VCSELs at Honeywell: the story continues

Honeywell VCSEL Optical Products, 830 East Arapaho Road, Richardson, TX, USA 75081

ABSTRACT

Honeywell continues to be the world’s leading supplier of VCSELs operating at 850 nm. This paper will cover new commercial application areas for 850-nm VCSELs, and will present new findings in VCSEL reliability science. In particular, newly-developing applications drive requirements for ever more reliable VCSEL design and fabrication, and for improvements in controls for ESD (electrostatic discharge) and EOS (electrical overstress) at manufacturing facilities both for VCSEL components and for higher-level assemblies employing VCSEL components. Honeywell efforts toward improvement of reliability and toward reduction of ESD exposure are described, as is an alternative approach to improving reliability of systems containing VCSELs without compromising their performance.

1 INTRODUCTION

The last few years were challenging for the VCSEL industry. Survivors see some improvements in the business climate, but face a continuing challenge to improve performance and reliability of their VCSEL products in an environment of low prices, little visibility, and reluctance to accept change, however well-intended.

1.1 The market perspective

The market for Vertical Cavity Surface Emitting Lasers continues to be nearly synonymous with short distance, high speed networking interfaces over multimode optical fiber using the Ethernet and Fibre Channel protocols. VCSELs are the optical engine for the transceivers used in these applications, with approximately 9.5 Million transceivers produced in 2003, a slight increase from 2002.1 Growth was due to expansion in the Ethernet space, and to the continuing requirements for high-speed storage access. 2004 looks to be another solid year with forecasts generally predicting 10 to 20% growth in the overall market, achieving nearly 11M VCSEL based transceivers. That is the good news. However, the transceiver market is even more commoditized than in 2003, and consolidation at the transceiver and subcomponent level will continue, which may be bad news for those companies without well-established products. It is the opinion of the authors of this paper that equilibrium numbers of suppliers of transceivers and subcomponents has not yet been achieved, and has actually progressed slower than predicted in previous chapters of the Honeywell story.2 Meanwhile, desperate competitive pressure has caused prices to drop even faster than expected, placing still more financial pressure on the various transceiver and subcomponent suppliers.

Of interest to VCSEL and transceiver manufacturers in 2003 was the emergence of demand for 850-nm-based 10Gbps optical links. While the total volume will be small in 2004, less than 100k units worldwide, it does demonstrate that the VCSEL value proposition still has mileage. In fact, it is still one of the few solutions that can claim operation to 85°C and above without some form of active temperature control. Extending reliable performance at high temperatures to 10 Gbps and beyond is enabled with innovative approaches to more than just VCSEL design, as a later section of the paper makes clear. Also of interest was the inability of suppliers to economically deliver CWDM optical transceivers to the Ethernet market to address the complete installed base of multimode optical fiber. This has led to the formation of study groups in both the Fibre Channel and the Ethernet standards organizations to look at methods of electronic dispersion compensation to more cost effectively address this market segment. It is estimated that as much as 75% of the currently installed multimode optical fiber lengths are not compatible with some proposed serial data solutions.

Also of keen interest to VCSEL and transceiver manufacturers in 2003 was the detour of Fibre Channel back to adopt 4Gbps interfaces. This was a significant move in the industry, and was led by concerns of the economic viability of 10Gbps optical components, and of the backward compatibility of the signaling layers. Also significant in this adoption was the use of optical modulation amplitude (OMA) which, together with relaxation of class 1 eye safety limits, greatly simplifies the manufacturing of fiber optic transceivers.
Development continues on VCSELs operating in both the first and second telecommunications windows. Some companies have announced products in the 1310nm region, but compliant high temperature performance continues to elude the industry. While recent results at Honeywell and elsewhere are encouraging, we expect modest adoption until significant field reliability data can be gathered.

For several years now, the emergence of VCSELs into large volume applications outside of data communications has seemed imminent. 2003 wasn’t the year. But it seems imminent.

