Failure Modes, Effects and Criticality Analysis and Accelerated Life testing of LEDs for Medical applications

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Agenda

1. Medical Diagnostic Application for LEDs

2. Failure Modes and Effects Criticality Analysis (FMECA)

- Failure Modes & Mechanisms of AlGaInP/GaP LEDs
- Initial FMECA Analysis (Before Accelerated Life Test)
- Residual FMECA Analysis (After Accelerated Life Test)

3. Accelerated Life Testing (ALT) of AlGaInP/GaP LEDs

- Inverse Power Law Model for High Current & Arrhenius Model for High Temperature Aging
- Logarithmic Degradation Rate modeling
- Optical Power vs. Vf performance during ALT
- Peak wavelength & Full Width Half Max (FWHM) during ALT

4. Regression Analysis of Prior Publ.Data for AlGaInP/GaP LEDs

5. Conclusions.

Medical Diagnostic Application for LEDs

Fig. 1.1a LED in Lighting / Fiber Optics Application

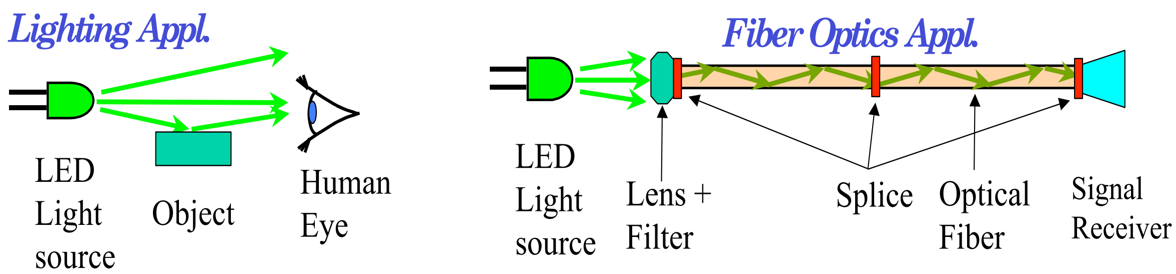
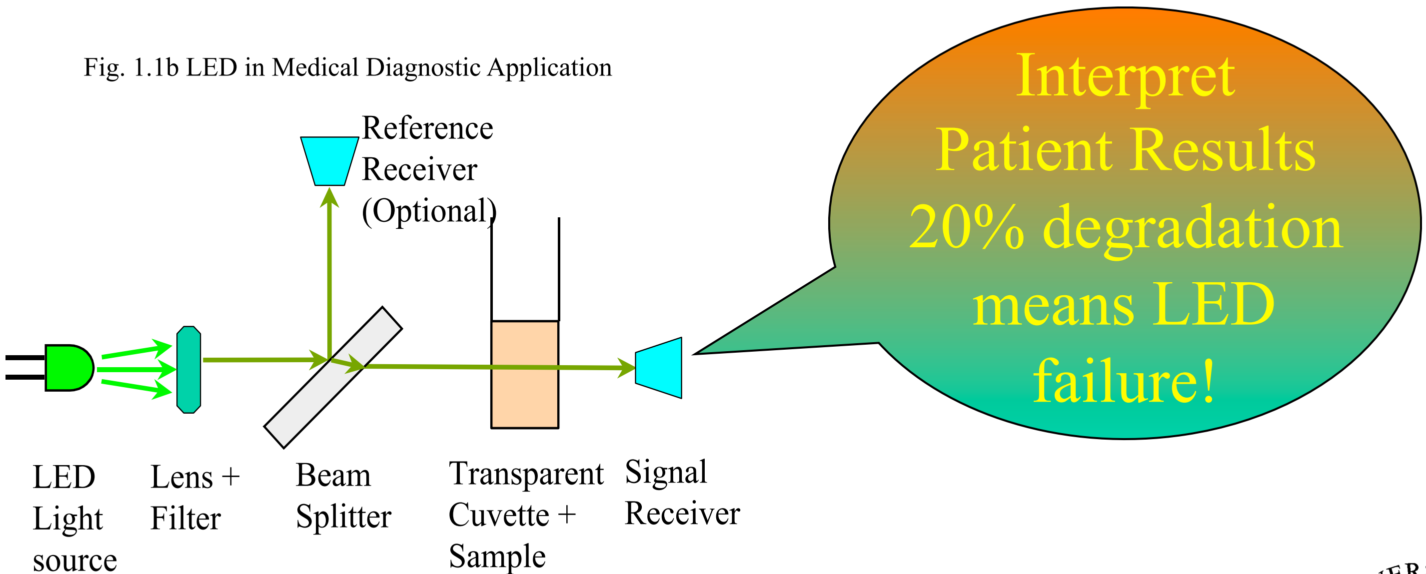


Fig. 1.1b LED in Medical Diagnostic Application



Generic AlGaInP/GaP LED structure & fab. process

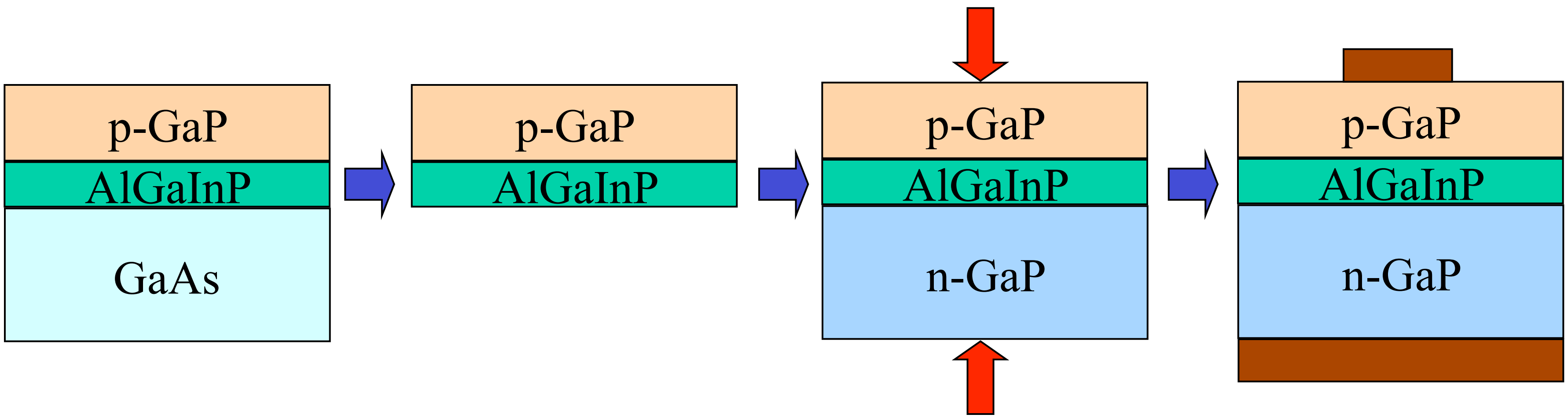
AlGaInP/GaP chip fabrication process, Vanderwater et al [6]

LED epitaxial structure grown on GaAs substrate

GaAs substrate chemically removed

n-GaP wafer bonded in place of GaAs substrate

Contacts added & packaging



High Temperature & Pressure

Diagram not to scale

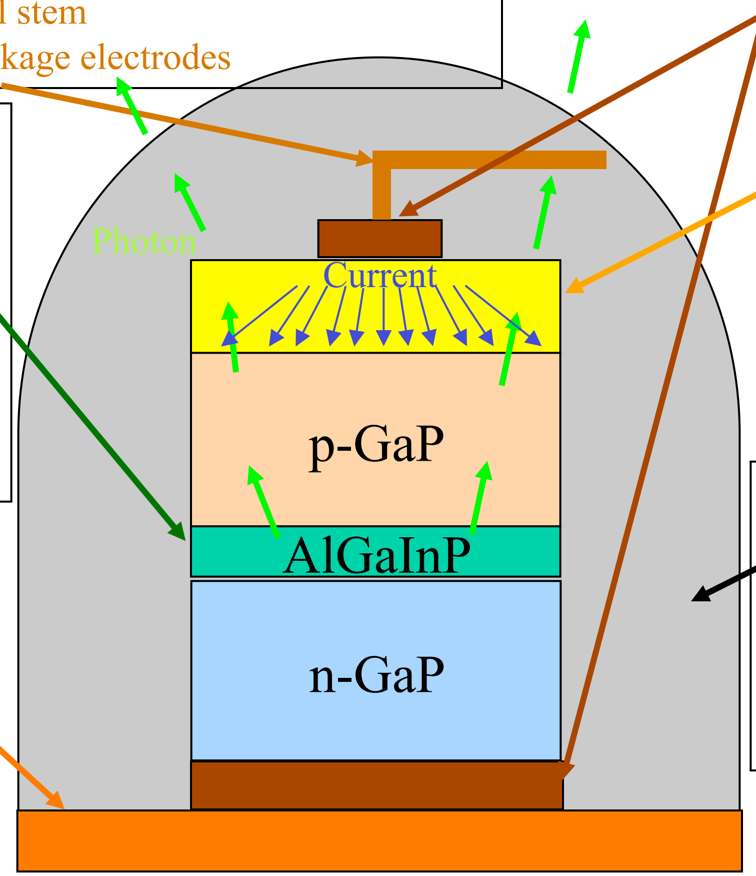
Failure Modes/Mechanisms AlGaInP/GaP LEDs

Packaging failure: Bond Wires [2]
- Electro-migration of bond wires
- Burnout due to excessive current
- Void formation at the solder metal stem
- Reaction of solder metal with package electrodes

P - N Metal contacts [2]:
- Interdiffusion

Active Region [6,7,12]:
- Dislocation growth
- Metal diffusion in AlGaInP
- Heating effects of AlGaInP active region resulting in enhanced current injection

ITO layer [16] for current spreading & light extraction:
- Loss of Oxygen from ITO
- De-adhesion



Packaging [2] failure: Heat sink
- Heat sink de-lamination

Plastic Encapsulation [21]:
- Discoloration
- Carbonization
- Polymer degradation

