STRENGTH DETERIORATION IN SUBSTRATE FOR SEMICONDUCTOR POWER DEVICES BY THERMAL CYCLIC TEST

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ABSTRACT

The fractures in aluminum nitride (AlN)-DBC (Direct Bond Copper) semiconductor substrate are caused by the residual stress due to the thermal stress produced in manufacturing process and thermal cycle. The fractural mechanism and strength were investigated based on fracture mechanics. The results obtained are summarized as follows;(1) The structural reliability of the substrate is influenced by the behavior of the residual stress. The repetition of thermal cycle increases residual stress, and lowers the strength of the substrates. (2) The residual tensile stress is distributed within narrow range of Al_2O_3 formed chemically on the surface of AlN, and its maximum stress is far larger than nominal fracture stress in four-point bending of monolithic AlN. This fact suggests the necessity of the fracture strength evaluation based on stress intensity factor. (3) The fracture of the substrate can be analyzed on the basis of the crack growth mechanism, which depends on stress intensity factor, K. The strength and/or fracture life of DBC substrate with the residual stress can be clarified through the thought mentioned above.

KEYWORDS

Substrate For Semiconductor, Direct Bond Copper, Thermal Cyclic Test Durability

INTRODUCTION

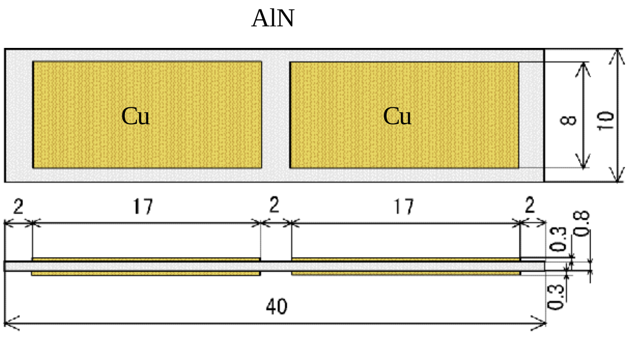
The electric power, consumed in the semiconductor parts for an industrial equipment, increases recently, with increasing in the demand of high-power, high integration, high reliability, modulation, low cost, and so on. Thus aluminum nitride (AlN)-DBC (Direct Bond Copper) semiconductor substrate have been developed and applied to practical parts because of better heat radiation required in practical service. The AlN-DBC semiconductor substrate is the joint body, which is strongly bonded copper plate to the surface of ceramic (AlN) by using Cu-O eutectic layer as a joint substance. The Cu-O eutectic layer is formed by reacting of Cu-O eutectic phase a small amount of oxygen with copper in high temperature (about 1300K) [1, 2]. Therefore, the followings become problems. The first is the fast fracture of ceramic due to generating of thermal stress in manufacturing process by difference of the thermal expansion coefficient between ceramic and metal. The second is the delayed fracture of ceramic due to thermal cycle stress under practical service condition.

In this study, the thermal cyclic test and four-point bending test were carried out. Moreover, the residual stress was analyzed and strength deterioration due to the thermal cyclic stress was discussed. In addition, the fracture strength of the substrate was evaluated based on fracture mechanics, and the fracture life was estimated from the viewpoint of long-term reliability.

