Reliability Modeling of MCMS - RELTECH Lessons Learned

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Abstract

The rapid development of advanced electronic packaging and interconnect technologies, specifically MCMs, requires effective ways of evaluating the reliability of these packages. Although some aspects of the technology, such as chip attachment, package sealing, and wire bonding are fairly mature, other issues such as the reliability assessment of high density interconnect structures are the subject of continuing study. The ARPA sponsored RELTECH program has concentrated on developing and applying methodologies for advanced interconnect technology assessment.

This paper will describe the reliability modeling performed under the RELTECH program, and will present lessons learned which can be used by other investigators in the advanced packaging fields.

Key words: MCM, packaging, reliability, modeling, analysis, thermo-mechanical

introduction

As with the development of hybrids, the use of MCMS is largely driven by the desire to increase packaging densities over common printed circuit board technologies, with the associated reductions in size and weight. MCMS also offer performance enhancements by reducing the length of the interconnect paths between circuit elements. System reliability can also be enhanced by reducing the number of solder joints between electronic packages and boards.

MCM technologies are typically described as MCM-L (laminate), MCM-C (co-fired ceramics), and MCM-D (deposited). The laminate technologies are best described as an extension of standard circuit board technologies, with smaller circuit features. The ceramic MCMs are similar to hybrid technologies where thick film conductors are screen printed onto the 'green' ceramic dielectric layers, and the entire assembly is laminated and fired.

MCM-D technologies typically utilize unreinforced dielectric materials deposited onto a substrate. The conductors are then sputtered or plated onto the dielectric layer, patterned, etched, and covered with dielectric. This process is repeated for as many layers as necessary for routing the inter-chip circuitry, with openings, or vias providing inter-layer electrical connections. Typical dielectric materials are polyimides and Si02, and the conductors are typically aluminum, copper, or gold. Figure 1 shows a sketch of typical vias connecting metal layers within an MCM-D.

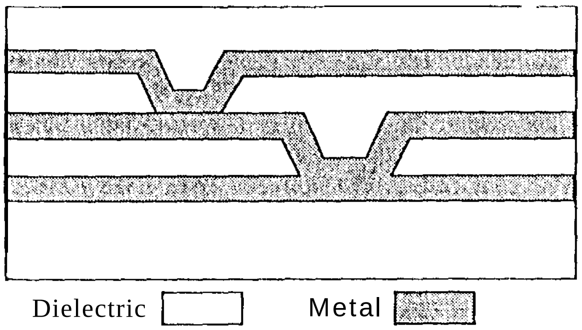

Figure 1 - Typical Vias in an MCM-D Interconnect.

The RELTECH program was created by ARPA, the military services, and NASA to assess key MCM technologies, identify the reliability issues inherent with each, and develop effective tests, inspections, or modeling methodologies to be used to evaluate the reliability of candidate technologies to be used in military, space., or commercial environments.

The assessment approach Used by RELTECH uses a multi-disciplinary [cam performing technical surveys, product evaluations, reliability modeling, accelerated environmental testing, and failure analysis. A candidate technology is selected based on its potential dual use applications, the level of maturity of the technology, and whether it uses new processes, designs, or materials.

An in-depth technical survey is conducted at the production plant, examining the design, production, and eval uation processes used by the company. "This technical survey provides key knowledge needed to begin identifying potential failure mechanisms for the technology in question. The types of failure mechanisms expected are used to determine key test structures to be used in the test vehicles (triple tracks for corrosion, Kelvin via strings for high sensitivity resistance measurements, weave chips and via strings for studying the durability of large number of vias, etc.).

The test vehicles are designed to be representative of the design, materials, production processing, and complexity of the intended use. The initial test vehicles are subjected to Product Evaluations (PEs), consisting of typical destructive physical analyses. The information gained in the PEs is used to compare the as-built product with the design parameters, identifying any necessary process controls or changes. This information is also used in constructing analytical models of the module used to predict thermal performance and internal stresses. The remaining test vehicles are sent through various accelera [cd environmental tests with some held back as control samples.

The tests related to durabil i ty (temperature cycling and temperature shock) are continued whenever possible until failures are observed. This is done in order to verify the predicted failure modes, and to attempt to determine the limits of the technology. The failure analysis is performed to determine the failure mechanism involved anti the location of the failure. This information is then used to refine or correlate the models, and then predictions can be extrapolated from accelerated test conditions to typical use conditions. This process is shown in Figure 2.

