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1           **Thermal Deformation Analysis of Tabbed Solar Cells Using**  
2                           **Solder Alloy and Conductive Film**

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27 **Abstract**

28 Finite element analysis (FEA) has been carried out with the aim of understanding the thermal  
29 deformation characteristics of two solar cell configurations. One of the solar cell models is tabbed by  
30 lead-free solder, the other model by conductive film (CF). A high temperature soldering process could  
31 weaken the bond and reduce the reliability of the cells because of the residual stress caused by the  
32 different thermal expansion coefficients of the materials. Moreover, solar irradiation generates  
33 temperature distribution across the surface of the solar cell, and the development of solar cells made of  
34 thinner crystalline silicon wafers will lead to the reduction in manufacturing costs. In this study, finite  
35 element analysis (FEA) of the manufacturing process has been carried out using both solder and CF  
36 bonding. Three temperature cycles were applied to analyze different environmental operating conditions  
37 and understand how thermal cycles affect the residual stress during actual service conditions. This  
38 investigation provides a comparison of thermal deformations between solder and CF bonded solar cells in  
39 order to understand which offers substantial reliability in the long term. Also this study explores the  
40 effects of various thicknesses of the silicon wafer on the residual stress and deformation of the solar cells.  
41

## 42 **1. Introduction**

43 In recent years, photovoltaic power generation has been extending all over the world due to the scarcity  
44 of fossil fuels. Consumptions of fossil fuels lead to serious environmental issues such as air pollution  
45 since fossil fuels release carbon dioxide, nitrogen dioxide, sulphur dioxide, carbon monoxide etc.  
46 However, power from solar panel is one solution without the consequences of polluting the environment.  
47 A solar panel consists of a photovoltaic cell which converts solar power to electrical power directly. One  
48 of the issues of solar panels is that it undergoes cracking and fractures due to thermal deformation of the  
49 silicon wafer during solar to electrical power conversion. Solar panels are required to be used more than  
50 30 years by considering the energy payback ratio (EPR). Therefore, the improvement in design  
51 considering the thermal deformation of solar cells is required.

52 Manufacturing companies try to lose some microns in silicon wafer thickness as a way to reduce costs  
53 and make solar cells more accessible. However, the trend toward thinner solar cells leads to problems of  
54 increased yield loss from breakage. Therefore, it is necessary to ensure the mechanical strength  
55 considering the effect of different geometric parameters on the thermal deformation within the solar cells.

56 Generally, a copper wire is used to interconnect solar cells in a solar panel via soldering. The solar  
57 cells and the wires are heated up to a high temperature of 220°C during the soldering operation <sup>(1)</sup>.  
58 Differences in the thermal and mechanical properties of the silicon used in cells and metal ribbon cause  
59 the residual stress around the bonding area, and lead to cracks and cell breakage after bonding <sup>(2-3)</sup>. The  
60 thinner wafers have higher risk of suffering from bowing and higher residual stress. One recent  
61 alternative is the use of a solar cell conductive film (CF) which enables low temperature bonding at  
62 180°C <sup>(4-5)</sup>. CF is an adhesive tape with dispersed conductive particles, developed for connecting solar  
63 cells with metal ribbons.

64 Silicon wafer breakage has become a major concern of all semiconductor fabrication lines since silicon  
65 wafer is considered a brittle material, and high stresses are induced during the manufacturing process.  
66 Chen et al. reported an approach for characterizing silicon wafer failure strength using a simple drop test  
67 to understand the stress distribution in wafer bulk before failure <sup>(6)</sup>. Based on the multimodal Weibull  
68 distribution, a new expression taking into account the surface, edge, and bulk flaws has been proposed by  
69 Rupnowski to describe the strength of silicon wafers <sup>(7)</sup>. Significant changes in fracture strength are found  
70 as a result of metallization morphology and crystallinity of silicon solar cells. Surface and edge defects  
71 such as micro-cracks, grain boundaries, and surface roughness are the most probable sources of

72 mechanical strength degradation; reduction of potential micro-cracks leads to an increase of mc-silicon  
73 wafer fracture strength <sup>(8)</sup>.

74 The plastic deformation of silicon wafers due to the thermal stress at high temperatures in integrated  
75 circuit (IC) fabrication can be controlled by process and equipment design <sup>(9)</sup>. Wafers with fully rounded  
76 profiles give the largest breakage energy and lowest wafer breakage ratio compared to edged counterparts  
77 <sup>(10)</sup>. The thermo-mechanical balance between cell and interconnector is an important issue for high  
78 performance and reliability of the modules <sup>(11)</sup>. The main parameters that affect the residual thermal stress  
79 of the cell are the temperature of the hot-air for soldering, cell thickness, soldering rod thickness, and  
80 soldering rod width <sup>(12)</sup>. The results indicate that the residual stress is mainly concentrated at the junction  
81 between the soldering track and the two edges of the cell. The increasing residual stress may cause  
82 damage to the wafer region near the electrode <sup>(13-16)</sup>. Therefore, the interconnection at lower temperature  
83 is needed to reduce the thermal stress due to soldering.

84 The stresses on thinner wafers during the manufacturing cycle have been analyzed by considering  
85 mechanical loads such as sawing, manual handling, liquid jets, transport systems and pick and place  
86 equipment <sup>(17)</sup>. In addition, FEA modeling has been used to investigate grinding and lapping of wire sawn  
87 silicon wafers <sup>(18)</sup>. It was reported that the temperature variation during slicing exhibited undesirable  
88 warp, micro cracks and nanotopography on wafer surfaces, which were responsible for brittle fracture <sup>(19-</sup>  
89 <sup>20)</sup>. In contrast, the cells have to withstand the tensile stresses under outdoor operation in the finished  
90 modules. These tensile stresses are induced by temperature changes and mechanical loads from wind and  
91 snow <sup>(21)</sup>.

92 Solar irradiation will generate a temperature distribution across a PV module surface during operation  
93 under the sun. It is noted that a PV module has to endure many thermal cycles under ideal and abrupt  
94 weather conditions during its life cycle. A typical thermal cycle involves warm up and cool down of the  
95 module which leads to more severe stress challenge for the structure. Hence, a comparative study of  
96 thermal deformations between solder and CF bonded solar cells is necessary by considering the  
97 manufacturing process and the operating conditions. A finite element model of a three point bending test  
98 was built in an earlier study to investigate and understand the effect of bending stress on the electrical  
99 reliability of anisotropic conductive film (ACF) <sup>(22)</sup>. In addition, the effect of the bonding force on the  
100 failure behavior of the ACF joints under temperature fluctuation environment was also investigated. The  
101 main failure mode of the thermally shocked ACF joints was a conduction gap of the joints with low

102 bonding forces and adhesive matrix delamination of the joints with high bonding forces <sup>(23)</sup>.

103 The present study aims to clarify thermal deformation of solar cells with different thicknesses of silicon  
104 wafer by considering thermal condition during manufacturing process and the used conditions under the  
105 sun. Sn-3.5Ag solder and CF are used to simulate the bonding interface and to carry out a comparison of  
106 the thermal deformation characteristics using FEM software.

107 The main objectives of this study are listed below:

108 1. Simulation of manufacturing process and using conditions of solar cells through FEM analysis, in  
109 order to determine the long term effects of residual stresses.

110 2. Compare the bonding materials, CF and solder, in order to determine which offers comparable  
111 reliability in the long term.

112 3. How different thicknesses of silicon wafers behave for both materials, in order to determine an  
113 adequate thickness.

114

## 115 **2. Analysis Method**

### 116 **2.1 Basic FEM model**

117 Finite element analysis was carried out by using ANSYS 14.5 (Ansys, Cecil Township, US). Due to the  
118 symmetry of the package geometries, only 1/4 of the solar cell assembly was modeled. The model built for the  
119 simulation consisted in three simple blocks. Each block represents a different material: silicon, copper and the  
120 bonding material in between. The symmetry conditions are applied in the z-axis in order to simplify the model.  
121 The model was adopted with 3-dimensional 8-node SOLID185 element which has plasticity, stress stiffening,  
122 large deflection, and large strain capabilities. Finer mesh is applied in the central part of the solar cell as the  
123 maximum stress point occurred in the tabbing section of the cell. The dimension of silicon solar cell was  
124 considered for this analysis to be 152mm × 152mm × 0.2mm. The schematics of the FEM model are exhibited  
125 in Fig. 1. Two FEM models were developed for the different bonding materials solder and CF. All the  
126 dimensions are shown in Table 1.

