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# The study on failure mechanisms of bond pad metal peeling: Part A—Experimental investigation

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## Abstract

For the experimental investigation on failure mechanisms of bond pad metal peeling, 31 failed SDRAM chips after the pad peeling are gathered, and SEM and FIB are utilized. From the results of this study, the vertical tension loading transferred by the capillary to the deformed ball is recognized as the direct driving force for the pad peeling and the crack on the bonding pad as well as its propagation into the oxide layers under the pad is identified as the direct cause of the pad peeling. Moreover, the propagation of the crack along the interface of the layers under the pad is explained as the initiation of 'ductile fracture type failure', which can be considered as a possible cause of the pad peeling. A schematic diagram for the process of the pad peeling is constructed based on the results of this research and the effect of the probe test on the pad peeling is also investigated to confirm the result of Hotchkiss et al. [Proceedings of the 51st Electronic Components and Technology Conference, 2001, p. 1175].

## 1. Introduction

Ultrasonic wire bonding is one of the major processes in electronic package that provides electrical interconnections between bonding pads and lead frames using fine gold wires. During the ultrasonic wire bonding process, however, several failures such as misplacement of ball, neck failure, ball tail, ball missing and bond pad metal peeling, etc., may be generated, which worsen the bond ability and ball bond reliability. Of those failures, bond pad metal peeling is a phenomenon detected after bonding operation and is recognized as a serious quality and reliability problem resulting in assembly yield loss. In the peeled-off pad, it is observed that a part of the bonding pad with or without a part of the oxide layers under the pad are separated from the normal pad with a bonded wire ball.

Such a bond pad metal peeling problem is known as a very complex one affected by not only the wafer FAB process but also the assembly process in the field of electronic packaging. Thus, only a few investigations to analyze the problem have been carried out until these days. One of them is performed by Mckenna [2]. In their research, they found a set of optimized bond parameters for improving pad cratering, lifted metal which is known as bond pad metal peeling, and lifted balls known as ball missing related with the bond reliability. Moreover they showed that bonding pad cratering is the result of microcracks in the silicon and oxide layers under the pad.

Tan et al. [3,4] identified the root causes of bond pad metal peeling of VSLI chip utilizing FIB, SEM, EDX and AFM. Especially, they found that the possible failure mechanisms of bond pad metal peeling might be related to the presence of an extra layer between pad metal and poly-Si layers and to the morphology of the poly-Si surface. Furthermore, they concluded that BOE (buffered oxide etch) etching time before the bond pad metal deposition was correlated to the poly-Si morphology and had a significant effect on the wire bonding quality. Recently, Hotchkiss et al. [1] showed that the

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damage of the pad metal surface during wafer probe test is resulted from the scrubbing action of probe needle on the pad surface and that the amount of probe damage on the pad surface directly affected both the lifted ball and the lifted metal.

In this paper, we focus on analyzing the failure mechanisms of bond pad metal peeling of SDRAM chip, which show a different aspect of the pad peeling from that of VSLI chip [3,4] because of the different layer structure under the bonding pad between these two chips. For this study, we use SEM and FIB to observe the surface shape and the shape of cross-section of the peeled-off pad, respectively. In addition, we investigate the experimental results obtained from the gathered SDRAM chips after the pad peeling to find the root causes of the pad peeling of SDRAM chip.

## 2. The loadings in the ball bonding process of ultrasonic wire bonding

The ball bonding process of ultrasonic wire bonding consists of four steps as follows: an air free ball formation process utilizing the intense heat transferred from EFO (electrical flame off) electrode at the end of gold wire; descent process of the capillary to deform the ball on the bonding pad that is heated by the high temperature of heater block; vibration process of the capillary to transfer the ultrasonic energy to the ball, which helps the diffusion and the adhesion between the deformed ball and the bonding pad; ascent process of the capillary from the deformed ball to finish the ball bonding process. Therefore, there are four main loadings transferred to the chip during ball bonding process of ultrasonic wire bonding (see Fig. 1).

First of all, thermal loading is applied over whole ball bonding process on the bonding pad and the oxide layers under the pad by temperature of the ball increased by EFO electrode and by the temperature of the heater block fixed in bonding machine. Then vertical compression loading is transferred by the capillary through the deformation of ball, and horizontal vibration loading that is to be the shear loading to the bonding pad as well as the oxide layers is applied by the capillary by means of the ultrasonic power of the bonding machine. Last of all, vertical tension loading is given on the deformed ball by the capillary during the ascent process of the capillary.