Diagram not to scale

Failure Modes & Effects Criticality Analysis

Severity Classification for Medical Diagnostic Application

Level	Rating	Description for Medical Diagnostic Instrument
Catostrophic	1	Inaccurate analytical result, Erroneous But Believable (EBB) result May lead to death of patient or user or Serious deterioration in their state of health
Critical	2	Incorrect diagnosis or use of less effective or inappropriate treatment
Marginal	3	Possible Erroneous But Believable (EBB) result, Test is used in conjunction with other diagnostic information.
Minor	4	Delayed or no medical test result, Incorrect result causing no difference in diagnosis or no inappropriate treatment, Incorrect result requiring reflex or confirmatory testing.
None	5	---

FMECA continued

Occurrence Classification

Level	Rating	Description
Frequent	1	A single failure mode probability > 20% of overall component failure probability
Resonably Probable	2	A single failure mode probability > 10% and < 20%of overall component failure probability
Occassional	3	A single failure mode probability > 1% and < 10%of overall component failure probability
Remote	4	A single failure mode probability > 0.1% and < 1%of overall component failure probability
Extremely Unlikely	5	A single failure mode probability < 0.1%of overall component failure probability

Failure mode criticality number

$C_m=\beta\alpha\lambda T$

- β – Failure Effect Probability
- α – Failure Mode Ratio
- λ – Failure Rate
- T – Operating Time

FMECA Initial (Before Accelerated Life Test)

Sr.#	Failure Modes/Mechanisms	Causes	Local Effects at LED level	System Effects in Medical equipment	Severity	Failure Effect Probability (ß)	Failure Mode Ratio (a)	Failure Rate	Operating Time (T) in hrs	Criticality #
1	Packaging failure (Heat Sink)	Heat sink de-lamination	- Decrease of optical output - Local heating effects	- Unscheduled module replacement - Delayed medical test results	3	0.4	0.3	1.8E-11	31500	6.7E-08
2	Degradation of plastic encapsulation	- Discoloration - Carbonization - Polymer degradation at high temperature	- Gradual decrease of optical output	- Excessive drift requires unscheduled calibration - Delayed medical test results	3	0.4	0.2	1.8E-11	31500	4.5E-08
3	Degradation of ITO layer	- Loss of Oxygen from ITO - De-adhesion	- Decrease of optical output - Non-uniform light emission	- Unscheduled module replacement - Delayed medical test results	4	0.3	0.1	1.8E-11	31500	1.7E-08
4	Packaging failure (Bond Wires)	- Electro-migration of bond wires - Burnout due to excessive current - Void formation at the solder metal stem - Reaction of solder metal with package electrodes	- Abrupt LED failure	- Unscheduled module replacement - Delayed medical test results	4	0.9	0.1	1.8E-11	31500	5.0E-08
5	Degradation of active layer	- Dislocation growth - Metal diffusion in AlGaInP - Heating effects of AlGaInP active region resulting in enhanced current injection	- Gradual decrease of optical output	- Excessive drift requires unscheduled calibration - Delayed medical test results	4	0.4	0.4	1.8E-11	31500	9.0E-08
6	Degradation of P-N metal contacts	- Interdiffusion	- Change in IV characteristics	- Design will accommodate minor changes in IV characteristics	5	0.4	0.2	1.8E-11	31500	4.5E-08

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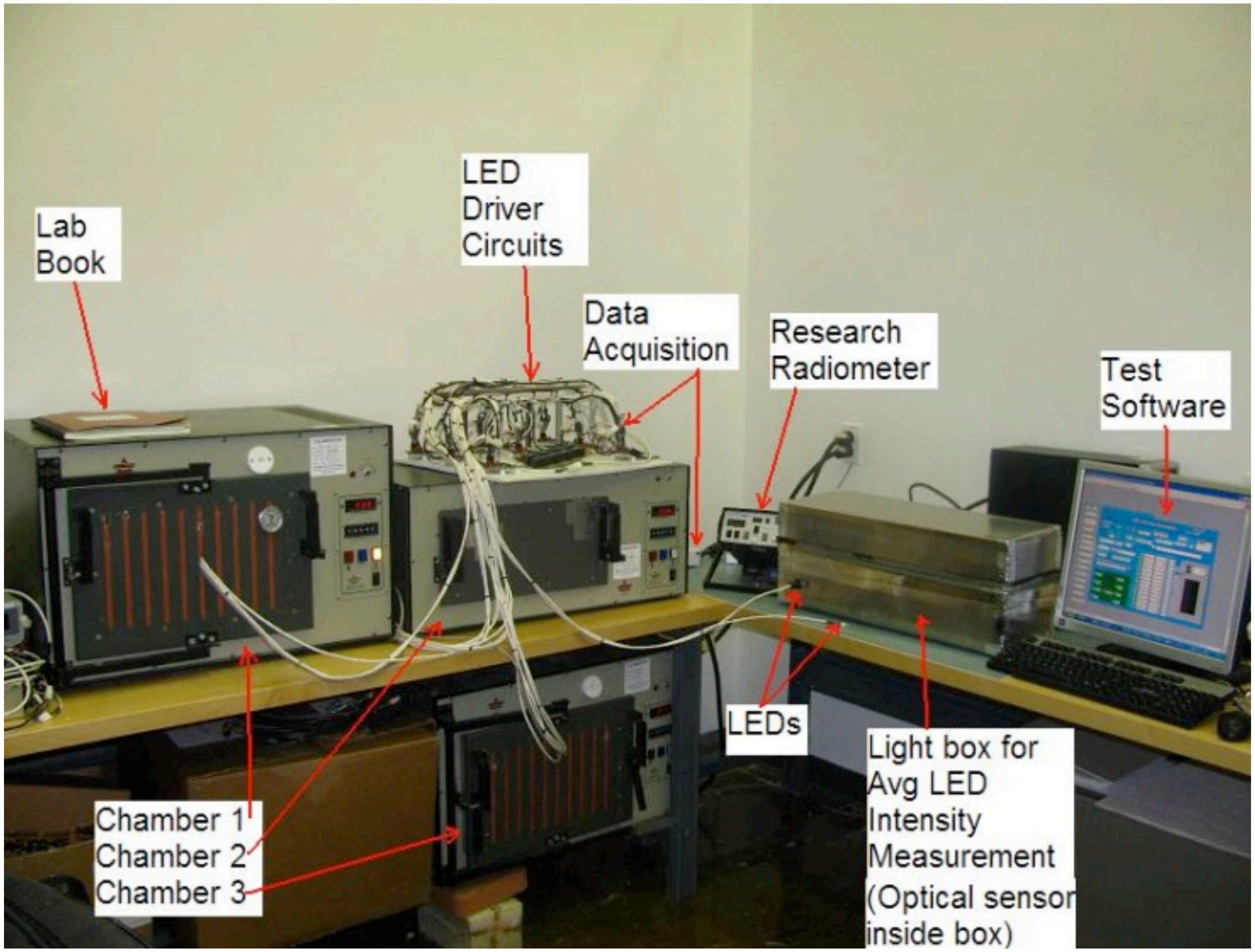
Accelerated Life Test Setup



Setup for LED Characterization

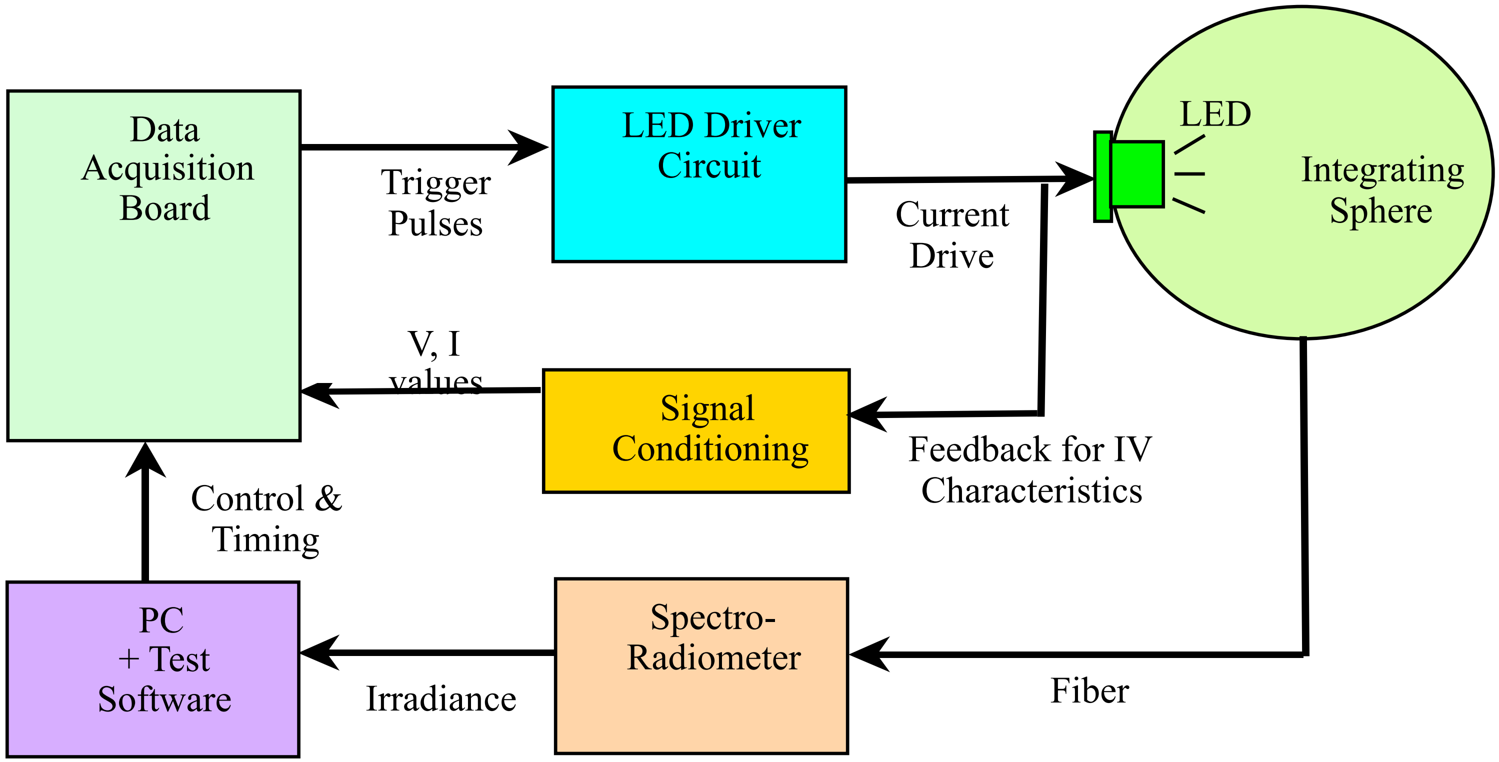


Fig. 2.3.3 Setup for LED Characterization

Accelerated Life Test Conditions

Test Conditions:

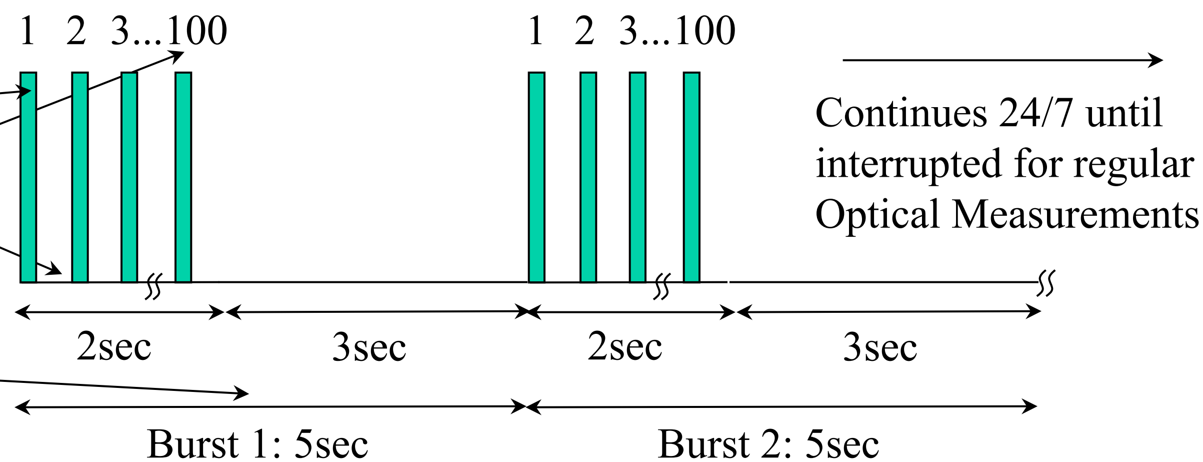
Chamber 1: 35°C
5 LEDs in each Batch

Chamber 2: 55°C
5 LEDs in each Batch

Chamber 3: 75°C
5 LEDs in each Batch

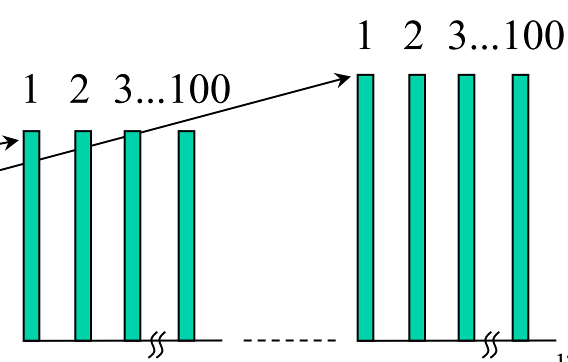
Burst/Pulse Testing:

- Pulse On: 0.1ms
- Pulse Off: 19.9ms
- # of Pulses: 100
- Burst On: 2s
- Burst Off: 3s
- Burst Period: 5s
- Duty Cycle: 100 x 0.1/5000 = 0.2%



LED Driver:

- Separate driver for each of the 15 LEDs
- Pulsed at constant Peak Current: 483mA for Batch 2
- Pulsed at constant Peak Current: 725mA for Batch 3



Inverse Power Law Modeling: Current Density

The inverse power law relation ship is given as

$$TTF = A.J^{-n} \qquad \text{- (1)}$$

Where TTF=Time to failure in hrs, J=LED Current density in Amps/sq^2, A & n are +ve constants

Taking Ln on both sides,

$$Ln(TTF) = LnA - nLn.J \qquad \text{- (2)}$$

This gives a straight line relationship where '-n' is the slope, LnJ is the accelerating variable and LnA is the y-intercept. The negative slope implies that as the current density increases, the TTF decreases.

Arrhenius Reaction Rate Modeling: Temperature

Arrhenius reaction rate model is $Rate = Be^{-\left(\frac{Ea}{KT}\right)}$ - (3)

Where T=Temperature in °K, Ea=Activation energy of the LED degradation, K=Boltzmann's constant, B is another constant.

Taking reciprocal of the 'rate' to get 'time' $TTF = Ce^{\left(\frac{Ea}{KT}\right)}$ - (4)

Where TTF=Time to failure in hrs, C=1/B is another constant. Taking Ln,

$$Ln(TTF) = LnC + \frac{Ea}{KT}$$ - (5)

A straight line relationship where 'Ea/K' as slope and LnC is the y-intercept. For graphing convenience, we use 'Ea' as slope and 1/KT as the accelerating variable. As temperature increases, 1/KT decreases and the TTF also decreases.

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Acceleration Factor Computation

Acceleration Factor for Inverse Power Law Model is given by

$$AF_1 = \frac{TTF_{Use}}{TTF_{Acc}} = \left(\frac{J_{Acc}}{J_{Use}}\right)^n \qquad - (6)$$

Acceleration Factor for Arrhenius Reaction Rate Model is given by

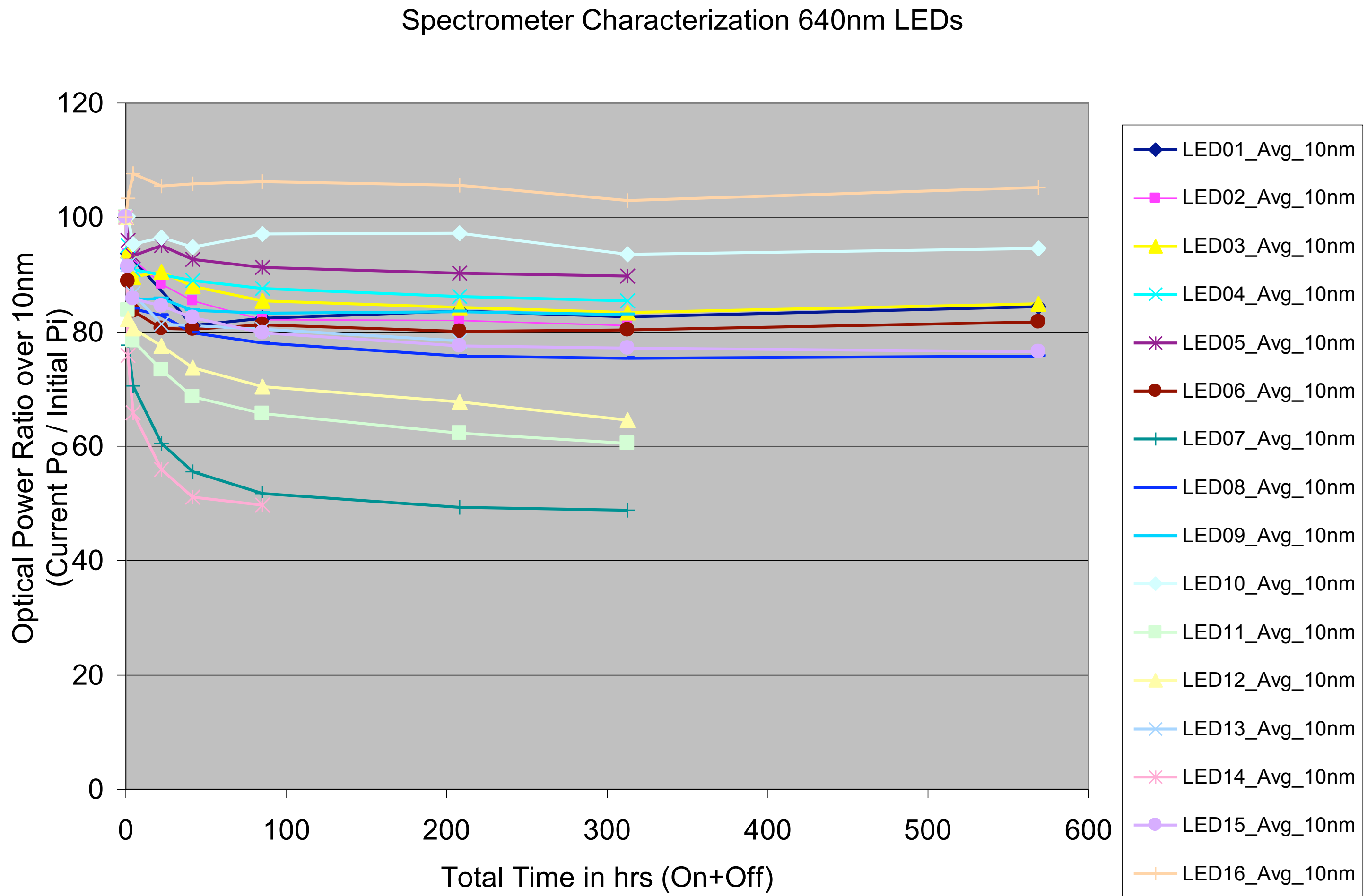
$$AF_2 = \frac{TTF_{Use}}{TTF_{Acc}} = e^{\frac{Ea}{K}\left(\frac{1}{T_{Use}} - \frac{1}{T_{Acc}}\right)} \qquad - (7)$$

Assume Ea & convert all TTF data to use Temperature T to estimate ‘n’
Take n above & convert all TTF data to use current density J to estimate ‘Ea’.
Repeat using Iterative Regression Analysis to estimate ‘Ea’ and ‘n’.

