Ultra-reliable AlGaInAs Diode Laser Technology Impacts the Industrial Laser Marketplace

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During the 1990's, AlGaInAs diode lasers advanced at an astounding rate driven by high R&D investment in single-mode 980nm pump lasers. Telecom-class diode laser manufacturers are applying the same advances to non-telecom applications. This white paper surveys AlGaInAs single- and multi-mode industrial laser applications ranging from 800-1000nm with a focus on highly reliable, high output power diode technology.

Overview of AlGaInAs Diode Laser Reliability

Diode lasers may exhibit both sudden (infant or random failure regimes) and gradual degradation (wear-out regime).

1. Infant failure regime

Infant failures arise from an intrinsic semiconductor defect or damage/imperfections introduced during device fabrication. A rigorous burn-in (high drive current, high temperature) screens out infant failures. Only a robust laser technology can be effectively screened since the high overstress required to eliminate diodes subject to early failure within a reasonable burn-in time must not introduce new failure mechanisms.

2. Constant random failure rate regime

Sudden failures due to randomly dispersed epitaxial defects are the predominant failure mode in this regime. The AlGaInAs random failure rate is accelerated by temperature, optical output power and drive current, generally following Eq. (1),

$$F(T_j, P, I) = F_{op} \bullet \exp\left(-\frac{E_A}{k_B}\left(\frac{1}{T_j} - \frac{1}{T_{op}}\right)\right) \bullet \left(\frac{P}{P_{op}}\right)^n \bullet \left(\frac{I}{I_{op}}\right)^m \qquad (1)$$

where T_j is the diode laser junction temperature, P is the diode laser output power, I is the diode laser drive current and k_B is the Boltzmann constant. The Arrhenius factor (E_A), exponential acceleration factors (m, n) and proportionality constant (F_{op}) are fitted by measuring device failure rates under various temperature and current accelerations. Random failure rates are commonly quoted in FIT (failures in time). One FIT corresponds to a single device failure per 10^9 hours of deployment. One thousand FIT is a useful yardstick, equating to ~1% of the device population failing annually. The more intuitive mean-time-before-failure (MTBF) can be easily calculated from FIT rates.

3. Wear-out regime

The AlGaInAs-based lasers discussed below show negligible wear-out degradation except during extremely accelerated high current and/or high temperature operation.

Since infant failure and wear-out do not occur, the overall failure rate of diodes discussed in this article follows Eq. (1). AlGaInAs laser diode technologies tend to have E_A~0.45eV, or in other words, a failure rate roughly tripling each 20°C. On the other hand, the current and/or power accelerations (m, n) and proportionality factor vary widely depending on manufacturing processes, emission wavelength and device geometry.

Multi-mode 100µm Stripe Width 910-980nm Lasers

Multi-mode InGaAs quantum well (QW) diode lasers are mainly used to pump Yb-based fiber lasers (FL) for telecom and industrial applications. Medical and material processing constitute growing niches for direct and fiber-coupled InGaAs diodes due to their superior combination of high output power and brightness. Because they were developed for telecom, multi-mode InGaAs diode lasers are backed by extensive reliability testing across a wide range of operating temperatures and drive currents, as shown in Table 1.

100µm InGaAs QW Multi-Cell Lifetest Results

Cell #	Fixture Temp. (°C)	Junction Temp. (°C)	Power (W)	Current (A)	Number of Lasers	Hours	Device Hours	Failures
1	92	129	5.2	7	75	5000	3.6E+05	5
2	55	107	8.4	10	40	5000	1.7E+05	8
3	70	126	7.8	10	19	5000	8.9E+04	2
4	85	145	7.0	10	20	5010	9.2E+04	2
5	55	125	9.5	12	20	5000	5.5E+04	13
6	70	145	8.5	12	19	5000	5.4E+04	11
Total					**193**		**8.3E+05**	**41**

Table 1. Design and results of a multi-cell lifetest investigating the reliability of multi-mode 100µm stripe 915nm and 940nm InGaAs QW diode lasers.

