MICROWAVE CURING OF ENCAPSULANTS FOR ELECTRONIC PACKAGES

H.Quinones / Alec Babiarz / David L. Gibson
Asymtek Headquarters
2762 Loker Ave West
Carlsbad, California 92008 USA

Abstract

Flip chip technology, including second level assemblies such as chip scale packaging (CSP) and direct chip attach (DCA) packages, may all soon need to be underfilled in order to meet the higher reliability and performance requirements of more demanding field environments. A properly dispensed underfill alone may not provide the full improvement expected from encapsulated packages unless a well controlled curing process of the encapsulant is performed. Material properties such as glass transition temperature, modulus of elasticity, coefficient of linear thermal expansion, creep characteristics, yield point, etc., are often dictated by the curing process kinetics and need to be within tight tolerances. Traditionally, most of these encapsulants have been cured by way of forced or natural convection methods. A novel curing method that takes advantage of the electronic and magnetic properties of encapsulants, namely, molecular polarization and resonant structures, is the variable frequency microwave (VFM). During this curing process, non-thermal effects, in addition to thermal mechanisms are present, resulting in a very fast curing time, which is typically 10 to 20 times faster than conventional methods. The VFM curing process takes place at a lower activation energy, offering a potential lower temperature curing process without compromising the desired physical parameters. The tensile stress, imparted by convection methods to the die upon cooling, can potentially be diminished. This is certainly a very attractive feature in flip chip manufacturing where temperature excursions, temperature transients and different CTE play a fundamental role in creating die fractures. A mechanical model is presented to explain this behavior. Data supporting the above claims is also presented. Active semiconductor device characteristics i.e., charge build-up, threshold voltages, current fluxes, UV dose levels, etc., will be shown. Material coupling properties to electro-magnetic fields are reviewed with emphasis on polymer and thermoset compounds used in the packaging industry.

Introduction

The flip-chip technology, introduced about three decades ago and proven to be a very robust interconnection technology for numerous applications, is encountering more challenges in today's environments and large package geometry. Flip-chip underfill, as known today, was first used to improve interconnection reliability in the early eighties [1]. Fatigue endurance was greatly improved (30 to 60) in time/cycles to failure, as well as improvement in mechanical support that lead to more reliable package under mechanical loading, both static and dynamic. The interconnection application space has been expanded significantly for the flip-chip by the introduction of the dispensed underfill. A novel curing method that uses variable frequency radiation by electromagnetic waves is proposed as an alternative to traditional force convection ovens. The variable frequency microwave (VFM) is capable of curing dispensed fluids on electronic packages such as underfill and dam and fill, in very short times (minutes rather than hours). Desired material and physical properties of these VFM cured materials are obtained, i.e., linear coefficient of thermal expansion, modulus of elasticity, glass transition temperature, etc., without affecting functionality or reliability of active devices in the die. Typically, underfill materials used in the packaging electronic industry are cured by way of heating generated by forced convection furnaces. Heat conduction from the surface to the interior of the materials follows the surface that has been heated by convection means. VFM heating occurs throughout the entire volume and at numerous sites, and does not necessarily heat the surrounding materials, i.e., air, cavity walls, etc. Hence, the short conductive paths in this volume result in a rather rapid heating rate. Desired physical properties for the cured

underfills need to be achieved for any curing process: linear coefficient of thermal expansion, CTE, modulus of elasticity, E, glass transition temperatures, T_g, etc., must have the values that optimize the reliability and performance of the package. VFM has been repeatedly shown to do so. In fact, in some instances some of the properties are shown to be better. [2]

Theory

Dielectric materials can react to an electric field because they contain charge carriers that can be displaced. This polarization can be pictured as the formation of dipole chains, which line up parallel to the incoming field and bind countercharges at elecrodes. Dielectric materials, such as dispensed fluid used in microelectronic packages, increase the storage capacity of condensers by neutralizing charges at the electrode surfaces which otherwise would contribute to the total external electro-magnetic field. The polarization is identical with the electric dipole moment per unit volume of a dielectric. A dispersion factor that is defined as the ratio of loss current to charging current in a condenser, and also known as the loss tangent, *tan*?, may not contain all the information. The conductance term needs not all stem from a migration or motion of electro-carriers, but could contain other energy consuming or dissipative processes. The existence of loss current in addition to the condenser or dielectric charging current is customary, and noncommittally introduced by way of a complex permitivitty:

$$?* ? ?'? j?''$$

The loss tangent becomes

$$\tan ? ? \frac{?''}{?'}$$

The product of loss factor and angular frequency is equivalent to a dielectric conductivity, ? [3].

