RELIABILITY ENHANCEMENT OF ACF JOINED FLIP CHIPS WITH PARYLENE C AS A PROTECTIVE COATING

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ABSTRACT
Electronic devices are entering every field of life nowadays. Also medicine uses electrical instruments and devices every day, and the safety and reliability are the key factors in that sector. Also the operational aspects of devices are of course vital and make the device useful and worth while. However, the hardware of the device plays also a key role, since without it the programs cannot function. Furthermore, the use of different packaging technologies determines the size and weight of the device. As the devices get more complicated, the packaging of electronics becomes more important.

In this study the reliability of anisotropically conductive adhesive joined flip chip components is considered with a parylene C protective coating on top. With this coating the compatibility with human body and the reliability in medical devices are ensured. Reliability testing was made in 8585 –constant humidity test with two different test substrate layouts and test chips. These contained thin chip and substrate structure and thick chip and substrate layouts. The results show that with thin, more space saving and lighter structure, the reliability can be dramatically improved. Furthermore, parylene C proves to be an excellent protection against humid environment enhancing the long term reliability even more.

KEY WORDS
Parylene C, flip chip, anisotropically conductive adhesive, reliability testing, humidity testing, conformal coating

1. Introduction
Medicine is using more and more electronics as the smart systems are developing. The development of medical devices and medical electronics started from x-ray device and the discovery of x-rays by Wilhelm Conrad Röntgen in 1895 [1]. From that invention on the development of medical electronic devices has been intense. When electronics are utilized in medicine, the safety and reliability of the devices are the most important things along with the functionality. Since electronics is in close contact with human body in medical applications, it needs to be protected the way that neither the device is harmed by the human body nor the human body is harmed by the materials used in the device or the functionality of the device. Especially in implantable applications, the requirements are high. Biomaterials are commonly used in the interface between living tissue and the implant to ensure biocompatibility. Since most of the materials used in electronics are harmful to the human body, the coating materials used have many reliability requirements to fulfill [2].

The coating materials, among all, are classified by the Federal Food, Drug, and Cosmetic Act (FDCA), the United States Pharmacopeia (USP) and National Formulary (NF) in U.S., and these classifications are valid also throughout the world. When a material is used that has already been classified by the organization mentioned above, the qualifying process of the device will be much lighter.

Typically especially in implantable applications metal casings are used, and only flexible parts of the devices are coated with some polymer [3]. However, in applications with limited implantation time, also polymer materials are used [4]. The challenge in the use of polymers as protective coating materials lies in the non-hermetic shield that they are giving. However, since device’s size is willing to be kept as small and as light as possible, the use of polymer materials should be considered where possible. Furthermore, some polymer materials offer thin coating layers and flexibility, where the use of flexible structures also becomes possible. Furthermore, polymer materials are safe with medical imaging technologies and the metal related artefacts in post-operative studies are minimized [5]. In non-implantable applications the use of polymer materials are even more attractive and thus the reliability studies offers valuable information for manufacturers of such devices.

Parylene C offers an attractive option to do the protection effectively and safely. It ensures a pinhole free and smooth coating to the electronic device without increasing the devices’ dimensions dramatically [6, 7]. Parylene C is classified by the United States Pharmacopeia (USP) as a

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class VI plastic which ensures the material to be biocompatible and suitable for even implantable applications [8]. With this material the medical device could be protected safely and reliably and still the flexibility of the device could be maintained, depending of the coating thickness of parylene C.

The miniaturization of electronics in medical devices plays a key role in the development of small and lightweight medical devices. Different miniaturization techniques are introduced in electronics and the most feasible ones to medical applications need to be studied carefully. In order to create the whole package as miniaturized as possible, also the sensing electrodes and elements need to be studied [9]. The use of flexible substrates and flip chip joining technology is one step towards miniaturized electronic equipment. In flip chip technology the active component is attached to the substrate without any casing and is thus saving space. Furthermore, with flip chip technology the contact paths are shortened, when the I/O connections are positioned underneath the chip, which improves the electrical performance of the package. Beyond flip chip technology more integrated packaging technologies should be considered, where active components may be integrated into substrates [10]. These kinds of technologies are still at early development stage and their reliability needs to be studied carefully before they may be used in medical applications.

One challenge in the reliability tests performed for the medical electronics lies in the lack of testing standards. The materials used to ensure the biocompatibility and harmlessness of the device to the human body have been tested for their biocompatibility using the test standards for that. On the other hand the electronics itself may be tested for its reliability using standards for that. The usefulness of these standards means different environmental conditions than the ones inside the human body, is still a question to resolve.