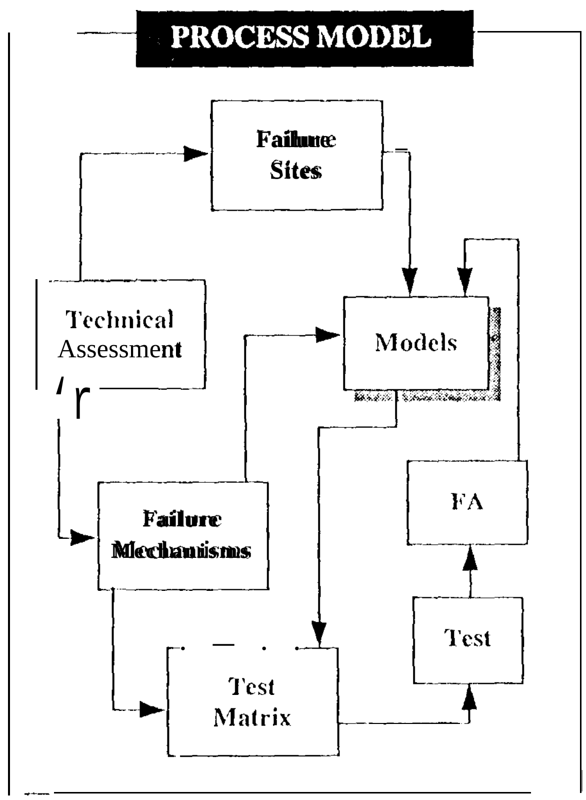

Figure 2- Process Model For RELTECH MCM Technology Assessment.

The technologies examined to date have been variations of (he MCM-D concept. Copper/polyirnidc, and aluminum/SiO2 high density interconnects.

As described above, a part of the REL TECH program has concentrated on the reliability modeling of these technologies. Through the use of finite element models, the modeling team has endeavored to identify potential failure mechanisms within the MCM interconnect structures duc to thermally induced stresses, both static and cyclical. The modeling effort has yielded valuable lessons learned in terms of the approach to a new technology evaluation. Some of the modeling activities which can benefit a new technology include the ability to perform design trade-offs prior to building prototype hardware, definition of accelerated test stresses, and facilitation of the failure analysis through identification of potential failure sites.

Reliability Modeling

The. reliability modeling of the MCMs has typically started with a thermal model of the entire MCM package. This model is referred to as a 'global' model, and is used to predict the thermal performance of the module. The temperature rise through the stack-up of materials from the top of the chip to the bottom of the package is evaluated, along with the temperature distribution within the various layers. This identifies any potential limitations due to adhesive or dielectric material selection.

infrared (IR) imaging is often performed on a de-lidded, powered module to obtain a temperature map of the module. This data is useful for double-checking the models. Unexpected temperature distributions or rises can be indicative of excessive voids in a bond line, delamination between layers, or non-typical material properties.

The temperature distribution of the global models are then used to calculate the thermal stresses induced in the module due to the mismatch in coefficient of thermal expansion (CTE) between the various materials used. This model can be used to predict critically high stresses, particularly in bond lines under chips or substrates.

once the global behavior of the module is understood, the modeling must then address individual failure mechanisms, if possible. MCM-D interconnects utilize metal vias surrounded by a dielectric which typically has a vastly different CTE. This CTE mismatch results in thermal stresses which arc dependent on the magnitude of the temperature of the module. As the temperature changes, the two materials are undergoing dimensional change at different rates. This, combined with the elasto-plastic properties of the materials determines the magnitude of the resulting stress. If a module is operated in a temperature cycling environment, these stresses can lead to cumulative damage, ultimately resulting in fatigue failure of one of the materials. The number and magnitude of the cycles to failure can be predicted if enough material information is known. The fatigue life is calculated by predicting the strain range in the material during each temperature cycle, and then using the Coffin-Manson theory to predict the number of cycles to failure for the given strain range.

Lessons Learned

Global Models

In preparing the global models, it is important to have detailed information on the materials used in assembling the module, the layout of the module, and the power dissipation of the active devices. These, as all models, are highly dependent on the material properties used, and on basic assumptions such as bond line void fractions.

Whenever possible, IR thermography, or other means of acquiring temperature distribution information should be used. This is invaluable in correlating the analytical predictions to the real performance. This kind of information is key to preparing models which arc representative of the real construction of the module.

An key lesson learned was how critical it is to be able to validate models for the operating environments. Typically, thermal models arc validated strictly in conduction. Although fine under a conduction cooling environment, the thermal path can vary greatly when convective cooling is intl-educed. One analysis required that the mode! be tested in an oven. Due [o the high thermal power output that was utilized, an accurate estimate of the convection was nearly impossible. Testing the item in an agitated liquid bath did provide what was believed to be known boundary conditions. However, other factors had to be determined, such as exact numbers for the flow Raleigh and Prandtl Numbers. This complicated the analysis but the correlation was reasonable. Figure 3 shows a view of the analytical model with the top cover of the module partially removed.