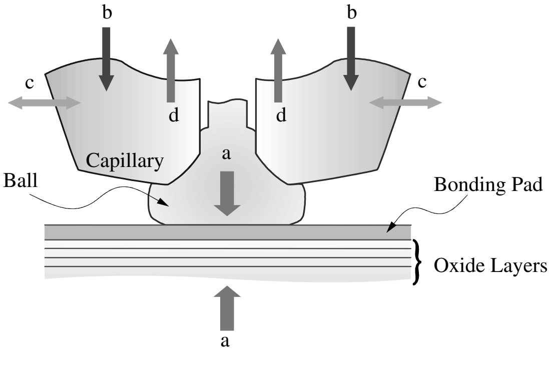


Fig. 1. Four main loadings transferred to the chip during ball bonding process of ultrasonic wire bonding.

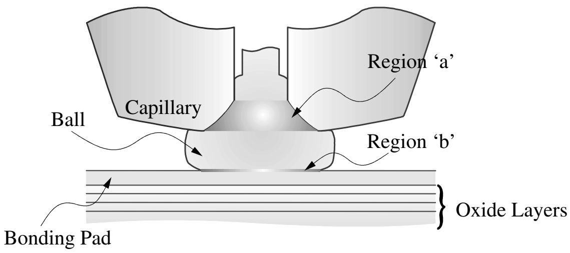


Fig. 2. Two types of adhesion occurring in ball bonding process of ultrasonic wire bonding.

Among these loadings, the vertical tension loading is an undesirable loading for the stable ball bonding process. When the adhesion of region 'b' in Fig. 2 occurs during the ball bonding process, the adhesion of region 'a' in Fig. 2 is also progressed simultaneously. Naturally, to prevent the adhesion of region 'a', the material as well as the geometry of the capillary and the surface treatment of the capillary tip are considered for the design of the capillary. The capillary tip, however, is contaminated by particles of the ball after large number of bonding processes. Such contamination of the capillary tip results in the adhesion of region 'a', that is, the adhesion between the capillary tip and the ball, therefore it will be the source of the non-uniform vertical tension loading. The shape of the capillary tip before the bonding process and the shape of the contaminated capillary tip after large number of the bonding processes are shown in Fig. 3. The particles contaminating the capillary tip are clearly observed in Fig. 3(b).

When the vertical tension loading is applied on the deformed ball, three types of separation may arise as presented in Fig. 4. Small number of bonding process makes the strength of adhesion between the capillary tip and the ball very weak, and the magnitude of the vertical tension loading negligible. Then, the capillary leads the normal bonding process shown in Fig. 4(a). However, after large number of bonding processes, the contaminated capillary tip strengthens the adhesion between the tip and the ball, and increases the magnitude of the vertical tension loading because the surface in the capillary tip that contacts to the ball is increased by the contaminations. Therefore, the capillary, in this case, leads the ball missing in Fig. 4(b) or the pad peeling in Fig. 4(c).

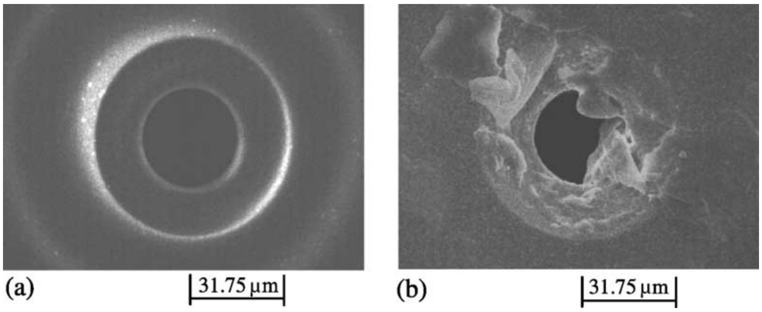


Fig. 3. Two shapes of the capillary tip (a) before the bonding process and (b) after large number of bonding processes.

