# ON-BOARD PACKAGE DECAPSULATION TECHNIQUES FOR FAILURE ANALYSIS

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## ABSTRACT

With the increasing demand for sleeker and light weight devices, printed circuit boards (PCBs) are getting very crowded due to numerous components mounted within a limited space. This also reduces the number of probing test points available for failure analysis/fault isolation (FA/FI) processes. Hence, FA engineers usually extrapolate conclusions about the missing signals without concrete evidence. In many cases, these analyses end with component level isolation, without deep dive investigation of the failure signature. In addition, package decapsulation is a commonly used technique for die level analysis but in the cases where package removal from the PCB destroys the failure signature, on-board decapsulation is more appropriate. On-board decapsulation allows precise system level FA/FI and gives engineers the ability to literally look inside the components by exposing the die and wire bonds of the component while they are still intact on the motherboard. In the present work, various on-board decapsulation techniques to remove package overmold while preserving wire bonds either gold (Au) or Copper (Cu) were evaluated. From an electrical FA standpoint, this technique allows precise FA execution by enabling in situ probing of the wire bonds. Hence, previously inaccessible data can be collected by simply using a microprobe station.

Key words: chemical decapsulation, PCB, failure analysis, fault isolation, wire bond

## INTRODUCTION

Inability to get accurate probe readings is a major time and money consideration for the FA/FI process. This is especially problematic with surface mount components that do not contain comprehensive test points. As devices shrink, the space for test points is becoming compressed and the number of traces that never reach the surface is increasing. This results in more signals that cannot be accessed and forces FA engineers to extrapolate conclusions about these missing signals without direct evidence. In many cases, these analyses end with component level isolation, without deep dive investigation of the failure signature. A variety of decapsulation techniques have been proposed in recent years. The principal concern in all techniques is how to decapsulate a package without damaging sensitive electronic components. However, most of these techniques focus on "package only" decapsulation. Although chemical decapsulation of packages is common in the integrated circuit (IC) world, on-board decapsulation of packages in which the package is still attached to the motherboard is not widely studied. In situations where package removal from the motherboard destroys the failure signature, on-board decapsulation ensures its preservation. A successful decapsulation procedure for system level FA/FI would expose die on-board with the wire bonds still intact. In addition, packages mounted on flex cables pose additional challenges when compared to rigid PCBs. There are several non-chemical ways to remove the overmold material. Chemical methods are best avoided mainly Cu thinning and acid retention within the part may deplete circuit boards with time. One crude way to remove overmold is by microabrasion. This technique can be performed with the help of an abrasive which can selectively remove overmold without damaging the die. In this case removal of the package from printed circuit board (PCB) is also not necessary. The areas around package where abrasion is not required can be masked by a Cu tape to avoid damage. However, this technique hasn't shown promise to preserve wire bonds.

Another non-chemical technique to remove overmold is by laser ablation [1]. Since this process is isotropic in nature, it leaves encapsulating material under the bond wires which may need to be cleaned up by applying another anisotropic technique. Die damage due to overheating is a concern as well. Due to these issues, laser ablation is applied first to remove majority of the overmold and as one approaches closer to die and wire bonds, Reactive ion etching (RIE)/Inductive coupled plasma (ICP) can be used. The primary advantage of RIE/ICP is its non-directional removal of epoxy material along with the ease of maintaining functionality of package. Although gentler, this could be a time consuming process and hence it is best to use laser ablation prior using plasma to expose the die [2]. However, RIE if run at higher process frequencies and temperatures could lead to damage making them unsuitable for decapping.

Chemical decapsulation requires the use of fuming nitric ($HNO_3$) and sulfuric acid ($H_2SO_4$) to break down the encapsulation material. Fuming acids are preferred because they react and dissolve the overmold material fast without etching the Au wire bonds or Aluminum (Al) bond pads. To preserve Cu wires, fuming $H_2SO_4$ is used. However, using fuming $H_2SO_4$ exclusively may end up damaging Al bond pads. Hence, to protect both Cu and Al structures which are widely used these days in integrated circuits these acids are used in combination. It can be performed manually or by using automated etchers. Manual decapsulation methods even while using the chemical resistant maskant could be messy and non-uniform. Cu wire bond damage due to uncontrolled etching is a well-known issue with acids. A successful demonstration of manual on-board chemical decapsulation was shown by Gonzales *et al.* [3]. This was done by applying a fast curing, easy to peel off acid resistant maskant around the area where chemical decapsulation was required. Although novel, similar results can be achieved if a gasket is used in place of the maskant. Also, this does not address the problems related to wire bond preservation and large form factor boards. Since wire bonding is the dominant method of electrical interconnection between the IC and the package, their preservation is essential when decapsulation is performed. Cu wire bonds are more prone to get attacked and damaged by acids as compared to Au. Hence, decapsulation of Cu wire bonds has long remained a challenge. Combining various techniques like pre laser decapsulation followed by chemical decapsulation (LCE), yielded some good results by minimizing the damage on the Cu wire bonds. However, it increases the time of decapsulation significantly [4]. Even with this method it has been realized that if the pre laser decapsulation is not carried with a defocused laser depth the subsequent chemical decapsulation will only exacerbate the Cu wire bond damage. Due to these difficulties Chen *et al*. [5], proposed Ag as an alternative to Au since in terms of process ability Ag wires are similar to Au. However, the comparative studies by Francois *et al.* [6], showed Cu to be more promising as compared to Ag. Subsequently, the chemistry related to decapsulation changes with all these alterations.

