

A Correlation Between Beta Degradation at Room Temperature versus Beta Degradation at Stress Temperature for Determining the Reliability of HBTs

E. Sabin, J. Scarpulla, E. Kaneshiro, W. Kim, D. Eng, D. Leung

TRW, One Space Park, Redondo Beach, CA 90278

ABSTRACT

The reliability of TRW's HBT devices has been measured using a highly accelerated WLR (wafer level reliability) technique, and results agree with less-highly accelerated oven reliability tests of HBT's and MIMC circuits. This paper compares the projected activation energy and MTTF derived from WLR tests where the current gain (β) is measured either at room temperature or at the stressing temperature. The latter is preferred from a test efficiency standpoint, but the former is more common. The results show that with a proper selection of a failure criterion for each, equivalent activation energies and MTTF's can be obtained. Unfortunately it is currently not possible to measure the emitter resistance or the low current turn on voltage while keeping the wafer at the stressing temperature. So if the reliability is needed for these parameters then it is suggested that the wafer be periodically cooled to room temperature for measurement.

INTRODUCTION

TRW's HBT process has consistently demonstrated high reliability (MTTFs well in excess of one million hours) under both accelerated short term or long term lifetest conditions, and has accumulated multi-millions of device hours in both commercial and high-value high-rel space applications. This paper discusses the WLR method, a highly accelerated technique that performs the stress in a few hours enabling a reliability prediction.

A traditional WLR method for determining the beta degradation lifetime of a HBT is to stress it at high temperature but measure the beta at room temperature [1]. This method requires heating and cooling of the wafer, but allows measurement of the beta at approximately usage conditions. A different way to determine the lifetime of a HBT is to measure the beta at the stressing temperature, while stressing the device, and use the degradation in the beta at the stressing temperature to determine the lifetime [2, 3]. This second method has the advantage of eliminating the need for heating and cooling of the wafer, thus, speeding up the testing cycle. Although this second method has a throughput advantage, there have been no studies comparing it with the traditional way to see if the same lifetime is predicted. Also, using this second method the lifetime of the HBTs can not be determined for the low current turn on voltage ($V_{be,on}$) or the emitter resistance (R_e).

This paper will present data on measuring the HBT lifetime using the traditional way in comparison with the new method. It will compare the lifetimes predicted by these two

methods to determine if they are statistically the same. Also, it will discuss the proper way to measure the lifetime for the low current $V_{be,on}$ and the R_e .

EXPERIMENTAL SETUP

The automated WLR equipment used to measure/stress the HBTs, consisted of a Cascade Summit 12000 prober, equipped with a Temptronics hot chuck, HP4142B modular DC source/monitor units, and Gravity probes [1]. The HBTs were produced by TRW's patented HBT process [4] and consisted of an $80 \mu\text{m}^2$ emitter. The WLR system was programmed so that at the start of the testing cycle a Gummel plot was made on both a control part and the device under test. The wafer was then heated to the stressing temperature, and after stabilizing, stressing commenced on the device under test while the control part was not stressed (hot control). The stressing was performed with a collector/base voltage of 3.5 Volts having the base at zero volts. The emitter voltage was adjusted to keep the collector current constant at 20 KA/cm^2 . The base-emitter voltage was generally around 0.95 volts during the stressing, so the collector/emitter voltage during stressing was approximately 4.5 volts. Also during the stressing the base current (I_{bs}) was recorded approximately every 10 seconds. The I_{bs} was then used to determine the beta at the stressing temperature by dividing the stressing collector current by I_{bs} . At selected times the wafer was cooled to room temperature and a Gummel plot was performed on the device under test at 25°C before being heated back to the stressing temperature. The chuck temperatures used to stress the devices were 295, 280, and 260°C . The junction temperatures under stress were calculated to be 407.5, 398.4, 375.8°C . At the end of the testing cycle a Gummel plot was again performed on the device under test and the control part. The Gummel plots were then used to determine the room temperature beta at a collector current of 1 mA, the $V_{be,on}$ at a collector current of $1 \mu\text{A}$, and the R_e at a collector current of 10 mA. Degradation in these values relative to their initial value was used to determine the time to failure for the devices under test. Changes in the value for the control part was used to insure that no unbiased thermal failure mode was present. Data for the control parts will not be shown since they changed less than 1% while the devices under test changed by more than 20%.

