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From design to manufacturing: new methods to fix the mechanical problems associated with device production

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Abstract

The design and manufacture of microelectronic devices requires perfect mastery of cutting-edge technologies. Our team is particularly interested in the problems of strain and reliability that need to be controlled at every stage of the device's design and manufacture. We developed an analytical model able to predict the strains and stresses in each of the layers and at each stage of manufacture. This model requires knowledge of realistic mechanical properties of the materials making up the device.

Nano-indentation AFM, colored picosecond acoustics and temperature-dependent ellipsometry, can be used to characterize the thermo-mechanical properties materials (Young's modulus E and coefficient of thermal expansion CTE α) but these techniques have major limitations: the measurements are local and/or perform to the extreme surface of the materials. We have therefore developed a more comprehensive and global characterization method, based on measurements of wafer curvature. First, this method is particularly effective for highlighting cross-linking problems in polymers. We used the method to characterize the thermomechanical properties of various materials used in an imaging device and studied the mechanical integrity of a representative structure using our analytical model and finite element simulations. Finally, in order to understand all the potential problems, we worked on the effects linked to the ageing of materials.

1. Introduction

Over the recent years, we developed an analytical model aimed at forecasting device strain [1]. This model, known as *Sigmapeps*, enables us to predict strain and stress distribution within a multi-layered structure. The similarity between the high and low temperature behaviors of elastic materials such as metals, dielectrics and ceramics, categorizes them as thermally stable on the temperature range to consider. For these materials, it is assumed that the coefficient of thermal expansion (CTE) and Young's modulus (E) remain constant throughout thermal loading.

However, polymers have become ubiquitous in microelectronics, finding application as adhesives, passive layers, and underfill. They are also widely used in the manufacture of imaging devices (lenses) as they can be shaped in a variety of ways. Polymer behavior is characterized by viscoelasticity: under stress, strain occurs with a time delay (phase lag), and

this effect becomes more pronounced with increasing temperature. It is therefore necessary to characterize their thermo-mechanical properties. They also exhibit a high contrast of properties with other integrated materials like oxides, metals or silicon. Nevertheless, before incorporating a polymer into a stack, it is necessary to ensure that it is chemically stable, which means checking that it is fully cross-linked.

2. General Instructions

A – Stability of polymers

In order to characterize resins, we need to check that the cross-linking is fully complete by repeating measurements. When the evolution of curvature is stable after several thermal cycles, we can conclude that the chemical cross-linking of the polymer is complete.

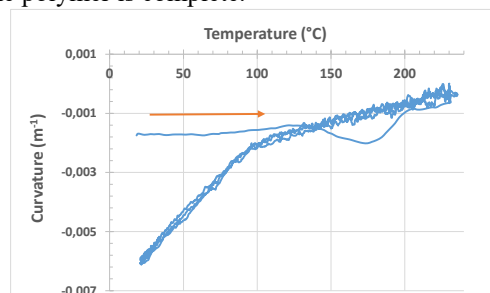


Fig. 1 Evolution of the curvature of the Resin/Si wafer after a partial curing cycle.

Figure 1 presents an interesting result for an initially unstable resin with a partial curing: the curvature, stable up to 120°C, starts to decrease and then increases above 180°C. When the cross-linking of the resin is partial, the rigidity of the polymer means that the resin/Si bilayer cannot be bent. The energy supplied by the temperature from 120°C onwards increases the number of cross-linking nodes in the resin and therefore increases its rigidity. Above 140°C, this curvature measurement shows a dual effect: an increase in rigidity due to an increase in crosslinking (the curvature starts to increase between 140 and 170°C), followed by a reversal of the trend, reflecting a softening of the resin, which has gradually moved towards a highly rubbery state. On cooling, the curvature of the bilayer containing the fully cross-linked resin changes towards higher values and the following cycles are perfectly reproducible. In this way, we are able to check whether the resins are stabilized or whether they need to undergo additional stabilization annealing. After stabilization, we are now able to characterize resins with the double curvature method.