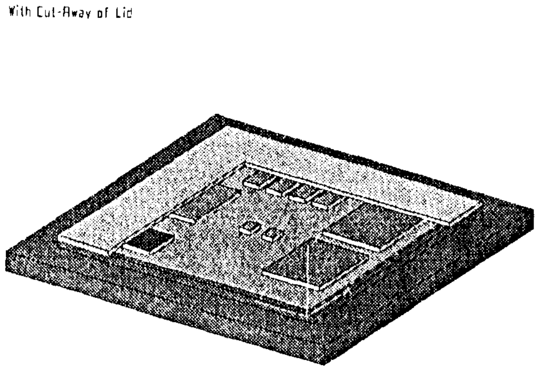

Figure 3 -View of Global Model With Cover Cut Away

IR thermal images created by Rome Labs (see Figure 4) indicated a chip attach problem with some of the test vehicles. The measurements showed an unexpected 16°C temperature gradient across the surface of a die. Further investigation with Sonoscan acoustic imaging, shown in Figure 5, concluded that there were significant voids or areas of poor adhesion in the die attach material. In the Sonoscan images, bright areas correspond to increased reflected acoustic energy, indicating a change in the material, such as a void or change of density.

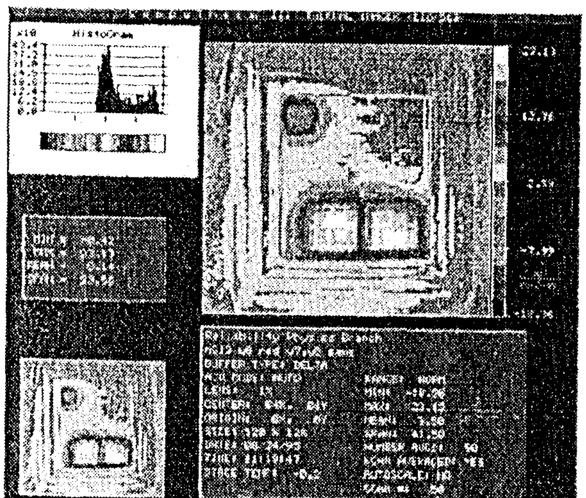

Figure 4 - IR Image Of Powered Module Showing Temperature Gradient Across Die.

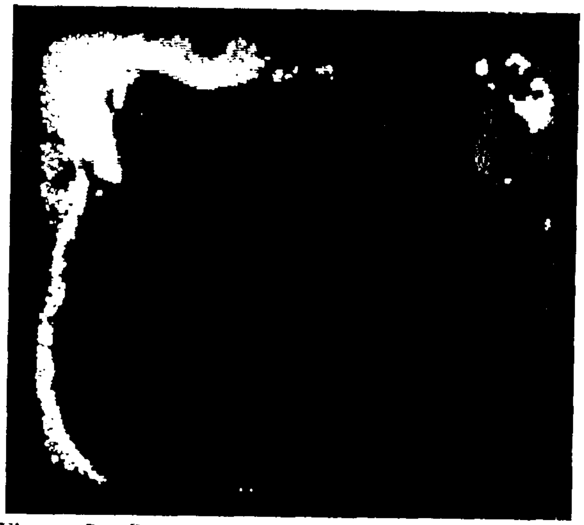

Figure 5 - Sonoscan Image Of Bond Line Under Chip

To model what detrimental effects this WOuld have on the component, the measured temperature gradient was applied across the chips within the thermal model, see Figure 6, and the resulting bond line stress was calculated. It was concluded that the bond line stresses were not critically high in this case.

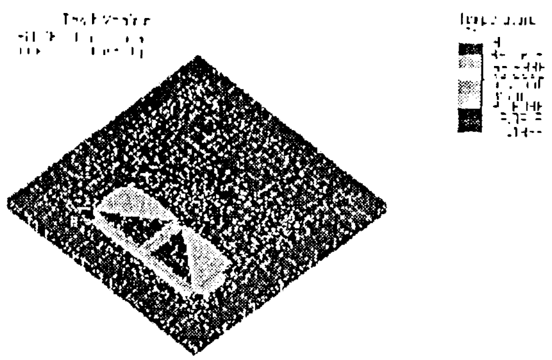

Figure 6- FEM With Gradient Applied Across Die.

In order to have a more complete understanding of the effects of voiding, a study was performed where the voiding was varied from 0% to 50%. The study showed that a 30% voiding best simulated the module. Other information from the study showed that the performance of the chip attach had a significant impact on the thermal profile while the substrate attach had minimal effect.

