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Finite element modeling of temporary bonding systems for flexible microelectronics fabrication

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ABSTRACT

One promising route to enable the manufacture of flexible microelectronics is through temporary bonding–debonding of flexible plastic substrates to rigid carriers, which facilitates effective substrate handling by automated tools. Understanding the thermomechanical properties of the temporary bonding system (flexible substrate–adhesive–carrier) could allow for improved control of bow and distortion of the flexible substrate that can adversely impact device fabrication. In this study, a thermomechanical analysis of this temporary bonding system is performed using finite element modeling (ANSYS) to understand how to control the stress-induced bow of the bonded system. This stress is developed during high temperature processing predominately through thermal mismatches between the carrier and substrate. However, viscous flow of adhesive can relax some stress to decrease the total extent of bowing of the bonded system. Interestingly, the viscoelasticity of flexible plastic substrate appears to be critical to the stress-induced bowing; viscous flow of the plastic substrate relaxes some stress of the bonded system and must be taken into account to achieve good agreement between simulated and experimental bow. By variation in the relaxation time (τ) and the relative relaxation modulus (α) of the adhesive, the simulation shows a limited range for the relaxation parameters over which the bow can be tuned for a specified carrier–flexible substrate system. These results suggest that further engineering of the adhesive is unlikely to dramatically decrease the bow of the bonded system as would be necessary for extension to large form sizes. Therefore, efforts should focus on new flexible substrates and rigid carriers; the model developed here can be utilized as a screening tool for this purpose.

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1. Introduction

Flexible electronics have attracted significant academic and commercial attention in recent years [1–5]. This paradigm-shifting technology provides the opportunity to create energy-efficient products that are lightweight, ultrathin, and rugged; moreover, these technologies exhibit potential for very large area electronics with the ability to flex, curve, conform, and roll [6]. Flexible electronics have been predicted for many years to be the next big thing in technology [7,8], but commercial products have not been forthcoming with the price point and performance for printed flexible organic electronics being a major challenge [9]. One alternative approach that should provide competitive processing in the interm is to use traditional microelectronic or display toolset to fabricate devices directly on a flexible substrate, but this is fraught with major challenges associated with the overlay registration and overall planarity of the substrate during processing. To overcome these challenges, we have been developing a temporary bond–debond approach that enables direct fabrication of high performance electronic devices on flexible substrates [3,5]. In this technique, the flexible substrate is temporarily adhered to a rigid carrier plate using a polymeric adhesive during device fabrication; after the fabrication is complete, the flexible substrate is separated from the carrier through a debond process. One problem that is encountered in this process is bowing of the bonded wafer, which can lead to wafer handling issues or delamination of the flexible substrate from the rigid carrier. Stress is developed during the bonding–debonding process and the fabrication process steps; this stress evolves predominantly through thermomechanical property mismatches between the carrier and the flexible substrate. The residual stress is relaxed through bowing of the bonded system (flexible substrate–adhesive–carrier). Additionally, flexible plastic substrates are not dimensionally stable like traditional glass or silicon substrates; deformation or distortion of the substrate may occur during high temperature processing. This distortion imposes difficulties in ensuring registration of layers during multiple

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photolithographic steps that are used to create an active device. Therefore, it is critical to minimize the bow–distortion of the bonded system. Previously, adhesives with different viscoelastic properties were investigated experimentally in the context of bow–distortion [10]. A more rigid adhesive with a low loss factor leads to less distortion of the bonded flexible plastic film, but this adhesive can also lead to large wafer bow depending upon the carrier properties. Nonetheless, acceptable stress-bow on 150 mm wafer scale (enable automatic handling) has been achieved with this adhesive by using a carrier with high modulus and coefficient of thermal expansion that is closely matched to the flexible substrate [11]. However, extension of this technology to GEN-II display size will require refinements in the bonded system to minimize the bow, while maintaining acceptable distortion for device performance. It is time consuming and expensive to formulate an adhesive by trial and error to control the deformation of the bonded system. Thus, a valid physical-based model of the bonded system would provide fundamental understanding of deformation behavior with the properties of carrier, adhesive and substrate. The theoretical understanding gained could then, in principle, be used to enable rational design of a bonded system with optimum properties of carrier, adhesive and substrate.

