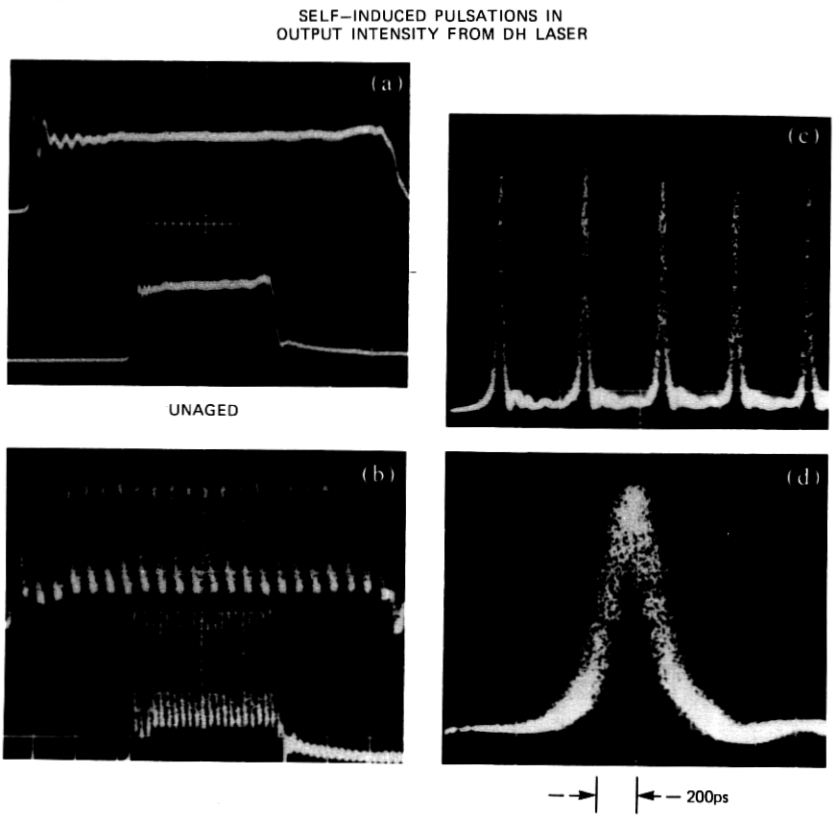


Fig. 25—Several properties of well-developed self-oscillations in GaAs lasers. The right-hand side shows pulses from such a laser with a pulse repetition frequency of about 500 MHz and an instrument limited pulse width of about 250 ps. The left-hand side illustrates the development, at 2 and 5 ns/div, of self-oscillation in a dc-excited laser after only 50 hours of aging at 70°C (see Ref. 98).

The properties of pulsations in GaAs lasers have been studied extensively, both experimentally and theoretically, for more than 10 years.[99-101] This considerable literature will not be reviewed here, although the references given provide access to it. Rather, an attempt will be made here to concentrate on relatively new work which the author believes is capable of best explaining the known facts about laser self-oscillations.

4.1 A phenomenological model

A recently devised model[102] is central to this explanation and may be understood with the aid of Fig. 26. The model relies on the presence of near-band-edge absorption at the lasing wavelength in the vicinity of regions of carrier depletion. Such regions may occur either near defects in the interior active volume or near the laser surfaces. The surfaces, being ubiquitous to present lasers, are particularly relevant for attention. This model is a saturable absorber[103,104] model, but it does not rely on the nonlinear properties of traps.[104,105] It would be an understatement to say that observation of these postulated traps has been elusive.[101] Increased absorption near regions of carrier depression is, conversely, expected to be normally present in lasers.

The second property that one needs in this model is shown in Fig. 27. For purposes of discussion, imagine the laser separated into two regions. We call one region the "end" region and the other the "bulk" region, even though the former may sometimes be interior to the

