Variable Frequency Microwave Curing of Polymer Materials in Microelectronics Packaging Applications

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Abstract

The use of variable frequency microwave technology in curing of polymer materials used in microelectronics applications is discussed. A revolutionary open-ended microwave curing system is outlined and assessed using experimental and numerical approaches. Experimental and numerical results are presented, demonstrating the feasibility of the system.

Introduction

A wide range of polymer materials, such as encapsulants, underfills and conductive adhesives are utilised in modern microelectronics packaging. These material are applied as fluids and are hardened through a cure process. Thermosetting polymers are commonly used, requiring heating to initiate or expedite curing. Currently technologies such as infrared, ultra-violet and convection heating are used for this purpose. These conventional curing processes can take several hours to perform, slowing throughput and contributing a significant portion of the cost of manufacturing.

The maximal heating rate possible with conventional technologies is limited by the thermal conductivity of the material. Convection heating raises the temperature of the air in contact with the surface of the polymer material and heat energy is transferred into the bulk through thermal conduction. Electromagnetic energy at infrared or ultraviolet wavelengths will penetrate a small distance (approx. 200-400 nm for UV and 1-1000μm for IR) into the load but conduction still limits the transfer into the bulk material. Electromagnetic energy at microwave frequencies (1–30 GHz.) will penetrate much further into the material leading to much more rapid volumetric heating. Fundamental problems with microwave heating of electronics components include highly uneven heating (hotspots) and arcing between components. These issues can be eliminated by rapidly varying the frequency of the microwave source – an approach referred to as variable frequency microwaving (VFM).

The FAMOBS system

This contribution focuses on a novel open-ended microwave oven proposed for the microwave curing of bumps, underfills and encapsulants during flip-chip assembly. The "Frequency Agile Microwave Oven Bonding System (FAMOBS), proposed by Sinclair et al [1], consists of a cavity which is partially filled with a dielectric material. A prescribed electro-magnetic field is excited within the dielectric part of the oven, creating a non-radiating evanescent field within the non-dielectric part of the cavity. Dielectric materials, such as polymers, placed within the non-dielectric part of the cavity are exposed to these evanescent electro-magnetic fields, inducing heating at a rate dependant upon field strength and material properties. Heating patterns generated in the polymer are therefore dependant upon the electric field distribution which is, in turn, dependant upon the operating frequency. The proposed system is able to selectively vary operating frequency enabling the resulting heating pattern and heating rate to be controlled. The ability to accurately control the curing process results in optimal cure quality and reduced overall process duration.

The open cavity aspect of this system allows it to be mounted on a precision placement machine enabling simultaneous micron-scale alignment accuracy and rapid localised curing of polymer components. The ability to perform localised heating/curing/bonding minimises induced thermal stresses and related reliability issues, whilst the reduction in cure time results in increased manufacturing productivity and decreased production costs. Figure 1 depicts the overall difference in energy budgets in convective and VFM cure processes. Figure 2 shows the productivity gain achievable through incorporating the assembly and cure tasks into a single process step.

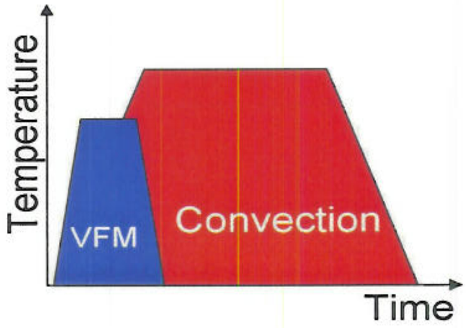

Figure 1: Reduction in overall energy budget with VFM technology

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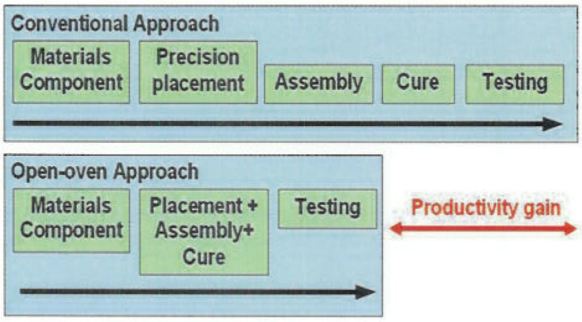


