Reliability of Copper-Plated Through-Package-Via (TPV) in Glass Packages with in-situ stress measurements using Raman spectroscopy

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Abstract—**This paper reports direct in-situ stress measurements with microscale spatial resolution in glass using Raman spectroscopy. This new technique is used to assess the reliability of copper-plated laser-drilled through package vias (TPV) in ultra-thin bare glass interposers. Bare glass panels of 3"x3" size, with 137µm and 237µm thicknesses were fabricated with laser-drilled through-package vias at 30 µm and 60µm diameter respectively. Glass panels were sputtered with a thin layer of titanium and copper. These thin films on glass were oxidized in order to obtain a CuO layer that acts as the stress-sensing film. Test coupons were subjected to known mechanical stress by bending. Analytical calculations and finite element models were used to investigate the relation of stress in glass with the peak shifts in Raman spectra in order to obtain the piezo spectroscopic coefficients. The stress near TPVs was estimated based on the obtained piezo spectroscopic coefficients.**

Keywords-Through package via (TPV); reliability; glass interposer; thermal cycling test; Raman spectroscopy

I. INTRODUCTION

The increasing need for high bandwidth for mobile products is expected to accelerate the demand for higher memory to-logic bandwidth for both mobile and high performance applications. Moreover, this increasing bandwidth requirement needs to be addressed with low power, large memory and low cost [1]. These requirements impose a shift from traditional 2D multichip packages to 2.5D and 3D packages with vertical integration. Several approaches are being pursued for such vertical integration, one of which is based on stacked ICs with Through-Silicon-Vias (TSVs) as 3D ICs. This approach can realize high bandwidth due to both short interconnect length and high number of parallel channels that they can support. However, numerous challenges remain, including cost, thermal management, testability, scalability and system integration with this approach. Another promising approach to achieve the same attributes is by using 3D interposers, not with TSVs in logic ICs but with TPVs in the package substrate, and assembling logic and memory ICs on both sides of ultra-thin interposer substrates, which are then assembled onto the printed circuit board with or without organic BGA packages in-between. These 3D interposers can be used to interconnect multiple ICs vertically through assembly on both sides, and in addition they can also be used to connect multiple ICs on the same side, in so-called side-by-side configuration, referred to as 2.5D assembly. This approach is scalable, testable and enables ultra-short interconnection length and ultra-high interconnection density between logic and memory ICs just like with TSVs. However, in both 3D and 2.5D configurations, interposer materials should have ideal electrical, thermal and mechanical properties, in addition to low cost manufacturing processes for through-vias, called through-package vias (TPV) and multilayer redistribution layers (RDL).

Various substrate candidates have been considered for interposer applications. These include organic, ceramic, metal, single crystal silicon, polysilicon or glass. Of these candidate materials for interposers, organic laminates are preferred because of their low cost and existing manufacturing infrastructure. However, they are limited in fine-pitch I/O capability due to thermal and dimensional instabilities during fabrication, requiring large capture pads for layer-to-layer via registration. Therefore, organic interposers face several challenges beyond 40 µm bump pitch. Warpage is another challenge which brings additional challenges in lithography for fine-line formation and assembly, and thus limits maximum I/O count per area. To address these shortcomings, silicon interposers have been developed, manufactured and used in special high performance applications. They are fabricated with standard back-end-of-line (BEOL) wafer processes to achieve the required wiring and I/O density. However, silicon interposers suffer from two major disadvantages: 1) high fabrication cost 2) poor electrical performance. However, manufacturing infrastructure exists.