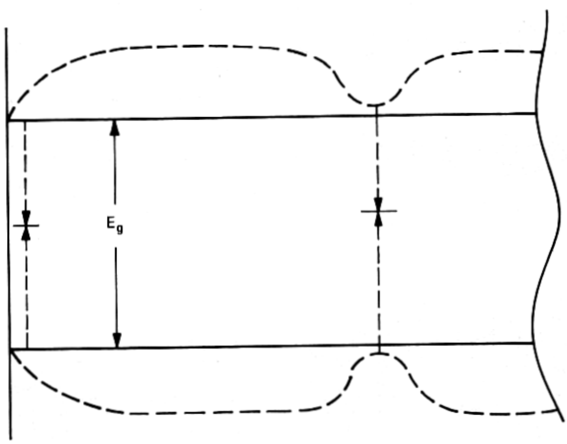


Fig. 26—The possibility of increased near-band-edge absorption near regions of depressed carrier concentration in semiconductor lasers. These regions can occur at the ends of the laser where surface or impurity-related recombination reduces the injected-carrier density, at interior defects which cause carrier recombination within the active volume, and possibly at the sides of the active volume. A portion of this absorption can be saturated by the optical fields (see Ref. 102).

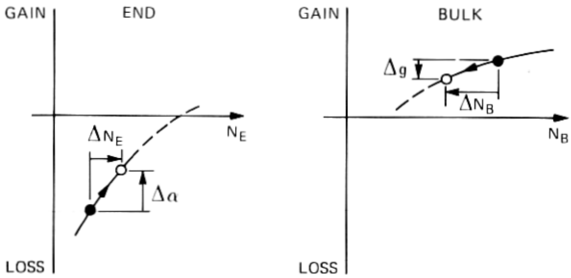


Fig. 27—A schematic illustration of the gain-loss function which the model of Ref. 102 assumes to be sufficient to cause pulsations in GaAs lasers in the well-developed limit. The laser is initially operating at the points indicated by the solid dots. If an infinitesimal change in operating point to the location given by the open dots results in a sufficiently large ratio $|\Delta\alpha/\Delta g|$, the laser will emit an optical pulse.

device. In the bulk region, one has a gain vs carrier concentration relationship which is locally characterized by a slope dg_B/dn_B, and similarly in the end region one has an absorptivity vs carrier concentration relationship which is locally characterized by a slope $d\alpha_E/dn_E$. A clearly sufficient way for this model to be applicable is that the slope in the gain region be adequately smaller than the slope in the end region. It should be noted that this does not necessarily require that the bulk region $g(n)$ relation be nonlinear. It is sufficient that the analogous relationship in the localized end region have a different slope. This may be due to defects, impurities, local heating, etc., in addition to any intrinsic gain nonlinearity which exists.

If these two properties are available in the laser, one can describe the pulsation phenomenon, in the well-developed limit, by the following argument. A pulse is initiated when stimulated emission begins in the bulk region. Photons are transferred by the simulated emission from the bulk region to the end region where they are absorbed. This results in a decrease in the total cavity loss which is larger than the decrease in the gain which created the photons. The latter is the instability sufficient to produce an oscillation. Consistent with experiment,[106] this explanation does not require lateral spatial nonuniformity to produce self-oscillations.

This pulsation model, when expressed in analytic terms, contains parameters which phenomenologically describe semiconductor laser operation.[102] Thus, it is possible to explore, using this model, the parametric dependences of the criterion for instability. It is also possible to explore questions such as the pulsation frequency dependence on device current. A typical result for the latter is shown in Fig. 28 for the well-developed pulsation case. There is considerable dependence of the pulse repetition frequency on current overdrive in this limit, but it is different from that anticipated in the small-signal limit.

