The range of VCSEL wearout reliability acceleration behavior and its effects on applications

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ABSTRACT

For nearly twenty years most models of VCSEL wearout reliability have incorporated Arrhenius activation energy near 0.7 eV, usually with a modest current exponent in addition. As VCSEL production extends into more wavelength, power, and speed regimes new active regions, mirror designs, and growth conditions have become necessary. Even at more traditional VCSEL 850-nm wavelengths instances of very different reliability acceleration factors have arisen. In some cases these have profound effects on the expected reliability under normal use conditions, resulting in wearout lifetimes that can vary more than an order of magnitude. These differences enable the extension of VCSELs in communications applications to even greater speeds with reliability equal to or even greater than the previous lower-speed devices. This paper discusses some of the new applications, different wearout behaviors, and their implications in real-life operation. The effect of different acceleration behaviors on reliability testing is also addressed.

Keywords: VCSEL, vertical cavity surface emitting laser, reliability, InGaAs

1. INTRODUCTION

The reliability goal for a mature optoelectronic product is to have wearout irrelevant during the planned operating life, a goal difficult to achieve in an environment where the operating requirements double every few years. In this paper we describe reliability of a device designed for 14 Gbps operation, but there are implications for devices of the next generations as well.

It is a common complaint that certain knowledge about reliability is only available for parts that have actually failed. For all parts not yet failed one must rely on models and statistics, both of which may take many years and thousands—or even millions—of parts to generate for new technologies. This leads to a preferred conservatism: when an equation has been found to apply, we are reluctant to move to a different technology where its applicability is unknown, or to make modifications to model parameters for similar devices even in the face of substantial new data. Sometimes, however, there is no choice, because new operating requirements require new devices.

The acceleration factor of VCSEL failure rate at an operating condition relative to some reference condition is almost invariably described by the modified Arrhenius equation,

\[ AF = \left(\frac{I_{OP}}{I_{REF}}\right)^N \exp\left[\frac{E_a}{k} \left(\frac{1}{T_{REF}} - \frac{1}{T_{OP}}\right)\right] \]

where \( I \) and \( T \) are the current and the absolute temperature of the active region, \( k \) is Boltzmann’s constant, and \( E_a \) is an activation energy. The exponent \( N \) can take on any value. The combination of the power law with parameter \( N \) and the exponential term with parameter \( E_a \) allows modeling of many different possible behaviors. (It should be noted that if there are multiple failure mechanisms, each can be described by the equation above, each with its own values of \( E_a \) and \( N \). If that is the case the net reliability is based on the superposition of all the mechanisms. Even in the case of multiple mechanisms in practice it is usually found that one mechanism will dominate the reliability behavior within a range of current and temperature. The fact that another mechanism could be dominant within a different range provides much of the motivation for this paper.)

The earliest 850-nm VCSEL reliability tests found \( E_a \) near 1 eV, but they ignored the current except to the extent that it affected junction temperature, effectively assuming \( N=0 \). With substantially more data and more sophisticated analysis, most VCSEL manufacturers subsequently found that for 850-nm AlGaAs VCSELs \( E_a \) near 0.7 eV and \( N \approx 2 \) more accurately described the reliability behavior over a wide range of conditions, though at least some manufacturers find that \( E_a=0.7 \) eV, \( N=0 \) better describes their devices. The fact that at multiple manufacturers

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activation energy near 0.7 eV has been found to describe AlGaAs 850-nm VCSEL reliability for both MOCVD and MBE epitaxial growth techniques, for both proton implant and oxide aperture fabrication techniques, and over a wide variety of current aperture sizes leads to high confidence in the predictive power of reliability models for VCSELs with GaAs quantum wells surrounded by AlGaAs barriers. This is all the more remarkable since the trajectories of degradation for different manufacturers sometimes differ, suggesting that the degradation mechanisms are not precisely identical. But what if the active regions change and the quantum wells are no longer in the AlGaAs system?

1.1 InGaAs quantum wells in VCSELs

VCSELs dominate optical data communications, with many times more fielded devices than any other technology. Most of the fielded devices have had GaAs quantum wells and AlGaAs barriers. Increasing speeds have necessitated increasing current densities, and those speeds combined with the push for increased packing density have increased the required operating temperature.

