Finite Element Analysis on Structural Stress of 32x32 InSb Focal Plane Arrays Integrated with Microlens Arrays

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Abstract

Basing on the temperature dependent elastic model of underfill and the Anand’s viscoplastic model of indium bumps, A three-dimension finite element model is developed to simulate the structural stress and its distribution in 32×32 InSb infrared focal plane arrays integrated with microlens arrays. To learn the stress and its distribution for large format array in a short time, a small 8×8 InSb IRFPAs is studied firstly, and the stress reaches the minimum with indium bump diameter 28µm, height 24µm. With the optimum typical structure, the stress in 32×32 InSb IRFPAs is obtained in a short time by twice over the arrays format from 8×8 to 32×32. Simulation results show that the largest Von Mises stress locates in InSb chip, as the array scale is enlarged, the Von Mises stress value in InSb chip is strongly determined by arrays format and almost increases linearly with array scale, but the Von Mises stress maximum in Si ROIC, underfill and indium bump almost keeps constant, and does not vary with increased array scale. The stress distribution for 32×32 arrays is uniform at contacting areas. These are favorable to reduce the crack in InSb chip, and improve the production ratio.

Keywords: Finite Element Analysis, Stress, Insb, Focal Plane Array, Microlens Arrays

1. Introduction

An indium antimonide (InSb) infrared focal plane array (IRFPA) detector with cut-off wavelength 5.5µm at 77K, has been widely used in military guiding system [1, 2]. For high spatial resolution, the IRFPAs arrays has been up 2048×2048 elements in size today, which increases the number of pixel, but reduces pixel size and the active area [3]. In this way the resolution is improved, whereas the smaller pixel size results in low detecting sensitivity and deteriorated signal-to-noise. Increasing the fill factor becomes an important development direction for large format IRFPAs. Microlens arrays have been employed to increase the fill factor, which can concentrate the incoming light into the photosensitive region and increase subsequent optical sensitivity of the IRFPAs assembly [4, 5]. InSb IRFPAs is usually fabricated by flip chip bonding technology. To reduce crosstalk, InSb substrate must be thinned, and the detector is back illuminated. For better performance, Microlens arrays is usually integrated on the back surface of IRFPAs, which means, microlens arrays is fabricated on the back surface of the thinned InSb substrate. In order to achieve lower level of electronic noise to the photon noise limit, it is necessary to cryogenically cool InSb IRFPAs to liquid nitrogen temperature (77K), yet InSb IRFPAs is usually assembled and stored at room temperature (300K). When the temperature rapidly reduces from 300K to 77K, fracture usually occurs in InSb chip due to the mismatch in the coefficients of thermal expansion (CTE) of neighboring components. The induced thermal strain and stress are the major causes of fracture in thinner InSb chip, especially in larger format infrared focal plane arrays, which limits the final yield.

At present, the reliability of flip chip assemblies is usually assessed by finite element simulations in conjunction with experimental verification [6, 7, 8]. Within the approach, the selection of material models is very significant. Basing on the temperature dependence of materials thermo-mechanical behavior, the temperature dependent elastic model of underfill is adopted to analyze the structure stress of InSb IRFPAs in this paper. Besides, the temperature dependent mechanical properties of the other materials are also adopted. Simulating large format InSb IRFPAs in 3-dimention is very time and memory consuming. To learn Von Mises stress value and its distribution in 32×32 array in a short time, the optimum indium bump
diameter and height is firstly obtained with an $8 \times 8$ InSb IRFPAs. Then, with the optimum structure, the sizes of InSb IRFPAs is doubled once again to learn the stress value varying tendency with array scale, thus, the stress and its distribution of $32 \times 32$ InSb IRFPAs is obtained in a short time.