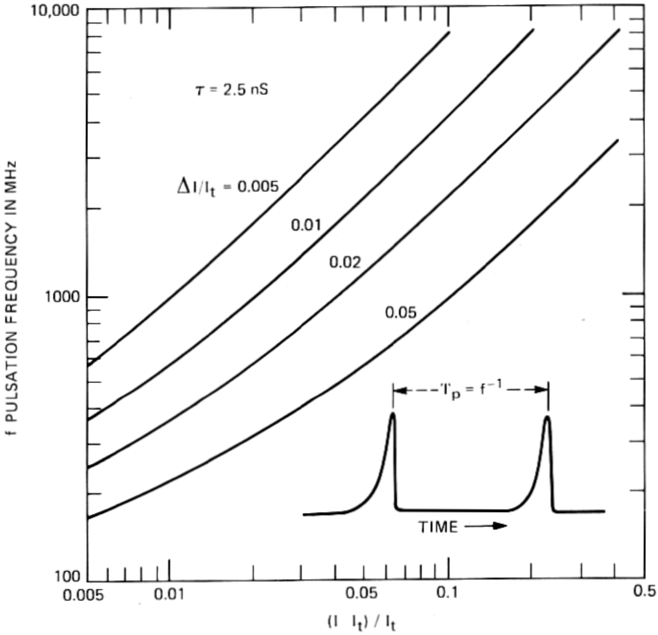


Fig. 28—The predicted pulse repetition frequency of a laser as a function of the fraction by which the laser drive current exceeds the current threshold. The parameter ΔI is the threshold difference between that of the real laser and the threshold it would have if the saturable absorber remained saturated. A near-threshold bulk carrier lifetime of 2.5 ns was used in constructing the figure (see Ref. 102).

The frequency dependence is controlled by the time it takes for carriers to refill the bulk region, following a pulse, to a gain sufficient to initiate the pulsation process again.

An important aspect of this model is the sensitivity of the instability criterion to values of the end-region laser parameters. Figure 29 gives an example of this dependence. Consider the case in which the optical absorptivity near the laser's end may be characterized at lasing threshold by a value of 200 cm^{-1}, a distance 4.75 μm, and where no extra scattering loss exists in the laser ($\alpha_s = 0$). In this case, the laser output will be temporally unstable if the slope ratio $|d\alpha_E/dg_B|$ is greater than 7, a rather substantial value. If, however, the end region absorptivity were to increase to a value of 2000 cm^{-1}, the instability criterion would be satisfied for a slope ratio of about 1.7, a substantially smaller value. We believe that such changes which increase the end region absorptivity can occur, especially during the first several hundred hours of laser operation, due to chemical and photochemical reactions at the active volume-air interface. We also believe that changes in the optical absorptivity can occur because of thermal changes in the laser.[107] This is illustrated by the abscissa of Fig. 29 which is marked in °C. Using literature absorptivities as a function of energy[108] and the well-known change in band gap with temperature, this abscissa gives the temperatures necessary to raise an initial 200 cm^{-1} absorptivity to the values indicated. For example, if the localized region is 50°C hotter than the bulk region of the device, its absorptivity is nominally 2000 instead of 200 cm^{-1}. The author believes it is plausible that such absorptivity increases can account for the often-observed tendency of initially stable lasers to develop self-oscillations after small amounts of aging.

These ideas have been quantified using a rate equation approach in which a common photon field interacts with separate end and bulk regions.[102,109] A computer-generated solution[109] of these equations is shown in Fig. 30, with parameter values again chosen to place the solutions in the well-developed pulsation region. Figure 30b shows the optical intensity as a function of time for a pulse repetition frequency

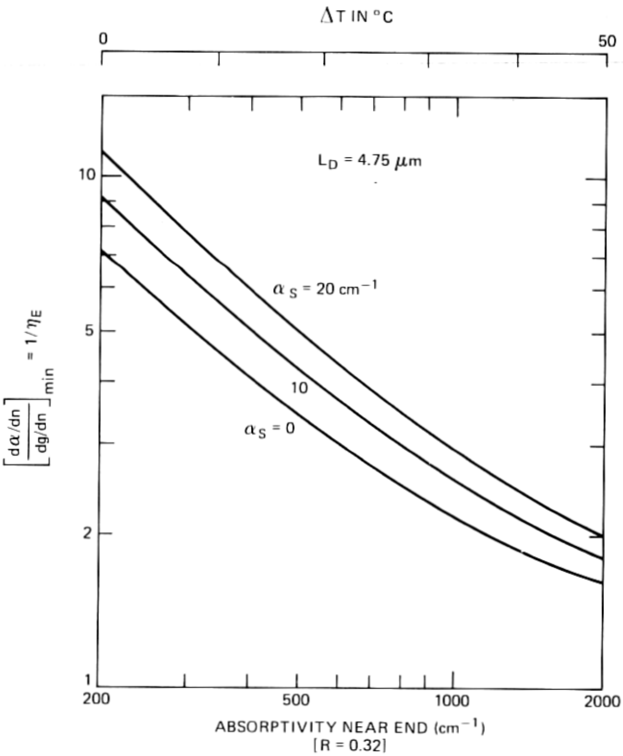


Fig. 29—The minimum ratio of $|(d\alpha/dn_E)/(dg/dn_B)|$ necessary to satisfy the instability criterion for producing well-developed pulsations modeled as a function of the average absorptivity within a distance 4.75 μm of the end of the laser. The upper abscissa shows the approximate temperature rise necessary to increase an intrinsic 200 cm^{-1} band-edge absorptivity to the values indicated. A local temperature rise of 50°C increases this absorptivity to 2000 cm^{-1} (see Ref. 102).

