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How to quantify and predict long term multiple stress operation: Application to Normally-Off Power GaN transistor technologies

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Abstract

The present paper is implementing a numerical application of the Boltzmann–Arrhenius–Zhurkov (BAZ) model and relates to the statistic reliability model derived from the Transition State Theory paradigm. It shows how the quantified tool can be applied to determine the associated effective activation energy. The unified multiple stress reliability model for electronic devices is applied to Normally-Off Power GaN transistor technologies to quantify and predict the reliability figures of this electronic type of product when operating under multiple stresses in an embedded system operating under such harsh environment conditions as set for Aerospace, Space, Nuclear, Submarine, Transport or Ground application.

Keywords:
Wide band gap semiconductor
III-nitrides
GaN
GaN-on-Si
Design-for-Reliability
Reliability
Transition State Theory
Quantum statistics
Maxwell–Boltzmann distribution

1. Introduction

The model of the Transition State Theory (TST) developed by E. Wigner [1] and M. Evans and M. Polanyi [2] in 1938 was considered to derive the unified reliability theory presented. Accordingly, the failure rates and reliability mathematics for Cumulative Distribution Function (CDF), Reliability function (R) and Probability Density Function (PDF) have been described when considering the TST concept. In former papers we have demonstrated how multiple stresses applied, may impact the effective activation energy suggested by the BAZ model [3,4]. We will see here how to apply the pre-defined model to the case of a Gallium Nitride Normally-off high power transistor (Enhanced-mode) and a detailed numerical application. The quantified tool will be applied to determine the minimum value of stressor parameters named $\chi$’s and the equivalent single associated minimum effective activation energy to predict long term operation under multiple stresses in harsh environment. The completed numerical application on a Normally-off transistor GaN reference GS66508P-E03 650 V enhancement mode manufactured by GaN Systems is proposed to support the methodology. The concepts of maximum rating limits and burnout conditions are key factors which will give insight to derive related stressors as parameters $\gamma$’s and $\chi$’s, both statistically represented by a normal distribution law.

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2. BAZ model and Transition State Theory

Shown in Fig. 1, is a free energy diagram of why things generally tend to degrade faster at higher temperatures as explained in chemistry and Reliability Physics books (see for example J.W. McPherson [5]). Stress-dependent activation energy observations seem to be general in nature (i.e., not confined just to a single failure mechanism or stress type), and works attempt to explore the conditions under which a stress dependent activation energy is theoretically expected. The generalized Eyring model presented by McPherson has been refined and adapted to this technology. A short discussion will recall the main highlights we have observed.

Fig. 1 simply related to the general model called Boltzmann–Arrhenius–Zhurkov (BAZ) also described by the Transition State Theory (TST) [1,2]. We have seen the stress factor $\gamma$. $S$ can precisely counterbalance the Arrhenius activation energy $E_a$ for a device at burnout due to an overstress (i.e. the energy of the transition state with burnout catalyst effect is at the same level as the initial state energy). In this case this...
works for any failure mechanism that is thermally determined as a rate function described by the Maxwell–Boltzmann distribution.

We have expressed the BAZ model as the lifetime \( \tau \) defined by the following equation:

\[
\tau = \tau_0 \cdot \exp \left( \frac{E_a}{k \cdot T_{\text{eff}}} \cdot c(\chi_i \cdot \gamma_i) \right)
\]  

(1)

With a dimensionless energy factor parameter \( c(\chi_i \cdot \gamma_i) \) given by:

\[
c(\chi_i \cdot \gamma_i) = 1 - \frac{k \cdot T_{\text{eff}}}{E_a} \sum_{i=1}^{M} (\chi_i \cdot \gamma_i \cdot S_{\text{BO}})
\]  

(2)

where the \( S_{\text{BO}} \) is the corresponding maximum catastrophic burnout failure limit related to each electrical stress parameter for \( i = 1 \) to \( M \) (current, voltage and power). \( T_{\text{eff}} \) is the absolute temperature that could depend also on the applied stress \( \chi_i \) when the Joule effect is occurring, \( \tau_0 \) is the time constant, and \( \gamma_i \) is the factor of loading characterizing the weight of the level of stress. This equation is seen as the generalization of the Eyring model as demonstrated in [2]. Indeed, when the stress parameter is set to \( S_{\text{BO}} \) leading to a sudden catastrophic failure we have: \( \chi_i = 1 \) and \( c(1) = 0 \) allowing calculating \( \gamma_i \) for a combination of stress parameters as:

\[
E_a = k \cdot T_{\text{eff}} \sum_{i=1}^{M} (\chi_i \cdot S_{\text{BO}}).
\]  

(3)

Because every \( \chi_i \) is in the range \([0; 1]\), this equation shows that the activation energy is compensated by a linear combination of stressor energies associated with each parameter.

