Deploying VCSELs for space applications
reliability and procurement guide

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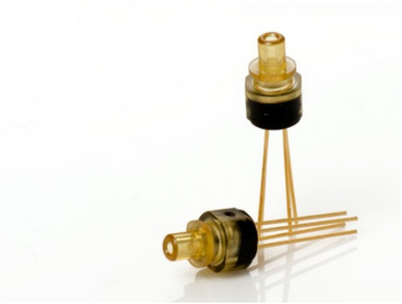
Outline

1. **Advantages of VCSELs**
2. **Performance / Reliability trade offs**
3. **VCSEL reliability**
   - Reliability models
   - Testing
4. **Failure modes**
5. **Suggestions for VCSEL procurement**



www.lasercomponents.com

www.photonics.phillips.com

Advantages of VCSELs (1)

esa

VCSEL = **V**ertical-**C**avity **S**urface-**E**mitting **L**aser

Manufacturing efficiency

- Easy wafer-level probing due to vertical emission
- Simpler processing & optics ⇨ low costs

Low threshold & operating current ⇨ low power consumption

- Current is confined through active region

Circular beam

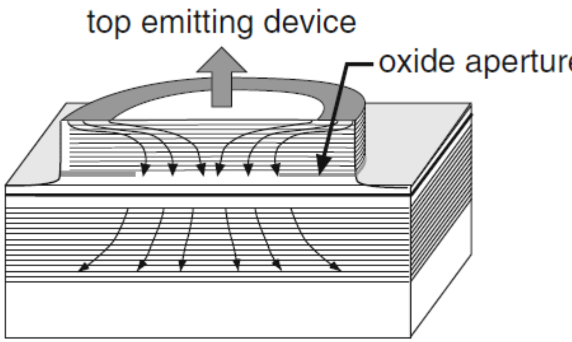
- Simple lens design & fibre coupling

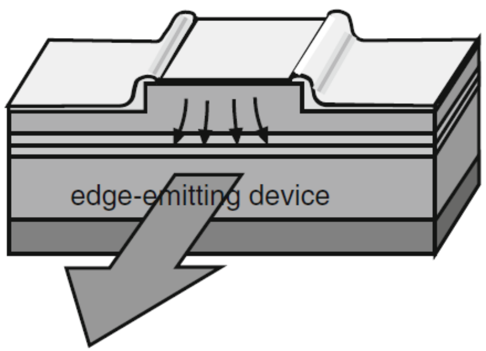
Single longitudinal mode

- Due to small optical cavity length
- Avoids need for optical isolators etc. which may otherwise be needed to prevent mode hops

Reliability advantage due to 'buried' active area

- Active area is usually 3-4µm from facet, and ~10 µm from lateral edges





[1] O. Ueda, S.J. Pearton; Materials and Reliability Handbook for Semiconductor Optical and Electron Devices

Advantages of VCSELs (2)

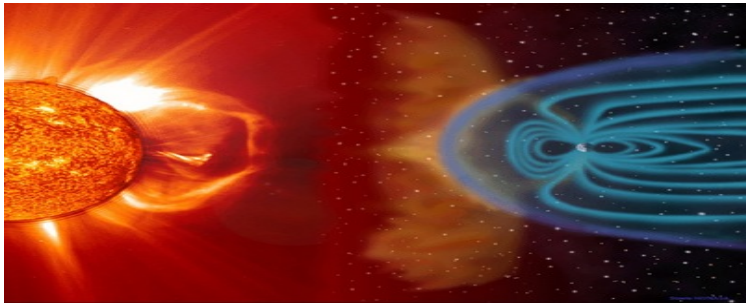
More tolerant to radiation damage compared to LEDs & edge emitting lasers

- Considered for applications in space, high-energy physics, nuclear power plants, future thermonuclear reactors [2]
- Sufficient radiation hardness for nearly all space applications [3]
- VCSEL radiation tolerance attributed to;

  a. *small active area*

  b. *large current density - Damage can be partially annealed with high drive currents & temperatures*

  c. *short carrier lifetime*



[2] F. Berghmans et al, Combined Gamma and Neutron Radiation Effects on VCSELs , IEEE Proc., 2002
[3] R.A. Morgan et al, Vertical cavity surface emitting lasers for space-borne photonic interconnects", SPIE Proc, vol. 2811, 1996

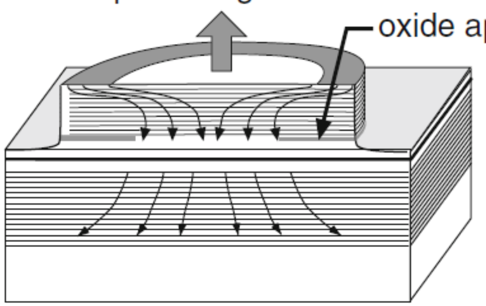
Performance / Reliability trade-offs (1)