2. Finite Element Model

Three-dimensional finite element model of InSb IRFPA, integrated microlens arrays with underfill encapsulate, is constructed using ANSYS. InSb IRFPA is typical flip chip bonding device, which is composed of InSb chip, indium bumps array, underfill, and Si ROIC substrate. Here microlens arrays are integrated on the back surface of InSb chip. For modeling expediency, indium bumps are assumed to be octagonal prisms, and no defects existing in the whole device. Owing to the geometrical symmetry, only one eighth of the overall package is modeled, and the three-dimensional finite element model of InSb IRFPA is shown in Figure 1. The thickness of InSb chip is set to 10 μm, for $32 \times 32$ array, the InSb chip dimensions of length and width are $1600 \mu m \times 1600 \mu m$, and Si ROIC substrate dimensions are $1650 \mu m \times 1650 \mu m \times 300 \mu m$. Microlens arrays integrated on the back surface of InSb chip is made of axial symmetrical plano-convex lens, the curvature radius of the microlens is 80 μm, the height and radius of the microlens is 4 μm and 25 μm, separately. Flip chip process is completed at 370 K, at this temperature, no residual stress is assumed to exist within the package. The finite element analysis is performed under thermal loading in the temperature range from 370K to 77K, and no transient heat transfer is considered and the temperature within the model is assumed to be uniform. The symmetry boundary condition and single node constraint on the symmetry plane are used for restraining the rigid body motion, and meshing the whole model free, refining InSb chip on one level refinement for accurate results.

![Figure 1. Three-dimensional model of infrared focal plane arrays integrating with microlens arrays](image)

3. Material Properties

Underfill is an epoxy-based polymer, usually used in flip chip packaging to bridge the thermal mismatch between the chip and the substrate. Underfill is usually described as viscoelastic material around its glass transition temperature ($T_g$) [8]. Yet, below $T_g$, the underfill mechanical properties including coefficient of thermal expansion and Young's modulus vary with the temperature, and shows significant temperature dependent elasticity [9, 10]. Usually, the glass transition temperature of typical underfill is 408K. InSb chip fracture happens in the thermal shock from room temperature to 77K, and this temperature range is far below $T_g$, so the temperature dependent elastic model is used to describe thermo-mechanical behavior of the underfill in this paper.

The CTE of underfill is measured using a thermal mechanical analyzer (TMA) operated in expansion mode by Y. He research group [9]. The TMA results demonstrate when the temperature approaches 398K, the CTE increases rapidly, which is the signature of the glass transition temperature. Below 363K, the CTE has a linear raising trend, increases from $19.4 \times 10^{-6} \text{K}^{-1}$ at 213K to $26.7 \times 10^{-6} \text{K}^{-1}$ at 358K. So, below 358K, the CTE can be approximated by the follow expression,
\[ \alpha(T) = 22.46 \times 10^{-6} + 5.04 \times 10^{-8} T (K^{-1}), \]  
(1)

where \( T \) is the absolute temperature in Kelvin. When \( T \) approaches 363K, the CTE begins to deviate from the above linear behavior, signaling the beginning of the glass transition.

The dynamic mechanical thermal analysis (DMTA) experiments also show that the elastic modulus \( (E) \) of underfill at 223K is approximately 9.5GPa, as the temperature increases, \( E \) decreases gradually. At 298K, \( E \) is about 8.2GPa. When the temperature approaches 398K, \( E \) decreases rapidly. Based on the TMA and DMTA data, below the glass transition \( T_g \), the stress index \( \alpha(T) \cdot E(T) \) of the underfill is approximately a constant, which is described as follows.

\[ \alpha(T) \cdot E(T) \cdot 0.2 \text{MPa/K}. \]  
(2)

Based on the above research results, the material parameters of underfill, which vary with temperature, such as coefficients of thermal expansion and Young's modulus from 50K to 400K are listed in Table 1. Besides, the Poisson’s ratio of employed underfill is 0.3.

**Table 1. The material parameters of underfill at different temperature**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>50K</th>
<th>100K</th>
<th>150K</th>
<th>200K</th>
<th>250K</th>
<th>300K</th>
<th>350K</th>
<th>400K</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTE/10^{-6}K^{-1}</td>
<td>11.22</td>
<td>13.74</td>
<td>16.26</td>
<td>18.78</td>
<td>21.30</td>
<td>24.06</td>
<td>26.10</td>
<td>28.86</td>
</tr>
<tr>
<td>E/MPa</td>
<td>17.82</td>
<td>14.56</td>
<td>12.30</td>
<td>10.65</td>
<td>9.39</td>
<td>8.31</td>
<td>7.66</td>
<td>6.93</td>
</tr>
</tbody>
</table>