Material Properties

In addition to accurate geometric data, the analytical models rely heavily on the quality of the material properties used. In recent studies, many days have been spent searching for material properties relevant to the problem being analyzed. It is important to remember that bulk properties arc often substantially different from thin film properties for the same material. This is particularly true for elasto-plastic properties for metals, used in predicting the stress and strain resulting from thermal effects in a module.

Additionally, care must be taken in modeling polymeric materials. These often have temperature dependent CTEs, as well as viscoelastic behavior which requires much more than just knowledge of the CTE at one temperature and Young's modulus. The material measurements performed by the University of Maryland CALCE center arc indicative of the data needed for modeling polymers [1].

Some of the common sources of material property information arc: the open literature, manufacturer specifications, as well as databases such as the onc maintained by Purdue University (CINDAS).

140C:II Models

One difficulty often experienced in modeling the small interconnect structures is the lack of suitable material physical properties, as mentioned above. When modeling small detail items where metallization thicknesses approach grain sizes, the existing bulk material properties are not applicable. For detailed local models it is necessary to obtain as-utilized material properties. In addition, obtaining these properties for certain materials is often very difficult. Polymers, for instance, can very greatly between lot and arc determinant upon what the operating temperatures arc and how that corresponds with any glass transition temperatures. References [1 ,2] describe the process utilized for a copper/polyimide interconnect structure.

When predicting stress distribution for these situations, it is also necessary to understand the processing steps, to gain an idea of the initial stress state of the materials. The deposition or curing temperatures used in a different processes can result in di fferent residual stress states when the module is at mom temperature.

When creating FEMs, care must be taken to ensure that errors arc not introduced by the finite element mesh density. It is prudent to perform sensitivity studies on the mesh size to determine the optimal mesh density, reducing both errors, and computer run time.

Fatigue Predictions

Most fatigue prediction methodologies arc based on the Coffin-Manson equation [3]:

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c$$

where

$\Delta\varepsilon$ is the total cyclic strain range over a single cycle.

Thus, $\frac{\Delta\varepsilon}{2}$ is equal to the strain *amplitude* in cyclic loading.

σ'_f is the fatigue strength coefficient.

E is Young's modulus for the material under cyclic loading,

$2N_f$ is the number of load *reversals* to failure. Thus, the number of cycles to failure is N_f, where each cycle is a single Figure 3 hysteresis loop.

b is the. fatigue strength exponent.

ε'_f is the fatigue ductility coefficient.

c is the fatigue ducti lity exponent.

As seen, this equation requires the usc of coefficients that describe the fatigue durability of the material in the plastic ant] elastic ranges. These coefficients arc derived from empirical data. This, however, requires extensive sample testing, and can bc difficult and Costly to perform on thin metal films. Average Value.s, said to bc representative of many materials have been published [4,5], The strain behavior of the problem at hand must be completely understood to determine whether the problem is most sensitive to 'the elastic or plastic components, to gauge tbc uncertainties in the predictions. When making fatigue predictions, it is important to study the sensitivity of the predictions to the coefficients used, and to correlate the models to test data whenever possible.

Analytical Tools

Finite element analysis tools abound for usc on workstations, as well as PCs. Most analytical tools arc able to perform thermal as well as linear static solutions. If the user will be simulating convective or radiative boundaries in addition to conduction, the analytical tools must be able to properly simulate these as well. When modeling the effects of large temperature excursions on a module, a package capable of properly handling material non-linearity is required. The analytical solution must be able to accommodate. elasto-plastic constitutive models for the material properties, and if creep c. ffects (such as seen in polymers) are 10 be modeled, the tool must be able to perform viscoelastic solutions as well.

These FEM analytical tools arc typically complex with long learning curves and usually best suited for experienced analysts. In an effort to reduce these complexities, Rome Laboratory has developed the Intelligent Multichip Module Analyzer (IMCMA), a finite element based thermal design tool [6]. IMCMA does not require the designer to be a the.rnurl/reliability expert and gives a thermal assessment in minutes depending on the complexity of the design and speed of the computer. The software has a Design of Experiment (DOE) capability which allows tradeoff studies to be performed in the early stages of MCM development, when changes are the most cost effective.

Conclusions

Analytical modeling is a powerful tool that can be used in conjunction with destructive physical analyses, accelerated testing, and failure analyses to fully understand the issues inherent to various MCM technologies. Although challenges include locating the appropriate material properties, correlating models to test data, and validating life predictions, modeling provides the ability to evaluate the effects of changes in various parameters, thus optimizing the design prior [o building prototypes. "l'his approach can result in shortening the design cycle and lowering overall development costs.

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Acknowledgments

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