Effects of Copper Pattern Density and Orientation on the Modulus of BGA Substrates

Burton Carpenter Burt.Carpenter@freescale.com
Freescale Semiconductor, Inc
6501 William Cannon Drive West
Austin, TX, 78735
512-895-4421

Betty Yeung Betty.Yeung@freescale.com
Freescale Semiconductor, Inc
2100 East Elliot Road
Tempe, Arizona 85284
480-413-7734

Yuan Yuan yuan2_us@yahoo.com
Austin, TX 78729
512-336-9737

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Abstract

Substrate material properties directly impact package mechanical performance. Estimation of substrate mechanical properties based on each component layer provides maximum flexibility and better accuracy. The component materials of a BGA substrate are the fiberglass-reinforced epoxy layers, copper and soldermask. Even when the material properties (modulus and CTE) of each component are known, the behavior of the final substrate is not easily determined because factors such as copper density and pattern have significant effects. For example, the copper pattern may be oriented such that conductor traces run in one direction for a considerable length. The modulus in the direction parallel to the traces will be different from the modulus in the direction perpendicular to the traces. Package mechanical simulations typically do not mesh the details of the copper patterns, but rather average within each layer, thus neglecting the orientation effects. Therefore FEM (Finite Element Model) simulations may yield inaccurate stress and warpage results.

This study utilized a test vehicle (TV) to study the copper pattern density and orientation effect on substrate modulus. Each TV sample was a two-metal-layer copper-clad laminate designed with one of eight simple geometric patterns. One set of patterns had Cu traces running parallel in one direction, with varied metal densities of 0%, 25%, 50%, 75% and 100% respectively. Measurements were made both parallel and perpendicular to the trace orientation. Also studied were a pattern of holes (continuous metal plane with unconnected holes) and a dot pattern (unconnected circular metal pads).

Substrate flexural modulus measurements were made using two types of instruments: DMA and Instron. Data was collected from -65 to 260°C. FEM simulations which meshed the details of copper patterns were used to calculate the overall substrate modulus. These correlated better with the empirical data than simulations utilizing traditional layer averaging.

The copper pattern had significant effects; the substrate modulus was always much lower in the direction perpendicular to the traces than the modulus in the direction parallel to the traces. The amount varied depending on temperature, but could be as high as 35%. When measured parallel to the copper traces, the substrate modulus was observed to increase with copper pattern density as predicted by theoretical mixture rules. However, the substrate modulus in the direction perpendicular to the traces was not easily predicted theoretically. Therefore, more sophisticated averaging techniques and simulations are needed.

Key words

Elastic Modulus, Flex Modulus, Homogenization Rules, Metal Density, Metal Pattern, Substrate

I. Introduction

Warpage of BGA (Ball Grid Array) packages needs to be understood and controlled to prevent field issues such as open solder joints during board assembly. Additionally, the associated stresses can drive failures in the solder joints or internally in the package. These mechanical behaviors are primarily driven by three materials: the epoxy mold compound, the Si die, and the substrate. An example of an organic BGA package is shown schematically in Fig. 1a. The CTE (Coefficient of Thermal Expansion) difference

between the mold compound and substrate results in warpage as the package temperature changes. Furthermore, the elastic modulus affects warpage and the amount of stress generated.

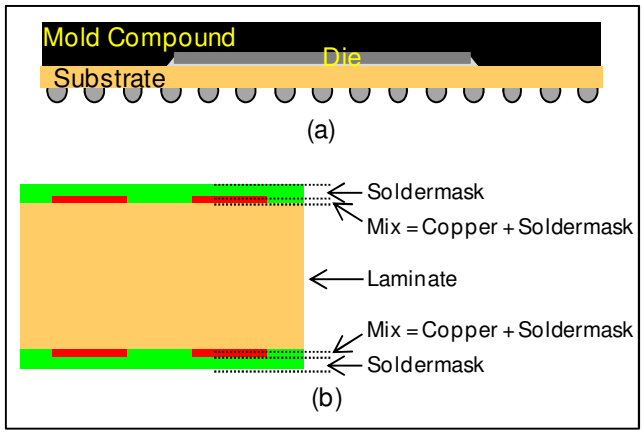


Fig. 1. (a) Schematic of a BGA package. (b) Schematic of a two-metal-layer substrate showing layers of soldermask, mixed Cu and soldermask, and laminate.

