

Micro-/Millimeter Wave Reliability Overview

Comprehensive GaAs device reliability studies, which began in the early 1980s, have continued to the present day. Over 38 million device-hours of accelerated life testing (at TriQuint Texas) has provided information about failure mechanisms, activation energies, and failure rates. With this knowledge process refinements have been made which have led to very mature and reliable product lines. Understanding the device physics underlying the reliability studies is an ongoing activity at TriQuint.

Reliability Background

GaAs device reliability involves probability statistics, time, and a definition of failure. Given a failure criteria, the most direct way to determine reliability is to submit a large number of samples to actual use conditions and monitor their performance against the failure criteria over time. Since most applications require device life times of many years, this approach is unfeasible. To acquire reliability data in a shorter time, an acceleration factor must be used to quicken the failure process. In most cases this acceleration factor is high temperature.

The rationale behind high temperature life tests is that most physical and chemical processes are accelerated by temperature. The rate of acceleration for each failure mechanism is a constant called the [activation energy](#). Most GaAs semiconductor failure mechanisms follow the [Arrhenius equation](#) which relates the rate of failure to temperature, time and activation energy.

To properly analyze life test data requires the adoption of a mathematical failure distribution. Several are commonly used including the Normal, Lognormal, Exponential and Weibull distributions. The measured life test data of GaAs semiconductor devices has been found to most closely fit the [Lognormal distribution](#).

Median life (T_m) is the time at which half of the population will exceed the failure criteria. Median life should not be confused with Mean-Time-To-Failure (MTTF). MTTF is the reciprocal of the [instantaneous failure rate, \$\lambda\(t\)\$](#) . The instantaneous failure rate is not a constant with time because of the lognormal failure distribution. One must specify an operating time at which to calculate the failure rate.

Statistical Confidence

Although not always practical, accelerated life tests should be conducted with very large sample sizes. The sample size and the lognormal sigma determines the confidence in the life time predictions. The larger the sample size the more confidence in the prediction. [Confidence limits](#) are defined in terms of percentage. A90% confidence interval means that if the life test were repeated on random samples from the same population that 9 out of 10 times the results would fall between the upper and lower limit.

Impact of Channel Temperature

Since most GaAs device failures occur in the FET channel, all life test data is referenced to the channel temperature. The importance of accurately determining the channel temperature of each device submitted to life test cannot be over emphasized. Variables affecting the channel temperature include: ambient temperature, device thermal impedance, package and mounting materials, power dissipation, RF levels, and substrate leakage currents. Channel temperatures are determined by [thermal modeling](#). Our life time predictions are quoted at a 140°C channel temperature. This does not imply that all devices should be operated at a 140°C channel temperature.

Typical High Temperature Life Test

To predict life times at normal operating temperatures, multiple high temperature life tests should be performed. The median life from each of the tests is transferred to an Arrhenius plot and fit with a line. The slope of the line is the activation energy. Median life at any temperature can then be determined. Typically three temperatures are used. (For further information reference JEDEC 50.1-91-165 committee letter ballot dated October 29, 1991.)

Three temperature [life test results](#) of representative samples can be used to estimate MIMIC life times. This data is available for MesFET, HFET, and pHEMTs under typical bias conditions. The failure criteria represented is 1 dB RF output degradation. This data can be used to estimate its reliability in the event that actual test data for a specific MMIC is unavailable. The approach is to use the channel temperature of the hottest FET on the MIMIC to predict the MMIC life time. Typically each MMIC has one FET that is hotter than the rest which dominates the lifetime for the entire MMIC. Good correlation has been observed between discrete FET lifetimes and MMIC lifetimes. Our study of passive components such as resistors and capacitors has shown them to be several orders of magnitude more robust than the FETs.

Two Path Reliability Process

TriQuint Texas has a [two path](#) reliability test flow. It involves monitoring the process reliability by conducting single temperature life tests on "plugbars" or process control monitors and performing selected multi-temperature life tests of specific representative MMICs for various customers. We have proven a very reliable GaAs process. The measured lot life test sigma is typically less than 0.7 and indicates a mature process. Most MMIC designs have a predicted median life better than 10 million hours at a 140°C modeled channel temperature. Other aspects of GaAs MIMIC reliability have also been investigated including ESD sensitivity, hydrogen poisoning, and radiation hardness. A recent summary of life tested devices is presented in the table below.