The data from Table 1 yield a best fit to Eq. (1) for E_A=0.43 eV and m=0, n=5.7, which permits the failure rate calculation under various operating conditions summarized in Table 2. The model yields MTBF = 1.3×10^6 hours (60% statistical confidence) at the typical 6.5W, 25°C heatsink operating conditions. To our knowledge, JDSU's is the only broad-area diode laser technology to have undergone a multi-cell testing and demonstrated telecom-class million-hour reliability at high output power. Furthermore, the multi-cell methodology for reliability provides users with a complete model, permitting customers to model their own system reliability as a function of varying diode deployment conditions.

100µm InGaAs QW MTBF for Different Operating Conditions

Heatsink Temp (°C)	Power (W)	Median Time (Hours)	Median Time with 60% C.L. (Hours)	Cumulative Failures in 1 Year	Cumulative Failures in 5 Years	Cumulative Failures in 10 Years	Cumulative Failures in 25 Years
25	2.6	6.0E+08	3.0E+08	0.0%	0.0%	0.0%	0.0%
	5.2	9.1E+06	5.4E+06	0.0%	0.2%	0.7%	2.3%
	6.5	2.1E+06	1.3E+06	0.2%	1.9%	4.4%	11.2%
	8	5.3E+05	3.5E+05	1.4%	9.2%	16.8%	31.8%
35	2.6	3.2E+08	1.7E+08	0.0%	0.0%	0.0%	0.0%
	5.2	4.8E+06	3.0E+06	0.0%	0.6%	1.6%	5.0%
	6.5	1.1E+06	7.4E+05	0.5%	4.2%	8.7%	19.3%
	8	2.8E+05	1.9E+05	3.3%	16.2%	26.9%	45.0%
45	2.6	1.8E+08	9.8E+07	0.0%	0.0%	0.0%	0.0%
	5.2	2.6E+06	1.8E+06	0.1%	1.4%	3.5%	9.2%
	6.5	6.1E+05	4.3E+05	1.2%	8.0%	15.1%	29.3%
	8	1.5E+05	1.1E+05	6.5%	25.5%	38.7%	58.0%

Table 2. Summary of multi-cell lifetest results providing customers with a virtual user's manual of failure rates across a diverse range of deployment conditions.

Single-Mode 805-860nm Lasers

Single-mode diode lasers operating at center wavelength bands of 810nm, 830nm and 850nm are widely used for printing, metrology, inspection, and beam transmission (e.g. range-finding, illumination, targeting and free-space communications) applications. High performance AlGaAs or GaAs active emitting region diodes are considerably more challenging to fabricate than InGaAs QW lasers. Because the active region is unstrained, threshold current density in AlGaAs or GaAs emitters is higher. The higher photon energy is more likely to spontaneously create semiconductor lattice defects, while the larger bandgap of AlGaAs raises device series resistance. Despite these handicaps, reliable single-mode AlGaAs emitter diode lasers operating at 200^{+}mW can be fabricated.

Figure 1 plots the data of 810-850nm diode lasers investigated by step stress testing, a common technique to rapidly assess both device reliability and robustness. In this test the laser output is maintained at constant 150mW power while the diodes' heatsink temperatures are stepped up by 10°C at 200h intervals.

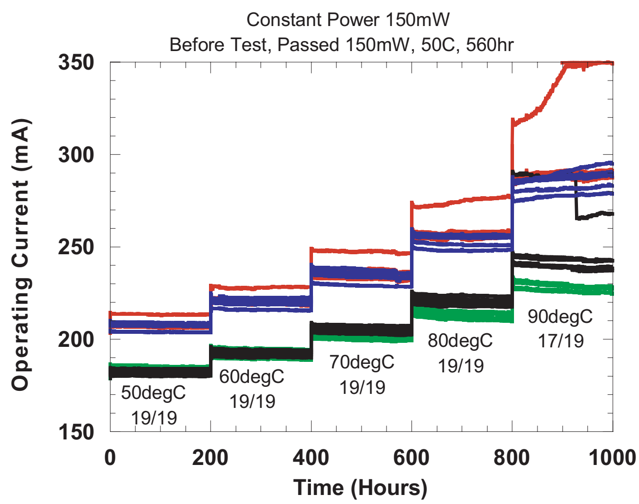

Fig. 1. Step stress test data on 810-850nm single-mode AlGaAs diode lasers (different colors represent different wafer material). Devices maintain 150mW operating power with no noticeable degradation to at least 70°C.