Figure 2: Productivity gain with open-oven VFM system

In electromagnetic terms, the microwave oven can be described as a terminated waveguide transmission line resonator. Resonant waveguide cavities are generally formed by introducing terminating conditions (usually very high conductivity walls) thus forming an enclosed box. If the waveguide is filled with a high permittivity, low loss dielectric material, a resonant cavity can be formed even if one end is 'open', due to high internal reflections at the dielectric/air boundaries - the FAMOBS oven takes this approach. The propagation of a wave through an enclosed space is determined by the Phase constant 'β' which a function of wave number 'k' and cut-off wave number 'k_c'. The wave number is a function of the dielectric materials through which the electromagnetic wave propagates. The cut-off wave number is determined by the geometry of the system. The wave number, cut-off wave number and propagation constant are defined by equations 1, 2 and 3, with symbols defined in table 1.

$$k = 2\pi f\sqrt{\mu\varepsilon} \qquad 1)$$

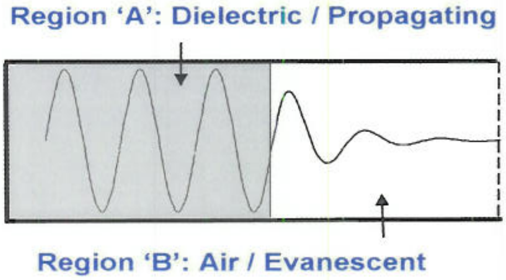
$$k_c \cong \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \qquad 2)$$

$$\beta = \sqrt{k^2 - k_c^2} \qquad 3)$$

Table 1: Definition of symbols used in equations 1 and 2

Symbol	Definition
ε	material dielectric constant
μ	material magnetic permeability
f	microwave frequency
m	Number half wavelengths in x direction
n	Number half wavelengths in y direction
l	Number half wavelengths in z direction
a	distance in x direction
b	distance in y direction
d	distance in z direction

In the FAMOBS system, the oven is arranged in such a manner that the wave number is greater than cut-off in the ceramic filled section of the oven and less than cut-off in the air section. This results in a real phase constant and a propagating wave in the dielectric section with an imaginary phase constant and evanescent wave in the air section. The fields in the ceramic filled section form a resonant modal pattern which drives an evanescent wave in the air section. The evanescent wave decreases exponentially in amplitude with distance from the ceramic-air interface and does not propagate out of the system. This system is shown in figure 3. The composition of the FAMOBS oven and a typical microelectronics load are depicted in Figures 4(a) and 4(b).



$k_a > k_c \rightarrow \beta_a$ real (propagating)

$k_b < k_c \rightarrow \beta_b$ imaginary (evanescent)

Figure 3: Wave propagation within FAMOBS system

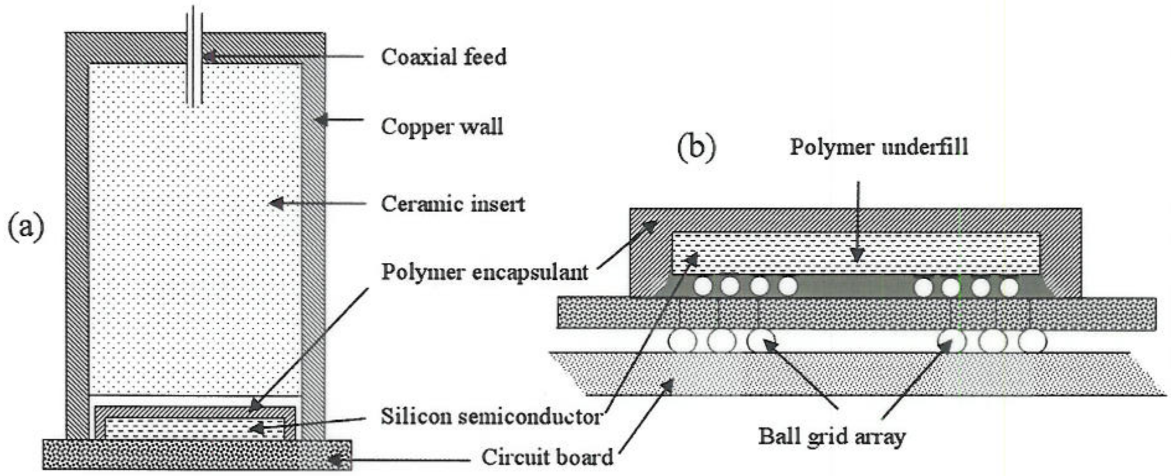


Figure 4(a) and 4(b): Illustration of FAMOBS system and of microelectronics load

Typically the system would be operated at X band frequencies (8-12 GHz) exciting a transverse magnetic mode within the ceramic insert, while system parameters would be in the ranges detailed in table 2.