PROCESS	1/2 um HFET	1/2 um Intermediate	1/2 um Low Noise	1/4 um BECO	1/4um pHEMT
StandardEvaluation Circuit	8286	6010	6011	6356	6014
Test Condition	8V 1.8 amps	7V 500 mA	8V 60 mA	5V 60 mA	8V 450 mA
Failure Criteria	20% change in lds or 1dB RF degradation	20% change in lds or 1dB RF degradation	20% change in lds or 1dB RF degradation	20% change in lds or 1dB RF degradation	10% change in lds or 1dB RF degradation
Median Life at 140C channel.	4E8 hours	2.4E8 hours	1E8 hours	2E8 hours	2E6 hours

The Arrhenius Equation and Activation Energy

$$tf_2 = tf_1 \exp Ea/k[1/T_2 - 1/T_1]$$

Where:

tf = time to failure

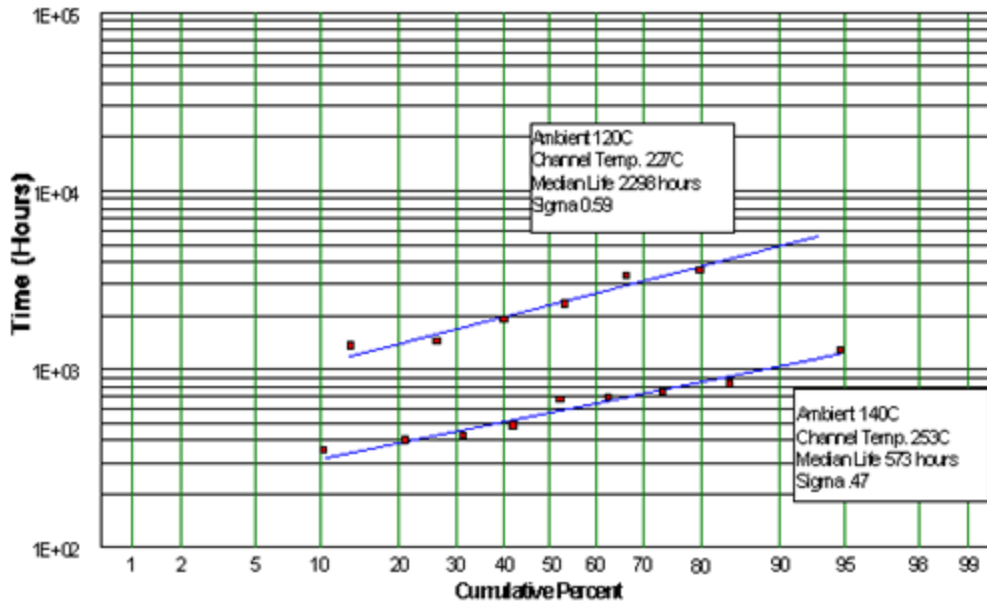
Ea = activation energy in electron-volts (eV)

k = Boltzman's constant 8.6142 E-5 (eV/°K)

T = absolute temperature in Kelvin (°C +273)

Lognormal Distribution

The lognormal distribution is most easily visualized with a graph. A lognormal graph is a plot of normal cumulative-percent-failure versus log time. If the life test data fits a straight line on this graph it indicates the data fits the lognormal distribution. The slope of the line is proportional to the lognormal sigma. The intersection of this line with 50% cumulative failure indicates the median life time. Median life is the time it takes for half of the devices to fail the specified criteria. An "S" curve on the lognormal graph indicates the measured failure data is bi-modal. In the case of a bi-modal distribution, the inflection point of the "S" indicates the percentage of the weaker population. An example of life test data plotted on a lognormal graph is shown below. For additional information reference MIL-STD-883 method 1016.



Example of lognormal graph of accelerated life test data for a two temperature test.

Definition of Failure Rate

$$\lambda (t) = f(t)/[1-F(t)]$$

Where:

f(t) = probability density function

F(t) = cumulative distribution function

$\lambda (t)$ = instantaneous failure rate

Since the time-to-failure most closely fits a lognormal probability distribution function, the following functions are substituted in the equation above to derive instantaneous failure rate.

$$f(t) = \frac{1}{st\sqrt{2\pi}} e^{-\frac{1}{2}\left[\frac{\ln(t)-\ln(tm)}{s}\right]^2}$$

$$F(t) = \frac{1}{s\sqrt{2\pi}} \int_0^t \frac{1}{t} e^{-\frac{1}{2}\left[\frac{\ln(t)-\ln(tm)}{s}\right]^2} dt$$

Where:

t = operating time in hours

s = lognormal standard deviation

tm = median life

Confidence Limits

Confidence limits can be calculated for median life predictions with the following equations:

$$\text{Upper limit} = t_m * \exp\left(\frac{t(df, \alpha) * \sigma}{\sqrt{N}}\right)$$

$$\text{Lower limit} = t_m * \exp\left(\frac{-t(df, \alpha) * \sigma}{\sqrt{N}}\right)$$