The conclusion of the step stress test is 150mW single-mode AlGaAs technology is extremely robust, showing no ill effects even when operated to a heatsink temperature of 70°C. The onset of rapid degradation by 90°C suggests the devices have entered a new operating regime, and would no longer follow a model based on Eq. (1). Their robustness permits an aggressive, but economical burn-in screening condition to insure all infant failures are extinguished before shipment.

An extensive test to establish reliability involved a total of 120 lasers run at constant current (~150mW), 60°C heatsink temperature for 1,500 hours. Zero failures and no noticeable wear-out were observed. Applying the E_A=0.45eV rule of thumb, each device hour at 60°C equates to just over six hours at 25°C. An analysis of these data yields predicted reliability at 150mW, 25°C of 810 FIT (60% confidence) or equivalently a $\geq 1.2 \times 10^6$ hours MTBF. If an application were to require higher reliability or different operating conditions, a more extensive multi-cell test could improve these statistically-limited values.

Multi-mode 808nm Pump Diodes

The 808nm pump wavelength has long been used for Nd:YAG diode-pumped solid state (DPSS) lasers. Like their InGaAs cousins, broad-area AlGaAs-based 808nm pumps are also increasingly used for medical and materials processing applications. Diode MTBF >10kh is preferred for solid state laser pumps; moreso when multiple pump diodes are required. Yet, the combination of the short wavelength and brightness (i.e., high power from a relatively small emitter area) challenges many 808nm vendors' device reliability.

Figure 2 plots accelerated lifetest data for twenty 100µm stripe 808nm lasers. After nearly a year of continuous operation, zero failures and negligible degradation are observed, from which a lower bound ≥175,000h MTBF at 1.2W, 25°C operation is deduced. Similar, but less extensive 808nm lifetest data exist for 100μm stripe lasers operated at 2.5W, 70°C, and 200μm 808nm stripe lasers at 3.5W, 60°C. In each case, a conservative lower bound of MTBF ≥100,000h at rated operating power, 25°C is established. Since DPSS and other 808nm applications have not yet gained an appreciation for the reliability demanded of applications involving multimode InGaAs, or even single-mode AlGaAs diodes, 808nm pump reliability has not yet been more comprehensively studied. JDSU will rectify this situation with the release during 2006 of a new class of 808nm diode laser which greatly raises the bar on both output power and demonstrated reliability.

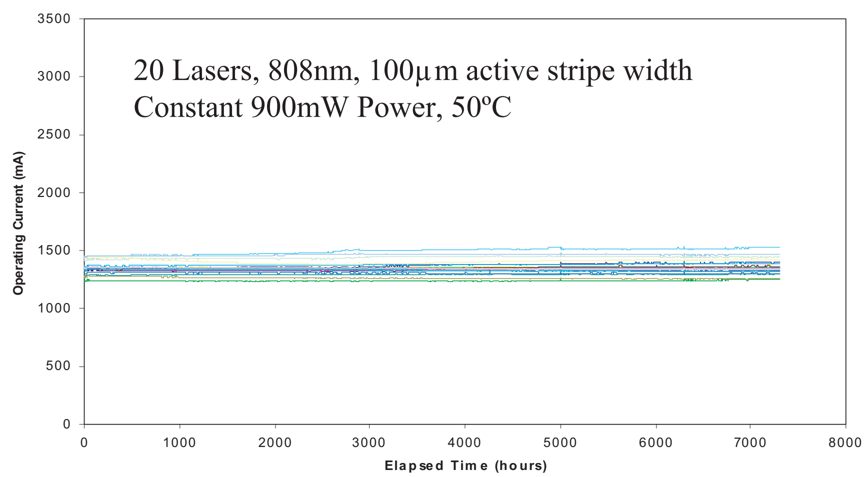

Fig. 2. Accelerated lifetest data for 100μm 808nm pump lasers showing negligible wear-out degradation and zero failures over 170,000 device hours. A conservative MTBF≥175,000h is estimated for normal rated 1.2W, 25°C operation.