#### 127 **2.1.1 Assumptions and restrictions**

128 In order to work with a simple model, some assumptions had to be made. All materials are bonded from the  
129 beginning. Any thermal expansion affects the surrounding materials from time zero. In a real process, materials  
130 expand independently during the first part of the manufacturing process and become bonded during the cooling

131 process (when solder solidifies or when conductive film reaches its adhesion point). However, this would have  
 132 required an adjustment to the contact surfaces at a certain point during the analysis. Although it is possible, the  
 133 complexity of the model increases dramatically. Solder was ignored in the conductive film model. In a real CF  
 134 cell, a very thin solder layer exists in the tabbing area. Also, the rest of the structure of a typical solar module  
 135 (frame, glass, etc.) was ignored. Using symmetry boundary conditions in two of the borders a simplified model  
 136 of only one quarter of a solar cell was built. No constrains were imposed on the open borders of the silicon  
 137 wafer.

## 138 2.2 The variable

139 To understand the effect of changes in the thickness of the silicon on the residual stress and  
 140 deformation, four thicknesses of silicon wafer were considered in this study, as shown in Table 2. Each  
 141 bonding material (solder or CF) was applied in four geometrical conditions for a total of 8 cases for  
 142 analysis and comparison.

## 143 2.3 Material Properties

144 The properties of solder, CF, and silicon were chosen as follows.

145 The total strain of solder is expressed as Eq.1.

$$\mathcal{E} = \mathcal{E}_e + \mathcal{E}_p + \mathcal{E}_c \quad (1)$$

146 where  $\mathcal{E}_e$  is the elastic strain,  $\mathcal{E}_p$  is the plastic strain, and  $\mathcal{E}_c$  is the creep strain.

147 The plastic strain was determined from the bilinear kinematic hardening rule. This rule assumes that the  
 148 total stress amplitude is equal to twice the yield stress as shown in Fig. 2. This rule can be considered as a  
 149 Bauschinger effect observed in the cyclic tensile and compressive loading.

150 The temperature dependent properties of solder were calculated from the stress-strain diagrams <sup>(24)</sup>.

151 The Creep strain of solder can be expressed by Norton's law for steady-state creep considering  
 152 temperature dependency,

$$\mathcal{E}_c = C\sigma^n \quad (2)$$

153 where  $\sigma$  is the equivalent stress, C and n are constants expressed as a function of temperature T as in Eq.3  
 154 and Eq.4, respectively.

$$C = 2.49 \times 10^{-9} \exp(-3.99 \times 10^{-2}T) \quad (3)$$

155

$$n = 2.49 \times 10^{-2}T - 5.09 \times 10^{-1} \quad (4)$$

156 A Maxwell viscoelastic model was used for CF to predict the stress or strain interactions under different

157 loading conditions. The Maxwell model can be represented by a purely viscous damper and a purely elastic  
158 spring connected in series.

159 In this model, the relaxation modulus,  $G(t)$  is determined by the Eq.5.

$$G = G_e + \sum G_i \exp(-t/t_i) \quad (5)$$

160 Material constants  $G_e$ ,  $G_i$ , and  $t_i$  were identified by dynamic viscoelasticity test as shown in Table 3.

161 The Williams-Landel-Ferry Equation (or WLF Equation) is used as time-temperature superposition  
162 principle to determine the stress relaxation behavior of CF <sup>(25)</sup>. The WLF equation has the form as Eq.6,

$$\log a_T = \frac{-C_1(T-T_R)}{C_2+(T-T_R)} \quad (6)$$

163 Where  $a_i$  is the shift factor and  $C_1$ ,  $C_2$  are constants.

164 For silicon, only elastic properties were considered as it is a brittle material. The Young's modulus and  
165 Poisson's ratio of silicon were 167GPa and 0.22, respectively <sup>(26)</sup>.

## 166 2.4 Analysis Condition

167 First, FEM analysis was carried out for the manufacturing process using solder bonding and CF bonding.  
168 The Sn-3.5Ag bonding consisted of heating from 298K to 493K for 15 seconds, then cooled immediately  
169 to 298K in the next 15 seconds. In the case of CF bonding, heating was up to 453K and a pressure of  
170 1MPa was applied during the whole process. Figure 3(a) exhibits the thermal profiles of the  
171 manufacturing process for solder bonding, while Fig. 3(b) shows the thermal profiles of the CF bonding.

172 As for the used condition, the effects of the thermal cycle and the thickness of silicon wafer are  
173 analyzed.

174 Three temperature cycles of 288~338 K, 278~318 K and 298~338 K as shown in Fig. 4 were applied to  
175 the analysis to understand the effect of different thermal cycles on the residual stress developed during  
176 manufacturing of the solar cell. The temperature increase and decrease rates are 50K/hour for the  
177 temperature cycles of 288~338 K and 40K/hour for 278~318 K and 298~338 K. Table 4 shows the  
178 temperature change for a simulation of 3 days. The thickness of silicon wafer considered in this case was  
179 200 $\mu$ m. A thermal cycle 288~338 K was applied to the analysis to clarify the effect of changes in the  
180 thickness of silicon on stress and strain distributions within the solar cell.

181

## 182 3. Analysis Result

### 183 3.1 Basic Model

184 The effect of two different bonding materials on solar cells deformation is explored in this section.



185 First, the analysis was carried out for manufacturing process using solder bonding and CF bonding.  
186 Thereafter, three temperature cycles considering different environmental operating conditions were  
187 applied to the analysis to understand how different thermal cycles affect the residual stress. The data was  
188 taken at the same time of analysis, in the same node for all models.

### 189 **3.1.1 Manufacturing process**

190 Results of the equivalent stress and strain were taken at 30 seconds of the manufacturing process to  
191 compare the effect of different bonding materials on the solar cells before exposing it to sunlight for its  
192 operation, as the temperature distribution redistributes the residual stress. The measurements were made  
193 in ANSYS 14.5 as time steps.

194 The equivalent stress distribution of the silicon after manufacturing for both solder bonding and CF  
195 bonding is exhibited in Fig.5. The maximum equivalent stress of silicon developed for solder bonding is  
196 95.2 MPa while it is 19.5 MPa for CF bonding. It can be observed that the maximum equivalent stress for  
197 solder bonding is about 5 times higher compared to CF bonding. Hence, the lower bonding temperature of  
198 CF in the manufacturing process makes it possible to have lower stress in the silicon. The residual stress  
199 was mainly concentrated at the edge of the tabbing track and the maximum residual stress observed at the  
200 margin of the cell edge.

201 In addition, the maximum equivalent strain of silicon is also 5 times higher for solder bonding than that  
202 of the CF bonding. Therefore, it can be said that CF bonding has a much greater reliability than solder  
203 bonding.

### 204 **3.1.2 Usage process**

205 The analysis of the cells during usage was carried out to understand the long-term effects of residual  
206 stresses that generated during the manufacturing process. Three temperature cycles of 278~318 K,  
207 298~338 K and 288~338 K were applied to the analysis. The times considered during the analysis were six  
208 months for solder and one month for the CF bonded cell.

209 Figure 6 shows the changes of stresses and strains of silicon with time for solder bonding. In this case  
210 the, stress in the silicon decreases with increase in temperature cycle. The decreasing order of the cycles  
211 for stress and strain are 288~338 K, 278~318 K and 298~338 K. In the case of the CF, the changes of  
212 stress and strain are negligible due to the fact that the strain is negligible in value and the decreasing  
213 order of the cycles are 278~318 K, 288~338 K and 298~338 K.

214 The variation of equivalent stress and strain of solder is shown in Fig. 7. In the case of CF, strain of

215 solder increases after passing 35 days for the cycle 278~318 K and about 60 days for the cycles 298~338  
216 K and 288~338 K. The increasing trend of strain is sharper for the cycle of 278~318 K compared to the  
217 other two cycles. The cycle of 288~338 K has a higher strain in first 55 days. However it becomes lower  
218 with time compared to the cycle of 278~318 K. It is noted that the stress of solder is similar for the cycles  
219 of 278~318 K and 288~338 K but lower for the cycle of 298~338 K.

### 220 ***3.1.3 Long term usage conditions***

221 In order to understand the creep deformation characteristics of solder in the long term, the analysis of  
222 the basic model was carried out for two years (730 days) under representative conditions. The thermal  
223 cycle used for the analysis was 288-338 K.

224 The variation of equivalent stress of solder with time is shown in Fig. 8(a). which indicates that the  
225 change of stress is not significant for the first year of usage, whereas stress decreases after a year. The  
226 strain increases sharply after 60 days during the first year as shown in Fig. 8(b). The increasing tendency  
227 towards more strain and plastic deformation with no change in stress is due to the creep of solder. The  
228 strain arises owing to CTE mismatches between joined materials in solar cell assemblies that expand and  
229 contract to different lengths as the temperature changes. It is noted that, the rate of change of strain  
230 becomes slower after a year. The equivalent strain of solder after two years of use is 6.68 [%]. However  
231 the creep strain has a tendency to saturate after about 400 days.

## 232 **3.2 Changes in the thickness of silicon**

233 This section explores the effect of varying the silicon wafer thickness on the residual stress and  
234 deformation considering the manufacturing and using process of solar cells.