To address these disadvantages of organic and silicon interposers, glass is emerging as an ideal interposer and package substrate material due to following reasons: 1) Matched CTE to silicon for low stress and high modulus for low warpage compared to organic packages 2) Excellent smoothness (1-2nm roughness) enabling fine-line formation 3) High electrical resistivity and low electrical loss, similar to ceramics, eliminating the requirement of having to insulate with liners in via walls 4) Availability in ultra-thin (30-100µm) form-factors enabling ultra-short interconnections with double-side assembly and 5) Availability in large panels leading to potentially low manufacturing cost. [2, 3, 4]. However, brittleness of glass raises reliability concerns during through-via hole formation, copper metallization and thermal cycling, which leads to mechanical stresses due to mismatch between glass and copper. In our previous studies, finite element modeling-based TPV design guidelines for lowering these thermo-mechanical stresses were presented and reliability of TPVs were experimentally demonstrated [5, 6]. FEM techniques,

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however, often provide qualitative trends in stresses and strains because of the lack of accurate thermo-mechanical properties of TPV materials leading to significant discrepancy between the modeled and fabricated structures. Direct stress measurement is a powerful method to validate the models and to refine the material properties accordingly. Such measurements are also effective in providing direct correlation between materials, geometries and reliability performance. This study demonstrates Raman spectroscopy as an effective technique to verify mechanical modeling-based guidelines and quantify stresses in glass in the vicinity of copper-plated TPVs. These measurements provide valuable guidelines for design and material selection.

A. Stress measurements with Raman piezo-spectroscopy:

When a material is illuminated with monochromatic light, photons can interact with lattice vibrations (phonons) of the material as illustrated on Figure 1.

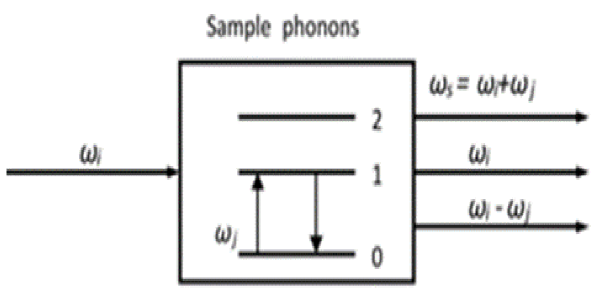


Figure 1.Interaction of photon and phonon

Due to this interaction, which is called Raman scattering, phonons in the material can be excited to a higher energy level or dropped to a lower energy level [7]. The first is called Stokes Raman scattering, the second Anti-Stokes Raman scattering. Thus, the scattered light contains different frequency components than the incident light. The spectrum of the scattered light shows frequency components at a frequency ωj higher or lower than the frequency of the incident laser light. These components can be detected as shown on Figure 2.

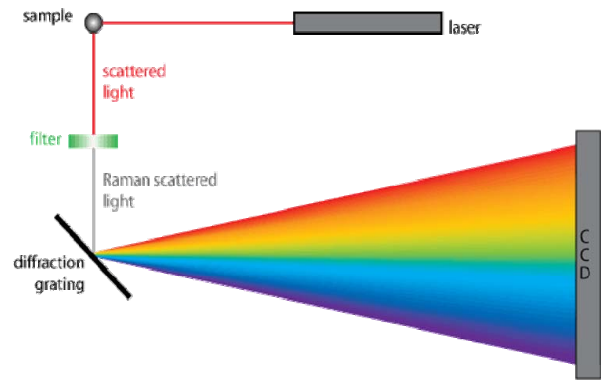


Figure 2. Raman spectrometer scheme

So, from the spectrum, one is able to know the characteristic frequency of the material vibrations: ωj. Shifting of photons to a higher energy level is the most common process to occur and Raman spectroscopy concentrates on detecting peaks associated to that process. As a result, the spectrum of scattered light contains information about characteristic frequencies of material vibrations. This spectrum can be altered when material is under stress which forms the basis for piezo spectroscopy.

Piezo spectroscopic effect is defined as the shift in the frequency of a spectroscopic transition in a solid in response to applied strain or stress. Thus, by measuring the shift in the spectra, the lattice strain can be determined. Compressive stress (σ negative) will result in an upward shift of the Raman peak, while tensile stress (σ positive) results in a downward shift. The relation between Raman shift and strain is calculated by secular equation in (1) where p, q ad r are material constants called phonon deformation potentials. Eigen values of λ give the difference between the Raman wavenumber of each mode in the presence of stress and in absence of stress. If uniaxial or biaxial stress is present in the sample, this secular equation is simplified.

