Detecting Underfill Delamination and Cracks in Flip Chip on Board Assemblies Using Infrared Microscope

Jicun Lu, Alastair Trigg, Jianhua Wu, and Taichong Chai
Institute of Microelectronics
11 Science Park Road
Singapore Science Park II
Singapore 117685
Phone: 65-770-5455
Fax: 65-774-5747
e-mails: jicun@ime.org.sg and alastain@ime.org.sg

Abstract

Infrared Microscopy (IRM) inspection of underfill delamination and cracks in Flip Chip board (FCOB) assemblies is reported in this work. The location and extent of chip/underfill delamination has been determined. Internal cracks in underfill can also be detected by IRM. Compared to scanning acoustic microscopy (SAM), IRM technique provides higher resolution images of underfill related failures and eliminates the “edge effect” which occurs in SAM. Underfill failures detected by IRM have been verified by destructive physical analysis, microscopy, and scanning electronic microscopy (SEM).

Key words:
Infrared Microscopy (IRM), C-Mode Scanning Acoustic Microscopy (C-SAM), Underfill, Delamination, Crack, and Flip Chip on Board (FCOB).

1. Introduction

In Flip Chip on board (FCOB) assemblies, the provision of underfill encapsulation provides a major enhancement in reliability. The underfill mechanically couples the silicon die to the organic substrate, thereby increasing the fatigue life of the solder as a result of reduced solder fatigue strain under cyclic thermal load. Underfill encapsulation also enhances reliability with respect to humidity. Therefore, the integrity of underfill encapsulation and its interfaces to chip and substrate are essential to long term reliability. It has been reported that failure of adhesion between underfill and chip is the primary failure mode in Flip Chip assemblies subjected to thermal cycling stress\(^1\). Delamination between chip and underfill causes solder joints to be subjected to high strain induced by coefficient of thermal expansion (CTE) mismatch between silicon and organic board, resulting in early failure. In order to understand how underfill failures affect the reliability of FCOB assemblies, detailed investigation of the failure modes is necessary.

SAM has been widely used in electronic package to detect delamination in various interfaces\(^4,5\). But, for underfill inspection, SAM operating at normal frequency of 15-100 MHz cannot detect delamination very close to the edge of the package, where the solder joints most susceptible to failure lie. In addition, SAM cannot detect underfill internal cracks under chip/underfill delamination since the air gap in delamination reflects nearly all the incident acoustic radiation. The spatial resolution of SAM is also not satisfactory for detecting subtle damage features in underfill.

In this study, IRM investigation of failures in FCOB, particularly with regard to failures in underfill, are reported. IRM has been used in semiconductor chip inspection for detecting metallization on chip\(^6\), bond pads damages\(^7,8,9\), among other factors, but the application of IRM to inspect underfill failures in FCOB has been rarely reported. In the current work, FCOB samples which failed electrically after thermal cycling have been studied. Since silicon is transparent to light with wavelength longer than that corresponding to the silicon absorption edge of 1.06 µm, failures in underfill can be readily detected in IRM technique. In order to interpret the infrared
image in terms of the failure modes, conventional destructive physical analysis, cross sectioning, optical microscopy, and scanning electron microscopy have been used.

2. Infrared Microscopy

Conventional IRMs usually have a charge coupled device (CCD) detector covering a wavelength range up to approximately 1100 nm. The IRM used in this study, however, uses a cadmium mercury telluride focal plane array having a wavelength range of 800 nm to 2400 nm. Wavelength discrimination is provided by filters on a remotely driven filter wheel within the cooled enclosure. For most of the work in this study, a filter centered on 1250 nm with a bandwidth of 400 nm was used. A schematic of the IRM is shown in Figure 1. The FCOB assembly is mounted on an XYZ table beneath the objective lens of the system. According to the location of illuminator, IRM can work in reflection and transmission modes as shown in Figure 1. For transmission mode, the infrared source is a small tungsten lamp. For reflection mode, the infrared source is either a tungsten halogen lamp in a conventional through lens microscope illuminator or else a fibre optic illuminator.

The contrast mechanisms in IRM are similar to those in conventional optical microscopy. Since the silicon chip is effectively transparent at wavelengths longer than 1.06 µm, the active surface of the silicon can be viewed from the back as shown in Figure 1. In bright field illumination, aluminum pads and tracks on the chip reflect nearly all the incident radiation so that they appear bright whereas passivation and underfill layers reflect less so they appear darker. With the system shown in Figure 1, true bright field images cannot be obtained at high magnifications since through lens illumination is not available. At low magnifications, however, illumination can be set up to provide close to bright field images. At higher magnifications, the image is essentially dark field so that the silicon aluminum interface appears dark. Since the FR-4 board and underfill are translucent to the infrared radiation, transmitted light images can be obtained in which the contrast is effectively the reverse of the bright field image.

3. Experimental Work and Results

3.1. Test Samples

In the FCOB assemblies, test chips are mounted on FR-4 board by solder joints. The test chips comprise aluminum tracks and bond pads with a solderable underbump metallizations (UBM). In this case, the board comprises copper tracks and solder mask on the surface. The gap between the chip and the board is filled by underfill encapsulation. A schematic of the FCOB is shown in Figure 2. The daisy chain configuration is designed so that all solder joints are connected in series for resistance measurement.