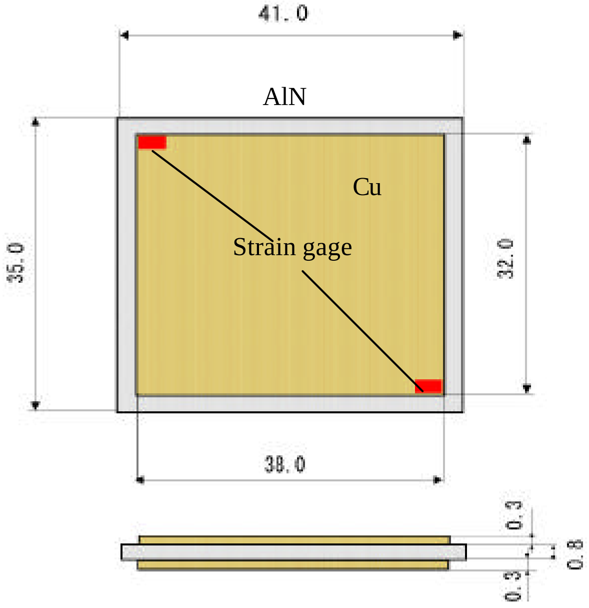
EXPERIMENT PROCEDURE AND ANALYSIS MODEL

Experimental procedure

Two types of tests were conducted to investigate the damage of the DBC substrates subjected to repetitive thermal cycle. The first is four-point bending test against the substrates subjected to 1~5 thermal cycles so as to identify the damage as the reduction of bending strength, compared with the virgin substrates. The second is the test to examine the fracture life due to thermal cycle, which is defined as cycle's number until fracturing of substrates. Two types of DBC substrate as shown in Figs.1(a)and(b) were prepared for each test. Thermal cycles against substrates are given by a to-and-fro motion of conveyer between heater box and freezer box under electric-timer-control. One thermal cycle was the sequence of heating (398K, 30min), cooling (room temperature, 10 min), cooling (243K, 10min) and heating (room temperature, 10 min) as shown in Fig.2. Four-point bending inner span was 10mm, and outer span was 30mm. The fracture of substrate in cycle life test was detected noticing the rapid fluctuation obtained by monitoring an output of strain gage putted on the Cu part.



(a) Four-point bending test



(b) Thermal cyclic test

Figure 1: Specimens

Analysis model

The residual stress produced in thermal cyclic test as well as manufacturing process was analyzed by FEM. The stress analysis was conducted under plain strain condition by using the model consisting of 3parts such as Cu plate, AlN plate and Al_2O_3 layer, bonding chemically each other as shown in Fig.3. As the first stage, the residual stress caused by bonding was analyzed within temperature range from 1323K to 293K. The change of the residual stress due to thermal cycle into the next stage was analyzed taking the stress caused by bonding into consideration. The thermal cycle conditions were agreed with experimental one. On evaluating the measured stress during the four-point bending test, the true bending stress by applied loading was added on the residual stress changed in two stages.

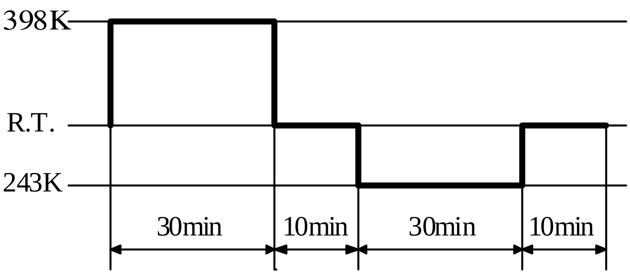
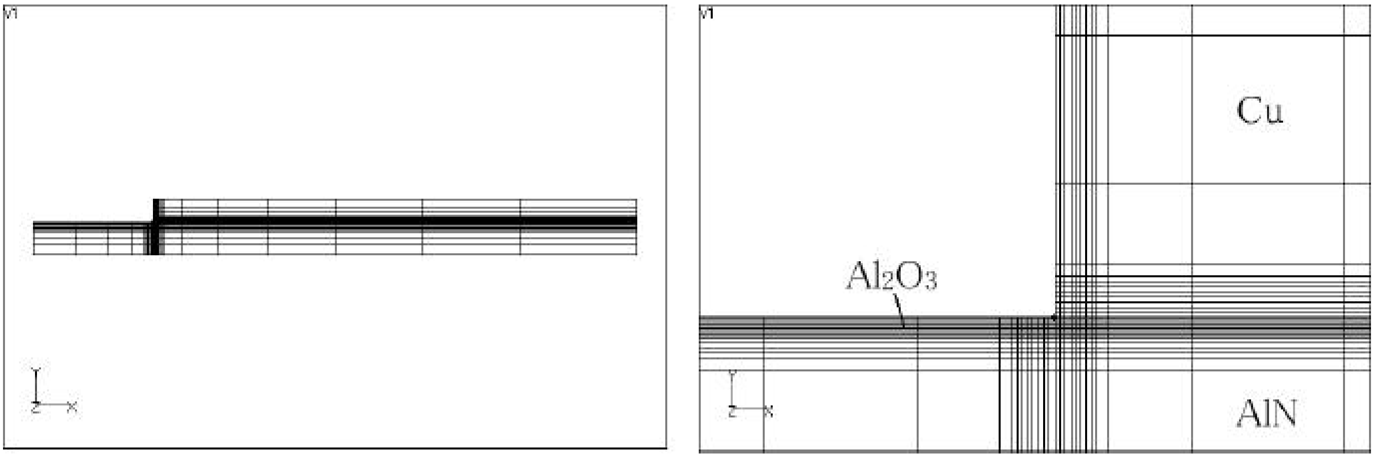


Figure 2: Thermal cyclic pattern

The stress intensity factor mentioned after was calculated



(a) Whole view

(b) Magnified view

Figure 3: Analysis model

from energy variation of the whole analysis model system before and after of crack growth [3].