A three-temperature lifetest was performed using 46 devices from wafers produced by TRW's HBT process. The device testing was divided between the three stressing temperatures with 21 devices tested at 295°C , 19 devices at 280°C , and 6 devices at 260°C . Initially, a -20% change in beta was chosen as the failure criterion for both the room

temperature beta and the stressing temperature beta. A +2 mV change was chosen as the failure criterion for the $V_{be_{on}}$, while a +5 % change was used as the failure criterion for the Re. Using these failure criteria, the time to fail (TTF) for each device was determined for the parameters, with the MTTF at each temperature being used to project a MTTF at a junction temperature of 125 °C. For beta degradation the MTTF for the second WLR method was then compared with the MTTF for the traditional WLR method and a statistical analysis was performed to determine if the MTTFs were comparable.

ROOM TEMPERATURE BETA DEGRADATION

Figure 1 shows the change in the room temperature beta ($Beta_{RT}$) as a function of stress time for devices stressed at a junction temperature of 407.5 °C. It can be seen in this figure that the beta for some of the devices degrade quickly while for other devices the beta degradation is slower. A cumulative probability plot of the TTFs for these devices is shown in Figure 2 for a failure criterion of -20% change in beta. This figure shows that the TTFs are linear on a log normal graph showing only one distribution. Figure 3 shows the before and after stressing Gummel plots for a device in the first 10% of the cumulative probability plot. It can be seen in this graph that the failure mode for this device is the base current increasing. Figure 4 shows the before and after stressing Gummel plots for a device in the last 10% of the cumulative probability plot. It can be seen in this figure that the failure mode for this device is the base current increasing, which is the same failure mode for the device from Figure 3. Therefore, it is felt that all devices fail with the same failure mode. An Arrhenius plot of the MTTF at each temperature is shown in Figure 5. The activation energy calculated from the data is 2.1 eV which is very similar to previous investigations which found an activation energy of 1.8 eV [4].

STRESSING TEMPERATURE BETA DEGRADATION

Figure 6 shows a plot of the change in the stressing temperature beta ($Beta_{ST}$) as a function of the cumulative stressing time for a device in the last 10% of the cumulative probability plot. This figure also shows the change in the room temperature beta ($Beta_{RT}$) for the same device. It can be seen in this figure that the $Beta_{RT}$ and the $Beta_{ST}$ track each other closely up to a beta degradation of -20%. After that time the $Beta_{RT}$ and $Beta_{ST}$ diverge. The TTF for this device (at -20% change in beta) is about the same whether it is determined from the $Beta_{RT}$ or from the $Beta_{ST}$ curve. If all HBTs failed similar to this HBT then it would not matter which beta curve was used to determine the TTF.

Figure 7 shows a plot of the change in $Beta_{ST}$ and $Beta_{RT}$ as a function of cumulative stress time for a device in the first 10% of the cumulative probability plot. It is seen in this figure that both the $Beta_{ST}$ and the $Beta_{RT}$ gradually degrade as the stress time is increased, but the room temperature beta degrades faster than the stressing temperature beta. The TTF for this device (at a -20% change in beta) is different

depending upon if it is determined from the $Beta_{RT}$ or the $Beta_{ST}$ curve. These beta degradation curves are typical for a device in the first 50% of the cumulative probability plot.

Figure 8 shows a cumulative probability plot of the TTFs determined from the $Beta_{ST}$ curves for devices stressed at a junction temperature of 407.5 °C and using a failure criterion of -20% change in the $Beta_{ST}$. Also shown in this figure is the data from Figure 2 as a comparison. It can be seen that the MTTF for the stressing temperature beta is larger than the MTTF for the room temperature beta. The correlation must be determined between the stressing temperature beta and the room temperature beta to use the stressing temperature beta for accurately predicting the HBT lifetime.