FEM (finite element method) simulations are routinely employed to estimate the stress and deformation (warpage) of new designs and/or packages. Since package geometries are often complex, simplifications are used. Little error is introduced treating both the mold compound and die as homogenous materials. However, the substrate is distinctly inhomogeneous. There are three simplification approaches: 1) treat the entire substrate as a homogeneous material with appropriately averaged (or "homogenized") CTE and modulus, 2) treat the substrate as a layered structure, each layer with known or homogenized properties, or 3) minimal simplification to design details such as copper metal patterns which requires meshing of very complex trace patterns. While the first approach is simplest, the FEM model behavior may differ significantly from the actual package due to material variations across the substrate. On the other hand, the third approach greatly increases the model computational requirements and is generally not practical for large packages and/or packages with fine metal pattern details. The second approach is therefore preferred. One important technique in approach 2 is the homogenization method for "mixed" layers, such as the copper/soldermask layers seen in Fig. 1b.

To understand the mixed layer effects on the substrate modulus, flex modulus measurements were made on simple test geometries with metal density varied from 0% to 100%, including some measurements parallel to and perpendicular to the bending axis. FEM models were created that exactly matched the metal configurations of the samples. In addition, classic mixture theory calculations were compared to the measurement data and FEM simulation results.

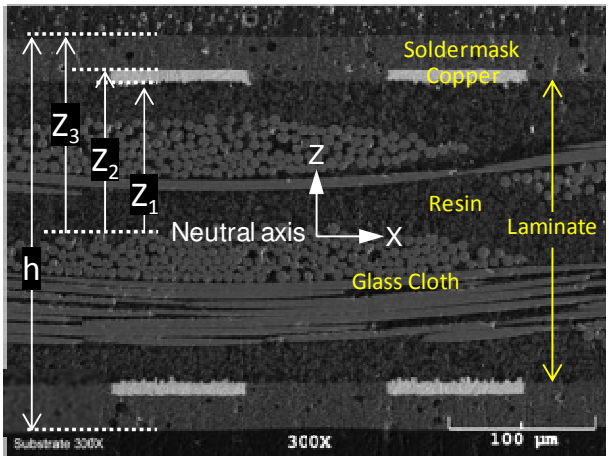


Fig. 2. Substrate cross section depicting the distance from the bending neutral surface to the outside of each layer.

II. Theory and Approach

Fig. 1b shows that the substrate is comprised of layers of various materials. Warpage in the substrate depends on flex modulus, not the averaged tensile modulus, and these are not equivalent for non-homogenous materials. The classic equation for the flex modulus of a stack of layers is (1) [3], which assumes a symmetrical stack, the layers being defined from the neutral axis as shown in Fig. 2. Equation (1) shows that the substrate equivalent flex modulus depends on the thickness and *order in the stack* for each layer. Also, considering that the mechanical bending forces in a BGA package are transferred layer by layer, creating FEM models with a layered structure provides maximum flexibility and greatest accuracy.

$$E_f = \frac{8}{h^3}\sum_{j=1}^{N/2} E_j\left(z_j^3 - z_{j-1}^3\right) \quad (1)$$

Where:

E_f = Effective flexural modulus of the stack
h = Thickness of entire stack
E_j = Young's modulus of j^{th} layer along the x direction
z_j = distance from the neutral plane to the outside of the j^{th} layer (reference Fig. 2)
N = total number of layers