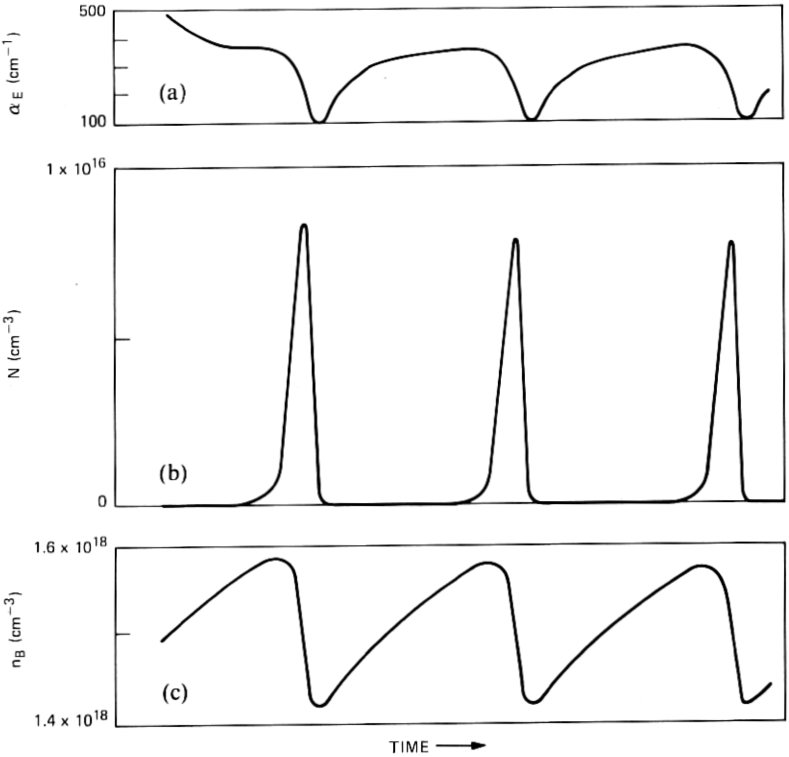


Fig. 30—Pulsations in a GaAs laser generated by integrating the equations of Ref. 102 on a computer. (a) The end region absorptivity. (b) The pulsating optical intensity (at a repetition frequency of about 500 MHz for the parameters chosen). (c) The bulk region carrier concentration.

near 500 MHz. Figure 30a shows the end region absorptivity as the device pulses. Between pulses, the absorptivity builds up to a value of about 350 cm^{-1} in this example, but during the pulse it is driven down to a value of about 90 cm^{-1} by photon absorption from the increasing optical field. Figure 30c shows that in the bulk region, the region which supplies the laser gain, the carriers build up between pulses but that the carrier density is then rapidly depleted by the stimulated optical emission. In this example, the bulk carrier density modulation is slightly more than 10 percent, but more typically it is a few percent.

4.2 Recent self-oscillation experiments

Several recent experiments have provided new insight into the injection-laser pulsation problem and into the possible relevance of the pulsation model described above. Figure 31 shows pulsation behavior from lasers investigated in the first of these experiments.[110] This figure shows the optical output of two lasers, A and B, following pulsed excitation of a rather special sort. Two current pulses, one a long 15-μs pulse with an amplitude just below lasing threshold, the other a short 20-ns with an amplitude large enough to carry the laser above threshold, were applied to the devices. The long pulse was initiated first, with the short pulse delayed by a time T_d. With $T_d = 0$ (both pulses simultaneously initiated), the optical output of laser A in Fig. 31 consisted of a relaxation oscillation which died out in a few nano-seconds. The laser did not self-oscillate. When the time delay T_d was increased to 11 μs, the leading edge ringing was substantially increased in both amplitude and duration but still the laser did not self-oscillate. This contrasted with the situation in laser B. In this case, with $T_d = 0$ a leading edge ringing was seen as before. But with the 11-μs time delay, the device exhibited a well-developed self-oscillation. Obviously, the relaxation oscillations and self-oscillations are closely related in these lasers.

