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Reliability Optimization of Gold-Tin Eutectic Die Attach Layer in HEMT Package

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Abstract

This paper compared the fatigue damage accumulationof the gold-tin eutectic die attach layer in different high electron mobility transistor (HEMT) packages with various types of die attach layers and substrates underthermal cyclic loading. The fatigue damage per cycle used in this study wascharacterized by the accumulation ofplastic work, whichwas derived by the finite element analysis (FEA). The effects of die attach layer's standoff height and thickness of substrateon fatigue damage accumulation was discussed. The results show that increasing the standoff height of the die attach layer is an effectiveway toprevent the early crack initiation in gold-tin die attach layer especially for a gallium nitride (GaN) die. It is also indicated that for a GaN die, a thicker die attach layer and a thinnersubstrateare preferable in order to retain a comparable lifetime with silicon (Si) die and Cu substrate system.

1. Introduction

Wide band gap semiconductors, typically based on silicon carbide (SiC) and gallium nitride (GaN), have attracted much attention in power devices, due to their advantages of higher thermal conductivity, higher breakdown field strength, higher operating temperature above 200˚Cand lower power loss compared to the commonly adopted silicon (Si) based devices[1, 2]. Among which, the GaN based semiconductors are mainly used in the high electron mobility transistor (HEMT), which combines the advantages of high speed and low-loss switching performance and makes themvery attractive for switching power supplies and microwavepower devices[3].

The die attach layer plays an important role in HEMT devices, including the mechanical adhesion, thermal stress compensation, as well as heatdissipation.The gold-tin (Au80Sn20)eutectic solder alloy has been widely adoptedas die attach materials in many power devices, especially for microwave devices and laser diodes[4]. Advantages have been proved for gold-tin eutectic solder alloy, such as high melting temperature of 278 ˚C,preferable high temperature reliability, high electrical ($1.64\times10^{7}/(\Omega\cdot m)$[5]) and high thermal conductivity (57 W/(m·K)[6]), high stiffness, as well aspossibilityof flux-free soldering.

Consideringthe high operation temperature and the large mismatch of coefficients of thermal expansion (CTE) between die and substrate, large thermal stresslevel and deformation may be expectedin power semiconductor devices. These will cause all kinds of delamination and consequently poor thermal interface between different materials, in which the fatigue damage of die attach layer will finally results in the failure of devices. However, currently, there are few publications regarding design rules of this type of package in terms of geometry and substrate materials preference. Therefore, in order to optimize the package design, it is necessary to investigate the geometric effects of the whole package structure on the reliability of die attach layer.

By using the finite element analysis (FEA) method, this paper compared the fatigue damage accumulation in gold-tin eutectic die attach layer in different HEMT packagesunder temperature cycling. Effects of die materials, standoff height (SOH) of die attach layer and thickness of substrate on the accumulation of fatigue damageunder thermal cyclicloading were investigated.

2. Finite element analysis method

The Anand constitutive model is a rate-dependent plasticity model for simulations such as metal forming[7, 8]. It is widely applicable for analyzing strain and temperature effects including solder joints and their hightemperature creep[9].Two main features are defined in the Anand constitutive model. Firstly, the explicit yield surface andloading/unloading criterion are not required for this model. The plastic strain is supposed to generate at all nonzero stress values, even if the plastic flow is extremely small at low stresses. Secondly, a singleinternal scalar"s"termed as deformation resistance is used to describe the averaged isotropic resistance to inelastic flowof the material[10, 11].

The deformation resistance, *s*, is an averaged isotropic resistance to macroscopic plastic flow, which is resulted from strengthening mechanisms such as dislocation density, solidsolution hardening, and grain size effects.Therefore, the deformation resistance, *s*, can be regarded proportional to the equivalent stress σ, as shown in eq. (1)[7]:

$$\sigma = c \cdot s; c < 1 \qquad (1)$$

where c is defined as eq.(2)[7]:

$$c = \frac{1}{\xi} \sin h^{-1} \left[\left(\frac{\dot{\varepsilon}_p}{A} \exp\left(\frac{Q}{RT}\right) \right)^m \right] \qquad (2)$$

Where $\dot{\varepsilon}_p$ is the plastic strain rate, A is the pre-exponential factor, Q the activationenergy, m is the strain rate sensitivity, ξ is the stress multiplier, R is the universal gasconstant, and T is the absolute temperature.