Increasing drive current

- Better performance – improves power, speed, jitter, rise/fall times…
- Worse reliability – by a factor proportional to I^2

Reducing lateral confinement (oxide aperture) [4]

- Better performance
  - Improves high-speed operation (lowers drive current, capacitance & inductance)
  - Single transverse mode
- Mostly worse reliability
  - Increases thermal resistance (junction temperature)
  - Increases current density

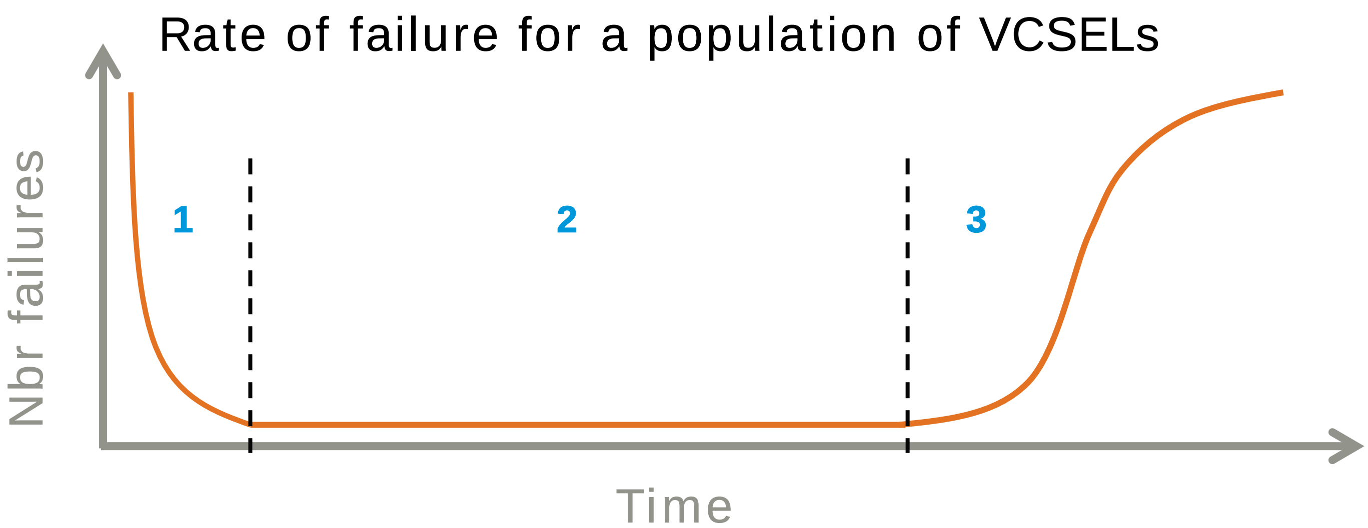


Material system – GaAs / AlGaAs

- Ease of fabrication & favorable performance - 850 nm is convenient with Si detectors
- Worse for reliability compared to; InGaAsP on InP substrates (1.3 & 1.55um) or InGaAs on GaAs (920-980nm)
  - GaAs active regions have mid-gap recombination centers from dangling bonds with self-propagating dislocations

[4] B. Hawkins *et al*, Reliability of Various Size Oxide Aperture VCSELs, Honeywell International

Reliability



1. Infant mortalities

- Weak parts giving high initial failure rate
- Captured during burn-in

2. "Maverick" (random) failures

- Apply to a small subpopulation of devices not made as intended
- Typically abrupt failure
- Cause of most in-field failures ⇨ **very difficult to capture!**
- Minimized through quality control & thorough failure analysis of manufacturer

3. End-of-life (wearout) failures

- Typically gradual failure
- Usually modelled using Lognormal distribution

Reliability – Acceleration Factor

$$AF = \left(\frac{I_{acc}}{I_{use}}\right)^{n} \times \left[exp\left(\frac{E_a}{k_B}\left(\frac{1}{T_{j,use}} - \frac{1}{T_{j,acc}}\right)\right)\right]$$

Current acceleration factor × Thermal acceleration factor

I = current

T_j = junction temperature = $T_{ambient} + R_{th} \times (I \times V - P_{optical})$

$_{acc}$ = at accelerated test condition

$_{use}$ = at specified usage condition

$n \approx 2$ for VCSELs (compared to ≈ 1 for edge emitting lasers)

E_a = Activation energy ~ 0.7eV

Reliability – Testing (1)

Example of manufacturer's reliability testing: Vixar [5]

- 6 different current, temperature conditions
- 32 devices tested per condition (total of 192 devices)
- Tests performed dry, dry pulsed, & humidity
- Example test matrices:

SM	85° C	105° C	125° C
1 mA			X
2 mA	X	X	X
3 mA	X	X	

MM	85° C	105° C	125° C
9 mA			X
11 mA	X	X	X
13 mA	X	X	

MM Pulsed	85° C	105° C	125° C
7 mA	X		X
18 mA	X	X	X
24 mA		X	
30 mA	X	X	X

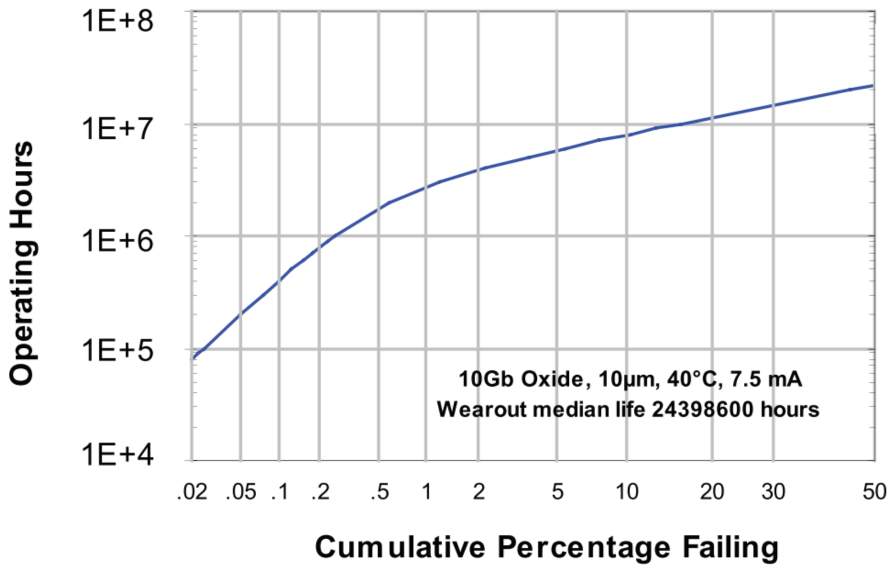
1 µs pulsed, 12.5% duty cycle

- Need ~50% failures to get good statistics – takes > 1 year with AF of 100
- $E_a = 0.7$ eV, $n = 2$

[1] O. Ueda, S.J. Pearton; Materials and Reliability Handbook for Semiconductor Optical and Electron Devices
[5] C. Steidl, Vixar application note: VCSEL reliability methodology
[6] Vixar 850nm Multi-Mode VCSEL data sheet: http://vixarinc.com/pdf/850M-0000-x002.pdf

Reliability – Testing (2)

Example of manufacturer's reliability testing: Finisar [7]



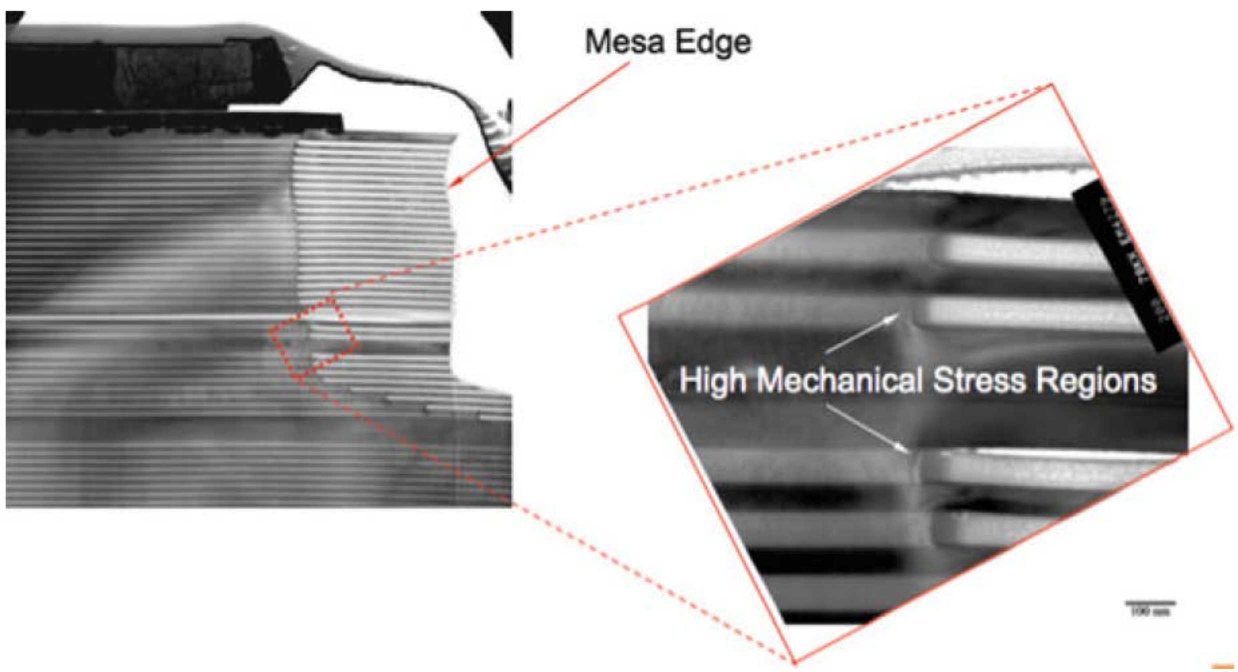
- $E_a = 0.7$ eV, $n = 2$, $\sigma = 0.7$
  - $\sigma = 0.6$ ⇨ longest-lived devices take 10x longer to fail than the early failures
- Also includes random failure rate (using field return history from earlier generations)