Two other important inferences are possible from these experiments.[110] First, we interpret the dc bias dependence of the oscillation as being of thermal origin. That is, when the laser has a current prebias

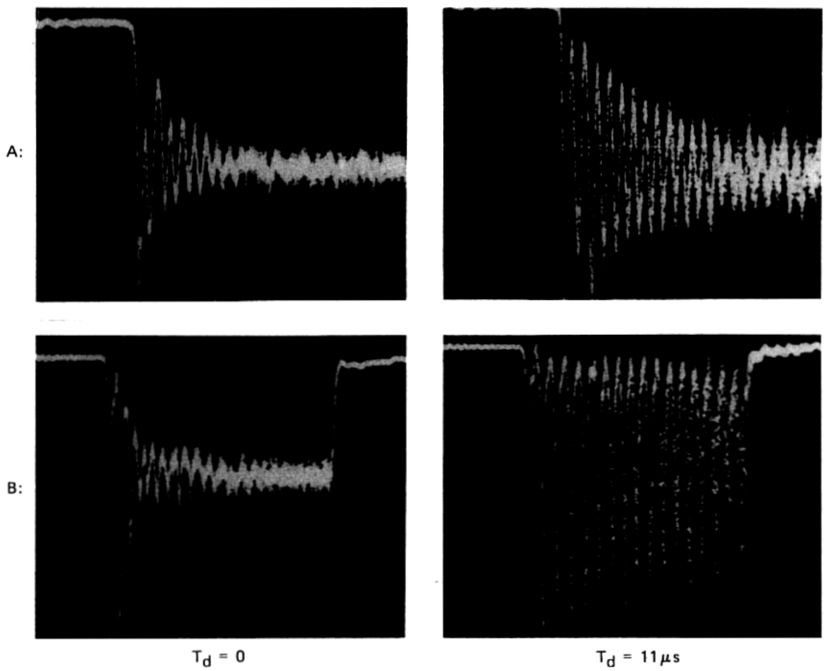


Fig. 31—Self-oscillations and relaxation oscillations in two GaAs lasers (A and B) illustrate current-bias dependences. The effects have been interpreted as suggesting the existence of localized regions of increased temperature in lasers which have a cw component in their current biases (see Ref. 110).

and is then pulsed above threshold, the temperature changes resulting from the existence of the prebias make the laser more susceptible to self-oscillation. Unfortunately, operation with a dc prebias is the normal mode of operation in lasers intended for telecommunications applications. The second inference from these experiments is that the mechanisms causing the self-oscillations are localized in the laser. The thermal changes mentioned could not be duplicated by simply changing the stud temperature of the laser. Thus, it was concluded that the temperature changes involved were nonuniform in the laser structure, consistent with those which might occur near the laser ends or at internal defects, as in the self-oscillation model just discussed.

A second relevant experiment[111] involved the MSBH lasers[89] previously discussed. A set of these was available which had windows in the n-side metallization through which the stripe of the laser could be viewed. In the upper part of Fig. 32, optical photomicrographs of two such lasers are shown. The spontaneous emission from these lasers appears to be quite uniform. In the lower part of the figure, the active volume of a pulsing laser is shown in two magnifications. The impor-