In literature, Raman spectroscopy has been used to quantify stresses in silicon around Through-Silicon vias (TSVs) [8]. High signal-to-noise ratio of Raman signals obtained from silicon, and availability of various formulae that relate stress in silicon to peak shifts enabled Raman stress analysis in TSVs. However, luminescence property of glass and its amorphous structure presents challenges in Raman analysis of TPVs in glass interposers [9]. This paper addresses this challenge with recent identification of shift in Raman scattering peaks in 620-650 cm-1 range in copper oxide. When a thin film of copper on glass is oxidized, its ductility decreases, which results in better transfer of glass stress to the thin copper oxide film. Therefore, thin film of copper oxide is approximately in the same stress state as the glass surface and can be utilized as a stress sensor. Monitoring the stress of copper oxide on glass using Raman spectroscopy can possibly give information about stress in glass. This forms the basis of this study.

II. SAMPLE PREPARATION

In order to assess the effect of mechanical and thermo mechanical stress on Raman spectrum, glass samples with TPVs were fabricated following the steps illustrated on Figure 3.

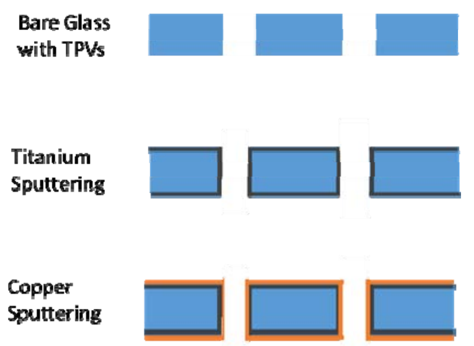


Figure 3. Glass panel fabrication process flow

Glass panels (3”x3”) were metallized by Ti/Cu sputtering. The thicknesses of glass were 137µm and 237 µm, and TPV diameters were 30 µm and 60 µm. TPV formation is achieved by laser drilling process. After Ti/Cu sputtering, the samples were fabricated following the standard semi-additive process as shown on Figure 4.

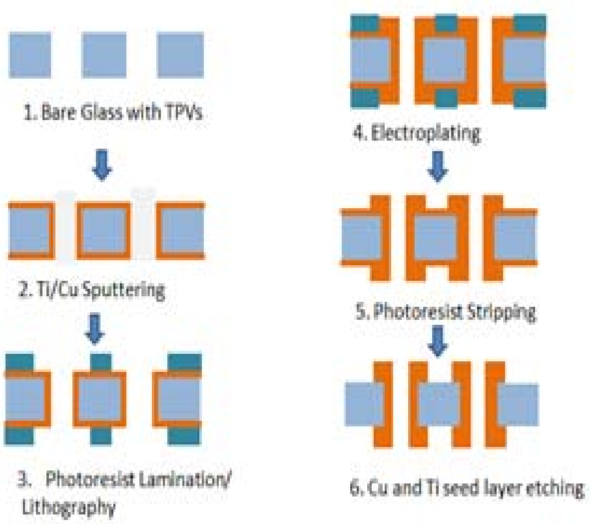


Figure 4. Glass panel fabrication process flow

For oxidation of the copper, samples were annealed at 250oC in air for 60 minutes. As a result, various glass panels with a thin CuO layer were prepared for Raman spectrum investigation. Fabricated samples are shown on Figure 5.

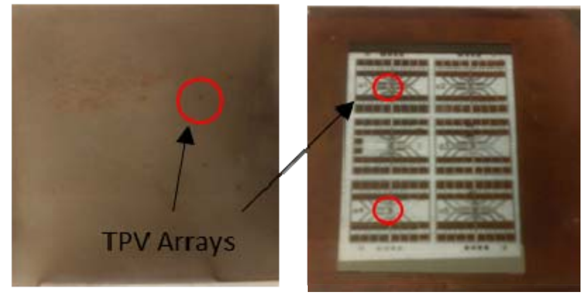


Figure 5. Fabricated coupons

For studying the effect of via diameter on Raman spectrum, polymer-laminated glass samples were fabricated on 100µm glass with varying via diameters, following the steps illustrated in Figure 6.

