The Applications of Synchrotron Radiation X-rays 3D Imaging Techniques to The
Study of Electromigration Failure in Flip-Chip Solder Joints

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Tian Tian

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ABSTRACT OF THE DISSERTATION

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The advanced packaging technology is a business of billions of dollars. The reliability issues of the packaging products are of keen interest. In the microelectronic industry, a major paradigm change from two-dimensional integrated circuit (2D-IC) to three-dimensional integrated circuit (3D-IC) is occurring. Electromigration (EM), referring to the atomic diffusion induced by a high electron current density, is one of the most serious reliability concerns of flip chip solder joints used in packaging technology. In the traditional study of the flip-chip solder joints by using two-dimensional (2D) examination procedure (e.g. Scanning Electron Microscopy), it has encountered two problems. One is the difficulty in uncovering the kinetics in the real test vehicle during EM, especially at the early stage, which requires a nondestructive monitoring. The other is that a 2D method would bring more
uncertainties of the void growth measurement in a real three-dimensional (3D) structure. As a nondestructive 3D imaging technique, synchrotron radiation based x-rays tomography or laminography can bring significant evidence on the in-situ characterization of flip-chip solder joints or other 3D packaging parts during accelerated reliability tests, such as EM tests. We have conducted tomography experiments in Advanced Light Source, LBNL, USA to measure the effective charge number of eutectic SnPb solders accurately. Also we have conducted laminography imaging experiments at the beamline ID15A at ESRF, Grenoble, France to investigate the new mechanism of the EM induced failure in Pb-free solder joints. A proposed link between the physical and statistical analysis of the failure is outlined on the base of the 3D characterization, and offers as a rapid way to estimate the life time of the test vehicles.
The dissertation of Tian Tian is approved.

Yu Huang

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Jenn-Ming Yang

King-Ning Tu, Committee Chair

University of California, Los Angeles

2012
This thesis is dedicated to my parents.
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PUBLICATIONS

JOURNAL PAPERS

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BOOK CHAPTERS


CONFERENCE PRESENTATIONS

1. Tian Tian, A.M.Gusak, O.Yu.Liashenko, Jung-Kyu Han, Daechul Choi, King-Ning Tu, “A new Physical Model for Life-Time Prediction of Pb-free Solder
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5. Tian Tian, King-Ning Tu, Kai Chen, Martin Kunz, Nobumichi Tamura, Tao-Chih Chang, Chau-Jie Zhan, “Preferred Orientation of 30um Fine Pitch Sn2.5Ag Micro-Bumps Studied by Synchrotron Polychromatic X-Ray Laue Microdiffraction”, 2012 TMS Annual Meeting, Orlando, FL


Chapter 1 Introduction to Electromigration

1.1 Packaging Technology

1.1.1 Overview of Electronics Packaging

Microelectronic industry has two major technologies: one is chip technologies and the other is packaging technologies. The latter includes a wide variety of technologies, for protecting enclosed devices from outside damages, mechanically and chemically.[1] Also, electronic packaging techniques provides the electrical interconnections of the input/output (I/O) on the Si chip and outside electronic system. Electronic packaging is involved with three levels of packaging as illustrated in figure 1.1.[2] The first level refers to the integrated circuit (IC) or chip level packaging. The second level refers to a system level packaging of multi-components with different functions to be assembled onto a board, which is called "motherboard". In some mainframe electronics (i.e. supercomputers), several motherboards carrying a large amount of ICs and several processors are required and connected by connectors and cables so that the extremely and highly transactional throughput can be achieved, which is referred to be the third level packaging.
Figure 1.1 Schematic diagram of the hierarchic three packaging level [1]
1.1.2 Flip-chip Technology

Flip-chip assembly, one of the major technologies of first (chip) level packaging providing the connection of an IC to external circuitry with solder bumps that have been deposited onto the chip pads, was developed to meet the trend of increasing miniaturization of electronic devices and the demand for high density I/Os by IBM in 1960s. The solder bumps are deposited on the chip pads on the top side of the wafer during the final wafer processing step. In order to mount the chip to external circuitry (e.g., a circuit board or another chip or wafer), it is flipped over so that its top side faces down, and aligned so that its pads align with matching pads on the external circuit, and then the solder is melt to complete the interconnect. The typical processing steps are summarized in figure 1.2. The schematic diagram of the cross-section of a flip chip mount is shown in figure 1.3.[3]
1. Integrated circuits are created on the wafer and pads are metalized on the surface of the chips

2. Solder dots are deposited on each of the pads

3. Chips are flipped and positioned so that the solder balls are facing the connectors on the external circuitry

4. Solder balls are then remelted (typically using hot air reflow)

5. Mounted chip is “underfilled” using an electrically-insulating adhesive

Figure 1.2 Process steps in flip chip assembly [3]
1.2 Electromigration Fundamentals

An ordinary household extension cord conducts electricity without mass transport because the electric current density in the cord is low, about $10^2\text{A/cm}^2$. The free-electron model of the conductivity of metals assumes that the conduction electrons are free to move in the metal, unconstrained by the perfect lattice of positive ions except for scattering interaction due to phonon vibration. This scattering does not enhance displacement of the ion and it has no net effect on the diffusion of the ion when the electric current density is low. However, the scattering by a high current density, above $10^4\text{A/cm}^2$, enhances atomic displacement along with the direction of electron flow. The enhanced atomic displacement and the accumulated effect of mass transport under the influence of electric field (mainly, electric current) are called electromigration (EM).
Due to the trend of miniaturization and the requirement of higher performances of the electronic devices, the size ICs is shrinking while the electric current density is increasing. In a thin film interconnect (i.e. Cu/Al interconnects, solder bumps), the current density is always high enough to facilitate EM, especially at the working temperature of 100°C. [4] EM is a serious reliability issue in the semiconductor industry, and has been attracting attentions from both academy and industry since 1960.

The diving force of the EM was proposed by Huntington and Grone: [5]

\[ F_{EM} = Z^* eE = (Z_{el}^* + Z_{wd}^*) eE \] (1.1)

where e, E and Z* are the charge of an electron, electric field, and the effective charge number of EM. Z_{el}^* is the nominal valence of the diffusing ion and Z_{el}^* eE is called the direct force. Z_{wd}^* is the effective charge number that represents the effect of momentum exchange between the electrons and the diffusing ion and Z_{wd}^* eE is called the electron wind force. The direct force and the electron wind are in opposite directions. The direction of the direct force is opposite to the electron flow direction, while the electron wind force is in the same direction as that of electron flow and leads to atomic transport from cathode to anode.

The EM induced void formation at the cathode and the hillock formation at the anode of the interconnects, can result in open circuit at the cathode or short circuit at the anode, which is one of the most serious reliability problems. Figure 1.4 shows the typical
EM induced damage at the cathode side (chip side) of the solder ball.[6] In this case, the void usually forms at the entrance corner of the electron flow and then propagates along the interface between the metallized pad (which is so called under bump metallization or UBM) and the solder ball until occupying the whole interface.

The effective charge number of EM, Z*, is one characteristic parameter of a certain material, representing its EM resistance, which is of high interest. There were several methods used to measure this parameter in previous publications, such as marker movement measurement, stress accumulation measurement and void growth rate measurement. However, limited by traditional 2D characterization methods, there is the intrinsic limitation in the Z* measurements. In Chapter 4, I will discuss the advantage of the application of quantitative 3D microtomography technique in the Z* measurement and show the experimental details.
1.3 Black's Equation of Mean-Time-to-Failure (MTTF)

Since EM is a critical reliability issue in interconnect and packaging technology, people are certainly interested in the estimation of the EM induced time-to-failure (TTF) of the electronic products. In 1967, James R. Black contributed to the concept of Mean-Time-To-Failure (MTTF) by relating it to current density and temperature,[7-9]

\[
MTTF = A j^n \exp \left( \frac{E_a}{kT} \right), \quad A = \left[ \left( \frac{\rho \frac{\lambda}{v}} \sigma_{cross} \right) \right]^{-1}
\]

(1.2)

where \( j \) is current density of electron flow, \( E_a \) is the activation energy of atom diffusion in electron volts, \( k \) is the Boltzman constant and \( T \) is the temperature of the film, \( \rho \) is the resistivity per unit volume, \( \lambda \) is the mean free path of electron with an average velocity \( v \),
\( \sigma_{\text{cross}} \) represents the effective cross section of the target (cm\(^2\)). The pre-factor A here only depends on the inherent properties of the material. MTTF thus depends on the current density and temperature. As the current density or temperature increases, the MTTF decreases. The value of current density exponent \( n \) whether it is 1, 2 or a larger number is still controversial. However, in most of the studies of MTTF the current density exponent \( n \) has been reported to be 2.[8] The model is abstract, not based on a specific physical model, but it flexibly describes the failure rate dependence on the temperature, the electrical stress, and the specific technology and materials. More adequately described as descriptive than prescriptive, the values for A, \( n \), and \( E_a \) are found by fitting the model to experimental data. Black's equation is valuable since it helps estimate the actually life time under normal device operating conditions by testing the device at an accelerated condition of high temperature and high current stress levels.[10]
Chapter 2 Introduction to JMA Theory and Weibull Distribution

2.1 Johnson-Mehl-Avrami (JMA) Theory of Phase Transformation

The JMA theory was presented by John, Mehl (1939) and Avrami (1941), which is a classical analysis of phase transformation described by the kinetic process of nucleation and growth. [11-13]

In the JMA theory, we can consider $V$ to be the total volume involved in the transformation, in which $V_T$ and $V_U$ is the transformed volume and untransformed volume, respectively, as shown in Figure 2.1.