The plastic strain rate $\dot{\varepsilon}_p$ can be described as eq. (3)[7]:

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$$\dot{\varepsilon}_p = A\exp\left(-\frac{Q}{R\theta}\right)\left[\sinh\left(\xi\frac{\sigma}{s}\right)\right]^{1/m} \quad (3)$$

The evolution equation is given byeq. (4) [7]and eq. (5)[7]:

$$\dot{s} = \left\{h_0\left|1-\frac{s}{s^*}\right|^a \cdot sign\left(1-\frac{s}{s^*}\right)\right\}\cdot\dot{\varepsilon}_p; a > 1 \quad (4)$$

with

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

whereh_0 is the hardening/softening constant, a is the strain ratesensitivity of hardening/softening, $s^*$is thesaturation value of s,$\hat{s}$ is the coefficient for saturation value of deformation resistance, and n is thestrain rate sensitivity.

The parameters in Anand model are related to material properties, such as $A, Q, \xi, m, h_0, \hat{s}, n, a,$and s_0, s_0 is theinitial value of the deformation resistance. The parameters of gold-tin eutectic solder alloy in Anand model are listed in Table 2.1[12].

Table 2.1Anand model constant for gold-tin eutectic solder alloy[12]

Anand constant	Units	Value	Description
s_0	MPa	69.99	Initial value of deformation resistance
Q/R	1/K	7578.7	Q = Activation energy R = Universal gas constant
A	S^{-1}	93.07	Pre-exponential factor
ξ	-	11	Stress multiplier
m	-	306280	Strain rate sensitivity of stress
h_0	MPa	0.573	Hardening / softening constant
$\hat{S}$	MPa	466.13	Coefficient for deformation resistance saturation value
n	-	0.046	Strain rate sensitivity of saturation (deformation resistance) value
a	-	1.402	Strain rate sensitivity of hardening / softening

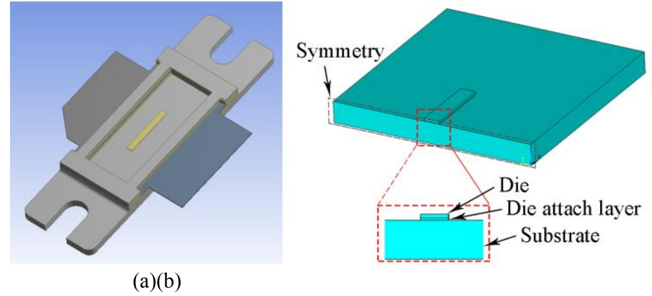
In order to simplify the solution of model,someassumptions have been applied to the model as followings:

- The 3D model is considered as a symmetrical model anda half model was simulated to save computational time without affecting the accuracyof the solution.
- The material parameters of substrate and die wereconsidered as constant during modeling;
- The formation of intermetallic compounds and the microstructure evolution of Au-Sn eutectic solder alloy wereneglected in the modeling, since they have limited effects on joint properties in low cooling rate cycles [13];
- The effects of the metallization layers of the die and substrate were not taken into account in order to simplify the simulation process.

3. Package structure and materials

According to an actual HEMT device, a simplified model with a symmetricstructure was used for simulation, as seen in Figure 3.1 (a) and (b). The simplified 3D model consists of three layers: copper substrate, die attach layer and semiconductor die with Si or GaN material. The material properties adopted in this study are shown in Table 3.1[14-16]. The Young's modulusof gold-tin eutectic solder alloyis considered to be linear with temperature ramp up.