Table 2: System parameters

Parameter	**Value**
Ceramic dielectric constant	2.0 - 30.0
Ceramic loss factor	< 0.003
Width	15 - 35 mm
Height	15 - 35 mm
Length	60 - 150 mm
Air Gap	< 5 mm

The system can be operated at a large number of discrete frequencies each resulting in a differing modal structure within the ceramic. The heating rate and pattern can be controlled through selection of appropriate operating frequencies (and therefore modes), operating power and duration of modes. This control of the heating enables the cure process to be optimised, resulting in increased process quality, increased system reliability, decreased process duration and decreased production costs.

Assessment of system

Experimental studies of the system have been conducted using a prototype FAMOBS system. The system comprises of a copper waveguide section containing a ceramic insert. A 30 Watt traveling wave tube with protection circuits and regulated power supply is connected to the system with a coaxial signal line. The cavity is illustrated in Figure 5 and the system illustrated in figure 6. The system can be driven at frequencies between 8 and 12 GHz. As ordered modal structures only exist at a number of discrete frequencies within this available range the production system would vary operating frequency to excite these modes. This capability has not been integrated into the prototype system, therefore only analysis of single modes is possible.

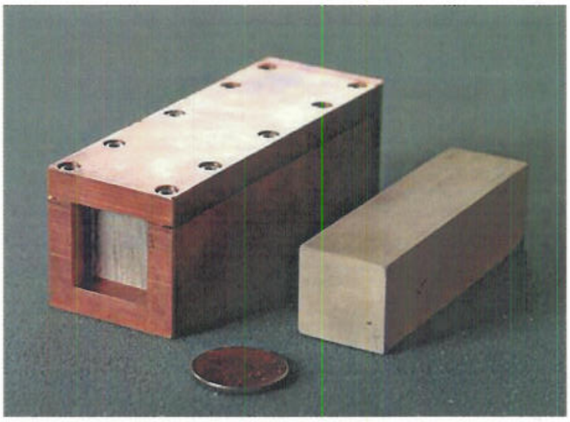


Figure 5: Experimental cavity with ceramic insert

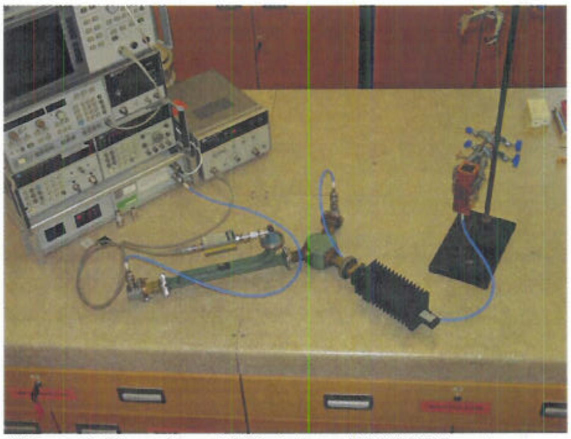


Figure 6: Experimental Prototype FAMOBS system

System assessment has consisted of heating thermal films and of heating and curing test samples of thermosetting polymer materials.

A numerical model describing the system has been developed to expedite the design process and aid understanding of the system processes. A design optimisation study will be performed to determine the optimal design and identify the most influential design parameters.

In order to accurately model the process of microwave curing a holistic approach must be taken. The process cannot be considered to be a sequence of discrete steps, but must be considered as a complex coupled system. Microwave energy is deposited into the dielectric materials, inducing heating. The absorption of heat energy initiates or expedites the thermosetting cure process within the polymer material. The cure process will increase the toughness and Young's modulus of the material which will influence the stresses induced inside the material by heating. Significant inter-linking between processes exists. The dielectric properties of the polymer material are influenced by temperature and degree of cure, leading to substantial alteration the electromagnetic field distribution during the process. The thermosetting reaction is often exothermal leading to further coupling between cure and temperature. Thus, despite the very different thermal and electromagnetic timescales, there is a requirement to closely couple the computational electromagnetic, thermal, curing and stress analyses.

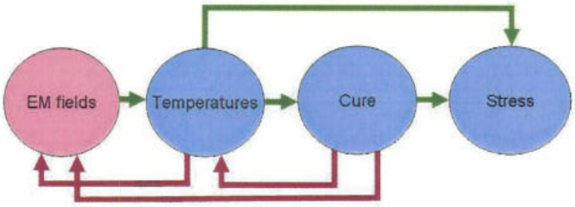


Fig. 7: Processes coupling in microwave curing

The numerical model utilised in this contribution is an extension of the approach developed by the authors for food processing applications (see Tilford et al [3]). The model comprises a Finite Difference Time Domain (FDTD) electromagnetic solver coupled with an unstructured finite volume method (FVM) multi-physics package, both of which were developed (or co-developed) by the authors. Electromagnetic and thermophysical solutions are solved within independent numerical domains, with coupling implemented through an inter-domain cross mapping process. The thermophysical analysis mesh is confined to the load material while the electromagnetic mesh is occupies the entire oven domain (encompassing the thermophysical domain). This approach enables the FDTD mesh to be varied without requiring modification to the thermophysical mesh. This is of great benefit in cases in which the dielectric properties of the load material (and therefore local propagation wavelength) vary during the heating process. The cross mapping algorithm transfers required data between the two domains based on spatial coordinate sampling approach.