When considering the simplest configuration where the main stressor is the breakdown voltage characterized by a term \( \chi_V \), suppose other stressors \( \chi_j \) to be equal to 0. Eq. (4) for \( \chi_V = 1 \) will allow determining \( \gamma_V \) as:

\[
\gamma_V = \frac{E_a}{k \cdot T_{\text{eff}}} \cdot V_{\text{BO}}
\]  

(4)

Combining Eqs. (4) and (2) leads to:

\[
c(\chi_V \cdot \gamma_V) = 1 - \chi_V.
\]  

(5.a)

We have seen similar equations can be obtained for other stressors when considered alone:

for pulse power dissipation:

\[
c(\chi_P \cdot \gamma_P) = 1 - \chi_P
\]  

(5.b)

for current:

\[
c(\chi_I \cdot \gamma_I) = 1 - \chi_I
\]  

(5.c)

Because the principle of superposition is not valid, it is understood that the situation is different when considering a multiple stressor configuration applied simultaneously.

Considering the situation of three stressors: a) \( \chi_I \) related to current limited by the maximum allowed current characterized by \( I_{\text{BO}} \), b) the breakdown voltage characterized by a term \( \chi_V \) and \( V_{\text{BO}} \), and c) stressor \( \chi_P \) related to power consumption related to the maximum allowed dissipation characterized by \( P_{\text{BO}} \).

Saying Eqs. (5.a), (5.b) and (5.c) are constrained by the boundary conditions defined for the burnout limits (subscribe \( \text{BO} \)), we obtained:

\[
c(\chi_i \cdot \gamma_i) = 1 - \frac{k \cdot T_{\text{eff}}}{E_a} \left[ (\gamma_I \cdot \chi_I \cdot I_{\text{BO}} + \gamma_v \cdot \chi_V \cdot V_{\text{BO}} + \gamma_P \cdot \chi_P \cdot P_{\text{BO}}) \right].
\]  

(6)

Merging Eq. (6) with Eq. (4), we were able to normalize burnout parameters and we got an expression of coefficient \( c(\chi_i \cdot \gamma_i) \):

\[
c(\chi_i \cdot \gamma_i) = c(\chi_i \cdot \chi_V \cdot \chi_P) = 1 - \chi_i - \chi_V - \chi_P
\]  

(7)

The simple schematic drawing given in Fig. 2 details contributions of stressors when three stressors are simultaneously applied as per Eq. (7).

The next chapter will show how a numerical application on a Power GaN Normally-Off transistor enhancement mode GaN transistor is implemented.

3. A Normally-off transistor GaN: data sheet and maximum rating definitions

As an example, the data sheet given (at the date of this publication) in Table 1 defines the parameters extracted from a Power GaN Normally-Off transistor GS66508P-E03 650 V enhancement mode GaN transistor (reproduced from data sheet GaN Systems www.gansystems.com).

Generally, maximum rating limits are defined and are considered with a given margin compared to burnout failure limits (\( M_c, M_v \) or \( M_p \) respectively for current, voltage and power dissipation).

Sudden catastrophic failures due to electrical overstresses can be characterized for each transistor lot. This consideration will help to define the sine qua non condition to consolidate the reliability model.

---

2 Pulse power dissipation or commutation losses needs (turn-on and turn-off energies) to be considered when using such Normally-off transistors in their application because of the switching time conditions from off-state to on-state operation can stress the device close to the limit of its SOA in pulsed mode.
Multiple stresses can be seen as a juxtaposition of stress amplitudes (not the superposition principle) leading to reduce proportionally the effective activation energy up to a zero value maximum limit (in this case the activation energy is exactly compensated by the cumulated stress factors). Let’s consider the following notation for burnout:

- \( \text{Activation energy} \)
- \( \text{Cumulated effective activation energy} \)
- \( \text{Maximum limit} \)

When conducting evaluation and qualification testing sequences as depicted in MIL Standards or similar, such DC stress tests are foreseen. We propose to implement such qualification test sequence and biasing depicted in Fig. 3 in the frame of the Robustness project we are conducting. The results will be presented in another paper in a future study. But indeed, they have several drawbacks:

- a) They are focused on validating simple stress conditions including high temperature stress superposed with a single DC bias stress at a time,
- b) They are based on the Arrhenius law considering accelerating factors managed by high temperature effects forgetting low temperature effects,
- c) They generally don’t address dynamic stress conditions (even RF or switching in operation) at high or low temperature.