$$? ? ? ?''$$

This dielectric conductivity sums over all possible dissipative mechanisms and refers to energy loss associated with frequency dependency, i.e., dispersion factors such as “frictions” present during dipole orientation when microwaves are interacting with dielectric materials (polymers, insulators, etc.) The principal mechanism of microwave absorption in polymers is the reorientation of dipoles by the imposed electric field. Materials with high dipole mobilities exhibit the most efficient coupling; therefore a selective heating will occur accordingly. It is important to notice that electronic polarization or atomic /ionic polarization observed at microwave frequencies is in phase with the alternate electric field, as a result ?” is zero and thus, this type of polarization does not contribute to microwave absorption. In electronic conduction, either free motion of electrons or collective ion diffusion is assumed. When charged particles move, an electrical current is induced. Such charged particle drift is characterized by the presence of dissipative mechanisms that result in heat generation, i.e., ohmic diffusion leads to joule heating. In the case of ideal superconductors, no dissipation takes place. The mechanism of polarizability that causes microwave absorption involves rotation and orientation of the polarized molecules, i.e., it is heat generated at the molecular level. These rotations are rather slow compared to atomic dipole rotation. They are not resonating with microwave frequencies. ?” is not zero and the dielectric performs dissipative mechanisms, i.e., heat is generated. The total polarizability as a function of frequency is depicted in Figure 1. Molecules with permanent electrical dipoles go through realignment by rotation of molecules. Molecules without permanent dipoles can have bonds distorted in both direction and length in response to the alternating electric field generated by the microwaves, which results in heat generation.

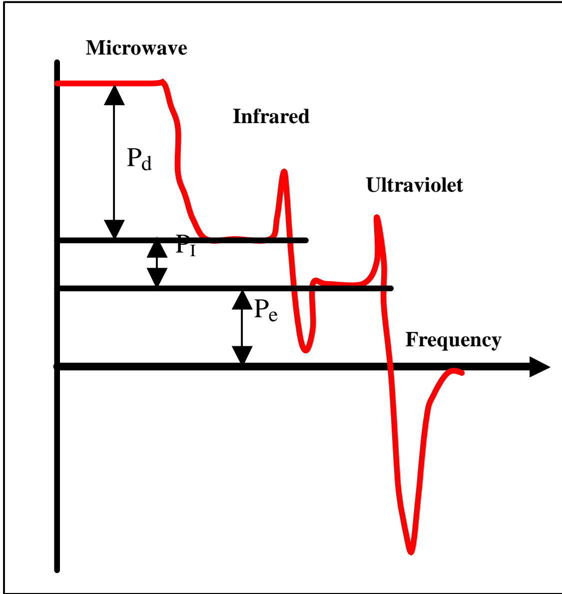

Fig. 1. Total polarizability and its frequency dependence. (Kittel)

The use of variable frequency microwave consists of a frequency sweep over a range of 4096 different frequencies (25 or more microseconds duration at each frequency). The bandwidth, 1 to 2 GHz and centered about a frequency of 6 to 8 GHz, results in uniform and homogeneous heating inside the microwave cavity. The rapid change of frequency of the alternating electrical field minimizes the probability of standing wave formation for long times that could result in charge build up. This sweeping is what allows metal materials to be placed in the VFM and not cause arcing. The integrity of the active devices in the die must be maintained throughout the microwave treatment and their reliability must not be adversely affected. The presence of high electrical potentials, although a necessary condition for damage to occur, is not sufficient to cause damage; high current is also needed. There is a well-established relationship between charge-to-breakdown on a gate oxide and charge density absorbed by the oxide during some time. This relationship is the Fowler-Nordheim tunneling current [4]. Through the gate oxide, for instance, which is equal to the charge flux collected by any "antennas" i.e., cases of floating non-terminated metal lines, is minimized by fast switching the node spatial location of the microwaves. Table 1 shows dielectric properties for some materials.