Significant speed increase can be achieved without modifying the quantum well materials. The threshold current can be reduced and operating current density increased by reducing aperture size; the photon lifetime can be tailored by adjusting mirror reflectance profiles; capacitance can be reduced by adding dielectric layers within the structure or by decreasing the radius of conducting material outside the current aperture; and high-temperature performance can be improved by adjusting composition and doping of nearby layers to minimize carrier losses. At some point, however, these and similar modifications reach a limit and further improvements in modulation speed or operating temperature range require new quantum well gain materials. GaAs-well devices have improved to meet the changing demands, but at some speed above 14 Gbps it appears that achievable performance with those wells will be insufficient. Even at 14 Gbps an inherently faster well would lead to better margin or enable operation at higher temperatures. Compressively-strained indium-containing quantum wells are one path to such higher speed.

VCSELs have been so reliable that it has often been the case that wearout lifetime to some commercially relevant failure rate, say, 0.1% failures, was many times longer than the time for a similar rate from random failures due to rare manufacturing defects or to damaging events. As current densities and temperatures rise the wearout failure rate increases at a rate much greater than the random rate increase, however. At a high enough stress (the combination of temperature and current) the wearout rate is completely dominant, which is what enables accelerated testing in the first place. If wearout rates cannot be improved eventually the faster and higher packing density systems will be less reliable than their slower predecessors. The addition of indium to the quantum wells improves their speed, but its effect on wearout reliability in 850-nm AlGaAs-based VCSELs has not been extensively studied.

To be sure, the addition of indium in many types of devices has been a source of reliability improvement, and it has often been suggested that addition of indium to 850-nm VCSELs would also improve reliability. These expectations are primarily based on one failure mode, climb dislocation growth, which has been a substantial life limiter for lasers and LEDs of many types, and which has certainly been observed in some VCSELs. Compressively strained indium-containing quantum wells in long wavelength edge-emitting lasers appear to be almost completely immune to dislocations of this kind.

However, 850-nm VCSELs differ from these long wavelength devices in a number of ways, each of which is generally associated with reduced reliability. The photon energy and the operating voltage are higher, resulting in higher energies available for defect creation and propagation; the operating current densities are generally higher, almost always over 10 kA/cm²; and the quantum wells are generally thinner, leading to higher volumetric current density as well. In addition, at 850 nm the quantum well barriers generally contain aluminum and devices containing adjacent Al-containing and In-containing layers have been problematic. Published reliability studies of 850-nm VCSELs fabricated with InGaAs wells and AlGaAs barriers have been scant, low-stress, and of short duration. Excellent reliability has been demonstrated for InGaAs-well VCSELs at longer wavelengths, but at those wavelengths the barriers usually do not contain much aluminum.

At Finisar we had additional reasons to be skeptical about the potential reliability improvement the addition of indium might provide. We had tested indium-containing wells in various VCSEL designs over more than a decade. We saw the performance differences we were looking for, but no improvements in reliability. In fact, until recently the reliability of our InGaAs test devices was often worse than for similar designs with GaAs wells. One important reason is that dislocations had never been the source of wearout failure in Finisar VCSELs, so immunity to climb dislocations would not affect our wearout results at all. The other reason is even more important. Since it was likely that indium would eventually be necessary for speed, in the last few years we embarked on an extensive experimental campaign to
determine whether different designs or growth conditions could bring InGaAs reliability up to the level enjoyed by our GaAs well parts. Among the potential variables are growth temperatures, precursor types, ratios, and gas pressures, growth rates, doping and composition of nearby layers, and composition of the wells themselves. We found an enormous variability in reliability results, as shown in Figure 1. Each dot in the figure represents the statistics of the hours to failure at an extremely stressful burn-in condition for samples from a single combination of the variables described above. It is not particularly surprising that some combinations were worse than others since the experimental aperture was wide, but the best results are a thousand times better than the worst, an enormous range.

![Figure 1](image)

The very short times to ten percent failures in Figure 1 are actual times at the very high stress condition. While at nominal use conditions the one hour line in the plot corresponds to many years of operation, to be truly acceptable would require a much smaller failure percentage and under conditions more extreme than the nominal use.

1.2 Evolution of reliability models

Until substantial numbers of failures occur in every test group, even those with lowest stress, the parameters of reliability models will likely change over time. (In our case these parameters are $E_a$ and $N$.) Early in testing only the highest stress groups will have failures, so only those groups contribute significantly to model generation. Depending on the trajectory of degradation it may be possible to extrapolate non-failing parts to failure, allowing more complete modeling much earlier in testing. These early results will be accurate only if the trajectory is similar to (a) of Figure 2 and the accuracy can only be confirmed much later unless the extrapolation is limited to parts already very near failure. If the failure trajectory is like (d) of Figure 2 extrapolation is impossible and all groups must be tested to actual failure.