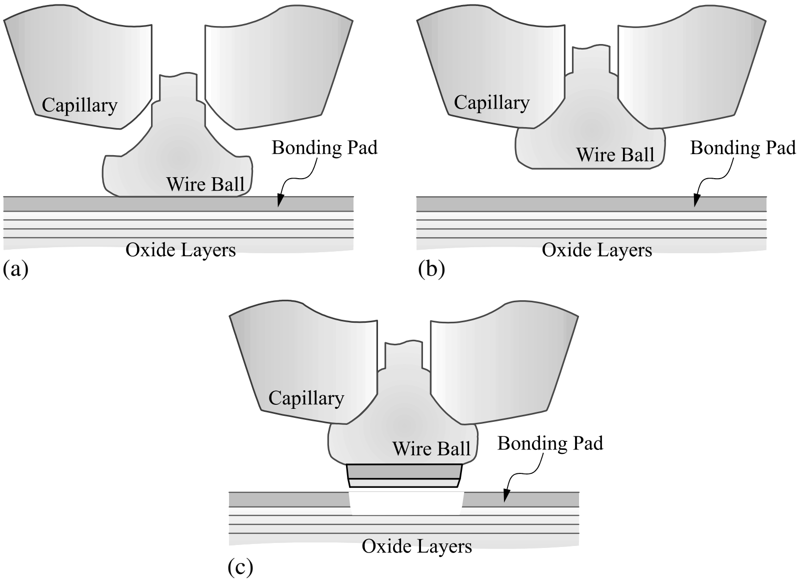


Fig. 4. Three types of separation occurring in ball bonding process of ultrasonic wire bonding.

From these ideas, we see that the vertical tension loading is generated by the contamination of the capillary tip and may suppose that it is the direct driving force for bond pad metal peeling. To estimate the relation between the magnitude of the vertical tension loading and bond pad metal peeling, we survey the number of bonding process of a capillary until the pad peeling occurs and the results will be discussed later in Section 4.

## 3. Observation of the peeled-off pad surface

For observation of the pad surface after peeling, 31 failed SDRAM chips are collected and SEM examinations for those specimens have been carried out. Then, it is found that the most part of collected chips have almost similar shape of failed surface. Fig. 5 shows SEM image of a typical peeled-off pad surface with the locally magnified shapes. From these figures, we find that there exist three different types of failure aspect in a peeled-off pad surface. The first type is shown in Fig. 5(b), which looks like scratched marks on the pad surface. The second type is presented in Fig. 5(a) and (c). These two figures show the sharply fractured shape of the bonding pad and/or undeformed shape of the remaining pad after the peeling along the direction of the vertical tension loading, which is the normal direction to the pad surface. The final type is given in Fig. 5(d) and (f). In these two figures, it is shown that the remaining pad on the peeled-off pad surface is deformed along the normal direction to the pad surface.

For the convenience of description for those failure types, we name the first type of failure as ‘ball missing type failure’ because its shape looks like the failed pad surface after ball missing. For the second type of failure,

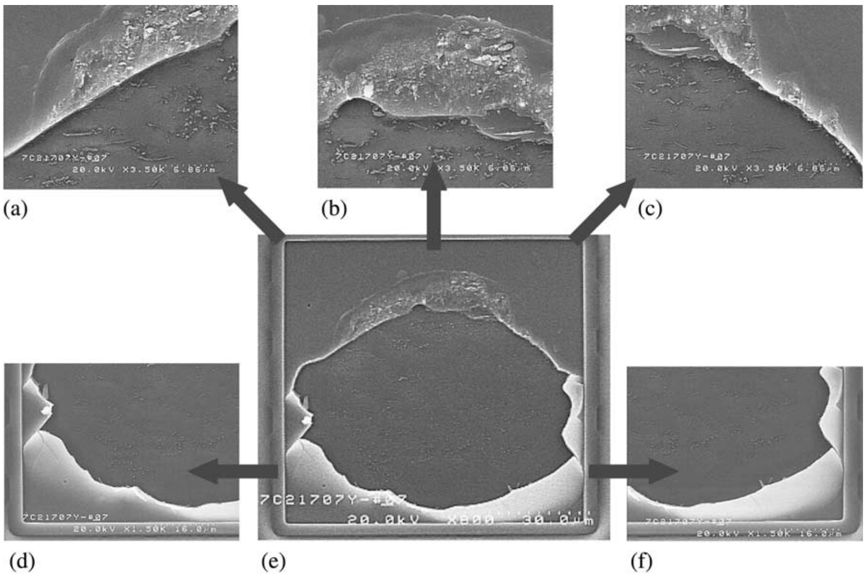


Fig. 5. The failed surface of a bonding pad after bond pad metal peeling.

we name it as 'brittle fracture type failure' because it looks like the fractured shape of a brittle material. The final type is named as 'ductile fracture type failure' because of the deformed shape of the remaining part of the pad after the pad peeling.