B - Double curvature method [2]

We consider an elastic bilayer composed of a film atop a substrate. The thickness of each layer is denoted as h_i , where i represents either the substrate (s) or the film (f). The disparity between the biaxial moduli, denoted as M_i , and the coefficients of thermal expansion α_i , results in a misfit stress within the film that varies with temperature.

$$\sigma_f(T) = M_f(\alpha_s - \alpha_f)\Delta T \quad (1)$$

Considering a specified temperature change ΔT , intrinsic strains during spin-coating or curing of polymers on wafers appear negligible. Hence, these strains are disregarded. The discrepancy in properties results in bilayer strain, causing the entire wafer to assume a spherical bend when constitutive layers are isotropic and have uniform thicknesses. This deformation induces a curvature in the wafer denoted as $\kappa(T)$, with $\Delta\kappa = \kappa - \kappa_0$ representing the deviation from the initial curvature κ_0 of the substrate. By introducing the thicknesses and modulus ratio as h and m , where $h = h_f/h_s$ and $m = M_f/M_s$, respectively, the change in curvature can be represented as:

$$\Delta\kappa = \frac{1+h}{1+2hm(2+3h+2h^2)+h^4m^2} \frac{6hm}{h_s} (\alpha_s - \alpha_f)\Delta T \quad (2)$$

where $\Delta T = T - T_0$, and T_0 a reference temperature. This model extends the principle of Stoney's model. It offers versatility for various h and m ratios, assuming a uniform mismatch stress within the film. Therefore, curvature κ is the sign of the incompatibility between film and substrate properties. The CTE difference is often substantial with polymer because they exhibit larger CTE than common substrate materials. With temperature-independent modulus M_i and CTE α_i , the curvature evolution is linear with T (2), and film properties can be derived by depositing the same thin polymer film on two distinct substrates. Moreover, polymer properties can be thickness-dependent, that is why formula (2) is preferred with polymeric films instead of the well-known Stoney expression [3] [4].

Using the thermally induced curvature method, we obtain the point of intersection of the $CTE = f(M_f)$ curves for the AsGa and Si substrates and the residue (Fig. 2).

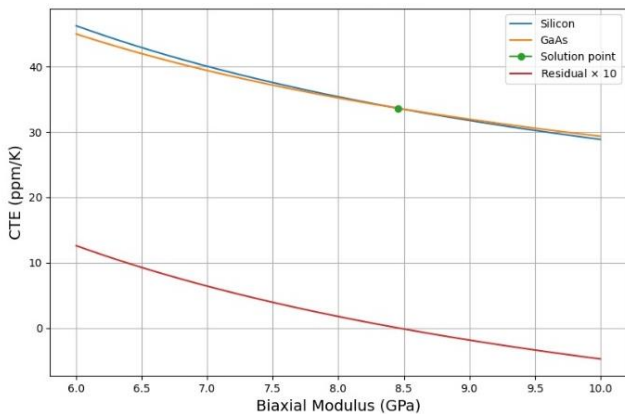


Fig. 2 - $CTE=f(M_f)$ for AsGa and Si substrates. Resin at glassy state

The results (Fig. 3) are cross-compared with measurements from other techniques (nano-indentation with AFM for the mechanical properties and temperature-dependent ellipsometry for the CTE), with a good agreement but these are dependent on the magnitude of the Poisson's ratio.

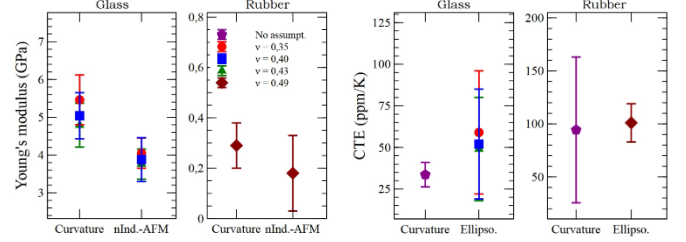


Fig. 3 - Cross-comparison of results in the glassy (left) and rubbery (right) states

C - Application

First, we will study the mechanical strength of a micron-scale polymer pillar with a thin dielectric film on its surface. This configuration is often met in imaging devices and varying thickness ratios between the polymer and the brittle hard coat will able us to limit influence failure under a 300K temperature change.

We will then show the impact of cracking in the protective layer of the device and how the polymer will undergo accelerated ageing. We will show that it is possible in some cases to repair the polymer using an additional process step.

3. Conclusions

Our approach consists of anticipating the problems of stress and strain of materials in the design and manufacture of microelectronic devices. This problem can be studied using innovative characterization techniques fed into analytical and numerical simulations. This combination of techniques broadens the range of possibilities and therefore covers and proposes a solution, including ways of improving integration parameters and/or repair degraded materials.

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