### 235 ***3.2.1 Manufacturing process***

236 A greater amount of stress is obtained for thinner cells in case of solder bonding. The effects of varying  
237 the silicon thicknesses on the maximum stress, and strain of silicon are shown in Fig. 9. The maximum  
238 equivalent stresses developed in solder bonded silicon of 50, 100, 150 and 200 $\mu\text{m}$  thickness are about  
239 260, 167, 122 and 95MPa, respectively, while in CF bonded silicon they are about 66, 38, 25 and 20MPa,  
240 respectively. It should be noted that the maximum obtained stress for CF is much lower compared to the  
241 minimum obtained stress for solder. For the thinnest silicon of 50 $\mu\text{m}$ , the maximum strain is 0.16[%] for  
242 solder bonding, while it is 0.04[%] for CF bonding. In the case of 200 $\mu\text{m}$  silicon, the maximum strain for  
243 solder is 0.057 [%] and 0.012[%] for CF. Results show that, for all materials and thicknesses, CF bonding  
244 results in much lower stresses than solder. With decreasing silicon thickness, silicon undergoes an

245 increase in strain and stress, as expected. The reduced thickness of the wafer implies that it is more  
246 flexible, which means that the strain is higher for the same thermal load. However the rate of change of  
247 silicon stress with respect to silicon thickness is much lower when CF is used. It is because; lower  
248 thickness wafer is more susceptible to higher temperature of soldering than the CF bonding.

249 The effects of changes in the silicon thicknesses on maximum stress and strain in the bonded materials  
250 are shown in Fig. 10. For the thinnest silicon of 50 $\mu\text{m}$ , the maximum stress and strain of solder are  
251 observed to be 22.7 MPa and 6.33[%], respectively, while 1.42 MPa and 7.65[%] for CF. In case of  
252 200 $\mu\text{m}$  silicon, the maximum stress and strain for solder are observed to be 23.8 MPa and 7.42[%], while  
253 1.41 MPa and 7.63[%] for CF.

254 It is clear that the maximum stress and strain for solder bonding are much higher than for CF bonding.  
255 Solder bonding may not be a suitable option when considering the current trend of reducing silicon  
256 thickness. A manufacturing process based on CF bonding has much more reliability compared to solder  
257 bonding for all thicknesses of silicon.

### 258 **3.2.2 Usage process**

259 The variation of equivalent stress and strain of silicon bonded by solder is shown in Fig. 11. The  
260 equivalent stress on the solar cell is reduced for all thicknesses of silicon passing through the temperature  
261 cycles. The decreasing order of the stress and strain for thicknesses of silicon is 50, 100, 150 and 200 $\mu\text{m}$ .  
262 The rates of variation of stress and strain are much higher for thin silicon wafers. While, in the case of  
263 CF, there is quite a small stress increase, then afterwards, there is no significant change of stress and  
264 strain with time as shown in Fig. 12.

265 The variation of equivalent stress and strain of solder is shown in Fig. 13. For the bonding materials,  
266 there is no significant change of CF stress and strain with time. However for solder, strain increases with  
267 a decrease in silicon thickness after some days, which is due to the creep properties of the solder. The  
268 change of strain with time is much rapid for thinner silicon and the strain increases sharply for 50  $\mu\text{m}$   
269 thickness of silicon. The stress of solder has no significant change with thickness of silicon. The residual  
270 stress and strain values of the CF are lower for the thinner silicon wafers. It is noted that creep  
271 deformation accumulates in the solder rather than in the more brittle components to which it is attached.

### 272 **3.3 Discussions**

273 This study was aimed to simulate the manufacturing process and usage conditions of two solar cell  
274 configurations using FEM software. In addition, different silicon wafer thicknesses were considered in

275 order to analyze the long-term development of induced stresses. The first solar cell model was considered  
276 to be tabbed by a lead-free solder. The solder joint was sandwiched in between the copper wire and the  
277 silicon wafer. The large life span of solar cells and its continuous loading and unloading led to creep  
278 deformation which was an important phenomenon to be considered. It is noted that high stresses were  
279 induced in the manufacturing process due to the higher bonding temperature of solder. Identical strain and  
280 stress contours were obtained for silicon since this material is modeled as perfectly elastic. In addition,  
281 the analysis identified the critical locations on the cell which were potentially susceptible to structural  
282 failure after a few thousand thermal cycles due to the creep strain. Hence, the real challenge came from  
283 the analysis to determine the effects of creep and stress relaxation in the long term as two years (730  
284 days) of usage conditions were applied. It is noted that the equivalent strain of solder at two years of  
285 usage was 6.683[%]. In addition, the change in residual stress in wafer exhibited inverse relationship with  
286 the thickness of the wafer. Hence, solder bonding was not considered be a suitable option for current  
287 trend of reducing silicon thickness since the reliability was decreased with thin wafers due to the higher  
288 temperature manufacturing process.

289 The second solar cell model was bonded by CF taking viscoelastic properties into account. It is noted  
290 that the maximum equivalent stresses of CF bonded cell were fairly below the stresses of the solder  
291 bonded cell due to the lower temperature bonding. In addition, CF provided low stress level compared to  
292 all thicknesses of silicon regarding the usage conditions. Therefore, CF bonding was considered to be a  
293 potential option to tab solar cells such as thin and next generation solar cells (100 $\mu$ m – 50 $\mu$ m).

294 There were a few limitations to the analysis; the constitutive model and the estimation of the fatigue  
295 failure was not considered in this paper.

296 The accuracy of the structural analysis usually depends on the constitutive model employed in the  
297 analysis. Herein, the bi-linear stress-strain relation for plastic strain and Norton's law for creep strain  
298 were used for the solder alloy since these constitutive models do not need a long computational time to  
299 obtain the results. However, as one of the authors has previously pointed out <sup>(27)</sup>, a precise constitutive  
300 model explaining both the nonlinearity of the stress-strain relation and the creep curve are required to  
301 obtain the **more physically based** results, though the longer computational time is required. The  
302 construction of a new constitutive model to obtain the more accurate data will be conducted in the **future**.

303 The estimation of the fatigue failure of solders has also already been discussed by one of the authors  
304 <sup>(28)</sup>. A prediction method was proposed using the creep strain amplitude after a few cycle of the cyclic

305 loading obtained from the analysis. It was reported that the creep strain amplitude has an advantage to  
306 estimate the fatigue failure of the solder alloy. This method may also be employed for the estimation of  
307 failure of the solar cells in [future work](#).

308 The fatigue failure of solar cells under an actual [usage](#) conditions should also be [addressed](#) to confirm  
309 the accuracy of the results of the paper. [However](#), it is necessary to investigate the fatigue failure [over a](#)  
310 [period of](#) twenty to thirty years. Therefore, an experimental method [based on](#) an accelerated test [such as](#)  
311 HALT (highly accelerated limit test) should be employed <sup>(29)</sup>.

312 [Regarding](#) the CF bonding, there is not enough research work for [an](#) estimation of the fatigue failure.  
313 Therefore, to confirm the accuracy of the results obtained in this paper, basic experiments related to  
314 fatigue failure should be conducted for CF bonding.

315

#### 316 **4. Conclusion**

317 The present study performed a finite element analysis of manufacturing process and using conditions of  
318 solar cells to investigate the effect of various thicknesses of silicon wafer and temperature cycles on the  
319 deformation and residual stress. Sn-3.5Ag solder and CF were employed as the bonding interface of the  
320 solar cells. The results are summarized as follows:

321 (1) As for the manufacturing process, considering all thicknesses of silicon cells, both the residual stress  
322 and strain are much lower for CF compared to the solder bonded solar cell. Hence, CF bonding seems  
323 to be a promising method to tab solar cells. The residual stress was mainly concentrated at the edge  
324 of the tabbing track of the cells and the maximum residual stress observed at the margin of the cell  
325 edge.

326 (2) As for the usage conditions considered, there is no significant change in either stress and strain with  
327 time for CF bonding, while, in the case of solder bonding, the stress on the solar panel decreases due  
328 to the imposed temperature cycles, however, the change in stress becomes small with time. The strain  
329 of the solder increases after some days due to creep deformation. However, the lower stresses and  
330 strains in CF bonded joints do not ensure the reliability over 30 years, as other factors may also play  
331 a role.

332 (3) The trend toward thinning cells may lead to an increase in the breakage risk of solar cells due to  
333 excessive residual stress during soldering. Even though silicon stresses increase as wafers become  
334 thinner, CF bonding still offers lower stresses and it is clearly the comparable manufacturing process

335 when using thin solar silicon wafers.