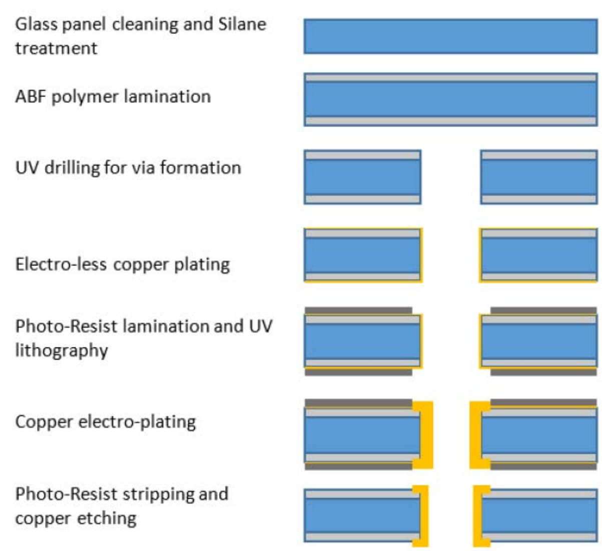


Figure 6. Fabrication process for polymer laminated glass

Bare glass surface was cleaned to remove organic residues using acetone, IPA and DI water respectively followed by baking to remove moisture. The bare glass surface was then treated with silane coupling agents for promoting adhesion to polymer. Then, glass was laminated on both sides using vacuum lamination followed by hot press and curing of polymer. The thickness of polymer used was 20µm. Polymer layer enables easier handling of glass and enhances resistance during 355 nm UV laser drilling of vias. The polymer-laminated glass was metalized by electroless and electrolytic plating up to around 1um copper thickness. This copper layer acts as a heat spreader during laser ablation and ablated glass particles sticks onto this copper layer. Via hole formation was achieved using UV laser ablation with 355nm wavelength. After TPV formation, this copper layer was completely etched, also removing the ablated glass particles from surface. Polymer-laminated glass with TPV holes was metalized using electroless plating to form a seed layer. Both sides were then laminated with a dry-film photoresist and patterned with UV lithography. After patterning, electroplating was applied to obtain approximately 4 um copper thickness on both surfaces. Fabrication was completed with photoresist stripping and micro etching the electroless seed layer. Figure 7 shows a fabricated coupon with varying diameters of TPV starting from 60µm rising up to 180µm diameter in increments of 30µm.

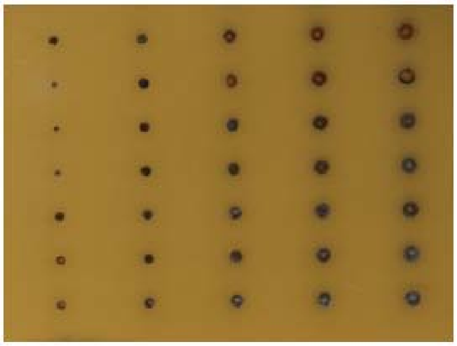


Figure 7. A glass interposer test coupon containing TPVs with different diameters

III. MICRO RAMAN MEASUREMENTS

For Micro-Raman measurements, samples were placed on a moving stage of the Thermo Nicolet Almega XR Dispersive Raman Spectrometer and enclosed inside a dark chamber to ensure only the laser hits the sample. Raman spectra were collected using laser micro Raman probe of 488 nm wavelength with a 50x microscope objective and around 3 µm spot size. With accurate background noise and baseline correction, peaks of CuO were accurately identified.