Table 1

	Temp ^{0}C	Freq. GHz	Loss Tan ?
Al_2O_3	25	3.7	.00075
Si_3N_4	25	8.5	.0036
Teflon	25	2.4	.00042
Epoxy	25	1.0	.015
Polyester	25	8.5	.0028
Concrete	25	1.0	.52

Dielectric Properties of various materials. (Westphal, Bur and Iglesias).

VFM Curing of Dispensed Fluid

Traditionally, convection furnaces have been used to cure different fluids that are dispensed on electronic packages. Fluids that are used to encapsulate components, fill cavities, underfill flip-chip die and CSP components need to reach a final solid state. This solidification is accomplished by a gelation state followed by various curing methods that involve cross-linking of polymeric materials. Historically, thermoset polymers have been used in electronic applications due to the opposing, yet attractive, properties found in the unreacted and polymerized states. The chemistry of these polymers requires that energy be put into the system to initiate polymerization and create a functional degree of intermolecular connection, which we refer to as "degree of cure". Traditionally convective or conductive sources of heat have been used to put energy into these systems. Experimentally, the method of Differential Scanning Calorimetry (DSC) is widely used to quantitatively characterize various degrees of cure. In DSC, the enthalpy of reaction of a polymer may be measured over specific temperature ranges. If ***h*** is the enthalpy of reaction for a partially polymerized polymer, and ***H*** is the enthalpy of reaction of an unreacted polymer, then we can write the expression

$$\frac{H ? h}{H} ? P$$

Where ***P*** is the fraction of polymer, which has reacted (polymerized). Hence, DSC can

provide us with a measure of polymerization in the dispensed underfill and other polymers used in the electronic industry. VFM offers an alternative to convection curing with successful results. Table 2 summarizes some examples of applications that were cured by VFM.

Table 2

	Power Watts	Time VFM min	Time Conv min	Cure %
Underfill	**160**	**7.0**	**30**	**80**
Dam&Fill	**1100**	**9.0**	**150**	**90**
Bonding	**360-500**	**5.0**	**150**	**80**
Coating	**260**	**2.5**	**360**	**-**

Wafer Charge Monitor Experiment

Wafer charging damage is a continuing problem in integrated circuits manufacturing. Many techniques based on the measurements of damage to oxides or device structures are not necessarily appropriate for uncovering the causes of damage. To determine whether electrical charge damage to gate oxides during processing is occuring, we need to determine if the wafer surface-to-substrate potential is sufficiently high to force current into the oxide, and if there is sufficient time for this electrical build up to cause damage to the devices. A test wafer, the CHARM-2 wafer [5], designed and built to capture these phenomena, was used. This 4-inch diameter wafer uses a J-V characteristic of the charging source and the intersection of the Fowler-Nordheim to obtain the current density at the oxide conduction voltage. Figure 2 below depicts both the positive current density J^+ and the negative current J^- at the oxide that could be responsible for damage to the gates of various active devices in the die. Recall that the extent of the damage depends on the product sensitivities. Here, different normalized contours are required to assess real damage in the devices. One way to quantize such variation is by a plot of damaging current density vs. antenna ratio for different times [6].

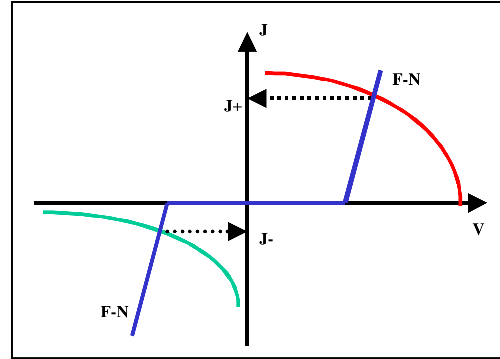

Fig. 2 Antenna ratio scale CHARM-2 and their intersection with the Fowler-Nordheim oxide conduction plot. (Wafer Charging Monitor, Inc.)

The 4-inch wafer contained 188 sites populated with EEPROM-based calibrated, polarity-sensitive sensors of wafer surface-substrate potentials, net charge flux and UV dose. The potential sensors are implemented by connecting a charge collection electrode (CCE) on the surface of the wafer to the control-gate of an EEPROM transistor, see Fig. 3 below. The voltage developed on the CCE changes the threshold voltage.