To determine the correct failure criterion for $Beta_{ST}$, a plot was generated of the changes in the $Beta_{ST}$ as a function of the changes in the $Beta_{RT}$ (see Figure 9). The $Beta_{RT}$ used to generate this plot came from the room temperature beta calculated from the Gummel plot, after the wafer was cooled to room temperature. The $Beta_{ST}$ that was associated with this $Beta_{RT}$ value came from the stressing temperature beta just before the wafer was cooled to room temperature. The data was then filtered so that only changes in a $Beta_{RT}$ of less than 0% is shown. It can be seen in this figure that the relationship between the changes in these two betas is nonlinear. A third order polynomial regression was performed on this data with the curve being forced to go through -100% $Beta_{RT}$ and -100% $Beta_{ST}$. The regression equation, shown in the figure, shows that for a change in $Beta_{RT}$ of -20%, the change in $Beta_{ST}$ is approximately -10%.

Therefore, for the $Beta_{ST}$ a failure criterion of -10% was chosen and the TTF for all the devices under test was determined. An Arrhenius plot of the MTTF for $Beta_{ST}$ at each temperature is shown in Figure 5 along with the activation energy which was found to be 2.0 eV. The TTF data used to make this plot was then compared with the TTF data used to make the Arrhenius plot of the room temperature beta and statistically there is no difference between the TTFs for these two plots. This data indicates that changes in the stressing temperature beta can be used to predict the lifetime of the HBTs, provided that the relationship between the changes in the stressing temperature beta and the room temperature beta is accurately known.

TURN ON VOLTAGE AND EMITTER RESISTANCE

Figure 10 shows an Arrhenius plot of the MTTF at each temperature for both the low current $V_{be_{on}}$ and the Re. The activation energy for both of these parameters was calculated to be 1.6 eV. The data used to make this plot came from the Gummel plots made on the devices under test at 25 °C. A failure criterion of +2 mV was used for the $V_{be_{on}}$ and a failure criterion of +5% was used for the Re. If at the stressing temperature, a Gummel plot was made on the device under test it would not be possible to determine, from this Gummel plot, the low current $V_{be_{on}}$ or the Re. Therefore,

keeping the wafer at the stressing temperature precludes the determination of the lifetime of the HBTs for $V_{be_{on}}$ or R_e . Also if the stressing temperature beta is the only parameter used for determining the reliability of HBTs it is possible to miss problems with $V_{be_{on}}$ or R_e . Since it is only possible to measure the $V_{be_{on}}$ and R_e at room temperatures it is suggested that during stressing, the wafer be cooled periodically to room temperature to measure these parameters.

SUMMARY

The MTTF of HBTs for beta degradation was measured using a traditional WLR method and a new WLR method. If a proper correlation is obtained between the beta degradation at room temperature and the stressing temperature, similar lifetimes can be predicted using these two methods. But, since it is not possible to measure the low current turn on voltage or the emitter resistance at the stressing temperature, lifetime predictions for these parameters should be made

based upon room temperature measurements. Therefore, it is suggested that the traditional WLR method be used to determine the reliability of HBTs for $V_{be_{on}}$ and R_e .

REFERENCES

[1] E. Sabin, S. Scarpulla, S. Dacus, "Automated WLR testing of HBT's", Proceedings of the GaAs reliability Workshop 18 (1999).
 [2] R. Welser, M. Chaplin, C. Lutz, N. Pan, "Base Current Investigation of the Long-Term Reliability of GaAs-Based HBT's", Proceedings of the International Conference on GaAs Manufacturing Technology 145 (2000).
 [3] B. Yeats, P. Chandler, M. Culver, D. D'Avanzo, G. Essilfie, C. Hutchinson, D. Kuhn, T. Low, T. Shirley, S. Thomas, W. Whiteley, "Reliability of InGaP-Emitter HBT's", Proceedings of the International Conference on GaAs Manufacturing Technology 131 (2000).
 [4] F.M. Yamada, A.K. Oki, D.C. Streit, D.K. Umemoto, L.T. Tran, T.R. Block, D.T. Okazaki, M.M. Hoppe & E.A. Rezek, "High-Reliability GaAs HBT Monolithic Microwave Amplifier" IEEE RFIC Symposium Digest, pp. 193-196, 1997 and IEEE MTT-S International Microwave Symposium Digest, pp. 141-144, (1997).