[7] Finisar, 10Gb Oxide Isolated VCSEL Reliability Report, https://www.finisar.com/sites/default/files/downloads/reliability_data_10gb_oxide_isolated_vcsel_reliability_report.pdf

VCSEL failure modes (1)

Mirror oxide climb dislocation

- <100> dark-line defects (DLDs)
- Most common source – cracking at the edge of the “mirror oxide”
- Fig. 6.23 from [1]: TEM cross section view of oxide edge

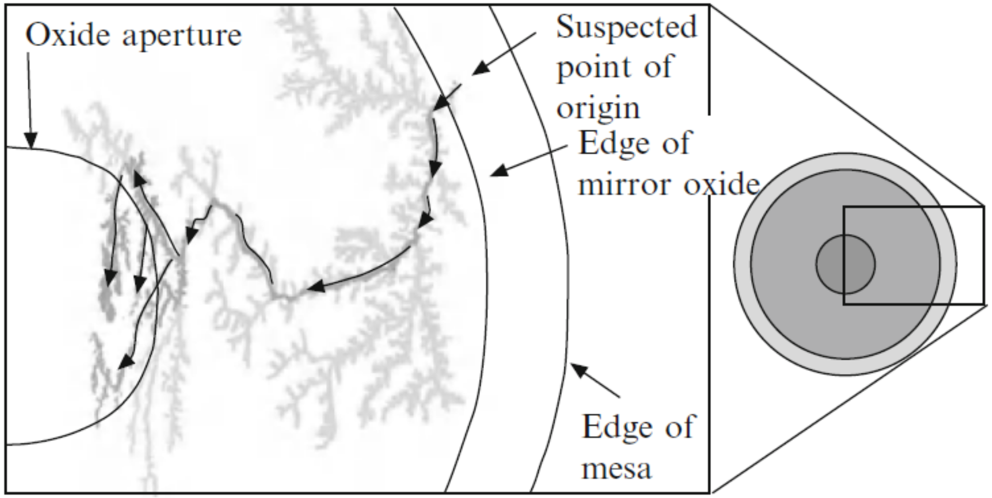


[1] O. Ueda, S.J. Pearton; Materials and Reliability Handbook for Semiconductor Optical and Electron Devices

VCSEL failure modes (1)

Mirror oxide climb dislocation

- <100> dark-line defects (DLDs)
- Most common source – cracking at the edge of the “mirror oxide”
- Climb dislocation travels towards emitting area (optical pumping)
- Can take years to occur!
- Fig. 6.24 from [1]



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VCSEL failure modes (1)

Mirror oxide climb dislocation

- <100> dark-line defects (DLDs)
- Most common source – cracking at the edge of the "mirror oxide"
- Climb dislocation travels towards emitting area (via optical pumping)
- Can take years to occur!
- *How to avoid?*
  - Grading the oxide layers
  - Electrically inactivate the edges of the VCSEL
  - Or - don't use AlGaAs/GaAs (e.g. InP)

[1] O. Ueda, S.J. Pearton; Materials and Reliability Handbook for Semiconductor Optical and Electron Devices

VCSEL failure modes (2)

Electrostatic Discharge (ESD)

- Particularly sensitive to long pulses – "Human Body Model" damage can occur @100-200V
- If occurs after burn-in, can cause failure months later!
- *How to avoid?*
  - Shipping in trays, not plastic barrels with allowed movement
  - Special precautions during assembly

Electrical Overstress (EOS)

- Longer pulse-width compared to ESD
- Caused for instance by test equipment switching transients – as little as 5V may cause damage
- *How to avoid?*
  - Developer should have well characterized the damage threshold limits
  - Carefully auditing all test equipment to ensure no 'spikes'