With the advent of gaskets and jet etchers it has become possible to perform chemical decapsulation on a variety of packages without any damage to the wire bonds. However, present chemical decapsulation methods even with the help of automated etchers are incapable to perform on-board chemical decapsulation. This is mainly due to the limitation in the size of the chambers. The small chamber designed mainly for “package only” decapsulation in automated etchers cannot accommodate the boards of large form factors. This means that when the size of the motherboard is bigger than the chamber of the tool, the board has to be compromised. In failure analysis world, it is not always in the best interest to remove a package before a fault is isolated down to die level. This is mainly because additional steps of package removal from a board could potentially introduce or mask any existing failure defeating the purpose of FA. A successful decapsulation procedure would expose die on-board while the wire bonds are still intact without compromising the failure signature. So far the vendors have tried to make automated etchers compact and during that process chamber size has reduced significantly. The chamber is large enough to just hold a package on the etch head with a safety clearance around the etch head so that chamber can be closed while performing the chemical decapsulation. The tools fit easily inside a fume hood and are easy to use. Since our goal was to preserve both board and package; our requirement to enable system level FA by this technique was to increase chamber size while preserving the simplicity of the equipment.

The present work discusses on-board decapsulation techniques executed through mechanical and chemical means. A larger chamber chemical etcher developed with vendors enabled decapsulation of the packages mounted on phone boards. While performing on-board chemical decapsulation, both Au and Cu wire bonds, Al bond pads were intact. No Cu thinning was seen post decapsulation. In addition, chemical decapsulation was done successfully on packages mounted on flex cables. From an electrical FA standpoint, this technique allows precise fault isolation by enabling direct probing of the wire bonds thereby helping to collect previously inaccessible signals.

## EXPERIMENTAL

In order to get better access, shields around the package requiring on-board decapsulation were removed. This also protected board from acid attack by providing better UV curable maskant coverage during chemical decapsulation. Optical microscope (OM) inspection pre and post shield removal was done to ensure that no damage was caused to the board prior to decapsulation. The dimensions of the package and exact size of the die were recorded by OM and 2D X-ray respectively to create a correct gasket type for chemical etching of overmold. Vendor information on amount of filler material helped to create an optimum recipe for overmold removal. Hence, etch time, ratio of chemicals and temperature was accurately managed. In addition, a functionality test was performed prior to chemical decapsulation of the samples to check validity of the process post decapsulation.

### 2.1. Microabrasion

For preparing the samples for microabrasion, 2D X-ray was initially done. This was to understand the die details such as location, wire bonds etc. A Cu tape was used around the package so that the board was not damaged with abrasives escaping to the board. Tool nozzle was set to a high pressure ~40 psi and sodium bicarbonate was used as an abrasive for overmold removal. Initial blast of abrasive material was used on the Cu tape before it was sprayed on top of the actual overmold that needed to be removed. The nozzle was swayed constantly from one corner to another as the bulk of the overmold was removed. The pressure was reduced to 30 psi to protect the die or any components underneath. To clean the board post microabrasion, pressurized air was used. The Cu tapes were removed post abrasion and areas were inspected for damage.