![Figure 2.1 A diagram representing the untransformed ($V_U$) and transformed ($V_T$) volume](image)

$V = V_U + V_T \quad (2.1)$
\[ 1 = X_U + X_T \]  \tag{2.2} 

where \( X_U = \frac{V_U}{V} \) and \( X_T = \frac{V_T}{V} \) are the fraction of untransformed volume and transformed volume, respectively. It is assumed that (i) transformation occurs by nucleation and growth, (ii) nucleation is random in space and time and (iii) each of the transformed region has the same isotropic growth rate of \( R_G \), then the number of newly transformed regions in the untransformed volume in the time interval between \( t \) and \( t+d\tau \) is given by

\[ N = R_N V_0 d\tau \]  \tag{2.3} 

where \( N \) is the number of newly transformed regions which nucleates in the untransformed volume, \( R_N \) is the rate of nucleation (the number of nuclei per unit time per unit volume), \( t \) is the initial time and \( d\tau \) is the time interval.

Since isotropic growth rate has been assumed for each transformed region, the radius \( r \) of the spherical volume of the transformed region that originates at \( \tau \) as shown in figure 2.1 is given by:

\[ r = R_G (t - \tau) \]  \tag{2.4} 

and therefore the volume of the transformed region \( (V_T) \) is:

\[ V_T = \frac{4\pi}{3} R_G^3 (t - \tau)^3 \quad \text{for } t > \tau \]  \tag{2.5} 

\[ V_T = 0 \quad \text{for } t \leq \tau \]

The differential change of the untransformed volume can thus be written as
\[-dV_U = NV_r = V_r R_N V_U d\tau \]  (2.6)

The negative sign here represents decrease of the untransformed volume. Also on differentiating Eq (2.1), we get,

\[-dV_U = dV_T \]  (2.7)

and,

\[dV_T = NV_r = V_r R_N V_r d\tau \]  (2.8)

by integrating Eq (2.8) and substituting Eq (2.5), we have,

\[V_T = \frac{4}{3} \pi \int_{t=0}^{t=r} V_r R_N R_G^3 (t - \tau)^3 d\tau \]  (2.9)

In the initial stage of transformation, we can conveniently assume that the volume of untransformed region is much more than the volume of the transformed region, \(V_u \gg V_t\), and thus the entire volume, \(V\), can be approximated to untransformed volume \(V_U\). Also by assuming that the nucleation rate is constant with time, we can re-write the Eq (2.9) to be:

\[X_T = \frac{V_T}{V} = \frac{1}{3} \frac{R_N R_G^3 t^3}{\pi} \]  (2.10)

The Eq (2.10) is only valid for initial stages of transformation where the transformed regions do not interfere with each other (i.e. no impingement or no overlapping occurs). While at the later stages of transformation, both impingement and overlapping take place as shown with the example of raindrops falling on the surface of a pond. To include the
Effect of interference, a concept of "extended volume" $V_{\text{ext}}$ has been introduced between the time interval $t$ and $t+d\tau$ as:

$$dV_{\text{ext}} = V_c R_N (V_U + V_T) d\tau$$  \hspace{1cm} (2.11)

where $dV_{\text{ext}}$ represents the differential change in volume of both transformed and untransformed regions. The growth of nuclei in the transformed region does not affect the untransformed region, which are called “phantom nuclei”. The growth of phantom nucleation does not contribute to the new phase transformation.

By arranging Eq(2.1)

$$1 = \frac{V_U}{V} + \frac{V_T}{V}$$

$$\left(1 - \frac{V_T}{V}\right)V = \left(\frac{V_U}{V}\right)V,$$

we can get

$$\left(1 - \frac{V_T}{V}\right)(V_U + V_V) = V_U \quad \text{(2.12)}$$

By substituting Eq (2.12) into Eq (2.8), we have

$$dV_T = \left(1 - \frac{V_T}{V}\right)V_c R_N (V_U + V_T) d\tau = \left(1 - \frac{V_T}{V}\right) dV_{\text{ext}} \quad \text{(2.13)}$$

By rearranging Eq (2.13), we have

$$dV_{\text{ext}} = \frac{-Vd\left(1 - \frac{V_T}{V}\right)}{\left(1 - \frac{V_T}{V}\right)} \text{, then } V_{\text{ext}} = -V \ln \left(1 - \frac{V_T}{V}\right) + \text{cons.} \quad \text{(2.14)}$$
The Eq (2.14) can be also written as

\[ X_T = 1 - \exp(-X_{ext}) , \]  

(2.15)

where \( X_T = \frac{V_T}{V} \), \( X_{ext} = \frac{V_{ext}}{V} \), and \( X_{ext} = \frac{4}{3} \pi \int_{\tau=0}^{\tau=\text{ext}} R_N R_G^3 (t-\tau)^3 \, d\tau \). If the nucleation rate is random and continuous, and the growth rate is isotropic and linear with time, in three-dimension case, \( X_{ext} = \frac{1}{3} \pi R_N R_G^3 t^4 \). Therefore, \( X_T = 1 - \exp\left(-Kt^4\right) \), where \( K = \frac{1}{3} \pi R_N R_G^3 \).

We assumed a dependence of \( t^4 \) for nucleation and growth in the above analysis. However, in general, time dependence should depend not only on the dimension of transformation, but also on the mode of nucleation and growth. Thus, the universal form of the JMA equation can be written as

\[ X_T = 1 - \exp\left(-Kt^n\right) = 1 - \exp\left[-\left(\frac{t}{\tau_0}\right)^n\right], \text{ where } K = \left(\tau_0\right)^{-n}, \]  

(2.16)

\( n \) is the mode parameter of transformation.

### 2.2 Weibull Distribution in Statistical Analysis of Time to Failure

In 1951 Waloddi Weibull presented the Weibull distribution in his groundbreaking paper, “A statistical distribution function of wide applicability” in the Journal of Applied Mechanics, which is the hallmark paper of Weibull analysis. The first example in the paper concerned the yield strength of Bofors steel.[14] Today, this distribution is widely used in dealing with the time to failure of electronic devices. It can
be derived theoretically as a form of extreme value distribution, governing the time to
occurrence of the "weakest point" of many competing failure processes. For example, if
a system consists of \( N \) identical components in series, and the system fails when the first
of these components fails, then system failure times are the minimum of \( N \) random
component failure times. The extreme value theory says that, independent of the choice
of component model, the system model will approach a Weibull distribution as \( N \)
becomes large.

The Weibull probability density function (PDF) is

\[
f(t) = \left( \frac{t}{\eta} \right)^{\beta-1} \exp \left[ -\left( \frac{t}{\eta} \right)^{\beta} \right], \quad (2.17)
\]

where \( \eta \) is the characteristic time when 63% of the components fail, \( t \) is the time to
failure and \( \beta \) is the shape parameter, which is the slope of the Weibull distribution plot.

The cumulative distribution function (CDF) is

\[
F(t) = 1 - \exp \left[ -\left( \frac{t}{\eta} \right)^{\beta} \right], \quad (2.18)
\]

where \( F(t) \) is the percentage of failures at time \( t \). The failure rate is defined the number of
new failures occur within a small time interval, \( \lambda(t) = \frac{f(t)}{1-F(t)} = \left( \frac{t}{\eta} \right)^{\beta-1} \). The
failure rate is constant when the shape parameter \( \beta = 1 \), decreases for \( \beta < 1 \), and increases
when \( \beta > 1 \). This implies that there is very little difference in the time to failure among all
components when \( \beta > 1 \), which means that there is a very short time period between first failure and the last failure. In most of real cases, \( \beta > 1 \) is more desirable in the microelectronic industry for reasons of reproducibility. [15]

2.3 Discussion

Eq (2.16) and Eq(2.18) show that the JMA equation and Weibull distribution are in a same mathematical form. We believe that there is an intrinsic link between these two equations, though they are applied in different fields. In Chapter 5, a couple of experiments will be presented, whose results give a preliminarily experimental support to this proposed link.
Chapter 3 Introduction to X-rays 3D Imaging Techniques

3.1 Overview of X-rays 3D Imaging Techniques [16]

X-ray computed tomography, CT, is a nondestructive technique for visualizing features in the interior of solid objects, and for obtaining digital information on their 2D geometries and properties. It is useful for a wide range of materials, including rock, bone, ceramic, metal and soft tissue. High-resolution X-ray CT is different from conventional medical CAT-scanning in its ability to resolve details as small as a few microns in size, even when imaging objects made of high density materials.