1.2 The manufacturing perspective
The photonics marketplace of the last several years presented significant challenges to those tasked with managing manufacturing capability. During the sharp rise in demand of the very late 1990’s, many optoelectronic component suppliers were unable to build capacity quickly enough. This led to interesting behaviors in the purchasing supply chain. One was purchasing more parts than really needed (or double-ordering from multiple suppliers), in hopes of obtaining a higher place in the allocation queue. (This was a major cause of the inventory glut experienced later.) Another interesting behavior was what we termed the “Tsunami Effect,” by which we were often surprised with enormous un-forecasted demand with essentially no lead time. These factors lead to significant difficulty in planning a smooth-running manufacturing process.

Abruptly in May of 2000 our customers’ demand dried up almost completely: some couldn’t say when or even if they’d ever need another part again. This new market dynamic was obviously devastating across the industry. One of its effects is the inability to forecast demand throughout the supply chain. As companies tightened their balance sheets, inventories dropped to near-zero levels and nobody wanted to risk making purchasing commitments without hard orders in hand. Moreover, the drop of prices and increasing competition among desperate companies barely clinging to life often made long-term commitments unnecessary for pricing. And for some of those taking advantage of suppliers’ attempts to maintain viability, such commitments may have seemed unreasonable—either the purchaser or the supplier might not exist at the end of the commitment.

During these extremely difficult times, some companies re-structured themselves to better compete in many ways, including revamping product portfolios, introducing new products, and leaning out manufacturing operations. From a manufacturing standpoint, we have implemented several strategies aimed at dealing with an environment of poor forecasting with very short lead times, coupled with a lean, cost-efficient operation. Now that the market seems to be gradually rebounding, we believe these strategies will enable us to serve an expanding market equally well.

1.3 The reliability perspective
While volumes are only slowly recovering, and while prices continue their precipitous declines, reliability expectations are not decreasing. In fact, the reverse is true, with new applications on average operating at higher speeds and higher temperatures than ever before, putting ever greater stress on the VCSEL. What was good enough last year is not good enough today. At the same time, significant changes in device structure may require re-qualification, not just of the VCSEL component, but of each of the assemblies that component supports, so improvements due to process controls are always preferred over improvements from design changes. For rapid and continuing progress, however, both are necessary.

Meaningful reliability tests are expensive. Honeywell VCSELs are extremely reliable, so tests to determine whether an intended improvement actually increases reliability takes a great deal of time, many months or even years. Such tests also require a substantial number of units to have any statistical relevance. And they are destructive, or they reveal nothing. In the cost-constrained environment described above, how can reliability continue to advance? Several partial answers to this question will be described below, boiling down to a few basic themes: use the full spectrum of product types to inform reliability modeling; reduce variability in each product type to improve reliability predictions and to reduce early failure rate; protect the VCSELs from life-limiting damage; and ruthlessly exploit reliability differences revealed in experimentation, regardless of the original purpose of the experiments.
2 IS IT OR ISN’T IT ESD?

“Your excuse is always that the VCSEL failure was caused by ESD!” It is the rare VCSEL reliability professional who hasn’t heard that only slightly hyperbolic complaint from a customer who had been anxiously awaiting failure analysis of a VCSEL that no longer works properly. Luckily, such failures are also rare, at least in VCSELs fabricated and assembled by the premier VCSEL companies. At Honeywell, our customer reliability failure rate as calculated for all device types and for all shipments in our history remains at single-digit ppm levels. When one is faced with a failure in the concrete—in my module—however, the fact that failures don’t come often offers little comfort. Quite rightly, a customer wants to know why the failure occurred and whether other parts of similar vintage should be suspect. And the statement that no mechanical or growth defects are evident and that the failure signature is consistent with ESD exposure doesn’t directly answer either question. It does sound like an excuse.

Nevertheless, it is likely that by far the majority of post-shipment failures of Honeywell VCSELs are caused by ESD, or by ESD’s big brother, EOS. There are several lines of evidence supporting this assertion. First, the failure analysis data, including forward- and reverse-bias IV measurements, visual and emission microscopy, and TEM (transmission electron microscope) images of returned parts, are consistent with the diagnosis. Most often there are no evident manufacturing defects and no apparent epitaxial defects. The IV measurements are consistent with dislocation growth in the VCSEL active layers\(^3 - 4\), and the imaging techniques confirm the presence of these dislocations. In some cases, the original ESD damage sites that nucleated the dislocation growth are evident, as is the case in Figure 1, a device intentionally exposed to an ESD event, then operated at elevated temperature and current to develop the dislocation networks from the original damage sites. This is a classic expression of ESD-induced VCSEL degradation as seen in Honeywell’s and in other’s VCSELs\(^5\). Damage always occurs first near the edge of the oxide, because that is where the current density is highest, but depending on the design details and whether the ESD polarity forward- or reverse-biases the junction the initial damage may be in the mirror or in the junction.

