High-Temperature Degradation of Wire Bonds in Plastic Encapsulated Microcircuits

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Abstract

Application of low-cost commercial plastic encapsulated microcircuits (PEMs) for military and aerospace applications requires rigorous analysis of their quality and reliability in harsh environments. It is known that degradation of Au/Al wire bonds limits reliability of PEMs at high temperatures; however, there is only limited information on acceleration factors of wire-bond failures. In this work a technique, which is based on in-situ evaluation of contact resistances (Rc), has been used to monitor degradation processes in wire bonds in two types of microcircuits encapsulated in 80-pin and 44-pin QFP plastic packages. The parts were stored at temperatures varying from 175 to 250 ^{o}C for up to 2,500 hours in some cases. Kinetics of Rc variations and temperature dependence of parameters of Weibull distributions were used to calculate activation energy of the degradation process and predict failure rates at temperatures below 175 ^{o}C. The mechanism of wire-bond failures and factors affecting the degradation process are discussed.

Key words: wire bonds, PEMs, failure, intermetallic, accelerating factor.

Introduction

In spite of a more than 35-year history of application of gold/aluminum wire bonds (WBs) in microelectronics, WB failures are still the largest cause of failures related to IC packaging [1]. Degradation of gold-to-aluminum WBs due to intermetallic transformations and dry corrosion remains one of the major reliability concerns, which has risen recently due to wide use of commercial plastic encapsulated microcircuits (PEMs) in high-reliability military and aerospace systems.

Extensive investigations of Au/Al bond degradation suggested the following mechanism of WB failures in PEMs [2-4]:

- Au/Al interaction starts during the bonding and results in formation of a relatively thin layer of intermetallics, which provides mechanical strength and low electrical resistance (milliohms range) to the contact.
- Interdiffusion reactions between Au, Al, and intermetallics continue during high-temperature assembly processes and/or operation of the part and result in development of multiple Au/Al intermetallic compounds, which stabilize when all Al metallization under the bond is consumed and the intermetallic compounds eventually transfer into a gold-rich Au_4Al composition.
- Au/Al interdiffusion goes along with the formation of voids inside the bonds at the gold/intermetallic interface and in aluminum contact pads along the periphery of the bonds. These voids are a result of coalescence of vacancies formed due to the difference between the diffusion rates of Al and Au atoms (Kirkendall effect) and initially do not degrade mechanical and electrical characteristics of the bond significantly.
- Thermal decomposition of molding compounds results in generation of halogens or halogen-containing molecules cleaved from the epoxy resin or flame retardant and their diffusion towards the bond. Corrosive reaction of the halogen molecules with Au_4Al intermetallics weakens the bonds mechanically and increases their resistance to the point at which the part fails.

The major environmental factor affecting the rate of wire-bond degradation in PEMs is temperature, and high-temperature storage (HTS) testing is widely used to accelerate WB failures. However, parameters of distributions of WB failure and accelerating factors of degradation are not well established, and the activation energies reported in literature vary in a wide range from 0.2 eV to 2.3 eV [2, 5]. This variety is partially due to differences in the techniques used, but also reflects the complexity of WB degradation, which depends on specifics of package design, materials, and processes used during assembly and indicates the necessity of assessment of WB quality for each lot of PEMs intended for high-reliability applications.

It has been shown that acceptable results of the wire pull strength test [6] and even the wire ball shear test [7], which is considered more informative, in as-manufactured microcircuits cannot assure reliability of the bonds. Poorly welded bonds with a spotty formation of intermetallics degrade much faster than normal bonds, and failures might occur in a few years of operation/storage even at relatively low temperatures. The possibility of having poorly bonded wires in a microcircuit suggests the possibility of infant mortality failures and the need of development of a technique that would allow revealing early WB failures.

The purpose of this work was to evaluate distributions of wire-bond failures in PEMs using a simple contact resistance measurement technique during accelerated HTS testing, predict the time of onset of wear-out failures at normal operating conditions, and develop a technique to reveal and evaluate the probability of infant mortality (IM) failures. For this purpose, reliability of wire bonds was evaluated during accelerated HTS at temperatures varying from 175 to 225 ^{o}C using microcircuits encapsulated in QFP-style packages.