Scribe or sawing damage

Epitaxial defects

Wearout

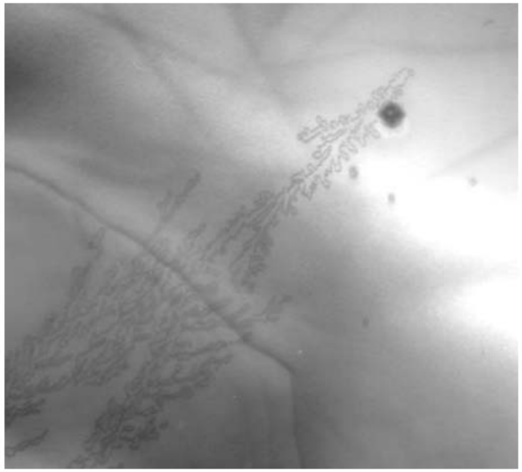
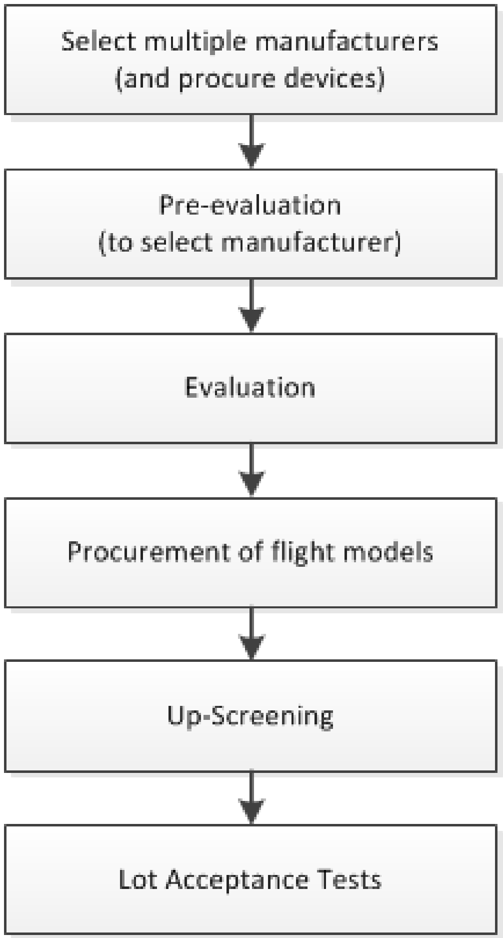


Figure 22. Plan-view TEM micrograph of a field-failed device subjected to a CDM event.

Figure from ref. [8]

[1] O. Ueda, S.J. Pearton; Materials and Reliability Handbook for Semiconductor Optical and Electron Devices
[8] Finisar Application Note: An Atlas of ESD Failure Signatures in VCSELs

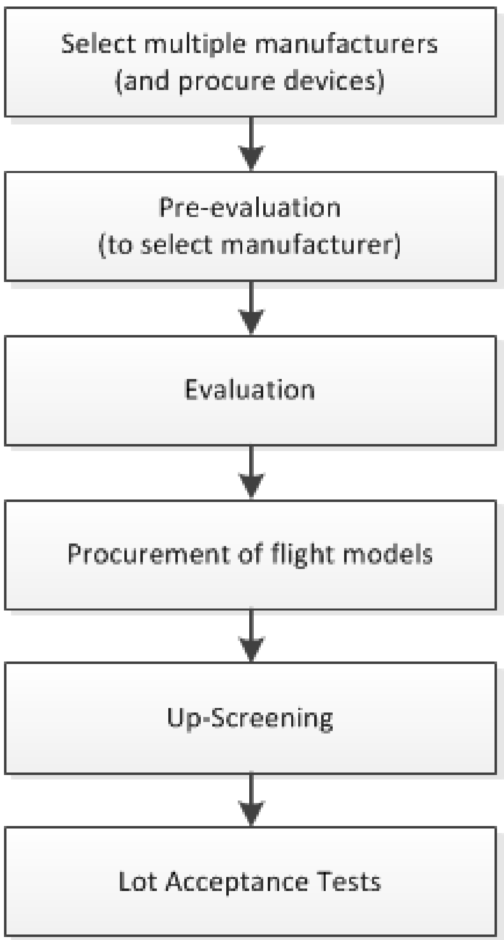
Some suggestions for VCSEL procurement



For a guide, see:

ECSS-Q-ST-60-13C: PA for Commercial electrical, electronic and electromechanical (EEE) components

