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Study of Discrete Voids Formation in Flip-Chip Solder Joints due to Electromigration Using In-Situ 3D Laminography and Finite-Element Modeling

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Abstract

Nowadays, the microelectronics industry broadly uses the flip-chip technology to enhance the packaging density. However, the small size and the unique geometry of the flip-chip solder joints induce the electromigration (EM) reliability issue. In this study, a Pb-free solder joints (SAC1205) was EM tested by a current of \(7.5 \times 10^3\) A/cm². During the tests, a three-dimensional (3D) X-ray laminography method was applied to in-situ observe the microstructure evolution. The laminography method allows for the non-destructive observation and provides the quantitative analysis among three dimensions. After EM testing for 650 hr, a new EM failure mechanism was found rather than the well-known models, the pancake void propagation and the under-bump-metallization dissolution. According to the laminography images at different testing stages, many voids simultaneously formed and grew during the entire procedure of testing. Most of them distributed in the current crowding region, but a few also located in the low-current-density region. As the testing time increased, voids grew bigger, coalesced with each other, and finally became large voids which occupied the interface and caused EM failure. The finite-element (FE) method was also applied to analyze the interplay between the microstructure evolution and current density redistribution. A series of 3D FE models were built based on the laminography images at different testing stages. The current density distribution from the FE analysis indicates that the multiple voids formation does not affect the global current density distribution until the voids merged together and became very large voids in the late stage of EM testing. The relieving of the global current crowding in the pancake void model was not found in this new EM failure mechanism. It was the local current crowding found in the new model that responsible for the EM retardation.

Introduction

In the past decades, the microelectronics industry puts the miniaturization of electronic devices at the top priority.\[1, 2\] To meet the demand of higher device density, the industry has look into the future trend of packaging technology, so various packaging techniques have been developed. Among them, the flip-chip (FC) solder joint is essential because it uses the area arrays of joints to conduct the signals and therefore dramatically rises the bandwidth.\[3\] However, the small size and unique geometry of FC joints induce reliability issues such as electromigration (EM).\[4, 5\] Two main failure mechanisms of EM have been reported: void propagation\[6, 7\] and under-bump-metallization (UBM) dissolution.\[8, 9\] To semi-in-situ observe the microstructure evolution, the samples were cross-sectioned and polished to the desired interface before the EM testing.\[10, 11, 12\] This makes the desired interface a free surface, which is an infinite vacancy source. Furthermore, the free surface caused oxidation, relieved the stress, and affected the heat dissipation. To avoid the influence of sample treatment, three-dimensional (3D) synchrotron X-ray laminography technique (SRCL) was applied to observe void formation in this study. Moreover, to understand the current density distribution with the microstructure evolution, a series of finite-element (FE) model were also built according to the 3D images.

The method of combining the 3D imaging technique and FE modeling has already been applied to geo-materials and bio-materials.\[13, 14, 15, 16, 17, 18\] N. Chawla and R. S. Sidhu used a serial sectioning method to obtain the 3D microstructure.\[13, 14, 15\] The image quality of 3D microstructure was easily affected by the polishing depth control and the polishing quality, and the samples cannot be tested after imaging. Instead of the serial sectioning method, P.G. Young et al. applied the computed micro-tomography (CT) technique to obtain the 3D images of the desired objects.\[16, 17, 18\] Although the resolution of micro-tomography is sufficient for the observation of bones or minerals, it has not been applied to the observation of microelectronic de-
ices. From the viewpoint of microelectronic devices, C. M. Tsai constructed a two-dimensional FEM which involves the initial pattern of the solder bump before EM testing.[12] His purpose was to correlate the current density and the displacement of the Pb particles to obtain the product of diffusivity and effective charge number (DZ*) of Sn. However, the atomic diffusion driven by EM was 3D, which was difficult to present in a 2D model. Furthermore, the microstructure evolved simultaneously during EM testing. As a result, the simple model that constructed only according to the initial pattern was unable to describe the ensuing changes.