“Tomos” is the Greek word for “cut” or “section”, and tomography is a technique for digitally cutting a specimen open using X-rays to reveal its interior details. A CT image is typically called a slice. Since a CT slice has a certain thickness of the object being scanned, whereas a typical digital image is composed of pixels (picture elements), a CT slice image is composed of voxels (volume elements). The gray levels in a CT slice correspond to X-ray attenuation, which reflects the proportion of X-rays scattered or absorbed as they pass through each voxel. X-ray attenuation is primarily a function of X-ray energy and the density and atomic number of the material being imaged. A CT image is created by directing X-rays through the slice plane from multiple orientations and measuring their resultant decrease in intensity. A specialized algorithm is then used to reconstruct the distribution of X-ray attenuation in the slice plane. By acquiring a stacked, contiguous series of CT images, data describing an entire volume can be
obtained, in the much same way as a loaf of bread can be reconstructed by stacking all of its slices. First developed for widespread use in medicine for the imaging of soft tissue and bone, X-ray CT was subsequently extended and adapted to a wide variety of industrial tasks. These latter developments, which demanded imagery of denser objects across a range of size classes and resolution requirements, provided key advances that greatly enhanced the potential for application of this technology to geological investigations.

To maximize their effectiveness in differentiating tissues while minimizing patient exposure, medical CT systems need to use a limited dose of relatively low-energy X-rays (<140 keV). They must also acquire their data rapidly because the patient should not move during scanning. To obtain the best data possible given these requirements, they use relatively large (mm-scale), high-efficiency detectors, and X-ray sources with a high output, requiring relatively large (mm-scale) focal spots. Because industrial CT systems image only non-living objects, they can be designed to take advantage of the fact that the items being studied don't move and aren't harmed by X-rays. They employ the following optimizations: (1) Use of higher-energy X-rays, which are more effective at penetrating dense materials; (2) Use of smaller X-ray focal spots, providing increased resolution at a cost in X-ray output; (3) Use of finer, more densely packed X-ray detectors, which also increases resolution at a cost in detection efficiency; (4) Use of longer exposure times, increasing the signal-to-noise ratio to compensate for the loss in signal from the diminished output and efficiency of the source and detectors.
3.2 Introduction to the Microtomography Beamline 8.3.2 in ALS, LBNL[17]

Beamline 8.3.2 is a super bend magnet source. The magnetic field is high from a 6 Tesla peak field superconducting bend magnet. The local field is 4.37 Tesla for this source point, ring current 400mA and ring energy 1.9GeV.[18, 19] Source size is 220μm×30μm FWHM. The beamline layout is shown in figure 3.1.

![Figure 3.1 Schematic layout of Beamline 8.3.2](image)

The monochromator is of the constant offset double crystal type and is 14m distant from the source. It has 3 modes of operation.
1) Multilayer monochromator light, wide band pass (~1%).

2) Si(111) crystal monochromator light, small band pass (1/7000).

3) White light mode with the monochromator optics removed.

The sample is in the hutch at 20m distant from the source. A total of 0.5mm of Beryllium windows is in the x-ray path from the source to the sample. The schematic of the end station is shown in figure 3.2.

![Figure 3.2 Schematic layout of the end station](image)

The x-rays enter the hutch with a beam size of 40mmx4.6mm and pass though the sample that is mounted on a rotation stage. The transmitted x-rays impinge on a
CdWO$_4$ single crystal scintillator that fluoresces the image as visible light that is relayed via lenses onto the CCD for data collection. The 30 degree mirror is present to move the CCD out of the orbit plane of the synchrotron as high energy x-rays can damage the CCD. The camera, scintillator and optics are contained in a light tight box that is on rails that allows the sample to scintillator distance to be changed to optimize for phase contrast imaging. Figure 3.3 shows the sample stage. X-rays enter on the left and pass through an example sample that is mounted on the 4” diameter rotary stage which in turn is mounted on horizontal and vertical translations stages for positioning.

The transmitted x-rays are detected by the scintillator, lens camera detector assembly shown in figure 3.4. During data collection the sample is rotated 180 degrees in small angular increments with an image recorded at each point. Typically the number of images recorded is 360-1440 dependant on the quality required.
Figure 3.3 Photo of an example sample mounted on the Sample rotation stage.
Figure 3.4 Photo of the detector box containing the scintillator, lens and CCD. The entire box is on rails so that sample to detector distance can be changed to allow for phase contrast imaging.
Typical exposure times are several seconds for Si(111) monochromatized light, 0.1 – 2 sec for multilayer light and 5-100msec for white light. Filters are available for hardening up the white light spectrum. These filters are also useful to reduce the specular low energy x-rays that are reflected from the multilayers above 25KeV. A data set typically takes 10- 60 min in time. If the sample is taller than 4mm the data can be tiled by repeating the measurement with the sample at a different height. This is done automatically. The maximum sample height is ~ 10cm. The maximum sample width is ~40mm – this being the beam width. Horizontal tiling to allow for wider samples has yet to be implemented. Data is written to a 5TB server and can be reconstructed on the data analysis PC that has 8 CPU and 32 GB of ram. Two reconstruction routines are available (Octopus from the University of Ghent [20]]) and Imagrec from the LLNL. The Octopus code is the fastest and takes a few minutes. Octopus requires a license. User licenses have been purchased that allow the user to log in the server and download the license for local use of Octopus on their home PC. Users are requested to download their data to portable hard drives via USB or Firewire as the server is not able to store the large data sets indefinitely. Post reconstruction software is currently the 3D visualization package Amira [21]. Interactive Data Language (IDL) is also installed.

3.3 Introduction to the Laminography Beamline ID15A in ESRF [22]

Current development in computed tomography (CT) with synchrotron radiation (SR) aims to increase the spatial resolution. One constraint, however, is the field of view of the detector, which is limited by the finite number of detector pixels. This limits the spatial dimensions of the object to be imaged and a sample has to be cut from the region
of interest of a larger object. In other words, high resolution CT permits non-destructive quality inspection only for devices smaller than the detector's field of view. Restricting the size of the sample to the micrometer range poses major problems for certain types of materials both in sample preparation and in structural stability during the tomographic scan. Furthermore, the imaging of laterally-extended objects suffers from a large variation of the beam transmission while rotating the object in a CT experiment leading to imaging artefacts. To overcome these limitations, synchrotron-radiation computed laminography (SRCL) was developed [23]. SRCL allows high-resolution non-destructive 3D imaging of regions of interests in flat but laterally-extended objects and devices which may include sensors, flip-chip devices and other microsystems.

Feasibility experiments at the ESRF beamlines ID19 and ID15 were carried out in the collaboration between ANKA/ISS (Forschungszentrum Karlsruhe, Germany), University of Karlsruhe, the German Fraunhofer Association and the ESRF Imaging Group. The SRCL method consists of the acquisition of projection data sets similar to standard CT, but with a rotation axis that is inclined at an angle theta < 90° instead of being perpendicular to the incoming beam like standard CT (see figure 3.5). When the device normal is aligned approximately parallel to the inclined rotation axis, the integral X-ray transmission onto the 2D detector does not change considerably during sample rotation. In particular this avoids projections with missing information where the integral transmission would tend to zero due to a long beam path within the sample.
The technological potential of SRCL for high-resolution non-destructive applications has already been demonstrated [24]. In particular, electronic devices were investigated with monochromatic as well as with white synchrotron radiation, providing detailed information about their interconnection technology. In comparison to laboratory methods, SRCL benefits additionally from the specific qualities of synchrotron radiation such as high photon flux, low angular divergence and high partial coherence in combination with high flux.

Figure 3.5 Comparison between the experimental setups for (a) computed tomography, and (b) computed laminography.
ID15A takes the on-axis radiation either directly or via a monochromator in the upstream optics hutch. The radiation is within the range of 30-500keV. The monochromator configuration (in air) can be easily changed to suit the particular experiment. A range of focusing and non-focusing bent and flat monochromators, developed by the beamline staff, and Al compound refractive lenses (CRL) are available for experiments. ID15A can take white or monochromatic radiation. During the last decade micro-tomography has been extensively used at synchrotron sources in order to study the morphology of different kind of samples. Efforts have been made to improve the spatial resolution. The time resolution has been neglected restricting micro-tomography to static conditions or on systems evolving over very long timescales. In order to cover this gap, ID15 has developed a fast micro-tomography system that is capable of collecting a full 3-D data set in less than one second allowing in-situ studies of system evolving on the timescale of a few seconds.

