Analytical thermal stress modeling in physical design for reliability of micro and opto electronic systems : Role, attributes, challenges, results

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ANALYTICAL THERMAL STRESS MODELING IN PHYSICAL DESIGN FOR RELIABILITY OF MICRO- AND OPTO-ELECTRONIC SYSTEMS: *ROLE, ATTRIBUTES, CHALLENGES, RESULTS*

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"Mathematical formulas have their own life, they are smarter than we, even smarter than their authors, and provide more than what has been put into them"
Heinrich Hertz, German Physicist

"If my theory is in conflict with the experiment, I pity the experiment",
Friedrich Hegel, German Philisopher

"A formula longer than three inches is most likely wrong"
Unknown Reliability Engineer

ABSTRACT

Some basic thermal stress and thermal stress related reliability problems in microelectronics (ME) and optoelectronics (OE) are addressed. The emphasis is on analytical ("mathematical") stress modeling and design for reliability. The review is based primarily on the author's research conducted during his eighteen-year tenure with Bell Laboratories, Basic Research, Physical Sciences and Engineering Research Division, as well as on his recent research, based on government contracts.

THERMAL LOADING AND THERMAL STRESS FAILURES

Various areas of engineering differ, from the Structural Analysis and Structural Reliability point of view, by the employed materials, typical structures used, and the nature of the applied loads. The most typical ME and OE structures are bodies made of a large variety of dissimilar materials. The most typical loads are thermal loads. These are caused by CTE mismatch and/or by temperature gradients [1-8].

Thermal loading takes place during the normal operation of the system, as well as during its fabrication, testing, or storage. Thermal stresses, strains and displacements are the major contributor to the finite service life and elevated failure rate of ME and OE equipment. Examples are ductile rupture, brittle fracture, thermal fatigue, creep, excessive deformation or displacement, stress relaxation (that might lead to excessive displacements), thermal shock, stress corrosion.

Elevated thermal stresses and strains can lead not only to structural ("physical") failure, but also to functional (electrical or optical) failure. If the heat, produced by the chip, cannot readily escape, then the high thermal stress in the IC can result in failure of the p-n junction [9]. Low temperature microbending (buckling of the glass fiber within the low modulus primary coating) in dual-coated optical fibers, although might be too small to lead to appreciable bending stresses and delayed fracture ("static fatigue"), can result in appreciable added transmission losses. Loss in optical coupling efficiency can occur, when the displacement in the lateral (often less than 0.2 micrometers) or angular (often less than a split of one percent of a degree) misalignment in the gap between two light-guides or between a light source and a light-guide becomes too large, because of thermally induced deformations or because of thermal stress relaxation in a laser weld. Small lateral or angular displacements in MEMS-based photonic systems (such as, say, some types of tunable lasers) can lead to a complete optical failure of the device. Tiny temperature-change-induced changes in the distance between Bragg gratings "written" on an optical fiber can be detrimental to its functional performance. For this reason thermal control of the ambient temperature is often needed to ensure sufficient protection provided to an optical device, whose performance is sensitive to the change in temperature.

As a matter of fact, the requirements for the mechanical behavior of the materials and structures in OE are often based on the functional (optical) performance of the device/system, rather than on its mechanical (structural) reliability. The requirements for the structural reliability might be much less stringent.

The thermally induced stresses and displacements in ME and OE systems can be linearly or nonlinearly elastic (reversible) or plastic (residual, irreversible), or can be caused by time dependent effects, such as creep, stress

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relaxation, visco-elastic or visco-plastic phenomena, aging, etc.

The ability to understand the sourses of the thermal stresses and strains in ME and OE structures is of significant practical importance, and so is the ability to predict/model/simulate and possibly minimize, if necessary, the induced stresses and displacements.

THERMAL STRESS MODELING

Thermally induced failures in ME and OE equipment can be prevented only if predictive modeling is consistently used in addition (and, desirably, prior) to experimental investigations and reliability testing [10-11]. Such testing could be carried out on the design (product development) stage, during qualification and manufacturing of the product (qualification testing), or during accelerated or highly accelerated life testing (ALT and HALT).

Accelerated testing, which is the major experimental approach in ME and OE, cannot do without simple and meaningful predictive models. It is on the basis of these models that a reliability engineer decides which parameter should be accelerated, how to process/interpret the experimental data and how to bridge the gap between what one "sees" as a result of accelerated testing and what he/she will supposedly "get" in the actual use condition.

Modeling is the basic approach of any science, whether "pure" or applied [12]. Research and engineering models can be experimental or theoretical. Experimental models are typically of the same physical nature as the actual phenomenon or the object. Theoretical models represent real phenomena and objects by using abstract notions. Such models typically employ more or less sophisticated mathematical methods of analysis, and can be either analytical ("mathematical") or numerical (computational). The today's numerical models are, as a rule, computer-aided, and finite-element analyses (FEA) are widely used in the stress-strain evaluations and physical design of ME and OE structures [13]. Experimental and theoretical models should be viewed, of course, as equally important and indispensable tools for the design of a viable, reliable and cost-effective product [10, 11,14,15].