The electromagnetic analysis is carried in out in a rectangular domain encompassing the extent of the FAMOBS cavity. This allows the use of tensor product meshes with a classical FDTD approach, where Maxwell's equations are solved in the time domain with harmonic excitation. A Yee scheme (Yee [4]) has been utilised in this implementation of a FDTD solver. In order to maintain numerical accuracy despite wavelength variation an automatic mesh generation algorithm has been employed.

The time-domain electromagnetic fields are integrated to a time harmonic solution for each thermal analysis timestep. A Fourier transform of the electric field is used to yield the power source term for the heating step. The difference between successive values of absorbed power at successive Fourier transfer analyses is used to determine when a converged time harmonic solution has been reached.

The PHYSICA unstructured finite volume multiphysics package was used to obtain solutions to temperature distribution, cure rate, degree of cure and thermal stress problems. Partial differential equations (PDE) describing these physical phenomena are formulated in a generalised finite volume form. Simultaneous solution of these PDE's yields accurate thermophysical results.

Electromagnetic and thermophysical domains are interlinked through a cross mapping algorithm, based on a spatial sampling approach and capable of creating rapid conservative mappings between the meshes. Two sets of mappings are generated; firstly dielectric data is mapped from the thermophysical analysis domain into the FDTD domain prior to EM solution. Subsequently, power densities are mapped from the FDTD domain into the thermophysical analysis domain prior to solution of thermophysical PDE's.

Initial Results

Initial experimental and numerical results have been obtained. Experimental assessment has focused on evaluation of field patterns using thermal films. Numerical models of the system have been produced and compared with the experimental results. Figure 8 shows a thermal film image in which the film colour is related to film temperature. As the dielectric properties do not vary significantly over the indicated temperature range the temperature can be considered to be proportional to the square of the electric field intensity. Figure 9 shows the electric field intensity in a cross section of polymer material obtained from the numerical model. Comparison of figures 8 and 9 show similar distribution of electric field with the exception of the centre area in which the experimental assessment shows two peaks in field intensity where 3 should be present. This deviation is likely to be due to mode degeneracy. Initial simulations of polymer heating have been undertaken. Figure 10 shows electric field solution of the system operating in a TM331 mode at 10.584 GHz. The apparent lack of field in the air gap is due to the scale of the contour plot. The fields in the air gap are significantly less than those in the ceramic and decay exponentially with distance from the interface. The exponential decay is illustrated in figure 11 which shows field intensity in unloaded load section. Figures 12 and 13 show the temperature and loss factor distribution over a cross section of polymer after 3 seconds of heating at 10 Watts. These demonstrate that heating of the polymer is feasible with the proposed system. The presence of hotspots and general uneven heating patterns are due to the single frequency operation of the system. Implementation of a frequency variation strategy should overcome these issues and provide a far more homogeneous heating pattern. The simulation results suggest that, as expected, the heating pattern is closely related the mode order excited within the cavity. The numerical model would appear to be numerically stable and capable of overcoming the complex challenges required to model this type of problem.

The heating rate predicted by the numerical model is greater than would be required in a production facility. The efficiency of the system is extremely high with the vast majority of energy being deposited into the polymer load.

Further work is required to assess the influence that the cure process will have on the material properties of the polymer material. This is likely to be a significant factor as the cross linking of polymer chains may have an impact on dielectric properties. Further simulations of heating processes with a realistic heating profile and of entire microelectronic package are required.