### 2.1. Manual on-board decapsulation

For manual chemical decapsulation, an acid resistant maskant which could be cured under UV light was applied to the periphery of the package and surrounding areas. This helped to protect the board from acid damage. The application of the maskant also created a cavity on the surface of the package where acid could be confined for etching. The board was preheated on a hot plate where PCB surface temperature did not exceed 45$^o$C. 90% Fuming nitric acid ($HNO_3$) was used for chemical etching. This acid was also preheated to ~85$^o$C on a separate heater. Droppers were used to introduce the hot fuming $HNO_3$ on the top of the package surface. Both the time taken to etch the package overmold material and amount of acid consumed in the process were each recorded. At the end of the experiment, the entire board was submerged in water to quench the reaction followed by cleaning the surface of the package with acetone. Acetone helped remove any overmold material sticking on the surface of the package after etching. Optical inspection provided estimation of the need for continuing further etching. The samples were finally air dried and oven baked for 24 hours at 90$^o$C.

**2.2. Automated on-board chemical decapsulation**

To prepare a gasket for chemical decapsulation, a milling tool was used. By knowing the details like package size, height and die dimensions, one can create a specific gasket for a particular device. With the automated etchers one has an ability to automatically mix different ratios of acids like $HNO_3$ and sulfuric acid ($H_2SO_4$) ranging from 1:1 to 9:1 mixture respectively. This ratio is decided based on the properties of mold compound and the type of wire bonds. In present case, 3:1 ratios of $HNO_3$: $H_2SO_4$ was used. Depending on the type of wire bonds and mold compounds, temperature of the jet etcher was set. In the present case, no bias was applied and reactions were carried out at room temperature even with Cu wire bonded devices. In the case of Au wire bonds the temperature can be set higher as those are more robust and etching can be faster. Etch time was decided by trial and error and in some of the cases it was simply based on user experience. Usually chemical decapsulation is pretty quick and it may take a couple of minutes to remove the overmold. If the filler particles are high then it may take a little longer. In one of the more extreme cases, it took 30 min to etch the overmold. Having some extra units initially to set up the recipe prevents any issues (like over/under etching) while etching the test sample. In order to set up the etch recipe, temperature, ratio of the acids and the etch time were fed in the tool user interface. The gasket was applied and the assembly was carefully placed on the etcher head. The chamber of the tool was closed and the recipe was run. Once the device was decapsulated, the board was quenched in water at room temperature followed by rinsing with acetone. For further cleaning, sonication can be done with acetone for a couple of minutes to detach the overmold sticking onto package surface. The board was then baked at 90$^o$C for 24 hours to remove the moisture. The functionality check was performed by powering the device on and confirming whether it is still functional. Various metrologies like SEM, CSAM, and 3D X-ray were then performed to look for any damage.

**RESULTS AND DISCUSSION**

The package on which microabrasion was done had Cu wire bonds. This was confirmed by 2D X-ray (Figure 3.1) taken prior microabrasion. Post microabrasion all the wire bonds were damaged and could not be seen under OM. Hence the device post abrasion did not boot up. Microabrasion process may also cause device to fail due to electrostatic discharge issues. Regardless, it turned out to be a very useful process for the pre-work for other decapsulation techniques like creating a gasket for chemical decapsulation. These details were found to be crucial to set up the recipes when automated etchers were used for chemical decapsulation.

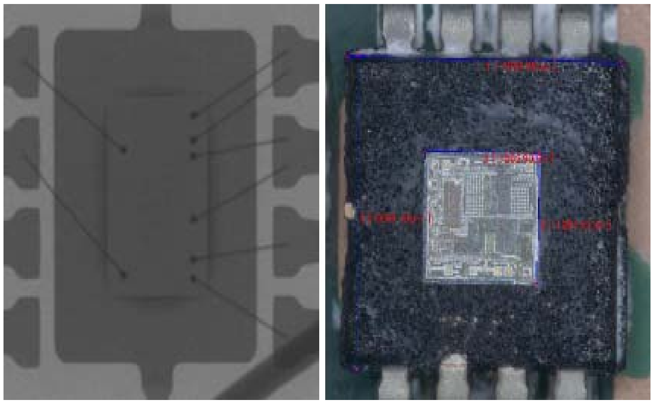

**Figure 3.1.** A package intact on a motherboard on which microabrasion was performed to expose the die

In another case, manual chemical decapsulation was attempted upon a wire bonded package mounted on a server board. This package had Au wire bonds. Post decapsulation, Au wire bonds were preserved as shown in Figure 3.2. However, issues such as non-uniform etching as well as the board damage were encountered. In another case, were Cu wire bonded packages were used, a large amount of damage to wire bonds was observed. Overall, manual chemical decapsulation did not meet the requirement for uniform etching with preservation of wire bonds (Au/Cu), board and die. Nonetheless, it is a low cost, simple technique and does not have limitation like the automated etchers to accommodate a motherboard inside the tool.