The failure analysis can be conclusive, as in the case of Figure 1, but if the original ESD damage is slight, or if the subsequent operation has grown the dislocation network to cover the entire active region, it may be impossible to make a definitive diagnosis. After all, it would be possible for a defect produced in the structure during epitaxial growth of the VCSEL layers to provide the nucleus for the dislocations. While the fact that every device has undergone a strenuous burn-in during the STABILAZE wafer-level burn-in process makes it unlikely that such a defect would be present in a shipping part, how can such a possibility be ruled out? This is where a second line of evidence, one only available to a VCSEL manufacturer shipping large volumes of multiple VCSEL designs spanning a wide range of aperture sizes, is compelling. Large volumes are important because, as mentioned before, for quality suppliers failures are in the low ppm level, so statistically relevant comparisons of failure rates only become possible when millions of shipped parts are considered. Figure 2 makes clear why multiple shipping designs are necessary for this argument: it is the comparison of designs that is the evidence. (The designs have been described previously.\(^3\)) The basic line of reasoning is simply that if non-wearout failures are primarily due to manufacturing defects, whether grown in or produced by the assembly process, then designs with larger total active junction areas will have higher non-wearout failure rates. A larger active area means there is a greater chance of encompassing such a defect within it; by a ratio strictly proportional to the junction area (this is always somewhat larger.
than the area of the aperture). If, however, failures of this type are primarily due to ESD or EOS events, the opposite is true, because smaller devices have substantially lower damage threshold voltages.\footnote{3}

Figure 2 compares real failure rates to predictions based on the assumptions that one or the other cause is dominant. There is little question that the non-wearout failure rates, whether measured internally by Honeywell production burn-in experience or externally by customer return experience, are consistent with the explanation that ESD is the dominant issue. It is certainly not consistent with the suggestion that manufacturing defects are the primary cause. The fit to the ESD/EOS explanation trend might be even more perfect than it at first appears, because the only slightly anomalous point is the field return experience for the largest diameter part (circles in the graph). Most of those failures, however, occurred at a single relatively small volume customer. They were not concentrated in any single lot, so it is not unreasonable to suppose that they might reveal a weakness in an ESD control program rather than pre-existing defects in the VCSELs. If that were the case, the relevant point would relocate downward as shown. Such manipulation is not strictly necessary; the basic argument holds even without it. Additional confirmation should become available when sufficient production volumes of our 10-µm diameter, 10 Gbps part have shipped to detect the anticipated ppm-level non-wearout failure rate.

In light of the above, and as more applications open for single mode VCSELs (many sensor applications, most long-wavelength applications) and for other reduced-diameter designs (10 Gbps and higher speeds), proper ESD controls will become even more necessary. We must abandon our complacency about controls that make ESD damage merely improbable; since we clearly will not abandon our reliability expectations, we must make ESD damage nearly impossible. Some steps Honeywell has taken in this direction are described below.

3 CAN WE FORGET ABOUT WEAROUT DEGRADATION?

The anticlimactic answer is: No. While a myth has circulated to the effect that VCSEL wearout reliability has gotten so good that we can now ignore it and concentrate only on infant and random failures, failures of the sort discussed in the previous section, VCSEL requirements continue to evolve. As reliability in existing applications improves, we inevitably find that someone wants to operate hotter, or faster, or in arrays, necessarily increasing stress due to temperature, current, or statistics, respectively. And of course the argument that wearout reliability doesn’t matter is specious. In the first year or two of operation, it’s true that infant and random failures may dominate the failure statistics, but in the fifth, or tenth, or twentieth operating year wearout dominates, often enormously so. Companies planning to still be around five years in the future can’t afford to ignore wearout even on well-established designs.