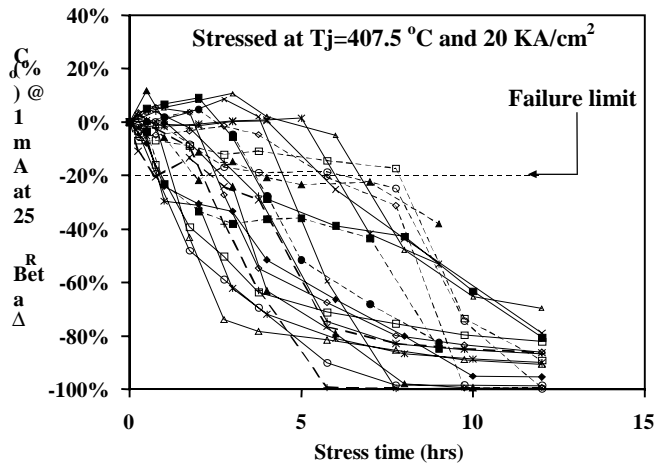


Figure 1: A plot of the room temperature beta degradation as a function of the stress time.

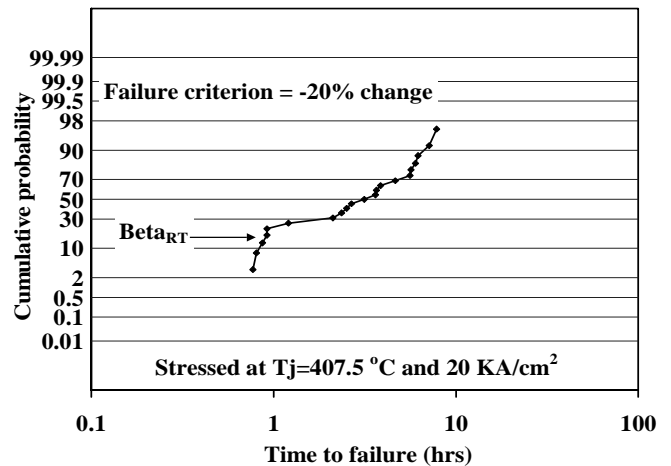


Figure 2: A log normal cumulative probability plot of the time to fail determined from the data in Figure 1.

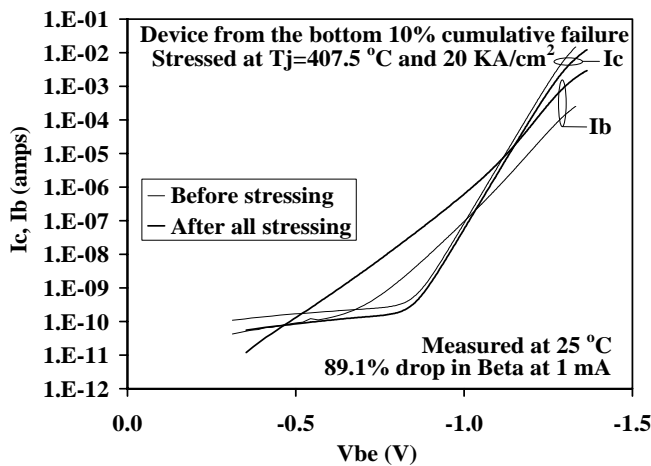


Figure 3: The before and after stressing Gummel plots of a device in the first 10% of the cumulative probability plot.