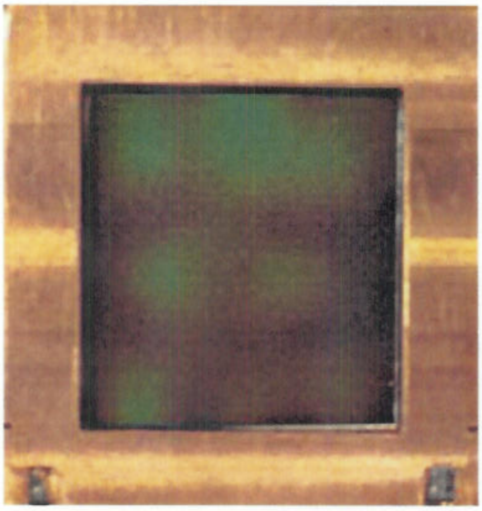


Fig. 8: Thermal film showing field distribution

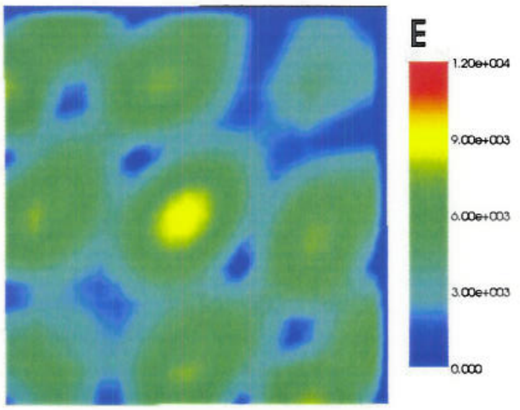


Fig. 9: Electric field distribution in cross section of polymer material

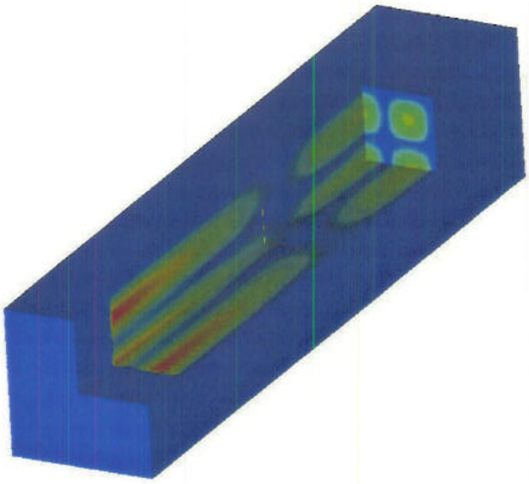


Fig. 10: Electric field distribution within FAMOBS oven.

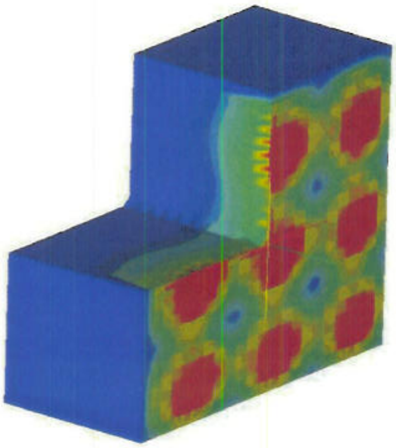


Fig. 11: Electric field distribution (unloaded) air gap.

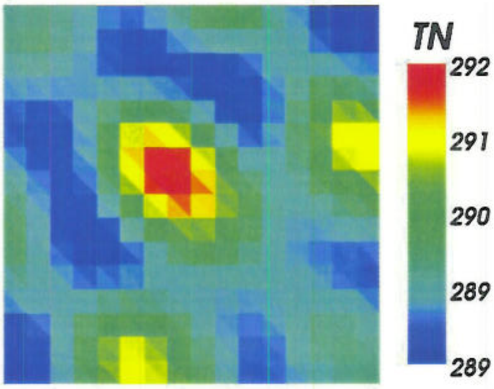


Fig. 12: Temperature distribution after 3 seconds heating.

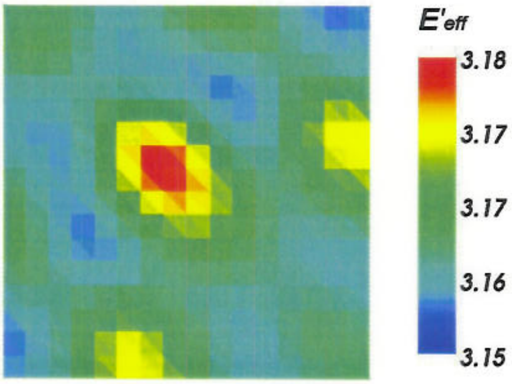


Fig. 13: Loss factor distribution after 3 seconds heating.

Conclusions

An open ended variable frequency microwave oven system capable of curing polymer materials used in microelectronics packaging applications has been assess experimentally and numerically. Initial results demonstrate that heating of polymer materials with the system is feasible. Further effort is required to extend the assessment of the system to incorporate full variable frequency operation and assessment of the heating and curing of entire microelectronics packages.

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