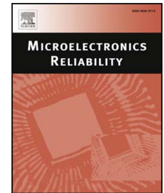
Microelectronics Reliability 80 (2018) 14–23

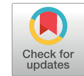
Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel



Warpage simulation for the reconstituted wafer used in fan-out wafer level packaging



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ARTICLE INFO

Keywords:
System-in-package
Epoxy molding compound
Cure kinetics
Viscoelastic
Process simulation

ABSTRACT

Fan-out packaging technology involves processing redistribution interconnects on reconstituted wafer, which takes the form of an array of silicon dies embedded in epoxy molding compound (EMC). Yields of the redistribution interconnect processes are significantly affected by the warpage of the reconstituted wafer. The warpage can be attributed to the crosslinking reaction and viscoelastic relaxation of the EMC, and to the thermal expansion mismatch between dissimilar materials during the reconstitution thermal processes. In this study, the coupled chemical-thermomechanical deformation mechanism of a commercial EMC was characterized and incorporated in a finite element model for considering the warpage evolution during the reconstitution thermal processes. Results of the analyses indicate that the warpage is strongly influenced by the volume percentage of Si in the reconstituted wafer and the viscoelastic relaxation of the EMC. On the other hand, contribution from the chemical shrinkage of the commercial EMC on warpage is insignificant. As such, evaluations based on the comprehensive chemical-thermomechanical model considering the full process history can be approximated by the estimations from a simplified viscoelastic warpage model considering only the thermal excursion.

1. Introduction

With the advantages of reduced body size, lower manufacturing cost, and better electrical and thermal performances, fan-out wafer-level package (FO-WLP) has become one of the primary approaches for system-in-package (SiP) based heterogeneous integration. The packaging process of FO-WLP typically starts with reconstituting from a Si wafer to an overmolded wafer. Schematic of the reconstitution process for a typical chip-first, face-down fan-out technology [1] is shown in Fig. 1. In this process, electrically-tested good Si dies are first singulated and placed facing down on a carrier that has the form of a wafer, on top of which a layer of adhesive tape holds the dies in position. Compression molding process is then applied to encapsulate the whole carrier with EMC. Lastly, the reconstituted wafer is separated from the carrier and tape. Subsequent processes including redistribution interconnect and bump fabrications are performed on the reconstituted wafer in the same fashion as on standard Si wafer, followed by singulating the reconstituted wafer to individual packages. Alternative integration approaches such as arranging Si dies to be facing up instead of facing down, using panel as opposed to wafer-shaped carrier, adopting interconnects fabricated using foundry back-end-of-line (BEOL) processes or coreless substrate, and attaching chip to redistribution interconnect (as opposed to processing interconnect on reconstituted wafer) were also explored [2]. While there are many process and integration schemes being considered for the FO-WLP, a common feature of the package is that the Si dies are embedded in EMC or polymer dielectrics [3,4]. During various thermal processes, dimensional instability of the encapsulant tends to induce shifting of die position and warpage of the reconstituted wafer or panel [5,6]. Because the thin film processes for fabricating the fine-pitch redistribution metal lines and the associated wafer handling have stringent planarity requirement, warpage of the reconstituted wafer is highlighted as one of the difficult challenges in the heterogeneous integration focus area of the 2015 International Technology Roadmap for Semiconductors (ITRS) report [7]. For addressing the warpage issue, it is essential to evaluate the underlying deformation mechanisms and incorporate them in the model for assessing and minimizing the reconstitution process induced warpage.

The driving forces for warpage of the reconstituted wafer can be attributed to the chemical shrinkage of the EMC and the mismatch in the coefficients of thermal expansion (CTEs) of dissimilar materials in the reconstituted wafer. The same driving forces are responsible for warpages in the conventional overmolded packages, and were investigated extensively in literatures. In particularly, many thermo-elastic models have been developed for simulating stress and warpage in packages [8,9] and in reconstituted wafer [5] or panel [10]. Because of the linear nature of the fundamental assumption, these models could

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https://doi.org/10.1016/j.microrel.2017.11.008
Received 13 September 2017; Received in revised form 10 November 2017; Accepted 11 November 2017
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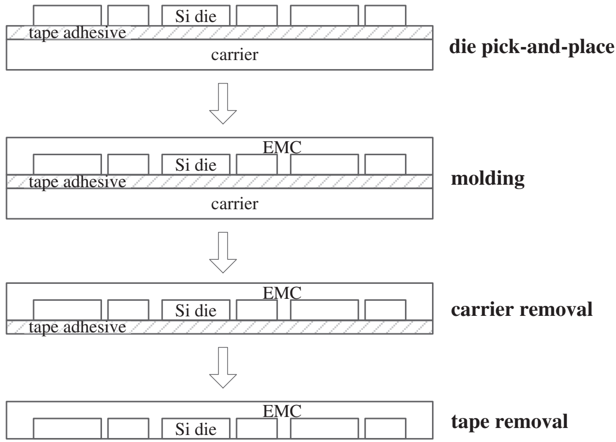

Fig. 1. Process of wafer reconstitution.

not account for the effects of molding or temperature ramp conditions used in the thermal processes. More comprehensive modeling approaches that take chemical shrinkage and viscoelastic relaxation into consideration were also developed for evaluating effects of process conditions on warpage. Chemical shrinkages during molding and post-mold curing (PMC) thermal processes are related to the polymerization conversion of the EMC and subsequent chemical aging at high temperatures. Estimation of the polymerization induced chemical shrinkage is typically through a linear relationship between the shrinkage strain and the degree of cure [11]. The effect of chemical aging on shrinkage strain can be modeled by a hybrid linear-and-power-law function of the aging time [12]. Viscoelastic relaxation and the influence of the thermochemical state on the constitutive behavior of the EMC can be considered by using a cure-dependent Prony series, e.g., [12]. By using the coupled chemical-thermo-viscoelastic approach, de Vreugd et al. [13] studied the cure-induced warpage of an overmolded Cu substrate, Chiu et al. [14] modeled the warpage evolution of a chip-scale package during the PMC process. Huber et al. [15] employed an inverse approach to obtain the chemical shrinkage and relaxation characteristics of EMC from the warpage measurement of a leadframe package. For the warpage of reconstituted wafer, investigation on the influences of chemical shrinkage and viscoelastic relaxation is limited: Deng et al. [16] studied the effect of polymerization-conversion induced shrinkage of the EMC on the warpage of reconstituted wafer.