Technique

The variation of contact resistances (Rc) in wire bonds was calculated based on forward voltage drop measurements of P-N junctions used at the input/output circuits in PEMs, in particular for ESD protection purposes. To calculate Rc variation the values of VF were measured before the stress [VF(0)] and after the stress [VF(t)] at a constant forward current (IF):

$$\delta R_c(t) = \frac{VF(t) - VF(0)}{IF}$$

At IF = 3 mA, the values of VF(0) were in the range from 0.7 to 0.9 V. These values can be measured with an accuracy of 0.1 mV or better, thus providing the accuracy of Rc measurements ~0.03 Ohm. However, measurements have shown that temperature variations would cause changes of VF with a rate of 2.3 to 1.5 mV/^{o}C. Considering possible temperature deviation during room-temperature measurements of ± 0.5 ^{o}C, the temperature-related error of Rc measurements would increase to ~0.25 to 0.35 Ohm.

Initial values of Rc are in the milliohm range, whereas the observed degradation-related variations were in the Ohms range. This allows the assumption that with a relatively high accuracy, the initial value of Rc can be neglected and the contact resistance of a degraded bond is equal to its variation, $\delta Rc(t) \approx Rc(t)$.

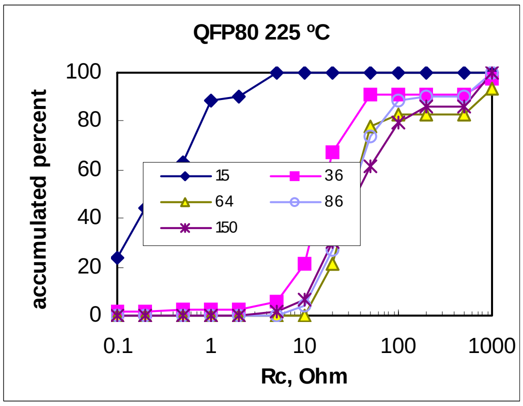
The parts used in this study were mixed-signal ASICs with dies manufactured by the same technology and then wire bonded and encapsulated into QFP80 and QFP44 packages by the same assembly shop using SUMITOMO EME6650RA molding compound. Different groups of microcircuits (from three to five packages in each group) were stored at temperatures of 175, 190, 198, 200, 210, and 225 ^{o}C for up to 2,500 hours in some cases. The VF measurements were carried out at room temperature periodically through these tests. The total number of wire bonds measured in each group during HTS testing varied from 105 to 175.

Test results

Figure 1 shows examples of distributions of Rc at 225, 200, and 175 ^{o}C for devices packaged in QFP80 and measured after different times of HTS testing. Similar distributions were obtained for these parts at other HTS conditions and also for devices in QFP44 packages. In all cases, after a certain period of time (induction period) during which Rc remained below 1 Ohm, the distributions shifted sharply to the right and a significant proportion of WBs increased Rc to more than 10 Ohms. Further ageing resulted in an increasing quantity of bonds with resistances above 100 Ohms, indicating an increasing number of bonds with unacceptable electrical characteristics.

Kinetics of variations of median contact resistances for microcircuits in QFP80 packages at different temperatures is shown in Figure 2. It is seen that during the induction period, which varied from ~12 hours at 225 ^{o}C to ~1,500 hours at 175 ^{o}C, the resistance of most WBs remains below ~0.1 Ohm, but then Rc sharply increases indicating wire-bond failures. Analysis showed that distributions of Rc and kinetics of their variation with time for QFP44 and QFP80 devices were similar.

After increasing above ~1 Ohm, Rc values measured with time of HTS for any particular bond changed erratically, sometimes manifesting a significant decrease in Rc. However, overall Rc variations had a clear trend to increasing with time. This erratic behavior and the presence of some induction period before sharp increasing in Rc had been reported in literature [2].



a)