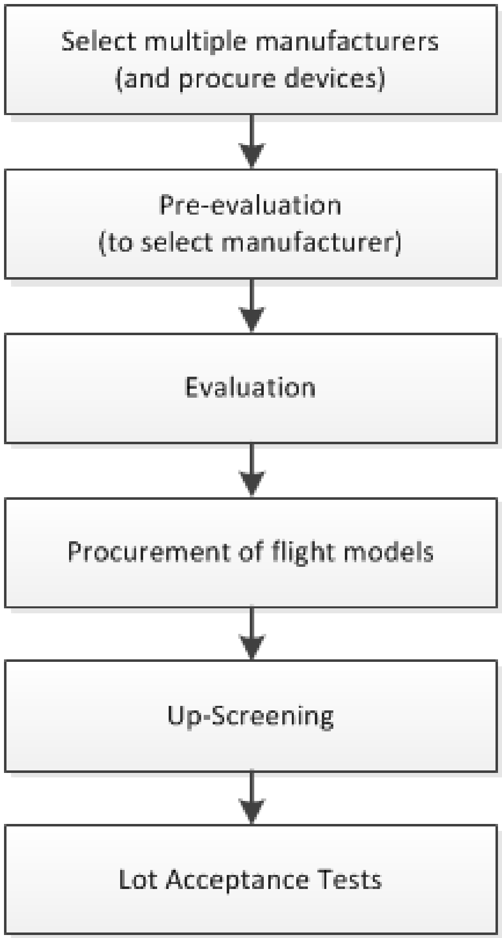
Some suggestions for VCSEL procurement



After checking performance parameters…

- Reliability parameters for the VCSEL of interest
  - The test matrix & sample numbers
  - Conditions tested – dry, pulsed, humidity
  - Uncertainty parameter for the reliability fit (e.g. σ for lognormal distribution)
  - Knowledge of the 'random' failure statistics (field data?)
- Known failure modes for the specific design
  - Designed specifically to reduce DLDs?
  - Designed to be robust in humid environments?
  - ESD/EOS limits?
- Check for parts and material restriction

Some suggestions for VCSEL procurement



Need an approved demonstration that the component will meet the requirements for

- Functional performance
- Quality
- Dependability
- Environmental resistance

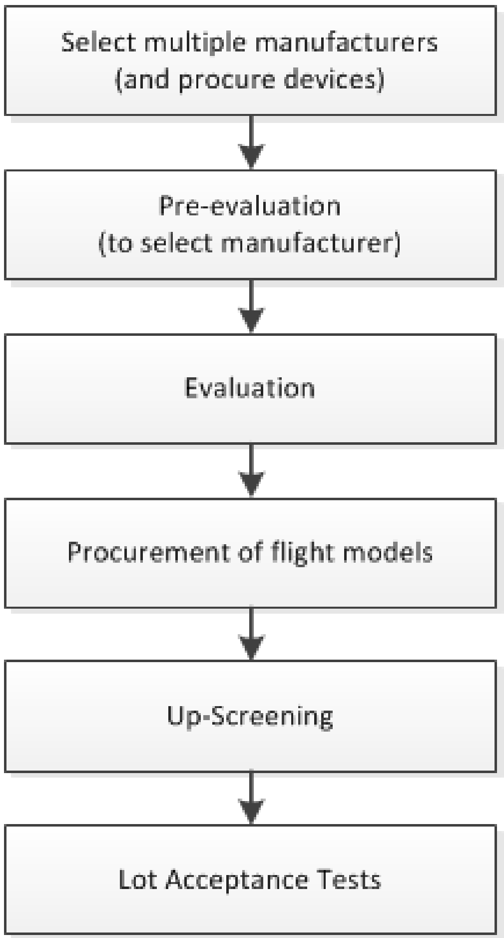
For instance, critical tests may include

- Constructional Analysis
- Operating life (with relevant conditions)
  - Vacuum operation?
  - Temperature step stress
- Thermal cycling/shock to test packaging
- Humidity exposure
- Bondability (if not wire bonded)
- May be possible to detect ESD/EOS events with a reverse-bias leakage test

Finally, audit/visit the preferred manufacturer

[8] Finisar Application Note: An Atlas of ESD Failure Signatures in VCSELs

Some suggestions for VCSEL procurement



Procure from a single batch

- with origin (batch number) to be provided

Aim to assess component with handling & processing as in the intended application

- Handling protocols to prevent ESD
- Tools & equipment as will be used in integration

Evaluation test program considerations:

- Radiation testing focus on displacement damage (DD)
  - Significant annealing occurs – for worst case test “off”
- Humidity testing – for worst case test “on”