336

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340

341 **Reference**

- 342 (1) A.M. Gabor, M. Ralli and S. Montminy. Soldering induced damage to thin si solar cells and detection of  
343 cracked cells in modules, 21st European photovoltaic Solar Energy Conference, Dresden, 2006.
- 344 (2) X.F. Brun and S.N. Melkote. Analysis of stresses and breakage of crystalline silicon wafers during  
345 handling and transport. *Journal of Solar Energy Materials & Solar Cells*, 93, 1238-1247, 2009.
- 346 (3) J. Wendt, M. Trager, M. Mette, A. Pfennig, and B. Jaeckel, The link between mechanical stress induced by  
347 soldering and micro damages in silicon solar cells, 24th European Photovoltaic Solar Energy Conference,  
348 Germany, ISBN: 3-936338-25-63420-3423, 2009.
- 349 (4) J.W. Kim, J.M. Koo and C.Y. Lee. Thermal degradation of anisotropic conductive film joints under  
350 temperature fluctuation. *Journal of Adhesion & Adhesives*, 28, 314-320, 2008.
- 351 (5) P.A. Wang, Industrial challenges for thin wafer manufacturing, Proc. 4th World Conference on  
352 Photovoltaic Energy Conversion, Waikoloa, HI, USA, 1, IEEE, Piscataway, 1179-1182, May 2006.
- 353 (6) P. Chen, M. Tsai and W. Yeh. Relationship between wafer fracture reduction and controlling during the  
354 edge manufacturing process. *Journal of Microelectronic Engineering*, 87, 1809-1815, 2010.
- 355 (7) P. Rupnowski and B. Sopori. Strength of silicon wafers: fracture mechanics approach. *International Journal*  
356 *of Fracture*, 155, 67-74, 2009.
- 357 (8) V.A. Popovich, A.Yunus and M.Janssen, Effect of silicon solar cell processing parameters and crystallinity  
358 on mechanical strength. *Solar Energy Materials & Solar Cell*, 95, 97-100, 2011.
- 359 (9) A. Fischera, Th. Grabollaa and H. Richtera. Mechanical strength of 300 mm diameter silicon wafers at  
360 high temperatures: modeling and simulation. *Journal of Microelectronic Engineering*, 45, 209-223, 1999.
- 361 (10) P. Chen, M. Tsai and W.Yeh. Relationship between wafer edge design and its ultimate mechanical  
362 strength,. *Journal of Microelectronic Engineering*, 87, 2065-2070, 2010.
- 363 (11) Y. Zemen, T. Prewitz, T. Geipel, S. Pingel, J. Berghold. The impact of yield strength of the interconnector  
364 on the internal stress of the solar cell within a module, 25th European Photovoltaic Solar Energy  
365 Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion, Valencia, Spain,  
366 4073-4078, 6-10 September 2010.
- 367 (12) C. Lai, C. Su and K. Lin. Analysis of the thermal stress and warpage induced by soldering in  
368 monocrystalline silicon cells. *Journal of Applied Thermal Engineering* 55, 7-16, 2013.
- 369 (13) C.H. Chen, F.M. Lin and H.T. Hu. Residual stress and bow analysis for silicon solar cell induced by  
370 soldering. International symposium on solar cell technologies, Taipei, December 2008.

- 371 (14) L. Yu, Y. L. Jiang and S. K. Lu. 3D FEM for sintering of solar cell with boron back surface field based on  
372 solidwork simulation. IERI Procedia 1 Singapore, 81 – 86, 2012.
- 373 (15) P. Chen, M. Tsai and W. Yeh. Relationship between wafer fracture reduction and controlling during the  
374 edge manufacturing process. Journal of Microelectronic Engineering, 87, 1809–1815, 2010.
- 375 (16) L. Bittoni. Aluminum pastes suitable for wide range thin crystalline silicon solar cells processing blistering  
376 and bowing effects reduction. 21st EPSEC, Dresden, 818-821, 2006.
- 377 (17) P.A. Wang. Industrial challenges for thin wafer manufacturing, Proc. 4th World Conference on  
378 Photovoltaic Energy Conversion, Waikoloa, HI, USA, 1, IEEE, Piscataway, 1179-1182, 2006.
- 379 (18) WW.J. Liu, Z.J. Pei and X.J. Xin. Finite element analysis for grinding and lapping of wire-sawn silicon  
380 wafers. Journal of Materials processing technology, 129, 2-9, 2002.
- 381 (19) S. Bhagavata and I. Kao. A finite element analysis of temperature variation in silicon wafers during  
382 wiresaw slicing. International Journal of Machine Tools & Manufacture, 48, 95–106, 2008.
- 383 (20) C. Funke, S. Wolf and D. Stoyan, Modeling the tensile strength and crack length of wire-sawn silicon  
384 wafers. Journal of Solar Energy Engineering, 131, 011012-1, 2009
- 385 (21) P. Grunow, P. Clemens and V. Hoffmann. Influence of micro cracks in multi-crystalline silicon solar cells  
386 on the reliability of PV modules. 20th European Photovoltaic Solar Energy Conference, Barcelona, Spain,  
387 2380-2383, June 2005.
- 388 (22) M.J. Rizvi, Y.C. Chan and C. Bailey. Study of anisotropic conductive adhesive joint behavior under 3-  
389 point bending. Journal of Microelectronics Reliability, 45, 589–596, 2005.
- 390 (23) J.W. Kim, J.M. Koo and C.Y. Lee. Thermal degradation of anisotropic conductive film joints under  
391 temperature fluctuation. Journal of Adhesion & Adhesives, 28, 314-320, 2008.
- 392 (24) Factual Database on Tensile and Low Cycle Fatigue Properties of Sn-37Pb and Sn-3.5Ag Solders, The  
393 Society of Materials Science, Japan, ISBN 4-901381-13-X, 2001.
- 394 (25) M. L. Williams, R. F. Landel, J. D. Ferry. The temperature dependence of relaxation mechanisms in  
395 amorphous polymers and other glass-forming liquids. Journal of the American Chemical Society, 77 (14),  
396 3701–3707, 1955.
- 397 (26) W. N. Sharpe, Jr. B. Yuan, and R. Vaidyanathan. Measurements of young's modulus, poisson's ratio, and  
398 tensile strength of polysilicon, Proceedings of the Tenth IEEE International Workshop on Micro Electro  
399 Mechanical Systems, Nagoya, Japan, 424-429, 1997.



- 400 (27) K. Ohguchi, K. Sasaki, and M. Ishibashi, A quantitative evaluation of time-independent and time-  
401 dependent deformations of lead-free and lead-containing solder alloys, *Journal of Electronic Materials*,  
402 35(1), 132-139, 2006.
- 403 (28) K. Ohguchi, and K. Sasaki, Investigation of effect of creep strain on low-cycle fatigue of lead-free solder  
404 by cyclic loading using stepped ramp waves, *Journal of Electronic Packaging*, 132, 041010-1-7, 2010.
- 405 (29) Y.-S. Chen, and L. H. Chuong, Efficiency improvement of the highly accelerated life testing system by  
406 using multiple hammers, *Journal of Mechanical Science and Technology*, 28 (12), 4815-4831, 2014.

## Figures Legends

1

2 Fig. 1: One quarter FEM model of the solar cell.

3

4 Fig. 2: Schematic diagram of bilinear kinematic hardening law.

5

6 Fig. 3: Temperature conditions of manufacturing process. (a) Solder bonding (b) CF bonding

7

8 Fig. 4: Temperature change during using conditions. (a)288K↔338K (b)278K↔318K (c)298K↔338K

9

10 Fig. 5: Equivalent stress of silicon. (a) Solder bonding (b) CF bonding

11

12 Fig. 6: Equivalent stress and strain of solder bonded silicon during using process. (a) Equivalent

13 stress (b) Equivalent strain

14

15 Fig. 7: Equivalent stress and strain of solder during using process. (a) Equivalent stress (b) Equivalent

16 strain

17

18 Fig. 8: Equivalent stress and strain of solder during two years of using process. (a) Equivalent stress (b)

19 Equivalent strain

20

21 Fig. 9: Effect of silicon thickness on the stress and strain of silicon. (a) Equivalent stress of silicon. (b)

22 Equivalent strain of silicon.

23

24 Fig. 10: Effect of silicon thickness on the stress and strain of bonding materials. (a) Equivalent stress of  
25 silicon. (b) Equivalent strain of silicon.

26

27 Fig. 11: Effect of silicon thickness on solder bonded silicon during using process. (a) Equivalent stress  
28 of silicon. (b) Equivalent strain of silicon.

29

30 Fig. 12: Effect of silicon thickness on CF bonded silicon during using process. (a) Equivalent stress of  
31 silicon. (b) Equivalent strain of silicon.