BI-METAL THERMOSTATS AND OTHER BI-MATERIAL ASSEMBLIES

Pioneering work in modeling of thermal stress in bodies comprised of dissimilar materials was carried out by Timoshenko [16] and Aleck [17]. Timoshenko based his treatment of the problem on a structural analysis (strength-of-materials) approach. Aleck applied theory-of-elasticity method. Both approaches were later extended in application to structures employed in various fields of engineering, including ME and OE [19-45]. Chen and Nelson [18], Chang [19], Suhir [20-22] used structural analysis approach, although the interfacial compliance introduced by Suhir was evaluated based on a theory-of-elasticity method [20, 21]. Zeyfang [23], Eischen et al [24], Kuo [25], Yamada [26] and others used the theory-of-elasticity treatment of the problem.

The application of the structural analysis approach [27] enables one to determine, often with sufficient accuracy and always with extraordinary simplicity, the stresses acting in the constituent materials, as well as the interfacial shearing and through-thickness ("peeling") stresses. This approach results in closed form solutions and in easy-to-use formulas (see, for instance [20]). It can be (and, actually, has been) effectively employed as a part of the physical design process to select the appropriate materials, establish the feasible dimensions of the structural elements, compare different designs from the standpoint of the induced stresses and deformations, etc. On the other hand, the theory-of-elasticity method is based on rather general hypotheses and equations, and provides a rigorous treatment of the problem. Typically, it requires, however, additional use of computers to obtain the final solution to the given problem. The theory-of-elasticity approach is advisable, when there is a need for the most accurate evaluation of the induced stresses. Applied within the framework of linear elasticity, this approach leads, in the majority of cases, to a singularity at the assembly edges or at the corner of a structural element. For this reason its application has been found particularly useful when there is intent to further proceed with fracture analysis of interfacial delaminations, crack initiation and propagation at the corners, etc.

The structural analysis (strength-of-materials) and theory-of-elasticity approaches should not be viewed, of course, as "competitors", but rather as different tools, which have their merits and shortcomings, and their areas of application. These two analytical approaches should complement each other in any comprehensive engineering analysis and physical design effort.

FINITE-ELEMENT ANALYSIS

Finite-element analysis (FEA) has become, since the mid-1950s, the major resourse for computational modeling in engineering, including the area of ME and OE (see, for instance, Lau, [28], Glaser [29], Akay and Tong [30]). The today's powerful and flexible FEA computer programs enable one to obtain, within a reasonable time, a solution to almost any stress-strain-related problem.

Broad application of computers has, however, by no means, made analytical solutions unnecessary or even less important, whether exact, approximate, or asymptotic.

Simple analytical relationships have invaluable advantages, because of the clarity and "compactness" of the obtained information and clear indication of the role of various factors affecting the given phenomenon or the behavior of the given system. These advantages are especially significant when the parameter under investigation depends on more than one variable. As to the asymptotic techniques and formulas, analytical modeling can be successful in those cases, in which there are difficulties in the application of computational methods, e.g., in problems containing singularities.

But, even when application of numerical methods encounters no significant difficulties, it is always advisable to investigate the problem analytically before carrying out computer-aided analyses. Such a preliminary investigation helps to reduce computer time and expense, develop the most feasible and effective preprocessing model and, in many cases, avoid fundamental errors. Those that have a hands-on experience in using FEA, know very well that it is easy to obtain *a* solution based on the FEA software, but it might be not that easy to obtain *the* right solution.

Preliminary analytical modeling can be very helpful in creating a meaningful and economic preprocessing simulation model. This is particularly true in OE and photonics, where high accuracy is usually required. Special attention should be paid and special effort should be taken to make the existing FEA programs accurate enough to be suitable for the evaluation of the tiny thermo-mechanical displacements in an OE or a photonic system. Another challenge has to do with the necessity to consider visco-elastic and time-dependent behavior of photonic materials, so that the long-term reliability of the device is not compromised.

It is noteworthy that FEA was originally developed for structures with complicated geometry and/or with complicated boundary conditions, when it might be difficult to apply analytical approaches. Consequently, FEA is especially widely used in those areas of engineering, in which structures of complex configuration are typical: aerospace, marine and offshore structures, some complicated civil engineering structures, etc. In contrast, a relatively simple geometry and simple configurations usually characterize ME and OE assemblies and structures. Owing to that, such structures can be easily idealized as beams, flexible rods, circular or rectangular plates, frames, or composite structures of relatively simple geometry, thereby lending themselves to analytical modeling.

DIE-SUBSTRATE AND OTHER BI-MATERIAL ASSEMBLIES

The mechanical behavior of bonded bi-material assemblies, and particularly die-substrate assemblies, was addressed in numerous studies [31-40]. Typical failure modes in die-substrate assemblies are [31]:

1) adherend (die or substrate) failure: a silicon die can fracture in its midportion or at its corner located at the interface;
2) cohesive failure of the bonding material (i.e., failure of the die-attach material); and
3) adhesive failure of the bonding material (i.e., failure at the adherend/adhesive interface).