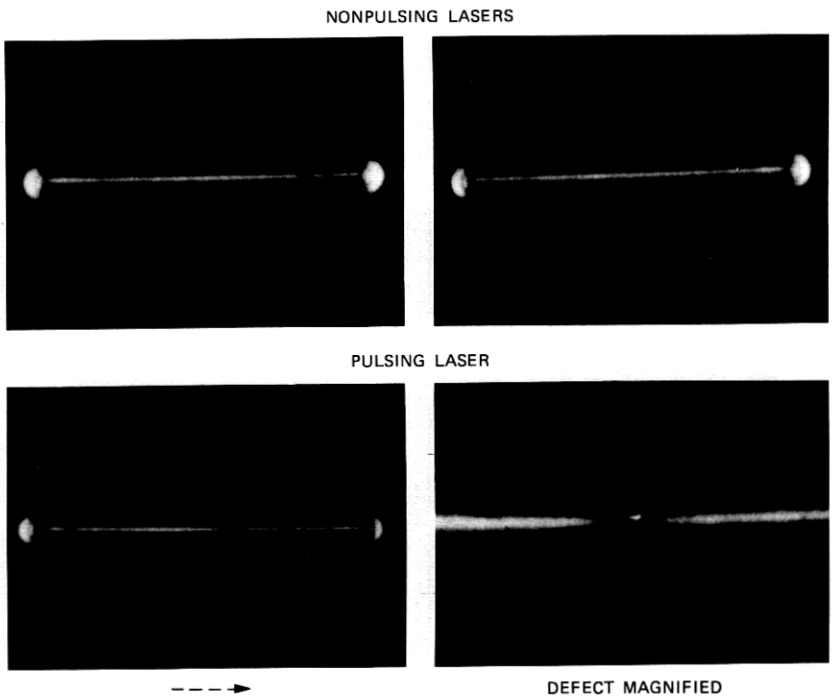
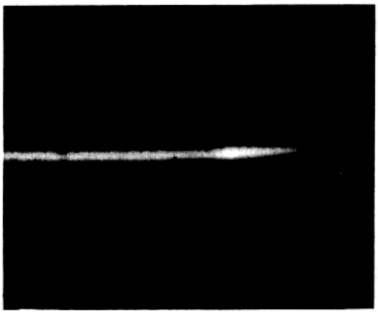


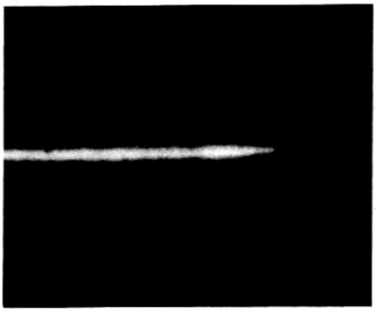
Fig. 32—Photographs of the electroluminescence from the substrate of pulsing and nonpulsing MSBH lasers. The lower-right photograph shows the grown-in defect which is assumed to be responsible for the self-oscillations in the light output of the lower laser (see Ref. 111).

tant point is the defect which is visible near the middle of the active structure. This defect is thought to be associated with the presence of pulsations in this laser. Forty-seven such lasers were examined. Eighteen of them pulsed as initially operated, and all 18 possessed visible defects within the active volume. Twenty-nine other lasers did not pulse initially and only one of these showed a visible defect, although four others could not be adequately photographed. The author feels that this establishes an important empirical correlation between the presence of active layer defects and the presence of pulsations in this structure. In addition, some lasers that did not pulse initially were aged at 70°C for 50 hours. The results depicted in Fig. 33 are typical of those devices from this group which developed pulsations after aging. As can be seen in the lower photomicrograph, a darkening near the mirrors has resulted from the aging process, and this correlates well with the presence of self-oscillation in these devices.[111] It is also interesting that the second voltage derivatives[90] of those lasers which pulsed in this experiment showed departures from constant above-threshold values[111] (see Fig. 23). Thus, the derivative technique shows promise for providing a simple, low-frequency, nonoptical, screening method for pulsations in these lasers.

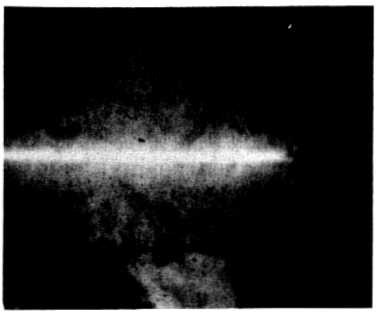
Figure 34 depicts the results of still another relevant experiment.[112] In this experiment, a slice of lasers was fabricated and the slice divided into two parts. In one part, the lasers were fabricated normally, but in the other part the mirrors were coated with Al_2O_3 quickly after cleaving. The idea was to test whether or not coating the mirror surfaces at an early stage of fabrication could inhibit the change in surface recombination or absorption which we had anticipated would be associated with the initiation or with the increase in the amplitude of self-oscillations. The upper curve in Fig. 34 shows the average operating current in the nine lasers which were not coated, as they were aged at constant light output at 70°C. The error bars show one standard deviation. The operating currents were automatically adjusted to maintain 5 mW of optical output from the lasers. The current increase depicted illustrates what we have called the saturable mode of laser degradation which is quite commonly observed during the initial periods of aging.[27] Note that the first ~7 mA of operating current increase occurs quickly after the laser is switched on after coming to thermal equilibrium at 70°C. The increase is due to the 10 to 15°C further temperature increase of the active volume as the device comes into initial operation.[8] The lower curve in Fig. 34 shows the analogous results which occurred in the seven lasers which had $\lambda/2$ Al_2O_3 mirror coatings on both facets. The saturable increase in operating current has been eliminated by the mirror coatings, as was apparently done previously by others.[29,30] The mirror coating has thus been shown to have an important influence on early changes in the operating current