Overall Acceleration Factor is given by

$$AF = AF_1 x AF_2 = \left(\frac{J_{Acc}}{J_{Use}}\right)^n e^{\frac{Ea}{K}\left(\frac{1}{T_{Use}} - \frac{1}{T_{Acc}}\right)} \qquad - (8)$$

Accelerated Life Test Data - Batch2



Peak LED current: 483mA

Chamb1: 35°C

Chamb2: 55°C

Chamb3: 75°C

Reference LED

Test Results: Using regression, Act Energy: 1.14eV, IPL n: 4.48

Failure Modes: Active region & encapsulation, Degradation Rate: Logarithmic with Time

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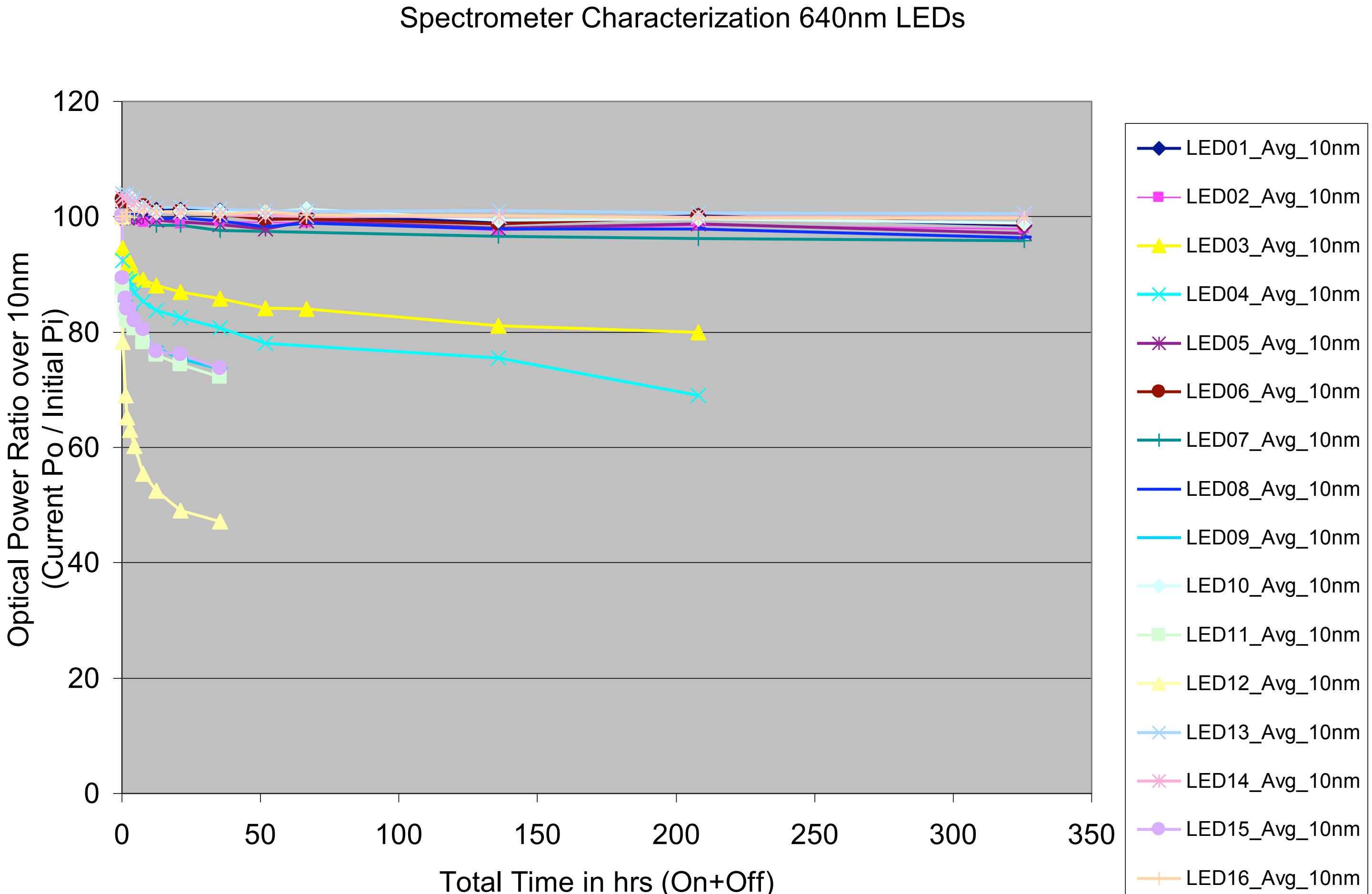
Accelerated Life Test Data - Batch3



Peak LED current: 725mA

Chamb1: 35°C

Chamb2: 55°C

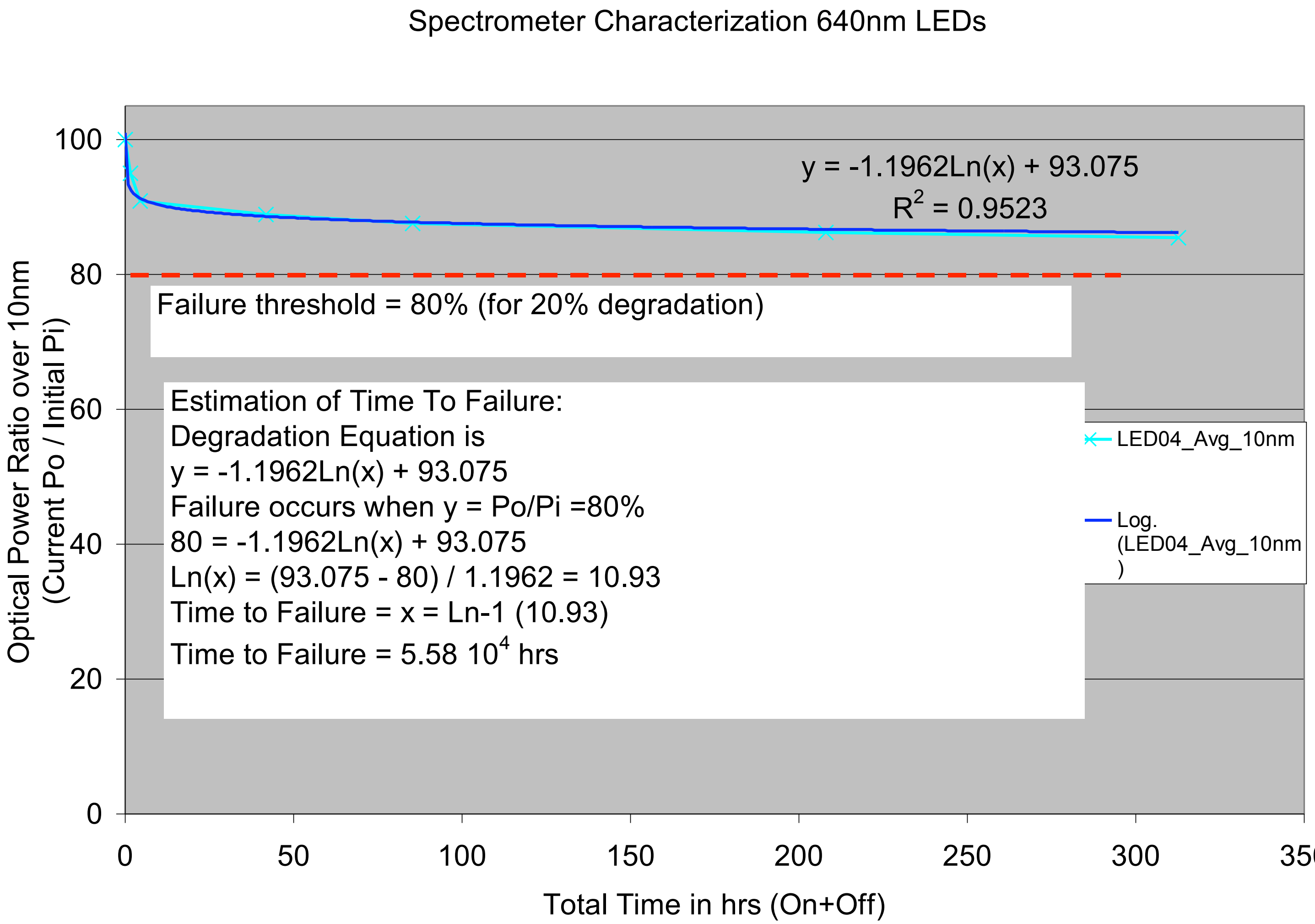
Chamb3: 75°C

Reference LED

Test Results: Using regression, Act Energy: 1.14eV, IPL n: 4.48

Failure Modes: Active region & encapsulation, Degradation Rate: Logarithmic with Time

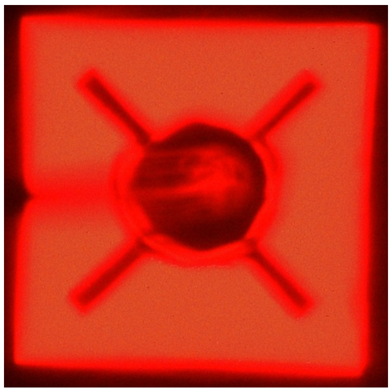
Logarithmic degradation: Time To Failure Prediction



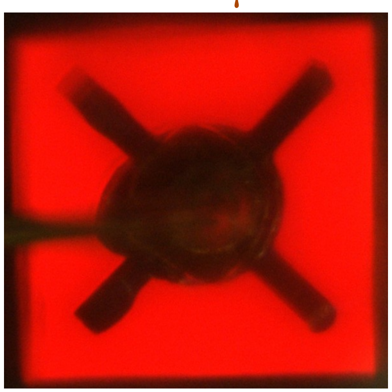
Logarithmic degradation rate of LED. In agreement with Yanagisawa et al [31]

