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Corrosion in Non-Hermetic Microelectronic Devices*

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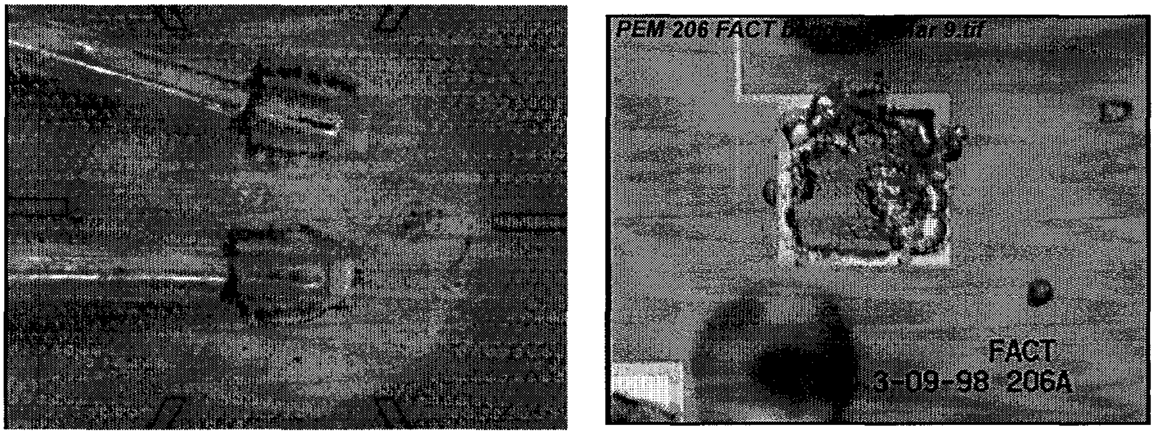
Introduction

Many types of integrated and discrete microelectronic devices exist in the enduring stockpile. In the past, most of these devices have used conventional ceramic hermetic packaging (CHP) technology. Sometime in the future, plastic encapsulated microelectronic (PEM) devices will almost certainly enter the inventory. In the presence of moisture, several of the aluminum-containing metallization features common to both types of packaging become susceptible to atmospheric corrosion (Figure 1). A breach in hermeticity (e.g., due to a crack in the ceramic body or lid seal) could allow moisture and/or contamination to enter the interior of a CHP device. For PEM components, the epoxy encapsulant material is inherently permeable to moisture.



Al metallization and Al/Al wirebond (CHP) *Au/Al wirebond (PEM)*

Figure 1. Optical photographs of corroded aluminum microelectronic features

A multi-year project is now underway at Sandia to develop the knowledge base and analytical tools needed to quantitatively predict the effect of corrosion on microelectronic performance and reliability. The issue of corrosion-induced failure surfaced twice during the past year because cracks were found in their ceramic bodies of two different CHP devices: the SA3711/3712 MOSFET and the SA3935 ASIC (acronym for A Simple Integrated Circuit). Because of our inability to perform a model-based prediction at that time, the decision was made to determine the validity of the corrosion concern for these specific situations by characterizing the expected environment and assessing its relative degree of corrosivity. The results of this study are briefly described in this paper along with some of the advancements made with the predictive model development.

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Corrosion in Cracked MOSFET and ASIC Devices

The potential durability of the Al traces and interconnects contained in compromised, non-hermetic MOSFET devices was experimentally characterized by determining (1) if any significant quantity of water could access the device during or after the polyurethane foaming operation (including possible exposure to external humid environment during short-term storage), and (2) if corrosion-accelerating contamination was introduced during fabrication. Accelerated aging exposures were performed and the extent of degradation was determined by microscopic examination and electrical functional testing.