Among those types of failure, 'brittle fracture type failure' may be considered as a unique failure aspect that is not expected in ductile metal such as an aluminum pad. When the vertical tension loading is applied on the deformed ball and induces the consequent pad peeling, the marks of failure have to be appeared on the pad along the surface normal direction because of ductile property of the pad. However, the marks are not found on the remaining part of the pad after peeling as shown in Fig. 5(a) and (c). It means that the 'brittle fracture type failure' is not caused by the vertical tension loading. From this viewpoint, we assume that 'brittle fracture type failure' is already made before the pad peeling occurs and that the failure will be a form of crack on the bonding pad and the oxide layers under the pad (see Fig. 6(a)). The confirmation of these assumptions will be stated in Section 4.

'Ball missing type failure' will be started from the region 'a' in Fig. 6(a) and be propagated along the adhered interfaces between deformed ball and bonding pad. Because this region, which contains geometric wedges, can form singular stress fields around their vertexes under the vertical tension loading, interfacial fracture between the ball and the pad may easily occur by this singular stress.

'Ductile fracture type failure' may begin after 'ball missing type failure' meets the crack on the bonding pad and interacts with the crack under the vertical tension loading (see Fig. 6(b)). In this case, the vertical tension loading, which will be the mixed mode loading of Mode I and Mode II for the crack, is directly transferred to the crack tip and develops the singular stress around the tip.

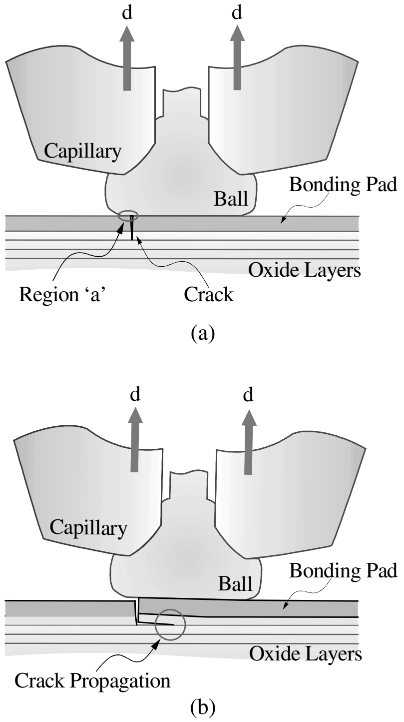


Fig. 6. The possible failure process of the pad peeling.

This mixed mode loading leads the propagation of the crack along the interface under the pad from the tip of vertically propagated crack into the oxide layers under the pad, which is related to the depth of the crack on the bonding pad. The crack may be propagated between the oxide layers or between the bonding pad and the oxide layer under the pad. Moreover, the propagation of the crack through the inner part of weak oxide layer may also be observed infrequently.

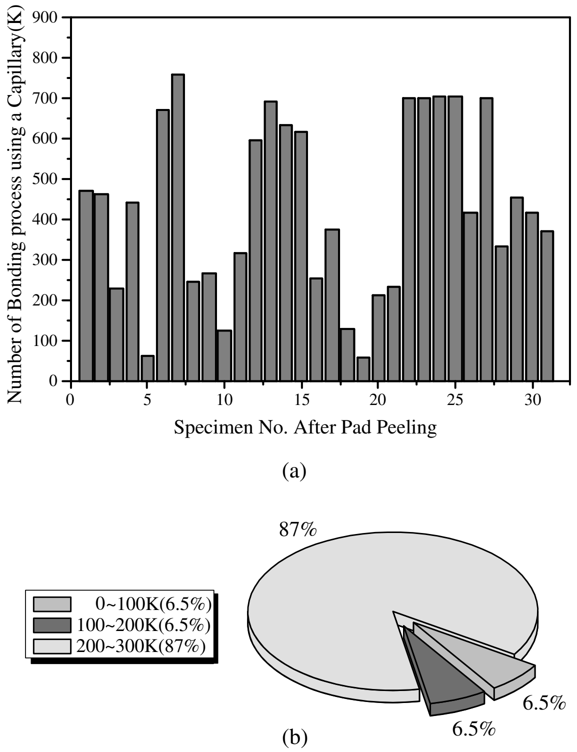
After the propagation of the crack under the pad is arrested, the loading is transferred to the bonding pad partially separated from the normal pad surface and breaks the separated pad off completing 'ductile fracture type failure'. This procedure suggests that 'ductile fracture type failure' is affected by the interfacial fracture toughness of each layer constructed under the pad.