One key assumption of (1) is that the material properties are constant and known within each layer. In reality, substrate laminate cores comprise resin and glass cloth. Using multi-ply glass cloth (made with two or more glass cloth sheets as shown in Fig. 2) can reduce structural variation sufficiently to allow the core to be treated as a single homogenous layer and reduces micro structural defects in the core [1]. The copper metal patterned layers are the real challenge. They contain two very different materials (Cu and soldermask in this case) patterned for the purposes of electrical connectivity and performance and not for mechanical uniformity. For example, region 3 in Fig. 3 has

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less metal and thus lower modulus than either regions 1 or 2. Additionally, metal traces normally run in parallel for considerable length, causing directional differences: the X-direction modulus of region 2 is greater than that of region 1. The problem then arises as to the appropriate modulus value to use for this layer (E_2 in equation (1)). If the differences resulting from density or pattern are small, then a single homogenized modulus value can be used.

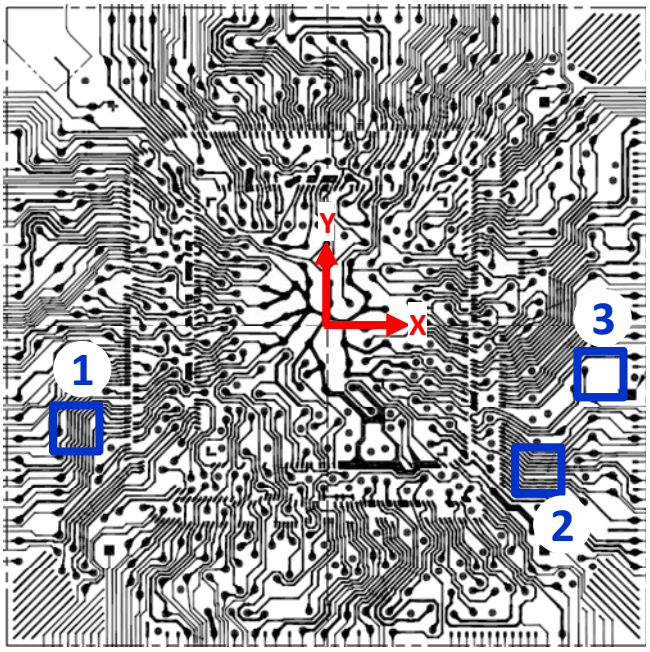


Fig. 3. Example of a typical substrate top-metal design highlighting three different regions.

Fig. 4 shows the set of test designs devised to understand these differences. These were two-metal-layer copper-clad laminate substrates designed with eight simple geometric patterns. In all cases, the top and bottom metal matched exactly. Patterns 2, 3 and 4 had Cu traces running parallel in one direction on 200µm pitch. For example, the 75% pattern consisted of 150µm wide traces with 50µm spaces in between. Patterns 1 and 5 were extremes with no metal and a solid copper plane, respectively. Collectively patterns 1-5 were used to study the density effect. Pattern 6 was identical to pattern 3 except the traces were oriented perpendicular to the bending axis. Patterns 7 and 8 were designed to have 50% metal density, but with circular features. Note that the metal was continuous in pattern 8 (holes), but discontinues in pattern 7 (pads).

Classical mixture theory can be applied to patterns 1-6 to estimate the layer modulus E_2, and thus the overall substrate flex modulus. Equation (2) applies when traces are parallel to the stress direction, such as patterns 2-4. The modulus of pattern 6 can be estimated by (3) when traces are perpendicular to the stress direction (the two materials are in series with the applied stress).

$$E_{M\parallel} = \nu_C E_C + \nu_S E_S \quad (2)$$

$$E_{M\perp} = [\nu_C/E_C + \nu_S/E_S]^{-1} \quad (3)$$

Where:

$E_{M\parallel}$ = Modulus of mix layer with both materials in parallel to the stress direction

$E_{M\perp}$ = Modulus of mix layer with both materials in series to the stress direction

ν_c = Young's modulus of copper in mix layer

ν_s = Volume fraction of soldermask in mix layer

E_c = Young's modulus of copper in mix layer

E_s = Volume fraction of soldermask in mix layer

#	Name	Details	Schematic
1	NON	Metal Density = 0% No Metal	
2	X25	Metal Density = 25% 50um Line/150um Space	
3	X50	Metal Density = 50% 100um Line/Space	
4	X75	Metal Density = 75% 150um Line/50um Space	
5	SOL	Metal Density = 100% Solid Metal Planes	
6	Y50	Metal Density = 50% 100um Line/Space	
7	CIR	Metal Density = 50% 148.5um diameter pads Hexagonal 200um pitch	
8	HOL	Metal Density = 50% 148.5um diameter holes Hexagonal 200um pitch	

Fig. 4. Description and naming of test patterns.