Corrosion characteristics

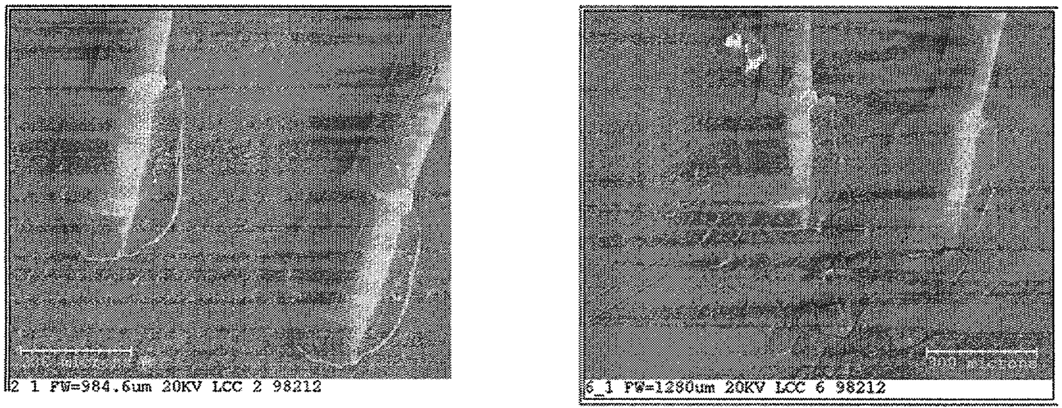
For atmospheric corrosion processes, a critical humidity level exists above which the corrosion rate significantly accelerates. Values typically range from 15% to 75% RH. Factors influencing this parameter include the metal itself, any surface oxide/contamination layers, and the atmospheric constituents. Above this critical level, the adsorbed water phase becomes "quasi-aqueous" and is thus capable of supporting faster electrochemical corrosion. In general, if the water content in the atmosphere is lower than the critical level, the corrosion rate is essentially not measurable. For the assessment discussed below, a conservative lower value of 15% RH was assumed.

The presence of halide ions is known to accelerate corrosion of aluminum and its alloys because of their destabilizing influence on the protective aluminum oxide surface layer. This observation was confirmed for this situation by purposely introducing a thin layer of sodium chloride and then exposing the devices to an elevated humidity and temperature environment. For these exposures, the initial contamination was performed by spraying arbitrarily small quantities of exposed surfaces with dilute NaCl solutions with an air brush and then immediately drying the layer. Two levels were tested: the lower level had a tenth the NaCl amount of the higher level. The qualitative results from these exposures (Figure 2) showed that the extent of corrosion indeed correlated with the level of chloride contamination:

- no Cl^-: no evidence of corrosion could be found,
- low [Cl^-]: corrosion was observed around bondpads, but no functional damage was produced,
- high [Cl^-]: significant corrosion was observed on all aluminum features including the Al/Au bondpad, wire, Al pad and failure occurred in relatively short time periods.

Environment

A number of moisture-transport measurements were performed which showed that the presence of polyurethane foam (relevant to the MOSFET but not the ASIC) should not have a significant effect on the probability of incurring corrosion damage. The foam itself does not produce water during curing, but is quite permeable to moisture. Under ambient New Mexico exposure, moisture transport through the polyurethane foam over a two-week period was not detectable. However, under heated, high humidity conditions, significant transport was observed. TGA/FTIR analyses were performed to characterize the exact composition of the gases being absorbed by a mol-sieve desiccant embedded in the foam sample. The important point to be made from these results is that when the external atmosphere remains dry, no water can be detected inside the foam material (during curing or over extended time periods). As discussed in the next paragraph, the expected weapon environment satisfies this requirement. A supporting finite-element analysis was performed (Mike Keenan, SNL) to calculate the distribution of water as a function of time, focusing specifically on how short-time exposures to moisture that may occur during manufacturing and/or surveillance could change the moisture present at the surface of the device. His results showed that the presence of the polyurethane foam could actually beneficially moderate short-term water transport.



No chloride and no corrosion

high chloride and significant corrosion of Al/Al wirebond and Al bondpad

Figure 2. SEM photographs of representative Al features showing the effect of chloride contamination level (exposure: 50°C, 95% RH, 30 days)