Fiber-Coupled Multi-mode 830nm and 920/970nm Diodes

Many industrial customers prefer plug&play fiber-coupled diode laser solutions. For years the printing industry has consumed high-brightness 830nm fiber-coupled multi-mode diodes for high resolution "computer-to-plate" and other applications. High power FL manufacturers require reliable, low cost 920nm or 970nm pigtailed pumps, especially when FL output power in the 100^{+} Watt range is desired. Since expensive industrial systems can go down if only a couple of diodes fail, excellent reliability at low cost is demanded. Stacked semiconductor laser arrays (i.e. bars) have failed to meet the more stringent industrial reliability requirements of high power industrial laser systems. A new generation of super high power FL and DPSS solutions will rely on pigtailed single emitters to reach new performance levels at acceptable reliability.

Figure 3 illustrates the reliability of one diode laser variety used in low-cost, high brightness industrial pigtailed products. Zero failures and negligible degradation establish ≥900,000 hours MTBF for standard 1.4W, 25°C diode operation. A version of the standard package passed numerous telecom-inspired robustness tests including vibration, 100× -40°C-70°C temperature cycling, 80°C/110 day high temperature storage, damp heat 40°C/95% relative humidity/56 day storage and $10^6\times$ on/off power cycling testing. Many tens of thousands of devices continuously deployed since the 1990's strongly corroborate the individual results of outstanding diode reliability and package robustness established by the in-house testing. Similar 915/940nm 100µm fiber-coupled product rated for 6.5W operation is scheduled to be upgraded to 8W fiber-coupled output power during 2006.

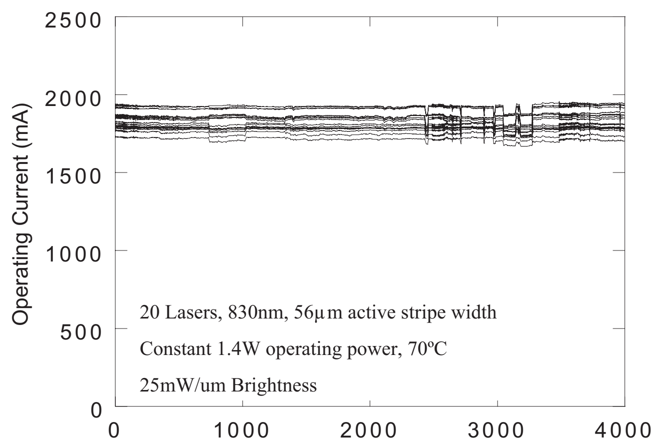

Fig. 3. Accelerated lifetest data for 56µm wide 830nm diode lasers used in a pigtailed industrial laser product. Negligible wear-out degradation and zero failures over 4000 hours establish a MTBF lower limit ≥900,000h at 1.4W, 25°C.

Conclusion

While diode laser development mainly targeted high dollar volume telecom applications, much of this technology is now available to cost-sensitive industrial applications. In fact, increasingly sophisticated industrial systems unable to afford significant downtime place a growing premium on diode reliability at an acceptable price point. The strict quality control and large production capacity of leading telecom diode laser manufacturers promise to fulfill these needs across a gamut of wavelengths and output powers.

JDSU alone is able to consistently demonstrate million hour MTBF's across a diverse product palate through a unique, rigorous and fully transparent reliability testing regime. Please contact us to discuss your diode laser applications.