III. Experimental

A. Test Vehicle Design

The eight test patterns of Fig. 4 were fabricated into two-metal-layer organic substrates using Hitachi Chemical E679FGB laminate and Taiyo Ink AUS308 soldermask. 12µm copper foil was laminated on both sides of the laminate, and then patterned by etching. Elastic moduli of these materials are shown in Table 1. Moduli of the soldermask were taken from DMA measurements provided by the manufacturer. DMA measurements were made on bare laminate at the same time as these test samples. Copper foil samples were separately measured to obtain

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those values in Table 1. Note that the room-temperature Young's modulus of copper was measured as 80GPa, considerably lower than the 120GPa typically reported for bulk copper. The reasons for this difference were not investigated here, but the literature reports that copper modulus can vary from 30-120 GPa depending on grain size, grain orientation and annealing conditions [5][6].

TABLE 1. MODULUS (GPA) OF SUBSTRATE MATERIALS
Measured (black), interpolated or extrapolated (red)

Material	-65°C	-45°C	25°C	125°C	150°C	175°C	200°C	225°C	260°C
Soldermask	6.2	5.8	4.2	0.3	0.1	0.1	0.1	0.1	0.1
Copper	88.5	86.6	80.1	70.4	67.9	64.3	60.6	57.0	51.9
Laminate	23.6	23.3	21.7	19.2	18.3	16.9	14.6	11.0	9.3

Layer thicknesses were measured by optical toolmakers microscope on cross sections with the average values reported in Tables 2 and 3. Since pattern 1 had no metal, the overall thickness was less than the other samples. The metal feature sizes were measured by optical toolmakers microscope from a top view of identical samples without soldermask. Due to etching variations during fabrication, some of the patterns did not exactly match the design targets. The resultant actual metal densities are reported in Table 4, and were used for all calculations and analyses. The samples were manufactured in matrix form, and then sawn into 38.3mm x 3.9mm specimens for the DMA and Instron measurements. Three of the actual etched metal patterns are shown in Fig 5.

TABLE 2. AVERAGE LAYER THICKNESSES OF TEST VEHICLE PATTERNS 2-8 (MICRONS)

j	Layer	Thickness	Z_j
1	Laminate	215	108
2	Mix Cu/SM	11	119
3	Soldermask	25	143
Total		287	N/A

TABLE 3. AVERAGE LAYER THICKNESSES OF TEST VEHICLE PATTERN 1 (MICRONS)

j	Layer	Thickness	Z_j
1	Laminate	215	108
2	Soldermask	25	132
Total		265	N/A

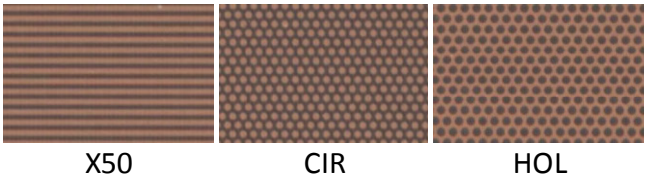


Fig. 5. Optical photographs of three of the metal patterns.

B. Instron Flex Test Procedure

Bulk flexural modulus measurements were performed at room temperature on the Instron Mechanical Test System by means of three-point bending. A support span of 15mm was used, with loading conducted at 2mm/min. Two samples were tested for each metal pattern. A typical load-deflection curve output during testing is shown in Fig. 6. Machine compliance is accounted for to derive accurate deflection values for modulus calculation.