SOA limits are defined for DC stresses but are half-finished when considering nominal operating conditions. They must be completed by switching stress conditions to be imposed to the designers. In order to highlight how the design rules must be taken into account, the next paragraph will provide such major inputs.

4. A Normally-off transistor GaN: reliability impact of turn-on/turn-off switching voltage induced by commutation losses

Since Normally-off GaN transistors start to conduct significant current at \( V_{GS(th)} = 1.6 \) V, care must be taken to ensure a low impedance path from gate to source when the device needs to be held off during dv/dt in a rectifier function. As the temperature coefficient of the eGaN FET is positive throughout its range of operation, this means that when the temperature of a localized region of the device increases, its current carrying capability is reduced causing the current to be dispersed to other areas of the die. This dispersion of the current equalizes the temperature of the die, and is known as “self-ballasting.” The power MOSFET, on the other hand, has a significant region of negative temperature coefficient operation (below 5.0 V on the gate) where there is no self-ballasting.

---

**Table 1**


### Absolute maximum ratings (at Tcase = 25 °C unless otherwise noted)

- \( T_J \) Operating junction temp.
- \( T_T \) Storage temperature range
- \( V_{DS(th)} \) Drain-to-source
- \( V_{GS(th)} \) Gate-to-source
- \( V_{GS} \) Continuous drain current (Tcase = 25 °C)
- \( V_{DS} \) Continuous drain current (Tcase = 100 °C)

### Electrical characteristics (at Tcase = 25 °C unless otherwise noted)

- \( V_{BD} \) Source-drain breakdown voltage
- \( R_{DS(ON)} \) Drain-to-source on resistance
- \( R_{on} \) Source-to-gate leakage current
- \( I_{DS} \) Drain-to-source leakage current
- \( V_{DS} \) Gate to source leakage current
- \( V_{GS} \) Gate threshold voltage
- \( V_{DS} \) Gate-to-source
- \( V_{DS} \) Drain-to-source
- \( V_{DS} \) Source-drain reverse voltage

### Table 3

Fig. 3. Safe operating area of Normally-Off GaN transistor showing boundary conditions defined for \( \chi \) and \( \gamma \) parameter determination.
Operation within this region creates localized hot spots within the die and, thus, limits the SOA capability of the die.

These considerations have been explained on literature by B. Cogo et al. [6,7] and J. Brandelero et al. [8]. From these papers, power device modeling published articles have shown turn-on turn-off switching voltage characteristics induced by commutation losses. Losses in the switches are usually the most important point to be considered in a converter design; however, switching losses are not always provided in datasheets. The following text is mainly inspired from large extract from the three papers.

As implemented in [7], turn-on and turn-off energies could be accurately determined separately for different switched voltages and currents by controlling the commutation of a full bridge in two different modes. The authors argue that due to the packaging of GaN EPC© devices, current measurement into device is not possible with a Rogowski probe or a current transformer without changing the power loop. This is also the case for almost all low voltage Silicon MOSFET packaging. Since the opposition method is a non-invasive method, it is suitable to be used to measure switching losses of “wide bandgap” devices. The opposition method consists of an association of two identical converters supplied by the same source, one operating as a generator, the other as a receptor (as shown in Fig. 4). Thus, a test bench using the opposition method was implemented in [8] to characterize switching energies, under actual working conditions, of an EPC1001 GaN power transistor. Consideration of such commutation (ripple) induced stresses is presented in Fig. 5, showing an overview of switching losses in a buck converter operating in two different modes: low current and high current ripple modes.

The authors have considered other losses as listed below:

- Inductor losses,
- Transistor conduction losses,
- Connection losses,
- Bus capacitor losses.

Taking into account such parasitic effects, we propose to introduce three (3) new stress factors at burnout failure limits which can be responsible for impact and degrade effective activation energy, including:

- **Turn-off controlled commutation**
  - Energy turn-off dynamic switching $E_{\text{off-surge}}$ (energy factor $\chi_{\text{Eoff-surge}}$).

- **Turn-on controlled commutation**
  - Transistor turn-on energy $E_{\text{on surge}}$, which includes the reverse recovery losses of the body diode (energy factor $\chi_{\text{Eon surge}}$).
  - Turn-on dynamic switching for $V_{\text{GS surge}}$ (energy factor $\chi_{\text{VGS surge}}$).