LASER BEFORE PULSATIONS DEVELOP



LASER AFTER PULSATIONS DEVELOP



DOUBLE EXPOSURE

Fig. 33—Photographs of the electroluminescent emission from the substrate of an MSBH laser before and after it developed self-oscillations. No defects were visible in the interior of the laser, but note the darkening near the mirror which developed in the pulsing laser (see Ref. 111).

of the device and on early device degradation. As previously stated, we do not believe that these operating current increases are terribly important in determining the ultimate lifetime of devices of this type.[27] Attention here is focused rather on the idea that it may be important in determining the pulsation behavior of the devices.

To emphasize this connection, consider the results shown in Fig.

35.[112] Here the room temperature depth of modulation of the (*not*-well-developed) self-oscillations in these same devices is shown as a function of aging time in a clean, dry 70°C nitrogen ambient. As can be seen, the uncoated lasers began with a maximum depth of modulation of about 30 percent. This was the maximum modulation depth which could be obtained for any current at which the optical output was below 10 mW/mirror face. This modulation depth increased significantly as the devices were operated, typical of the usual tendency which exists in GaAs lasers.[98] This behavior should be contrasted with that of the lasers shown in Fig. 35 which had the Al_2O_3 mirror coatings. The latter lasers also initially possessed modulation depths near 30 percent, but in these devices the modulation depth did *not* increase significantly, nor did the oscillation frequency decrease, with aging.[112] The author believes that this result shows conclusively that self-oscillations *can* be associated with near-mirror effects. These results also give hope that by using proper mirror coatings it may be possible to stabilize the pulsation properties of lasers or even to eliminate the mirror-associated pulsations completely.

In any case, the new pulsation model[102] and the several experiments

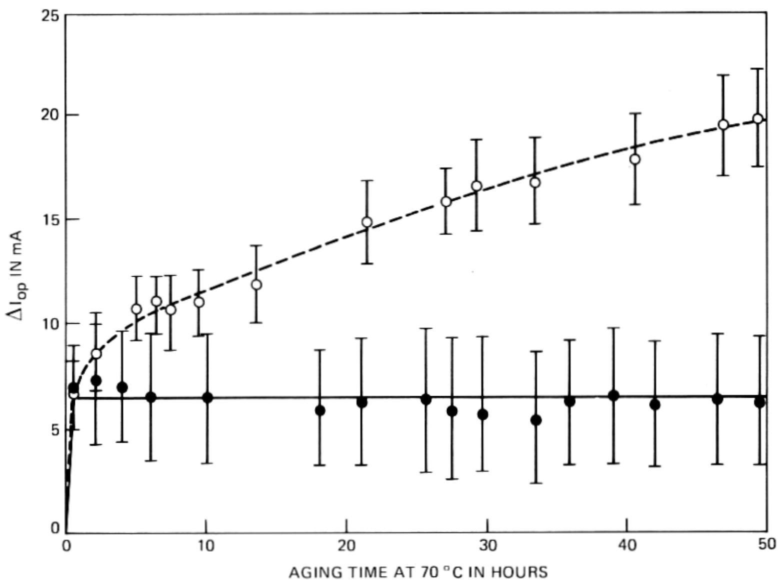


Fig. 34—The average increase in operating current (the error bars show one standard deviation) required to maintain 3 mW/mirror optical output in a 70°C dry-nitrogen ambient is plotted vs time for nine uncoated (open circles, dashed curve) and seven $(\lambda/2) - Al_2O_3$ facet coated (filled circles, solid curve) DH lasers. The initial rapid increase in operating current is due to heating when the devices are first turned on following thermal equilibration at 70°C. These results definitively show that the saturable-mode of degradation is a surface-related effect (see Ref. 112).