An adhesive failure is not expected to occur in a properly fabricated joint. If such a failure takes place, it usually occurs at a very low load level, at the product development stage, and should be regarded as a manufacturing or a quality control problem, rather than a material's or structural one.

A crack on the upper ("free") surface of the die is due to the normal stress acting in the die cross-sections. This stress is more or less uniformly distributed throughout the die and drops to zero at its ends. The crack at the die's corner at its interface with the substrate should be attributed to the interfacial (shearing and "peeling") stresses. These stresses concentrate, for sufficiently long assemblies with stiff enough interfaces, at the assembly ends and are next-to-zero in its midportion.

Measures that could be taken to bring the induced stresses down depend on the type/category of the stress responsible for the particular failure mode. In the case of a crack in the midportion of the die, it is the improved thermal match between the die and the substrate materials and/or a lower bow of the assembly that can improve the situation. In the case of a crack at the die's corner, the employment of a thicker and/or lower modulus adhesive can be helpful.

Die-substrate assemblies, as well as many other bi-material assemblies, are characterized by a substantial thermal expansion (contraction) mismatch of the adherends (silicon and the substrate) materials, as well as by thin and low modulus adhesive (die-attach) layers, compared to the thickness and Young's moduli of the adherends. Such a situation results in the fact that the attachment (die-attach) material experiences shear only, and also in the fact that only the interfacial compliance of the adhesive (die-attach) layer, and not its coefficient of expansion, is important [20]. It has been shown also [20, 22, 31] that thermally induced elastic stresses in sufficiently large bi-material assemblies do not increase with a further increase in the assembly size, and that a substantial relief in the interfacial stresses can be achieved by using thick and low modulus adhesives. This can result also in an improved adhesive and cohesive strength of the adhesive (die-attach) material, and reduce the likelihood of occurrence of the brittle crack at the chip's corner.

In the case of small-size assemblies (e.g., those with chips, not exceeding, say, 5mm), thick and low modulus adhesives can lead to the decrease in the stress in the chip itself as well. For large chips, however (larger than, say, 10mm), other measures should be taken, if there is a need to bring down the stresses in the midportion of the die: a substrate material with a better match with silicon should be used; a die-attach material with a lower curing temperature (and/or lower glass transition temperature) could be employed; application of a flexible substrate could be considered, etc.

As to the thermal stress modeling in bi-material assemblies, it has been found [32] that the approach, previously used in application to a thin film structure [33], can be successfully employed to further simplify thermal stress prediction in a bi-material assembly as well. This approach suggests that the interfacial shearing stress can be evaluated using an assumption that this stress is not affected by (not coupled with) the "peeling" stress. Such an assumption is conservative, i.e., results in a reasonable overestimation of the maximum shearing stress compared to the stress level obtained from the coupled equations [21]. After the shearing stress function is determined, the "peeling" stress can be computed from an equation that is similar to the equation of bending of a beam lying on a continuous elastic foundation [27].

The developed models were applied to many problems in ME and OE and beyond. The model suggested in [20] was applied by Hall et al. [34] and other researchers [35] to tri-material assemblies. An assembly should be treated as a tri-material one (as opposite to an adhesively bonded assembly), if the adhesive layer in it is not thin and/or if its Young's modulus is not significantly lower than the Young's modulus of the adherend materials. In such a situation the CTE of the bonding material has to be accounted for. An analytical model for a tri-material assembly, in which all the materials are treated as "equal constituents/members" of the assembly, i.e., in which the geometries (thicknesses) of all the assembly components and material's properties (elastic constants and CTEs) of all the materials are important, was developed in [36].

Luryi and Suhir [33] applied the model developed in [20] to the case of semiconductor crystal growth. They suggested a new approach to the high quality (dislocation free) epitaxial growth of lattice-mismatched materials. The authors have shown that lattice-mismatch strain can be simply added to the thermal-mismatch strain and, owing to that, can be easily and naturally incorporated into stress analysis models developed earlier for thermally induced strains. This paper has triggered a substantial experimental effort (more than hundred citations of it could be found in the literature) and is still widely referenced in the physical literature (see, for instance, [38]).

Suhir and Sullivan [39] have developed an axisymmetric version of the model suggested in [20] and applied it for the evaluation of the adhesive strength of epoxy molding compounds used in plastic packaging of IC devices.

Suhir [22] and Cifuentes [40] addressed plastic and elastoplastic deformations in the solder layer and in the beams experiencing thermal loading.

SOLDER JOINTS

Numerous models have been developed for the evaluation of thermal stresses in, and prediction of the lifetime of, solders joint interconnections (see, for instance, [41-46]). Typically, the stresses in the solder joints are caused by the thermal expansion (contraction) mismatch of the chip and the substrate materials, or, in assemblies of ball-grid-array (BGA) type, by the mismatch of the package structure and the PCB (system's substrate).