According toJEDEC Standard JESD22-A104D, the temperature profile from 0 to 125 ˚Cis used as boundary conditions during modeling. The rate for temperatureramp up and down is set as 5 ˚C /min, and the dwell times at maximumand minimum temperature are 10min and 5min, respectively.Furthermore, it is assumed that the plastic work accumulation became stabilized after the first three cycles[17]. Therefore, four thermal cycles are performed in this studyfor modeling,and the temperature profile is designed in Figure 3.2.



(a)(b)

Fig. 3.1 (a)Schematic diagram of product, (b) Simplified structure

Table 3.1 Material properties[14-16]

Material	Young's modulus (GPa)	Poisson ratio	CTE ($10^{-6}\cdot K^{-1}$)
Si	120	0.28	2.8
GaN	295	0.25	3.2
Au80Sn20	0, 79.45	0.3	18
	25 ˚C, 70.95		
	50 ˚C, 62.45		
	100 ˚C, 45.45		
	125 ˚C, 36.95		
Cu	124	0.34	16.9

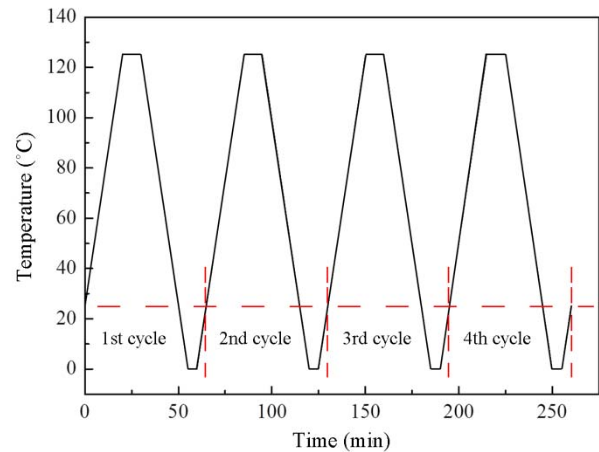


Fig. 3.2Temperature cycle profiles used in the simulation

4. Results and discussion

4.1 Effects of die materials on plastic work densityevolution

The plastic work density distributionin the die attach layersof packages with different die materials after the 4th thermal cycle were simulated with FEA, as shown in Figure 4.1 (a) and (b).It shows that the maximum plastic work density is located in the outer lower corner for both cases, which is the most critical area to be considered.

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In this paper, the elements with maximum plastic work energy are considered as critical elements. The plastic work density obtained in this study was the average value of these elements. The evolution of plastic work density for Si and GaN based model was plotted in Figure 4.2. The plastic work densities in die attach layer increase linearly with the increase of thermal cycle number for both Si and GaN based models.

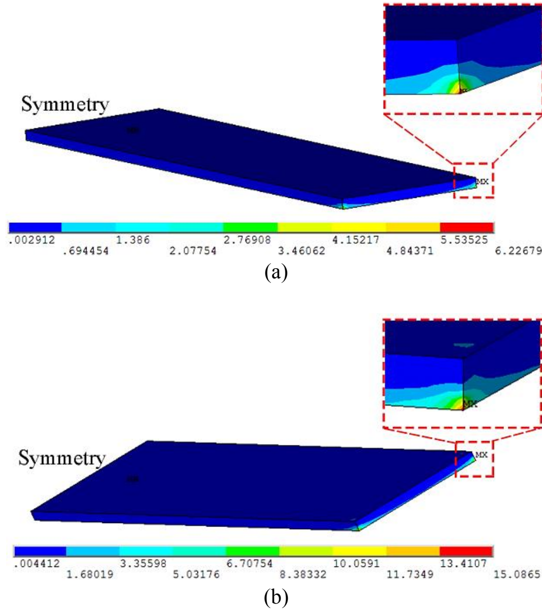


Figure 4.1 Distributions of plastic work density in die attach layer after 4th cycle, (a) Si based model, (b) GaN based model

