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Minimizing thermally induced interfacial shearing stress in a thermoelectric module with low fractional area coverage

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ABSTRACT

High temperature differences between the ceramic parts in thermo-electric modules (TEMs) intended for high temperature applications makes the TEMs vulnerable to the elevated thermal stress leading to possible structural (mechanical) failures. The problem of reducing the interfacial shearing stress in a TEM structure is addressed using analytical and finite-element-analysis (FEA) modeling. The maximum shearing stress occurring at the ends of the peripheral legs (and supposedly responsible for the structural robustness of the assembly) is calculated for different leg sizes. Good agreement between the analytical and FEA predictions has been found. It is concluded that the shearing stress can be effectively reduced by using thinner (smaller fractional area coverage) and longer (in the through thickness direction of the module) legs and compliant interfacial materials.

1. Introduction

Thermo-electric modules (TEMs) have recently received increased attention in connection with the development of advanced energy technologies [1,2]. Extensive research is being conducted in integrating thermo-electric devices into microelectronic ICs for the purposes of both cooling and pumping heat. On-chip solid-state cooling has been addressed by many researchers. Thin film thermoelectric micro-coolers might exhibit high cooling capability [3,4], provide highly localized cooling and temperature stabilization and could be effectively integrated into Si-based microelectronic systems. Nano-structured Bi_2–Te_3-based thin-film thermoelectric coolers could be integrated into state-of-the-art electronic packages [5]. MEMS-based thermoelectric devices [6] are also an attractive and possible alternative to solve many thermal management related problems in microelectronics. Improving material properties in order to enhance the power factor and the thermoelectric figures of merit are important areas of interest [7,8]. Although finding an optimal TEM design and the adequate materials is important to maximize the efficiency of TEMs, the mechanical stability and reliability of the TEMs is equally important. For instance, in the case of thermo-electric coolers in CPU cooling applications, while the designers concentrate on improving the functional performance of the TEM designs, the reliability of TEMs is also a major concern: their mechanical failure would cause over-heating and significant reduction in the CPU lifetime [9].

Elevated thermal stresses are viewed today as major bottle-necks for reliability and robustness of high temperature TEM technologies. These stresses are caused, first of all, by the significant differences in temperature between the “hot” and the “cold” ceramic plates in a TEM design (Fig. 1). The thermal stress problem can be solved by selecting adequate thermoelectric materials [10,11] as well as by finding effective ways to reduce the stress level [12].

In this study an analytical and a finite-element-analysis (FEA) models are used to evaluate the thermal stresses in a simplified (two-leg) TEM design. State-of-the-art finite element modeling software, ANSYS [13], is used with an objective to validate the previously suggested analytical model [12]. The obtained information is intended to be helpful as a useful guide when creating a mechanically robust TEM design.

The rest of this paper is organized as follows. The analytical model is described in Section 2. In Section 3, we have employed the model to calculate the shearing stress in different TEM designs. Discussion of the results and comparison with FEM data are also presented. The paper concludes in Section 4 with a summary and possible future work.

2. Analytical modeling

2.1. Assumptions

The following major assumptions are used in the analysis:

- All the materials behave in the elastic fashion.
- Instead of addressing the actual three-dimensional TEM structure, a two-dimensional longitudinal cross-section of this

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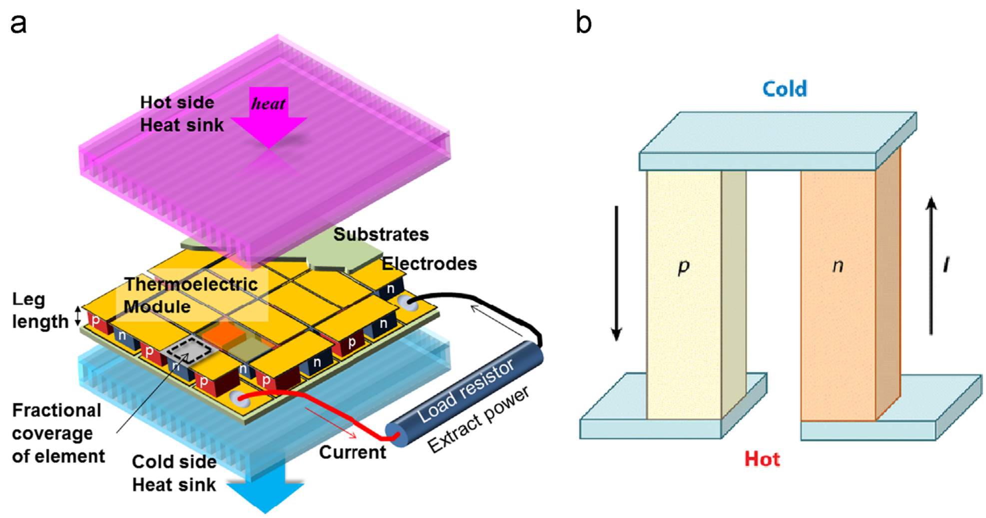

Fig. 1. Thermo-electric module; (a) general view; (b) a two leg module with n-type and p-type legs.

structure idealized as a long-and-narrow strip could be considered.