32

33 Fig. 13: Effect of silicon thickness on solder during using process. (a) Equivalent stress of silicon. (b)

34 Equivalent strain of silicon.

Fig. 1 (a)

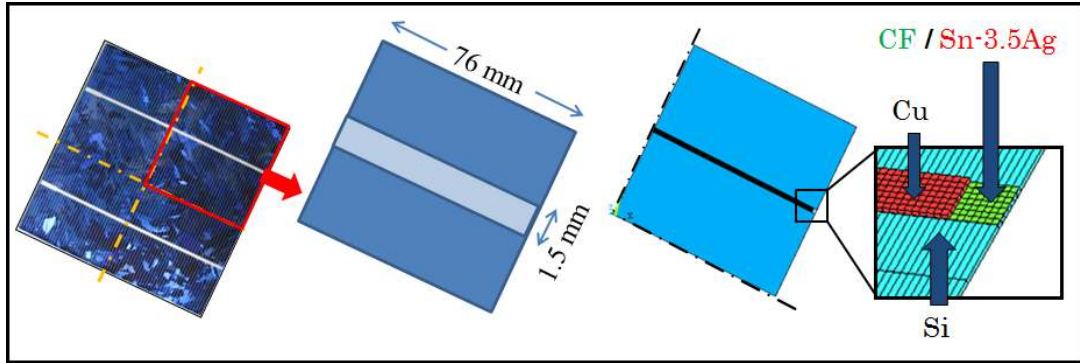


Fig. 2

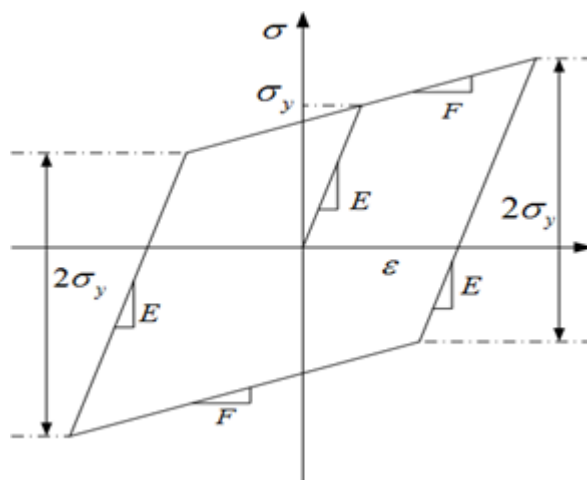


Fig. 3 (a)

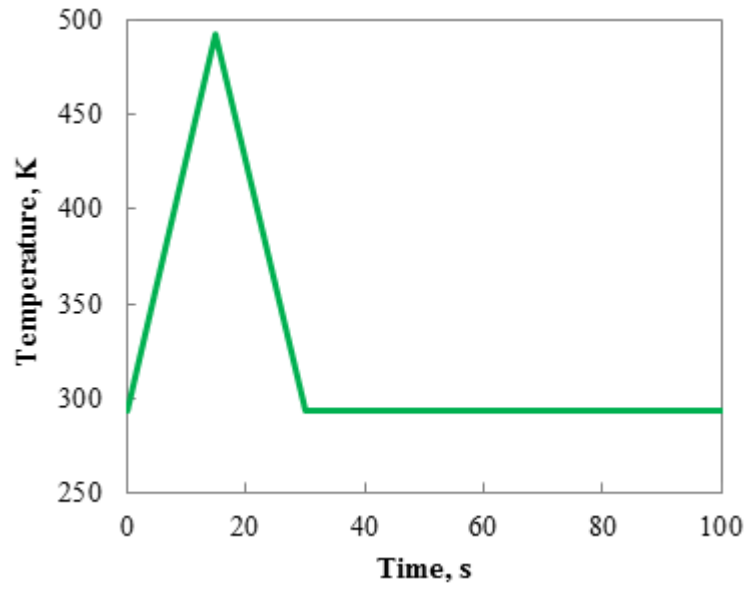


Fig. 3 (b)

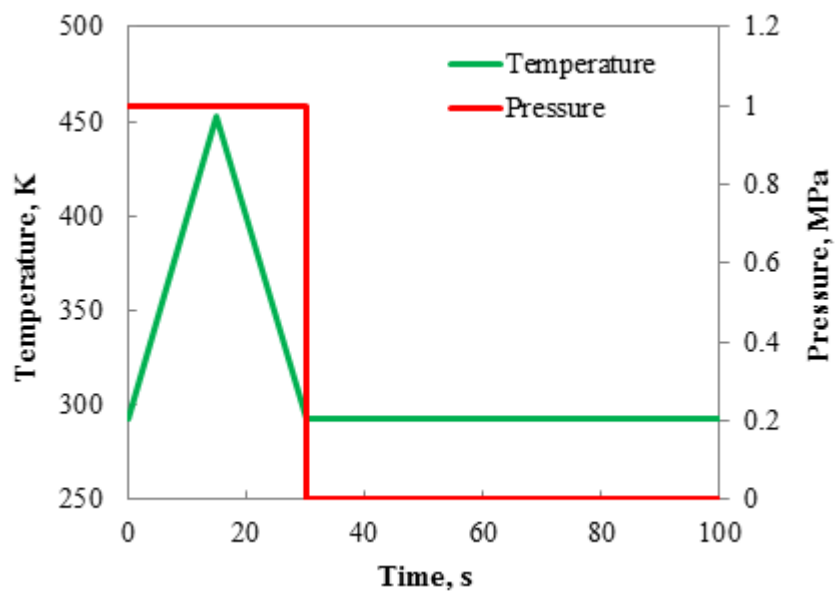


Fig. 4

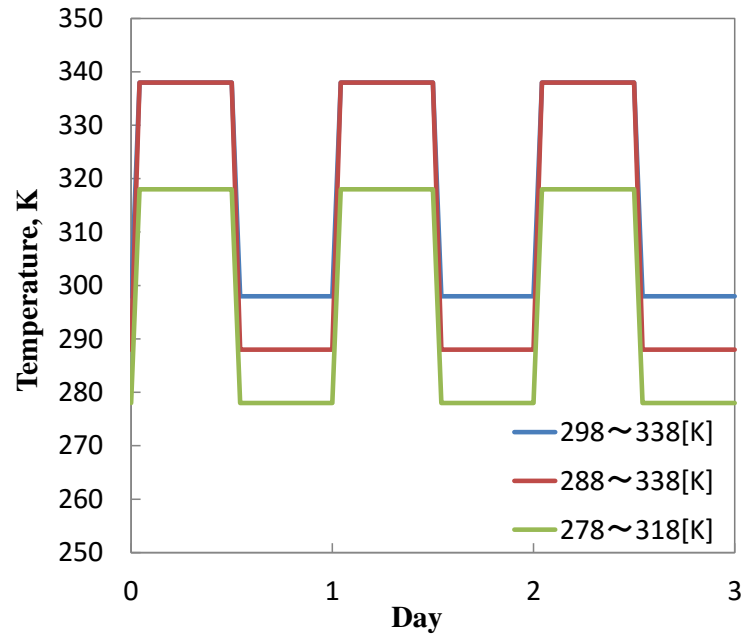


Fig. 5 (a)

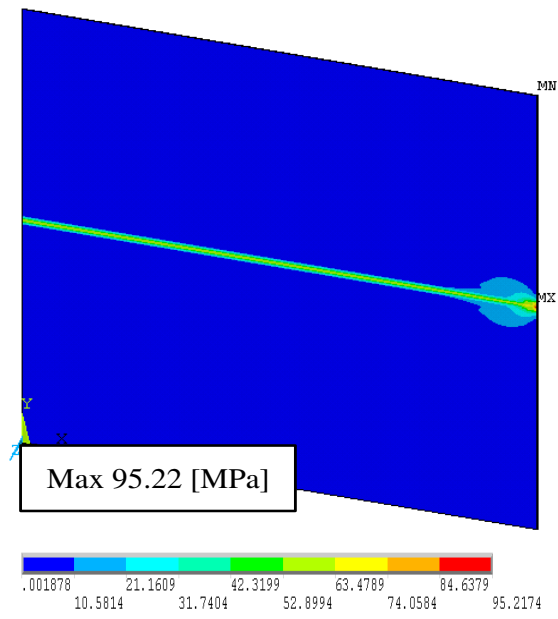


Fig. 5 (b)

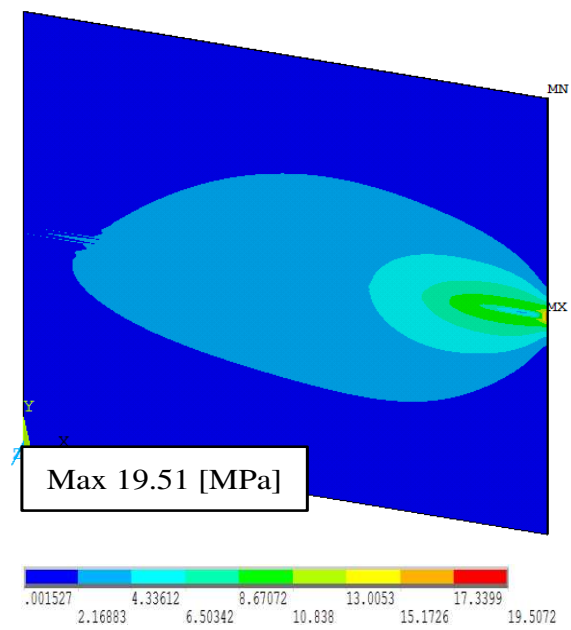


Fig. 6 (a)

