INVESTIGATION OF "BENIGN" IONIC CONTENT IN EPOXY THAT INDUCES MICROELECTRONIC DEVICE FAILURE

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Introduction

Microelectronics and the devices dependent upon them have the extremely challenging requirements of becoming more capable and less expensive every year. This drives the industry to pack more functions into an ever smaller footprint until the next technological revolution. Adding to this situation is the removal of lead from the bill of materials followed closely by efforts to remove halogens. One result of this cycle and materials changes is new modes of device failure that lead root cause investigations back to the basics of chip fabrication (fab) and packaging processes and materials. Herein is presented the root cause analysis of a current leakage failure where ionic content in a non-halogen containing epoxy molding compound is shown to be the cause.

Experimental

The microelectronic device under study here is a pMOS (hole based metal oxide semiconductor) chip packaged in a six lead SSOT (Super Small Outline Transistor) form factor. The bill of materials consisted of a change from a widely used epoxy mold compound containing halogenated fire retardants (EMC-H) to a new green non-halogen containing epoxy mold compound (EMC-G), a change from soft solder to epoxy die attach, a new shrunken die (new fab process) without passivation, a change from gold to copper bond wires, and a copper lead frame.

The packaged device's durability was evaluated by exposure to high temperature reverse bias (HTRB) stress in accordance with JEDEC standard JESD22-A108C. Specifically, the device was heated to 150°C and a -48V potential applied to the drain with the gate and source voltages tied to 0V. This exposure lasted 168 hours before cooling to 55°C where the bias was removed.

EMC-G and EMC-H were studied to determine what mobile charged species they may contain and the level of charge and mobility as a function of temperature. EMC-G and H were received from the suppliers as uncured powder and cured at 175°C for 2, 4, 5, and 7 hours to simulate various post mold cure (PMC) times and accelerated bake recovery. The cured powers were then ground and sieved to yield 70 mesh particles. These were then charged into deionized water and refluxed for 20 hours. The extract was then filtered and injected into a Dionex ICS-2000 ion chromatograph (IC) via its auto sampler separately for anionic and cationic sensitive column sets. The detected peaks were identified and quantified via ionic calibration standards. We identified only the ions and their concentration. The side groups on the ions were not identified.

The level of charge and mobility of these detected ions were measured as a function of temperature using a TA Instruments 2970 Dielectric Analyzer (DEA) with an alternating potential of 1 volt at a frequency of 0.3 Hz, a clap pressure of 400 N and over temperature ranges of 35 to 260°C at a ramp rate of 10°C/minute and under isothermal conditions. The samples used for this analysis were injection molded leadless packages with no die or wire bonds present. This yielded cured rectangles of the epoxies from assembly site equipment exposed to representative temperature and pressure conditions as the SSOT package.

Results & Discussion

HTRB stress exposure induced a majority of the pMOS devices under study here to exhibit failure mode I_{DS}. This indicates a current flowing between the drain and source of the device in the absence of an external bias. Therefore, an internal electrical potential persists in the device due to the applied stress. These failures recovered upon baking the devices without bias for 24 hours at 150°C. Failure analysis (deconstruction) of the device revealed the die attach, die, and wire bonds to be of correct construction. Removal of EMC-G from the surface of the die resulted in recovery of failing devices showed this epoxy to be the likely root cause of failure. Replacement of the die's passivation layer reduces but did not eliminate the failures.

Ion chromatography of standard EMC-H and the new green EMC-G revealed the ions that were extractable from these epoxies with boiling water. Such an extraction method is under wide use in the electronics industry to measure the ions in epoxy that may act to damage microelectronics. These ions and their concentration (ppm) are summarized in Table 1 for those with concentrations greater than 2 ppm and plotted in Figure 1 for EMC-G.

Table 1: Ionic content and concentration for EMC-H and G

	EMC-H	**EMC-G**			
Ion	5h PMC	7h	5h	4h	2h
Sodium	0.16	3.6	2	3.1	3.4
Ammonium	0.16	7.2	9.8	10.35	13.3
Magnesium	26	nd	nd	0.4	0.23
Calcium	nd	nd	nd	2.93	0.95
Chloride	0.43	1.5	1	2.73	1.8
Glycolate	4.4	2.8	1.25	1.55	1.6
Formate	8	6.1	3.05	3.8	2

Such extracts are given closely scrutiny in the industry for evidence of ions known to accelerate Kirkendall[1] atom migration such as bromide and chloride which Horsting[2] identified to be an autocatalytic root cause for wire bond failure. Here Br- is absent in both epoxies and Cl- is present in relatively low concentrations. The failure mode and deconstruction analysis strongly suggest Cl- to be an unlikely root cause. EMC-H has a high level of extractable Mg+2 that experience indicates to be benign. Ionic data from EMC-G indicated longer PMC time at 175^{0}C reduces ammonium concentration. Extrapolation of this reduction to zero concentration predicts it to disappear after 13 hours. Formate ion increased somewhat in concentration with longer PMC times in EMC-G

