650V GaN HEMT Reliability for Automotive Applications

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Five Stages of Automotive Qualification

1. Product Qualification (Q101: Cookbook standard)
2. Extended Qualification (Beyond Q101)
3. Intrinsic Reliability (Lifetime/acceleration)
4. Extrinsic Reliability (FIT/PPM/MTBF)
5. Field Reliability

Note: this applies equally to commercial qualification
Product Qualification
1. AEC Q101
2. Testing beyond qualification
Most data from: TPH3205WSQA: Two Chip Normally-off, AEC-Q101

- D-mode GaN HEMT in series with an E-mode low voltage silicon FET.
- Package: TO-247
- $V_{DS(\text{min})} = 650\, \text{V}$,
- $V_{(TR)DSS} = 800\, \text{V}$,
- $R_{DS(\text{on})\text{eff}} = 62 \, \text{m\Omega}$,

Some data is also presented on TP65H035WSQA, qualified to 175C/650V
TPH3205WSQA: Qualified to AEC-Q101 Standard

- First step towards producing products for automotive market
Post HTRB Dynamic Ron key reliability test for GaN

1000 Hours HTRB
Vds = 650V
150 Deg C

Ron shift <20% for all parts

Dynamic $R_{on}$ changes saturates after 250 hours
TP65H035WSQA
175C Q101 Automotive Qualification Test Data
Includes electrical, package and functional testing

• Key Qualification Tests @ 175C
  • HTRB @ 650v
  • HTGB
  • Temperature Cycle (TC)
    • -55C to 175C
  • HTOL

Data showing the percent shift in Idss, Vth and Dynamic R(ds)on before and after 1000 hours of HTRB, at 650Volts, 175C

This meets and exceeds the requirements for passing automotive qualification per the Q101 Rev. D1 specification
Qualification testing “beyond” Q101 includes HTOL, Gate Robustness, Radiation, HV Switching.

Circuit: Boost converter
- Input / Output voltage: 200V / 400V
- Operating frequency: 300kHz
- Operating temperature: Tj = 175°C
- Output power: 410W
- Test time: 3000 hours

Accelerated Single Event Burn Out
- Facility: RCNP at Osaka University
- Neutron source: White beam compliant with JEDEC JESD89A
- Total fluence: $1.3E+09$ neutron/cm²
- Results: $<1.5$ fit(CL60) @Vds=600V with no failure
Intrinsic vs Extrinsic Testing
Extrinsic vs Intrinsic Testing
Both are required to be able to publish FIT/PPM/MTBF Data

**Extrinsic Reliability**
- Early Life Failure

**Intrinsic Reliability**
- Wearout
Pick the correct conditions for the test you need to run

Intrinsic Testing ~1200V
Extrinsic Testing ≤ 900V
Keep out of breakdown region!
Intrinsic Reliability
Intrinsic Failure focuses on Wear out

Wear out testing only addresses end of life

\[ m = \text{shape parameter of Weibull, also called } \beta \]
High Temperature Reverse Bias Primary Failure Mode
Lateral breakdown from Field Plate to Drain

• Under high electric field defects form in the dielectric
• Dielectric failure allows short from Gate-to-Drain
• Same mode observed in Infant Mortality, Useful Life and Wear out
• Failure mode limits the lifetime of the device in most mission profiles
Determination of voltage and temperature acceleration factors: Physics of Failure

Three temperature/Three voltages

HVOS Testing to Failure:
- Voltage: 1000 V to 1200 V
- Temperature: -20°C to 150°C

- **Temperature Acceleration**
  - Arrhenius: $E_{aa}=-0.30 \text{ eV}$

- **Voltage Acceleration**
  - V Model: $e^{-\gamma \Delta V}$
  - $\gamma=0.026$

**Note:** The standard calls for the use of the V model for voltage acceleration unless there is data supporting an alternative: V model results in the "shortest" lifetime.
HVOS: Wear out lifetime exceeds typical 10 year customer requirement by large factors

Acceleration factor and wear out are very important parameters for understanding device reliability.