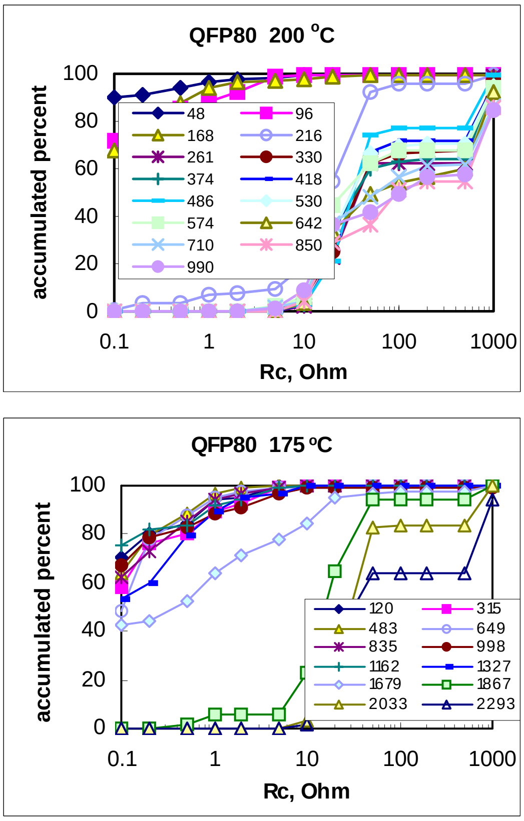


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Figure 1. Distributions of contact resistances during high-temperature storage of ASICs in QFP80 packages at 225, 200, and 175 °C. The legends show time in hours of HTS.

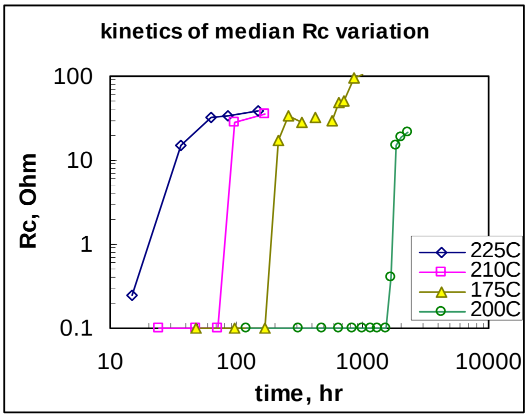


Figure 2. Median contact resistance variation with time at different temperatures for devices in QFP80 packages.

Assuming that a bond fails when Rc increases above 10 Ohms, a distribution of times to failure can be obtained. Figure 3 shows failure distributions during HTS testing at different temperatures for QFP80 and QFP44 devices. It is seen that the experimental data can be reasonably well approximated with straight lines in Weibull coordinates. This allows calculation of the fraction of devices failing by the time (t) using a Weibull cumulative distribution:

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \quad ,$$

where η is the characteristic life, and β is the shape parameter (slope of the line).

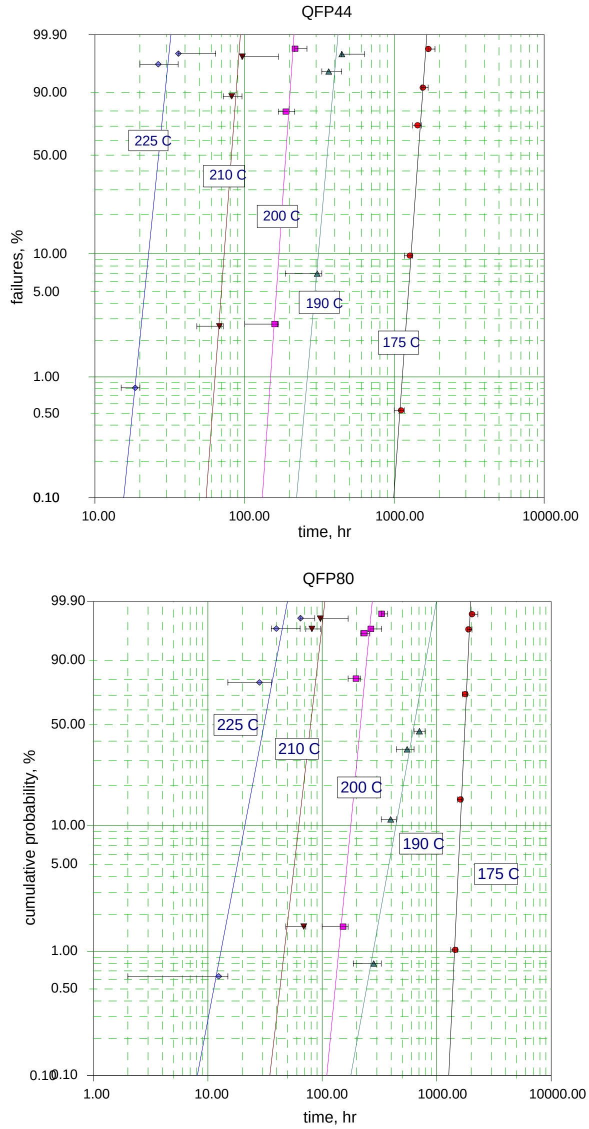


Figure 3. Weibull distributions of wire-bond failures during high-temperature storage life testing for QFP44 and QFP80 parts.