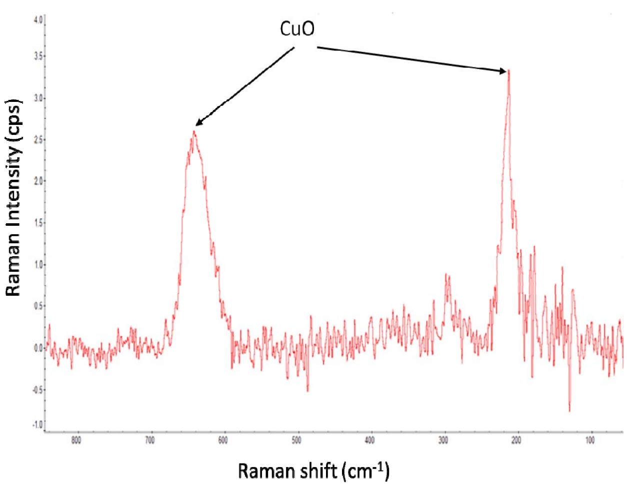


Figure 8. Raman spectrum of Copper Oxide

Figure 8 shows Raman spectrum of CuO, and peaks around 160-230 and 620-660 ranges. These wavenumbers are close to the values reported in the literature [10]. In this study, focus is on the peak that appears in the range 620-660 cm^{-1}.

Ti/Cu-sputtered glass samples of 3”x3” size with 237 µm thickness and 60 µm TPVs are shown in Figure 5. They are bent to a radius of curvature of approximately 250 mm which resulted in biaxial tensile stress on surface. Figure 9 shows the average of 5 series of spectra collected from glass surface before and after bending. Tensile stress due to bending resulted in approximately 5 cm^{-1} downwards in the spectrum of surface CuO.

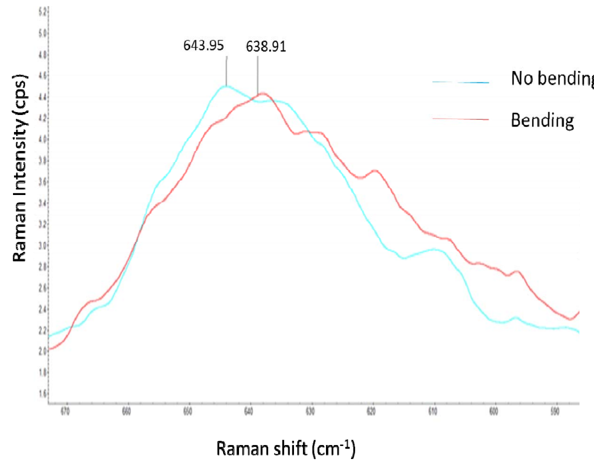


Figure 9. Raman Spectrum during bending of glass

Secondly, 3”x3” Ti/Cu sputtered sample with 137 µm thickness and 30 µm TPVs was heated up to approximately 150 ºC using heat gun and then cooled down to around -40 ºC using liquid nitrogen.

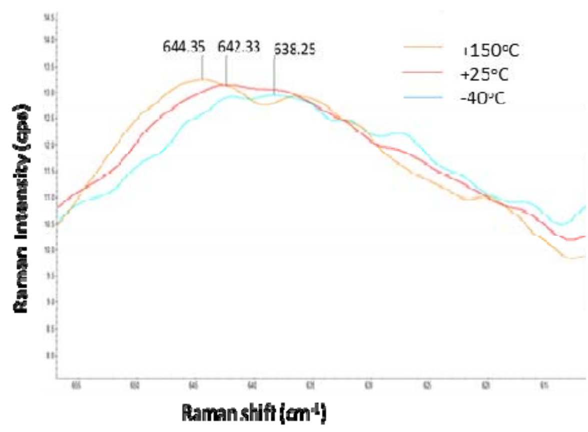


Figure 10. Raman spectrum during thermal excursions

Figure 10 shows Raman spectra collected at temperature extremes and room temperature from CuO surface near TPV entrance. Peak location is shifted to higher wave numbers with temperature, which indicates that the stresses near via shifts from tensile to compressive as temperature rises from low extreme to high extreme.

Thirdly, the effect of via diameter on Raman spectrum was investigated. Although the glass was laminated with polymer, Raman signal was collected from the area of TPV entry where polymer is partially ablated by UV laser and copper contacted the glass. Therefore, it is still possible to get measurements from copper oxide layer contacting the glass with a thin intermediate layer of copper.