After assembly, the samples were subjected to thermal cycling stress. The temperature profile was from -40°C to 125°C with a dwell time of 20 minutes. Assemblies with 10% increase in electrical resistance were classified as failures. First failures were registered failures after 3500 thermal cycles. Although electrical failure
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occurs due to fatigue cracks in the solder, delamination and cracks in the underfill accelerate the fatigue damage and may be the primary causes of failure modes during thermal cycling.

For the IRM inspection of the FCOB samples, the backside of the silicon chips needs to be polished to minimize scattering of the infrared radiation. The surfaces of chip were polished on diamond paper down to 0.5 µm and then further polished to 0.05 µm using aluminum paste on a cloth polishing wheel. At this stage, no scratches were visible when viewed under dark field microscopy at magnifications up to 800 times.

3.2. Underfill Delamination and Cracks

3.2.1. C-SAM

Twenty failed assemblies were examined by 100MHz C-SAM. It was found that delamination occurred over a large area of the chip/underfill interface and in particular near the solder joints. A typical C-SAM image is shown in Figure 3. Some linear features, apparently emanating from the solder joints, were observed. The area close to the chip edge cannot be effectively imaged due to the “edge effect” in C-SAM as a result of focusing nature of acoustic beam. In these FCOB assemblies, the outmost solder joints are about 0.4 mm away from chip edge and hence lie within this unobservable “edge-effect” area.

Figure 3. 100 MHz C-SAM image of chip/underfill interface in FCOB assemblies.

3.2.2. IRM

After C-SAM examination, three samples were back polished and inspected by IRM. Both reflection and transmission modes were employed. IRM at low magnification showed clearly the underfill delamination and the linear features observed using the C-SAM. A typical IRM image of the same sample examined by C-SAM is shown in Figure 4.

The area of underfill delamination area shown in IRM is identical to that observed using C-SAM. In the IRM, delamination is detectable due to the difference in reflection coefficient between the polyimide surface and the underfill on one hand, as well as the polyimide surface and an air gap.

At higher magnifications, the linear features observed in both C-SAM and IRM can be seen more clearly and correspond to cracks in underfill, Figure 5. Most cracks emanate from individual solder joints and may connect two adjacent solder joints, penetrate into the interior of the chip, or out towards the edge. These cracks occur near all solder joints. It is believed that the cracks result from local CTE mismatch between underfill and eutectic solder during thermal cycling.

Figure 5. IRM images of underfill delamination and cracks with high magnification. Transmission Mode.

At high magnifications, interference fringes can be seen arising from multiple reflection in the air gap between chip surface and underfill areas of delamination. The dark fringes correspond to $2d = p\lambda$, where $d$ is the thickness of the air gap, $\lambda$ is the wavelength, and $p$ is the order of the fringe. Since at least six fringes can be counted, the maximum air gap is at least 3.75µm thickness. Since the filter
has a bandwidth of approximately 400 nm, the spatial coherence is a concern. Theoretically, the maximum order of fringes $m_{max}$ is

$$m_{max} = \frac{2\pi\Delta\lambda}{\lambda} = \frac{2 \times 1250}{400} \approx 6$$

Hence, the maximum size of gap that can be measured from fringes at this wavelength is $6 \times (1.25/2) = 3.75\mu m$. In some instances, there appears to be extrusion of the eutectic solder into the cracks during thermal cycling (Figure 6). In this case, the IRM is operating in transmission mode. Solder extruded in crack blocks the transmission of infrared light, so that it appears dark in the image. Since underfill has a higher CTE than eutectic solder (26ppm/°C), the solder joint is subjected to compressive stress at the temperatures below the curing temperature of underfill (150°C). Hence, extrusion into a neighboring gap or crack can occur during cyclic thermal loading.

$$m_{max} = \frac{2\pi\Delta\lambda}{\lambda} = \frac{2 \times 1250}{400} \approx 6$$

![Figure 7. SEM image of cross section. The sectioning site is the marked line in Figure 4.](image)

**Figure 7.** SEM image of cross section. The sectioning site is the marked line in Figure 4.

**3.2.3. Destructive Physical Analysis**

Although nondestructive analysis is the first choice for routine analysis, destructive physical analysis is required to validate the interpretation of techniques such as C-SAM and IRM. After IRM and C-SAM investigations have been carried out, all the samples were cross-sectioned at specific sites.

Underfill delamination has been clearly observed using scanning electron microscopy (SEM) in cross section, Figures 7. It can be seen that the delamination occurs at the chip passivation/underfill interface. The maximum size of air gap in the delamination is about 2 µm. It is the variation of size of gap that induces the interference fringes.

Underfill cracks have been characterized in two directions: X-Y (parallel to chip surface) and Z direction (vertical to chip surface). Figure 8(c) shows a crack in the underfill in X-Y direction by cross sectioning and SEM observation. The cross sectioning site is along the line marked in C-SAM and IRM images, shown in Figures 8(a) and 8(b), respectively.