Where:

tm = median life at test temperature

α = (1-percent confidence)/2

t(df, α) = value from students' t distribution

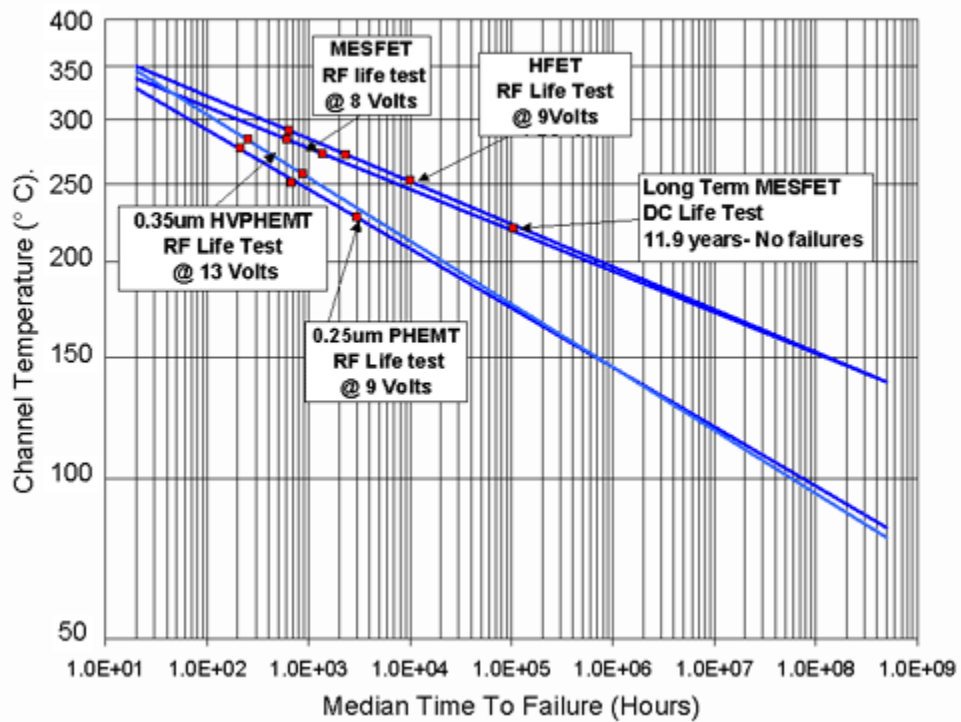
N = sample size

df = degrees of freedom (N-1)

σ = The lognormal standard deviation

Typical TriQuint Texas MesFET, HFET, and pHEMT Data

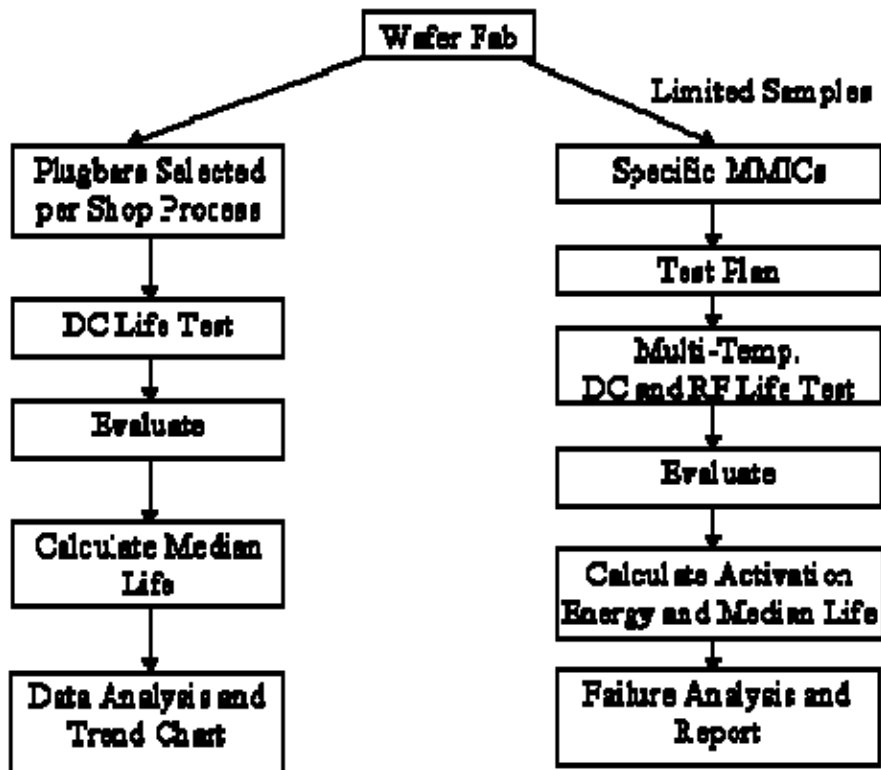
Typical Process Life Test Results



The median life for any process can be calculated at any channel temperature using the equation and coefficients below.