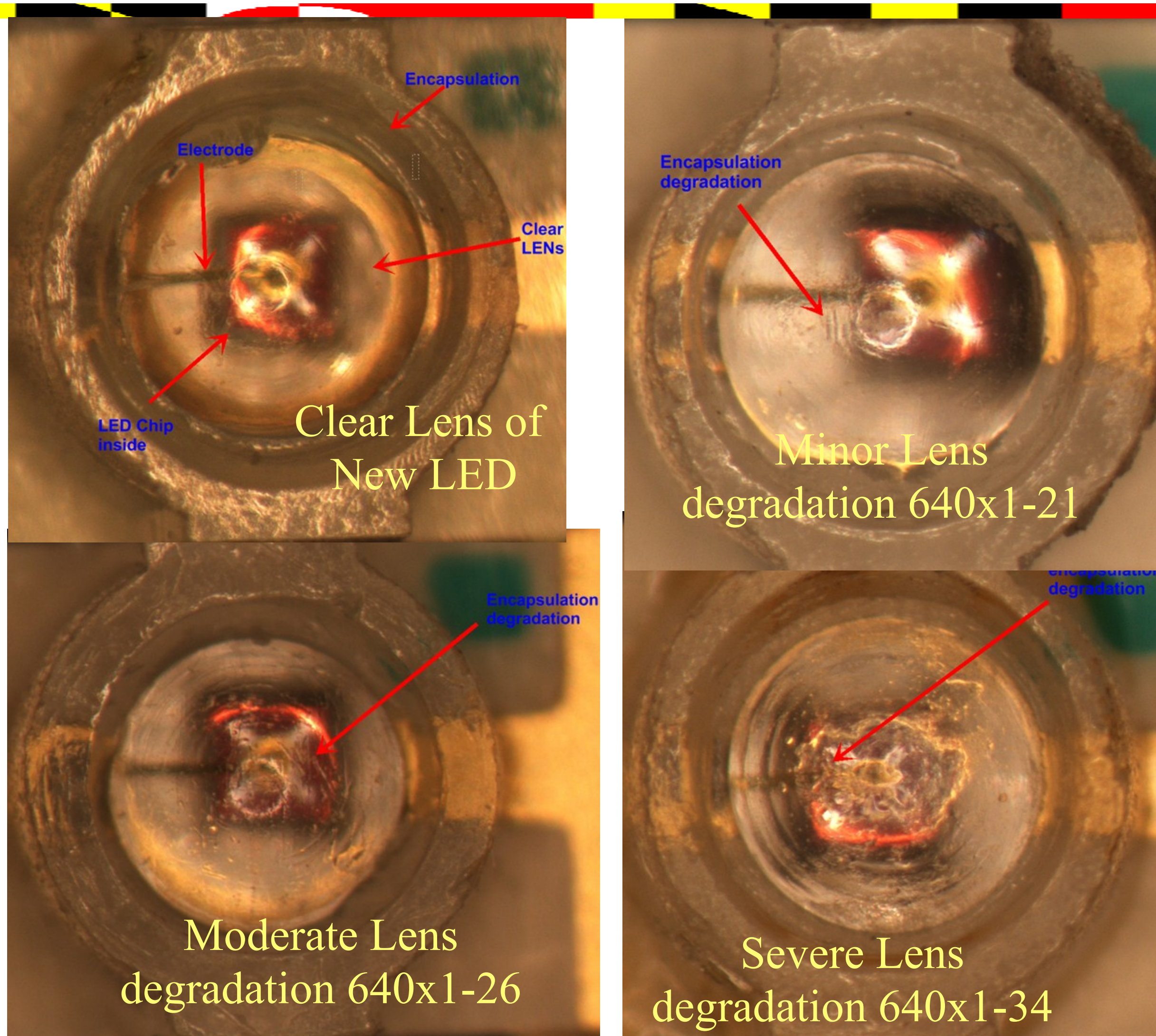
Accelerated Life Test: LED Photos

New Chip
(340x340µm)
On at 40µA

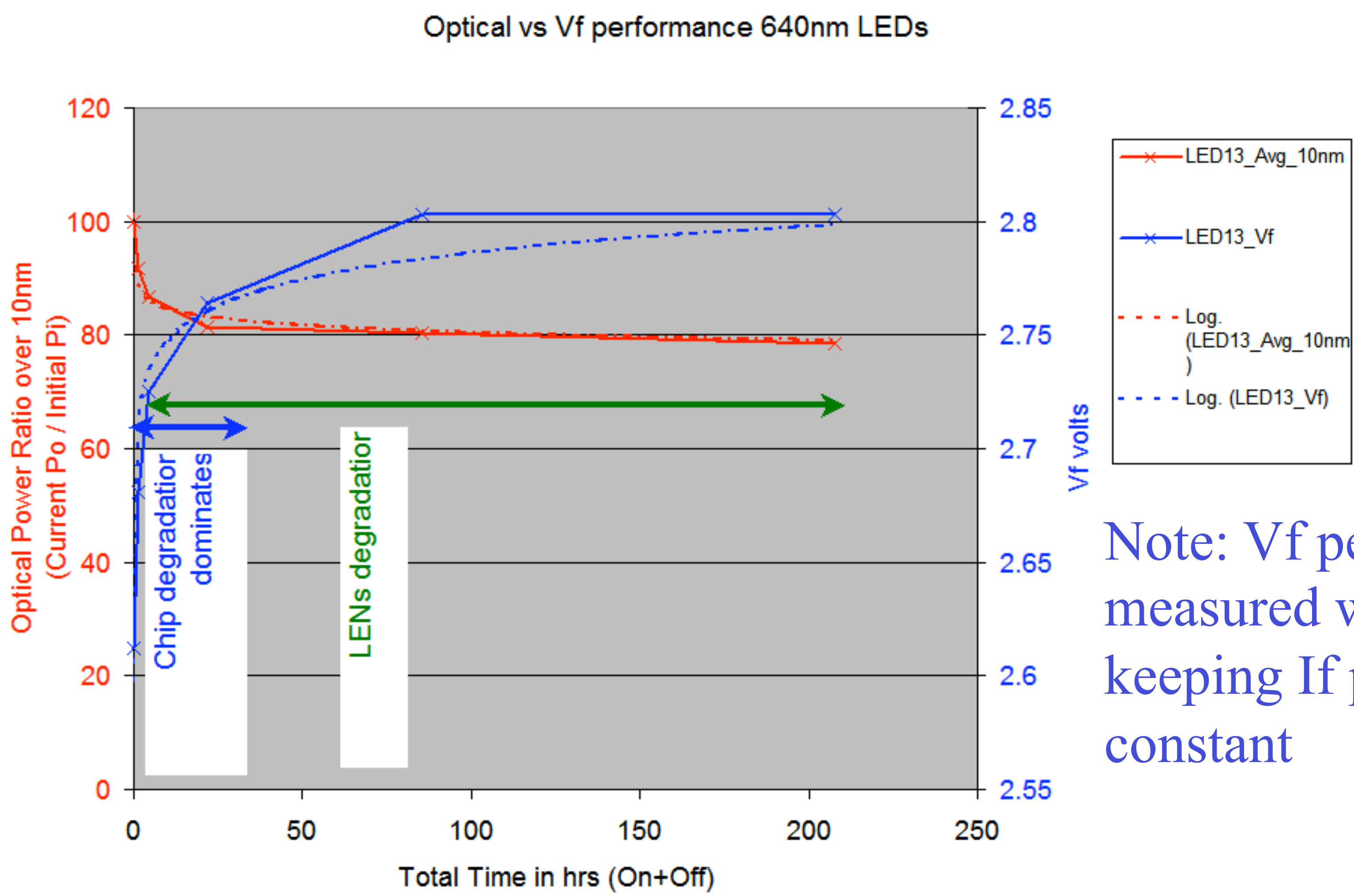


640x1-26
On at 40µA





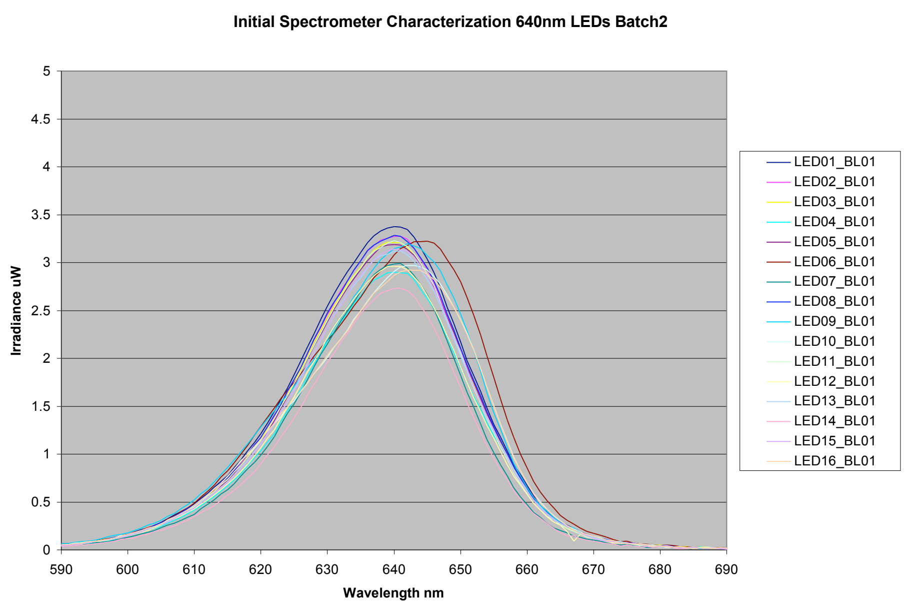
Chip (Vf) Vs LENs degradation



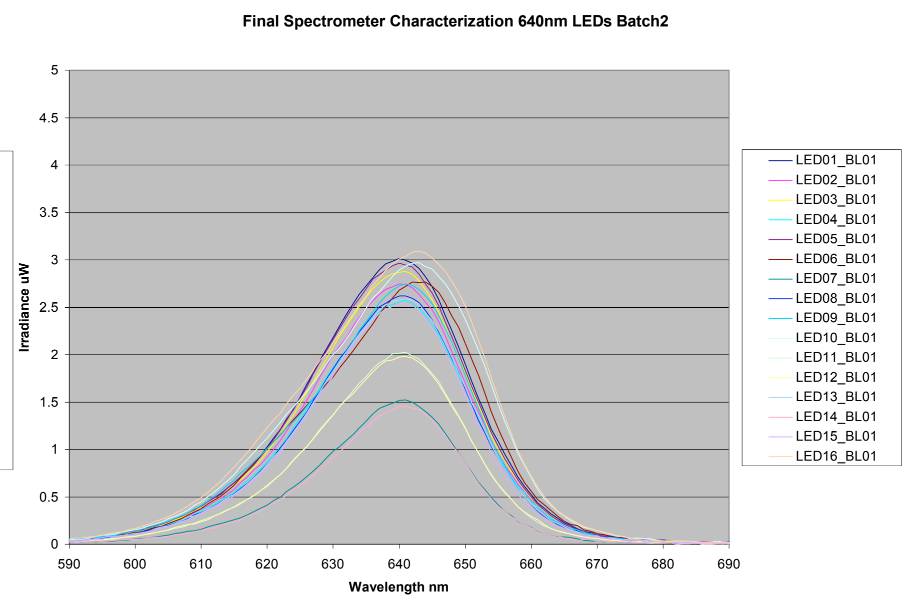
Note: Vf peak measured while keeping If peak constant