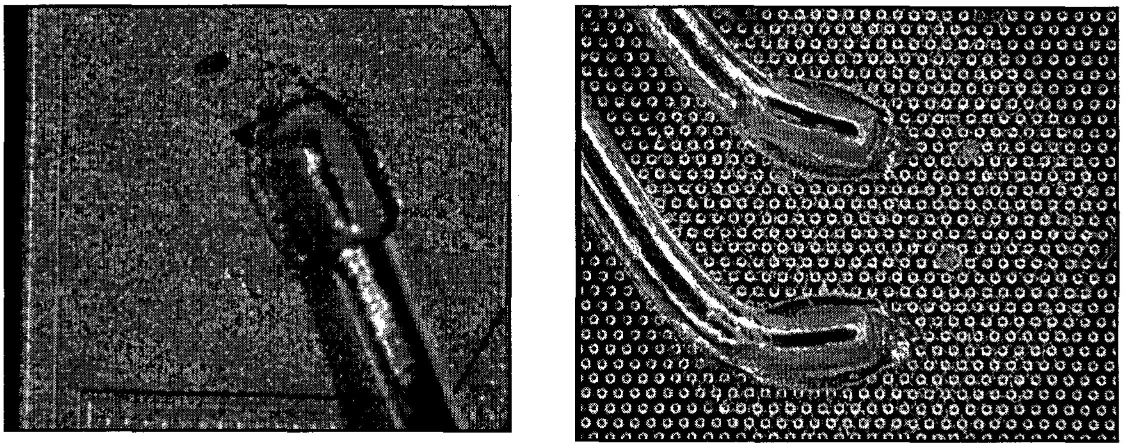
Another important piece of moisture-related information concerns the water levels that are actually measured in field returned units. The majority of these units contained atmospheres with a dew point less than -50°C. Significantly, even the worst case value (-20°C dew point or about 4% RH) is much less than the critical humidity defined above for Al corrosion. Finally, no evidence could be found that corrosion-enhancing contamination (e.g., any compounds containing halogenated alkali or alkaline earth elements) existed on the surface of actual, randomly selected, MOSFET or ASIC devices.

Findings: MOSFET/ASIC Corrosion

The environmental data show that the internal weapon environment is expected to be sufficiently dry during both manufacturing and storage that significant degradation cannot occur and therefore corrosion is NOT a viable failure mechanism. Plus, the lack of corrosion observed (Figure 3) following direct short-term exposures of the device interiors to humid conditions provided additional confidence for the worst-case situation in which some moisture gets inside the system.

Predictive Model Development

Important progress is being made on a physical-based continuum-level model that will ultimately permit a quantitative assessment of corrosion in microelectronics to be performed. To date, accomplishments in four key areas have been made: (1) development of corrosion characterization/monitoring techniques, (2) measurement of intrinsic kinetic parameters, (3) identification of the factors that affect corrosion, and (4) reliability simulation using a preliminary mathematical model.



Al/Au wirebond: 50°C / 95% RH for 38 days *Al/Al wirebond: 130°C / 85% RH for 8 days*

Figure 3. Optical photographs of uncorroded Al metallization after exposure to various accelerated aging conditions

Corrosion Monitoring

Corrosion has been characterized and quantitatively monitored as a function of environmental and device-configuration variables using two test structures: a Sandia developed test chip and transparent quartz slides containing Au/Al wirebonds. The chip device was primarily used to monitor bondpad resistance (a measure of the extent of corrosion) and the quartz-based structure was attractive for characterizing corrosion initiation and propagation behavior. A good correlation exists between time-based resistance measurements, visual/optical observations, and expected environmental effects (e.g., increased rate at higher temperature and humidity). These results validated the use of change in resistance as a measure of the extent of corrosion. Relative to contamination, two techniques were used to simulate contamination during manufacture and contamination due to exposure to industrial pollutants.

Kinetic Property Measurement

Typical kinetic results obtained from the test chip device showed that under the constant environmental conditions, a linear kinetic relationship exists between bondpad resistance and time. Considerable scatter was observed in these rate data between individual bondpads on the same test device, a situation that was probably due to physical configuration effects (bond location, water condensation, presence of intermetallic compounds, galvanic coupling) or possibly the stochastic nature of the Al corrosion process.

Mechanism Identification

Thin-film Al test structures were used to identify how Al bondpads actually corrode. Using backlit optical microscopy, the density and size of the corroded areas were both shown to increase with increasing time. Digital image analysis enabled quantification of corrosion initiation and propagation rates. Importantly, corrosion was only observed in the area of the Au/Al couple where the Au was thin enough to be porous. This observation, combined with the lack of any observable corrosion on non-bonded Al pads or Al/Al wirebonds (in either NaCl or chlorine gas), clearly demonstrated the critical function of the Au/Al galvanic couple. The corrosion that did exist on the test chip bondpads appeared to be general rather than localized. Cross-sectioned bondpads identified the existence of a physical crevice under the periphery of the bond that could function as a site for capillary condensation and condensed phase water.