The first micro-tomographic experiments at ID15 were performed approximately eight years ago. The measurements were performed using a classical tomography system: collecting step by step, getting images of the sample using monochromatic x-ray radiation. It immediately turned out that this type of design was not well suited for high energy imaging: data collection took from 4 to 8 hours due to very low efficiency of the scintillator screen. Also, the light optics was damaged by the radiation in a day. The origin of diffused color-centres in the light optics is the Compton scattering in the lenses themselves, an effect which does not occur at low energies, where the color-centres are produced by photoelectric absorption only within the region impinged by the direct x-ray
beam. Three solutions were adopted in order to overcome these problems: i) the experiments were conducted in filtered white-beam radiation to increasing the x-ray flux, ii) the refractive objective was replaced by reflecting objective and a beam-stop was mounted on the secondary mirror to protect the camera and secondary optics, and iii) the YAG:Ce scintillator was replaced by LAG:Eu scintillator, which has better efficiency at high energies. As a result tomographic scans were performed in less than a minute with a spatial resolution of ~2µm.

By optimizing the CCD-detector (back illuminated chip with many readout ports using frame transfer mode), the architecture of the data acquisition system (continuous scans) and the rotation stage (high-precision high-speed air-bearing rotary stage) is possible to collect a full tomographic data set at 2µm spatial resolution in a few seconds (flux limited) and at ~2µm resolution in less than one second (detector limited) even when the synchrotron operates in 4 bunch mode. Recently phase contrast experiments with polychromatic high-energy radiation have been exploited with very encouraging results. The white high-energy x-ray beam does not have any temporal coherence, but it still has spatial coherence due to the small source size. The projections can be collected at one sample at the detector distance and the phase information recovered in the near field region. This is practically always the case at high energies. Therefore, phase-contrast tomography can be performed at same speed as absorption contrast tomography. Furthermore, the absorbed dose is small due to the small x-ray absorption at high energies which allows the measurement of systems sensitive to radiation damage like biological samples. Figure 3.6 shows the high resolution micro-tomography setup.
Figure 3.6 Setup on Beamline ID15 in ESRF
Chapter 4 Quantitative X-ray Microtomography Study of 3-D Void Growth Induced by EM in Eutectic SnPb Flip-chip Solder Joints

4.1 Motivation

Electromigration (EM) in solder joints, referring to the atomic diffusion induced by electron wind force, is one of the most serious reliability concerns in the packaging industry [4]. In the past 20 years, it is realized that electron wind force can serve as the driving force in intermetallic compounds (IMCs) formation [25], under-bump-metallization (UBM) dissolution [26], phase separation [27], and pancake void formation at the cathode side [28], which would all contribute detrimentally to the failure of the electrical and mechanical properties of solder joints. According to Huntington’s theory [6], the characteristic of EM in a certain material can be represented by the parameter of effective charge number ($Z^*$). Therefore, an accurate measurement of $Z^*$ (or $DZ^*$, $D$ is the diffusivity of the material) of EM is of interested, where the critical issue in the determination of the magnitude of $Z^*$ (or $DZ^*$) is how accurate is the measurement of the atomic diffusion flux. In the previous publications on EM in the eutectic SnPb or Pb-free solder joints, to measure the diffusion flux induced by electron flow quantitatively, people tried several ways, such as the measurements of marker movements [29], stress accumulation rate [30] or the edge displacement rate of solder alloy strips [31]. All the above analysis is based on the reduced 2-dimension (2D) model, such as by scanning electron microscope (SEM) [29, 31] or synchrotron x-ray Laue microdiffraction with 2D scanning mode [30]. However, one dominated issue in the study of EM in a flip chip
joint, different from that in Al or Cu thin film interconnect lines, is its unique 3D geometry [4]. Thus, most of 2D examinations could bring two problems in this kind of study. One is the difficulty in uncovering the kinetics in the real test vehicle during EM, which requires nondestructively monitoring. The other one is that 2D measurement will bring uncertainties of the flux measurement in a real 3D structure. Synchrotron based x-ray microtomography [32] is a good method to solve the problems mentioned above. Since it is nondestructive, it enables the ex-situ study on EM at different time stages and can provide the evidences for the kinetics study. Moreover, as a 3D imaging technique, computed tomography helps in determining the diffusion flux inside solders in a much more accurate way. In this chapter we report two different types of EM induced void growth existing in eutectic SnPb solder studied by synchrotron monochromic x-ray absorption microtomography technique and provide the measurement of DZ* in a more accurate way.

4.2 Sample Description

The composition of the solder bumps used in this study is eutectic SnPb, and their dimensions are about 110 um (height) by 90 um (contact opening diameter). The trilayer thin films of the under bump metallization (UBM) on the chip side are Al(0.3 um) / Ni (V) (~ 0.3 um) / Cu (~ 0.7 um). On the substrate side, the bond-pad metal layers are Ni (5 um) / Au (0.05 um). This configuration is very similar to the ones described elsewhere [33]. We prepare two kinds of samples. One (Sample I) was cross sectioned by first grinding with SiC sand papers to the center of the solder joints, and then polished by submicron Al₂O₃ powders to produce a smooth surface. This is a typical way of sample
preparation in the previous in-situ or ex-situ studies on EM in flip chip solder joints. The reason we did it is to create a free surface to release the stress induced by electron flow inside the solders and also to reveal what cannot be studied by 2D examination (see figure 4.1). The other sample (Sample II) was just polished to leave 2 rows of solder joints at the edge of the flip chip, without damaging the joint we tested. In this sample, the solder balls are surrounded by the underfill material, were maintained to under the real working environment condition during the EM test.

Figure 4.1 Sample preparation and experimental setup of the Si strip.
4.3 Experimental Setup in ALS

The experiment was conducted on Beamline 8.3.2 at the Advanced Light Source of Lawrence Berkeley National Laboratory. In this technique, the parallel x-rays with a beam size of 40 mm (width) by 4.6 mm (height) pass through the sample that is mounted on a rotation stage. The transmitted x-rays impinge on a 0.5 mm thick CdWO4 single crystal scintillator that fluoresces the image as visible light that is relayed via lenses onto the Cooke PCO 4000 CCD with 4008×2672 pixels for data collection. The contrast of the imaging comes from different attenuation lengths of metals. The energy range of Beamline 8.3.2 is from 8 KeV to 40 KeV. Figure 4.2 shows the attenuation lengths of five materials (Si, Sn, Pb, Cu, Al) according to different photon energies. In this work, we chose to use 27.5 KeV monochromatic x-ray to scan the eutectic SnPb solders. During data collection the sample was rotated by 180 degrees in an angular increment of 0.125 degree and at each angular step an image was recorded with 500 ms exposure time. Therefore, 1440 images were taken in a single scan. Post 3D reconstruction was conducted by Octopus from the University of Ghent [34] and the commercial 3D visualization software Avizo 6.0 [35]. The limitation of spatial resolution of this technique depends on both the number of pixels of the CCD and the defect of focus of the scintillator [36]. In this study, the voxel size after reconstruction process is about 1.8um, as set by the lens magnification and CCD pixel size. Before the start of the accelerated EM tests, we scanned the solder joints for initial imaging in three-dimensions as a reference. After a prescribed time of EM stressing, the sample was rescanned to examine the changes inside the solder joints.
Figure 4.2 Plot of attenuation lengths of five materials (Si, Sn, Pb, Cu, Al) as a function of different photon energies.

4.4 Data Analysis

Figure 4.3 shows the reconstructed 3-D image of a type I sample stressed by $1.35 \times 10^4$ A cm$^{-2}$ at 100 °C for 64 h. The bumps are readily seen as they are made of the high-Z materials Sn and Pb, which is strongly attenuating, as well as Cu lines. The Al interconnects between the bumps and the Si chip on the top are not seen as they have low X-ray attenuation. In bump A, the electron flow is from the substrate side to the top side, while it is opposite in bump B. Figure 4.4 illustrates the evolution in the top and the bottom of bumps A and B by digital slicing images from within the bump. Figure 4.4(a) and (b) shows the slice images of bumps A and B before and after the EM test,
respectively, in the YZ plane, near the free flat polished surface. Figure 4.4(c) and (d) shows those in the XZ plane, near the center of the bump. Figure 4.4(e) and (f) shows the joints in the XY plane, near the top of the joints. Figure 4.4(g) and (h) shows joints in the XY plane, 5 μm from the bottom side of the bump.