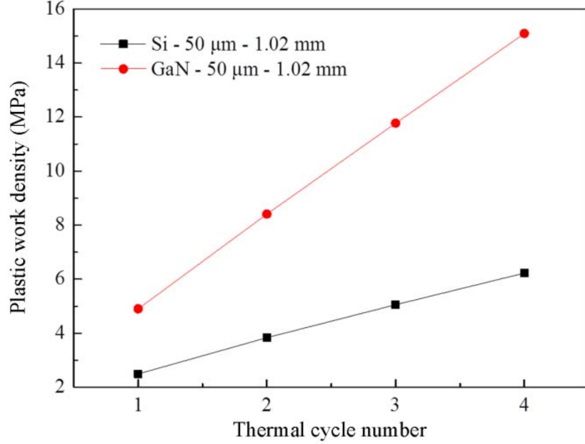


Fig 4.2 Evolution of plastic work density in die attach layer

However, a larger plastic work density was obtained in GaN based model after the fourth cycle when compared with Si based model. It is suggested that the larger deformation will be induced at the corner of die attach layer due to the much larger difference of Young's modulus between GaN die and gold-tin layer. Therefore, higher plastic work density generated in GaN based model, which will lead to a shorter fatigue life time when compared with Si based model.

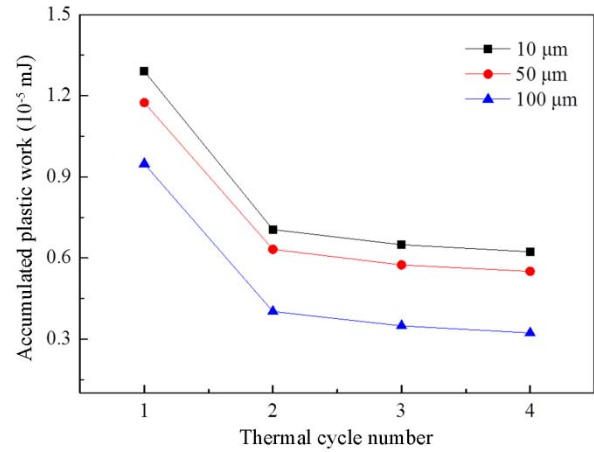
4.2 Effects of SOH onthe accumulation of plastic work

It is reported that the accumulated plastic work of critical elements over load step can be termed as ametric for predicting the fatigue life time of solder alloys[10]. The accumulated plastic work ΔWcan be described as eq. (6):

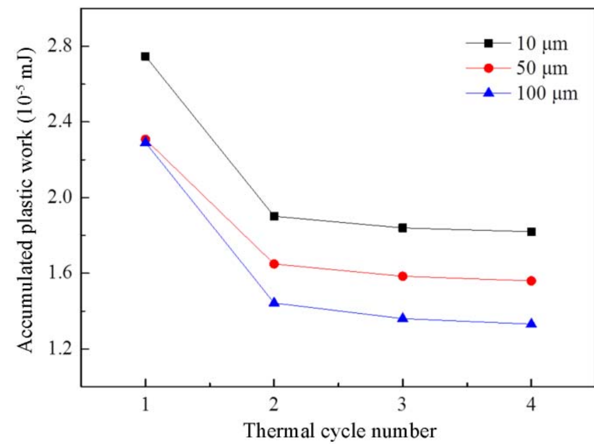
$$\Delta W = W_i - W_{i-1}, i = 1, 2, 3, 4 \quad (6)$$

where$W_{i-1}$is the plastic work of the last cycle. In this study, the effects of die attach layer'sSOH on the accumulation of plastic work ΔW were analyzed as shown in Figure 4.3 (a) and (b). Similar trendshave been observed for both Si and GaN based models. Firstly, the accumulation of plastic work tends to be stableafter the second thermal cycle in all models. The accumulated plastic work after the third and fourth cycle is quite similar. Secondly, the amount of accumulated plastic work increaseswith decreasingSOHafter each cycle in all models.Moreover, the accumulation of plastic work in GaN based models appears to be more sensitive to SOH.