In this paper the results for 8585 –constant humidity reliability tests are presented, the use of parylene C as an attractive choice for protecting electronic devices in medical applications. The test structures used are consisted of anisotropically conductive adhesive (ACA) joined flip chip components on FR-4 substrates. Furthermore, the used test structures contain different thicknesses of test substrates and different sizes and thicknesses of chips as well. In parallel with the test structures protected with parylene C coating, tests have also been run to similar structures without any coating. In that case the reliability improvement can be clearly seen when parylene C is used. Furthermore the improvement of the reliability by using thinned chips and thinner substrates are shown.

2. Experimental

2.1 Test specimen

The test samples used in this study consisted of flip chip joined test chips on FR-4 substrates. The main properties of FR-4 substrate material are given in Table 1. In the table, the glass transition temperature (T_g) for the materials is given which refers to the temperature at which amorphous materials change from hard and brittle state into more rubber-like state. Coefficient of thermal expansion (CTE) both below and above T_g have been listed and the moisture absorption of the material in weight percent. These material properties are important when studying the failures of the interconnections.

The joining was made using anisotropically conductive adhesives (ACA). The specimen had two different layouts and structures as described below. A test specimen with thin chips and substrates had a test board of 45 x 80 mm in dimensions and it had 8 test chips attached. The substrate was single sided, 100 µm thick, and had 19-20 µm thick copper wiring with NiAu finishing. Due to the thickness of the substrates, they were relatively flexible containing only one layer of glass fiber cloth. The test chip was 80 µm thick and the dimensions were 5 x 5 mm. The chips had 69 square copper bumps in peripheral array, height of the bumps was 20 µm and they were 100 x 100 µm in dimensions. The pitch was 250 µm. A photograph of one test board can be seen in Figure 1. The attachment was done using an anisotropic conductive film (ACF), which was commercially available epoxy-based thermoset adhesive. It was 40 µm thick and had 8 µm diameter Au coated nickel particles forming the connective path. The main properties of the adhesive are listed in Table 1 with name tag ACF 1.

A test specimen with thick chips and substrates had a test board of 30 x 50 mm with NiAu coated copper wiring. The thickness of the substrate was 1 mm. Each of the substrates had one site for a 300 µm high, 8 x 8 mm test chip with 275 gold bumps. The height of the bumps was 15 µm and they were 100 µm in diameter. The test chip had many test structures but in this study only the daisy chain structure encircling the chip was used. 192 bumps participated to the daisy chain structure. Figure 2 shows a photograph of this test vehicle. The ACF used to interconnect the chips was commercially available epoxy-based thermoset which was 40 µm thick containing Au coated polymer balls as conductive particles. The main properties of the adhesive are listed in Table 1 under ACF 2. Both of the adhesives used in this study contained also non-conductive SiO₂ filler particles, 0.8 µm diameter, in order to reduce the coefficient of thermal expansion (CTE).
Figure 1. A Photograph of a test substrate after chip bonding in test lot TN_PARY. The wiring for real time measurements can been seen at the bottom.

Figure 2. A photograph of a test specimen in test lot TK_NON. Test wiring for real time measurements can be seen on the right hand side.

Table 1
Main properties of the materials used in the study

<table>
<thead>
<tr>
<th>Property</th>
<th>FR-4</th>
<th>ACF 1</th>
<th>ACF 2</th>
<th>Parylene C</th>
</tr>
</thead>
<tbody>
<tr>
<td>T&lt;sub&gt;g&lt;/sub&gt; / °C</td>
<td>130-140</td>
<td>113</td>
<td>112</td>
<td>87-97</td>
</tr>
<tr>
<td>CTE (below T&lt;sub&gt;g&lt;/sub&gt;) / °C</td>
<td>12-16</td>
<td>39</td>
<td>40</td>
<td>40-50</td>
</tr>
<tr>
<td>CTE (above T&lt;sub&gt;g&lt;/sub&gt;) / °C</td>
<td>-</td>
<td>552</td>
<td>561</td>
<td>-</td>
</tr>
<tr>
<td>Moisture absorption /wt%</td>
<td>0.1</td>
<td>2.1</td>
<td>1.9</td>
<td>0.01-0.06</td>
</tr>
</tbody>
</table>

The used test chips were specially designed for reliability testing and had a daisy chain test structure encircling the chip. With the daisy chain test structure the resistance of the joints participating in the daisy chain structure was measured, later called the daisy chain resistance, R<sub>DC</sub>. The daisy chain forms a conductive path through each interconnection between chip and substrate. This is illustrated in Figure 3. With this structure the failures in the interconnections can be seen by dramatic changes in the daisy chain resistance. Measuring this resistance allowed the failed joints to be detected. Daisy chain measurement is a widely used technique for investigating the joint reliability.