With highly-reliable products, however, it can be difficult even to determine what the wearout reliability is, let alone whether it has improved. Accurate modeling of failure rates at real operating temperatures requires extremely long tests with extremely large samples at multiple stress conditions, so it is not economically feasible to perform such tests often. For some particularly reliable designs, Honeywell no longer conducts such exploratory tests at all (though sample testing at extremely stressful levels continues as a part of individual wafer acceptance for all Honeywell designs).\footnote{3,6}

Honeywell produces reliability models for each production design, models that predict failure rates at any desired
operating conditions. The philosophy of model creation is to err on the side of conservatism for both random and wearout failure prediction. Conservatism enters the random failure model in that we apply a base rate higher than the data supports (to allow for possible under-reporting of low-ppm failures) and we assume the early rate will continue throughout the operating life (compounding any infant mortality rate with ongoing random failures). For the wearout portion of the model, however, the conservatism is based on the fact that the model is not often updated. This is conservative because, even in the absence of any design change, Honeywell continuously reduces the variability in the output of our processes, resulting in a smaller spread of variation in reliability as well, and inevitably decreasing the early failure fraction of the population.

This second aspect of model conservatism deserves some amplification. Wearout phenomena in general, and our VCSEL wearout in particular, often use the lognormal distribution model. The lognormal distribution is described by two parameters: μ, the log of median failure time, and σ, the standard deviation of the log of time to failure. μ is a measure of “average life” and σ is a measure of the spread of failure times. Within a given process, reducing σ increases the likelihood that all parts fail at exactly e^μ hours, and decreases the likelihood that they fail earlier. Thus, reducing the variability that can lead to different failure times—things like aperture diameter, doping, and efficiency—has no effect on the time at which 50% of the parts have failed, but it has an enormous effect on the time at which 1% or 0.1% of parts have failed. Within a given process, σ can be drastically reduced through variability reduction, but μ can only be increased a small amount, by removing part of the population. Unless the original process variability is absurdly large, truly significant increases in μ require changes in design.

3.1 Oxide VCSEL wearout reliability improvement

While Honeywell does not change the reliability models often, we do periodically conduct high stress reliability tests for various purposes. These tests can provide a snapshot of what improvement, if any, the process has undergone since the last model. As we would hope, all such recent snapshots show better results than the models predict.

Figure 3. Evolution of reliability of several oxide VCSEL designs at typical operating currents. Solid line is published model prediction, dashed line is earlier model, and solid squares represent results of recent accelerated sample testing, not yet sufficiently complete to incorporate into an improved performance model. Approximate oxide aperture diameters are 17, 14, and 5 μm for 2021(60), 2046, and single mode, respectively.
Figure 3 shows the current model predictions for several oxide VCSEL designs at 40°C and typical operating currents. The lines show the distribution models we use to predict reliability for customers, with the straight section to the right where wearout dominates the failure rate and the curved section to the left where random failures may dominate. (At higher temperatures the wearout curve becomes dominant over the entire width of the graph.) The solid squares show actual results from high-stress testing (125-150°C ambient and 2-4× normal operating current), accelerated to the graph condition. In each case the squares are based on results from multiple wafer samples, with typical sample sizes greater than one hundred parts and test times of many months. Improvements since initial model creation are based both on variability reduction (all designs) and on design enhancements (2046 and single mode).

3.2 Proton VCSEL wearout reliability improvement

We stated in 2001 that we would no longer attempt to update the proton VCSEL reliability model, since it was becoming impossible to develop meaningful failure data. The introduction of a version with a different layout in 2002, however, led to collection of some additional data during our internal qualification process. Those qualification burn-ins were extended until we actually began to collect some failures, with the results shown in Figure 4.

In every case but one, the cumulative failure percentage is at least a factor of two better than the model predictions. The one exception can perhaps be explained by the relatively small sample size, and the greater weight accorded a single failure when samples are small. The same explanation applies to the scatter in the plotted points, and is another reason that models are typically updated only when very large samples under a large range of test conditions can be combined to remove the statistical noise.

3.3 Further improvements on the horizon

Most of the graphs of the previous sections show more than three million hours (over 300 years!) until even 1% of the population fails. So can we ignore wearout reliability after all? Figure 5 shows one reason that we cannot. VCSELs designed for higher speed operation are typically smaller, and must be operated at higher current densities than lower speed devices. This is true even when the design is optimized for reduced current density requirements as the Honeywell 10 Gbps VCSEL is.