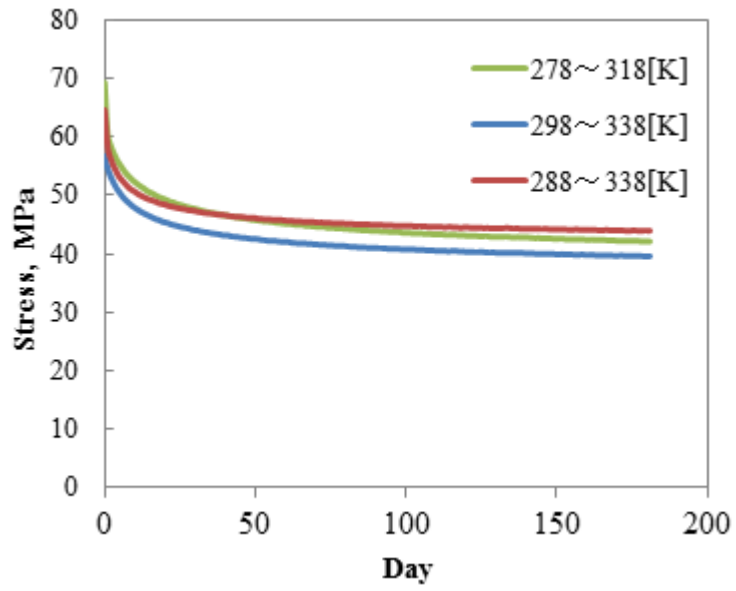


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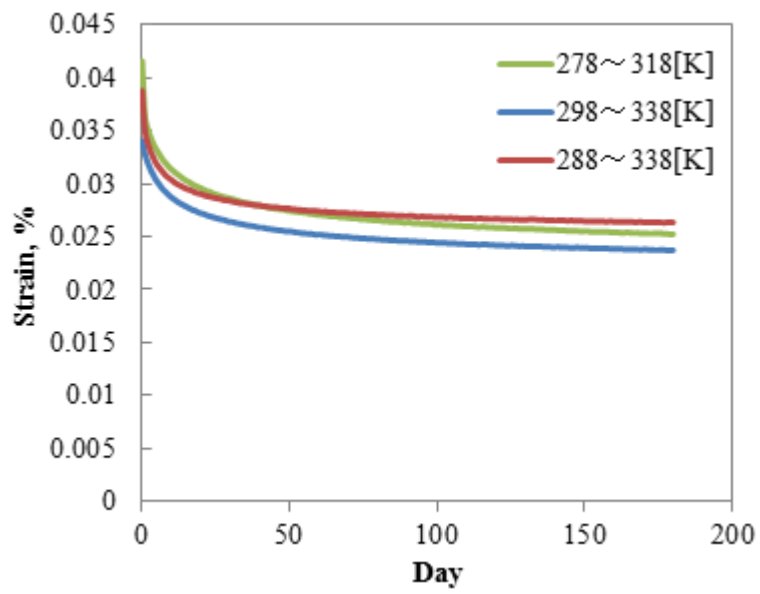




Fig. 7 (a)

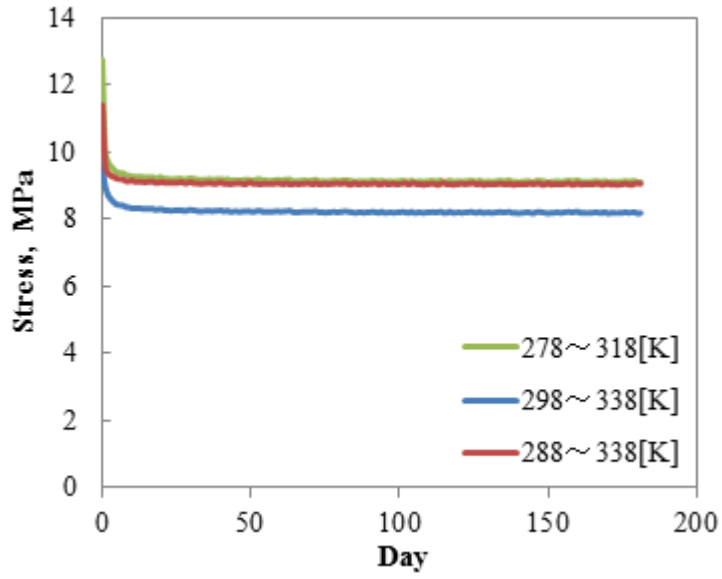


Fig. 7 (b)

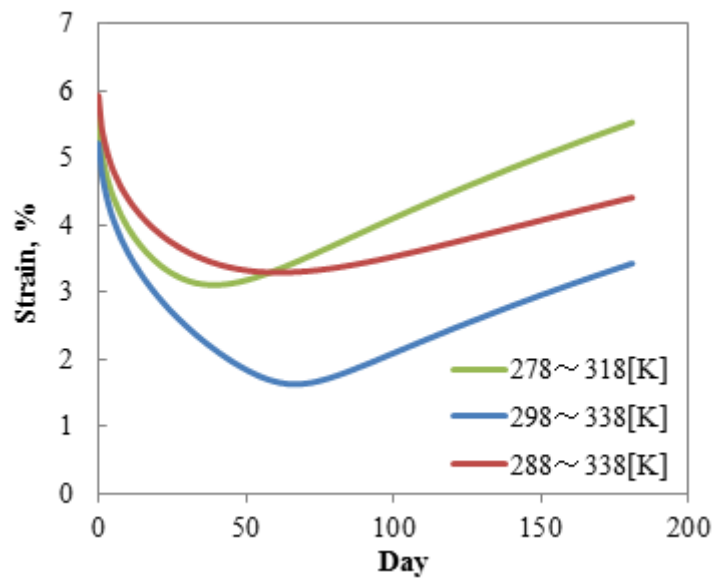


Fig. 8 (a)

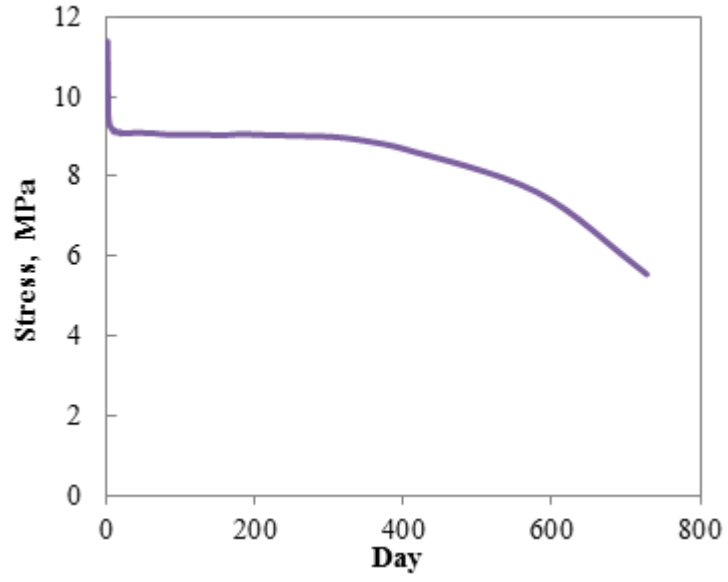


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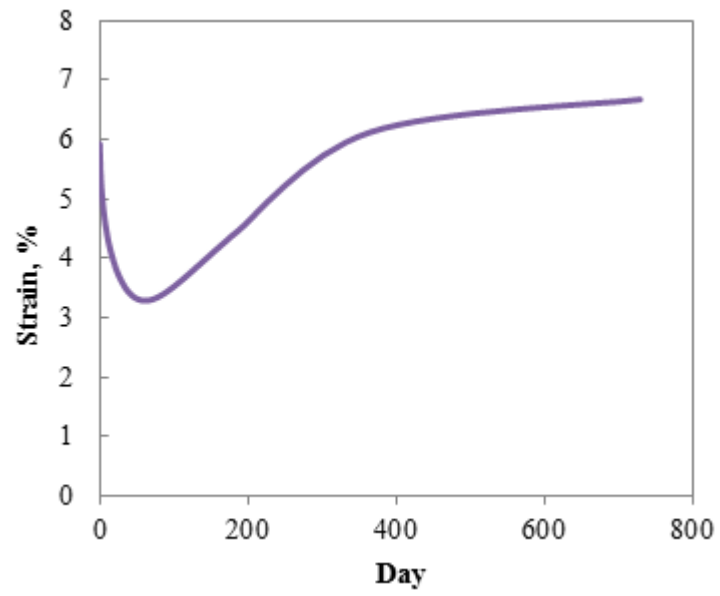