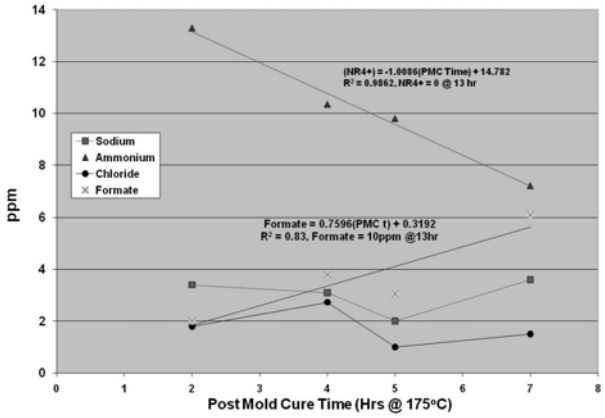

Figure 1: Plot of ions and their concentrations as a function of PMC time at 175^{o}C for EMC-G. Only those ions changing with PMC time are shown

In order for the ions present in EMC-G to induce a trapped potential or charge within a package they would have to migrate to the surface of the die in sufficient concentration and strength and then remain there when the bias is removed and the device is at ambient temperature. DEA analysis of EMC-H and EMC-G reveal that these epoxies have very different levels of ionic conductivity and that EMC-G changes significantly upon additional heating, compared to EMC-H, see Figures 2 and 3.

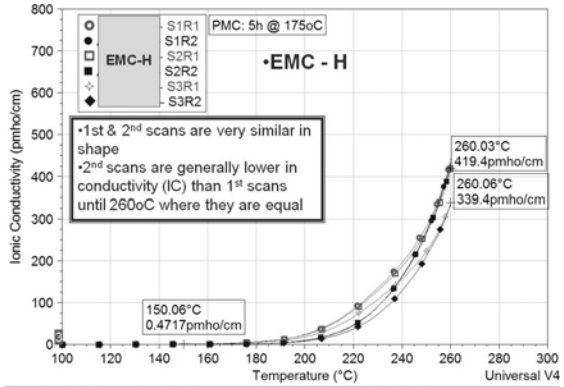

Figure 2: Ionic conductivity of EMC-H as a function of temperature. Plot consists of three samples run twice.

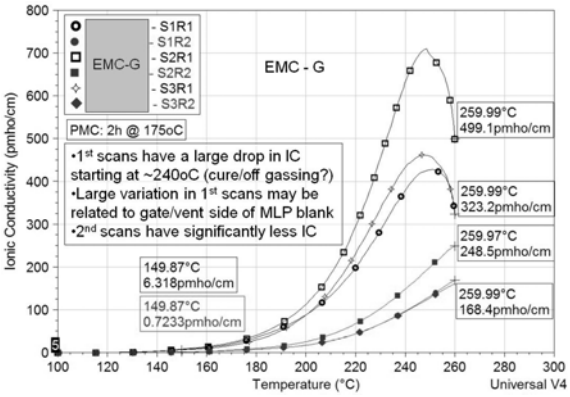

Figure 3: Ionic conductivity of EMC-H as a function of temperature. Plot consists of three samples (S) run (R) twice.

The three initial ionic conductivity scans of EMC-G revealed a rapid rise followed by a rapid decline at temperatures greater than 245^{o}C. Reheating the same samples significantly reduced ionic conductivities and the changes at elevated temperatures. The second scan response was similar to EMC-H's. EMC-G's change in ionic conductivity at elevated temperatures was determined by holding it at 175^{o}C the PMC condition in the DEA, see Figure 4. The starting condition here was a 2 hr PMC at 175^{o}C. With time EMC-G's exhibited a rapid drop in ionic conductivity that reached a plateau after approximately 20 hours of PMC.

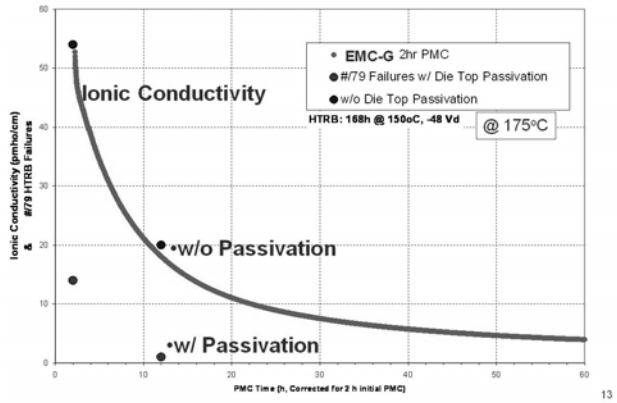

Figure 4: Ionic conductivity of EMC-G at 175^{o}C overlaid upon the number of device failures with and without die top passivation layers.