RESULTS AND DISCUSSION

Experimental results

Figure 4 shows the relationship between nominal fracture stress in the four-point bending tests and number of thermal cycles. The nominal fracture stress reduced with increasing of thermal cycles, and so it was found to be verified that the damages due to thermal cycles were accumulated with increasing thermal cycle.

The fracture of the substrate in the thermal cyclic life test shows the morphology of exfoliation between Cu and AlN at 140 cycles as Fig.5, and the occurrence of such exfoliation fracture could be detected by monitoring the output of strain gage.

Analytical result

Figure6 shows the distributions of the residual stress obtained through estimating fracture strength by bending tests. In the Fig.6, the stress is expressed as equivalent normal stress. The stress is concentrated within narrow range near the bonding surface of AlN, and reduces rapidly from surface to inner. The maximum stress, called fracture stress in following, is generated at point A in every specimen as shown in Fig.6. Figure7 shows

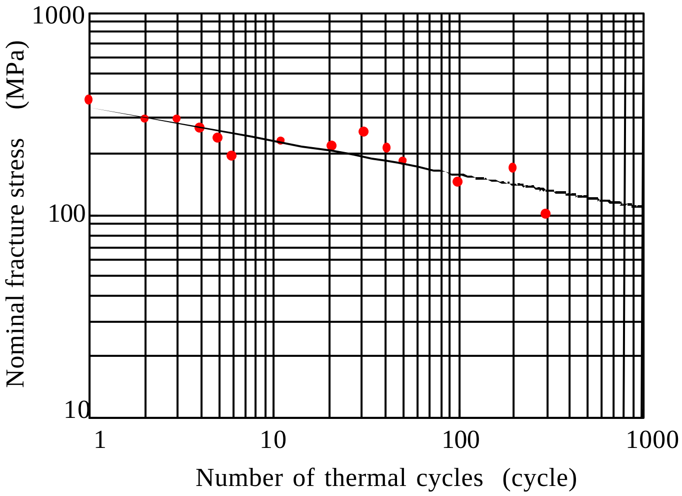


Figure 4: Relationship between nominal fracture stress in the four-point bending tests and number of thermal cycles

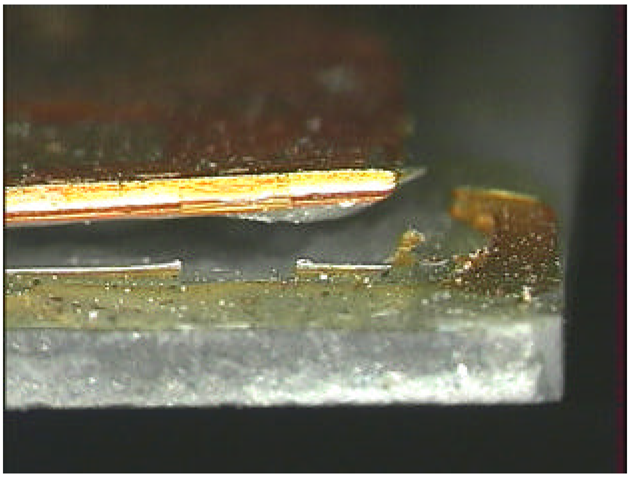
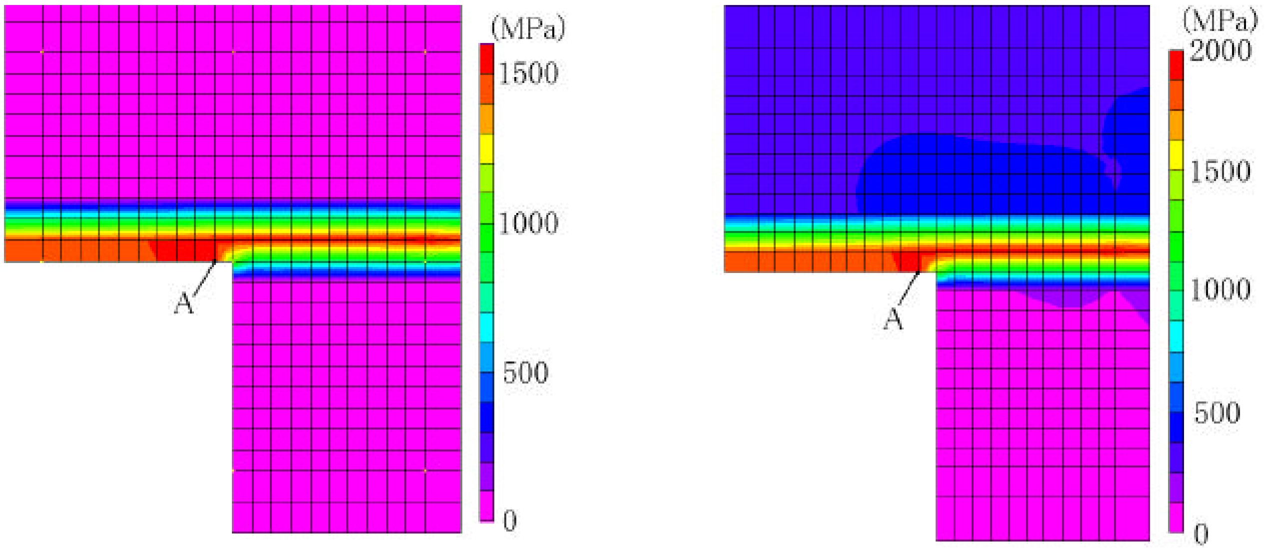