Figure 3. An imagination of the daisy chain structure connecting the interconnections.

2.2 Attachment process

Joining was made using a TORAY FC1000 semi-automatic flip chip bonder. The bonding temperatures and times used were in the range recommended by the adhesive manufacturer. The used bonding profile had first a pre-bonding step, where the ACF was attached to the substrate. After this, the carrier tape was removed which protects the adhesive from contamination. The final bonding was conducted using the pressure of 80 MPa which was in the range recommended by the adhesive manufacturer.

2.3 Protective coating

The parylene C coating was made using vapour deposition polymerisation at room temperature. The coating was made with Parylene Labtop coating furnace. In this technique, parylene deposits from a gaseous diradical state to a solid state on the surface of the sample in vacuum chamber. With this processing technique the coating forms an even layer to the substrate ensuring full coverage of the device. The main properties of parylene C are listed in Table 1. The coating thickness for parylene C was measured from a cross section made, and can be seen in Figure 4. The thickness was 26.7 µm which is rather thick coating layer. With the coating technique used much thinner coatings can be achieved if wanted.

Figure 4. A Micrograph showing the parylene C coating formation and thickness of one sample from test lot TK_PARY.
2.4 Test lots

In this study all together four test lots were prepared for testing. The test lots are listed in Table 2 and are named using TN as a sign for thin chip and substrate structure and TK as a sign for thick chip and substrate structure. Furthermore, PARY is used for parylene C coated samples and NON for non-coated samples. Every test lot consisted of eight equivalent samples.

<table>
<thead>
<tr>
<th>Name</th>
<th>Thin</th>
<th>Thick</th>
<th>Parylene C</th>
</tr>
</thead>
<tbody>
<tr>
<td>TN_NON</td>
<td>X</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>TN_PARY</td>
<td>X</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>TK_NON</td>
<td>X</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>TK_PARY</td>
<td>X</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Test lots used in the study

2.5 Reliability testing

In this study the test specimen were subjected to 8585 constant humidity test which is commonly used in electronics. The test followed Jedec standard 22-A101-B where the testing conditions were 85 °C and 85 % relative humidity with tolerances ± 2 °C and ± 5 %, respectively [11]. The test chamber used was Tabai Espec PL-1KPH temperature and humidity chamber. During constant humidity testing the resistance measurements were performed using continuous real-time measurement system with a data logger from National Instruments. The voltage across each chip’s daisy chain structure was measured through a 1 kΩ shunt resistor. The measurements were carried out every 60 seconds. The wiring to accomplish these measurements can be seen in Figures 1 and 2 as described in the captions. The specimen in the reliability test was considered failed when the voltage across the daisy chain structure was tenfold to the original one.

As described earlier, the thin and thick test specimen had also differences in the layout of the chip. The thin chip had 69 bumps with a pitch of 250 µm and the thick chip had 192 bumps participating the daisy chain structure (and thus significant in this study) with a pitch of 190 µm. Both of the substrates used in the study were FR-4 material, but in thick substrates the copper wiring was over etched and thus giving smaller contact areas to the connections. Despite these differences the materials and processes used in these two test structures were similar. The results from the constant humidity test are shown in Figure 5. As can be seen, the long term reliability of the thin chip and substrate structure both with (TN_PARY) and without (TN_NON) parylene C coating is dramatically better than thick chip and substrate structures (TK_PARY and TK_NON). However, in the thin chip and substrate structure without coating, i.e. test lot TN_NON, two of the samples were failed right after the test started. These two test samples were considered as infant mortalities that were caused due to some errors or impurities during the manufacturing process. These two samples were then left out from the reliability results of the test lot.

The results show a clear improvement of reliability when thin chip and substrate structure is used. This result can be due to the more flexible structure of the thin chip and substrate letting the structure to deform more under the stresses caused by adhesive moisture intake and differences in CTEs. As parylene C protects the structure from moisture intake, the time for first failure is much longer for the test lot TN_PARY than with TN_NON. This same phenomenon can be seen in TK_PARY and TK_NON.

