A Statistical Approach to Characterizing the Reliability of Systems Utilizing HBT Devices

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Abstract: This paper presents a statistical approach to characterizing the reliability of systems with HBT devices. The proposed approach utilizes the statistical reliability information of the HBT individual devices, along with the analysis on the critical paths of the system, to provide more accurate and more comprehensive reliability information about the HBT systems compared to the conventional worst-case method.

Introduction

As users of hetero bipolar transistors (HBTs), we have built systems with quite a few HBT devices on critical paths. There has been extensive research on individual HBTs regarding performance, reliability, and failure mechanisms. However, the evaluation and assessment of the system-level reliability of the HBT systems is also of great importance. To determine system-level reliability, the worst-case approach is typically used. This practice is to equate the life of the HBT device(s) under the worst bias condition(s) to the life of the system. However, because of the statistical nature of the life of the individual HBTs, this worst-case practice does not necessarily provide the life of the weakest link in the system.

In this paper, we present a statistical approach to including reliability information of HBT devices in order to obtain more accurate and more comprehensive information of HBT system-level reliability.

Reliability Characterization

HBT device reliability

HBT device reliability has been extensively studied and HBT device life has been demonstrated to follow the following equation [1-3]

$$ttf = CJ^{-\alpha} e^{E_a / kT_j} \tag{1}$$

Here, C is a constant; *ttf* is time to failure; J, α, Ea, k and T_j are HBT device current density, current exponent, activation energy, Boltzmann constant, and junction temperature, respectively.

In addition to equation (1), the following factors are to be considered in the proposed statistical approach. First is to factor in the statistical nature of HBT device reliability. HBT device life is typically log-normal distributed with a standard deviation of 0.6~0.7 for the ln-normal lifetime or 0.25~0.35 for log-normal lifetime [2-5]. The nature of the distribution along with its parameters is the key to assessing system reliability. Second is to deal with the competing mechanisms of HBT devices. Both high and low activation energy (high-Ea and low-Ea) phenomena have been found for HBT device reliability. Some studies have shown Ea's of the order of 1eV or more on GaAs HBTs [2,4,6], on InGaP/GaAs HBTs [3], and on InP-based HBTs [5,7,8] while other studies have Ea's of 0.45eV on GaAs/AlGaAs HBT amplifiers [9], 0.68eV on InGaP HBTs [10], and different Ea's for different failure mechanisms on GaAs HBT amplifiers [11]. Third is to note that the current bias and junction temperature are not totally independent since junction temperature is a function of current injection. There are some methods and techniques proposed for estimating junction temperatures of the HBTs under current/voltage biases [13-16].

System-level Reliability

Worst-case approach

The typical system-level reliability approach is the so-called worst-case approach. It utilizes the life of the critical HBT device(s) under the worst-bias condition to estimate the life of system. The assumption behind this approach is that the worst-bias condition of the critical HBTs gives the shortest life and, therefore, the life of the system is defined by this "weakest link." The procedure for the worst-case approach is summarized in the left column of Table 1.

There are some concerns about the worst-case approach. First, because of the statistical nature of the life of the HBT devices, this worst-case practice does not necessarily produce the life of the weakest link in the system. Depending on which failure percentage for HBT life (i.e., mean time to failure (MTTF), or time to 10% fail $t_{10\%}$, or time to 1% fail $t_{1\%}$, or time to 0.1% fail $t_{0.1\%}$, etc.) is used during the worst-case analysis, the reliability estimation by the approach can either be too pessimistic or too optimistic. Second, the worst-case approach does not consider the HBTs under other "worse" cases, which could become the worst case(s), especially if the number of HBTs under the worse case(s) is much greater than that under the worst case. Third, the worst-case approach usually yields "point estimates" of HBT device life with no statistics (point estimate) or system behavior (only estimates on worst-case HBT devices) involved.

Statistical approach

To address the above concerns and to provide more comprehensive and a more accurate HBT system-level reliability assessment, we propose a statistical approach to first simulate the life distributions of each critical HBT in the system and then to obtain the system life distribution. This approach is focused on the statistical nature of the individual HBTs. It includes worst case *and* potential worse cases, considers the number of individual HBTs under each bias condition, and takes competing failure mechanisms into consideration. For easy comparison, the procedure of the statistical approach is listed in parallel with that of the worst-case approach in Table 1.