$T_m = T_{m0} \cdot \exp(E_a / K T)$				
	MESFET	HFET	PHEMT 0.25	PHEMT 0.35
$E_a =$	1.86	1.79	1.3	1.21
$T_{m0} =$	9.1161E-15	6.9013E-14	3.2424E-10	2.8291E-09
$K = 8.61739E-5 \text{ (eV/}^\circ\text{K)}$				
$T = ^\circ\text{C} + 273 \text{ (Temperature in Kelvin)}$				

Two Path Reliability Program at TriQuint Texas



The reliability monitoring path involves sampling plugbar FETs from each process per the governing shop process. They are assembled into pin grid array (PGA) packages in which they are electrically tested and subjected to high temperature DC life test. The ambient oven temperatures are 207°C and 250°C for power and low noise devices respectively. All life test are conducted in a dry nitrogen atmosphere in non-hermetic fixtures. Many special plugbar tests are also requested and performed involving process changes to verify no reduction in reliability. Trend charts are developed for the various product types to verify a minimum level of reliability.

RF life testing in the past has been customer driven and often customer funded. When reliability information is requested for a specific chip, the bias and RF requirements of the chip are compared against the available test set capacity and loading to determine feasibility of performing the test. A test plan is written by the reliability team and the test is conducted per the plan upon customer approval. Life testing of chips with special requirements beyond our existing capability can be very expensive due to the high cost of customized life test equipment.

GaAs MMIC Radiation Survivability Studies

TriQuint Texas has been active in investigation of radiation effects on GaAs MMICs. The effects studied included neutron fluence, transient upset and total dose. The robustness of GaAs devices to radiation environments is demonstrated in the table below.

Summary of Radiation Hardness Test Results

Test Device	Total Dose(rads)	Neutron Dose (N/cm ²)	Transient upset (rads/sec)
FET (Power Profile)	Survived 1E7, failures at 4E7	Survived 5E14, soft failures at 1E15	Survived 1E10 failures at 1.9E10
FET (LN Profile)	Survived 8E7, Soft failures at 1E8	Survived 5E13, soft failures at 5E14	Survived 3E11 failures after multiple pulses of 3E11
Capacitor Leakage	Greater than 10% change at 1E6	Survived 5E14	Showed large photocurrents but no failures through 2.6E11
GaAs Resistor (Pwr and LN profile)	Greater than 10% change at 6E7 (LN) and 1E8 (Pwr)	Survived 5E14, soft failures at 1E15	Showed large photocurrents but no failures through 2.6E11
Power Amplifier MMIC	Survived 1.4E6, Not tested to failure	Survived 1E13	Survived 1.4E10, Not tested to failure
LN Amplifier MMIC	Survived 1.4E6, Not tested to failure	Survived 1E13	Survived 1.1E10, Not tested to failure

A detailed explanation of radiation tests can be found in chapter 12 of a book called *Reliability of Gallium Arsenide MMICs*, Edited by A. Christou © 1992 John Wiley & Sons, written by W. T. Anderson of NRL. Results of additional radiation tests on TriQuint (formerly TI) devices are described in this book.

Thermal Modeling

Thermal characteristics of GaAs devices affect their reliability. Predicting accurate channel temperatures for GaAs devices requires detailed knowledge of the power dissipation, geometry of the metal layers around the channel, the method of die attach to the substrate, and the thermal boundary conditions of the substrate. Compared to silicon devices, the channel temperature of GaAs devices may be much hotter due to the small feature sizes and the higher thermal conductivity.

Measuring the hot spot on a FET is nearly impossible due to the small physical geometry. Heat generation occurs directly beneath the gate finger which can be as small as 0.25µm. The best infrared measurements available today have 5 µm resolutions. Liquid crystal measurements are thought to be able to resolve 1.5µm but lack accuracy and are subjective. The best method we have to determine hot spot temperature is thermal modeling. Two methods are used for modeling GaAs devices. The analytical approach uses simplified boundary conditions but solves for an exact solution. The finite difference approach more accurately defines the physical geometry but takes longer to develop and solve. TriQuint Texas uses a finite difference modeling technique which has been verified with infrared measurements. Thermal models are used for both life test and end use conditions to predict channel temperatures and life time. A two dimensional slice of a three dimensional finite difference model is shown below. Note the detail that is included in the model.