Lifetime prediction

The mean time to failure and slope, β, were calculated for distributions in Figure 3 using "Weibull++" software (available from RealSoft) and plotted versus the temperature of testing in Figures 4 and 5. The mean life can be rather accurately fitted to a straight line in Arrhenius coordinates with an activation energy of 1.52 eV. This value is within the range of activation energies (from 1.04 to 1.9 eV) reported by S. Biddle for WB failures in PEMs encapsulated in different molding compounds [8]. Temperature dependence of the slope is less distinct;

however, the data for β indicate a trend of decreasing linearly with temperature.

As expected, the characteristic life for both part types was close; however, the values of slope (β) were somewhat larger for devices in QFP44 packages. For both parts β was relatively large at all temperatures, indicating a fast wear-out process when degradation of wire bonds occurs rapidly after a certain period of time, which depends on the temperature.

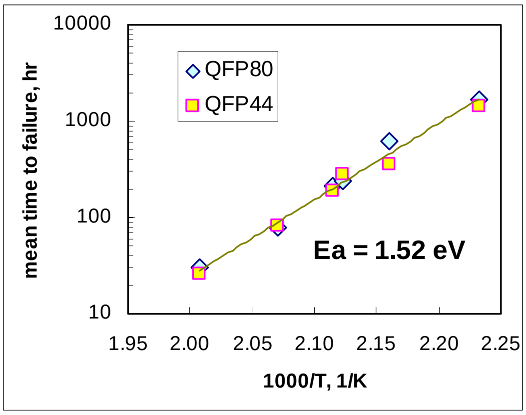


Figure 4. Temperature dependence of the mean life of wire bonds in ASICs.

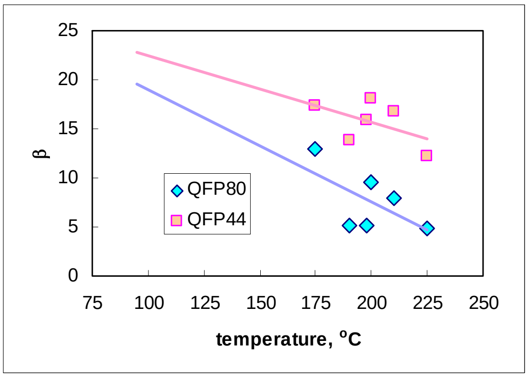


Figure 5. Temperature dependence of the shape parameter β.

Using an exponential approximation for the characteristic life time (η) and a linear approximation for the slope, β, parameters for Weibull distribution at temperatures below 175 °C were calculated. Results of these extrapolations are shown in Table 1.

Based on these calculations, estimations of the time to first failure in a system using PEMs can be made. Assuming that 100 parts with 100 wire bonds each are used in the system, the time to the first failure would be equal to $t_{0.01}$. The calculated times to 0.01% failures, $t_{0.01}$, are shown in Table 1.

For the two types of packages, the lifetime predictions for the system did not vary significantly. At 150 °C the time to failure in both cases was more than 1 year, and at 85 °C the time to the first failure exceeded several thousands of years. This makes the probability of failure for microcircuits that operate within a typical commercial temperature range of -40 to +85 °C due to intrinsic or wear-out degradation of wire bonds extremely low.

Table 1. Calculated parameters of Weibull distributions for operational temperatures.

T, °C	η, hrs.	QFP80 β	QFP80 $t_{0.01}$, yrs.	QFP44 β	QFP44 $t_{0.01}$, yrs.
150	2.1E4	13.3	1.22	19.1	1.51
130	1.8E5	15.6	11.4	20.4	13.1
85	5.3E7	20.7	3920	23.5	4,130

Infant mortality failures

Using a distribution of wear-out WB failures for normal bonds, it is possible to reveal defect-related infant mortality failures by comparing the time to the onset of wear-out failures with the time to first failure. An example of such a comparison is shown in Figure 6. During HTS at 200 °C one wire bond failed after 45 hours, whereas the rest of the wires started failing after 100 hours. This first failure is outside the 99.99% confidence bounds and can be considered as an infant mortality failure.