The swelling of the adhesive due to the moisture intake causes hygroscopic stresses [12] which then cause the ACF joint to fail. During 8585 -reliability testing moisture enters the adhesive and condenses into liquid water phase. In adhesive matrix the water molecules then have two different states, “free” or “unbound” state and “bound” state [13]. Unbound water molecules are settled to the adhesive matrix in nano-pores or free-volumes and bound water molecules interact with the polymer forming hydrogen bonds or other chemical reactions [13]. The hygroscopic swelling is suggested to be caused by the bound water molecules affecting the polymer chains and thus causing swelling [13]. If the swelling is caused by the bound water molecules, the hygroscopic swelling would then be a two-step process, where in the first step the water molecules are entered to the polymer’s free-volumes and at the second state they are forming hydrogen bonds with the polymer [13]. If this holds true, a short-term exposure to humid environment would be reversible as water molecules are releasable from the polymer with the same temperature as the first penetration has occurred [13]. Also this strengthens the assumption that the two test samples from test lot TN_NON that were failed at the very beginning of the test were not failed due to the testing environment.

3. Results and discussion

The constant humidity test lasted altogether 14,000 hours. However, testing with thick chip and substrate structures were stopped after 7,000 hours of testing while every other sample was failed but one in test lot TK_PARY. Thin chip and substrate test lots continued in the test for the whole 14,000 hour test. This was due to the long lasting structure of thin chips and substrates. The structure of thick chips and substrates was much more sensitive to moisture and they were failed much earlier.

As the material parameters are presented in Table 1, we can see that both of the used adhesive materials were showing similar values. Furthermore they were from the same material manufacturer and the only real difference in the adhesive was the different material of the conductive particles. That is why we can assume that the most relevant thing in the large difference of the reliability results is the structure of the test specimen.
Furthermore, the absorbed moisture may change the material parameters of the adhesive, i.e. $T_g$, CTE and Young’s modulus [13, 14]. This weakens the structure of the polymer and failures are more likely to occur. The failures occur in humid environments typically in form of cracks and delamination that are caused due to swelling and the change of material properties. In ACF interface there may already be initial delaminations due to contamination during processing which are increased during humidity ageing [15]. Furthermore the interfacial adhesion of the adhesive is weakened due to moisture thus causing delamination.

According to the previous studies and literature, delamination was expected to be the failure mechanism in the test lots studied in this paper. Cross sectioning was made to samples from test lots TK_NON and TK_PARY since they had larger amount of failed samples. After cross sectioning the samples were grinded to see the interconnections and samples were analyzed using scanning electron microscopy (SEM). The results from cross sectioning are shown in Figures 6 and 7 and delamination can clearly be seen in test samples. One difference was noticed in the test samples from test lots TK_NON and TK_PARY. In test lot TK_NON the delamination occurred between the bump and pad in all the samples studied and as can be seen in Figure 6. In test lot TK_PARY the delamination occurred either between the bump and pad or between the chip and the bump which is shown in Figure 7. In these cases the forces present in the structure have probably been different due to the protective coating. This has caused the internal forces to work the way that the adhesion between chip and bump has given up first. Under the Au bump there was only Al track on the chip. From the SEM image it seems that the delamination proceeded in the interface between gold and aluminium, but the actual location of the delamination was not studied more intensively.

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Figure 5. Reliability test results from 8585 –constant humidity test.

![Figure 5](image1.png)

Figure 6. A Micrograph of a joint in a test sample from test lot TK_NON. The delamination is proceeding between bump and pad breaking the conductive path.

![Figure 6](image2.png)

Figure 7. A Micrograph of a joint in a test sample from test lot TK_PARY. The delamination is propagating in the interface between chip and bump at this point.

![Figure 7](image3.png)
4. Conclusion

This study considered the reliability of ACF joined flip chip components in humid environment. The test structures were protected using parylene C polymer material in order to make the structure biocompatible and appropriate for medical applications. The aim of the study was to see the behavior of parylene C as a protective coating and the differences in two separate test structures: thin and thick. In thin test structure thinned chips and thin FR-4 substrates were used while in thick test structure thick chips and thick FR-4 substrates were used.

The results showed a great difference between thin and thick structures both with and without parylene C coating. The thin structure proved to be much more reliable and parylene C coating improved the reliability even more. According to this study, thin and flexible miniaturization solutions would be an option for medical devices. They show high reliability and offer medical devices lightness and small size.

Parylene C coating proved to be an excellent barrier against moist environment. In applications where polymer coating materials are considered adequate enough, parylene C is a good option. The coating process is somewhat slow and complicated for parylene C and special equipment is needed to process the coating, but on the other hand the coating process ensures a pinhole free and uniform coating to form.

The failure analysis carried out with the thick test lots showed delamination as the reason for failures, as expected. The protective coating did not change the failure mechanism itself, but it changed the propagation route of the delamination. This gives an idea of different stresses occurring in the structure during testing with non-coated and coated samples.

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