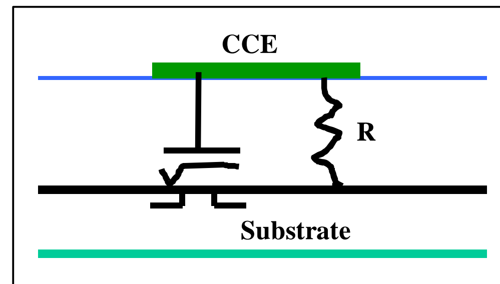

Fig. 3 CHARM-2 Charge-flux sensor.

These flux sensors were implemented in pairs, where one sensor is used to measure negative charge flux and the second is used to measure positive charge flux. The value of the resistor in parallel with the transistor determines whether we are measuring UV dose (low resistance value) or current flux. Different sensors are designed to cover about 5 orders of magnitude in the current densities. Wafers were subjected to two different VFM treatments: the first experiment consisted of a common profile: five minutes exposure of the wafer to microwave radiation, the resulting temperature profile which was monitored by an IR pyrometer is depicted in Figure 4. The

center frequency was 6.1 GHz, 120 Watts and a sweep rate of 0.1 s (4096 frequencies for duration of 25 microseconds at each). The range of the sweep was 0.75 GHz. The wafer was tested and programmed prior to any VFM treatment.

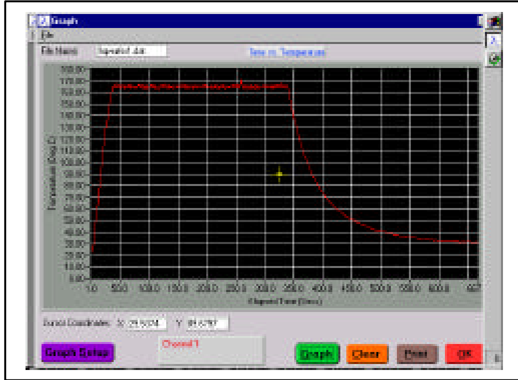

Fig. 4 Temperature profile for wafer using VFM.

As depicted in this figure, a very controlled temperature profile was obtained with a very narrow band at the maximum temperature. The heating rate was chosen to be within the same order of magnitude as the cooling rate. The cooling rate is an intrinsic property of the wafer or package, and it is characterized by the thermal time constant. The use of this heating rate prevents stress induced into the package of much larger magnitude than that resulting from the cooling rate.

Results

First experiment observations: following the VFM curing cycle, the wafer was tested to determine potential shifts and damage in the devices. The UV sensors, which are integrating devices, respond to voltages in the range between 3.2eV and 8eV. However in the present experiment the UV sensors did not respond, since there is essentially no difference between the values recorded by the most sensitive UV sensor (UV_S_2Na), and the non-response value recorded by the least sensitive UV sensor (UV_S_10.Na). Thus, there is very little UV intensity produced by the VFM. See Table 3 below for a summary of these results.

Table 3

UV RESPONSE			
UV_S10.Na		UV_S_2.Na	
Ave	**StdD**	**Ave**	**StdD**
1.58	**0.05**	**1.58**	**0.05**

Results from experiment 1, UV dose response on a 4-inch wafer treated by VFM.

The results for the electrical potential after the VFM are summarized in Table 4.

Table 4

Potentials					
Negative Potentials			Positive Potentials		
Ave	**StdD**	**95%**	**Ave**	**StdD**	**95%**
-1.4*	**0.1**	**-1.3**	**1.6***	**0.1**	**1.7**

Results from experiment 1, Electrical potential response. (* Sensors did not respond-value represents upper limit).

In general there was no sensor response to the electrical testing after the cure cycle. Actual maps for this experiment are depicted in Figures 5 and 6.