![Figure 2](image)

Late in testing only low stress groups will not have failures, but eventually failures begin to accumulate even in those groups. With a tentative model already set by the failures in higher stress groups, computed $E_a$ and $N$ will change upward if low stress failures occur later than the tentative model predicts, or downward if the failures occur earlier than the tentative model prediction. If the new failures lead to a new model that still shows good fit to the accelerated
cumulative failure distribution, the new model is the one that will more accurately predict actual operating condition lifetime. If they lead to apparent bimodality it suggests that more than one failure mechanism is present.

2. PRODUCTION InGaAs QUANTUM WELL DESIGN RELIABILITY TEST

2.1 Wearout reliability test description

Finisar had been in production of a GaAs quantum well device for the 14 Gbps Fibre Channel market for some time, so there was a mature design for the VCSEL structure.15 Reliability testing of that GaAs well device found the traditional Ea=0.7, N=2 model to hold.15 Aiming for even better performance margin and toward future products at even higher speeds, in 2011 an active region using InGaAs quantum wells was placed in this mature design using the production combination of the variables described above. Qualification epitaxial runs and fabrication lots were produced and samples were assembled and put into extended stress tests at multiple conditions. For purposes of the study, failure was defined as -1 dB from the original emitted power at 6 mA and 25°C. As the first failures occurred in the highest stress groups additional test conditions and additional samples at some existing test conditions were added to establish the desired high model confidence. The groups in the wearout test are summarized in Table 1. As of the fourth quarter of 2012, the continuing groups had accumulated over 10,000 operating hours. At least some failures had occurred in all but the lowest stress groups, and some parts in the lowest stress groups had sufficient degradation that reasonable extrapolation to failure was possible (behavior like (a) in Figure 2 and at least -0.5 dB degradation at last test time), which allowed the construction of a preliminary reliability model.

Table 1. Burn-in conditions and quantities of units, including 1281 parts in main wearout study and another 1804 in subsequent validation groups. Samples are from multiple epitaxial runs and multiple fabrication lots. Of the 1281 main study parts, after fourteen months all but 116 in low stress groups have actual or confident extrapolated failure times. Note from typical LI every 30°C from -10 to +170°C that most devices are lasing under all burn-in conditions.

<table>
<thead>
<tr>
<th>Ambient temperature</th>
<th>Burn-in current</th>
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<tbody>
<tr>
<td>85°C</td>
<td>6 mA</td>
</tr>
<tr>
<td></td>
<td>9.5 mA</td>
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<tr>
<td></td>
<td>12 mA</td>
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<td>15 mA</td>
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<td>100°C</td>
<td>1000</td>
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<td>125°C</td>
<td>50</td>
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<tr>
<td>150°C</td>
<td>75</td>
</tr>
<tr>
<td>170°C</td>
<td>20</td>
</tr>
</tbody>
</table>

2.2 Test results

A large number of additional units have produced test results entirely consistent with those of the main study, but are not included in Table 1. Routine wafer acceptance tests at 150°C and 8.5 mA on more than 6700 units from dozens of additional wafers are not included because those tests have fixed test duration rather than continuous operation to failure. Also not in the table because extended burn-in was conducted in wafer form rather than on assembled components, consistent results were obtained on 220,000 additional test devices at 150°C and 9 mA.

The preliminary results of the study were surprising. As was the case in previous Finisar VCSEL designs, wearout failures were verified by electrical signature and by TEM to be dislocation-free, but the acceleration of degradation with current and temperature was unusually high. The preliminary model shows activation energy Ea >1.3 eV and current acceleration exponent N > 3. With the state of the groups still without failures, both of these values will almost certainly increase as the model evolves. The numbers are not unprecedented in VCSELs: Graham found Ea=1.2 and N=4 in 1.3-μm VCSELs16 and both Sale and Honeywell found N=5 in 670-nm VCSELs.17,18 but to our knowledge such high values have not previously been reported in multimode VCSELs at 850 nm.1 While the acceleration factors are high, the model appears quite robust, as demonstrated by several typical tests.