Accelerated Life Test: Spectrum change

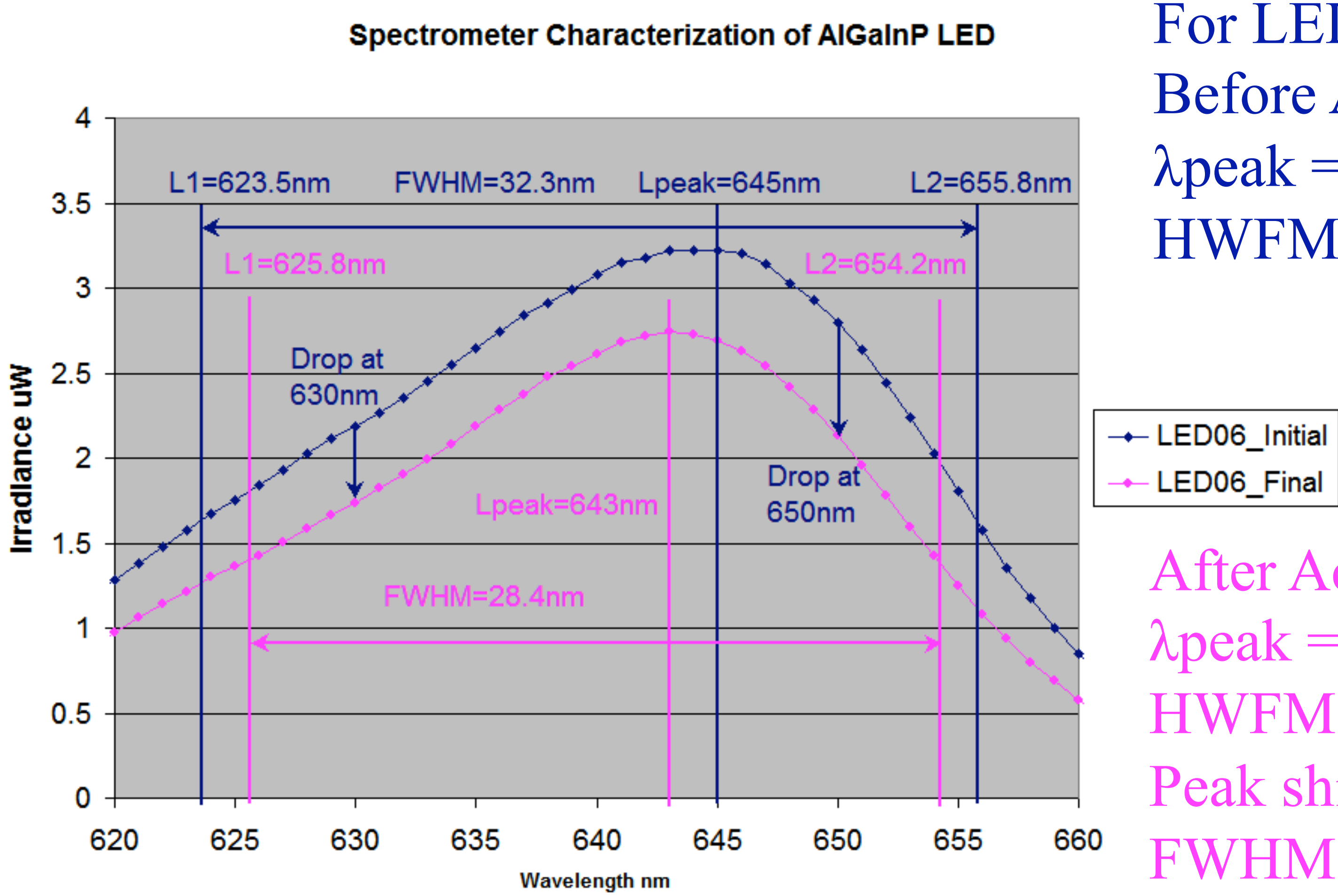
Before Accelerated Life Test



After Accelerated Life Test



Accelerated Life Test: Peak Shift & narrow FWHM



For LED 640x1-26
Before Acc. Life Test
λpeak = 645nm
HWFM = 32.3nm

After Acc. Life Test
λpeak = 643nm
HWFM = 28.4nm
Peak shifted to left
FWHM narrowed

Results of Accelerated Life Test Batch2

UUT	Temp C	TTF hrs Observed 20% degrd	MTTF	Acc Factor	Act. Energy eV	TTF hrs Estimated 20% degrd	Equation for Logarithmic degradation model	LENs degradation	Vf Increase %	% Drop @ 630nm rel to 640nm	% Drop @ 650nm rel to 640nm
640x1-21	35	Suspend	3457.9			1755.6	y = -1.4537Ln(x) + 90.86 R2 = 0.8617	Minor Surface	4.0	3.2	-0.2
640x1-22	35	Suspend				335.9	y = -2.8548Ln(x) + 96.606 R2 = 0.9119	Minor Few Bubbles	4.6	4.4	0.4
640x1-23	35	Suspend				8282.1	y = -1.4323Ln(x) + 92.922 R2 = 0.9367	Minor Surface	6.5	4.6	1.0
640x1-24	35	Suspend				55851.2	y = -1.1962Ln(x) + 93.075 R^2 = 0.9523	Moderate Edge of globe	7.1 -> 5.2	4.7	1.0
640x1-25	35	Suspend				1.8E+08	y = -0.8057Ln(x) + 95.326 R2 = 0.8927	Moderate Surface	4.9	3.5	2.6
640x1-26	55	207.9	201.9	17.1	1.24	195.0	y = -1.5697Ln(x) + 88.277 R2 = 0.9025	Moderate Surface	2.9	5.2	9.6
640x1-27	55	1.5				0.3	y = -4.3842Ln(x) + 73.933 R2 = 0.9732	Moderate Surface	7.9 -> 6.4	4.9	2.1
640x1-28	55	41.7				38.7	y = -1.9411Ln(x) + 87.094 R2 = 0.9864	Minor Few Bubbles	7.5	5.6	0.8
640x1-29	55	Suspend				1225.0	y = -1.4315Ln(x) + 90.179 R^2 = 0.9535	Minor Few Bubbles	2.5	3.8	12.5
640x1-30	55	Suspend				9.7E+17	y = -0.4285Ln(x) + 97.745 R2 = 0.5402	Minor Few Bubbles	4.5	0.3	0.0
640x1-31	75	4.4	48.8	70.8	0.98	1.5	y = -3.2403Ln(x) + 81.238 R^2 = 0.9684	Moderate Surface+Bubles	3.6	6.0	2.6
640x1-32	75	4.4				3.2	y = -2.748Ln(x) + 83.18 R^2 = 0.9754	Minor Few Bubbles	11.7 -> 7.0	6.1	3.2
640x1-33	75	85.3				125.9	y = -1.8618Ln(x) + 89.002 R^2 = 0.9464	Minor Very Few Bubbles	8.8	4.1	2.3
640x1-34	75	1.5				0.2	y = -4.6769Ln(x) + 71.53 R^2 = 0.9691	Severe Surface	8.6 -> 4.5	4.6	3.5
640x1-35	75	85.3				113.4	y = -1.9047Ln(x) + 89.011 R2 = 0.9633	Minor Few Bubbles	11.5 -> 7.8	4.2	4.1

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Results of Accelerated Life Test Batch3

UUT	Temp C	TTF hrs Observed 20% degrd	MTTF	Acc Factor	Act. Energy eV	TTF hrs Estimated 20% degrd	Equation for Logarithmic degradation model	LENs degradation	Vf Increase %	% Drop @ 630nm rel to 640nm	% Drop @ 650nm rel to 640nm
640x1-41	35	Suspend	175.2			9.7E+16	y = -0.5742Ln(x) + 102.46 R2 = 0.7083	Moderate Surface	-0.8	1.1	1.5
640x1-42	35	Suspend				4.7E+22	y = -0.3873Ln(x) + 100.22 R2 = 0.7377	Minor Surface	-1.6	1.8	4.4
640x1-43	35	208.1				316.3	y = -2.339Ln(x) + 93.465 R2 = 0.9704	Moderate Bubles	8.6	5.0	-0.8
640x1-44	35	35.3				34.1	y = -2.5448Ln(x) + 88.985 R2 = 0.8966	Minor Surface	5.6	5.7	0.0
640x1-45	35	Suspend				6.8E+19	y = -0.4472Ln(x) + 100.42 R2 = 0.7487	Severe Surface Scratch	0.3	2.0	3.4
640x1-46	55	Suspend	6.0	29.2	1.47	1.2E+16	y = -0.6064Ln(x) + 102.43 R2 = 0.8948	Moderate Surface	-0.9	0.9	2.7
640x1-47	55	Suspend				4.0E+11	y = -0.7681Ln(x) + 100.51 R2 = 0.9481	Minor Surface	-1.6	1.2	1.7
640x1-48	55	Suspend				1.6E+14	y = -0.6449Ln(x) + 101.1 R2 = 0.8551	Moderate Surface	-1.6	1.2	1.6
640x1-49	55	7.8				6.0	y = -2.7834Ln(x) + 84.99 R2 = 0.9781	Minor Surface	7.5	6.6	0.0
640x1-50	55	Suspend				3.9E+13	y = -0.7512Ln(x) + 103.5 R2 = 0.8257	Minor Surface	-2.2	1.5	-0.9
640x1-51	75	4.4	3.7	47.9	0.89	3.8	y = -2.8983Ln(x) + 83.881 R2 = 0.9886	Minor Surface	7.5	6.8	0.1
640x1-52	75	0.3				0.1	y = -5.7886Ln(x) + 68.472 R2 = 0.986	Minor Surface	6.6	6.5	0.0
640x1-53	75	Suspend				3.9E+17	y = -0.5841Ln(x) + 103.66 R2 = 0.9172	None	-1.6	1.0	2.7
640x1-54	75	Suspend				3.4E+17	y = -0.5618Ln(x) + 102.68 R2 = 0.9082	Minor Surface	-2.3	0.2	1.9
640x1-55	75	7.8				7.0	y = -2.7536Ln(x) + 85.365 R2 = 0.9692	Minor Surface	10.1	6.2	0.5