Figure 4.3 3-D reconstructed image of a type I sample after a 64 h EM test with a current density of $1.35 \times 10^4$ A cm$^{-2}$ at 100 °C. In bump A, the electron flow was from the bottom to the top, while the electron flow was in the opposite direction in bump B. There was an Al thin film connecting the top of bump A to the top of bump B which is not shown as its absorption was too low for the imaging X-ray energy used.
Figure 4.4 Void evolution at the top and the bottom of bump A and bump B in sample I, as illustrated by digital slicing views. (a and b) Slice images of bumps A and B before and after the EM test, respectively, in the YZ plane, near the free surface. (c and d) Slice images in the XZ plane, near the central bump axis. (e and f) Slice images in the XY plane near the top. (g and h) Slice images in the XY plane close to the bottom.
Comparing the slice images in Figure 4.4, it can be seen that, after 64 h, there are three changes involved in bump B induced by EM: (i) the pancake-shaped void formation at the current crowding point [37]; (ii) the morphological change of the polished surface, which has a bulge and a dimple; and (ii) the growth of pre-existing voids, which were originally round before the EM test but became elongated. Clearly, the evaluation of the total atomic diffusion flux or the opposite vacancy flux must take into account all three of these changes. The total EM-induced atomic flux $J_{EM}^{total}$ can be calculated by

$$J_{EM}^{total} = J_{pancake \ void} + J_{morphological \ change} + J_{pre-existing \ void \ growth}$$

$$= (V_{pv}/A_{pv} \Omega t) + (V_{mc}/A_{mc} \Omega t) + (V_{pvg}/A_{pvg} \Omega t)$$

(4.1)

where $V_{pv}$ ($=13,180 \ \mu m^3$), $V_{mc}$ ($=14,206 \ \mu m^3$) and $V_{pvg}$ ($=6176 \ \mu m^3$) are the measured volumes of the pancake void, the dimple on the polished surface and the pre-existing void change, respectively, $A_{pv}$ ($=1046 \ \mu m^2$), $A_{mc}$ ($=376 \ \mu m^2$) and $A_{pvg}$ ($=673 \ \mu m^2$) are the measured cross-section areas of the pancake void, the dimple on the polished surface and the volume change of the pre-existing void normal to the atomic flux direction, respectively, $\Omega$ ($=2.78 \times 10^{-11} \ \mu m^3$) is the average vacancy volume in the eutectic SnPb alloy [31] and $t$ is the time of the EM test. On the basis of these values, we obtain $J_{EM}^{total} = 9.2 \times 10^6$ atoms $\mu m^{-2} s^{-1}$.

In obtaining the above values, an intensity-based segmentation algorithm was used to label the voids inside the solder and thus, by counting the number of voxels labeled as voids, the volumes and cross-sections of the voids can be determined, where the error was within $\pm 10\%$. Knowing $J_{EM}^{total}$, the average product of diffusivity and
effective charge number of EM, DZ*, in the eutectic SnPb alloy, could be calculated by [38]

\[ J_{EM}^{total} = -CD\Omega \frac{d\sigma/dx}{kT} + CD \frac{Z^* eE}{kT} \]  (4.2)

where C (=1/Ω) is the concentration of atoms per unit volume of the eutectic alloy, D is the effective diffusivity of the eutectic SnPb solder at 100 °C, dσ/dx is the back-stress gradient along the electron flow path, E is the electric field, where E = ρj, ρ ∼22 μΩ cm) is the resistivity of the solder and j is the applied current density, and k and T are Boltzmann’s constant and temperature, respectively. DZ* = 3.3 × 10⁻⁹ cm² s⁻¹ at 100 °C was obtained by assuming that all the stress had been released by the morphological change of the free surface.

In bump A, the evolution at the bottom side can also be seen. Before the EM test, there were two pre-existing small spherical voids, located at the bottom side of the solder bump (see Fig. 4.4(a), (c) and (g)). After the 64 h of EM testing, these two voids had grown bigger, but the shape was no longer spherical and the growth direction was along that of the electron flow direction (see Fig. 4.4(b), (d) and (h)). Similar evidence is shown for the type II sample in Figure 4.5. Before the EM test, there was a typical pre-existing void of volume 14,469 μm³ located at the bottom of the solder (see Fig. 4.5(a)). After 12 h of EM testing (1.57 × 10⁴ A cm⁻² at 120 °C), the void grew dramatically along the electron flow direction, and its volume reached 38,577 μm³, as shown in Figure 4.5(b). The reason for this type of growth and its shape change is due to current crowding. After 24 h of EM testing (see Fig. 4.5(c)), the void volume had increased to
50,114 μm³. This dramatic void growth could be another critical failure mode in real devices. Knowing the rate of volume change, the growth rate in the second 12 h was found to be slower than that in the first 12 h, which is likely caused by the build-up of back stress (see detail below). Since the length of the atomic diffusion path was shorter at the later stage, the back-stress gradient became larger, serving as a balance to retard the atomic diffusion. Furthermore, the solder joint shown in Figure 4.5 was unpolished and buried completely in underfill. As such, there was no release of the stress to a free surface. In this case, the vacancy flux contributed primarily to the pre-existing void growth. Figure 4.5(d) is a snapshot illustrating the volume evolution of the pre-existing void during the EM test. By measuring the growth of the void, the vacancy flux and thus the DZ* of the solder can be calculated. The DZ* in the first 12 h at 120 °C is about 9.5 × 10⁻⁹ cm² s⁻¹, while it is 4.6 × 10⁻⁹ cm² s⁻¹ in the second 12 h, if the back-stress gradient is ignored. On the other hand, if the back-stress gradient is taken into account, the DZ* of the eutectic SnPb solder would be higher than 9.5 × 10⁻⁹ cm² s⁻¹ (Z* is higher than 19, by taking D = 5 × 10⁻¹⁰ cm² s⁻¹[39]).

The average back-stress gradient increase in the second 12 h of the EM test can be evaluated by

\[
J_{EM1}^{total} = -CD\Omega \left(\frac{d\sigma}{dx}\right)_1 + J_{void1}
\]

\[
J_{EM2}^{total} = -CD\Omega \left(\frac{d\sigma}{dx}\right)_2 + J_{void2}
\]

(4.3)

(4.4)
where \( J_{EM_1}^{total} \) and \( J_{EM_2}^{total} \), \( J_{\text{void}_1} \) and \( J_{\text{void}_2} \), \((d\sigma/dx)_1\) and \((d\sigma/dx)_2\) are the total atomic diffusion flux induced by EM, the average atomic diffusion flux measured by volume change of the pre-existing void, and the average stress gradient along the electron flow path during the first 12 h and second 12 h, respectively. Assuming the total vacancy flux was constant, \( J_{EM_1}^{total} = J_{EM_2}^{total} \) the average stress gradient increase is

\[
\frac{(d\sigma/dx)_2 - (d\sigma/dx)_1}{\Omega} = \frac{\frac{kT}{CD\Omega}}{D} = \frac{0.052 \text{ MPa} \cdot \mu\text{m/sec}}{D}
\]

(4.5)

By taking \( D = 5 \times 10^{-10} \text{ cm}^2 \text{ s}^{-1} \), \( (d\sigma/dx)_2 - (d\sigma/dx)_1 = 1.05 \text{ MPa/\mu m}. \)
Figure 4.5 The solder bump in sample II was powered by a $1.57 \times 10^4$ A cm$^{-2}$ electric current at 120 °C. The electron flow enters the bump from the bottom and exits from the top. (a–c) Slice images in the YZ plane close to the central plane of the bump: (a) before the EM test, (b) after 12 h of EM testing and (c) after 24 h of EM testing, respectively. (d) An incremental view of the three voids overlapped in a 3-D view at the three times when the measurements were made.
The DZ* of the type II sample, which is at least \(9.5 \times 10^{-9} \text{ cm}^2 \text{ s}^{-1}\), is of the same order of magnitude as the one obtained from the type I samples but slightly higher, as the test temperature was increased by 20 °C, which increased the effective diffusivity. 

\[
D = D_0 \exp\left(-\frac{E_a}{RT}\right)
\]

in the DZ* was larger due to the higher temperature (\(D_0\) is the pre-exponential factor, \(E_a\) is the activation energy in kJ mol\(^{-1}\) and \(R\) is the gas constant). Since \(Z^*\) is insensitive to temperature [40], \(E_a = 0.66 \text{ eV}\) can be calculated in the following way:

\[
\frac{9.5 \times 10^{-9} \text{ cm}^2 / \text{s}}{3.3 \times 10^{-9} \text{ cm}^2 / \text{s}} = D^{120^\circ C}Z^{*} / D^{100^\circ C}Z^{*} = \frac{D^{120^\circ C}}{D^{100^\circ C}} = \exp\left(-\frac{E_a}{R \times 393 K} - \frac{E_a}{R \times 373 K}\right)
\]

(4.6)

### 4.5 Summary

In summary, 3-D imaging by synchrotron radiation-based X-ray microtomography has been used to study quantitatively the growth of voids in eutectic SnPb flip-chip solder joints in EM. The products of effective diffusivity and the effective charge number, DZ*, in eutectic SnPb alloy were measured at 100 and 120 °C. The average back-stress gradient increase and the activation energy of effective diffusivity in eutectic SnPb alloy were also calculated. The SR microtomography study in this chapter shows that in real devices a dramatic growth of the pre-existing voids towards to the current crowding point in a flip-chip solder joint can be driven by the electron flow and becomes a potential reliability issue.
Chapter 5 Rapid Diagnosis of the Life Time of Pb-free Flip-chip Solder Joints in EM Tests by High-resolution Laminography

5.1 Motivation

The void formation induced by EM at the cathode side is one of the most serious reliability concerns in the electronic packaging industry [4]. One major study in this field is how to predict the life time of the solder joints in the accelerated life tests within an acceptable testing time. Thus a reasonable mode based on the real failure mechanism during accelerated EM tests, is valuable to be applied to predict the life time of the test vehicles under a certain stressing condition.