## 4. Results of experimental analysis

The collected 31 failed SDRAM chips are used for experimental analysis. First of all, we survey the total number of the bonding processes of a capillary until the pad peeling occurs in order to find the effect of the vertical tension loading that is supposed to be the direct driving force for the peeling. Fig. 7 shows that about 87% of capillaries are used over 200 K times of bonding before the pad peeling occurs. It means that a capillary after less than 200 K times of bonding has a weak probability of occurrence of the pad peeling, therefore the magnitude of the vertical tension loading is considered to be small. However this loading may be grown to a meaningful magnitude after more than 200 K times of bonding because of the contamination of a capillary tip (see Fig. 3(b)) and, in this case, a capillary has a strong probability of occurrence of the pad peeling. This result indicates that the vertical tension loading of the capillary after large number of bonding may be considered as a direct force for the pad peeling.

To confirm the assumptions for 'brittle fracture type failure', we have performed PCT (pad cratering test) that is a etching test using NaOH solution for many bonding pads after regular ultrasonic wire bonding in which no pad peeling occurs. PCT allows visual inspection of the pad surface after removal of the bonded ball without any scratch on the pad. The two special SEM images of the pad surface after PCT are shown in Fig. 8.

Fig. 8 demonstrates that the cracks are generated on the bonding pad even though the pad peeling does not occur and these cracks have nearly same aspect with the crescent shaped cratering as presented in [2]. Thus, we confirm that the crack on the bonding pad may be generated in an arbitrary pad during regular ultrasonic wire bonding process.



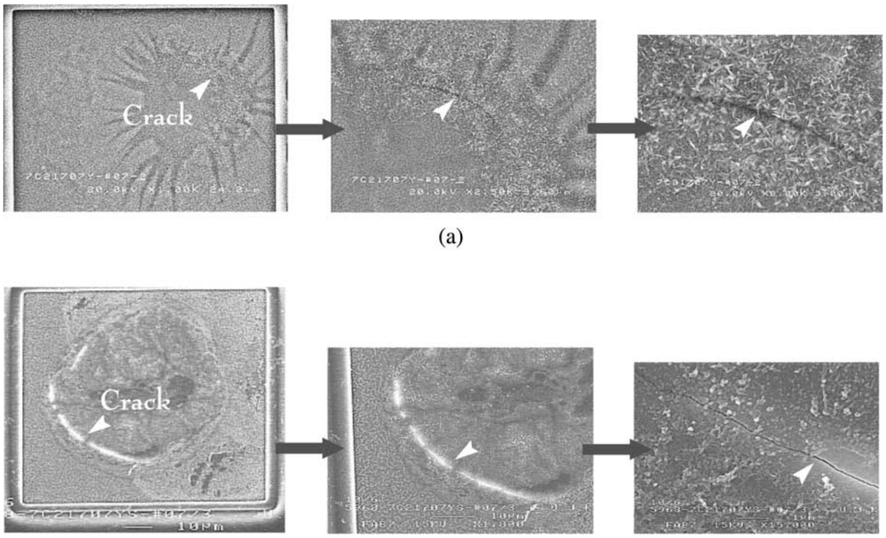
(a)

(b)

Fig. 7. (a) The number of bonding process using a capillary until the pad peeling occurs (b) its percent distribution.

The depths of these cracks vertically propagated into the oxide layers are not fixed for each cracked pad because of the process variations of ultrasonic wire bonding and the structure variations of the bonding pad as well as the oxide layers under the pad. The various depths of the cracks on the pad surface, however, may be observed in Fig. 9.