The majority of the suggested models are based on the prediction and improving of the solder joint fatigue, which is caused by the accumulated cyclic strain in the solder material. This strain is due to the temperature fluctuations resulting from either the changes in the ambient temperature (temperature cycling) or from heat dissipation from in the package (power cycling). Various (viscoplastic) models for the prediction of the fatigue life-time of the solder material were suggested by Akay et Tong [30], Morgan [41], Hwang [42], Ianuzzelli, Pittaresi and Prakash [43] and many others.

The ultimate strength of solder joint interconnections is typically measured by using shear-off tests. A new, "twist-off", technique for testing of solder joint interconnections was suggested in [44]. It unables one to mimic best the actual state of stress of such interconnections. The technique was developed in application to flip-chip (FC) and ball-grid-array (BGA) assemblies.

One effective way to bring down the thermal stresses in solder joints is by employing a flex circuit [45-46]. The developed models can be used to assess the incentive in the application of such circuits, as well as the expected stress relief. Juskey and Carson [47] suggested that flex circuits be used as carriers for the direct chip attachment (DCA) technology. Flex circuitry offers a low cost and reliable system with a low thermal stress level. The flexible material of choice for today's manufacturing environment is polyamide. This material is able to withstand high temperatures during reflow soldering, and possesses good electrical and mechanical characteristics.

Solder materials and solder joints are as important in photonics, as they are in microelectronics. There are, however, a number of specific requirements for the photonics solder materials and joints: ability to achieve high alignment, requirement for a low creep, etc. [48]. "Hard" (high modulus) solder materials (such as, say, gold-tin eutectics) are thought to have better creep characteristics than "soft" (such as, say, silver-tin) solders. It should be pointed out, however, that "hard" solders can result in significantly higher thermally induced stresses than "soft" solders [49], and therefore their ability to withstand creep might be not as good as expected, not to mention the short-term reliability of the material.

Thermally induced stresses in optical fibers soldered into different ferrules were modeled in [49]. Modeling was based on the solution to the axisymmetric theory-of-elasticity problem for an annular composite structure comprised of the metallized silica fiber, the solder ring, and the ferrule. The obtained relationships enable one to design the joint in such a way that the solder ring is subjected to relatively low compressive stresses. It has been shown that neither low expansion ferrules, nor high expansion ones, might be suitable for a particular solder material and thickness of the solder ring.

Solders are often used as continuous attachment layers in electronic and photonics assemblies. Stress concentration at the ends of such attachments can lead to plastic deformations of the solder material. These deformations were addressed by Suhir [22] and Cifuentes [40]. This problem has become recently of significant importance in connection of using Indium as a suitable attachment of the quantum wells of GaAs lasers to metal substrates. The developed models enable one to assess the size of the zone, in which the plastic deformations are possible, and to assess the effect on the state of the inelastic strain in the device. The plastic stresses will not propagate inwards the assembly, if its length exceeds appreciably the total length of the areas occupied by the elevated stresses. This consideration provides a practically useful criterion for the selection of the length of the continuous solder layer in the application in question.

DESIGN RECOMMENDATIONS

Based on the modeling of thermal stresses in typical adhesively bonded assemblies, i.e., in assemblies with appreciable CTE mismatch of the adherends and a homogeneous adhesive or solder layer, the following general recommendations, aimed at the improvement of their ultimate and fatigue strength, have been developed:

- equalize the in-plane and bending stiffness of the adherends, and use identical adherends, if possible;
- use as high an adherend in-plane stiffness as possible;
- use low modulus adhesives; as an alternative to using a low modulus adhesive throughout the joint, use such an adhesive only at the ends of the joint, i.e. in the region of high interfacial stresses, while a higher modulus adhesive is used in the midportion of the assembly;
- vary, if possible, the adherend thickness along the assembly in a proper way and/or slant the adherends edges for a thicker adhesive layer at the assembly ends;
- keep the stresses within the elastic range, if possible;
- minimize "peeling" (in the case of multimaterial and thin film structures) and axial (in the case of solder joints) stresses.

"GLOBAL" AND "LOCAL" MISMATCH AND ASSEMBLIES BONDED AT THE ENDS

In those cases when the adhesive layer is not homogeneous, or when the components are just partially bonded or soldered to each other, both "global" and "local" mismatch loading takes place [50-53]. The "local" mismatch loading is due to the mismatch of the dissimilar materials within the bonded or soldered region, while the "global" mismatch loading is caused by the mismatch in the unbonded region. Examples are: solder joint interconnections, optical glass fiber interconnect adhesively bonded or soldered at its ends into a ferrule or a capillary; optical glass fiber in a micromachined (MEMS) optical switch packaged into a dual-in-line package, etc.