Recalling chapter II and these parasitic effects, we can express the energy factors as a juxtaposition of stressor parameters as listed in Table 2 each of them defined by their $\gamma$ parameters and their associated $\chi$’s bounded by their maximum rating limits calculated from Eqs. (4) and (5.a), (5.b) and (5.c). To do so, activation energy related to the

Fig. 4. a) Circuit used in the proposed method to measure switching energy of transistors, b) typical voltage and current waveforms for the “turn-off loss measurement mode” and c) for the “turn-on loss measurement mode”.

From [7].
ohmic contact (TiAl:GaN system based alloy) and Schottky contact (TiN:GaN system alloys) are considered for EPC technology.

As summarized by Del Alamo in 2009 [9], relatively high activation energies have been reported from 1.05 to 2 eV for GaN technologies. This paper highlighted an electrical degradation mechanism for GaN HEMTs that is associated with the strong piezoelectric nature of GaN and AlGaN. Under high voltage conditions, the high electric field that is produced introduces strong tensile stress in the AlGaN barrier layer that peaks right below the gate edge. This results in an increase in stored elastic energy inside the AlGaN. If exceeding a critical value, crystallographic defects are formed that are electrically active. The damage consists of dimples, cracks crystallographic damage on the drain side of the device right next to the gate edge. These have shown the presence of prominent that extent through the AlGaN but stop at the GaN interface and, in extreme cases, metal diffusion from the gate down the crack. In addition, the level of crystallographic damage correlates with the degradation in the electrical characteristics of the device.

Linking to Eq. (3), and as a preliminary analysis, let’s consider the activation energy associated with metallurgical diffusion mechanism as the main effect characterized by a value close to 2.1 eV. Of course this value must be assessed and confirmed on a given GaN technology process after a series of simple high temperature storage test sequences. The effective junction temperature $T_{\text{eff}}$ must also be related to the case temperature and the thermal resistance of the junction case.

**Table 2**

List of the 10 stressor parameters and related values used impinging on the effective activation energy applied to GS66508P-E03 650 V enhancement mode GaN transistor (assuming $E_a$ and $T_{\text{eff}}$ — see detail in text).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Maximum rating values (MR)</th>
<th>DC limit BO</th>
<th>DC BO values</th>
<th>Dynamic biasing stressors</th>
<th>Surge BO limits</th>
<th>Transient stressors</th>
<th>Transient BO limits</th>
<th>$\gamma$ (Eq. 4)</th>
<th>Calculated $\gamma$ values at $T_{\text{eff}} = 298$ K</th>
<th>$\chi_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Current</td>
<td>$I_{\text{DSon}}$</td>
<td>34 A</td>
<td>$I_{\text{DSon,BO}}$</td>
<td>68 A</td>
<td>$I_{\text{DSon,sgeBO}}$</td>
<td>90 A</td>
<td>$\gamma_{\text{DSon}}$</td>
<td>1.20</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>2 Voltage</td>
<td>$V_{\text{GSon}}$</td>
<td>10 V</td>
<td>$V_{\text{GSon,BO}}$</td>
<td>900 V</td>
<td>$V_{\text{GSon,sgeBO}}$</td>
<td>20 V</td>
<td>$\gamma_{\text{GSon}}$</td>
<td>4.09</td>
<td>50%</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 5.** Ideal Hard Switching (extracted from EPC WP009) for a) turn-off transition, b) turn-on transition, c) typical turn-off energy calculation (from [8]) based on switch voltage and current and d) measured switching energy for different switched currents and voltages, for the 100-V eGaN FET EPC1001.
Calculated values for $\gamma$ at $T_{\text{off}} = 298$ K (Eq. (3)) and $\gamma_{\text{ABE}}$ (Eq. (4)) are completed in Table 2 (assuming the Boltzmann constant $k = 8.61733 \times 10^{-5}$ eV·K$^{-1}$) and $E_a = 2.1$ eV. These parameters are related to burnout parameter limits from which we know they are characterized by a Gaussian or Standard distribution law. Consequently each of them can be written in terms of mean and standard deviation factor as follows:

$$ f_{\text{sd}}(S_{\text{BOfailure}}) = \frac{1}{\sigma_{\text{BO}} \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{S_{\text{BOfailure}} - \mu_{\text{BO}}}{\sigma_{\text{BO}}} \right)^2} \quad (8) $$

where $\mu_{\text{BO}}$ and $\sigma_{\text{BO}}$ are respectively the mean and the standard deviation of statistical distribution law of every $S_{\text{BOfailure}}$.