Fig. 9 (a)

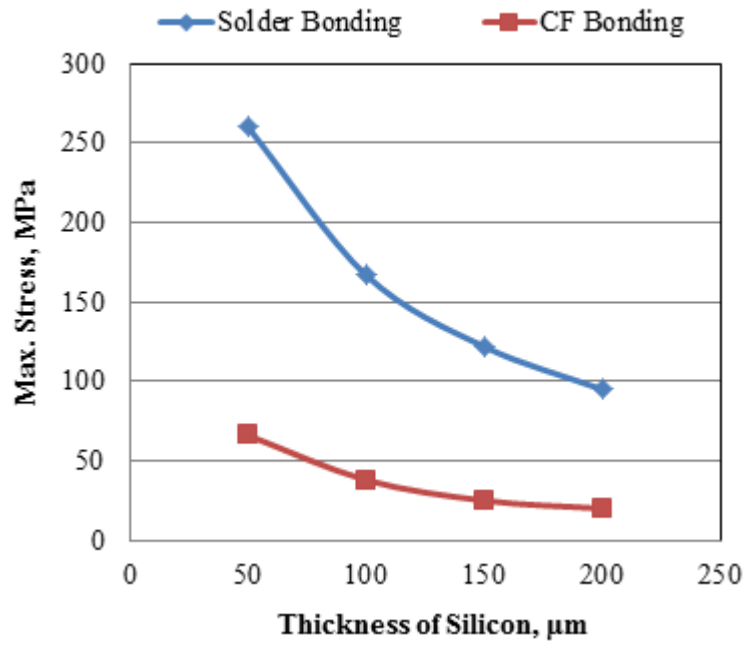


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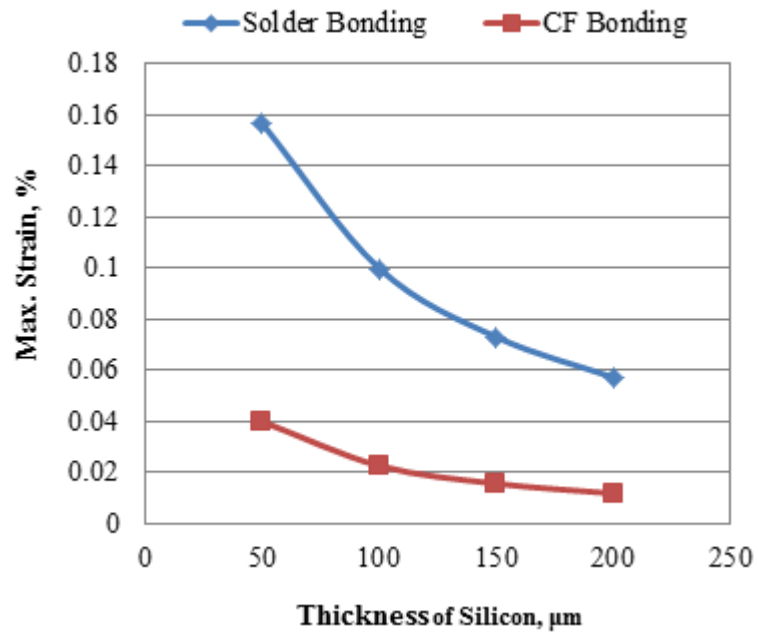


Fig. 10 (a)

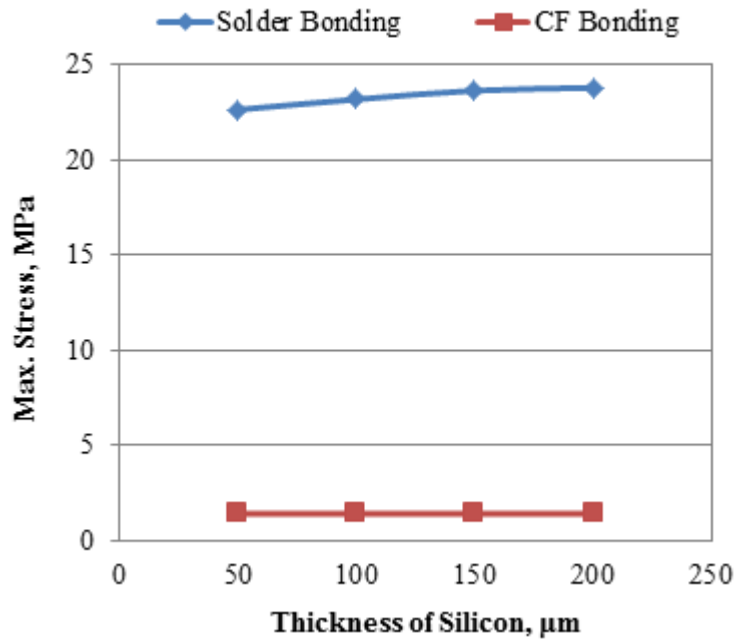


Fig. 10 (b)

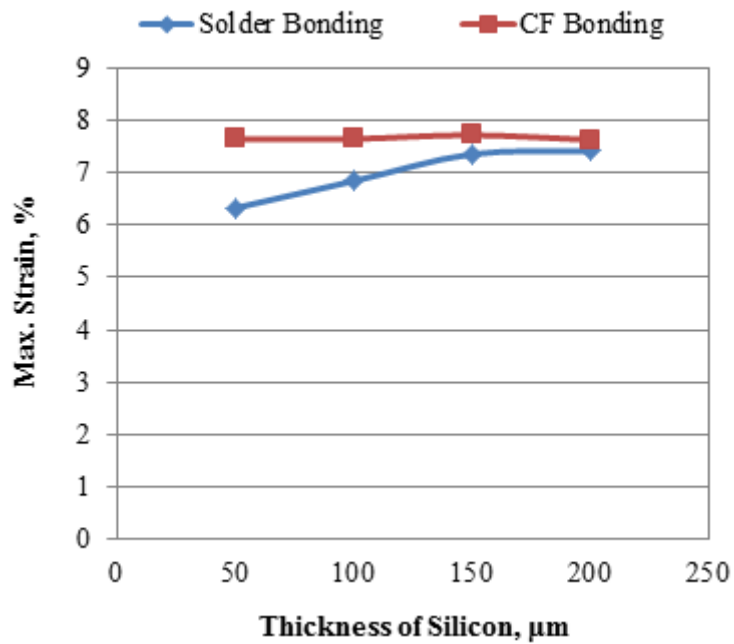


Fig. 11 (a)

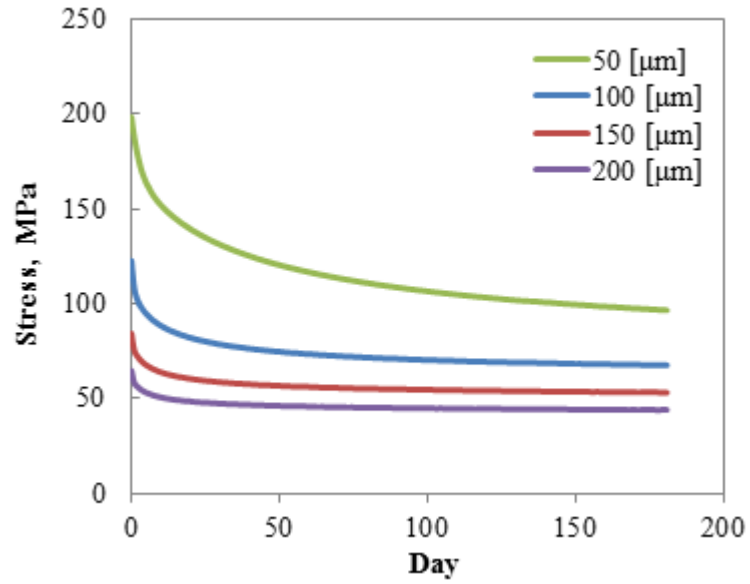


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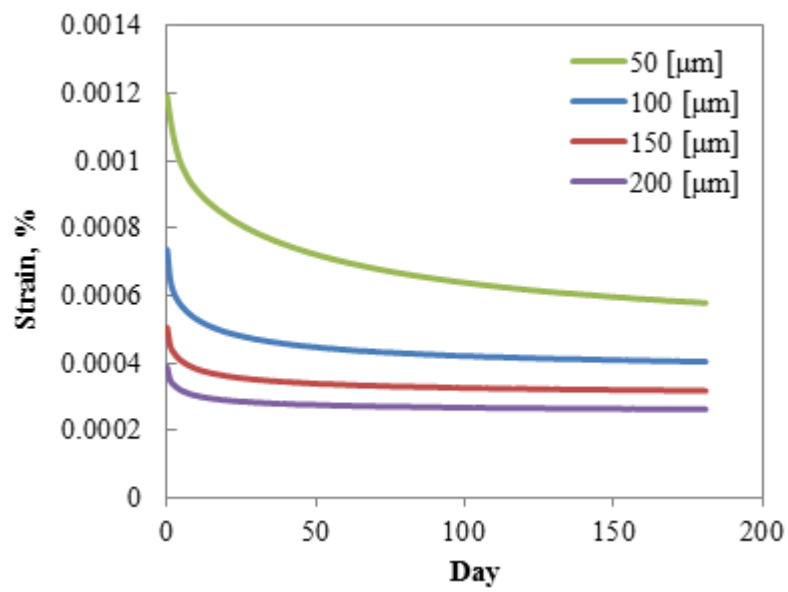