This data should not be used to report FIT rates or PPM quality!

Typical Use conditions lifetime $\sim 10^8$ hours
Extrinsic Reliability: *Early Life Failure (ELF)*
Field Reliability Data

Parts Per Million (PPM)
Failure in Time (FIT): Failures per billion device hours
Mean Time Between Failure (MTBF)
PPM Method vs. FIT Method

PPM Method assumes infant mortality failures will continue: Weibull $m < 1$

FIT Method assumes constant failure rate: Weibull $m = 1$

Exponential Distribution

All definitions are from JEDEC Standard JESD74A

$m =$ shape parameter of Weibull, also called $\beta$
900V test data shows constant failure rate validates use of exponential model

- Stress parts at high voltage until some small percentage failed
  - Calculate Weibull parameters
  - Confirm m=1

900 V test to failure confirms that m = 1, justifying use of exponential function

Do not assume exponential distribution without supporting data!
Setting ELF Targets: ~1 FIT

- MTBF (Mean Time Between Failures)
- Do not confuse MTBF with time to first failure
  - Parts remaining = \(e^{-\frac{\text{expected lifetime}}{\text{MTBF}}}\)
  - 100 year MTBF
  - 10,000 PPM/Year
  - 1,142 FIT
- 87 million hour MTBF = 100 PPM/Year = 11 FIT

FIT = \(10^9/\text{MTBF}_{\text{hours}}\)
- 88 PPM/Year = 10 FIT
- 8.8 PPM/Year = ~ 1 FIT

Note: MTBF units always seem really large. Do not let the numbers lull you into a false sense of security.
Problem: Use of Temperature Acceleration Alone to demonstrate ELF FIT<1 requires large number of parts/resources. Even for Silicon!

<table>
<thead>
<tr>
<th>Eaa</th>
<th># Parts</th>
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<tr>
<td>1.0</td>
<td>6,286</td>
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<tr>
<td>0.7</td>
<td>28,008</td>
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<td>0.5</td>
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<tr>
<td>-1.0</td>
<td>133,191,711</td>
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</table>

Assumes “standard” HTRB Qual Conditions: 150C/650V/1000 hrs per test

Power Electronics run at relatively high temperatures, reduces acceleration factor of standard HTRB testing

Voltage Acceleration is required
Early Life Failure
Industry First for High Voltage GaN

- 4000 Devices Tested
- 1e^9 accelerated device hours
- Voltage Range: 520V – 900V
- Temp Range: 25C – 175C

Temperature and voltage conditions can be used to generate lifetime estimates based upon mission profile

<table>
<thead>
<tr>
<th>Voltage</th>
<th>FIT</th>
<th>MTBF hrs</th>
<th>PPM/Yr</th>
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<tbody>
<tr>
<td>520 V</td>
<td>0.42</td>
<td>2E+09</td>
<td>3.6</td>
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<tr>
<td>480 V</td>
<td>0.15</td>
<td>7E+09</td>
<td>1.3</td>
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<tr>
<td>400 V</td>
<td>0.02</td>
<td>5E+10</td>
<td>0.2</td>
</tr>
</tbody>
</table>

ELF @ 150C
Field PPM Rates showing excellent reliability in line with other WBG devices in production

• >400k production parts shipped to date
  • 3 Billion device hours
• To calculate field return rate we “discount” the number of device hours by \( \frac{1}{2} \) (so that we do not take “credit” for parts that have not actually shipped to users yet)

• Field failure rate:
  • 20 PPM/Year
  • FIT = 2.2
Pitfalls to avoid in reliability testing

• Acceleration testing: pick reasonable conditions and if using voltage acceleration stay out of the breakdown region

• Use the appropriate voltage acceleration model
  • V model is generally appropriate unless you can justify a different one
  • 1/V Model may give you false sense of security

• Do not use wear out data to predict field reliability
  • Early Life Failure Testing: JESD74A
Conclusion: Five stages in automotive qualification demonstrated

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