Modulus determination was based upon ASTM D790 [4] per the following relation:

$$E_B = L^3 m / 4bd^3 \quad (4)$$

Where:
E_B = modulus of elasticity in bending
L = support span
b = width of beam tested
d = depth of beam tested
m = slope of the tangent to the initial straight-line portion of the load-deflection curve

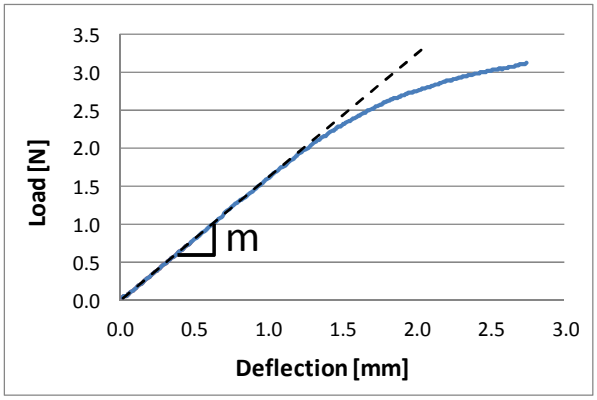


Fig. 6. Typical load-deflection curve generated from the Instron flex testing.

C. DMA Test Procedure

A TA Instruments DMA Q800 was used to measure dynamic flexural modulus. The measurement length was defined by the 15mm test fixture span. The temperature was ramped from -65°C to 260°C at 3°C/min at a fixed frequency of 1Hz. Fig. 7 is a typical output plot, from which the elastic (storage) modulus was tabulated at specific temperatures. Two samples were measured for each pattern, and the averaged value are reported.

IV. FEM Simulations and Classical Calculations

The regular trace patterns shown in Fig. 4 made it possible to perform FEM simulation of the various TV samples with *actual* trace details. Fig. 8a shows FEM meshing of a sample cross section, and Fig. 8b shows meshing of a trace pattern. FEM simulation with detailed trace patterns are called *FEM Exact* in Table 4. By comparison, *FEM Smeared* simulation used (2) to estimate the modulus of the copper/soldermask mix layers. When homogenized in this way, no efforts are made to distinguish the X50 and Y50

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patterns. The FEM simulations applied a static three-point bending load to emulate the experimental condition, allowing the calculation of an equivalent flex modulus. *Classic* flex modulus calculations were also done using (1), the mix layer modulus E_2 calculated by either (2) or (3).

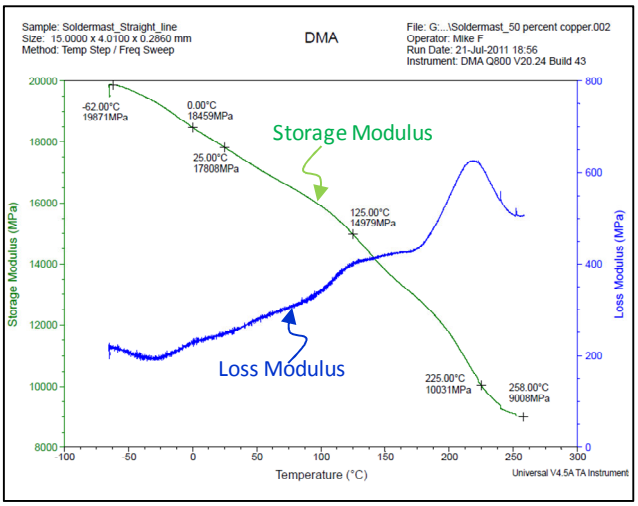


Fig. 7. DMA graph of storage modulus versus temperature from first run of sample X75.

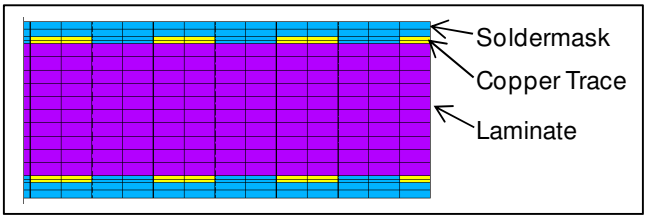


Fig. 8a. Partial end view of FEM model for pattern X50 containing 50% Cu.