The interaction of the interfacial shearing stresses caused by the "global" and "local" mismatches in a typical bi-material assembly adhesively bonded or soldered at the ends [51-53] can be qualitatively summarized as follows:

- The interfacial shearing stresses caused by the "local" mismatch are antisymmetric with respect to the mid-cross-section of the bonded area: these stresses are equal in magnitude and opposite in directions (signs).
- The "local" shearing stresses concentrate at the ends of the bonded area and, for sufficiently long bonded joints and stiff interfaces (thin and high-modulus adhesive layer) are next-to-zero in the midportion of the bonded area.
- For short-and-compliant bonded areas, the "local" shearing stresses are linearly distributed over the length of the bonded area, and their maxima at the assembly ends can be significantly lower than the maximum stresses in long-and-stiff bonded areas.
- The shearing stresses caused by the "global" mismatch act in the same direction over the entire length of the bonded joint. This direction is such, that in the inner portions of the joints (i.e., in the portions located closer to the mid-cross-section of the unbonded region), the total interfacial stress should be computed as the difference between the "local" and the "global" stress. In the outer portions of the

bonded joints, the total stress should be computed as the sum of the "local" and the "global" stress.

- In the case of short-and-compliant joints, the total stress is indeed larger than each of the stress categories. Since, however, both the "local" and the "global" stresses in short-and-compliant joints can be very low compared to the stresses in long-and-stiff assemblies, the total stress can be very low as well, despite the fact that, for the outer (peripheral) portions of the bonded joints, this stress is obtained as a sum of the "local" and the "global" stresses.
- In the case of long-and-stiff joints, the "global" stresses concentrate at the inner edges of the bonded joints and rapidly decrease with an increase in the distance of the given cross-section from these edges. In such a situation, the interaction of the "local" and "global" stresses is always favorable, i.e., at the inner edge, it results in the total stress, obtained as a difference between the "local" and the "global" stress, and, at the outer edge, is due to the "local" stress only.
- For sufficiently long-and-stiff bonded joints, the magnitude of the "global" stress at the inner end is equal to the magnitude of the maximum "local" stress, so that the total shearing stress is zero.

Although substantial relief in the total stress can be achieved by employing bonded joints with short-and-compliant attachments, this approach usually cannot be recommended, because insufficient bonded areas do not allow one to produce reliable enough joints. However, in the case of solder joint interconnections, both the favorable effect of the short-and-compliant joint and the unfavorable effect of the summation of the "local" and the "global" thermal stresses/strains at the assembly ends should be considered.

The interaction of the "local" and the "global" stresses, with consideration of the effect of the coefficient of thermal expansion (contraction) of the epoxy material itself, was studied in detail in [51] for a glass fiber interconnect whose ends are epoxy bonded into capillaries. The necessity of taking into account the CTE of the adhesive material was due to the fact that the cross-sectional area of the adhesive ring was considerably larger than the cross-sectional area of the glass fiber. Therefore the longitudinal compliance of the adhesive ring was comparable with the compliance of the fiber, although the Young's modulus of the adhesive material was substantially lower than Young's modulus of the silica material, and could not be neglected.

Understanding of the interaction of the "global" and "local" stresses is particularly important in connection with the ME and OE assemblies bonded at the ends. In some ME assemblies of the flip-chip type the solder joint stand-off is so low that it is practically impossible to bring in the underfill material underneath the chip, especially if the chip is large. On the other hand, there might be no need for that, since the underfill material works only at its peripheral portions [51, 52]. Predictive modeling of the mechanical behavior of such an assembly is crucial in order to establish the adequate width of the adhesive layer: this width should be large enough to provide sufficient strength of the assembly. The stresses in such an assembly will not be higher than in an assembly with a continuous underfill.

ASSEMBLIES WITH LOW MODULUS ADHESIVE LAYER AT THE ENDS

Interfacial shearing and peeling stresses in adhesively bonded or soldered assemblies concentrate at the assembly ends. These stresses can be reduced by employing a low modulus material at the assembly ends [54]. A similar effect can be achieved by slanting the edges of the assembly components [55], thereby increasing the thickness of the adhesive layer at the assembly ends. The interfacial stresses at the ends of polymer coated optical fibers can be reduced by using a low modulus coating at the fiber ends [56-57]. The mechanical behavior of such ME and OE structures is, in a sense, opposite to the situation that takes place in an assembly adhesively bonded at the ends. Indeed, in an assembly with a low modulus adhesive/coating at the ends, it is the midportion of the assembly that is characterized by an elevated Young's modulus of the adhesive (coating), while in the case of an assembly bonded at the ends, the of the assembly is characterized by a "low" (actually, zero) Young's modulus of the "attachment".

THERMALLY MATCHED ASSEMBLIES

There is an obvious incentive to employ thermally matched materials in ME and OE assemblies. Such an assembly is used, for instance, in a Si-on-Si flip-chip (FC) design [58-59], and in a ceramic Cerdip/Cerquad ME package design [60]. Some photonics structures (say, holographic memory assemblies) are composed of identical and, hence, thermally matched adherends and a compliant (thick and low modulus) adhesive [61-63].