In the past few years, pancake-shape void formation and propagation was found to be the main failure mode of flip chip solder joints in the EM tests, since the unique line-to-bump geometry results in significant current crowding effect at the current entrance of the solder bumps. Accordingly, a few kinetics models describing the pancake-type void propagation has been built-up [22, 41-42].

However, the main experimental evidence of the previous modeling works is SEM observation. Restricting the study of the flip chip joint to the traditional two-dimensional (2D) examination procedure can yield two problems. One is the difficulty in uncovering the kinetics in the real test vehicle during EM, especially at the early stage, which requires nondestructively monitoring. The other one is that a 2D measurement will bring
more uncertainties of the void growth measurement in a real three-dimensional (3D) structure. The both problems would result in the main limitation of the pancake-type void modeling works.

Recently, the applications of synchrotron based x-rays non-destructive 3D imaging techniques enabled us avoid the 2D problems just outlined. A few experiments have been done by our group. The quantitative ex-situ computed tomography study was conducted at beamline 8.3.2 at the Advanced Light Source (ALS) of Lawrence Berkeley National Laboratory (LBNL), to measure the effective charge number $Z^*$ of eutectic SnPb during EM tests precisely, by monitoring the dramatic growth of pre-existing voids inside the solder. Moreover, the synchrotron-radiation computed laminography (SRCL), an alternatively 3D imaging technique, which is designed for flat samples, was justified that it is feasible to study the EM-induced voids formation and evolution at the interface between UBM and solder bumps at the high energy beamline ID15A at the European Synchrotron Radiation Facility (ESRF), which will be shown in this chapter. The imaging results show that the mode of damage evolution at the interface was quite different from the failure mode of pancake-shape void formation and propagation model at the early stage. And the results are proposed to be fitted by Johnson-Mehl-Avrami(JMA) phase transformation theory. And an intrinsic link between JMA model and the Weibull distribution of life time will be discussed.
Based on the synchrotron radiation based x-rays 3D imaging observations, we propose that the JMA phase transformation model can serve as a new physical model for life time prediction of Pb-free solder joints in EM tests.

5.2 Sample Description

The figure 5.1(a) shows the test vehicle we used in this study provide by National Semiconductor Cooperation, a single printed circuit board (PCB) with 4 identical wafer-level chip size packaging (WL-CSP) test chips labeled as U1, U2, U3, U4. The dimension of one chip is $3000\mu m \times 3000\mu m$ and consists of 36 solder balls. The diameter of each solder ball is $250 \mu m$. The flip chip configuration and dimension are shown by the figure 5.7(a), a schematic diagram of the cross-section of the sample tested.
Figure 5.1 (a) a single test PCB with 4 test chips labeled as U1, U2, U3 and U4, (b) reconstructed micro-tomography 3D image of a failed test chips, with a melted solder ball at the upper left corner region, (c) the layout of the test chip.
5.3EM Test System in UCLA

To collect the life times of the test vehicles for statistical analysis, we conducted a series of the accelerated EM tests in UCLA. The multiple-channel EM test system is shown in figure 5.2. The top figure shows the complete EM test system which is consisted of three temperature ovens, power supplies for constant current stress (bottom-left), and data collection system (bottom-center) in order to meet the capability to simultaneously run multiple chips. A USB adapted voltage measurement DAQ (Data Acquisition) device was employed for in-situ measurement of voltage drop on the testing chip, and thus the resistance change on each sample is automatically measured by the device and recorded by a computer about every 5 mins.

Figure 5.2 EM test system consisted of three temperature ovens, power supplied and DAQ (data acquisition) device.
During the EM tests, the four test chips on a board were connected in series and current flowed through only one pair of bumps in each chip. When one of the four chips failed, a hook wire was soldered to bypass the failed chip and maintained the current flowed through the remaining chips. For example, if U2 failed (figure 5.1(a)), the TTF of U2 would be recorded, the failed unit would be bypassed and the subsequent EM test was pursued till all of the four chips are failed.

Totally, we have three types of sample studied (see figure 5.3). The EM tests were running with two different current densities: $7.5 \times 10^3 \text{A/cm}^2$ (low-current), and $1 \times 10^4 \text{A/cm}^2$ (high-current), at the same temperature $125^\circ\text{C}$. For each test condition, four same type test boards were tested (i.e. 16 test chips in series), thus there were 16 TTFs (see figure 5.4). The sample types and testing conditions are summarized in table 5.1.
Figure 5.3 Three types of sample with different solder compositions and UBM structures.

Figure 5.4 a set of four boards connected in series for electromigration test (i.e., 16 chips in series)
Table 5.1 Three types of sample were tested under two conditions. The solder composition SN100C includes Sn, Cu(0.65%), Ni(500ppm), Bi(110ppm), Pb(140ppm)/
The solder composition SAC1205 includes Sn, Ag(1.2%), Cu(0.5%).

5.4 Synchrotron Radiation Laminography Study in ESRF

To study the early damage evolution at the interface between UBM and solder ball, the ex-situ SRCL imaging experiments were conducted on the high energy beamline ID15A at the ESRF. The general technique has been described elsewhere in Chapter 3. The main difference between laminography and tomography is that in the former the rotation axis of the sample is not perpendicular to the x-ray beam and the algorithm is developed for imaging regions of interest (ROI) in flat, especially. Before the start of the accelerated EM tests, the solder joints were scanned for initial imaging in 3D as reference. After a given period of EM stressing, the samples were re-scanned to check the changes inside. In the ex-situ SRCL imaging, test vehicles were powered with the same two current densities: $7.5 \times 10^3 \text{A/cm}^2$ (low-current), and $1 \times 10^4 \text{A/cm}^2$ (high-current),
and both were at the same temperature 125°C, which is same as the one we used in the statistical study. Figure 5.5 shows show the digital slice images of the interface between the solder ball and UBM from top view at different time stages in three samples, which were stressed by low-current density. The voxel size of the slice images is about 0.84µm. Clearly, the imaging results show that the void nucleation and growth in these samples is different from the prediction of the traditional model assuming that pancake void only forms at the current crowding point and then propagates along the interface. In these images, the voids nucleate everywhere at the interface, even though the nucleation rate and growth rate of the voids at the current crowding area is larger. Also, a detailed look shows that the voids nucleation rate and growth rate in these three different samples is different indicating different failure mechanisms. Roughly speaking, the solder composition SN100C forms better interface with UBMs than that of SAC1205.
Figure 5.5 Top-view images of the interface between UBM and solder bumps in three different samples, stressed by $7.5 \times 10^3 \text{A/cm}^2$ at $125^\circ\text{C}$, at different time stages.
5.5 Experimental Results

5.5.1 Statistical Analysis by Weibull Distribution

Statistical study of 16 TTFs with each EM condition has been carried on Type 1 samples, show in table 5.2 The cumulative distribution function (CDF) of the TTFs can be fitted by Weibull distribution

\[
F(t) = 1 - \exp\left(-\frac{t}{\eta}\right)^\beta,
\]

shown in figure 5.6(b), to get

1) \(\eta = 619.3\text{hr}, \beta = 2.34\) under the high-current EM condition;

2) \(\eta = 3469\text{hr}, \beta = 1.85\) under the low-current EM condition,

where \(\eta\) is the characteristic life time of the reliability under a certain testing condition, \(\beta\) is the shape parameter.

<table>
<thead>
<tr>
<th>EM condition</th>
<th>TTFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1 \times 10^4)A/cm(^2) at 125(^0)C</td>
<td>571.5, 566.5, 483.5, 735.5, 475.5, 334.5, 418.5, 1205.1, 661.5, 370.0, 342.5, 370.5, 661.5, 475.5, 159.0, 932.5,</td>
</tr>
<tr>
<td>(7.5 \times 10^4)A/cm(^2) at 125(^0)C</td>
<td>2873.5, 972.0, 3319.0, 2291.0, 2085.0, 1920.0, 3172.5, 1791.0, 696.0, 1921.0, 3234.0, 1945.0, 3890.0, 5818.0, 6420.0, 6700.0</td>
</tr>
</tbody>
</table>

Table 5.2 16 TTFs of Type 1 sample in each EM testing condition
5.5.2 Physical Analysis by JMA Phase Transformation Model

The SRCL imaging results of Type 1 samples, shown by figure 5.7(b-g), reveal that in real cases, the nucleation sites of voids are scattered on the interface at the early stage, even though later the growth rate of the voids in the current crowding region would be faster. This process is similar to the phenomenon of phase transformation described by JMA kinetics model,

\[ X_T = 1 - \exp\left(\frac{-t}{\tau}\right)^n, \]  \hspace{1cm} (2.16)

where \( X_T \) is the degree of phase transformation at the time \( t \), \( \tau \) is the characteristic time of the transformation, and \( n \) is the parameter indicating the mode of new phase growth. Here we can define the degree of the void occupying at the interface \( A_v/A_i=X_T \) and \( \tau \) is the characteristic time of the voids growth. By measuring the voids area \( A_v \) at different time stage and whole interface area \( A_i \), and thus fitting the relationship between \( \ln\left(\frac{-\ln(1-X_T)}{\tau}\right) - \ln t \) linearly, we can get the value of both \( \tau \) and \( n \) under each testing condition, shown in figure 5.6(a),