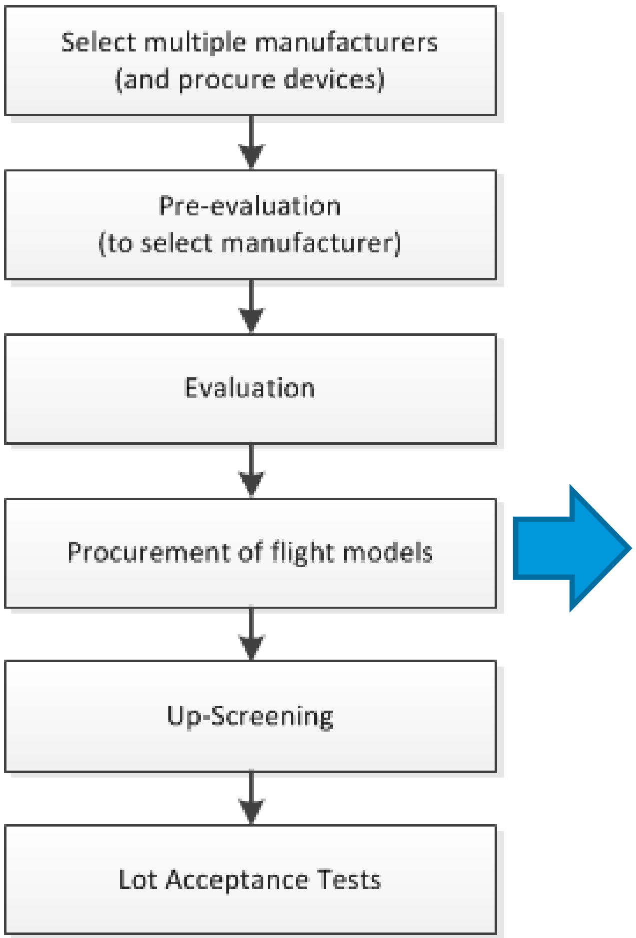
Establish lab that will perform LAT & up-screening

- Test all planned sequences & draft procedures

Draft purchase order

- Quality system in place at manufacturer
  - Configuration control
- Tests & screening methods - test reports will be supplied?

Some suggestions for VCSEL procurement



Order sufficient excess to prevent problems (2x)

Manufacturing including production controls

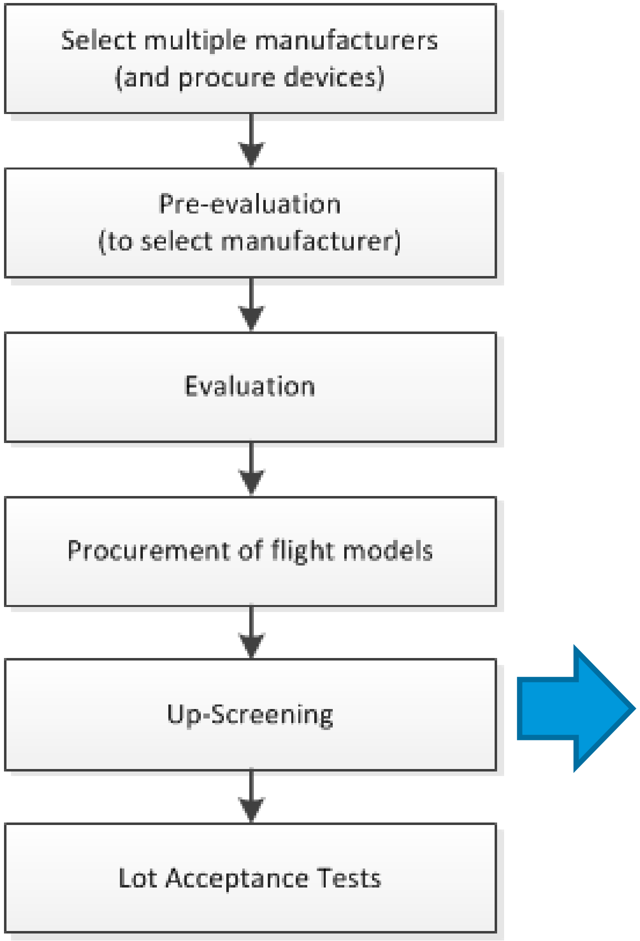
Incoming inspection

- ESCC 2045000 - Internal Visual Inspection of Discrete Non-Microwave Semiconductors

Product Assurance aspects...

- Procure from single batch
- Traceability information for all sub-parts
- Certificate of Conformance (CoC)
- ...