Indium is commonly used as an attachment material in packaging structures intended for operation at extreme cold-temperature environment applications. For its high homologous temperatures, e.g., 0.70Tm (in K) at room temperature (300K), when the thermally activated strains impose on the attachment of indium, due to the coefficients of thermal expansion mismatch between packaging materials, it gives rise to a complex deformation behavior. This deformation behavior is associated with the irreversible, temperature and rate (or time) dependent inelastic characteristics, are known to be viscoplastic [11]. Here Anand model is used to describe the viscoplastic mechanical behavior of indium bump, and the model accommodates the strain rate dependence on the stress using the following expression

\[ \dot{\varepsilon}_p = A \exp(-\frac{Q}{RT})(\sinh(\xi \frac{\sigma}{s}))^\frac{1}{a}, \]  
(3)

where \( \dot{\varepsilon}_p \) is the inelastic strain rate, \( A \) is the pre-exponential factor, \( Q \) is the activation energy, \( R \) is universal gas constant, \( T \) is absolute temperature, \( m \) is strain rate sensitivity of stress, \( \xi \) is multiplier of stress, \( s \) is coefficient for deformation resistance saturation value, and \( \sigma \) is stress. The evolution equation for the internal variable \( s \), which includes the three mechanisms of strain hardening, dynamic recovery, and static recovery, is derived as follows,

\[ s = h_0 \left| -\frac{s}{\hat{s}} \right| \text{sign}(1 - \frac{s}{\hat{s}}) \dot{\varepsilon}_p; \alpha > 1, \]  
(4)

\[ s^* = \hat{s} \left( \frac{\dot{\varepsilon}_p}{A} \exp\left(\frac{Q}{RT}\right) \right)^n, \]  
(5)

where \( h_0 \) is hardening/softening constant, \( \alpha \) is strain rate sensitivity of hardening or softening, \( s^* \) is the saturation value of \( s \), \( \hat{s} \) is the coefficient, and \( n \) is the strain-rate sensitivity for the saturation value of deformation resistance. Based on the compression test data, the material parameters of indium bump in Anand’s model were acquired to simulate the steady-state viscoplastic behavior and stress/strain responses by Rui Wu Chang research group in 2009 [11]. As stated before, indium will undergo a wide range of homologous temperatures due to its low melting-temperature; the dependence of thermal properties on temperature has to be considered. So, the CTEs for indium as functions of temperature, implemented in the model, which are given in Table 2 [12].
The thermo-mechanical behavior of InSb chip and Si ROIC are modeled as linear elastic. For InSb IRFPAs, the service conditions require functions at cryogenic temperatures, i.e. below the temperature of liquid nitrogen (77 K). In such case, the temperature in the service is expected to change from cryogenic temperature to room temperature. During this wide temperature change, the CTEs of InSb and Si ROIC are not constant values, but temperature-dependent. The CTEs varied with the temperature are also given in Table 2. In the simulation, all the other employed parameters are listed in table 3, where \( \mu \) is the Poisson’s ratio.

### Table 2. The CTEs (10^{-6} K^{-1}) of InSb chip, Indium bump and Si ROIC at different temperature

<table>
<thead>
<tr>
<th>Materials</th>
<th>50K</th>
<th>100K</th>
<th>150K</th>
<th>200K</th>
<th>250K</th>
<th>300K</th>
<th>350K</th>
<th>400K</th>
</tr>
</thead>
<tbody>
<tr>
<td>InSb chip</td>
<td>-0.2</td>
<td>2.38</td>
<td>3.91</td>
<td>4.38</td>
<td>4.75</td>
<td>5.1</td>
<td>5.35</td>
<td>5.82</td>
</tr>
<tr>
<td>Indium bump</td>
<td>23</td>
<td>27</td>
<td>27.5</td>
<td>28.5</td>
<td>29.5</td>
<td>31</td>
<td>32.4</td>
<td>33.5</td>
</tr>
<tr>
<td>Si ROIC</td>
<td>-0.28</td>
<td>-0.33</td>
<td>0.5</td>
<td>1.41</td>
<td>2.1</td>
<td>2.62</td>
<td>2.98</td>
<td>3.25</td>
</tr>
</tbody>
</table>

### Table 3. The liner elastic material parameters

<table>
<thead>
<tr>
<th>Materials</th>
<th>( E/\text{MPa} )</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>InSb chip</td>
<td>409000</td>
<td>0.35</td>
</tr>
<tr>
<td>Indium bump</td>
<td>10600</td>
<td>0.45</td>
</tr>
<tr>
<td>Si ROIC</td>
<td>163000</td>
<td>0.28</td>
</tr>
</tbody>
</table>