1) \( \tau=768.5\text{hr}, n=0.7 \) under the high-current EM condition;

2) \( \tau=3905.7\text{hr}, n=0.52 \) under the low-current EM condition.
Figure 5.6(a) illustrates the linear relationship between \( \ln(-\ln(1 - X_T)) \) ~ \( \ln t \) of sample I (stressed by \( 7.5 \times 10^3 \) A/cm\(^2\) at 125°C) and sample II (stressed by \( 1 \times 10^4 \) A/cm\(^2\) at 125°C), respectively, fitted by JMA-like model. The slope of the linear line is \( n \) (mode of void growth), while the intercept of the line is \( -n \ln \tau \). The parameters of \( n \) and \( \tau \) of the both samples by fitting the JMA-like model, were shown in Table 5.3. Figure 5.6(b) shows the distribution of the TTFs, measured from two groups of solder joints tested at 125°C, by \( 7.5 \times 10^3 \) A/cm\(^2\) and \( 7.5 \times 10^3 \) A/cm\(^2\) respectively. The shape parameters and characteristic life time of them fitted by Weibull distribution, are shown in Table 5.3.
Figure 5.7(a) The schematic diagram of the cross-section of a Type 1 tested solder joint, showing the configuration and dimensions of the sample. Figure 5.7(b)-(d) show the SRCL digital slice images of the sample I at the interface between the solder ball and the UBM before EM test (figure 5.7(b)), after 13 hr EM test(figure 5.7(c)), after 77 hr EM test(figure 5.7(d)), respectively, by $7.5 \times 10^3$ A/cm$^2$, at 125°C. Figure 5.7(e)-(g) show the SRCL digital slice images of the sample II at the interface between the solder ball and the UBM before EM test (figure 5.7(e)), after 13 hr EM test(figure 5.7(f)), after 77 hr EM test(figure 5.7(g)), respectively, by $1 \times 10^4$ A/cm$^2$, at 125°C.
<table>
<thead>
<tr>
<th>EM condition</th>
<th>Mode of void growth n</th>
<th>Characteristic time $\tau$ (hr)</th>
<th>Shape parameter $\beta$</th>
<th>Characteristic time $\eta$ (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$7.5\times10^3$A/cm$^2$ at 125$^0$C</td>
<td>0.52</td>
<td>3905.7</td>
<td>1.85</td>
<td>3469</td>
</tr>
<tr>
<td>$1\times10^4$A/cm$^2$ at 125$^0$C</td>
<td>0.70</td>
<td>768.5</td>
<td>2.34</td>
<td>619.3</td>
</tr>
</tbody>
</table>

Table 5.3 A summary of the parameters of $n$, $\tau$, $\beta$, $\eta$ fitted by JMA-like model and Weibull distribution under two EM test conditions.

5.5.3 *Intrinsic Link between Weibull Distribution And JMA Theory*

From the above analysis, clearly, we found that Eq (2.16) and (2.18) are in a same form. As shown in table 5.3, the values of $\eta$ and $\tau$ are in a good agreement, when they are under the same EM test condition. This agreement between JMA-like model and Weibull distribution, indicates an intrinsic link between the physical failure mechanism and the statistics of lifetimes of solders induced by EM.

Here we need to recall the Black’s equation of MTTF

$$MTTF_{\text{Black}} = A j^{-m} \exp(Q / kT),$$

(1.2)
where $A$ is a constant, $j$ is the current density, $m$ is the model parameter, $Q$ is the activation energy of the atomic diffusion, and $kT$ has the usual meaning. And the MTTF extracted by Weibull distribution is

$$MTTF_{\text{Weibull}} = \int_0^\infty t \cdot F(t) \cdot dt = \eta \cdot \Gamma(1 + 1/\beta), \quad (5.1)$$

where $\Gamma(*)$ is the gamma function. If $MTTF_{\text{Black}} = MTTF_{\text{Weibull}}$, the characteristic time $\eta$ can be represented by

$$\eta = \frac{A}{\Gamma(1 + 1/\beta)} j^{-m} \exp(Q/kT). \quad (5.2)$$

On the other hand, the characteristic time in the JMA kinetics model is

$$\tau = \tau_0 \exp(E/kT), \quad (5.3)$$

where $\tau_0$ is a constant under a stable driving force, $E$ is the activation energy in the phase transformation process. Obviously, Eq. (5.2) and Eq. (5.3) show identical form, if we assume

(1) $Q = E; \quad (5.4)$

(2) $\tau_0 = \frac{A}{\Gamma(1 + 1/\beta)} j^{-m}. \quad (5.5)$

The physical meaning of the first assumption is that in the “solder to void” phase transformation process, the activation energy is determined by the atomic diffusion barrier. In the second assumption, $A$ is the constant from the Black's equation,
comprising the material properties and the geometry of the interconnect, and $\beta$ in the gamma function is the shape parameter of the Weibull distribution, indicating the uniformity of the quality of the interconnects. Both these two parameters can be extracted by fitting with experimental data, the same goes for the current density exponent $m$, whose value is usually between 1 and 2. In summary, once the sample structure and processing uniformity are determined, $\tau_0$ is determined by the testing current density, indicating that the phase transformation is driven by EM. To quantitatively confirm the above assumptions, a series EM tests was carried on the same type of samples under different conditions and analyzed in the typical way (fix current density $j$ to find the activation energy $Q$, and then fix the temperature $T$ to find the current density exponent $m$) to extract the parameters in the Black’s equation as follows, $Q=0.97$ eV, $A=0.155 \text{ hr} \cdot \text{A}^2/\text{cm}^4$, $m=2$. With the calibration of joule heating induced temperature increases, the semi-theoretical values of $\tau$ of sample I (3646 hr) and sample II (704 hr) calculated by Eq. (5.3)-(5.5), which agrees with the measurements of characteristic lifetime $\tau$ of JMA-like model.

One critical gap between the Weibull distribution and the JMA-like model is that the latter one is the model applied on the voids growth in a single solder bump, while the former one is a model in statistics summarizing the lifetimes of a large number of solder bumps. Conceptually, the agreement between these two models comes from the similarity as the weakest-link distribution in them. The Weibull model can be derived theoretically as a form of extreme value distribution, governing the time to occurrence of
the "weakest point" of many competing failure processes.[44] For example, if a system consists of $N$ identical components in series, and the system fails when the first of these components fails, then the system failure times are the minimum of $N$ random component failure times. The extreme value theory says that, independent of the choice of component model, the system model will approach a Weibull distribution as $N$ (the number of components in the system) becomes large. The same reasoning can also be applied at a single component level having a multiple failure modes, if the component failure occurs when one of many competing failure processes reaches a critical level. In a single unit, there are $N$ (the number of voids) voids growing at the same time. The fastest void growth determines the phase transformation rate of the solder. In other words, the JMA-like model observed is a Weibull approximation in one solder bump during the competition of many voids growth simultaneously.

### 5.5.4 Summary

In summary, SRCL technique was employed to detect the void nucleation sites and propagation rate in flip chip solder joints quantitatively. A JMA-like model was proposed to depict the failure process at the interface instead of the model of the propagation as a single pancake void during the EM test. In the study, the prediction of the lifetime of the sample of more than 3000 hr was determined on the basis of the nondestructive x-rays 3D imaging results of less than 80 hr. It is confirmed by the Weibull statistical results of lifetimes. This model enables us to predict the characteristic lifetime of the solder joints at the early stage in accelerated EM tests as a rapid diagnosis.
Chapter 6 Discussion and Future Work

EM is one of the most serious reliability issues in microelectronic packaging industry. Synchrotron radiation x-rays 3D tomography and laminography techniques offer us a chance to explore the details of failure mechanism in flip-chip solder joints induced by EM.

In Chapter 4, a series of ex-situ studies on EM in eutectic SnPb flip chip solder joints using the synchrotron radiation based x-ray microtomography technique were shown. The 3D imaging technique revealed the effects induced by electron wind force inside the solders, such as the pancake void growth, pre-existing void growth, and morphological change on the free surfaces, quantitatively. The products of effective diffusivity and the effective charge number of EM DZ* in eutectic SnPb alloy under 100°C and 120°C was calculated, respectively. Also, the average stress gradient increase rate in the Sample II was discussed.

In Chapter 5, the SRCL technique was employed to detect the void nucleation sites and propagation rate in flip chip solder joints quantitatively. A JMA-like model was proposed to depict the failure process at the interface instead of the model of the propagation as a single pancake void during the EM test. As a result, a proposed link between JMA phase transformation theory and Weibull statistic distribution was developed. The direct link between the characteristic time in JMA equation and Weibull distribution provides us a rapid way to estimate the life time of the test vehicle under EM
basing on the 3D imaging characterization. The time needed to make the life time estimation can be reduced down to 3% of the time typically needed.