It is suggested that thedie attach layer with a higher SOH is more capable of accommodatingplastic deformation. Consequently the higher SOH results in less plastic work accumulation inside die attach layer, which implies that a longer crack initiation time is expected.Based on the results above, it is notable that increasing the standoff height of the die attach layer is an effective way to prevent the early crack initiation in gold-tin die attach layer especially for a GaN die.



(a)



(b)

Fig 4.3 Effects of SOH on the accumulation of plastic work in die attach layer, (a) Si based model, (b) GaN based model

4.3 *Effects ofsubstrate thicknesson the accumulation of plastic work*

The effects of substratethickness on the accumulation of plastic work were simulated and shown in Figure 4.4 (a) and

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(b). As shown in the figure, the accumulation of plastic work indie attach layer became stable after the second thermal cycle in both Si based and GaN based models. Moreover, due to the higher Young's modulus of GaN die material, there are more plastic work accumulated in die attach layer in the same geometrymodel, as seen in Figure 4.4 (b).

However, the highest plastic work accumulation was gained with the thickest substrate in both Si and GaN based models in this paper.The thicker substrate has less flexibility in deformation during thermal cycling, which will transfer more stress into die attach layer and result in higher plastic work accumulation.

Therefore, in order to have a longer fatigue life time, a thinner substrate is more desirable for GaN based power devices. Furthermore, a thinner substrate has a higher efficiency in transferring heatfrom package to heat sink, which is essential to maintain a stable work for power devices.

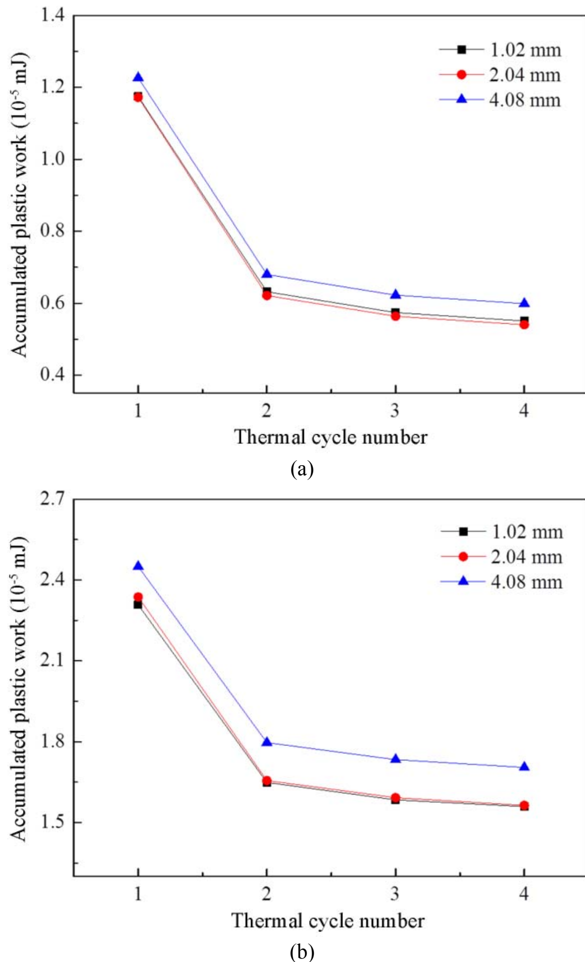

Fig 4.4Effects of substratethickness on the accumulation ofplastic work in die attach layer, (a) Si based model, (b) GaN based model

5. Conclusions

In this paper, finite element analysiswas performed to comparatively investigate the influence of die materials, die attach layer's standoff heightand substratethickness on the fatigue damage accumulation in gold-tin eutectic die attach layer under thermal cyclicloading.The results suggested that a much higher plastic work density was gained in gold-tin die attach layer in the GaN based model. Moreover, it is suggested that a thicker die attach layerand a thinner substrate are more preferable for GaN power devices in this paper.The optimization of package design helps to maintain a longer fatigue life for power devices. In the further, more works will be focused on the optimization of package design for various working conditions, and a guideline is expected to be given.

Acknowledgments

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