In this study, we introduced a new observation method to trace the microstructure evolution stage-by-stage during the EM testing. The method combined the high-resolution laminographic imaging and the FEM constructed according to the real-time 3D laminography images. It showed several advantages. First, the laminography technique provided high-quality and high-resolution 3D images, which is dedicated to inspect the structural components of flat objects such as solder joints in microelectronic devices[19, 20, 21] or cracks inside plate-like engineering materials.[22, 23] We observed numerous discrete voids formation and growth during the EM testing. None of previous studies kept a stage-by-stage tracing of the microstructure evolution during EM testing. Second, the laminography technique imaged the microstructure without any destruction, unlike the afore-mentioned in-situ SEM or X-ray radiography observation method.[9, 26, 11, 12] As a result, the test environment of the sample was similar to the real ambient of usage and maintained the same in the different stages of testing. Third, the FEMs were constructed according to the 3D images in different EM testing stages so the interaction between the current density distribution and the micro-structure evolution during testing could be well examined.

In our study, lead-free solder bumps were EM tested by a high current density (7.5×10^3 A/cm^2) for hundreds of hours (630 hr), and were imaged by SRCL at different EM stages. The experimental results from the reconstructed laminographic volumes allowed for revealing and quantifying the void evolution at associated EM testing stages. As a consequence, a series of finite element model (FEM) were further established according to these 3D images so as to examine the correlation between the void formation and the current density distribution.

Methods

For EM tests, we adopted a PCB with 4 identical wafer-level chip-scale-packaging test chips. The dimension of one chip is 3000 µm × 3000 µm and there were 36 solder balls in a chip. The solder was lead-free solder SAC1205, consisting of Sn, Ag (1.2%), Cu (0.5%), and Ni (0.05%). A constant 2.5 A current was applied to one selected chip, and the current density is 7.5×10^3 A/cm^2 on the UBM opening. During current stressing, a furnace and a thermocouple were also used to set and monitor the surface temperature of the chip at 130 °C.

The sample structure is illustrated in Fig. 1 (a). The diameters of passivation opening and UBM opening were 210 µm and 270 µm, respectively, and the bump height was 220 µm. The top trace was 1 µm thick Al, the top UBM was 7.5 µm thick Ti/Cu/Cu layer, and the bottom trace was Cu. They provided good adhesions on the top and bottom surface of solder. The arrows show the routes of electron. It entered solder joint from the top right corner and left from the bottom trace. The solder therefore suffered from the downward electron flow. In particular, the top interface of Bump 1 where a high flux of electrons entered was our major region of interest (ROI).

In order to in-situ observe the EM, non-destructive observation by 3D synchrotron X-ray computed laminography imaging was applied to the afore-described FC specimens. The experiment was performed at the beamline ID15A[27] of the European Synchrotron Radiation Facility (ESRF) in Grenoble, France. The laminography setup is illustrated in Fig. 1 (b). Details of the experimental technique are given in references[28, 29, 30] We used an axis inclination angle of about 25° (θ ≈ 65°) and white beam illumination. The solder at initial state (0 hr) were firstly scanned in X-rays before the EM tests. Then the sample was conducted by the EM testing. Once the EM testing reached certain stages, the current stressing was temporarily stopped, and the sample was scanned by laminography again. For each scan, the sample was mounted on a rotary stage and continuously rotated by 360° in the X-ray beam, where 1999 angularly equidistant projections of 1024 × 1024 pixels were collected using an indirect CCD detector.[31] The exposure time of each projection was 600 ms.[32] The effective pixel size of the detector was 0.84 µm, resulting in a field of view (FOV) of 0.86 mm × 0.86 mm. Finally, the 3D volumes of the solders of interest at different EM stages were reconstructed using a filtered back-projection algorithm.[30] Following the time sequence of EM testing, in-situ 3D non-destructive observations of the microstructure evolution in FC solder joints were achieved.

Image analysis was subsequently applied to the reconstructed 3D images. The 3D images can reveal the statistical information concerning the void growth. In addition, these 3D experimental volumes can be used for constructing finite element models so as to find out the current density re-
distribution due to those void formations.

In order to build the 3D FE models directly from the obtained 3D images, some additional treatments were needed on the laminography images, which are summarized in Fig. 2. (1) The 3D volumes of different EM stage have to be well aligned to the same position in order to trace the microstructure evolution. (2) Different materials in terms of voids and solder matrix were segmented by grey-level thresholding method, and the segmented elements were labeled, forming the binarized 3D images of models. (3) The 3D binarized volumes were then converted voxel by voxel into the format of finite element model. (4) Since the entire solder as a global model was too computational consuming with meaningful details, a submodel method was applied. (5) In this method, global models were built first with large elements ignoring some details. (6) Then the global models were solved with proper boundary conditions (2.5 A at 130 °C). (7) Submodels containing only the ROI that is the top part of the solder where the most severe EM damage occurred were built with fine elements. (8) Accordingly, the boundary conditions of the submodels were interpolated from the results of the global models. (9) Finally, the submodels (ROI) were solved. (10) The results data and illustration were acquired.