### 5. BAZ model applied to Normally-off GaN transistor

As a result the related parameters $\chi_i$’s are statistically represented by a similar distribution law and Fig. 7 represents a 3D-plot of such normalized stress factor $\chi_i$ vs the catastrophic burnout limit $S_{\text{BOfailure}}$ of a Normally-off transistor GaN. When a parameter failure limit is affected by the temperature as for example observed on breakdown voltage decreasing when the temperature is decreasing [10], this effect can be easily considered within the reliability model thanks to the $\gamma$ parameter.

In this example we have considered normalized stress conditions and we can see the behavior of the coefficient $c(X_i, X_v, X_p)$ for three $X_p$ values (from 0 to 0.5) and varying $X_i$ and $X_v$ from 0 to 1. Having such a mapping, we need to consider that the $X_i$ parameters are limited by their maximum rating values as given in Table 3 and thus the value achievable by the coefficient $c(X_i, X_v, X_p)$ is quantified when multiple stresses are combined. Accordingly the related triplet $(X_i, X_v, X_p)$ can be calculated and a new reliability criterion can be drawn which relates simply as a single condition all constraints associated with $E_a$, all derating limits (both statics and dynamics) and thermal condition. We propose to set coefficient $c(X_i, X_v, X_p)$ verifying:

$$ c(X_i, X_v, X_p) > 30\% \quad (9) $$

This value is chosen in order to guarantee an effective activation energy greater or equal to 0.7 eV for a worst case wearout failure mechanism. In such a case, to demonstrate long term life in operation for Space Application as shown in Fig. 6, we will need to run sampling devices under biasing for a 3000 hour endurance lifetest sequence at $T_{\text{eff}} = 280$ °C (to achieve 80% lot failure) in order to be equivalent to 30 years at $T_{\text{eff}} = 110$ °C (for 0.1% failure). Note that this is equivalent to MTTF (at 110 °C) = 1.5 million hours or more than 170 years.

Now, we can draw the major conclusion of this section that is: when multiple stresses are applied simultaneously, the derating parameters and their maximum rating limits values need to be set in order to counterbalance an equivalent activation energy not inferior to 30% of $E_a$. Iso-planes $c(X_i, X_v, X_p) = constant$, are shown in Fig. 7 and represent combination of triplet rates to get a given value of $c(X_i, X_v, X_p)$ in view to satisfy a foreseen activation energy goal.

The drawing in Fig. 8 presents the methodology to determine operating worst case conditions which can be supported by the device under operating conditions and environmental multiple stressors in order to guarantee a time to failure rate of less than 1% after 30 years at junction temperature lower or equal to 110 °C as shown Fig. 6.

In the same spirit we defined the stressor energy concept ($\gamma$ linearly proportional) and we can introduce a new concept for the internal energy of a device to be straightforward linear relation with the electrical mode under consideration. Gradual degradation or sudden catastrophic ones are evidenced and signed by electrical failure modes. In the following we will try to define the mathematics of this perception.

### 6. A numerical application example for a Normally-off GaN transistor

In the following we are assessing the multi-stress induced effect the reliability figures on a GS66508P-E03 650 V enhancement mode Normally-off GaN transistor. The Arrhenius activation energy due to thermal stress only is assumed to be $E_a = 2.1$ eV.

![Fig. 6. Probability of failure vs $T_{\text{eff}}$ and time $t$ (assuming $E_a = 0.7$ eV). The lifetest sequence proposed on top will demonstrate less than 0.1% failure at 110 °C after 34 years).](image)

![Fig. 7. 3D-plot of normalized stress factor $\chi_i$.](image)

<table>
<thead>
<tr>
<th>Parameter limits</th>
<th>$V_{\text{GOff}}$</th>
<th>$P_{\text{GOff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>@ Burnout (a)</td>
<td>900 V</td>
<td>470 W</td>
</tr>
<tr>
<td>@ Maximum rating (b)</td>
<td>650 V</td>
<td>235 W</td>
</tr>
<tr>
<td>@ Derating limits (c)</td>
<td>487.5 V</td>
<td>117.5 W</td>
</tr>
<tr>
<td>$X_{\text{raw}} (c)/(a)$</td>
<td>54.2%</td>
<td>25%</td>
</tr>
</tbody>
</table>
In order to assess the reliability model and to define the limits of the Safe Operating Area (SOA) we need to define some specific condition of endurance testing with high enough stress to accelerate failure mechanisms.

Future reliability test programs are designed in order to simulate and accelerate various failure mechanisms one at a time. Power converter equipment based on Normally-Off GaN transistors as shown in Section 4 are designed in order to minimize to a less extent the commutation losses. Switching conditions between off and on states with short transition time are implemented but such losses cumulated during operation may generate multiple stress behavior. In order to simulate such operation we can design a reliability test program with two kinds of stress test at high \( V_{\text{DSoff}} \). The BAZ model proposed helps to simulate such occurrence of multiple stress conditions and to take into account their interactions.

