Microwave Device Reliability Characterization
-The Mechanics of Life Test Execution and Analysis

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Microwave Device
Reliability Characterization
-The Mechanics of Life Test
Execution and Analysis

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Reliability Lab Charter

- Perform All Due Diligence Testing to Establish and Maintain the MMIC Fab Process Reliability to ensure ‘NoDoubt’ Mission Assurance
- Provide Reliability Expertise Within RFC, IDS and Company Wide
- Anticipate Test Capability and Capacity Needs to Enable Nimble Response to Programs’ Needs
- Search for New Paradigms in Testing and Reliability Benchmarks Industry Wide
- Implement Lean Methods and Automation to Optimize Quantity and Enhance the Quality of Test Execution and Data Analysis
Reliability Lab Test Capabilities

- Life Testing:
  - Process Reliability Monitoring
  - DC Biased Temperature Accelerated Life Test
  - RF Operational Life Test (S & X-Band)
  - RF Temperature Accelerated Life Test (X-Band)
  - Pulsed DC Electromigration (DC TALT)
  - Current Density Testing (DC TALT)

- Characterization:
  - Capacitor Time Dependent Dielectric Breakdown Testing
  - LabVIEW Based Parametric Characterization
  - Resistor TCR Characterization
  - Light Emission Microscopy
  - Liquid Crystal Failure Analysis
What Affects Reliability?

- Technical or lay, we all know that the reliability or longevity of “things” is driven by stress.

- The list of life reducing stresses include: temperature, temperature cycling, humidity, voltage/electric field, current density, mechanical stress, thermo-mechanical stress cycling, radiation etc.

- The dominating stresses depend on the application environment.

- Most of us would instinctively recognize Temperature as a common stress for many “things”.

*Temperature is a common stress driver of reliability*
Our “things” of interest are microwave devices made of compound semiconductor materials (GaAs, GaN etc)

Temperature and voltage/electric field are the important stresses in the application of microwave devices

In the space/defense environment many of the others are mitigated by the application environment.

This presentation will focus on temperature activated degradation. The reliability metrics from the statistical formalism will be introduced and the procedures to obtain them will be detailed.

**Main Theme: Thermally activated reliability metrics**
Elements of the Statistical Formalism

- **The Lognormal Lifetime Distribution**
  - Failures are distributed ‘normally’ when plotted on log time scale

- **The Cumulative Failure Fraction Plot**
  - A linear plot can be taken as evidence for lognormal lifetime distribution

- **The Arrhenius Reaction Rate Model**
  - \( t = t_0 e^{E_a/kT} \)
  - The Arrhenius acceleration relationship is then
  - \( ML_1/ML_2 = e^{E_a/kT_1}/e^{E_a/kT_2} \)

- **The Reliability Metrics from above are:**
  - Median Life (ML) or MMTF
  - Sigma (\( \sigma \)) the dispersion – standard deviation of the log of lifetimes
  - Activation Energy

*The Metrics: Median Life, Sigma and Activation Energy*
The Lognormal Failures Distribution

Lognormal Failure Distribution

MedianLife

15 yr Mission

σ=1

Distribution is ‘normal’ when plotted on log time scale
Trade Off Between ML and $\sigma$

To maintain ‘Same’ Reliability at lower ML, $\sigma$ has to be smaller.

Failure Rate in FITs through mission time is negligible.

FIT is a failure unit.
And it is equivalent with 1 failure/10$^9$ hr.
The Lognormal Failures Distribution

Note Margin Between Distribution Tail and Mission Time
The Cumulative Failure Fraction Plot

Note on the X scale both the Probability and Score scales are shown

The Plot is linear
\[ \ln(\text{TTF}) = \sigma z + \ln(\text{ML}) \]

The exponential curve fit in Excel returns the form
\[ \text{TTF} = \text{ML} e^{\sigma z} \]

The extraction of ML and \( \sigma \) is direct

A linear plot is taken as evidence for lognormal lifetime distribution
The Arrhenius Reaction Rate Model

$$ML = C \cdot e^{\frac{Ea}{kT}}$$

Or

$$1000/T = A \cdot \ln(ML) + C$$

The Plot is a straight line using these scales

The logarithmic curve fit in Excel returns this form and from the slope A the Activation Energy

$$Ea = 1000k/A = 0.0862/A$$

k is Boltzman’s constant in eV*K⁻¹

**Arrhenius Plot**

$$y = -0.0429 \ln(x) - 1.3647$$

**The Ability to Thermally Accelerate Aging is Key to the Process**
Life Test Scope

- Life Tests at minimum 3 temperatures are required to establish a credible trend
- Tch for the Life Tests is determined from self heating due to DC operating power dissipation and base plate temperature setting
- Test Vehicles are 12 Schottky Gate Field Effect Transistors per temperature group
- 20% Decrease in Drain Current is the Failure Criterion
- Drain Current is a key performance parameter and it is correlated with RF Power output capability
Drain Current aging at Tch=329°C - Linear trend plot
Life Test Data Analysis

- Drain Current aging at Tch=329°C - Logarithmic trend plot

The Times-to-Fail are tabulated and ranked and used in the next step.