There is substantial difference in the mechanical behavior of the assemblies with an appreciable mismatch in the CTE of the adherends and the behavior of thermally matched assemblies, particularly those with identical adherends. While in assemblies with an appreciable thermal mismatch of the adherends, the CTE of the adhesive material (as long as this material is thin and has a low Young modulus) does not affect the mechanical behavior of the assembly, in assemblies with identical adherends, the CTE mismatch between the adhesive and the adherends' materials is definitely important. In addition, the mechanical behavior and reliability of the adhesive material is quite different. In assemblies with mismatched adherends and thin and low modulus adhesives, the adhesive layer, when no appreciable peeling stresses arise, is subjected to pure shear, while in the case of matched assemblies (identical adherends) the adhesive layer experiences both shearing stresses at the ends and tensile (compressive) stresses in the inner portion of the assembly.

Thermal stresses in solder joints in thermally matched silicon-on-silicon flip-chip assemblies reach their maximum values at the interfaces and concentrate at the joints' corners [58-59]. The stresses, acting in the axial direction (these stresses are analogous to the "peeling" stresses in thin film structures), are the highest.

The case of identical ceramic adherends was considered in connection with choosing an adequate coefficient of thermal expansion for a solder (seal) glass in a ceramic package design [60]. It has been found that the best result can be achieved by using a probabilistic approach, in which the coefficient of thermal expansion of the solder glass is treated as a random variable. The package manufactured in accordance with the developed recommendations exhibited no failures. Based on the performed analysis, it has been concluded that in order to successfully apply a probabilistic approach (see, for instance, [64]) customers should require that vendors provide information concerning both the mean value and the standard deviation of the parameter of interest.

Several thermoeleastic models [61-63] were developed for the prediction of the mechanical behavior of the bonding material in adhesively bonded assemblies with identical nondeformable adherends. The analyses were carried out in application to assemblies used in advanced holographic memory devices. It has been shown, particularly, that the interfacial compliance of the adhesive layer, in the case of sufficiently large-and-thin assemblies with thermally matched adherends, is half the magnitude of the interfacial compliance in the case of assemblies with mismatched adherends. It has been shown also that the elevated interfacial shearing stresses are somewhat higher for a circular assembly than for a rectangular one. These stresses also occupy a narrower zone around the assembly edge. An inhomogeneous adhesive layer, which is important for the considered application, was examined. The developed models enable one to establish the conditions, at which the requirement for the undistorted boundaries of the inner "pieces" of the adhesive is fulfilled.

THIN FILMS

Typical thermal stress failures in thin films fabricated on thick substrates are interfacial delaminations (including delamination buckling), and film cracking and blistering. Numerous investigators [65-71] analyzed thermal stresses in thin films. Based on the obtained results, practical recommendations for a physical design of a reliable thin film structure have been formulated. For instance, it has been found that

- the thermal stress in the given film layer of a multilayer film structure is due to the thermal expansion mismatch of this layer with the substrate, and not with the adjacent film layers [68];
- the edge stresses in the film are affected by the edge configuration [70]: circular assemblies are somewhat "stiffer" than the rectangular ones, i.e., result in higher stresses that concentrate at a narrower peripheral ring;
- stress in a thin film, which does not experience bending stresses, is not affected by the assembly bow, while the assembly bow and the stresses in the substrate are strongly affected by the stresses in the film [71].

The effect of lattice mismatch of semiconductor materials during crystal growth of thin germanium films on a thick silicon substrate was addressed, along with the effect of thermal mismatch, by Luryi and Suhir [37]. It has been shown that by using a "tower-like" surface of the substrate (such a surface can be achieved by high-resolution lithography, by employment of porous silicon, etc) one can grow dislocation free semiconductor films.

POLYMERIC MATERIALS AND PLASTIC PACKAGES

Polymeric materials are widely used in ME and OE engineering (see, for instance, [72-78]). Examples are: plastic packages of integrated circuit (IC) devices, adhesives, various enclosures and plastic parts, polymeric coatings of optical silica fibers, polymeric light-guides. There are numerous and rapidly growing opportunities for the application of polymers for diverse functions in the "high-technology" field. Organic electronics is a rapidly developing directions of ME engineering. Polymeric materials are inexpensive and lend themselves easily to processing and mass production techniques. The reliability of these materials, however, is usually not as high as the reliability of inorganic materials and is often insufficient for particular applications, thereby limiting the area of the technical use of polymers. Therefore there exists a crucial necessity for the advancement of the experimental and theoretical methods, techniques and approaches, aimed at the prediction and improvement of the short/long-term performance of polymeric materials for different ME and OE applications.