The effect of thermal cycling on the state of residual stress for systems in which stiff elastic substrates bonded by viscoelastic polymeric adhesive has been investigated previously using numerical techniques, including finite element methods [12–15]. In this work, this modeling is extended to a *tri-layer* structure of dissimilar materials where a viscoelastic adhesive is sandwiched between a rigid carrier and a flexible (viscoelastic) plastic substrate. This geometry is identical to that utilized for the temporary bonding for the fabrication of flexible electronics. Previously, we have found that the deformation behavior of the system correlated directly with the relative loss factor of adhesive to that of flexible plastic substrate based upon limited experimental work [10]. One unanswered question is the role of the viscoelastic behavior of flexible substrate on the bow–distortion in the temporary bond–debond process. For this problem, it is important to consider coupled thermal–structural displacement and the stress–strain field due to differential thermal expansion, which are difficult to apply using analytical solutions. Therefore, we have developed a finite element model using ANSYS for simulating the bow of a bonded system for understanding how physiochemical properties of the individual components (flexible substrate, adhesive and rigid carrier) impact the performance towards the manufacture of flexible electronics using the temporary bond–debond process.

2. Experimental methods

2.1. Materials

Two types of adhesive supplied by Henkel Corporation were used in this study: a solution-based elastomer pressure sensitive adhesive (Elastomer PSA) and a solvent-less ultraviolet photo-curable pressure sensitive adhesive (UV PSA, product no: WFP20141-94B). Silicon wafers, alumina wafers and D263T, AF45 and Corning Eagle 2000 glass wafers (150 mm diameter) were utilized as carriers. Heat-stabilized polyethylene-naphthalate (HS-PEN, 125 μm thickness) obtained from DuPont Teijin Films (tradename Teonex Q65A) was utilized as the flexible substrate.

2.2. Processing

In the bonding process, the adhesive was first spun coat on the carrier and a post-apply bake (PAB) was applied for Elastomer PSA to remove the solvents in two steps: 80 °C for 30 min and 130 °C for 15 min to ensure that residual solvent was removed. Subsequently, the flexible HS-PEN substrate was laminated on the adhesive coated carrier using a hot roll laminator (Western Magnum). For UV PSA, the bonded wafer was exposed to UVA light (400–315 nm) after lamination using a Dymax UV curing unit for 20 s through the transparent plastic to cure the adhesive. Finally, the bonded wafer was baked under vacuum at 180 °C for 60 min to simulate the maximum temperature of exposure during actual processing.

In order to understand the viscoelastic relaxation of the adhesives, bulk, molded samples of both adhesive formulations were fabricated. For Elastomer PSA, the solvent was evaporated at ambient condition for several days to prevent bubble formation during bake. The adhesive was then baked to remove the residual solvent. For UV PSA, the adhesive was UV cured under N_2. Then both adhesives were cut into rectangular strips approximately 7.5 mm × 4 mm × 1.2 mm (height × width × thickness) for characterization.

2.3. Characterization

The relaxation modulus of the adhesives and HS-PEN was characterized using a dynamic mechanical analyzer (DMA, Texas Instruments Q800) in tensile oscillation. The strain was held constant at 1% and the time dependent decrease in stress was recorded to obtain the relaxation modulus for each material. The bow of bonded wafers was measured at ambient conditions using an Optical Stylus Sensor (Tamar Technology). The bow was defined as the physical deviation of center point of the median surface of the wafer from a best fit plane through the points at 120 mm diameter, where the median surface is the locus of the points equidistant between the front and back surfaces. Fig. 1 illustrates schematically how bow is calculated.

3. Model development for bonded system

3.1. Finite element modeling

Finite element modeling using ANSYS "Structural" materials model provided rigorous simulation of the stress and strain fields in the 150 mm bonded wafer system. This model is capable of simulating systems with a range of materials that exhibit linear or nonlinear behavior and that are elastic, inelastic and/or viscoelastic. The dimensionality of the problem was reduced using the axisymmetric idealization assumption, which converts the problem from 3-D to 2-D. Further reduction in model complexity was obtained by examination of the symmetry of the bow in 2-D, such that only half of the bonded wafer was modeled. Thus, the geometry for modeling of the bonded system consisted of three rectangular areas that were 75 mm wide. A schematic of model bonded system is shown in Fig. 2. The height of the bottom section, which corresponds to the different carriers examined experimentally,

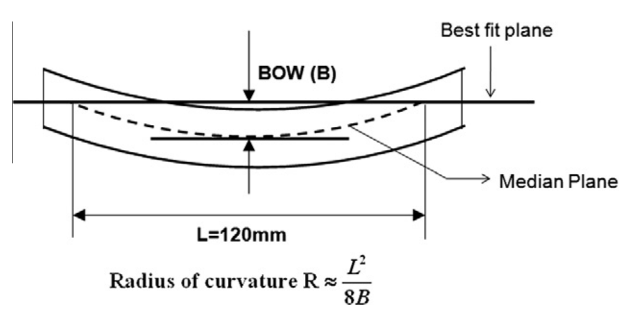

Fig. 1. Bow by measuring the location of the median surface at the center of the wafer and determining its distance from the best fit plane.