There are other requirements that push 10 Gbps VCSELs closer to reliability limits, as well. In order to optimize low temperature performance, it is necessary to use designs for which threshold current is increasing and slope efficiency is decreasing at elevated temperatures, which means the average VCSEL current increases substantially to maintain a constant emitted power. In addition, the requirement for a particular encircled flux distribution in the fiber leads to optics whose coupling efficiency may drop as the VCSEL NA increases.
with that increasing current. The combination of all these effects leads to reliability dropping from a respectable two million hours to 1% failures at 25°C, to only a little over 10,000 hours (less than a year and a half) at 85°C. One system level solution to the problem is described in a later section. Wouldn’t it be nice, though, if we could just make the VCSEL so much better that it was a non-issue? Well, maybe we can.

While conducting some epitaxial growth experiments for another purpose, we produced some VCSELs of the type labeled 2046 above, and compared their reliability under very stressful conditions to that of standard-population parts. We found that wearout reliability is, to some extent at least, an adjustable parameter.

The results are summarized in Figure 6. While the definitive experiments are currently underway, it seems probable that wearout reliability can be enhanced by perhaps an order of magnitude. Of course, it can be decreased by an even greater amount if the wrong epitaxial growth conditions are chosen.

![Extremely accelerated life testing (150°C, 20 mA) of experimental designs](image)

Demonstration of different regimes of wearout failure rate. Each point represents the median degradation in a large sample of VCSELs; each line is a different wafer. Like point shapes signify like designs.

![Demonstration of consistency within a wafer. Each line represents the degradation trajectory of a single VCSEL.](image)

Figure 6. Results of highly accelerated life testing of three different epitaxial designs. In both graphs the current production design (on which the reliability model is based) is the middle group, degrading approximately 30% in 600 hours.

### 4 MANUFACTURING AUTOMATION

Ionizers! One of many lessons taught by the experiences of shipping millions of VCSELs is that one-in-a-million events happen. To avoid the kinds of ESD problems described above, we have installed ionizers at every step where a VCSEL might be handled without the complete conductive enclosures provided by most of our automated equipment. At first, ionizers looked like an expense, but with the anticipated effects on total reliability, they now look like savings. This has been a typical result at Honeywell, that reliability drives many of our automation decisions. Today, many products are handled only by automated equipment from the time the wafer is sawed into chips until the final TOSAs (transmitter optical subassemblies) are in their shipping containers.

#### 4.1 Manufacturing, the ultimate laboratory for flaw-finding

We have maintained both out-sourced and vertical integration manufacturing models. Many companies fall in love with one or the other of these strategies but we believe when properly used both have their place. Vertical integration enables tight control of yield, materials management, process controls, lean techniques, and cycles of learning, giving key feedback to the design community for improving the manufacturability of new products. On the other side, out-sourced manufacturing gives the advantages of cost control, capacity management, reduced capital expense, and flexibility, which can be crucial given the roller-coaster volume requirements of this marketplace.
We have found, through painful experience, that the choice of a manufacturing partner is critical. Photonics requires special controls and processes which very few manufacturing companies possess. One of our litmus tests is that if the engineers of a manufacturing company don’t already know the basic VCSEL vocabulary—threshold, slope efficiency, active alignment, wiggle/rattle testing, coupling efficiency, and the like, there will likely not be a successful relationship. There are some excellent photonics manufacturing service companies, though—and their number is growing.

We have intentionally maintained in-house manufacturing capability for every process step for the cycles of learning reasons mentioned earlier. It is critical to actually build a large volume of parts with careful engineering observation to learn the nuances of a product. Those pesky one-in-a-million events can have consequences wildly out of proportion with their frequency, and the factory floor is the best source for real-life manufacturing data there is. Another reason we keep many processes in house is that we want to carefully automate the key processes in an environment we control since automation is a key part of our VCSEL manufacturing and reliability strategy. We have now reached the point where we never handle individual units in production. They are handled as wafers or in strips or trays of components, or sometimes handled on a sample basis for certain steps. Our packaging operation—from picking chips from wafers through loading parts in the shipping packages—is totally automated on a cellular basis. A number of factors drove us to this level of automation.