### 4. Simulation Results and Analysis

To learn Von Mises stress value and its distribution in 32×32 array in a short time, firstly an 8×8 InSb IRFPAs is studied by varied indium bump diameters and height in a suitable range with fixed InSb thickness 10\( \mu \)m, simulation results is illustrated in Figure 2. Here indium bump diameter increases from 12\( \mu \)m to 40\( \mu \)m in step of 4\( \mu \)m with fixed indium bump height 8\( \mu \)m, 16\( \mu \)m and 24\( \mu \)m, respectively. Apparently, when the indium bump height is fixed at 8\( \mu \)m, as the indium bump diameters increases from 12\( \mu \)m to 40\( \mu \)m, the maximal Von Mises stress in InSb chip first reduces linearly from 1310MPa to 721MPa, then increases gradually to 970MPa. The maximal stress value in InSb chip is obviously far larger than that without underfill, which is 79.2MPa at indium bump height 8\( \mu \)m [13, 14]. This phenomenon is because the underfill provides good support and constrained reinforcement on InSb chip. But too much constraint makes the stress value in InSb chip becomes much larger, compared with the structure without underfill. As indium bump height is fixed at 16 or 24\( \mu \)m, the maximal Von Mises stress in InSb chip versus indium bump diameters almost have the similar varying tendency. The maximal stress in InSb chip all reaches the minimum at the same indium bump diameter 28\( \mu \)m at three indium bump heights. The only difference is that when the height of indium bump increases from 8\( \mu \)m to 24\( \mu \)m in step of 8\( \mu \)m, the maximal stress in InSb chip decreases slightly. Apparently, when the height of the indium bump is set to 24\( \mu \)m, the maximum stresses in InSb chip reaches the minimum with indium bump diameter 28\( \mu \)m.

For obtaining the Von Mises stress value and its distribution in 32×32 InSb IRFPAs in short time period, an optimum typical structure with indium bump diameter 28\( \mu \)m, height 24\( \mu \)m and InSb thickness 10\( \mu \)m, is selected. As the indium bump number in row and column increases from 8 to 32 in step of double, that means InSb IRFPAs scale increases from 8×8 to 16×16 and 32×32, here model meshing, constraints, loading are all identical, Simulation results are shown in Figure 3. Apparently, the Von Mises stress maximum in InSb chip almost increases linearly with array scale, and Von Mises stress maximum in Si ROIC, underfill and indium bump almost keeps constant, and does not vary with increased array scale. Besides, comparing with the maximal stress value appearing in InSb chip, the maximal Von Mises stress in Si ROIC is almost 50% in 8×8, and about 30% in 32×32, which means the Von Mises stress in Si ROIC is smaller than that appearing in InSb chip as the increased array scale, the phenomena comes from employed thinner InSb chip (10\( \mu \)m), which tends to distortion compared with thicker 300\( \mu \)m Si ROIC. Even though underfill has only 24\( \mu \)m thickness, the maximal Von Mises stress in underfill is also smaller than that in InSb chip due to that underfill has larger CTE than InSb.
chip. It is worth noticing that the maximal Von Mises stress appearing on indium bumps almost keeps at 16.4 MPa, compared with the maximal stress values appearing in InSb chip, the maximal Von Mises stress appearing in indium bumps is much smaller, and is almost 2.4% that appearing in InSb chip for 8×8 array, 1.5% for 32×32 array. This is obviously different from conventional PbSn solder joints flip chip device, where the maximal stress concentrates on PbSn solder joints [10]. The stress concentrating in InSb chip originated from the thinner InSb chip (10 μm) is employed, as the InSb chip becomes thinner and thinner, its anti-deformation intensity becomes smaller and smaller, which arouses the stress appearing in whole IRFPAs device redistributes and the maximal Von Mises stress is shifted to InSb chip.

![Figure 2. The maximum stress of InSb as a function of varied indium bump diameter with three indium bump heights](image)

When temperature of InSb IRFPAs is gradually reduced from 370K to 77K in 71 seconds, Von Mises stress distribution on top and bottom surface of InSb chip for 32×32 array is shown in Figure 4. It is clear that the maximal Von Mises stress values 1060MPa in InSb chip locates on the diagonal, which is far away from the neutral point. Besides, the Von Mises stress existing on contact areas between InSb chip and indium bumps is concentrated and uniform, its stress value is about 470MPa, larger than that of non-contact region. The stress distribution of InSb chip top surface is contrary to InSb chip bottom surface stress distribution, the stress appearing on those regions situating over the contacting areas between InSb chip and indium bumps, where are just the microlens sites, is much smaller than its surrounding regions. The larger stress on surrounding regions of microlens originates from the thinner InSb chip (10 μm) at the surrounding regions of microlens than the center of microlens InSb chip (14 μm). Apparently, the stress distribution of InSb chip for 32×32 arrays is distinctly different from the stress
distribution in the structure without underfill, where the stress distribution of InSb chip is radiating, and the stress values decrease from inner to outer region [7].