Regression Analysis of Published Data: AlGaInP

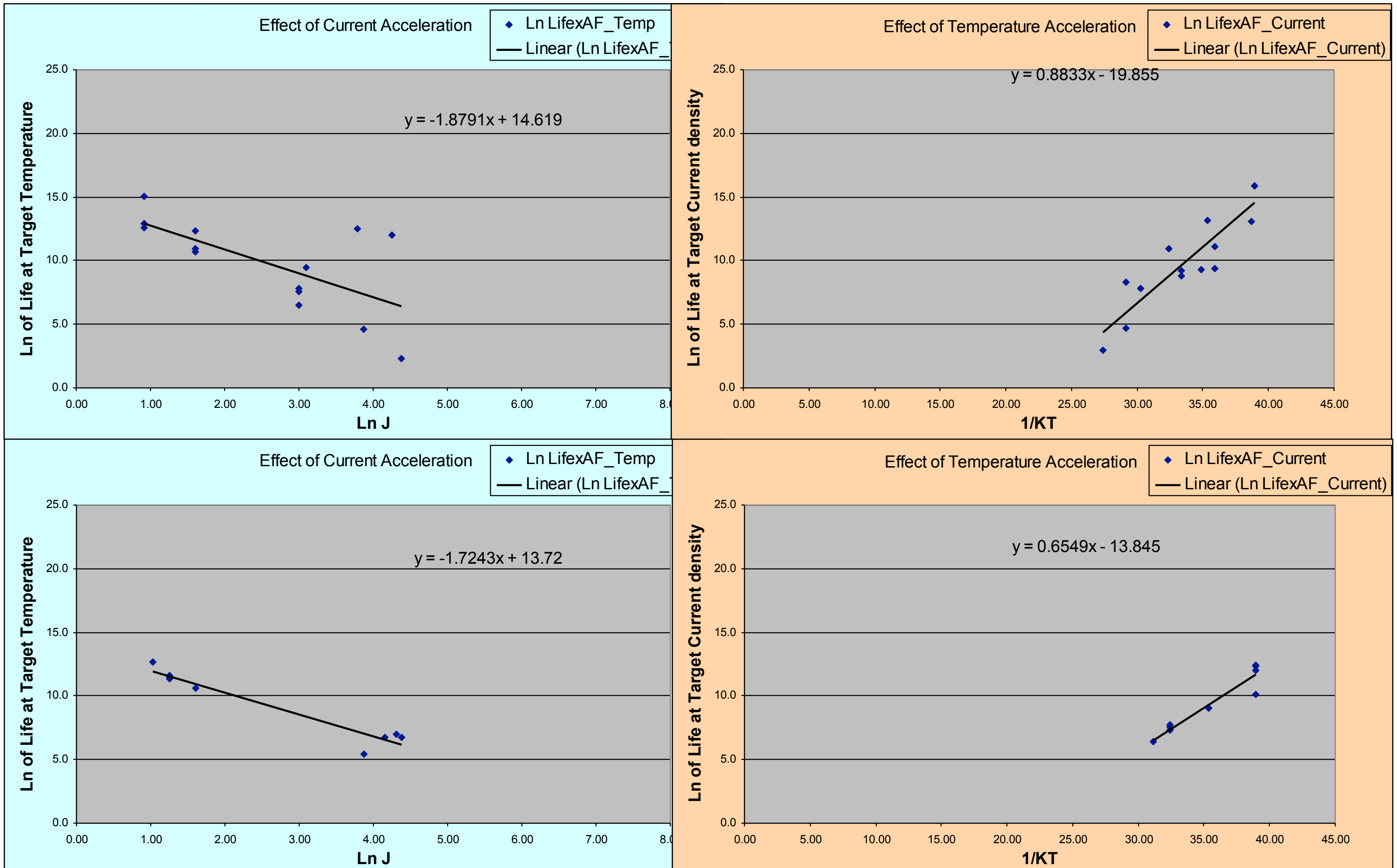
Current Density: Inverse Power Law | Temperature: Arrhenius Reaction Rate

DH-DC
IPL
n=1.88

Arrhen.
Act.En.
=0.88eV

MQW-DC
IPL
n=1.72

Arrhen.
Act.En.
=0.65eV

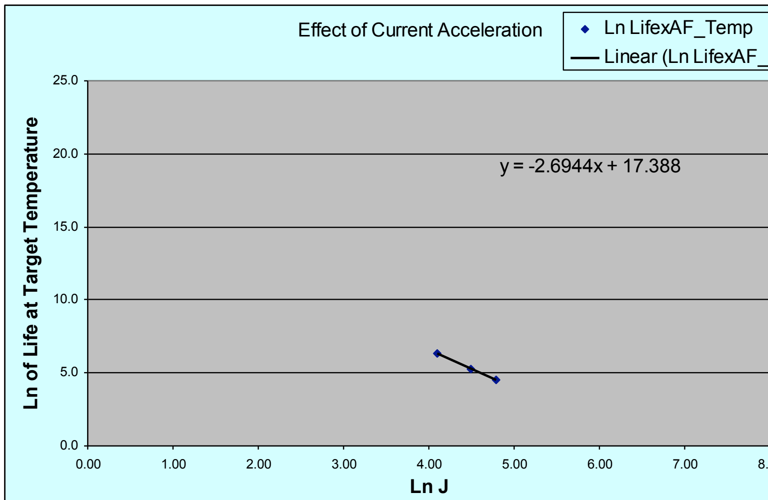


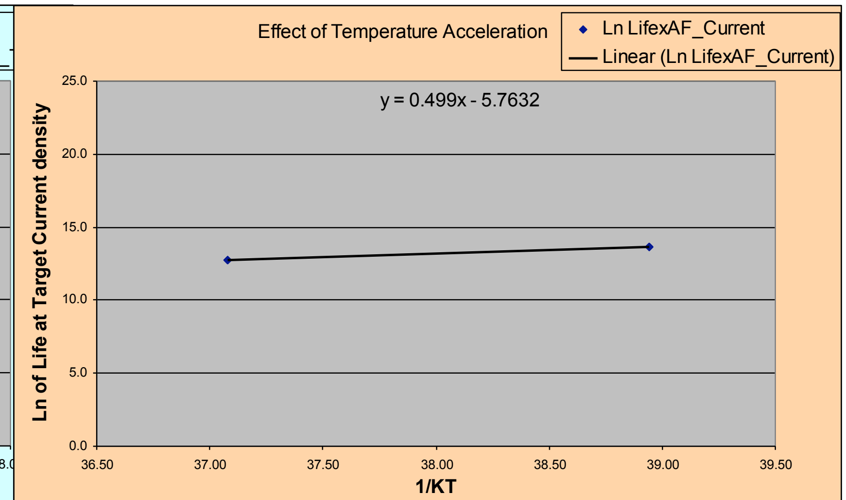
Regression Analysis of Published Data: GaN

Current Density: Inverse Power Law — Temperature: Arrhenius Reaction Rate

DH-DC
IPL
n=2.69

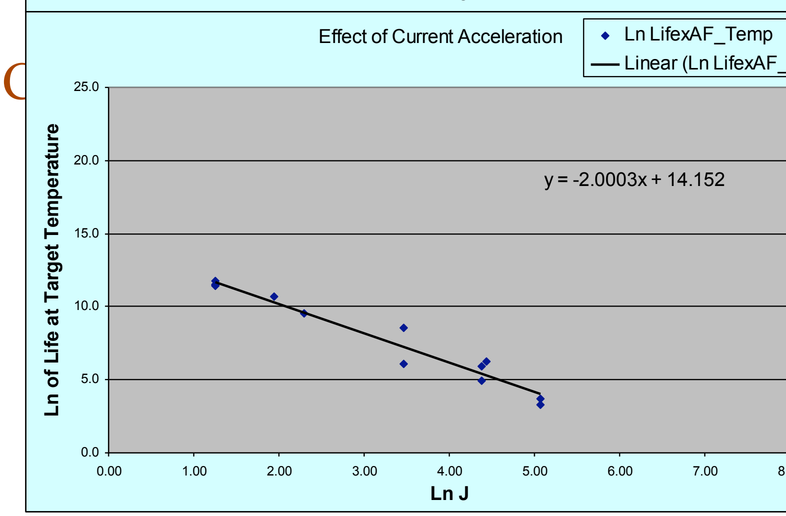
Arrhen.
Act.En.
=0.49eV

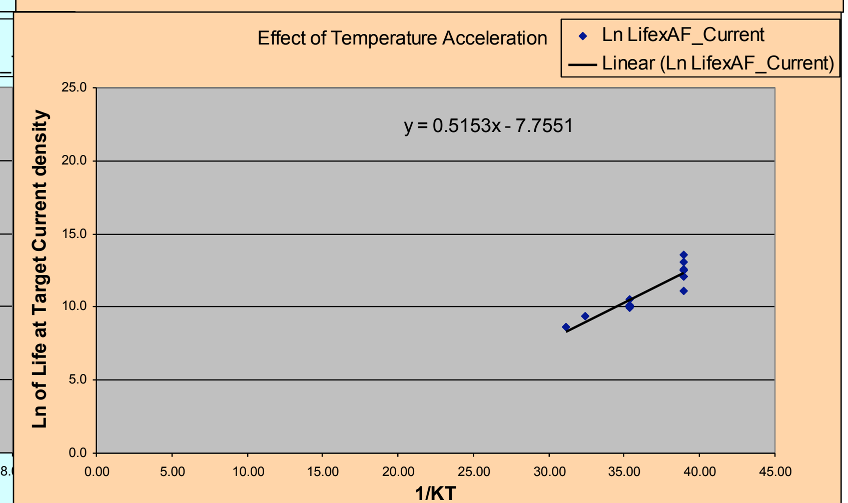




MQW-DC
IPL
n=2.00

Arrhen.
Act.En.
=0.51eV





FMECA Initial (Before Accelerated Life Test)