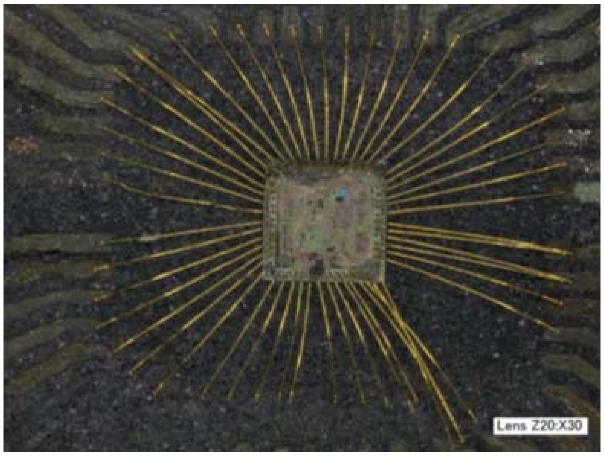

**Figure 3.2.** Manual chemical decapsulation performed on a package mounted on a motherboard with Au wire bonds

Next, an automated jet etcher was used to perform on-board chemical decapsulation. Automated etchers are known to provide uniform etching for “package only” decapsulation. These tools have capability to preserve wire bonds (Au/Cu). Experiments were carried out on packages with Au and Cu wire bonded devices without application of electrical bias and at room temperature. The process was successful to decapsulate packages with full preservation of wire bonds, bond pads and package surroundings.

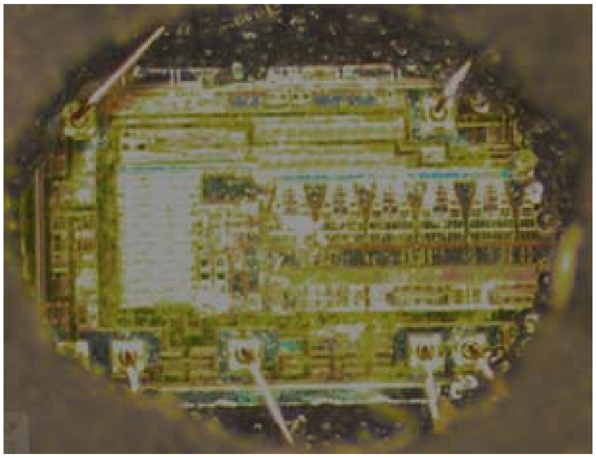

**Figure 3.3.** A Cu wire bonded package post decapsulation etched on an automated jet etcher

However, the PCB had to be trimmed in order to fit it inside the tool as shown in Figure 3.4. This is because the automated jet etchers are designed to perform “package only” decapsulation. Hence the chamber size of the tools is not large enough to accommodate boards. Initially, chemical resistant maskant was also applied on the board prior decapsulation. However, gaskets are equally capable of preserving the board.

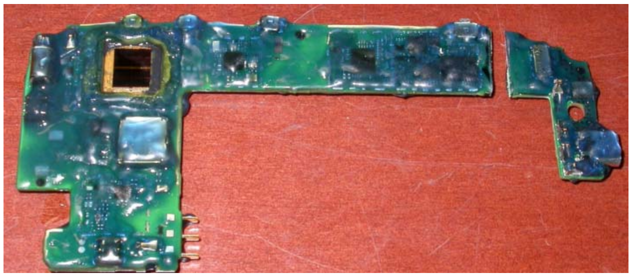

**Figure 3.4.** An image of a phone board that had to be cut to fit inside the conventional automated chemical etcher

Since chemical decapsulation was successful on a trimmed board, the chamber size was the only issue to be addressed. Hence, a large chamber etcher was developed with vendors to enable on-board chemical decapsulation. This tool allowed accommodating boards as large as phone boards as shown in Figure 3.5. Previously, only the boards with 2.5” X 3.2” dimensions could be fitted inside the tool. With the development of larger chamber etcher, it became possible to fit and etch any package on a board with form factor up to 6” X 6”. Experiments were carried out with the help of fuming $H_2SO_4$ and fuming $HNO_3$ acids mixed in various ratios, without application of an electrical bias and at room temperature. These packages were tested pre and post for functionality to confirm the validity of the process. The exposed die on-board with wire bonds intact was then accessible for analysis such as optical microscope inspection, SEM, X-Ray and CSAM analysis. These studies provided further proof that no damage was done to the die or wire bonds while performing on-board chemical decapsulation.

**Figure 3.5.** An inside view of the chamber of chemical etcher capable of accommodating a PCB from a phone board

Figure 3.6 shows a fully assembled phone of form factor 4.5” X 2.8” with the back cover removed. Various packages mounted either on flex or rigid PCB from this phone were etched successfully without disturbing the assembly of the phone.