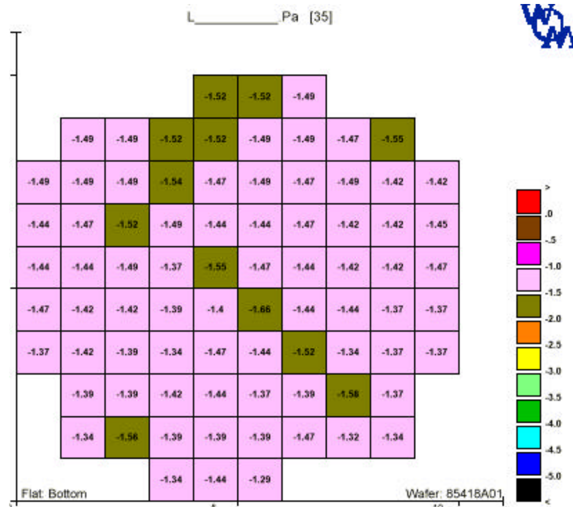

Fig. 5 Voltage: negative electrical potential sensor with large charge collection electrode.

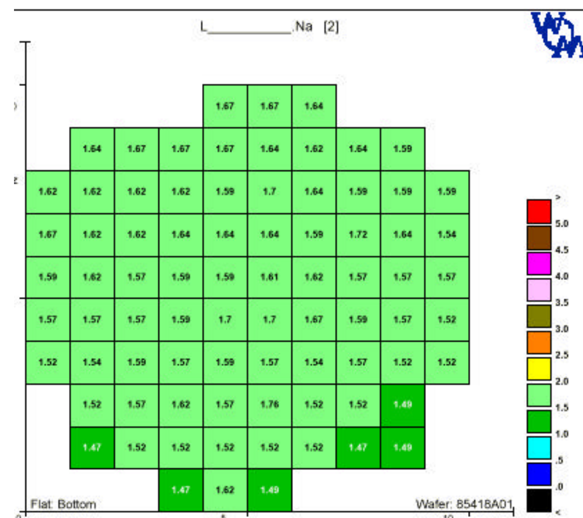

Fig. 6 Voltage: positive electrical potential sensor with large charge collection electrode

The results of this first experiment clearly showed that the VFM cure cycle does not cause any shifting in the transistors and therefore no adverse effect is induced by such VFM treatment.

The second experiment consisted of three simulated cure profiles in the VFM on a 4-inch wafer. The center frequency was 6.425GHz and a bandwidth of 0.75GHz was utilized. The sweep rate was 0.1s for the first cycle and 140W forward power for a duration of 5 minutes with maximum temperature of 165^0C. For the second cycle, the sweep rate was 0.2s and a forward power of 120W for 8 minutes with maximum temperature of 150^0C The third cycle had 160W forward power, a sweep rate of 0.1s for 10 minutes, and the maximum temperature was 170^0C. Figure 7 displays the three temperatures vs. time cycles for this second experiment

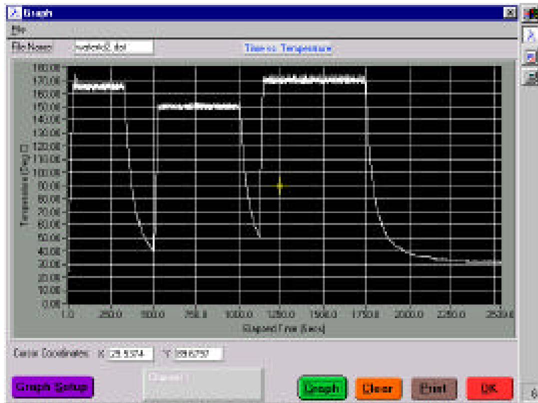

Fig. 7 Temperature profiles for three curing cycles in the VFM.

Results

The second experiment did show some shifts in the electrical voltage for some devices, but the shift was very small. From the magnitude of these changes, one concludes that the VFM, even with 0.2s sweep rate, does not cause any functionality damage to the active devices of the silicon wafers. The process of manufacturing wafers does often cause larger shifts in active device parameters than those found in the VFM, yet they are acceptable. A very "benign manufacturing process" would yield results comparable to those obtained in this second experiment on the 4-inch CHARM-2 wafer subjected to such VFM series of cure processes. An actual wafer map with results is depicted in Figure 8.