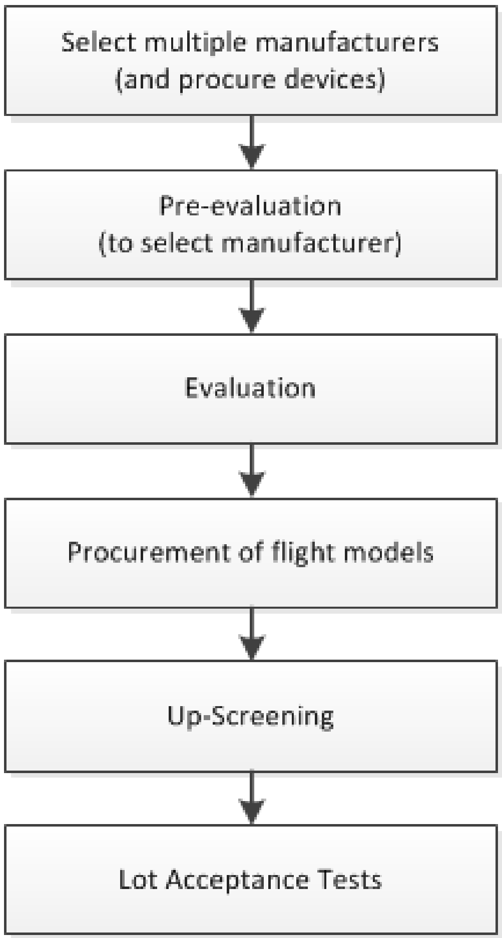
Some suggestions for VCSEL procurement

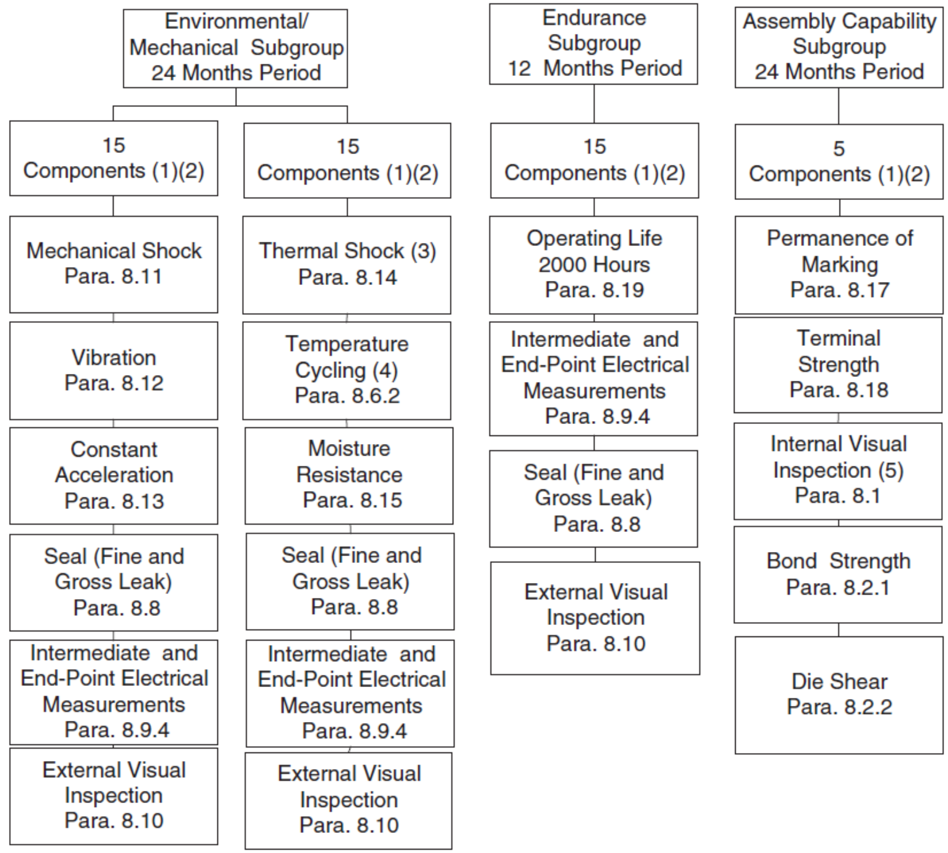


Performing up-screening tests as defined during evaluation phase

- Remove all parts that are “out of family” (e.g. 6-sigma)

Some suggestions for VCSEL procurement





For inspiration, see

- Generic specification ESCC 5000 – Discrete semiconductor components hermetically sealed
- Basic specification ESCC 23202 - Validation and Lot Acceptance Testing, Guidelines for Laser Diodes

Summary

- VCSELs are quite robust and suitable for space (compared to other lasers and LEDs)
  - Main challenges due to dark-line defects (same as for other AlGaAs/GaAs lasers)
  - And ESD/EOS (VCSELs particularly sensitive)

- A well planned procurement process is key for quality assurance of final product

- Will be new reliability challenges as modulation speeds increase
  - 14-40 Gbps
  - Higher current densities to achieve faster rise/fall times
  - Better thermal management

References

[1] O. Ueda, S.J. Pearton; Materials and Reliability Handbook for Semiconductor Optical and Electron Devices

[2] F. Berghmans et al, Combined Gamma and Neutron Radiation Effects on VCSELs , IEEE Proc., 2002

[3] R.A. Morgan et al, Vertical cavity surface emitting lasers for space-borne photonic interconnects", SPIE Proc, vol. 2811, 1996

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[6] Vixar 850nm Multi-Mode VCSEL data sheet: http://vixarinc.com/pdf/850M-0000-x002.pdf

[7] Finisar, 10Gb Oxide Isolated VCSEL Reliability Report, https://www.finisar.com/sites/default/files/downloads/reliability_data_10gb_oxide_isolated_vcsel_reliability_report.pdf

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