With the results of FE analysis, the correlation between the microstructure evolution and the corresponding current density distribution at each EM stage becomes clear. As a result, the EM-induced 3D failure mechanism was interpreted.

Result and Discussion

Figure 3 shows the laminography 3D images of microstructure evolution during EM testing. In the beginning, only a few small voids were seen at the UBM/solder interface. This demonstrates the advantage of laminography that direct 3D observation without any destruction can give richer real information of EM-induced void growth, which is hardly gained on 2D surfaces. Unlike the pancake-type void growth damage mechanism observed in previous studies, a new EM failure mechanism was discovered here. It is clearly identified that a considerable number of discrete voids nucleated and grew independently at the UBM/solder interface in Bump 1 of interest. Especially, after 103 hr the voids tended to form more intensively in the vicinity of the current crowding spot. This microstructure evolution is important because it dramatically changed the consequent current density distribution in the EM testing.

Resorting to 3D imaging analysis, quantitative information of void growth can be extracted. Figure 4 reports the total number of voids, total volume of voids, average volume of voids, and the average void growth rate. The total volume of voids increased with the testing time. However after 100 hr of EM testing, the average void growth rate dramatically dropped by over 50% from 957.1 µm³/hr (at 108.0 hr) to 444.5 µm³/hr (at 303.0 hr). The change of total volume of voids as a function of time can be taken to be an S curve in the Johnson-Mehl-Avrami theory of phase transformation. It is slow in the beginning due to low nucleation rate, and then in the later stage it slows down again due to heavy impingement of voids which will reduce both nucleation and growth.

In Fig. 4, the void growth mechanism can be divided into two stages. Stage I: before 108.0 hr, new void formation was the dominant phenomenon; Stage II: after 108.0 hr, voids grew by cross-linking and impingement. In addition, there
was a sharp increment in void number from 42 to 159 at the beginning of the test which indicates that in spite of pre-existing voids, EM still caused multiple voids growth at the interface. The average volume of voids continued to increase through the entire test although the increasing rate of the average volume slowed down after 100 hr of testing. These two curves in Fig. 4 indicate two facts: 1. The merge and cross-linking of voids continuously happened after 47 hr of the entire EM testing; 2. The rate of voids cross-linking was slightly higher than the rate of new voids formation in stage II.

The dispersed void growth and propagation mechanism proposed in this study can be more clearly reflected by the projection of voids onto the plane of UBM opening shown in Fig. 3. Before the EM testing time reached 90 hr, new voids formation could still be found in the projections. Even new voids were continuously found in the entire testing time period, it is clear that the individual new voids formation dominated the beginning of EM testing. The some cross-linking of voids was found. And After 90 hr testing, the merges and cross-linking between voids became obvious. The red and yellow regions indicate the voids forming in the early stages of EM testing; the green, blue, and purple regions indicate the voids forming in the late stages. Pointed out by the arrows in Fig. 3, the green and blue regions between the red and yellow ones are the cross-linking of voids.

Through the 3D FEMs built according to the laminography images, the current density distribution during EM testing was simulated, and one example is shown in Fig. 5. The dispersed voids due to the EM testing were resolved clearly between the top UBM and the solder. These voids significantly affected and redistributed the current density near the current crowding spot, which was the entrance point of the electron flow. The distortions induced the local current crowding around the dispersed voids, which will be discussed in details in the following paragraphs. The dispersed voids affected the current density distribution in a different way from the pancake-type void does. Once the pancake-type void formed, the void blocked the current penetration. Then as the void propagated, the current detoured through a longer path and accumulated along the tip of pancake-type void. As a result, the original current crowding region was shifted along the growing path of the pancake void and the associated EM got slightly relieved because the larger void spread the crowded current onto a longer edge. However at the same time, the longer route of current flow caused the higher heat generation. This extra heat generation might enhance the electromigration and the thermomigration. In contrast, the discrete voids found in this study did not change the global current density distribution significantly during the void formation in EM testing. Although the dispersed voids caused the local redistribution of current density, the remaining solders between different voids allowed the passage of current and maintained the global current density distribution rather similar to the initial state.