Figure 5: Fracture morphology of the substrate in the cyclic life test



(a) 1 thermal cycle loaded specimen (b) 5 thermal cycle loaded specimen

Figure 6: The distributions of the residual stress (equivalent normal stress).

relationship between analyzed fracture stress and number of thermal cycles. The true fracture stress is above 1900MPa and far larger than the four-point bending strength of the monolithic smooth AlN plate, 380MPa. Moreover, the stress is not constant and reduces with increasing of thermal cycles. Thus, the maximum tensile stress is not suitable for the criterion of the fracture. Therefore, the following discussions are according to the next assumptions; (1) the fracture occurs from the initial defect existing at the maximum stress point, and the defect can be regarded as initial crack, (2) sizes of initial cracks are almost same in every substrates tested, (3) the crack growth depends on the stress intensity factor, K, (4) unstable fracture occurs on reaching of K to fracture toughness value, K_{IC}.

Discussion based on assumption of crack growth

As for the time dependent crack growth in ceramics, the crack growth rate, *da/dt*, is evaluated as follows

$$\frac{da}{dt} = CK^n = C\left(\varphi\,\sigma_R\sqrt{\pi a_0}\right)^n = C\left(\sigma_R\sqrt{\pi a_{eq}}\right)^n \qquad (1),$$

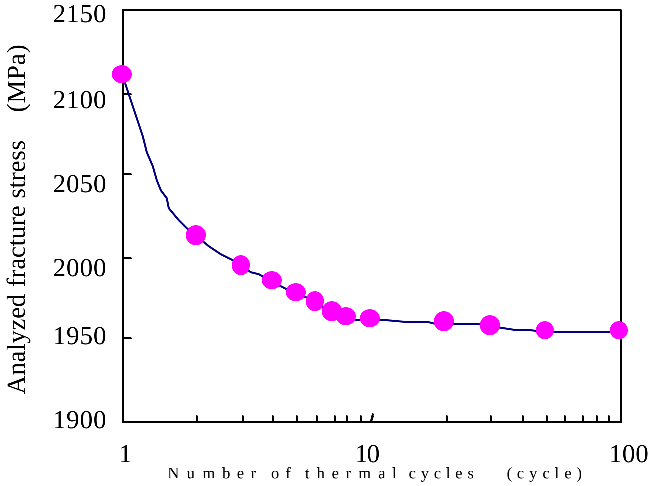


Figure 7: Relationship between analyzed fracture stress and number of thermal cycles