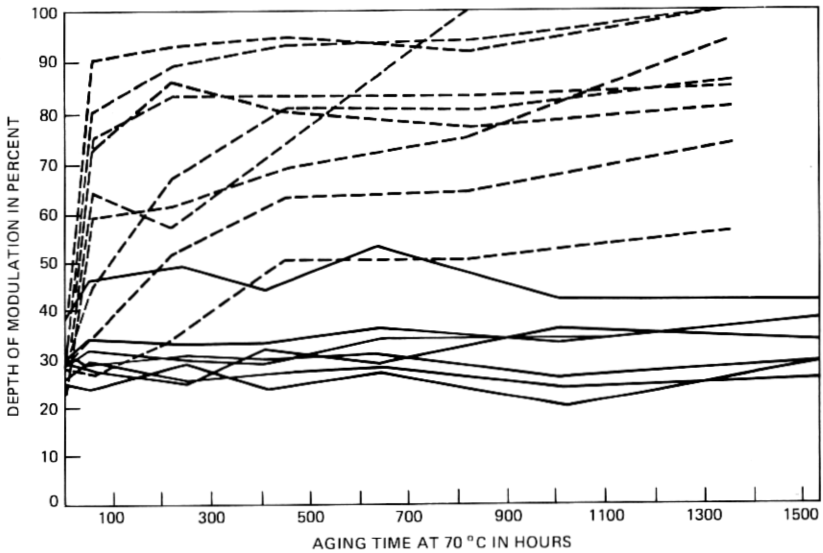


Fig. 35—The depths of modulation of the lasers depicted in Fig. 34 (dashed curves are uncoated, solid curves are Al_2O_3 coated) are plotted vs time of cw operation in a 70°C dry nitrogen ambient (see Ref. 112).

described[110-112] have certainly generated hope that a fundamental understanding of the origins of self-oscillations can be attained and have given this area of current applied laser research a good deal of momentum. This is useful even if some of the details of the model, for example, ultimately turn out to be incorrect. It is also anticipated that many of these concepts will be applicable to other injection lasers, such as those based on InP which are now being investigated for longer wavelength operation.

V. SYNOPSIS

No aspect of current laser research is more important than the identification of an appropriate structure (see Fig. 1 again). This structure must not only allow the laser to operate with reliability, with optical linearity, and with temporal stability, but it must also be easy to make. The last is a considerable challenge.

With regard to laser reliability, it is important to note the good progress which has been made in recent years culminating in the achievement of a million-hour-extrapolated room-temperature mean-time-to-failure. Several different areas in which the search for further improvements continues have been mentioned. These include facets, interfaces, and the physics of recombination-aided defect migration. Means for obtaining further improvements include optimization of each of the many fabrication steps, including mirror coatings. Sample annealing and p-surface anodization were mentioned as two possibly important areas through which further reliability improvements can be found.

With respect to optical linearity, it is now well understood that the spatial position of the mode in a GaAs laser should be stabilized, and that once this is accomplished, the optical linearity is much improved. Fortunately, many structures now exist which adequately accomplish mode stabilization, but it is difficult to choose from among them that structure which is optimum from the viewpoint of ease of fabrication and long laser life. A considerable effort is still being expended in attempting to define this optimum structure.

Pulsations in semiconductor lasers has been a subject of considerable interest for many years. The recent model which has been discussed above appears to be the first that contains the ingredients of a solution to this problem. The model relies on near-band-edge absorption, particularly absorption near regions of carrier depression such as those associated with laser ends and with defects. Recent pulsation experiments are generally consistent with this model, but it still needs further corroboration and exploitation. Even if the pulsation problem has been understood in essence using this model, a great deal of work remains to explore its parameter dependences and to decide which of the many structures available will be the most pulsation-resistant.

VI. ACKNOWLEDGMENTS

The work discussed in this paper would not have been possible without the active collaboration of many people. The author would particularly like to mention the efforts of H. R. Beurrier, R. L. Hartman, W. B. Joyce, R. C. Miller, F. R. Nash, and T. L. Paoli. It is also important to acknowledge the active support of the semiconductor laser materials and processing groups under the able leadership of N. E. Schumaker and B. Schwartz.

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