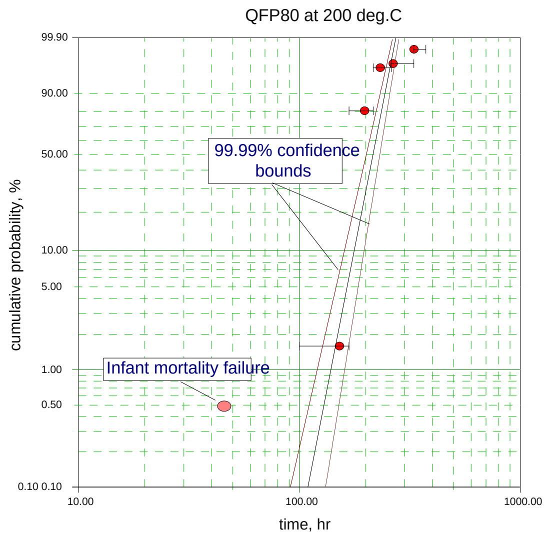


Figure 6. Weibull distribution indicating an infant mortality failure.

To check for the presence of IM failures during HTS testing at other temperatures, the times to 0.01% failures, which can be considered as the onset of wear-out failures, were calculated at different test conditions. These times were then compared with the experimental time to first failure (t_{1exp}). It was assumed that infant mortality failures correspond to the condition $t_{1exp.} < t_{0.01}$. Results of these calculations for QFP80 packages are shown in Table 2 and indicate two cases of IM failures.

Table 2. Parameters of distributions for microcircuits in QFP80 packages.

Storage temperature, °C	175	200	210	225
Number of WBs tested	164	168	105	105
Time to first failure, hrs.	998	48	72	36
Number of first-time failures	2	1	2	85
Time to 0.01% failures, hrs.	1,136	86	26	5
Infant mortality failures	1	1	0	0

Considering that the total number of tested wires was 542, the probability of IM failures can be estimated as ~0.4%. Unfortunately, no data on activation energy of IM failures (E_{IM}) are known, and the obtained results do not provide the necessary statistics for estimations. However, it is reasonable to assume that the activation energy of defect-related WB failures is lower than for wear-out failures. This assumption is supported by results reported in [9], where degradation of WBs formed on Al bonds contaminated with P-glass was 0.4 eV, whereas for normal bonds it was ~0.7 eV.

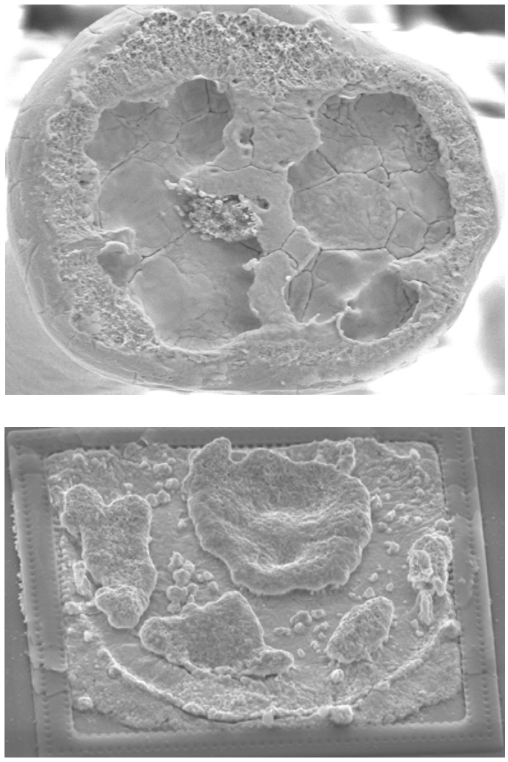
Due to a relatively high activation energy of wear-out failures for the devices, it is reasonable to assume that E_{IM} is in the range from 0.5 to 1 eV. In this case the time to failure at 85 °C, which is equivalent to 45 hours at 200 °C, would be approximately 1.5 years at E_{IM} = 1 eV and only to 0.3 year at E_{IM} = 0.5 eV. Additional analysis should be performed to evaluate activation energy of infant mortality failures and get more accurate estimations of the risk of early WB degradation.

Analysis of QFP44 devices did not reveal IM failures. As both parts are manufactured using similar processes and materials, this result is likely due to the fact that the probability of having a defect, e.g., contamination at the contact pad, is lot related. The possibility of having more defective WBs in QFP80 packages also concurs with the lower level of the slope β. The results indicate that β might be a more lot-sensitive parameter compared to the characteristic life.