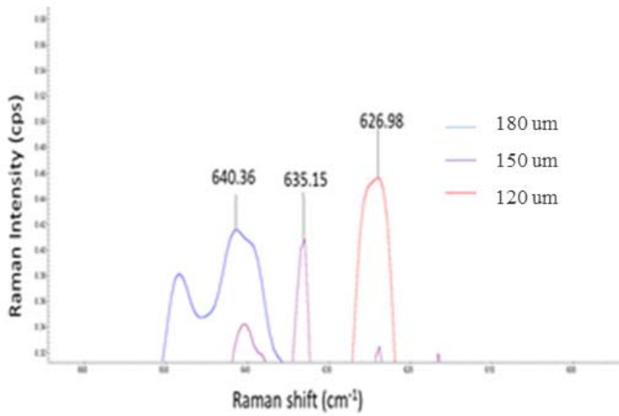


Figure 11. Raman Spectrum With Different Via Diameters

Figure 11 shows the Raman spectra collected from the edge of TPVs with varying diameters. It was observed that peak location shifted to higher wave numbers as TPV diameter decreased. This indicates an increase in tensile stress on glass surface with decreasing TPV diameter.

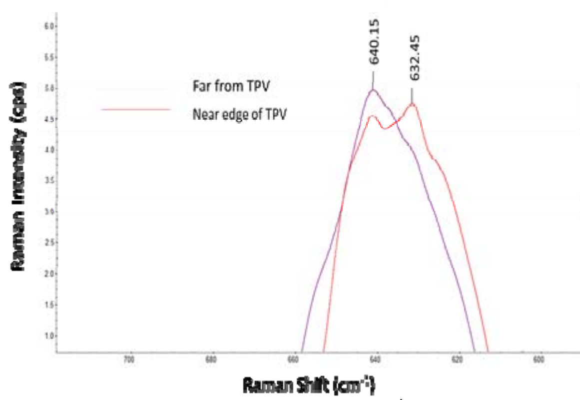


Figure 12. Raman spectra near and far from TPV

Figure 12 compares the Raman spectra collected from the edge of TPVs and far from TPVs. It was observed that peak location shifted to lower wave numbers near TPV compared to far from TPV. This is expected because TPV edges act as stress concentrators, whereas outside of its impact zone, which is approximately one diameter, TPV stress is not sensed.

A. Estimation of piezo spectroscopic coefficients

Mechanical modeling and analytical calculations were used to interpret results from Raman measurements. The material properties shown in Table I are used for calculations.

TABLE I. MATERIAL PROPERTIES

Material	E (GPa)	Poisson's Ratio	CTE (ppm/K)
Copper	120	0.34	19.4
Glass	77	0.2	3.8
Polymer	0.7	0.3	180

When glass that is sputtered with a thin film of titanium and copper is bent, tensile stress forms on the upper surface, which can be approximated as shown in Figure 13 [11].

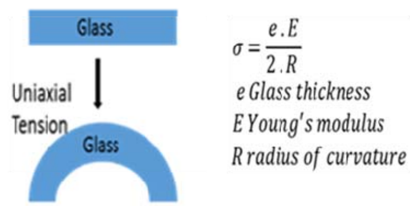
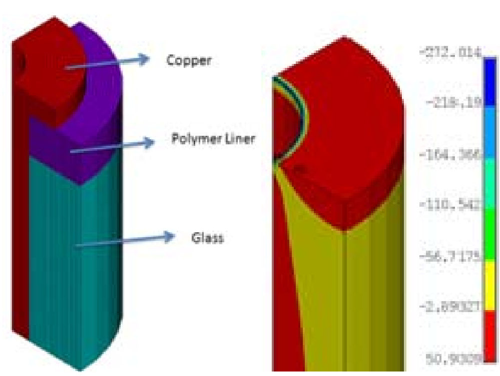


Figure 13. Bent Glass and the resulted stress

Using the formula shown in Figure 7, uniaxial tensile stress in glass during bending can be approximated as 29 MPa. This stress reflected itself as 5 cm^{-1} shift in Raman spectra as illustrated in Figure 4. Based on this measurement, piezo coefficient of sputtered CuO films can be estimated as 0.16 cm^{-1} /MPa.

B. Direct Measurement of TPV Stresses

Thermomechanical stress in TPV can be estimated using finite element modeling. Figure 14 shows the 2-D Axisymmetric model of TPVs in glass interposer.