**Figure 3.6.** Chemical decapsulation performed on a package mounted on a flex cable while the phone stayed fully assembled

Figure 3.7 shows a high magnification image of the package mounted on flex cable that was etched while still mounted on phone board (Figure 3.6). No damage was seen on the top of the die. CSAM was also done to see the internal damage to the die. No delamination or cracks were seen further confirming the success of the etching process. The flex cable as well as the entire phone assembly was inspected for acid damage. OM inspection didn’t show any etching damage on cable. This was attributed to a good gasket that was used during the etching process. Also, a reduced etching time protects the board. Upon functionality check, the device was able to boot up completely post decapsulation.

Upon closer look at the wire bonds, no damage was seen. Additionally, thickness measurements taken along the length of these Cu wire bonds post chemical decapsulation did not show any Cu thinning (Figure 3.8). The Al pads were also inspected closely and no damage was diagnosed.

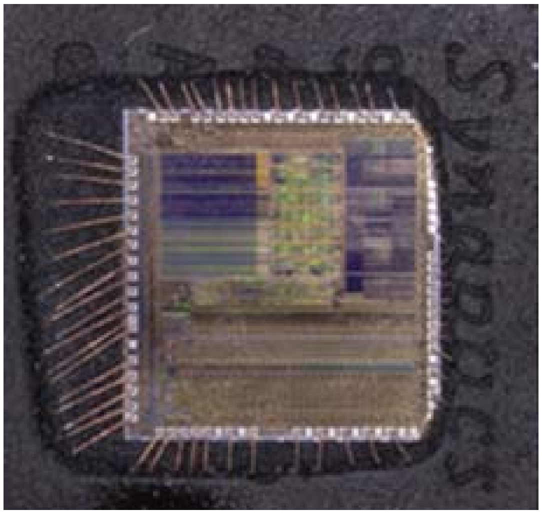

**Figure 3.7.** An image of a decapsulated package mounted on a flex cable

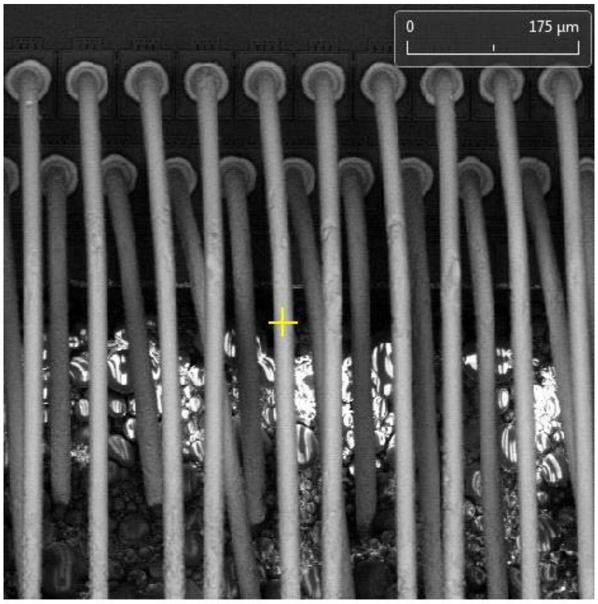

**Figure 3.8.** A SEM image of a chemically decapsulated package with Cu wire bonds and Al bond pads intact, post decapsulation

Hence, with the development of on-board decapsulation, access to all the required signals becomes available by exposing the die on-board. In the cases where test points are limited or traces are buried, exposing die and probing wire bonds directly provides necessary information. Hence, this technique enables system level FI/FA as well as reduces time to root cause identification.

## CONCLUSIONS

Various on-board decapsulation techniques were evaluated. Chemical decapsulation provided a successful demonstration for a component on-board decapsulation while preserving all wire bonds and retaining device functionality. This was also found to be only standalone technique. The proof of concept was shown on rigid or flex PCBs common to wearable and mobile devices. Decapsulation performed with microabrasion was shown to be helpful for pre work for chemical decapsulation experiments. Upon manual chemical etching, the packages with Au wire bonded devices were preserved. However, non-uniform etching, board corrosion and wire bond damage were some of the issues which were encountered. By developing automated etchers which could fit entire PCBs, successful etching was performed on the packages mounted on both rigid and flex PCBs. Cu and Au wire bonds were preserved while performing experiments at room temperature and without application of electrical bias. Successful functionality test post chemical decapsulation on automated etchers further validated the process.

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