Overlaying the change in EMC-G's ionic conductivity and its change in ionic content as a function of PMC time at 175^{o}C, revealed a simultaneous drop in ionic conductivity and extractable ammonium ion concentration, as shown in Figure 5. Simultaneous to the drop in ammonium there was a rise in formate ion. This does not appear to significantly raise the ionic conductivity of the epoxy. Of course this is not a completely 1:1 comparison. Liberated ions from PMC are captured during 20 hours of DI water reflux for chromatographic analysis. The assumption here is that the ions remaining in the epoxy after PMC without water

exposure are the same type and concentration. Since ambient pressure boiling water is not known to extensively damage bonds within epoxy it is likely that the ionic species and content in both situations are similar. Therefore, the results reveal that EMC-G's ionic conductivity and its change with elevated temperature exposure correlate strongly with the extractable concentration of ammonium ion.

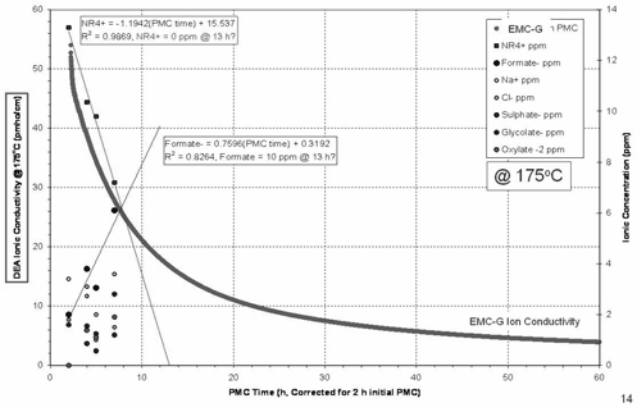

Figure 5: Ionic conductivity and ion concentration of EMC-G versus time at 175°C

Figure 6 shows the result of holding EMC-G at 150°C and then rapidly raising the temperature to 175°C after 24h. This experiment tests the validity of the correlation between ammonium and ionic conductivity with PMC at 175°C when bake recoverability is observed at 150°C. Clearly, Figure 6 demonstrates that EMC-G exhibits a drop in ion conductivity during 150°C baking for 24 h. Raising the temperature of the sample rapidly to 175°C after this bake simulation reveals that the ion conductivity of the sample is reduced to 17 pmho/cm. Thus, the 24h 150°C recovery bake is equivalent to baking the sample at 175°C for only 13 hours. This time frame coincides with the prediction for the ammonium concentration to approach zero via ion chromatography data.

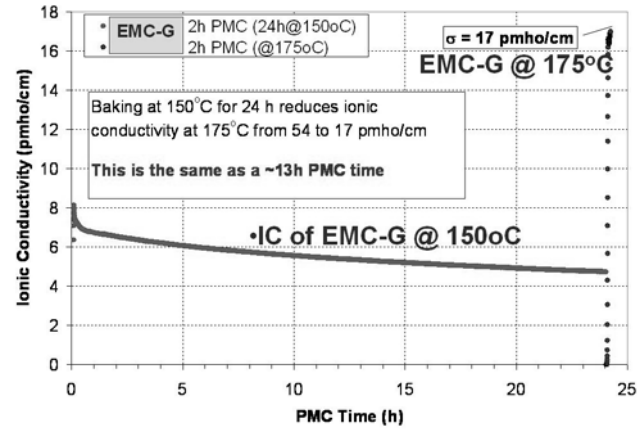

Figure 6: Change in ionic conductivity of EMC-G during isothermal hold in the DEA at 150°C followed by a rapid ramp up to 175°C.

Literature does provide further evidence of such a correlation with research on this topic completed by Rauhut[3] and Mosbarger[4]. Rauhut studied the correlation between an EMC's ionic conductivity and packaged device's survivability under high temperature storage life (190°C, 1000h) and moisture exposure (30°C/60%RH). He found evidence for a correlation between lower ionic conductivity and longer device life times among many epoxies. He also showed evidence for agreement with the observation presented here for a drop in ionic conductivity with longer PMC time.

Mosbarger investigated the change in electrical resistance of EMCs during temperature ramps and as a function of PMC time. His findings agree directly with our DEA evidence. His research demonstrated a dramatic drop in resistance with rising temperature and a significant rise in resistance with longer PMC times.

Conclusions

The main conclusion from this research is the identification of the ammonium ion present in EMC-G as the most likely root cause of the pMOS device failures. The failure mechanism hypothesis is ammonium migration at elevated temperature towards the -48V bias where accumulation takes place at the die's surface and upon cooling the positive static potential induces current flow. This new knowledge alleviated manufacturing from random EMC substitution and fab process optimization trials saving valuable time and the necessity of new product change notifications (PCN). The corrective action is instead to work with the epoxy supplier to impose new incoming raw material acceptance criteria based on IC analysis without reformulation of the epoxy. Thus, a PCN and the usual price reduction requests could be avoided. This knowledge also improves internal EMC selection processes so that such epoxies undergo additional study before selection for packaging.

Acknowledgements

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