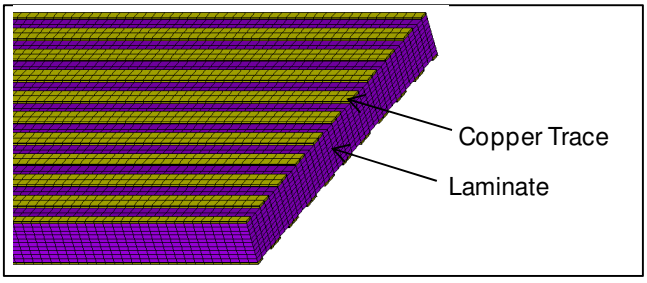


Fig. 8b. Top view of FEM model for pattern X50 containing 50% Cu; soldermask not shown.

V. Results

Five methods were used to measure or estimate the flex modulus for each of the substrates made from the eight test patterns. The room-temperature data is summarized in Table 4, where (2) was used for the classic theory predictions for all patterns except pattern Y50. Since Y50 is expected to behave according to (3), both are shown in the table.

TABLE 4. FLEXURAL MODULUS VALUES (GPA) AT 25°C FOR SAMPLES WITH SOLDERMASK.

Sample		Measurements		Predictions		
Actual % Cu	Pattern	DMA	Instron	Classic	FEM-Smear	FEM-Exact
0%	NON	13.3	13.9	13.6	13.6	13.6
33%	X25	15.3	14.7	15.2	15.7	15.2
50%	X50	17.1	16.8	17.1	17.6	17.1
75%	X75	21.8	19.6	19.8	20.4	19.8
100%	SOL	22.7	21.2	22.6	22.5	22.5
50%	Y50	14.1	14.4	17.1/12.1	17.6	14.5
36%	CIR	13.8	13.9	15.5	16.1	14.0
50%	HOL	15.7	15.5	17.1	17.7	16.6

There is excellent agreement between the exact FEM simulation method, and the DMA and Instron empirical data. This holds across the entire temperature range as shown in Fig. 9. The deviation between measurement methods averaged 2%, and 10% at the largest. The average deviation between any measurement and the exact FEM simulation was 2%; the largest was 10% at room temperature, 22% across all temperatures. The deviations were greatest at the higher temperatures for higher metal content patterns. This was likely due to extrapolation errors for the copper modulus values used in the simulations.

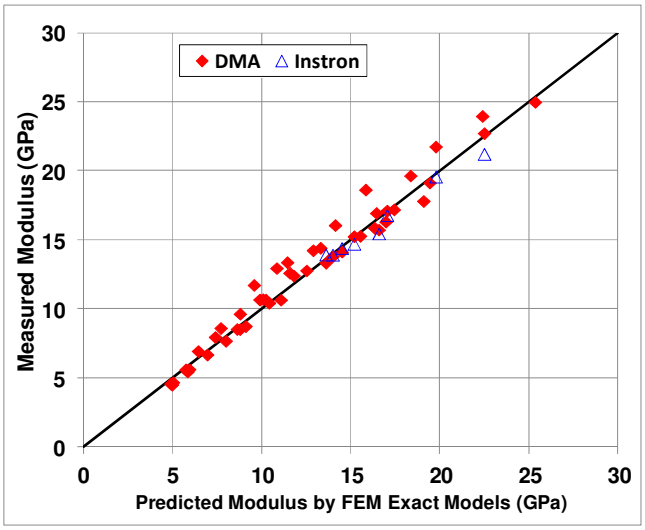


Fig. 9. Comparison of measured and simulated flex modulus for all temperatures studied.

From Table 4 it is clear that trace pattern affects modulus. For the same 50% copper the X50 modulus is larger than the one for HOL; the HOL modulus is larger than that for Y50.