- The bonded TEM ceramic components can be treated, from the standpoint of structural analysis, as elongated rectangular plates that experience linear elastic deformations, and approximate methods of structural analysis and materials physics can be used to evaluate the induced stresses and displacements.
- The interfacial shearing stresses can be evaluated based on the concept of the interfacial compliance [14].
- The interfacial compliances of the bonded components and the TEM legs can be evaluated, however, based on the Rebière solution in the theory-of-elasticity for a long-and-narrow strip (see, e.g., [14]).
- The assembly is thick and stiff enough, so that it does not experience bending deformations, or, if it does, bending does not affect the interfacial thermal shearing stresses and need not be accounted for.
- The interfacial shearing stresses can be evaluated without considering the effect of "peeling", i.e., the normal interfacial stresses acting in the through-thickness direction of the assembly.
- The longitudinal interfacial displacements of the TEM bonded components can be sought as the sum of (1) the unrestricted stress-free displacements, (2) displacements caused by the thermally induced forces acting in the cross-sections of the TEM components and (3) additional displacements that consider that, because the thermal loading is applied to the component interface, the interfacial displacements are somewhat larger than the displacements of the inner points of the component.
- TEM legs provide mechanical supports for the TEM bonded components (ceramics) and their interfacial compliance is critical when one intents to buffer the interfacial stress, but do not experience thermal loading themselves.

Some additional, more or less minor, assumptions are indicated in the text of the paper.

2.2. Interfacial compliance

Analytical modeling uses the interfacial compliance concept suggested in Refs. [14–16]. The concept enables one to separate the roles of the design (its geometry and material properties) and the loading caused by the change in temperature and/or temperature gradients. The approach is based on and reduced to the evaluation

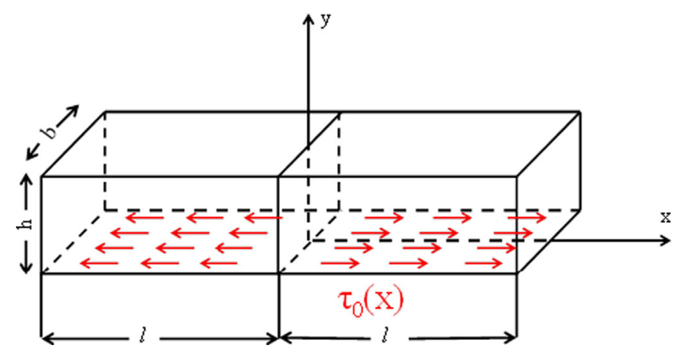

Fig. 2. Elongated strip subjected to shear loading.

of the longitudinal interfacial compliance of a strip subjected to the longitudinal shear loading applied to its long edge (Fig. 2). An important assumption underlying the rationale behind the employed analytical model is that the actual 3D structural element (experiencing in a multi-material body interfacial loading caused by the dissimilar materials in the body) can be substituted by an elongated strip that is, in effect, the longitudinal cross-section of the body. The following approximate formula for the longitudinal displacements of the edge of such a strip has been used [14–16] to evaluate the longitudinal displacements of a strip loaded over its long edge by a distributed shear loading:

$$u_0 = -\frac{1-\nu^2}{Ehb}\int_0^x Q\,(\xi)d\xi + \kappa\tau_0(x) \tag{1}$$

Here E and ν are the modulus of elasticity and Poisson′s ratio for the strip material, κ is the longitudinal compliance of the strip (defined as the ratio of the longitudinal displacement to the loading $\tau_0(x)$, h is the thickness of the strip, b is its width, and $Q(x)$ is the distributed longitudinal force acting at the x cross section of the strip. The first term in Eq. (1) reflects an assumption that the displacement of the strip′s edge at the x cross section is uniformly distributed over the cross section. The second term account for the deviation of the actual, non-uniform, distribution of this force: the longitudinal displacements at the strip edge, where the load $\tau_0(x)$ is applied, are somewhat greater than at the inner points of the cross section. The structure of this term reflects an assumption that the correction in question can be calculated as the product of the shearing load $\tau_0(x)$ in the given cross section and the longitudinal compliance of the strip, as well as an assumption that the displacement determined by this term is not affected by