Sr.#	Failure Modes/Mechanisms	Causes	Local Effects at LED level	System Effects in Medical equipment	Severity	Failure Effect Probability (ß)	Failure Mode Ratio (a)	Failure Rate	Operating Time (T) in hrs	Criticality #
1	Packaging failure (Heat Sink)	Heat sink de-lamination	- Decrease of optical output - Local heating effects	- Unscheduled module replacement - Delayed medical test results	3	0.4	0.3	1.8E-11	31500	6.7E-08
2	Degradation of plastic encapsulation	- Discoloration - Carbonization - Polymer degradation at high temperature	- Gradual decrease of optical output	- Excessive drift requires unscheduled calibration - Delayed medical test results	3	0.4	0.2	1.8E-11	31500	4.5E-08
3	Degradation of ITO layer	- Loss of Oxygen from ITO - De-adhesion	- Decrease of optical output - Non-uniform light emission	- Unscheduled module replacement - Delayed medical test results	4	0.3	0.1	1.8E-11	31500	1.7E-08
4	Packaging failure (Bond Wires)	- Electro-migration of bond wires - Burnout due to excessive current - Void formation at the solder metal stem - Reaction of solder metal with package electrodes	- Abrupt LED failure	- Unscheduled module replacement - Delayed medical test results	4	0.9	0.1	1.8E-11	31500	5.0E-08
5	Degradation of active layer	- Dislocation growth - Metal diffusion in AlGaInP - Heating effects of AlGaInP active region resulting in enhanced current injection	- Gradual decrease of optical output	- Excessive drift requires unscheduled calibration - Delayed medical test results	4	0.4	0.4	1.8E-11	31500	9.0E-08
6	Degradation of P-N metal contacts	- Interdiffusion	- Change in IV characteristics	- Design will accommodate minor changes in IV characteristics	5	0.4	0.2	1.8E-11	31500	4.5E-08

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FMECA Residual (After Accelerated Life Test)

Sr.#	Failure Modes/Mechanisms	Causes	Local Effects at LED level	System Effects in Medical equipment	Severity	Failure Effect Probability (ß)	Failure Mode Ratio (a)	Failure Rate	Operating Time (T) in hrs	Criticality #
1	Packaging failure (Heat Sink)	Heat sink de-lamination	- Decrease of optical output - Local heating effects	- Unscheduled module replacement - Delayed medical test results	3	0.4	0.3	1.8E-11	31500	6.7E-08
2	Degradation of plastic encapsulation	- Discoloration - Carbonization - Polymer degradation at high temperature	- Gradual decrease of optical output	- Excessive drift requires unscheduled calibration - Delayed medical test results	3	0.6	0.7	1.8E-11	31500	2.3E-07
3	Degradation of ITO layer	- Loss of Oxygen from ITO - De-adhesion	- Decrease of optical output - Non-uniform light emission	- Unscheduled module replacement - Delayed medical test results	4	0.3	0.1	1.8E-11	31500	1.7E-08
4	Packaging failure (Bond Wires)	- Electro-migration of bond wires - Burnout due to excessive current - Void formation at the solder metal stem - Reaction of solder metal with package electrodes	- Abrupt LED failure	- Unscheduled module replacement - Delayed medical test results	4	0.9	0.1	1.8E-11	31500	5.0E-08
5	Degradation of active layer	- Dislocation growth - Metal diffusion in AlGaInP - Heating effects of AlGaInP active region resulting in enhanced current injection	- Gradual decrease of optical output	- Excessive drift requires unscheduled calibration - Delayed medical test results	4	0.6	0.6	1.8E-11	31500	2.0E-07
6	Degradation of P-N metal contacts	- Interdiffusion	- Change in IV characteristics	- Design will accommodate minor changes in IV characteristics	5	0.4	0.2	1.8E-11	31500	4.5E-08

Conclusions

Performed Initial FMECA Analysis of LED for Medical Application

Accelerated Life Testing (ALT) of AlGaInP LEDs

Logarithmic degradation rate modeling

Used Arrhenius Model for High Temperature Aging

Used Inverse Power Law Model for High Current Aging

Optical vs. Vf performance and Spectrum change during ALT

Regression Analysis of Prior Publ. Data for AlGaInP / GaN LEDs

Comparison of Prior published and Accelerated Life test data.

Performed Residual FMECA Analysis after Accelerated Life Test

Approach to verify LED suitability for Medical diagnostic appl.

References

[1] Aris Christou, 'Photonic Materials, Devices and Reliability', 2006
[2] Mitsuo Fukuda, 'Reliability & Degradation of Semiconductor Lasers & LEDs', 1991
[3] Shuji Nakamura & S.F. Chichibu, 'Introduction to Nitride Semiconductor Blue Lasers & LEDs', 2000
[4] K. Wada & S.W. Pang, 'Defects in Optoelectronic Materials', 2001
[5] Ali Mosleh, 'Bayesian Methods for Risk and Reliability', 2007
[6] Vanderwater et al. 'High-brightness AlGaInP light emitting diodes', Proceedings of the IEEE, Vol. 85, Issue 11, Pages 1752-1764, Nov. 1997
[7] Grillot et al. 'Sixty Thousand Hour Light Output Reliability of AlGaInP LEDs', IEEE Transactions on Device and Material Reliability, Vol. 6, No.4, Pages 564-574, Dec 2006
[8] Kish et al. 'Highly reliable and efficient semiconductor wafer-bonded AlGaInP/GaP LEDs', Electronics Letters, Vol. 32, Issue 2, Pages132–136, Jan 1996.
[9] Chang et al. 'AlGaInP multiquantum well light-emitting diodes', IEE Proc.-Optoelectron., Vol. 144, No. 6, December 1997
[10] Kish et al. 'High luminous flux semiconductor wafer-bonded AlGaInP/GaP large-area emitters', Electronics Letters, Vol. 30, Issue 21, Pages 1790-1792, October 1994
[11] Krames et al. 'Status and Future of High-Power LEDs for Solid-State Lighting', Journal of Display Technology, Vol. 3, Issue 2, Pages 160–175, June 2007
[12] Streubel et al. 'High Brightness AlGaInP Light-Emitting Diodes', IEEE Journal of Selected Topics in Quantum Electronics, Pages 321–332, March-April 2002
[13] Altieri et al. 'Analysis of internal quantum efficiency of high-brightness AlGaInP LEDs', The 4th International Conference on Numerical Simulation of Optoelectronic Devices Proceedings NUSOD '04, Pages 13-14, August 2004
[14] Liang et al. 'Comparison of temperature dependent electroluminescence of InGaN/GaN and AlGaInP based LEDs', Optoelectronics, The 6th Chinese Symposium Proceedings Pages 196-199, Sept. 2003.
[15] Philips, 'LUXEON Reliability Datasheet RD25', Pages 9-10, July 2006
[16] Lin et al. 'Highly reliable operation of indium tin oxide AlGaInP light emitting diodes', Electronics Letters, Vol. 30, No.21, October 1994
[17] Su et al. 'High Reliability of AlGaInP LEDs with tensile strain barrier-reducing Layer', IEEE Photonics Technology Letters, Vol. 16, Issue 1, Pages 30-32, Jan. 2004
[18] Lacey et al. 'The Reliability of AlGaInP visible LEDs', Quality & Rel. Engineering, Vol. 16, Issue 1, Pages 45 - 49, 2000.

References (continued)

[19] Dutta et al. 'High Brightness and Reliable AlGaInP-Based LED for POF Data Links', IEEE Photonics Technology Letters, Vol. 9, No 12, December 1997.
[20] Meneghini et al. 'A review on the Reliability of GaN based LEDs', IEEE Transactions on Device and Materials Reliability, Vol. 8, No. 2, June 2008.
[21] Meneghini et al. ' A review on the physical mechanisms that limit the reliability of GaN based LEDs', IEEE Transactions on Electron Devices, Vol. 51, Issue. 1, Jan 2010.
[22] Levada et al. ' Analysis of DC Current Accelerated Life Tests of GaN LEDs Using a Weibull-Based Statistical Model', IEEE Transactions on Device and Materials Reliability, Vol. 5, No. 4, Dec 2005.
[23] Buso et al. 'Performance Degradation of High-Brightness LEDs Under DC and Pulsed Bias', IEEE Transactions on Device and Materials Reliability, Vol. 8, No. 2, June 2008.
[24] Trevisanello et al. 'Accelerated life test of High Brightness LEDs', IEEE Transactions on Device and Materials Reliability, Vol. 8, No. 2, June 2008.
[25] Meneghesso et al. 'Degradation mechanisms of GaN-based LEDs after accelerated DC current aging', Electron Devices Meeting Digest, Pages 103-106, Dec 2002.
[26] Levada et al. ' High Brightness InGaN LED degradation at high injection current bias', 44th Annual International Reliability Physics Symposium Proc., Pages 615-616, Mar 2006.
[27] Meneghesso et al. 'Failure mechanisms of GaN-based LEDs related with instabilities in doping profile and deep levels', 42nd Annual International Reliability Physics Symposium Proceedings, Pages 474-478, April 2004.
[28] Osinski et al. 'AlGaN/InGaN/GaN blue light emitting diode degradation under pulsed current stress', Applied Physics Letters, 69 (7), August 1996.
[29] Barton et al. 'Life tests and failure mechanisms of GaN-AlGaN-InGaN LEDs', 35th Annual International Reliability Physics Symposium Proc, Pages 276-281, April 1997.
[30] Barton et al. 'Degradation mechanisms in GaN/AlGaN/InGaN LEDs and LDs', 10th Conf. on Semiconducting & Insul. Materials Proc., Pages 259-262, June 1998.
[31] Yanagisawa T., 'Estimation of the degradation of InGaN/A1GaN Blue LEDs', Microelectronic Reliability, Vol. 37, No. 8, pp. 1239-1241, 1997.
[32] Yanagisawa T. ' The degradation of GaAlAs red LEDs under continuous and low-speed pulse operations ', Microelectronics Reliability 38, pp. 1627-1630, 1998.
[33] Narendran et al. 'Life of LED-Based White Light Sources', IEEE/OSA Journal of Display Technology, Vol. 1, NO. 1, September 2005.