In this study, a coupled chemical-thermomechanical model that considers the cure kinetics, the chemical shrinkage, and cure-dependent viscoelastic behavior was developed for a commercial EMC. The coupled chemical-thermomechanical model of the EMC was then implemented in numerical finite element (FE) procedure for simulating warpage evolution of reconstituted wafer during its fabrication process, and for investigating the effects of EMC property and Si die arrangement on warpage. Accuracy of the numerical results was validated by using experimental digital image correlation (DIC) measurement data.

2. The chemical-thermomechanical constitutive behavior of the EMC

The EMC considered in this study is an 89-wt%-silica-filled commercial compound formulated specifically for the fan-out packaging application. To evaluate the effects of curing and aging chemical reactions on the thermomechanical constitutive behavior of the EMC, the thermochemical analyses using differential scanning calorimetry (DSC) were performed for determining the cure kinetics of the compound, dynamic mechanical analyses (DMA) under either uniaxial or torsional cyclic loadings on partially- or fully-cured EMC specimens were conducted for characterizing the cure-dependent constitutive behavior, and thermal mechanical analyses (TMA) under isothermal curing conditions were used for evaluating the chemical aging shrinkage.

2.1. Cure kinetics

Because the curing of epoxy resin in typical molding compound is through the usage of catalysts and heat, the level of crosslinking reaction can be characterized by the degree of cure, given by

$$\alpha = \frac{H(t)}{H_u} \tag{1}$$

where $H(t)$ is the heat released by the crosslinking reaction up to time t and H_u is the ultimate heat of reaction. To establish the relationship between the degree of cure of the EMC and its thermal history, DSC experiments were conducted by using TA Instrument Q200 differential scanning calorimeter. The heat releases of uncured EMC samples weighting 10 to 20 mg under constant rates of heating (between 2 and 100 °C/min from room temperature to 300 °C) or isothermal conditions (125 °C, 145 °C and 165 °C) were measured and integrated over time to determine the values of $H(t)$ and H_u. The degrees of cure of the EMC under constant rates of heating were then calculated by using Eq. (1) and fitted to the Kamal's autocatalytic model [17], given by

$$\frac{d\alpha}{dt} = \left[k_1 \exp\left(-\frac{Q_1}{RT}\right) + k_2 \exp\left(-\frac{Q_2}{RT}\right)\alpha^m\right](1-\alpha)^n \tag{2}$$

where m and n are the reaction order constants, k_1 and k_2 are the reaction rate constants, Q_1 and Q_2 are the activation energies, R is the universal gas constant, and T is the temperature. The model constants for the EMC and the corresponding curing evolution under heating are shown in Table 1 and Fig. 2, respectively. It can be seen from Fig. 2 that the Kamal's autocatalytic model agrees well with the constant-heating-rate experimental data. Comparisons of the model predictions and the experimental results for the curing reactions under isothermal conditions are shown in Fig. 3, from which it can be seen that the non-isothermal-reaction based model underestimates the curing rate of the 165 °C isothermal reaction, but correlates well to the experimental results for the lower temperature cases.

2.2. Cure-dependent viscoelastic behavior

The coupled chemical-thermomechanical constitutive behavior is considered by expressing the total strain in the material as the superposition of the mechanical, chemical and thermal strains, i.e.,

$$\varepsilon_{ij} = \varepsilon_{ij}^{s} + (\varepsilon^{c} + \varepsilon^{t})\delta_{ij},\ i, j = 1, 2, 3 \tag{3}$$

where ε_{ij} is the strain, δ_{ij} is the Kronecker delta, and the superscripts s, c and t denote the mechanical, chemical, and thermal components, respectively. The relationship between the stress and mechanical strain is assumed to be isotropic and linear viscoelastic, and can be expressed in a convolution integral form given by

$$\sigma_{ij}(t) = \delta_{ij}\int_{0^-}^{t} \kappa(t-\eta, T, \alpha)\frac{d\varepsilon_{kk}^{s}(\eta)}{d\eta}d\eta + \int_{0^-}^{t} 2G(t-\eta, T, \alpha)\frac{de_{ij}^{s}(\eta)}{d\eta}d\eta,\quad i, j = 1, 2, 3, \tag{4}$$

where σ_{ij} is the stress, ε_{kk} is the sum of normal strains ($\varepsilon_{kk} = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$), e_{ij} is the deviatoric strain, δ_{ij} is the Kronecker delta, κ and G are the bulk and shear relaxation moduli, respectively. In Eq. (4), the effects of chemical reaction and temperature on the mechanical constitutive relationship are considered by cure- and temperature-dependent relaxation moduli. Characterizations of the

Table 1
Material constants for the cure kinetics model (Eq. (2)).

k_1 (1/s)	k_2 (1/s)	Q_1/R (K)	Q_2/R (K)	m	n
1.58×10^4	3.55×10^5	6910	6804	0.727	1.376

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