Table 1. Worst-case approach and statistical approach

	Worst-Case Approach	**Statistical Approach**
1.	Determine critical paths of the system.	Determine critical paths of the system.
2.	Determine the worst-bias condition of the critical HBT devices under system operating condition.	Determine the worst- and *a number of worse* bias conditions of the critical HBTs under the system operating condition $\mathbf{J} \in (J_1, J_2 \ldots J_n)$. Find the bias conditions that bias the largest number of HBTs ($J_{n+1}, J_{n+2} \ldots J_{n+k}$) and determine *the number of HBTs under each worst/worse- bias condition* $\mathbf{N} \in (N_1, N_2, \ldots N_n, \ldots N_{n+k})$.
3.	Determine the failure criteria for the critical HBT devices.	Determine the failure criteria for the critical HBT devices.
4.	Project the life of the critical HBT device(s) under the worst-bias condition.	Simulation: Project the life *distributions* $\mathbf{D} \in (D_1, D_2, \ldots D_n, \ldots D_{n+k})$ of the critical HBTs under each bias condition, using known activation energies $\mathbf{E} \in (Ea_1, Ea_2, \ldots, Ea_m)$. Randomly choose the *exact* $\mathbf{N} \in (N_1, N_2, \ldots N_n, \ldots N_{n+k})$ number of HBTs under each condition.
5.	The shortest HBT life is assumed as the life of the system under its operating condition.	The simulation gives the *life distribution* of the critical HBTs in the system.
6.	N/A	Derive the system life distribution. Any point estimate of the system life can be calculated from the distribution with any desired level of failure percentage and confidence level.

The statistical approach yields more comprehensive reliability information about the system. Instead of a single HBT life representing the system reliability, it provides a set of simulated life distributions of all critical HBTs in the system and a simulated system-life distribution. It may sound like tremendous, time-consuming work, but it only takes computer time.

The inputs of the simulation are

1. current bias conditions of the individual HBTs, i.e., $\mathbf{J} \in (J_1, J_2 \ldots J_n)$;
2. number of HBTs under each bias condition, i.e., $\mathbf{N} \in (N_1, N_2, \ldots N_n, \ldots N_{n+k})$
3. activation energies for different failure mechanisms, i.e., $\mathbf{E} \in (Ea_1, Ea_2, \ldots, Ea_m)$.

Log-normal distribution is assumed with the same standard deviation for the different current biases and equation (1) is used for device-level life projection in the simulation with pre-determined failure criteria for critical HBTs. The determination of the failure criteria is the same as in the worst-case approach. The failure criteria depend on the functionality of the circuits and system and can be different for different critical HBTs. Either DC or AC or both parameters may be used, but the failure criteria need to be correlated to the functionality of the circuits or even to the system. One example is to correlate the DC parameter degradation to AC parameter degradation [4, 6, 9].

After defining the failure criteria for the critical HBTs in the system, the key steps are to determine which bias conditions and it's ~~the~~ corresponding number of HBTs are to be included in the statistical simulation and how to incorporate the competing failure mechanisms into the system-life simulation.

1. Determination of bias conditions for the simulation

The bias conditions **J** (J_1, J_2, ...J_n, ...J_{n+k}) that need to be included in the simulation are those that may yield shorter or the shortest HBT device life, i.e., worst and worse conditions and conditions that have a large number of HBT devices.

Assume that J_1 is the worst (highest)-bias condition of the HBTs in the system and J_2 the second-highest bias condition, then, the life of the HBTs, t_1 and t_2, under J_1 and J_2, respectively, follows log-normal distribution with medians of μ_1 and μ_2 ($\mu_2>\mu_1$) and same standard deviation σ, i.e.,

$$t_1 \in \Phi(\mu_1,\sigma) \quad and \quad t_2 \in \Phi(\mu_2,\sigma)$$

When the two life distributions are one σ apart (μ_2-μ_1=σ), the probability of one randomly chosen t_2 (life of a HBT biased at J_2) being smaller than μ_1(MTTF from J_1) is

$$P_{1(\mu_2-\mu_2=\sigma)} = \Phi(t_2 < \mu_1) = \Phi(z < \frac{\mu_1-\mu_2}{\sigma}) = \Phi(z < -1) = 0.1587$$

and the probability of at least one of *n* randomly chosen t_2 being smaller than μ_1 is

$$P_{n(\mu_2-\mu_1=\sigma)} = 1-(1-P_{1(\mu_2-\mu_1=\sigma)})^n$$

The above two equations describe the probability of the shortest device life coming from one out of *n* HBTs biased under a non-worst-case condition J_2. Table 2 shows the probability of at least one HBT biased under J_2 having a shorter life than μ_1 when μ_2-μ_1=σ (case I), 2σ (case II), and 3σ (case III).

Table 2. Probability of HBT(s) under non-worst-case bias giving shortest device life compared to MTTF under the worst case.