Mathematical Modeling

Although a number of physical processes have yet to be completely characterized, a preliminary PEM corrosion model was developed and exercised to improve the efficiency of the experimental activities and to provide a focal point for achieving the ultimate project objective. This model was based primarily on the ongoing experimental studies and utilized the following governing equation that describes the rate of relative increase in bondpad resistance (R_{BP}):

$$R_{BP} = I(defects)k_o(t)P_{Cl_2}\left\{1-\exp\left[-\left(\frac{H(t)}{\eta}\right)^{\beta}\right]\right\}\exp\left[-\frac{E_a}{RT(t)}\right]$$

This simple equation contains four distributed parameters: an identify function (I) which contains the probability that a defect in the plastic exists over the bondpad, a surface reaction rate constant (k_o), that includes the previously discussed stochastics of corrosion propagation in aluminum and two environmental parameters [temperature (T), and relative humidity(H)] that vary with time and incorporate a specific time-based uncertainty. β and η are Weibull distribution parameters, R is the gas constant, and E_a is the activation energy. As a vehicle for the model development and capability demonstration, a numerical reliability simulation was performed in which LM185 voltage reference devices were aged in desert, gulf coast, and arctic environments. In addition, a very sensitive failure criteria was assumed (bondpad resistance < 2%). Chlorine gas (P_{Cl2}) was the only contaminant considered. Values for the kinetic parameters (and their variability) were calculated using averaged kinetic rate constants obtained from laboratory experiments. Because of the presence of the non-deterministic parameters and the knowledge that much more complicated chemical and physical processes must be incorporated in the future, a new computational reliability technique being developed at SNL was used to numerically solve this equation. The primary result from this hypothetical simulation (Figure 4) shows that the Gulf Coast environment does causes a faster reduction in reliability compared to the other conditions, but the absolute level and extended time indicate that this degradation is probably not very important.

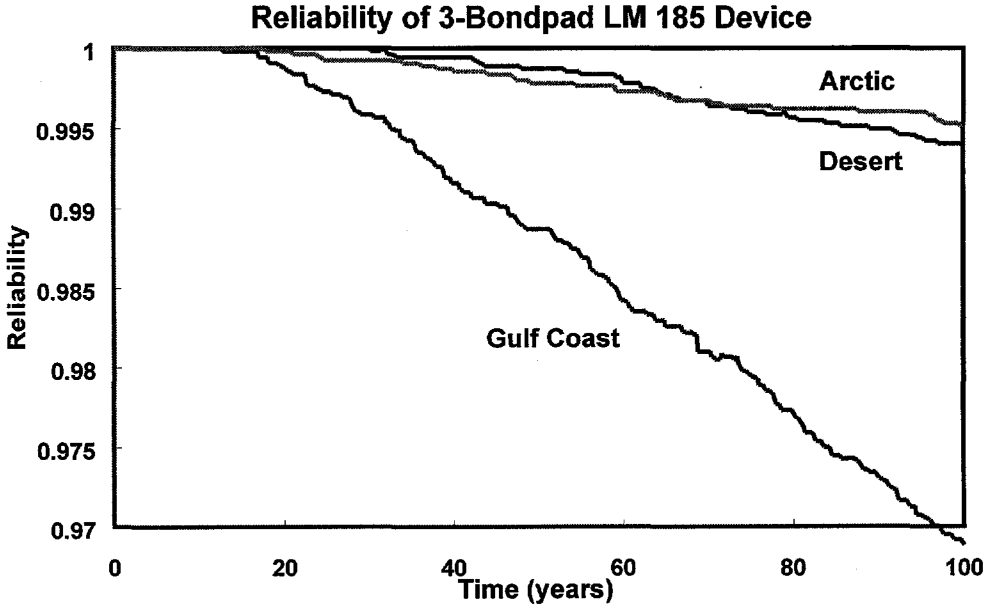


Figure 4. Results of a reliability simulation of a non-hermetic microelectronic device in three different external environments.