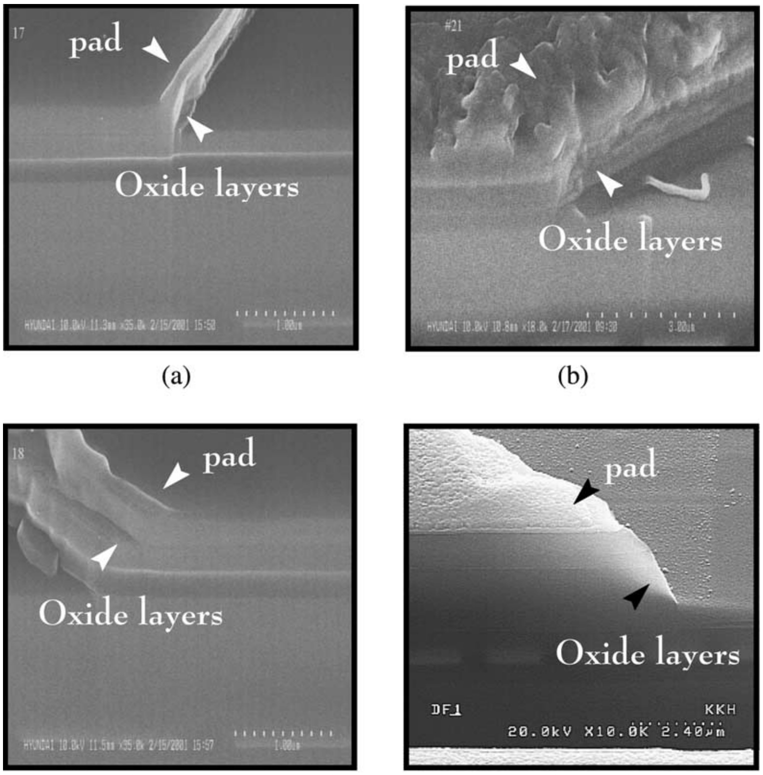
Fig. 9 shows the cross-section shapes of the region of 'brittle fracture type failure' in the peeled-off pads and presents the various fractured oxide layers after the pad peeling obtained from FIB and SEM. The sharply fractured shapes and/or the undeformed shapes along the surface normal direction of the remaining pads after the pad peelings represent the existence of cracks on the bonding pad before the pad peelings begin. Moreover the vertically fractured shapes of the oxide layers represent the propagation of the cracks into the oxide layers. The depths of the cracks propagated into the oxide layers can be regarded as the thickness of the oxide layers that are peeled off in Fig. 9 because these may be the origins of the crack propagations along the interface of the layers under the pad. Therefore the initiation of 'ductile fracture type failure' is strongly affected by interfacial fracture toughness of the layers under the bonding pad and it can be considered as a possible cause of the pad peeling. That is similar to the viewpoint of



(a)

(b)

Fig. 8. SEM images of the cracks on the bonding pad.



(a)

(b)

(c)

(d)

Fig. 9. SEM images of the cross-section of the fractured oxide layers after FIB works.

Tan et al. [3,4] for investigation of the root causes of bond pad metal peeling.

With these three types of failure, we make a schematic diagram for the process of the pad peeling in a SDRAM

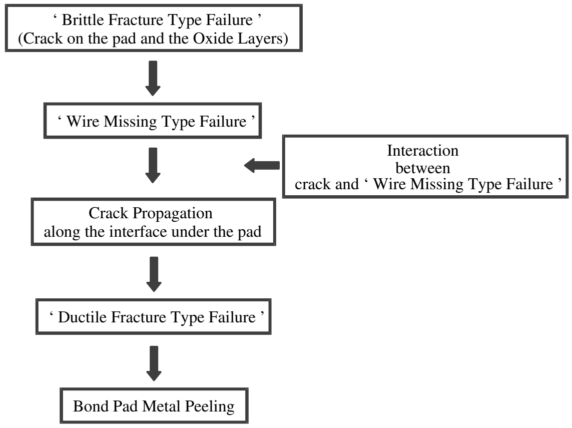


Fig. 10. A schematic diagram of the pad peeling process for a SDRAM chip.

chip. Fig. 10 shows the occurring process of bond pad metal peeling during ultrasonic wire bonding. Note that the crack on the bonding pad and its propagation into the oxide layers, namely, 'brittle fracture type failure', is the first failure of the pad peeling process. Therefore it may be considered as the direct cause of bond pad metal peeling because it is the beginning of the pad peeling. Then 'ball missing type failure' brings about the fracture of adhered interfaces between the deformed ball and the bonding pad, and makes the interaction with the crack on the pad (see Fig. 6(b)). The next step is 'ductile fracture type failure' that contains the beginning of the propagation of the crack along the interface of the arbitrary layer under the bonding pad and the breaking the peeled pad off. Finally, the process of bond pad metal peeling is finished after 'ductile fracture type failure'.