![Figure 8. Underfill internal cracks detected by C-SAM, IRM, and SEM.](image)

The cracks initiate from the interface of the chip passivation to underfill and develop across the underfill into the solder resist layer. The delamination in C-SAM image correlates well with the area with fringes in IRM image. The cracks can be observed in the IRM operating with transmission mode, but cannot be observed in C-SAM. This effect can be contributed to the fact that nearly all the incident acoustic pulse is reflected at the chip/air interface in delamination, therefore cracks beneath delamination cannot be detected in C-SAM.

To provide a plan view of underfill cracks, the samples were polished in direction of chip surface normal. The chip, passivation layer, and Al tracks were polished away to reveal the underfill so that underfill cracks could be examined using SEM. Observations from the different analytical tools at the same site of a sample are shown in Figure 9. While the cracks seen on the cross section correlate well with those observed in the IRM, C-SAM cannot detect these cracks around solder joints. The crack beneath the aluminum tracks cannot be observed in IRM since aluminum is opaque to both visible and infrared light.
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Figure 9. Plan view of underfill cracks observed by C-SAM, IRM, and optical microscopy.

4. Discussion

The merits of the different analysis tools, IRM, C-SAM and cross sectioning/SEM are shown in Table 1.

Table 1. Comparison of different analysis tools for detection of failures in underfill.

<table>
<thead>
<tr>
<th>Tools</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>C-SAM</td>
<td>1) Non-destructive</td>
<td>1) “Edge effect”</td>
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<tr>
<td></td>
<td>2) Very sensitive to delamination</td>
<td>2) Planarity of interface is required</td>
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<tr>
<td></td>
<td></td>
<td>3) Poor spatial resolution</td>
</tr>
<tr>
<td>IRM</td>
<td>1) Non-destructive</td>
<td>1) Chip backside polishing is required</td>
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<tr>
<td></td>
<td>2) High spatial resolution</td>
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<tr>
<td></td>
<td>3) Can detect size of air gap in delamination</td>
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<td></td>
<td>4) Can detect crack under delamination</td>
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<tr>
<td>Cross Sectioning / SEM</td>
<td>1) Direct observation</td>
<td>1) Destructive</td>
</tr>
<tr>
<td></td>
<td>2) Very high spatial resolution with SEM</td>
<td>2) Smearing of materials may hide damages in package</td>
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</table>

5. Conclusions

Infrared microscopy has proved to be a powerful, nondestructive tool for inspection of underfill related failures in FCOB assemblies. It can locate both delamination and indicate the size of the gap between the chip and underfill encapsulation. It can also detect small cracks in underfill, including those near which delamination has occurred. Some more subtle damage features, such as extrusion of solder into underfill cracks, are also detectable with this technique.

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References


About the authors

Jicun Lu received his M.S. Degree in Electronic Materials and Devices in 1995, his B.S. Degree in Physics in 1992, and is a currently Ph.D. candidate all in Fudan University, P. R. China. From 1997 to 1998, he has been an industrial attachee at Institute of Microelectronics in Singapore. He has been engaged in reliability test, failure analysis, and simulation for advanced electronic package. Jicun Lu is an IMAPS member.

Alastair Trigg obtained his B.Sc. Degree from Exeter University in 1972, and his Ph.D. Degree from London University in 1978. From 1975 to 1995, he worked for the Hirst Research Centre of the General Electric Company, in the UK in a variety of roles. These included work on SEM and surface analysis techniques for the characterization of semiconductor devices and materials, development of Multichip Module (MCM) technology, hybrid fabrication and application of reliability and growth techniques to new consumer products. From 1987 to 1990, he was Deputy Director of the Research Initiative on Silicon Hybrids, a collaborative project to develop Multichip modules and subsequently became project leader for manufacture of high stability oscillators for space applications. In 1995, he joined the Institute of Microelectronics in Singapore where he is working on infrared microscopy, surface analysis, and the development of passive components for MCMs.

Jianhua Wu received her B.E. Degree in Mechanics and M.E. Degree in Computational Mechanics from Huazhong University of Science and Technology (HUST), China, and her Ph.D. Degree in Mechanical Engineering from National University of Singapore. She currently is a senior research engineer in Institute of Microelectronics, Singapore. She worked on the reliability and failure analysis in solder ball & bump interconnection packages, CAE application in package thermal and reliability performance, design and process optimization and advanced packaging technology development. She leaded/supported several electronic package research consortium (EPRC) projects, as well as involved BGA, Flip Chip on board and MCM technology development. Her current research interest focuses on RFID product development.

Chai Tai Chong received his B.E. Degree in Mechanical Engineering from Heriot-Watt University Scotland in 1987. From 1988 to 1993, he worked in the Texas Instruments, Singapore as a Packaging Development Engineer responsible for the development of LOC die attachment technology. He joined the Advanced Packaging Development Support Department of IME in 1993, where he is currently a Member Technical Staff. His areas of research interest are package reliability and material analysis. He has published more than 10 papers and has 3 patents in the area of package reliability.