We always tout that the main reason for our automation is improved reliability and quality. Our VCSELs have a well-earned reputation for reliability, and the manufacturing process is a key component in our overall reliability methodology. A significant problem with handling individual units is that such handling can be a prime contributor to random defects, such as mechanical damage or ESD. Our STABILAZE wafer-level burn-in process allows burn-in to be done at the chip level rather than at the component level so we no longer need to handle individual components for this process. (Several years ago we generated data suggesting that component burn-in might actually do more harm than good for our VCSELs, in that the chance of doing random damage in handling may outweigh any beneficial effects of burn-in as a screening tool.) STABILAZE allows us to stabilize the parts with 100% burn-in while virtually eliminating the chance of random damage. Automated inspection is another key facet of our reliability program. The effectiveness of manual visual inspection at any level is quite suspect, even at the chip level. So we have implemented a fully automated inspection for chip damage just before the chips are picked from the sawed wafer to assure removal of any potential reliability defect.

![Automated wafer inspection and STAI](image)

Automation for quality has a similar basis—any time a human touches the part there is a significant chance of human error, no matter how many Poka-Yoke tools are used. Mixed parts, part damage, and variation are all direct results of human interaction with devices. When we moved from one-at-a-time testing by operators to true automated testing using machine handling, we found as much as ten-fold improvements in test repeatability—this despite the fact that the test fixturing, test software and algorithms, and instrumentation were identical for the manual and automated systems.
4.2 Other reasons for manufacturing automation

For many critical process steps, automation is required to achieve optimum performance. We have used at least half a dozen different methodologies for aligning VCSEL components into fiber receptacles. We discovered early on that automation of the beam search and find part (the alignment proper) of the process is an absolute requirement to consistently meet the performance objectives of our customers. Meanwhile, customers continued to effectively tighten alignment specifications, which led us to more and more fully automate the process until today the entire process—parts feed, alignment, epoxy applications, and part transfer to the next step—are fully automated. Steps such as epoxy application to a TO component and receptacle are difficult and complex operations for humans to consistently perform perfectly. By automating all of these steps, we have significantly reduced the variation in the process, resulting in dramatic improvement in process capability as measured by the resultant measures of coupling efficiency.

Most people immediately assume automation is implemented to reduce costs. While the benefits are real, due not only to labor savings but also to the yield improvement gained from variation reduction as discussed earlier, there are many potential downsides to be considered as well, even apart from cash-flow considerations. Under-utilization of the capital leads to obvious issues when paying for the depreciation. Because maximizing equipment uptime is critical for automated systems, well-staffed engineering and repair and maintenance functions are a necessity. The technical support required is one reason we maintain the bulk of our automation close to the engineering support in our Richardson facility.

Planning for automation starts with conceptual design. Attempting to retrofit automation on an existing product, designed for manual assembly, often leads to the frustration of a feeble process. Lack of robustness is a recipe for disaster in an automated assembly process, where large volumes of parts are produced in short order. Design and manufacturing engineers need to be challenged to deeply understand all the material and process variation inherent in the design before automating the process. Gaining this “tacit knowledge” of the process by exploring the effects of input variations is where Six Sigma tools such as designed experiments can be extremely valuable. While yields are generally quite good for a normally-running process, high-speed automation can build a lot of scrap quickly if something goes astray. For this reason rapid feedback and tight process controls are paramount.

Manufacturing is an aspect of photonics technology that is only now starting to be addressed in earnest, as the technologies mature. During the economic struggles of the past few years some companies have cut their “burn rate” and hunkered down. Honeywell, and other companies with products to deliver, instead continued to invest in manufacturing infrastructure to streamline and improve the quality and reliability of their manufacturing processes, as
well as establish a capability for large-volume production. Those who have are well-positioned to be leaders as the volume demands increase over the next several years.

5 TEMPERATURE COMPENSATION FOR 10 GBPS VCSELS

In data communications applications, it is often necessary to compensate the changes in optical power from a laser through some form of control network. By far, the most common practice is utilizing a monitor photodiode that samples the optical output in a control loop. The control loop will generally adjust the bias current to the laser to keep a constant amount of optical signal on the monitor photodiode. This is generally referred to as an average power control (APC) control loop, and compensates changes in both the laser threshold and slope efficiency. In other applications, a microprocessor can be used to program desirable characteristics over temperature. These approaches have generally been optimized to minimize the changes in optical power over temperature. Such approaches may require modification for future designs, as the example below, employing a 10 Gbps VCSEL demonstrates.