This diagram may provide a systematic scheme for preventing the pad peeling to the electronic packaging researchers. For example, to prevent the first step in the pad peeling procedure presented in Fig. 10, researchers need to consider the optimization of the pad thickness, the oxide layer structure and/or the driving force for the crack on the pad surface. Also, to prevent the third step of the procedure, they need to concentrate on finding methods to increase the interfacial fracture toughness between each layer under the bonding pad as shown in the study of Tan et al. [3,4].

The effect of wafer probe test on bond pad metal peeling is also investigated to confirm the results of Hotchkiss et al. [4]. The number of the probe tests carried out for a pad and the number of the pad peelings for each number of the probe tests are surveyed. Fig. 11 presents the number of the pad peeling along the number of probe test and shows that about 23% and 65% of the total pad peelings occurs after once and twice of the probe test, respectively. These findings suggest that the pad peeling is easily generated in the pad after the probe test comparing with the pad without the probe test and that the probe test is also a possible cause of the pad peeling. These results are well agreed with those of Hotchkiss et al. [4].

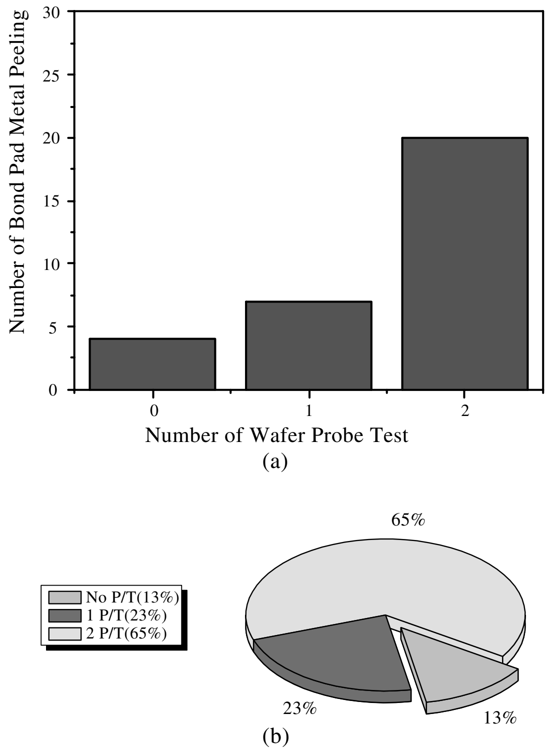


Fig. 11. (a) The number of the pad peeling along the number of the probe test and (b) its percent distribution.

## 5. Concluding remarks and further study

For the experimental study on failure mechanisms of bond pad metal peeling, 31 failed SDRAM chips after bond pad metal peeling are gathered, and SEM and FIB are utilized. Through this investigation, a typical shape of the peeled-off pad surfaces of the most part of the gathered SDRAM chips is found and three different types of failure aspect are assumed from the typical shape of the one. Various proofs for those assumed types of failure are also found.

The results of this investigation indicate that the vertical tension loading of the capillary is the direct driving force for the pad peeling and the crack on the pad as well as its propagation into the oxide layers is the direct cause of the pad peeling. Moreover, the propagation of the crack along the interfaces of the layers under the bonding pad is explained as the initiation of 'ductile fracture type failure', which can be considered as a possible cause of the pad peeling.

Based on all of these results, a schematic diagram for the process of bond pad metal peeling is constructed, which may help the researchers to find the systematic scheme for preventing the pad peeling in a SDRAM chip. In addition, the effect of the probe test on the pad peeling is also investigated to confirm the results of Hotchkiss et al. [1] and it is found that the probe test is another possible cause of the pad peeling.

For the further study, we will carry out the numerical analysis for the whole ball bonding process of ultrasonic wire bonding to find the major driving force for the crack on the bonding pad and its propagation into the oxide layers under the pad which is the direct cause of bond pad metal peeling. The results of this analysis will be presented in the accompanying paper [5].

## Acknowledgements

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