Fig. 12 (a)

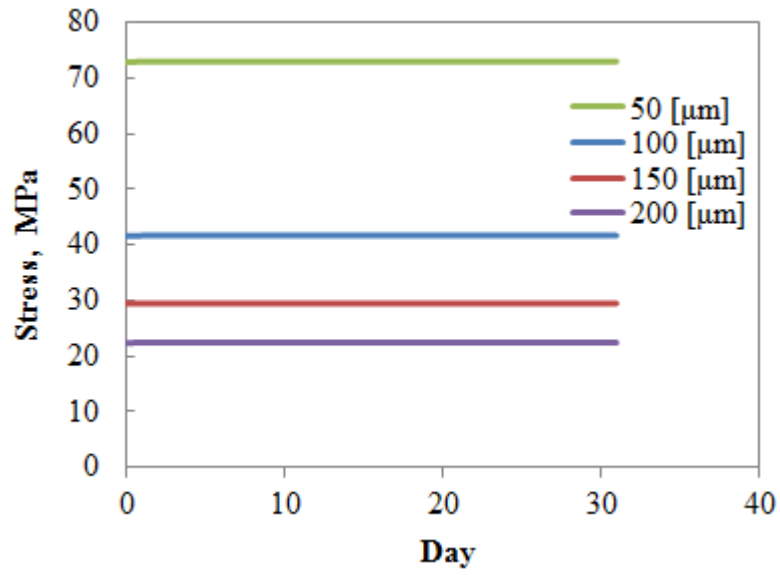


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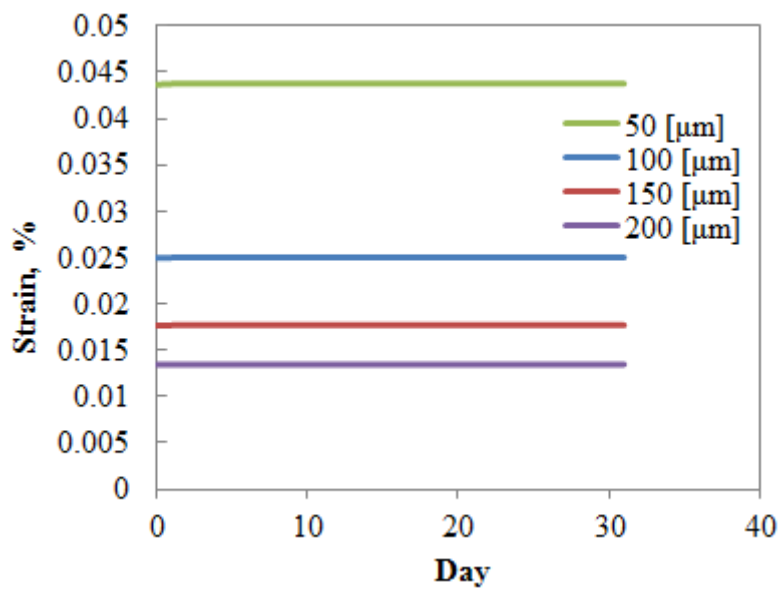


Fig. 13 (a)

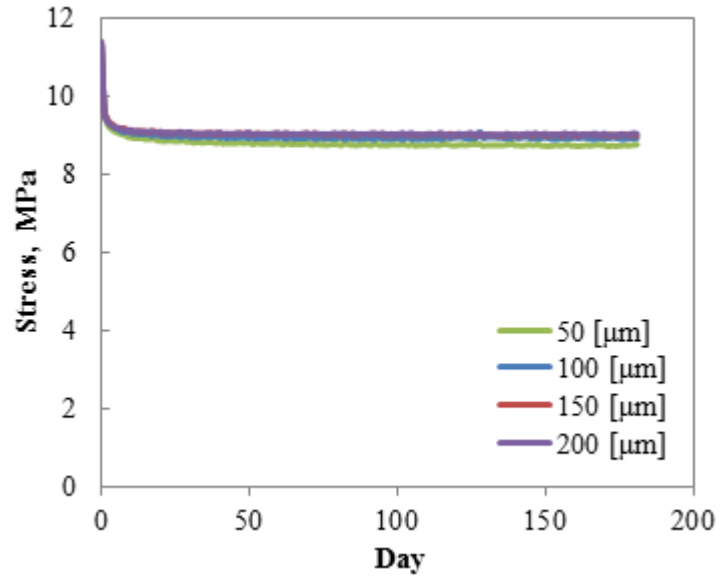
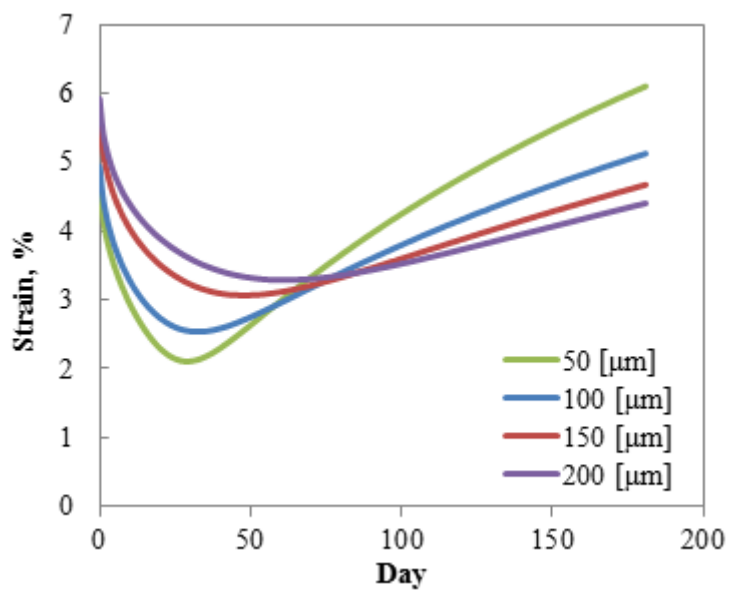


Fig. 13 (b)



## Table Legends

1

2 Table 1 Dimensions of materials of the FEM model.

3 Table 2 Changes in the thickness of silicon

4 Table 3 Relaxation modulus and relaxation time for CF.

5 Table 4 Temperature change during using conditions. (a)288K↔338K (b)278K↔318K (c)298K↔338K

6



Table 1

Model Dimensions	Si	CF	Lead-free solder	Tab line
Thickness, $\mu\text{m}$	200	25	25	200
Length, mm	152	152	152	152

Table 2

(a) Changes in the thickness of silicon				
Changes in parameters	Case name			
	Basic Model	Case 1	Case 2	Case 3
Thickness of silicon ( $\mu\text{m}$ )	200	150	100	50

Table 3

	$G_i$ [Mpa]	$t_i$ [s]
$G_e$	18.52	
$G_{1,t_1}$	76.04167226	1.67719E-17
$G_{2,t_2}$	66.64145084	1.93474E-16
$G_{3,t_3}$	70.32219498	2.23184E-15
$G_{4,t_4}$	73.7978527	2.57456E-14
$G_{5,t_5}$	79.62871406	2.96991E-13
$G_{6,t_6}$	88.64931451	3.42596E-12
$G_{7,t_7}$	105.5638331	3.95205E-11
$G_{8,t_8}$	136.2689132	4.55893E-10
$G_{9,t_9}$	190.1902796	5.259E-09
$G_{10,t_{10}}$	273.2235596	6.06656E-08
$G_{11,t_{11}}$	290.8875059	6.99814E-07
$G_{12,t_{12}}$	130.6660281	8.07278E-06
$G_{13,t_{13}}$	34.74453208	9.31243E-05
$G_{14,t_{14}}$	8.230024055	0.001074244
$G_{15,t_{15}}$	5.927283979	0.012392045

Table 4

Days (Hours)	Temperature (K)		
	298~338 K	288~338 K	278~318 K
0 (0)	298	288	278
0.041 (1)	338	338	318
0.5 (12)	338	338	318
0.541 (13)	298	288	278
1 (24)	298	288	278
1.041 (25)	338	338	318
1.5 (36)	338	338	318
1.541 (37)	298	288	278
2 (48)	298	288	278
2.041 (49)	338	338	318
2.5 (60)	338	338	318
2.541 (61)	298	288	278
3 (72)	298	288	278