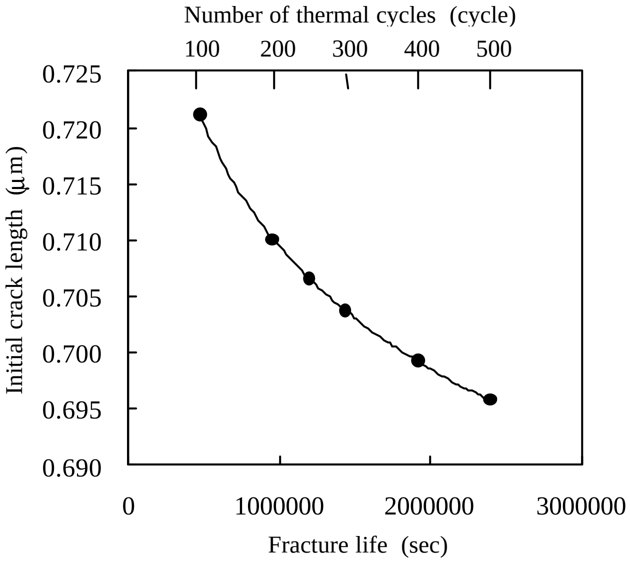
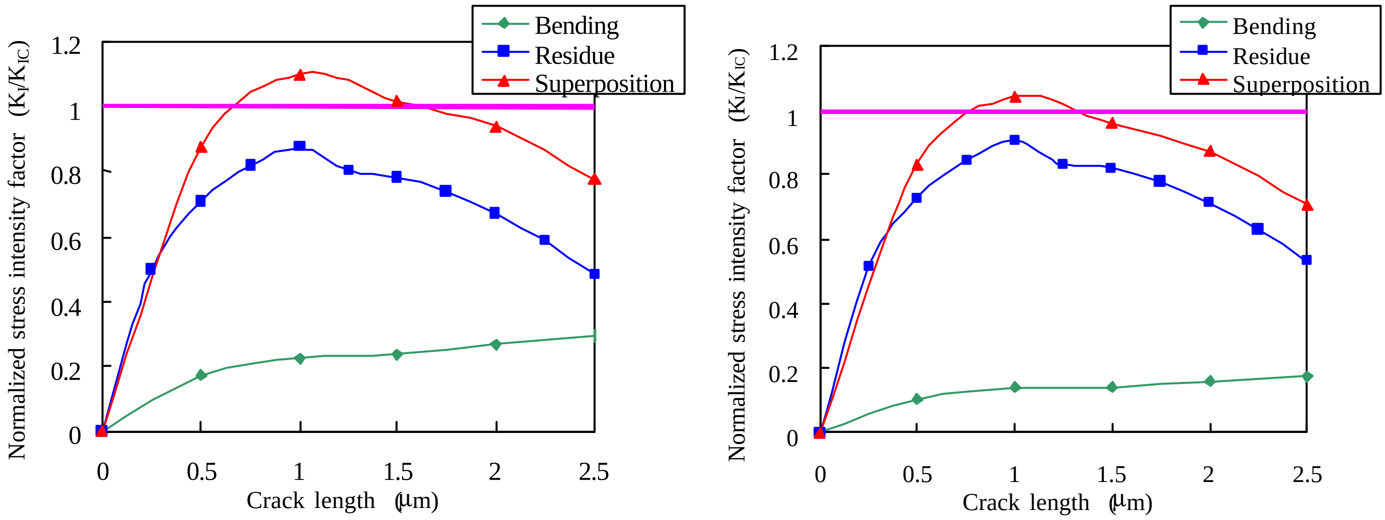


Figure 8: Relationship between the calculated fracture life and assigned initial crack length



(a) Non thermal cycle loaded specimen (b) 5 thermal cycles loaded specimen

Figure 9: Relationship between normalized stress intensity factor and assigned crack length

where a_0 is initial crack length, C and n, material constants, , shape factor, $_R$, residual stress, $2a_{eq}$, surface crack length of equivalent semi-circular defect. The fracture life is defined as the duration of crack growth from initial length to final one causing unstable fracture of substrates, and so can be calculated by integrating eq.(1). Figure8 shows the relationship between the fracture life obtained by calculation and initial crack length assigned on the substrate as parameter. It was surmised from the number of cycles that the initial crack length is nearly 0.72 micrometer.

Figure9 shows relationship between stress intensity factor normalized by fracture toughness value and assigned crack length on the two specimens, where either thermal cycles of 0 and 5 were conducted. Though, both of residual stress and bending stress are different in either of specimens, the superposition stress intensity factors in both specimens reach fracture toughness value on reaching of crack lengths to 0.6~0.8micrometer. This crack length is well agreement with the crack length evaluated from result obtained in the cyclic life test mentioned above.

As a result, the fracture of the DBC substrates can be analyzed as the crack growth from initial defect depending on stress intensity factor, K. If the size of initial defect is known, the bending strength and/or thermal cycle life is predictable.

REFERENCES

1. Mizunotani, Y. and Hashima, M. (1986) Toshiba review, 41, 9, 811.
2. Sugiura, K. and Iwase, A. (1989) Toshiba review, 44, 81 626.
3. Kobayashi, H. (1993); *Fracture mechanics*; Kyoritsu syuppan, Tokyo