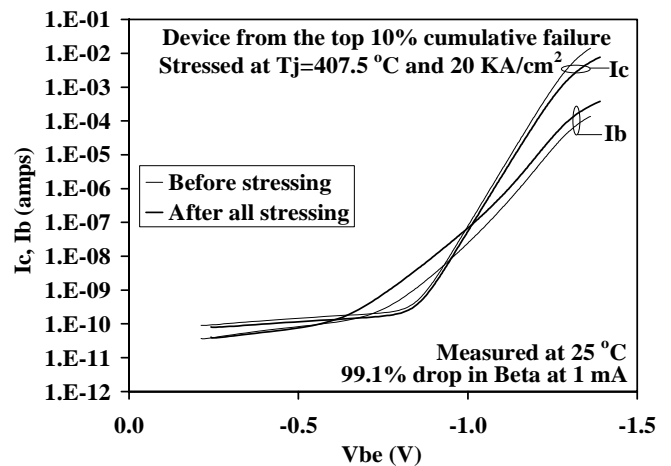


Figure 4: The before and after stressing Gummel plots of a device in the last 10% of the cumulative probability plot.

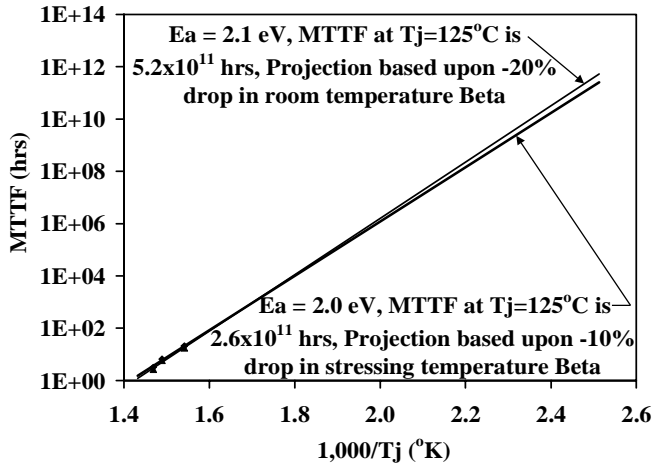


Figure 5: An Arrhenius plot of the MTTF for room temperature and stress temperature beta degradation. A previous investigation [4] found an activation energy of 1.8 eV which is similar to the current investigation.

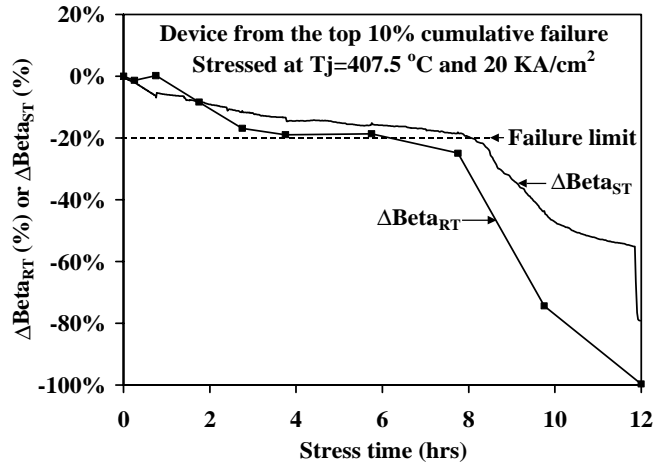


Figure 6: A plot of the change in Beta_{ST} and Beta_{RT} as a function of the stress time for a device in the last 10% of the cumulative probability plot.

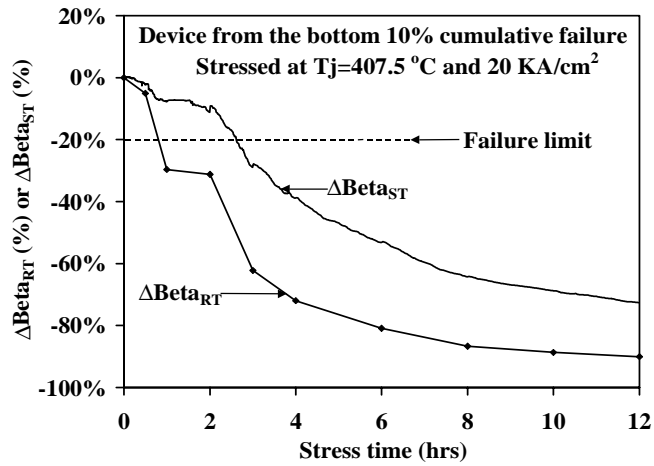


Figure 7: A plot of the change in Beta_{ST} and Beta_{RT} as a function of the stress time for a device in the first 10% of the cumulative probability plot.