Recent improvements in the mechanical properties of molding compounds, plastic package designs, and manufacturing technologies have resulted in substantial increase in the reliability of plastic packages of IC devices. There is, however, one major industry-wide concern associated with these packages – moisture-induced failures (“popcorn” cracking). Such failures occur during surface mounting the packages onto printed circuit boards by means of high temperature reflow soldering. “Popcorn” cracking is usually attributed to the elevated pressure of the water vapor, generated due to a sudden evaporation of the absorbed moisture [73]. It has been shown, however [74], that thermal stresses also play an important role, both directly, due to their interaction with mechanical vapor-pressure-induced stresses in the underchip portion of the molding compound, and indirectly, by triggering the initiation and facilitating the propagation of the interfacial delaminations.

It has been suggested [74] that constitutive equations, obtained as a generalization of von-Karman’s equations for large deflections of plates, be used as a suitable analytical stress model for the prediction and prevention of structural failures in moisture-sensitive plastic packages. Such a generalization accounts for the combined action of the lateral pressure, caused by the generated water vapor, and the thermally induced loading. The developed model can be used, particularly, for the selection of the low stress molding compounds, for comparing different package design from the standpoint of their propensity to “popcorn”-cracking, in the development of “figures-of-merit” [75], which would enable one to separate packages that need to be “baked” and “bagged” from those that do not, etc. Thermal loading in plastic packages of IC devices is due to both the temperature gradients and the thermal expansion (contraction) mismatch of the dissimilar materials in the package. Since the coefficient of thermal expansion and Young’s modulus of the molding compound are temperature dependent, the constitutive equations account for this dependence. The developed equations were applied to the delaminated underchip layer of the molding compound. This layer is treated as a thin rectangular plate clamped at the support contour. It has been shown, in particular, that, from the standpoint of structural analysis, the distinction between “thick” and “thin” packages should be attributed primarily to the level of the in-plane (“membrane”) normal stresses in the underchip portion of the compound: in “thick” packages this portion exhibits bending only, while in “thin” packages it is subjected to both bending and in-plane (“membrane”) loading. The obtained data, which are in good agreement with experimental observations, have indicated that the geometric characteristics of the package (the underchip layer thickness, chip and paddle size, etc.) have a strong effect on the package propensity to failure. The obtained results have been used indeed to develop guidelines (“figures-of-merit”) which enable one to separate packages that need to be “baked” and “bagged” from those that do not, as well as for guidelines aimed at the preliminary selection of the feasible molding compound for the given package design.

THERMAL STRESS INDUCED BOWING AND BOW-FREE ASSEMBLIES

Thermal stress induced bowing can prevent further processing of BGA packages or of thin (TSOP) plastic packages [79], can lead to cracking of ceramic substrates in thin overmolded packages [80,81], or can have another adverse effect on the design or processing of plastic packages of IC devices. It has been shown [79-81] that employment of additional (surrogate) layers can dramatically improve the situation.

There is an obvious incentive for the use of bow-free (temperature change insensitive) assemblies in ME and OE packaging. It has been shown [83, 84] that this can be achieved if a thick enough bonding layer is introduced to produce an appreciable axial (in-plane) force. This force is necessary to create a bending moment that would be able to equilibrate the thermally induced moment produced by the dissimilar adherends. A bi-material assembly (i.e., an assembly with a very thin and/or a very low-modulus bonding layer) cannot be made bow free. This is because the thermally induced forces acting in the components of a bi-material assembly are equal in magnitude and opposite in sign, and create a bending moment that can be equilibrated by the elastic moment only. Such a situation inevitably leads to non-zero deflections, whether large or small. To be bow-free, a multi-material assembly should be made statically indeterminate. It should contain at least three dissimilar materials, so that the resulting bending moment, caused by the induced forces in all the three materials, is zero.

A sufficiently large axial force in the bonding material can be created by one or a combination of two or more of the following measures:

- by using a bonding material with a high elastic modulus;
- by using a bonding materials with a significant thermal mismatch with the adherends;
- by using a bonding material with a high curing temperature, and/or
- by making the bonding material thick.

It is only the last measure, however, that, while resulting in a desirable elevated thermally induced force in the bonding material, does not necessarily lead to an elevated axial stress in it. Computations based on the developed analytical models [83,84] have indicated that the “thick” bonding layer in a bow free assembly can still be made thin enough (about 4 mils or so) to “do the job”, provided that the material and/or the thickness of at least one of the adherends is adequately chosen.

PROBABILISTIC APPROACH

Probabilistic models are useful in situations, in which the "fluctuations" from the mean values are significant and in which the variability, change and uncertainty play a vital role (see, for instance, [60, 64, 85, 86]). In the majority of such situations the product will most likely fail, if these uncertainties are ignored. Probabilistic (statistical) models are currently used in "high-tech" engineering primarily for the design and analyses of experiments. These models are very seldom used as a physical design tool. In this connection we would like to emphasize that wide and consistent use of probabilistic models would not only enable one to establish the scope and the limits of the application of deterministic models, but can provide a solid basis for a well-substantiated and goal-oriented accumulation, and effective utilization of empirical data. Probabilistic models enable one to quantitatively assess the degree of uncertainty in various factors, which determine the performance of a product. Then a reliability engineer can design a product with a predictable and low probability of failure. A good illustration to these statements is the success of the design described in [60]).