First, as shown in Figure 3 using the model to accelerate all failures to a common stress condition shows a reasonable fit with no evidence of bimodality.

* The N value is not just due to the wavelength: Duggan, et al. found N=2 in their red-emitting VCSELs.19
Second, Figure 4 shows the cumulative failure distributions of each stress condition taken separately have similar $\sigma$, and that it is similar to the $\sigma=0.567$ of the overall lognormal cumulative failure distribution model. (Cumulative failure distributions have a location parameter that varies with test condition and a shape parameter that is presumed constant. In our case the distribution is lognormal, with location parameter $\mu$ and shape parameter $\sigma$.) In addition, the median accelerated failure times of each group taken separately fall close to the overall model median.

Figure 4. (a) Cumulative failure distributions of each group of Table 1, showing consistent $\sigma$. (b) Accelerated failure time distributions compared to the solid line overall median model prediction at nominal use condition of 55°C, 6 mA. One group at 125°C, 12 mA differs more than 2×; as it is intermediate in both current and temperature it may indicate an error in applied stress, but even this group is less than 3×. (All groups included except the two with too few failures for individually reliable statistics.)
Third, we have seen consistent results from wafers grown to the same design but in different reactors, and processed many months apart.

As with Finisar GaAs-well parts, degradation is graceful, with gradual reduction in power over time. One example group is shown in Figure 5.

![Figure 5. Degradation trajectories of fifty parts in the 85°C, 12 mA group.](image)

3. DISCUSSION

The high—and likely to go higher as the reliability test continues—acceleration factors have some profound implications. The most important one is that it appears that wearout reliability at normal use conditions will actually be higher than that of previous designs. In addition to the rapid reduction in failure rate with the lower stress at operation, the InGaAs well devices can provide the required performance at a lower operating current. This combination leads to predicted life at worst case operation that is substantially longer for the InGaAs design but at the same time, at the extreme conditions required for short-term reliability tests the InGaAs well parts will show shorter lifetimes. These differences can be quite large, as shown in Figure 6, which plots the log of the ratio of the lifetimes of the two device types. The dotted line separates the regime where the InGaAs model predicts longer life than the GaAs model, with InGaAs winning in the lower left, the region containing the worst case system operating conditions.
As noted previously, GaAs-well devices otherwise the same as those of the present study have lower acceleration. And while the exact physics of failure remain elusive, at Finisar both GaAs- and InGaAs-well devices appear to degrade with recombination-enhanced creation or multiplication of point defects near the quantum wells. While it is tempting to assume that for both designs the specific defects are identical, with the only difference being the rate of acceleration with applied stress, it is at least possible that we have two different mechanisms coexisting in the indium containing devices. If that is the case, the mechanism with the higher acceleration would always account for failures at high stress, but the lower acceleration mechanism might actually account for most failures at lower stresses. (This situation is actually assumed in Telcordia GR-468 testing, where “random” failures are by default assigned activation energy of only 0.35 eV, guaranteeing their dominance at low stress.) So the obvious question is “How can we know that we do not have two wearout mechanisms?”

In a sense the question is unanswerable because certainty would only be available after operation with zero acceleration stress for the full product lifetime, typically a decade or two. But we can compare the actual failure rate at the lowest stress conditions in our study to that predicted by each model separately. Based on that comparison we can at least set a bound on what lower-acceleration mechanism could be present. With fourteen months of continuous operation the traditional \( Ea=0.7, N=2 \) mechanism would already predict a greater number of failures in the lowest stress groups than we actually observe. Our conclusion is that Finisar InGaAs VCSEL wearout reliability is well-described by the high-acceleration model above and that we can draw inferences about lifetimes at lower stress conditions based on that model.

4. CONCLUSIONS

While there were reasons to question the wearout reliability of 850-nm data communication VCSELs incorporating InGaAs quantum wells, with proper design and growth conditions we have demonstrated that under use conditions these devices can be even more reliable than their GaAs-well predecessors. This is an especially important result as we look ahead to the next speed node, where VCSELs operate at 25 or 28 Gbps, requiring the inherently better speed performance that the addition of indium provides.

In reliability testing there is no substitute for time, so even as testing proceeds on the next generation of VCSELs what we have learned from the devices described here provides a basis for optimism. The data compels a new acceleration model for a new generation of Finisar VCSELs and it appears wearout reliability once again meets its goal.
REFERENCES