The data from Table 4 has been plotted in Fig. 10. The measurement data is plotted as points, the estimated values as lines. The experimental data from patterns 1-5 (the patterns where (2) should apply) are shown as solid squares. Patterns 6-8 have different symbols. The blue "Classic (Parallel)" line is calculated from (1) with E_2 determined by

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(2). Likewise, the black "Classic (Series)" line uses (3) to determine E_2. In both cases the substrate overall thickness was assumed constant; since the NON pattern test sample was thinner than the others, the measured thickness deviates from the theoretical line. The fuchsia "FEM (Parallel)" line is the exact FEM simulation results for patterns 1-5. This simulation used the actual sample thickness for each calculation, thus matching experimental results for the NON pattern. Note that the exact FEM and classic theory lines are identical when using the same sample thickness (all cases except NON).

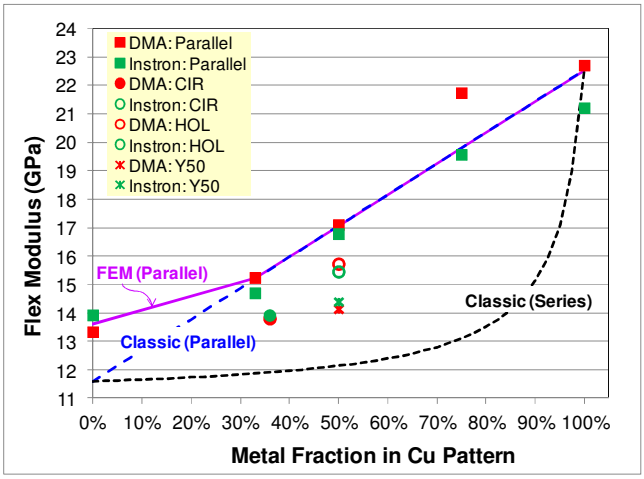


Fig. 10. Flex modulus at room temperatures plotted versus copper metal content.

The moduli of patterns 6-8 are lower than those of patterns 1-5 for equivalent metal content as observed by both measurement and simulation. This was expected since the metal can carry the most load when it is completely oriented parallel to the direction of stress. The room-temperature modulus of Y50 (the opposite of X50, when there is no metal in parallel to the stress) was 2.6GPa (15%) lower than X50. The difference was 35% at 260°C. This demonstrates the degree of error induced by ignoring trace orientation effects. However, Fig. 10 shows that the modulus of Y50 is still considerably greater than that estimated by using (3) in the theoretical calculation. This trend held across all the temperatures examined.

VI. Conclusion

A test vehicle with eight different simple geometric patterns was used to study the influence of copper metal density and pattern on the flex modulus of organic substrates. Two sets of measurements were done (DMA and Instron bend testing), and three sets of estimates were done, including FEM simulations using exact geometry models, FEM simulations with averaged or "smeared" modulus values for the copper/soldermask layers, and calculations from classic bending theory using idealized mixture rules for the copper/soldermask layers. The conclusions are:

1. Measurements using either DMA or Instron produced the same results.
2. Meshing exact geometries of the Cu pattern in the FEM models gave results matching empirical data.
3. For metal patterns aligned parallel to the primary bending axis, measurement, exact geometry FEM simulation, and classic theory calculation agree.
4. For metal patterns aligned perpendicular to the primary bending axis (the two materials in series with the stress), and other discontinuous metal patterns, the exact geometry FEM simulation accurately predicted the modulus, but using a simple series mixing rule underestimated the modulus.
5. Simulations using a single averaged or "smeared' modulus value for the copper/soldermask layer overpredicted the modulus for the traces in series to the stress, or for discontinuous patterns.

In summary, the deviations by ignoring metal pattern and orientation can be large, as high as 35% of the substrate flex modulus, and cannot be ignored for warpage simulations. The traditional methods of using a single value for the mix layers will therefore not accurately predict the overall package warpage, and will fail to identify local variations within the package. Improved mixture rules therefore need to be identified and will be the subject of further investigation.

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