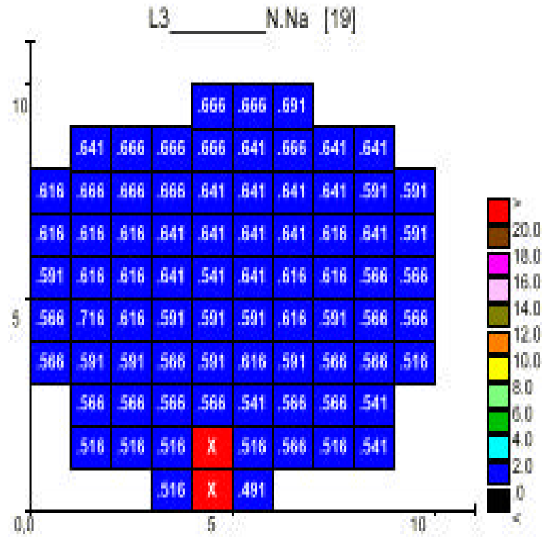

Fig. 8 Voltage: positive electrical potential sensor with large charge collection electrode.

The sites with X's represent values that were faulty at the time of first programming prior to VFM and were not used for evaluation.

Die Stresses

A rather common problem in package fabrication is the warping on die resulting from curing, sometimes from simply die joining. The curvature that the die acquire from these processes may be a problem, in particular, when the die is subjected to thermal shock, where low temperatures are required, as well as stresses induced by mechanical loading and handling that may result in die fractures. The back of the die may reach very high tensile stresses from curing or joining, and subsequent loading causes these stresses to surpass the silicon ultimate tensile stress and cracking occurs. Die with defected surfaces, scratches, etc., are more likely to have this kind of damage. During the traditional convection oven curing process, the package, including die, die-carrier, board, etc., is heated to about the same temperature, the cure temperature. Upon cooling, all different components of the package contract according to their respective CTE's. Because often the die carrier has a larger CTE (about 18E-6 per degree Kelvin),

the die (about 3E-6 per degree Kelvin) is forced to flex and stresses are induced. Figure 9 shows a qualitative example of temperatures during convection oven curing.

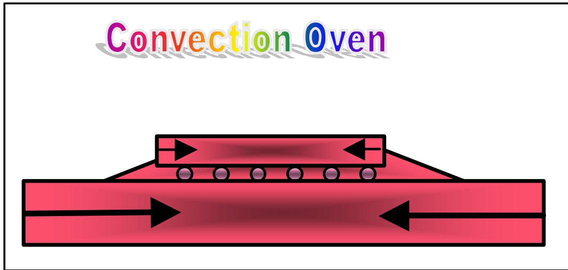

Fig. 9 Convection oven produces an almost complete isothermal profile

However, for the case of VFM curing, not all components of the package reach the same temperature. In fact, as explained above, those polymers that have already been cured (i.e., the board and/or the die carrier), do not react to the microwave as well as the uncured underfill. Hence, the die (doped die are very good absorbers of microwave energy) and the uncured polymer will reach higher temperatures. Figure 10 depicts a qualitative profile of temperatures in a package during VFM curing.

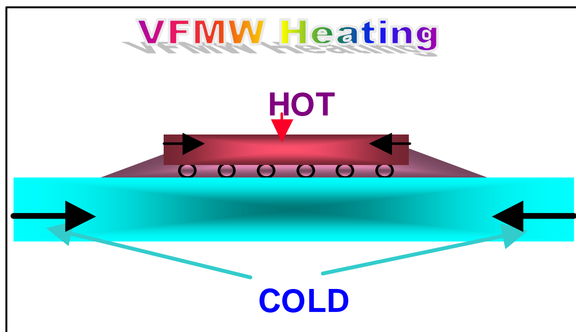

Fig. 10 VFM produces different temperatures on different components of the package.

The result of this non-isothermal profile is a lower curvature on the die. This can be understood from the fact that the die carrier, which in general has a higher CTE than the die, has a temperature excursion which may be much less than the die. This is certainly a very attractive feature of the VFM technique that has enormous potential for minimizing the die-cracking problem for many packages.

Some data has been generated [7] that shows some improvement in the adhesion strength of the underfill to both the die-underfill interface and the die-die carrier interface with VFM curing. A plausible explanation may bee the surface charge phenomenon that occurs at material interfaces that have different electrical conductivities.