The current density distribution at different stages of EM test supports this phenomenon, too. Figure 5 represents the current density distributions of solder ROI evolving with the EM testing. In the microstructure evolution, discrete voids formed near the global current crowding region and grew individually as the EM testing time increased. After long time testing, the voids coalesced with each other and then became large planar voids, which caused the EM failure. Therefore, the EM failure mechanism observed in this study was a new one, although at the very later stages some pancake-like void morphology (due to coalescence) at the IMC/solder interface and the UBM dissolution were observed.

During the stage of voids cross-linking (Stage II), the void growth rate dramatically decreased (Fig. 4), and this could be explained through the current density distribution obtained by FEMs. In Fig. 5, the current density distribution close to the global current crowding region at different testing stages was displayed in magnified views. It is shown that the global current density marked by the dashed curve did not significantly change with the testing time. However, the new void formation caused the local current crowding effect around the void. Because the void blocked the electron flow, the electron flow had to split and bypass the void. As a result, low current density regions were established at the front and the back of the void with respect to the direction of electron flow, and high current density region formed on the two sides of the void. This local current crowding around the dispersed voids also spread the current to a larger area and relieved the impact of EM during the test. The global current crowding was inherently induced by the sample geometry. In the case of pancake-type void, the growth and propagation of void could spread the current from crowding in a small spot to a long edge of void to relieve the EM.[33, 34] This also happened in the case of dispersed voids. Although the discrete voids did not change the global current crowding phenomenon, the dispersed voids induced local current crowding and provided much longer edges around the voids. The locally high current density at the two sides of the void promoted the depletion of solders, and thus the void continued to grow and coalesce with adjacent voids at the later stages of EM.

According to the above observation, the correlation between the void propagation and the current density distribution should be discussed by two different viewpoints. From
the viewpoint of global current density distribution, the high
current density induced higher opportunities for the voids to
nucleate and grow. The correlation coefficient between the
opportunity probability of void growth and the current den-
sity in solder was 0.673. This indicated that the EM was the
dominant failure mechanism although the thermo-migration
may also take place at the same time during the EM testing.
On the contrary, the dispersed voids formation and growth did
not affect the global void current density distribution until the
major coalescence between voids in the early stage of testing.
Once the coalescence caused the void large enough to block
the original path of current (503 hr), the current detoured and
the global current density distribution was affected. From the
viewpoint of the local current density distribution, every dis-
persed void distorted the local current density distribution
and caused the local current crowding around the void because
the current should split and bypass the void. The local cur-
rent crowding effect enhanced the pancake-type growth of the
individual voids in the early stage of EM testing. After the co-
alescence happened, both of the coalescence and the pancake-
type growth of the individual voids played important roles.

Conclusions
The EM-induced damage mechanism in FC solder joints in
terms of void formation and growth at the UBM/solder in-
terface has been observed non-destructively in-situ in 3D by
synchrotron radiation computed laminography (SRCL). Then
the observation has been further directly coupled to a 3D fi-
nite element modeling for the first time in order to understand
the multiple void growth model in relation to the current den-
sity distribution. From the 3D experimental observation, a
new failure mechanism was discovered: dispersed voids nu-
cleation, growth, and agglomerate to form very large voids.
From the quantitative analysis of the obtained 3D volumes,
we found that the EM-induced damage evolution can be di-
vided into two stages. (I) At the beginning of EM testing (be-
fore 108.0 hr), individual small dispersed voids formed and
grew at the UBM/solder interface. (II) Then in the later stage
of testing (from 108.0 hr onwards), those voids coalesced and
cross-linked with each other, forming larger flat voids. Un-
like the pancake-type void mechanism, the dispersed voids
nucleated at random positions of the interface, not only at
the global current crowding spot although the global current
crowding spot was still the most favorable site for the void
formation. From the 3D FEM, we found that these dispersed
voids did not alter the maximum global current density dis-
tribution as the pancake-type void does the global current
crowding phenomenon stayed similarly in the EM test (i.e.
up to 500 hr) before intensive coalescence event took place near
the current entrance point. However, the local current crowd-
ing effect induced by the individual voids made the voids also
tend to grow in the electron flow direction like the pancake
void did, and consequently also relieved the EM. This ex-
plains why the measured void growth rate maintained at a
similar value in the early stage I while slowed down in the
late stage II of the EM testing. Finally, the cause for the new
observed failure model was discussed.

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