Figure 4. Von Mises stress distribution of InSb chip top and bottom surface for 32×32 array.

The Von Mises stress distribution of indium bumps is illustrated in Figure 5. The maximal von Mises stress appears on the contact area between indium bumps and InSb chip, and locates on diagonal indium bumps, which has the larger distance to neutral point. On top surface of indium bump, the Von Mises stress shows interesting gradient distribution. For those indium bumps locating on diagonal, the stress reduced direction is along the diagonal line from far to the neutral point. For non-diagonal sites, the gradient direction is along the line from indium bumps position to the neutral point. That is the stress distribution on top surface of indium bumps shows circle structure from outside to inside. Apparently, the gradient is obviously larger for the outermost four rows and columns indium bumps, the stress gradient difference is about 7.5MPa. But, the Von Mises stress difference on top surface of the inner indium bumps is about 0.1MPa, it is so small that this stress distribution can be assumed to be uniform.

Figure 5. Von Mises stress distribution of indium bumps for 32×32 array.

Underfill encapsulant is usually dispensed in the gap between InSb chip and Si ROIC to provide mechanical reinforcement and reduce thermal stresses on indium bumps, all these for avoiding fatigue and crack growth during temperature cycles. Here, the temperature dependent elastic model is used to describe the mechanical behavior of underfill. When the temperature of InSb IRFPAs drops from 370K to 77K, Von Mises stress distribution in underfill top surface and bottom surface are separately shown in Figure 6. Apparently, the stress distribution existing on contact areas between InSb chip and underfill is uniform (about 160MPa), but around indium bump octahedral shell, the stress is obviously enlarged to about 200Mpa. At the four corners of underfill top surface, Von Mises stress is smallest, where the underfill can shrink freely. The whole Von Mises stress existing on contact areas between underfill and Si ROIC is also uniform, and the stress around indium bump octahedral shell is also bigger. Besides, the Von Mises stress
on the quadrilateral borders of contact areas of underfill bottom surface is slightly smaller, and its value is about 113MPa.

Figure 7 is three-dimension Von Mises stress distribution of Si ROIC. Obviously, the maximal Von Mises stress appearing on Si ROIC locates at the contacting areas between indium bumps and Si ROIC, where locating on the diagonal near the neutral point. The Von Mises stress distribution in Si ROIC is almost concentrated strongly on the contacting areas between indium bumps and Si ROIC, it is about 300MPa. The stress on contacting areas between and underfill and Si ROIC is uniform (about 150MPa). The stress mainly concentrates on a thin layer at top surface of Si ROIC, and the stress on bottom surface is so small that it is ignorable. Besides, on the quadrilateral borders of Si ROIC top surface, the Von Mises stress is obviously larger than that on the non-contact areas. This is distinctly different from the stress distribution in the structure without underfill, where the stress distribution on the quadrilateral borders of Si ROIC top surface is ignorable [15, 16]

**Figure 6.** Von Mises stress distribution of underfill top and bottom surface for 32×32 array.

**Figure 7.** Von Mises stress distribution of Si ROIC for 32×32 array.

5. Conclusions

Basing on finite element analysis, the thermal stress and its distribution in 32×32 InSb IRFPAs integrated with microlens arrays is systematically researched in this manuscript. First, a small 8×8 InSb IRFPAs is investigated, simulated results show the thermal stress reaches the minimum with indium bump diameter 28µm, height 24µm. In order to learn the thermal stress value in 32×32 InSb IRFPAs in short time, with the above optimal structure, the stress in 32×32 InSb IRFPAs is obtained by twice over the arrays format from 8×8 to 32×32, simulation results show that as the array scale is enlarged, the Von Mises stress value in InSb chip is enlarged, but the Von Mises stress maximum in Si ROIC, underfill and indium bump almost keeps constant, and does not vary with increased array scale. The stress distribution for 32×32 arrays is uniform and concentrated at contacting areas.
6. Acknowledgments

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7. References