Let’s consider two types of stresses imposed simultaneously:

a. the off-state at \( V_{\text{DS}} \) close to the breakdown voltage or close to burnout of the transistor: i.e. the Voltage stressor

b. the \( I_{\text{DS}} \) current at high \( V_{\text{DS}} \) induced during the switching time which can be set under equivalent static condition to simulate the Joule effect induced by commutation losses: i.e. the Power stressor.

The following will explain how to handle these stresses in parallel and to assess the combined activation energy to be considered for accelerating factor determination.

Space industry defines maximum rating and associated derating condition for safe operation in use as the following: voltage should never exceed 75% of the maximum rating of any voltage \( V_{\text{DS}} \text{ or } V_{\text{GS}} \).
and currents ($I_{DS}$) and never exceed power dissipation greater than 50% of the maximum rated power dissipation. In addition to that $T_{junction}$ must remain lower than 110 °C during the flight mission.

As per data measurements performed of COTS samples on the GaN transistor GS66508P-E03 650 V we obtained the following Table 3:

Eq. (7) factor $\kappa(\chi_i, \gamma_i)$, gives the value of this term when mechanisms Voltage Stressor and Power Stressor are applied:

$$\kappa(\chi_i, \gamma_i) = 1 - 54.2\% - 25\% = 20.8\%.$$

When the two stressors are applied simultaneously at their derating limits, the effective activation energy is reduced to 0.437 eV. Such activation energy is reducing drastically MTTF foreseen for Space application and then even compliant to Space rules the MTTF is no more acceptable.

When stressor percentages are lowered by reducing $V_{mos}$ voltage to 330 V and $P_{diss}$ to 140 W their contribution to the effective activation energy is 33.6% of $E_a$ (i.e. 0.7 eV) as shown in Fig. 7. In other words this model helps to assess the impact of the mission profile on the final activation energy expected and then assesses margin to Design for Reliability Space equipments. We need to be very careful when applying Quality Standards which are not considering multiple-stressor impacts and new rules for HiRel application are recommended to be set accordingly.

7. The BATHTUB curve model

Considering N “good” devices of interest randomly selected from a homogeneous manufacturing lot. The term “good” means the devices are non-discriminate, they are functional and their performance and electrical parameters are statistically normally distributed (Gauss or Normal statistics). Let’s consider the most representative electrical parameters (biasing or leakage currents, biasing or breakdown voltages) to be a representative sensor of the healthiness of the devices. For the sake of simplicity, we focus on the failure mode used for reliability consideration which is the most representative electrical parameter. Such a parameter can be considered as a signature or saying a measure of the internal energy $\epsilon$ as referred in Fig. 9 where for example be the pinch-off drift of a GaAs MESFET technology plotted as a square root of time degradation mechanism (gate sinking metal diffusion in active layer). This Fig. 9 is a schematic drawing of the TST and applied to the reliability of electronic parts showing how the BAZ model is applying. Other mechanisms as Early Failure or Infant Mortality and Random Failures are positioned as they may occur earlier assuming different gradients of degradation time (assumed to be linear or super linear).

7.1. How to determine the distribution function or the probability for a device at energy state $\epsilon$.

Because devices are characterized by their electrical parameters measured experimentally we have a physical indicator tool to quantify the energy change during aging and saying the drift of a parameter failure mode $\Delta E_{FM}/E_{FM0}$ is directly linked to the internal energy as:

$$\Delta \epsilon(t) = -\alpha_1 \cdot kT \cdot \frac{\Delta E_{FM}(t)}{E_{FM0}}$$

$$\sigma_{\epsilon}(t) = \alpha_2 \cdot \sigma_{E_{FM}}(t)$$

where $E_{FM0}$ is the electrical parameter measured at $t = 0$, $\Delta E_{FM}(t)$ and $\sigma(t)$ are respectively the mean and the standard deviation of electrical parameter (Gaussian distribution) depending on aging time.

Eqs. (10.a) and (10.b) are supported by the fact that Free energy of a device is proportionally increasing with temperature; when the failure mode degrades. Consequently, the Free energy increases with time (the sign “-” is introduced because percentage of parameter drift is negative).