Analysis of failed wire bonds

Several parts of both types after HTS testing were subjected to failure analysis using cross-sectioning, SEM examinations, and wire pull testing followed by decapsulation. As expected, a severe degradation of intermetallics and wire lifting was observed in most cases. Figure 7 shows examples of degraded WB and indicates a spotty, uneven distribution of intermetallics along the gold-aluminum interface.

Wire pull testing was carried out on three parts of each type after 100 hours at 200 °C and 800 hours at 198 °C. An average pull force was extremely low, varying from 0.23 to 1.1 g-f with standard deviations changing from 0.15 to 0.6 g-f.



a)

b)

Figure 7. SEM views of degraded WBs after 800 hours at 198 °C. Note spotty intermetallic formation and cracking of the glassivation around the contact pad and penetration of intermetallics under the glassivation step coverage (left side of the perimeter).

Discussion

A raise in contact resistances of Au/Al WBs during HTS up to 20 to 70 mOhms was observed in [10, 11] and was considered as a condition of WB failure related to intermetallic transformations and Kirkendall voiding. However, this relatively minor increase in Rc in most cases would not cause failures of microcircuits [12], and it is more reasonable to assume that only at Rc above 1 Ohm electrical failures would occur.

The time required to complete intermetallic transformations, consume Al metallization under the bond, and form a gold-rich Au_4Al phase is relatively small. At 175 °C this process takes ~150 hours, and at 250 °C only ~0.5 hour is required to stabilize intermetallics [3]. Dry corrosion, which is caused by bromine attack at Au_4Al and Au_5Al intermetallic compositions, and the following oxidation of aluminum bromide [4], result in formation of relatively large voids along the gold-intermetallic interface and/or periphery of the bonds and eventually cause separation of the bond. At this condition, the connection between the balls and the contact pad is mostly maintained by molding compound, and the contact resistance is sensitive to minor mechanical deformations in the package and manifests erratic behavior.

The rate of WB degradation in PEMs was found to be changing at a certain critical temperature, which is in the typical range of HTS testing, 175 to 250 °C [5, 13]. This effect was related to the changes in diffusion characteristics of molding compounds when the temperature exceeded the glass transition temperature (Tg) of the polymer encapsulant. In our previous study [14], variations of the activation energy of WB degradation in SOIC8-style packages were observed at ~190 °C and explained by formation of a gap between MC and the die at temperatures exceeding Tg. The formation of the gap allows oxygen to reach WB, intensifies thermo-oxidative degradation of MC in the bond vicinity, and increases generation of halogens, thus changing the rate of degradation at high temperatures.

Contrary to what was observed before for SOIC8 packages, cross-sectioning of ASICs in QFP80/44 packages did not reveal discoloration in the molding compound along the internal areas of the assembly. This indicates that no gaps between MC and assembly were formed at high temperatures and no thermo-oxidative degradation in the vicinity of wire bonds occurred. The absence of die-MC delaminations was also confirmed by the results of acoustic microscopy.

With the limited access of oxygen, the rate of bromine generation is due mostly to thermal decomposition of the molding compound rather than to thermo-oxidative decomposition. This explains relatively high activation energy of the wire bond failures, which did not change in the range from 175 to 225 °C. Thermo-gravimetrical analysis of MC and measurements of isothermal mass losses carried out directly on QFP44/80 packages showed that the activation energy of MC degradation is ~1.5 eV. This value is close to the activation energy of WB failures and suggests that the decomposition of MC might be a dominant factor affecting reliability of WBs in PEMs.

Conclusions

An application of a forward voltage drop technique for evaluation of reliability of wire bonds in PEMs during accelerated HTS testing has been demonstrated. The technique allows evaluation of degradation of contact resistances in the range from ~0.5 Ohm and above and can be used for qualification testing directly on a given lot of PEMs intended for high-reliability applications.

Analysis of Rc distributions during accelerated HTS testing of PEMs allows for calculation of the WB lifetime (time to the onset of wear-out failures) in the operating range of temperatures. A comparison of lifetime with the time to first failure allows for discrimination of infant mortality failures of WBs.

The activation energy of WB degradation in QFP-style packages encapsulated with SUMITOMO EME6650RA molding compound was constant over the range of temperatures from 175 to 225 °C. This is probably due to a good mechanical integrity of the packages, which prevents formation of through-gaps between MC and die-lead frame assembly and limits access of oxygen to MC and WB intermetallics.

The activation energy of WB degradation, Ea = 1.52 eV, corresponds to the thermal degradation of MC and suggests that the thermal stability of MC is a dominant factor of WB degradation.

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