However, we believe the link between JMA and Weibull is not limited in that between the two characteristic times, $\tau$ and $\eta$, but also exists between two mode parameters, $n$ and $\beta$. One idea to link $n$ and $\beta$ is that both of them have geometrical dependences.[45]

In Chapter 2, the general form of JMA equation is shown as Eq (2.15 and 2.16),

$$X_T = 1 - \exp(-X_{ext}) = 1 - \exp(-Kr^n),$$

Where $X_T$ is the fraction of transformed volume at time $t$, $X_{ext}$ is the fraction of extended volume.

We can consider that a nucleus growing in 1-dimension. If it is nucleated at $t=\tau$, the length of the transformed line at $t$ is given by

$$V_T = r = R_G(t - \tau)$$

(6.1)

where $R_G$ is the isotropic growth rate, and it is shown in figure 6.1(a). Then we can have the extended volume as

$$X_{ext} = R_GR_N\int_0^t (t - \tau)d\tau = \frac{1}{2}R_GR_Nt^2$$

(6.2)

where $R_N$ is the nucleation rate. Then we have the JMA equation for 1-dimensional case as
\begin{equation}
X_i = 1 - \exp\left(-\frac{1}{2} R_G R_N t^2\right) = 1 - \exp(-K't^2) .
\end{equation}

In this case, the mode parameter \( n \) is 2.

If we consider the 2-dimentional case, which in a thin planar film, a growth of spherical nucleus will cease growing in the direction normal to the plane of the film. In other words, it grows as a circular disk in two-dimensional way. If it is nucleated at time \( t=\tau \), the volume of the transformed region at \( t \) is given by

\begin{equation}
V_t = \pi R_G^2 (t - \tau)^2 h
\end{equation}

where \( R_G \) is the isotropic growth rate, and it is shown in figure 6.1(b). Then, we have the extended volume as

\begin{equation}
X_{ext} = \pi h R_G^2 R_N \int_0^t (t - \tau)^2 d\tau = \frac{\pi}{3} h R_G^2 R_N t^3 .
\end{equation}

Thus, the JMA equation for 2-dimentional case is

\begin{equation}
X_i = 1 - \exp\left(\frac{\pi}{3} h R_G^2 R_N t^3\right) = 1 - \exp(-K''t^3) ,
\end{equation}

where the mode parameter \( n \) is 3.

Similarly, in the 3-dimensional isotropic growth case, see figure 6.1(c), as what we have derived in Chapter 2, the JMA equation is

\begin{equation}
X_i = 1 - \exp\left(\frac{\pi}{3} R_G^3 R_N t^4\right) = 1 - \exp(-K'''t^4) .
\end{equation}

The mode parameter in the 3-dimentional case is 4.
In Weibull distribution of failure, we can assume a frequency of failure which is the probability of failure per unit time and is given by \( v(t_i) \). It implies that \( v(t_i)dt_i \) is the probability of failure within the time period between \( t \) and \( t+dt \). Since \( 1-x \approx \exp(-x) \) for \( x<<1 \), the probability of no failure in the very short period of \( dt \) is thus given by:

\[
1 - v(t)dt \approx \exp(-v(t)dt) \tag{6.8}
\]

Therefore, the probability of no failure in the time interval from 0 to \( t \) is the product of probabilities at each interval:

\[
p_0(t) = \prod_{i=1}^{N} \exp(-v(t_i)dt_i) = \exp\left(-\sum_{i=1}^{N} v(t_i)dt_i\right) = \exp\left(-\int_0^t \! v(t_i)dt_i\right), \tag{6.9}
\]

where \( N \) is the number of subintervals in the time interval from 0 to \( t \). Then, the Weibull distribution function of failure \( F(t) \) is simply given as

\[
F(t) = 1 - p_0(t) = 1 - \exp\left(-\int_0^t \! v(t_i)dt_i\right). \tag{6.10}
\]
To explore the geometrical effects in the Weibull distribution, we need a few assumptions as follow,

(a) No preexisting void;
(b) Nucleation of tiny voids due to counter flux of vacancies with a frequency \( f \) per unit volume;
(c) Nucleation time dependent process which implies that growth of voids takes much less time than nucleation;
(d) Growth of pancake voids when vacancies or tiny voids emerge;
(e) Migration of voids under electron wind force with a constant velocity \( v \).

If a tiny void migrates only in 1–dimensional direction to nucleate void at the end where electrons come in, the length of the void migrating in 1-dimensional direction in the time interval \( t_i \) and \( t_{i+1} \) and will be \( v(t-t_i) \). The volume of migration is then given by \( V=hw v(t-t_i) \), where \( h \) and \( w \) are the height and width of void respectively. Then the probability of no failure in a subinterval is

\[
p_0(t) = \prod_{i=1}^{N} \exp(-fhwv(t - t_i)dt_i) = \exp(-\sum_{i=1}^{N} (fhwv(t - t_i)dt_i)) = \exp(-\frac{1}{2} fhwvt^2), \quad (6.11)
\]

where \( f \) is a constant frequency of nucleation of tiny voids due to counter-flux of vacancies. Therefore,

\[
F(t) = 1 - p_0(t) = 1 - \exp(-A't^2) \quad \quad (6.12)
\]

where \( A \) is a constant and the shape parameter \( \beta \) is 2.
If tiny voids migrate in 2 dimensional directions to nucleate void at the electron entrance, the volume of the migration in this case will be \( V = p[v(t-t_i)]^2 h \), where \( h \) is the height of the void. Then the probability of no failure in a subinterval is

\[
p_0(t) = \prod_{i=1}^N \exp(-f \pi [v(t-t_i)]^2 h dt_i) = \exp(-\sum_{i=1}^N (f \pi [v(t-t_i)]^2 h dt_i)) = \exp(-\frac{1}{3} fh \pi v^2 t^3),
\]

(6.13)

Therefore,

\[
F(t) = 1 - p_0(t) = 1 - \exp(-A'' t^3)
\]

(6.14)

where \( A \) is a constant and the shape parameter \( \beta \) is 3.

Similarly, in the 3-dimensional case, the spherical volume that the tiny voids migrate within each subinterval is given as \( V = (4/3) p[v(t-t_i)]^3 \). Then the probability of no failure in a subinterval is

\[
p_0(t) = \prod_{i=1}^N \exp(-f \frac{4}{3} \pi [v(t-t_i)]^3 dt_i) = \exp(-\sum_{i=1}^N (f \frac{4}{3} \pi [v(t-t_i)]^3 dt_i)) = \exp(-\frac{1}{3} fh \pi v^3 t^4)
\]

(6.15)

Therefore,

\[
F(t) = 1 - p_0(t) = 1 - \exp(-A'''' t^4)
\]

(6.16)

where \( A \) is a constant and the shape parameter \( \beta \) is 4.

Figure 6.2 shows the possible geometry or dimension of the voids at the cathode interface of typical flip chip solder joints. Figure 6.2(a) shows an extreme case of 1-dimensional case with a needle-like shape; (c) shows a 2-dimensional case; (b) shows the
growth mode in-between 1- and 2- dimensional cases. Since in traditional 2D cross section characterization studies, all these three cases show a similar “pancake shape” void and people cannot tell the differences among them. Therefore, it is hard to get the evidence to study the geometrical effects in the failure mechanism and thus missing the link of mode parameters between JMA theory and Weibull distribution. However, by taking the advantage of the high resolution 3D microtomography technique, shown in figure 6.3, we experimentally prove the existence of these three cases in real devices. A solder joint tested at room temperature and at $3.7 \times 10^4$ A/cm$^2$ for 20.5hrs is shown in figure 6.3(a). It represents an extreme case of 1-dimensional failure mode which has a needle-shape void and is not commonly found. Figure 6.3(c) represents 2-dimensional case of failure mode showing that the voids randomly nucleate and grow at the cathode interface after current stressing for 135.5hrs at $1 \times 10^4$ A/cm$^2$ and 125°C. Figure 6.3(b) represents the case between 1- and 2- dimensional failure modes showing that the void growth after current stressing for 177.5 hr at $1 \times 10^4$ A/cm$^2$ and 125°C.
Figure 6.2 shows the schematic of the possible growth modes of “pancake void” at the cathode interface of typical flip chip solder joints. (a), (b), and (c) represent 1-dimensional, in-between 1- and 2-dimensional, and 2-dimensional growth modes, respectively.
Figure 6.3 shows 3D synchrotron x-ray tomography images of “pancake voids” in (a) 1-dimension; (b) in between 1- and 2-dimension; and (c) 2-dimension, respectively.
To explore the link between mode parameter $n$ in JMA theory and the shape parameter $\beta$ in Weibull distribution, we have shown that both of them have a similarly geometrical dependence and proved the existence of geometrical differences of void growth in real tests by 3D microtomography images. However, this is just our first try and more efforts are on the way.
Chapter 7 Reference


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