(a)

(b)

Figure 14. (a)TPV model (b) Radial stress distribution

During thermal cycling at low temperature, copper-plated TPV contracts and creates radial tensile stress and circumferential compressive stress in the glass. At high temperature, copper of TPV tends to expand which leads to radial compressive stress and circumferential tensile stress in the glass .This phenomenon is depicted in Figure 15.

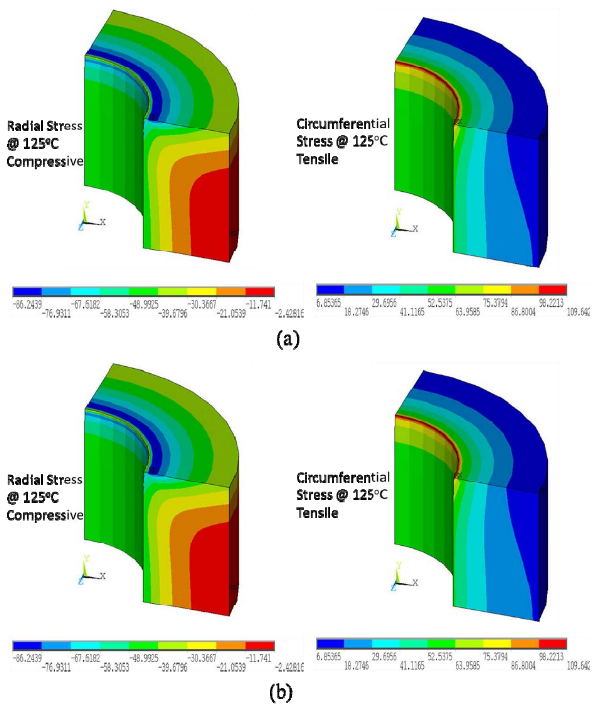


Figure 15. Stresses at (a) cold and (b) hot extremes during thermal cycling

Stress on TPV surface can be considered biaxial and it has radial and tangential components. Thus, it can be expressed as linear function of Raman peak shift. As the via diameter increases from 60 μm to 180 μm in steps of 30 μm, total principal tension on surface near via entrance almost linearly decreases from approximately 125 MPa to 45 MPa. This explains the trend of shifting to lower wavenumber with decreasing via diameter which was illustrated in Figure 11.

Using the piezo coefficient of CuO and Raman spectra from Figure 11, the hydrostatic stress on CuO surface can be roughly estimated. From Figure 11, a change of TPV diameter from 180 μm to 150 μm is associated with a 5 cm^{-1} shift, which translates into 29 MPa change in hydrostatic stress. Finite element modeling predicts a change of stress state on CuO surface approximately from 70 MPa to 45 MPa, with 25 MPa difference. As a result, there is 13% discrepancy between FEM based estimations and Raman measurement based predictions. The results from the two methods follow similar trend with change in TPV diameter, however they don't match perfectly because of possible errors in calculating the piezo coefficients, grain orientation variation in polycrystalline copper oxide, and differences between finite element model and physical TPVs.

IV. CONCLUSIONS

This study demonstrates direct stress measurements in glass substrates using Raman spectroscopy. Because glass is not Raman-active, a thin film of copper oxide, which shows distinct peak shifts, is deposited onto the top of glass surfaces. Then these glass samples were bent to a certain curvature radius which leads to a uniaxial stress on glass. This stress, which was analytically calculated, led to peak shifts in Raman spectrum. By relating the peak shifts in Raman spectrum and associated hydrostatic stress, the piezo coefficients of copper oxide are estimated. This technique is then applied to measure the stress near copper–plated through package vias in glass interposers. Finite element modeling results follow similar pattern as Raman spectrum measurements, validating the technique, despite discrepancy between measurements and simulation results. This simple and elegant technique can be effectively used to assess the stress state at various locations, thus relating to reliability of glass interposers and packages for various applications. Copper oxide films deposited on various locations of glass interposer, can act as transducers to give information about stress underneath them using Raman microscopy. This low-cost method can enable process monitoring by tracking of stresses on glass interposers during fabrication processes.

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