Production Potential for VFM Curing

The potential for utilizing VFM curing in production requires process qualification. The VFM oven is still a batch process and does not produce product on a continuous flow. Consequently, the "in-line" system requires an input buffer station and some carrier considerations. To gain the maximum throughput, the total number of parts in the oven must be maximized. The throughput calculation is as follows. Units per Unit Time = (Number of Units in the Oven) / ((Convection Cure Time)/10) + Time to Load Parts + Time to Unload Parts). Therefore, if the load and unload times are 20 seconds each and the conventional cure time was 30 minutes at 150°C, then the oven would have to be loaded with 30 parts to obtain 500 UPH. (Units per hour)

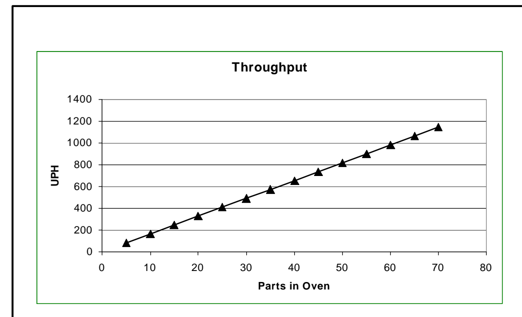

Fig. 11 shows the relationship between throughput and number of parts in the oven.

Clearly, the more parts that can be shuttled into the oven per cure cycle the higher the potential for the technology. One of the benefits is the difference between the number of parts in the oven versus conventional cure. The amount of parts at risk in the cure stage is significantly better for VFM curing. Recall, that partial curing, followed by further curing in a different cycle, i.e., two cycles curing, may result in unreliable products, the

interfacial propensity to cracking is larger and optimum physical parameters of the underfill may not be obtained.

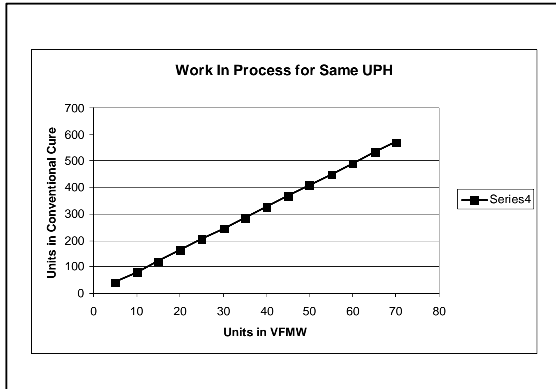

Fig. 12 shows how many parts are required to have in a conventional oven versus the VFM oven for the same UPH and cure conditions as in Figure 11.

Various experiments were carried out to evaluate VFM throughput. Single magazine with a die underfill can yield more than 1000 UPH. Dam and fill processes have lower UPH and curing cycles for these products are somewhat longer.

Conclusions

Flip chip has become a very reliable interconnection technology, in particular because of the properly dispensed underfill. Its use encompasses a large range of electronic packaging applications, from large computer systems to electronic appliances and automotive.

The VFM curing technique uses heating at the molecular level. This technique is selective in that, it heats up those materials that best absorb energy in the microwave range, GHz, i.e., material with high loss tangent factors. The interaction, between the VFM and active devices is minimal, and no adverse effects appear to be present in VFM as defined in this paper.

A potential to lower die stress in the VFM curing has been demonstrated by the authors as well as other sources (see Lambda microwave technical reports).

Short curing cycles are possible with the VFM, and materials can successfully be cured within minutes.

Physical parameters for cured materials are similar to those obtained by convection curing.

Throughput for the VFM highly depends on the number of parts per boat. For single die the authors demonstrated about 1100 UPH for die underfill.

Acknowledgment

The authors would like to thank Mr. R.L. Ciardella for facilitating the completion of various VFM experiments. Thanks to Ms. Drussila Cursi for some of the data generation.

References

[1] H.Quinones, “Underfill reliability, why underfilling flip-chip improves reliability”, Flip Chip and Ball Grid Array Conference in Singapore, Center for management technology, April 1994.

[2,7] Lambda Corporation Technical Papers

[3] G.Roussy and J.A.Pearce “Foundations and Industrial Applications of Microwaves and Radio Frequency Fields”. John Wiley & Sons. N.Y.1995

[4] R.H. Fowler, L. Nordheim, ‘Electron Emission in Intense Electric Fields”. March 31, 1928, pp.173-181.

[5,6] W. Lukaszek, ‘Understanding and Controlling Wafer Charging Damage’, Solid State Technology Journal, June 1998.