With the advent of the IEEE 802.3ae (10GB Ethernet), the requirements for laser operation over temperature have increased. The general problem is the tradeoff between speed and reliability of the optical source. For a given laser design, the speed of the laser is roughly proportional to the square root of the current above threshold. Thus in order to get the most speed from a laser, it is desirable to drive a large amount of current. Contrary to this is the reliability of the laser, which decreases both as the square of the current, and exponentially with temperature. (The higher currents also lead to an increase in joule heating.) The graph in Figure 9 demonstrates the relationship between speed and reliability for one laser design. The red line is the speed of the laser plotted with the right hand axis, and the blue, magenta, and green lines are the Mean Time To Failure (MTTF) of a VCSEL for 0, 40, and 80C respectively.

In VCSELs the relationship to speed is more complex due to the multitransverse mode nature of the device. Generally, one can observe differences in the modulation characteristics as a function of temperature, and more specifically, depending on which side of “T-zero” (T₀) the laser is operated. (The T₀ point in a VCSEL is the temperature at which the threshold current is a minimum over temperature.) Also, the slope efficiency (amount of light output increase for a given increase in drive current) can affect the modulation performance. In a VCSEL, the slope efficiency increases with decreasing temperature. Figure 10 shows the characteristic shapes of variation of threshold and slope efficiency over temperature, though specific values may differ from device to device. The red line is the variation of threshold current, and the blue line is the variation of slope efficiency over temperature. When operated in a constant optical power mode, the VCSEL described here would have the operational characteristics shown in Figure 11. In this graph, the red points represent the relative speed, and the blue points represent the bias point to maintain a constant optical output power. As the temperature decreases, the optical performance is degraded due to a reduction in speed. At high temperature, the reliability of the VCSEL is compromised due to the increase in the bias current. Ideally, the speed would be flattened as function of temperature, and the biasing current would be reduced at the high temperatures. Only a control concept other than strict APC can accomplish this. One such is described below.
One of the unique features of VCSELs is the ac operation over temperature, particularly with respect to the $T_0$ point. Two simple measures of the optical performance are the overshoot in the eye diagram and the amount of jitter. These are plotted in Figure 12.

As the graphs of Figure 12 make clear, it is not necessary to drive a VCSEL as far above threshold to achieve a particular performance level at high temperatures. This can also be seen in the eye diagrams of Figure 13 where the average power was held constant. While the power (and thus the current required to achieve it) are clearly marginal at 0°C, the same power is more than adequate at 25, 50, and especially at 85°C. In other words, at 85°C we are driving the VCSEL much harder than is necessary to get excellent ac performance.

The proposed scheme here takes advantage of the fact that one does not need to drive the VCSEL so far above threshold to achieve acceptable performance at high temperatures, which has the benefit of increasing the reliability at high temperature where it is most problematic. The scheme abandons average power as the primary control mechanism and use a memory, microprocessor, thermistor, or other means to reduce the amount of bias current (and thus optical power) at high temperatures and to increase the current (power) at low temperatures to increase device reliability and improve the AC performance over temperature. Consider the graph in Figure 14, where the time to 1 percent failure is plotted as a function of the ambient temperature. The solid diamonds represent the traditional method of average power control, while the open squares represent the new proposed method. The time to 1% failures increases by about a factor of five the highest temperatures where it matters the most, without any reduction in performance. If only all reliability improvements came for free…
CONCLUSIONS

Before Honeywell became the first supplier shipping true production VCSELs in 1996, we thought it necessary to establish the reliability of the technology, for ourselves and for our potential customers. Despite the many improvements since that time, VCSEL reliability continues to be a critical element of this business. And despite the cost constraints untimely imposed by the market, investments in reliability improvement must continue, because the requirements will always be a moving target, usually receding into the distance as fast as we can chase them. The good news is that through concerted effort at all levels, chip, component, and system, we may actually be gaining on them a little.

REFERENCES