Thus, the probability density function is now assumed to be a function of the energy at time $t$ described by a Gaussian distribution law:

$$f(\epsilon, t) = \frac{1}{\sigma_{\epsilon}(t) \cdot \sqrt{2\pi n}} e^{-\left(\frac{\epsilon - \epsilon_{FM0}}{\sigma_{\epsilon}(t)}\right)^2}.$$  (11)

Knowing this probability density function and recalling the set of equations we are able to model:

A) Wearout failures based on:

- The number of failed device at time $t$ assumed to be Wearout failure:

$$N_{wearout}(t) = \int_{t_0 - \gamma_S}^{t} \rho_{wearout}(\epsilon) \cdot f_{wearout}(\epsilon, t) \cdot d\epsilon.$$  (12)

- The number “Good” devices defined by:

$$N_{Good}(t) = \int_{0}^{t_0 - \gamma_S} \rho_{wearout}(\epsilon) \cdot f_{wearout}(\epsilon, t) \cdot d\epsilon.$$  (13)

- The normalization when considering the total number of device is given by:

$$N_T(t) = N_{Good}(t) + N_{wearout}(t) = \int_{0}^{t} \rho_{wearout}(\epsilon) \cdot f_{wearout}(\epsilon, t) \cdot d\epsilon.$$  (14)

B) Random failures:

- Random failure mechanisms can be discriminated versus time in Eqs. (12) to (14) considering that the appropriate distribution
function or probability that a device at energy state $E$ is defined by a function of energy $I_{\text{random}}(E)$ and assuming the adequate density of states, or the number of energy states per unit volume in the interval $\Delta E$ is $\rho_{\text{random}}(E)$.

C) Infant mortality model

- Infant mortality is defined by Eqs (12) to (14) considering that the appropriate distribution function or probability that a device at energy state $E$ is defined by a function of energy $I_{\text{random}}(E)$ and the adequate density of state or the number of energy states per unit volume in the interval $\Delta E$ is $\rho_{\text{random}}(E)$.

Early failure, random failure and wearout mechanisms can be discriminated with time thanks to Eqs. (12), (13) and (14) respectively accommodated in order to depict the full bathtub curve. Doing so, the Instantaneous Failure Rate (IFR) $\lambda(t)$ is defined by:

$$\lambda(t) = \frac{N_r(t)}{N_r(t)} - \frac{\int_{E_0}^{\infty} \rho(e, t) \cdot f(e, t) \cdot d}{\int_{E_0}^{\infty} \rho(e, t) \cdot f(e, t) \cdot d} \quad (15)$$

with the corresponding superposition of failure mechanisms and their appropriate definitions.

All these equations are linked to the suitable densities of state $\rho_{\text{internal}}(E)$, $\rho_{\text{random}}(E)$ and $\rho_{\text{wearout}}(E)$. Appendix A is describing how such densities of state can be calculated and quantified based on a Maxwell–Boltzmann statistical approach.

8. Discussion

The generalized BAZ model based on simultaneous multiple stress conditions has been presented and is fully depicted thanks to considering absolute maximum ratings and burnout limit normalization. The methodology implemented for the GaN transistor process in Section 5 can be easily generalized to any type of electronic device for any failure mechanism that is thermally determined as a rate function described by the Maxwell–Boltzmann distribution.

To complete our study, here are some views related to advantages and comments of the proposed methodology.

To illustrate this, let’s considering Hot Carrier Injection mechanism and impact ionization stress mechanism. They are mostly observed to have higher failure rates at low temperature than at high temperature. Hence, negative activation energy must be set for low temperature range while positive activation energy must be introduced for high temperature range.

The BAZ model is a single effective activation energy representing no more than one effective mechanism. For multiple activation energies, we have to consider that the multiple mechanisms are statistically independent and they must be dealt with a stochastic process. This will allow the total equivalent failure rate at any temperature and/or combination of stresses to be a sum of FIT. This is exactly what the approach proposed by J. B. Bernstein [11,12] is offering as related to the Multiple High-Temperature Operating Life (M-HTOL) test. It can certainly be an outstanding combination with the BAZ model. This merging will be studied and developed in a future paper in preparation with J.B. Bernstein.

8.1. Advantages

The Transition State Theory was set in the generalized BAZ model. It helps to elaborate a useful tool aiming to develop a methodology to define, quantify and predict the complete reliability Bathtub curve for any electronic device. Furthermore, it takes into consideration a combination of multiple stress conditions merging intrinsic and extrinsic constraints and electrical modes. It provides a good simple support to model the catalyst effect induced by many stressors as for example thermal and dynamic biasing or radiation stresses. Anticipating combined effects due to various stressors, we have shown how efficient is the model applied to new emerging technologies as GaN processes: helping to quantify and reduce evaluation and qualification test time sequences.