Logarithmic trend plot is a better visual indicator of ML.
Life Test Data Analysis

- The Time-to-Fail values are tabulated and ranked

- For each failure the cumulative failed fraction, Q, is calculated using the median ranking formula:
  \[ Q = \frac{F-0.3}{N+0.4} \]
  F is the number of failed parts; N is the number of parts in the test

- Q is converted to the z score using NORMSINV function in Excel

<table>
<thead>
<tr>
<th>F cum # failures</th>
<th>Q [fraction] (F-0.3)/(N+0.4)</th>
<th>Z score</th>
<th>TTF [hr] sorted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.05645</td>
<td>-1.58528</td>
<td>450</td>
</tr>
<tr>
<td>2</td>
<td>0.13710</td>
<td>-1.09346</td>
<td>570</td>
</tr>
<tr>
<td>3</td>
<td>0.21774</td>
<td>-0.77984</td>
<td>670</td>
</tr>
<tr>
<td>4</td>
<td>0.29839</td>
<td>-0.52904</td>
<td>700</td>
</tr>
<tr>
<td>5</td>
<td>0.37903</td>
<td>-0.30802</td>
<td>950</td>
</tr>
<tr>
<td>6</td>
<td>0.45968</td>
<td>-0.10125</td>
<td>1100</td>
</tr>
<tr>
<td>7</td>
<td>0.54032</td>
<td>0.101246</td>
<td>1174</td>
</tr>
<tr>
<td>8</td>
<td>0.62097</td>
<td>0.308024</td>
<td>1200</td>
</tr>
<tr>
<td>9</td>
<td>0.70161</td>
<td>0.529045</td>
<td>1200</td>
</tr>
<tr>
<td>10</td>
<td>0.78226</td>
<td>0.779842</td>
<td>1700</td>
</tr>
<tr>
<td>11</td>
<td>0.86290</td>
<td>1.093456</td>
<td>1900</td>
</tr>
<tr>
<td>12</td>
<td>0.94355</td>
<td>1.585278</td>
<td>2100</td>
</tr>
</tbody>
</table>

The resulting z-score and TTF data is plotted using the Cumulative Failure Fraction Plot

The Id trend plot is reduced to the TTF and Z-score data array
The Cumulative Failure Plot Provides ML and $\sigma$ Directly.

The exponential curve fit in Excel returns the form

$$TTF = ML^* e^{\sigma*z}$$

The extraction of ML and $\sigma$ is direct.

ML=1031 hr

\[ \sigma = 0.52 \]

The Cumulative Failure Plot: $Tch=329^\circ C$
All 3 Cumulative Failure Plots

The extraction of ML and \( \sigma \) is direct for all 3 temperature groups

<table>
<thead>
<tr>
<th>Tch[°C]</th>
<th>ML[hr]</th>
<th>( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>345</td>
<td>365</td>
<td>0.57</td>
</tr>
<tr>
<td>329</td>
<td>1031</td>
<td>0.52</td>
</tr>
<tr>
<td>308</td>
<td>4053</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Tch and ML are ready to be plotted on the Arrhenius coordinates

The Cumulative Failure Plot Provides ML and \( \sigma \) Directly
The Arrhenius Plot for the 3 Life Tests

- $Tch$ is converted to $1000/Tch$ in $[^oK^{-1}]$.
- Note negative sign forces Temperature increase bottom to top.

<table>
<thead>
<tr>
<th>$Tch$ [$^oC$]</th>
<th>ML [hr]</th>
<th>$1000/Tch$ [$^oK^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>345</td>
<td>365</td>
<td>-1.618</td>
</tr>
<tr>
<td>329</td>
<td>1031</td>
<td>-1.661</td>
</tr>
<tr>
<td>308</td>
<td>4053</td>
<td>-1.721</td>
</tr>
</tbody>
</table>

- ML and $1000/Tch$ are plotted on the Arrhenius Coordinates.
- $Ea=0.0862/A$
- $Ea=2.01eV$
Reliability Metrics Summary

The Reliability Metrics based on all 3 temperature groups used in this example are:

<table>
<thead>
<tr>
<th>Tch[°C]</th>
<th>ML[hr]</th>
<th>σ</th>
<th>Ea[eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>345</td>
<td>365</td>
<td>0.57</td>
<td>3.45</td>
</tr>
<tr>
<td>329</td>
<td>1031</td>
<td>0.52</td>
<td>2.90</td>
</tr>
<tr>
<td>308</td>
<td>4053</td>
<td>0.35</td>
<td>2.01</td>
</tr>
</tbody>
</table>

The 2.01eV Arrhenius Line Projects ML = 1.3E10 at a Mission Tch = 150°C
The Conservative 1.5eV Arrhenius Line Projects ML = 2.1E8 at Tch = 150°C
Reliability Metrics Summary

Normalized Failure Rate Plot is Used to Validate Our Extraction and Calculation Protocols
The Equipment/Set Up

Device Package
4 DUTs Inside

Drain Bias

Heater Stage

Gate Bias

The Equipment Uses a Servo Feedback Loop Which Adjusts the Gate Voltage to Keep Constant Drain Current
The 2nd Key Stress in the application of microwave devices - Voltage/Electric field

RF Operational Life Tests Are Used to Mitigate High Field Effects Also Known as Hot Electron Effect
References