Probability($t_2<\mu_1$) when	μ_2-μ_1=1σ	μ_2-μ_1=2σ	μ_2-μ_1=3σ
1 Device From J2	0.1587	0.0228	0.0013
2 Devices From J2	0.2922	0.0451	0.0026
3 Devices From J2	0.4045	0.0669	0.0039
4 Devices From J2	0.4990	0.0881	0.0052
5 Devices From J2	0.5785	0.1089	0.0065
10 Devices From J2	0.8224	0.2060	0.0129
20 Devices From J2	0.9684	0.3695	0.0257
50 Devices From J2	0.9998	0.6844	0.0630
100 Devices From J2	1.0000	0.9004	0.1220

From Table 2, the more HBTs are biased under non-worst-case condition J_2, the more likely (0.9998 for 50 HBTs under J_2) the shortest HBT device life occurs in an HBT under non-worst-case condition. The above approach to generate similar information in Table 2 for any distribution distance and for any time to fail percentage is used to determine the non-worst-case bias conditions necessary to be considered in the statistical approach, given a risk probability. For example, if we regard 5% as the risk we are willing to take, then the following bias conditions may not need to be included:

1. Whose device life median is 2σ apart from the worst bias and has fewer than 3 devices;
2. Whose device life median is 3σ apart from the worst bias and has fewer than 50 devices;

From the above analysis, it is easy to see that two HBT systems with the same worst-case but different bias distributions can give different final life distributions and projected system life. Figure 1 shows the simulated (100 runs; more runs result in a similar distribution but a smoother curves) HBT system-life distributions assuming the same activation energy but different current bias conditions (blue and red) or different number of HBT devices under each bias condition (red and green). Both life and frequency values are arbitrary numbers (a. u.), just to show that the distribution may not be a log-normal distribution as individual HBTs, but is rather a function of the inputs of **E**, **J** and **N**.

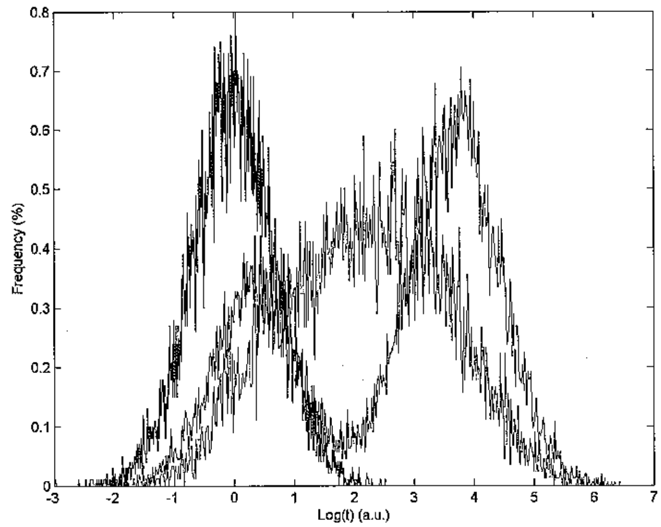

Figure 1. HBT system life distribution as function of bias **J** and HBT number **N**.

Competing failure mechanisms

The impact of activation energy **E** (Ea_1, Ea_2, ..., Ea_m) is shown in Figure 2. Red, green, and cyan lines represent the simulated (100 runs) final HBT life distribution in a system with activation energies of 0.3eV, 0.8eV, and 1.2eV, respectively, assuming the same current bias conditions for all critical HBTs, the same number of HBTs under all bias conditions, and the same temperature profiles for each current bias condition. The lifetime value is in arbitrary numbers. Larger activation energy tends to move the final distribution to the right, indicating a longer system life overall.

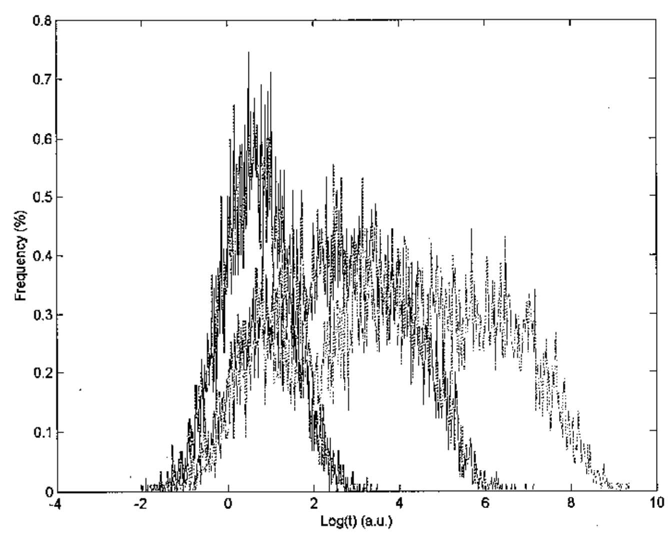

Figure 2. HBT system life distribution as a function of activation energy **E**.

Assume **E** (Ea_1, Ea_2, ..., Ea_m) is the activation energies for certain HBT devices used in a system, then Figure 2 gives the life distributions of those HBTs under each of the activation energies. The reliability at a certain life (i.e., at any $\log_t$ under a bias condition and temperature) can be calculated for each activation energy for the HBTs. Then the reliability at this certain life point is the product of all the calculated reliability. Then the cumulative failure fraction at the life point is one minus the calculated reliability. Based on the final reliability/failure fraction information, the system life can also presented as any point estimate with any desired confidence level.

Summary

We have presented a statistical approach to characterizing the reliability of systems with HBT devices on critical paths. The approach includes measuring the statistical reliability of the individual HBT devices in the system and therefore yields more accurate and more comprehensive reliability information about the system.

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