There is no need to conduct multiple stress test sequences rather it is proposed to perform only a simple storage stress associated to deep electrical characterization and develop a good knowledge of physics of failure (based on very detailed constructional analyses and failure analysis methods).

The generalized BAZ model takes into consideration other stressors than temperature defining accelerating factor for DC and AC parameters in a simultaneous combined form. It is applicable to support low temperature acceleration models as well.

Finally, the model is easy to be implemented and consolidated and provides a useful tool for determining and recommending design rule consideration for breakthrough technologies: it covers Design for Reliability methodologies as required in the Prognostics and Health Monitoring (PHM) paradigm.

The generalized BAZ model is an extension of the Arrhenius law not only applicable to diffusion and storage test stresses but also valid for other combined harsh environment stressors cumulated with temperature.

8.2. Other comments

Of course the generalized BAZ model is supported by the hypothesis that the internal energy of a device is perceived or observed by an electrical mode signature: either a leakage current of a performance parameter. This is not always the case as some hidden failure mechanisms can be activated (i.e. not seen as continuous electrical degradation but rather as sudden catastrophic failure). This is noticed for latent (cumulated or not) effects (due to contaminants, ESD, EOS, increase of dislocation density, radiation as displacement damage DD for example) or even for crystal dislocation accumulation in active and non-active regions. When these physical and/or electrical precursors are not yet active, they can be later activated by temperature and electrical stressors.

In all these particular cases, the generalized BAZ model is failing or less accurate to predict failure and the end of life limit. If so, the Early Failure or the Random Failure stages of the Bathtub curve can be overestimated. On the other hand, one needs to identify failure analysis techniques or electrical characterization method to pinpoint electrical precursors to model the behavior of the reliability. On the other hand, it is necessary to collect and validate how the stressors are acting to accelerate the failure mechanisms expected.

These limitations of the generalized BAZ model will require some refinement or new techniques of characterization to be instigated. We will address such considerations in our future studies and in particular for the case of small size node (lower than 30 nm) of Si semiconductor integrated processes called Deep-Sub-Micron (DSM) technologies.

8.3. Special care to be considered when applying this methodology — how to consolidate it?

Existing and new failure analysis techniques need to be controlled and implemented. Similarly, constructional analysis and knowledge of semiconductor physics modeling are pre-requisites in any case. These two prerequisites will let us understand failure mode created under dynamic operating conditions. The use of such emerging and non-stabilized technologies imposes careful implementation of adequate Design Rules. In particular, dynamic stress (switch off and switch on inducing losses) for implementation of GaN Power Switch transistor.
devices is of particular concern and can be viewed in light of such generalized BAZ methodology proposed. As a consequence, design and reliability simulation tools are important threads to be under control. Design rules as well as electrical and physical characterizations are key phases to be structured.

9. Conclusion

The principle of the generalized BAZ model exposed in Ref. [2] was recalled. An example of a Normally-Off GaN Power switch transistor detailing from the data sheet the maximum rating limits was considered. We have seen how other dynamic maximum rating limits must be pondered in detail and in particular for switching bias operating conditions (also to be related to specific Design Rules to define).

The generalized BAZ model was refined and adapted to the GaN technology. As an example we have completed numerical Application on a Normally-off transistor GaN reference GS66508P-E03 650 V enhancement mode manufactured by GaN Systems. The concepts of maximum rating limits and burnout conditions have been useful to derive key parameters as $\chi_i$'s and $\gamma_i$'s, both statistically represented by a normal distribution law. In particular such normalized stress factors $\chi_i$ vs the catastrophic burnout limit $S_{\text{BO,burnout}}$ of a Normally-off transistor GaN were displayed. As a consequence, when multiple stresses are applied simultaneously, the derating parameters and their maximum rating limits values are imbricated to derive the equivalent effective activation energy.

To complete our approach, the BAZ Multiple Stress Model will be associated with the approach proposed by J. B. Bernstein related to the Multiple High-Temperature Operating Life (M-HTOL) test [11,12]. This extension will be developed in a future common paper under preparation.

Finally this model helps to assess the impact of the mission profile on the final activation energy expected and then assess margin to Design for Reliability Space equipments. This gives reliability quantification rule for effective $E_a$ and related condition of stress to assess RUL (Remaining Useful Life) condition. We need to be very careful when applying Quality Standards which are not considering multiple-stressor impacts and new rules for HiRel application are recommended to be set accordingly. A short discussion was presented to recall the main advantages, drawbacks and some special care to implement the methodology.

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