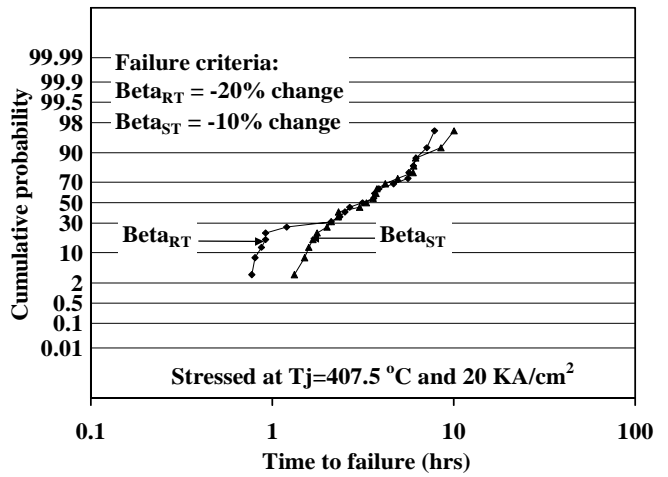


Figure 8: A log normal cumulative probability plot of the time to fail for both Beta_{ST} and Beta_{RT} .

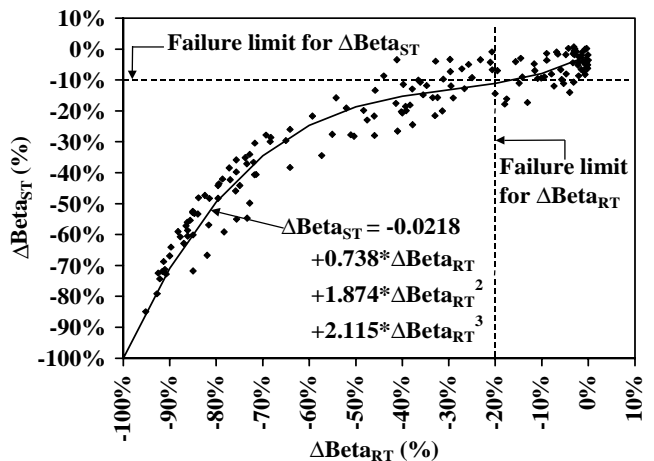


Figure 9: A plot of the change in the Beta_{ST} as a function of the change in the Beta_{RT} .

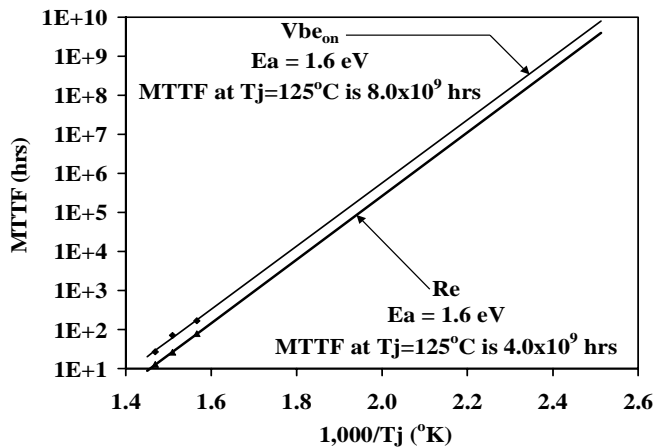


Figure 10: an Arrhenius plot of the MTTF for the turn on ($V_{\text{be}_{\text{on}}}$) and the emitter resistance (R_e).