OPTICAL FIBERS AND OTHER PHOTONIC STRUCTURES

Various problems of the thermal stress modeling in bare and coated optical silica fibers are addressed in [3, 7, 87-98]. Low temperature microbending can result in substantial added transmission losses in dual-coated optical fibers. Based on the developed analytical stress models [90], it has been shown that the initial curvatures can play an important role in the low temperature behavior of a silica fiber and that certain curvature lengths are less favorable than others from the standpoint of the possible fiber buckling. It has been shown also [91] that the magnitude of the spring constant of the elastic foundation provided by the primary coating layer could have a significant effect on the buckling conditions, and that, in the case of thick and relatively low modulus secondary coatings, both coating layers should be considered when evaluating the spring constant. For thin and high modulus secondary coatings, however, only the primary coating material could be considered when evaluating the spring constant of the elastic foundation.

Application of a mechanical approach to the evaluation of low temperature added transmission losses [92] enables one, based on the developed analytical stress model, to evaluate the threshold of the low temperature added transmission losses from purely mechanical calculations, without resorting to optical calculations or measurements. The model (confirmed by actual optical measurements) presumes that the threshold of the elevated added transmission losses coincides with the threshold of the elevated thermally induced stresses applied by the coating (jacket) to the silica fiber.

Various aspects related to thermal stresses and thermal stress related behavior of solder materials for photonics applications were addressed in [53]. Thermal stresses in, and optimal physical design of, solder joints for metallized optical fibers soldered into ferules was analyzed, based on a developed analytical stress model, in [54]. It has been demonstrated that an adequate modeling of what could be expected in an actual joint is a must: the selection of the right enclosing material and the right thickness of the solder preform (for the given solder material) should be conducted prior to manufacturing of the joint.

Mechanical behavior and elastic stability of bare, polymer coated and metallized optical fiber interconnects was modeled in [93-95]. It has been shown that low modulus polymer coatings have significant advantages over high modulus metallizations, as far as the stresses in the coating (metallization) are concerned, and typically should be preferred despite of their sensitivity to moisture penetration. An analytical stress model developed in [94] enables pone to select the appropriate enclosure material for mimimizing the thermally induced bending stresses in an optical fiber interconnect experiencing ends-offset and thermally induced compressive loading because of its mismatch with the enclosure material. In those cases when low buckling stresses are a problem, thicker polymer coatings can be used to improve the elastic stability of a polymer coated fiber [95].

Suhir and Vuillamin [96] have demonstrated, based on the developed analytical and FEA models, that the gradient in the distribution of the CTE along one of the diameters of a glass fiber cross-section can be responsible for the undesirable "curling" phenomenon that often occurs during drawing of optical silica fibers.

Optical silica fiber materials exhibit highly nonlinear (but still elastic) behavior when subjected to tension or compression. This effect was considered, along with the effect of the nonprismaticity, in the model [97] developed for a fused biconical taper (FBT) coupler experiencing thermally induced tension.

An effective method for thermostatic compensation of temperature sensitive devices was suggested in [98] in application to Bragg gratings. It has been shown that there is no need to use, for particular applications, mechanically vulnerable ceramic materials with a negative CTE: regular and more mechanically reliable materials can be successfully used for the objective in question. It has been recently demonstrated [99, 100] that a newly developed nano-particle material (NPM) can make a substantial difference in the state-of-the-art of coated optical fibers: this material has all the merits of the polymer coated and metallized optical fibers without having their drawbacks.

CONCLUSION

The following conclusions can be drawn from the above overview:

- Predictive modeling is an effective tool for the prediction and prevention of mechanical and functional failures in microelectronics and photonics materials, structures, packages and systems, subjected to thermal loading

- Experimental and theoretical models should be viewed as equally important and equally indispensable to the design of a viable, reliable and cost-effective product. The same is true for analytical and numerical (FEA) models.
- Special effort should be taken to make the existing FEA program accurate enough to be suitable for the evaluation of the thermal stresses and displacements in photonics structures. In such a situation, analytical modeling of a simplified structure of interest can be very useful for the selection and mastering of the preprocessing FEA model.
- Application of the probabilistic approach enables one to quantitatively assess the role of various uncertainties in the materials properties, geometrical characteristics and loading conditions, and, owing to that, to design and manufacture a viable and reliable product.

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- **2000 IEEE-CPMT Outstanding Sustained Technical Contribution Award** for outstanding, sustained and continuing contributions to the technologies in fields encompassed by the CPMT Society;
- **2000 SPE International Engineering/Technology (Fred O. Conley) Award** for outstanding pioneering and continuing contributions to plastics engineering; and
- **1999 ASME and Pi-Tau-Sigma Charles Russ Richards Memorial Award** for outstanding contributions to mechanical engineering.