Reliability of printed wire bonds

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Abstract

Additive manufacturing is an emerging domain with numerous potential applications. The concept of those new processes offers many advantages such as design flexibility, truly 3D packages and low cost for customization. The aerosol jet printing could enable wire bonding-like techniques that are unachievable with round wires today, combined with serious advantages for high frequency applications. However, this new field is starting off with many challenges to address, with the reliability as a focal point. The focus of this study is the reliability of printed wire bonds. Polyimide and silver inks were printed using an aerosol jet system (OPTOMEC Aerosol Jet ® HD Decathlon™).The results are focusing on the reliability of the adhesion of polyimide ink (UTD-PI-AJ) in an ethanol-based diluent and a silver ink, the HPS-108AE1 from Novacentrix, on different surface types: silicon oxide, pure aluminum and gold (ENIG). The adhesion is first addressed by a qualitative tape test at room temperature. The test samples are then put into an environmental chamber for a Deep Thermal Cycling (DTC) stress. The samples cycled 1000 times between -20°C and 85°C. They were inspected for physical defects at 250, 500 and 750 cycles. The visual inspection for defects focuses on cracks and delamination. The printed wire bonds were simulated by printing polyimide ink into a gold plated flat ceramic substrate (28 LCC from Kyocera) and then printing conductive silver ink from opposite pin leads. A layer of polyimide ink was then added on top of the printed lines. Crossover lines were finally printed on top of the last polyimide layer, again from opposite pin leads, creating an array of superimposed printed wire bonds. The reliability of printed wire bonds is tested through a Highly Accelerated Stress Test (HAST, 110°C, 85%RH, 264h) under bias. The samples were inspected at 66h, 132h and 198h for visual defects such as cracks, delamination and silver electro-migration. Cross-sections were performed on samples before and after HAST. All defects were characterized regarding of their time and condition or appearance and of their dimensions.

Key words

Reliability, printed electronics, silver, polyimide

I. Introduction

Aerosol jet printing is part of the new family of additive manufacturing processes. The last few years have seen some data starting to be published on the many advantages of what is widely called 3D printing. This new field has many strong arguments such as: low temperature processes, efficient use of the materials (printing only the quantity that is needed, without wastes), the ability to quickly fabricate prototypes using little to no costly fixturing and flexibility [1][2]. Adding materials on a substrate by a deposition method could also be a way to create interconnects that are more flexible. For example, wire bonding is a well-known process that is working fast and efficiently; in most cases. Sometimes, the interconnection need is extending beyond what it is possible to achieve by the old-fashioned way. Fig.1 is showing a need for vertical wire bonds.

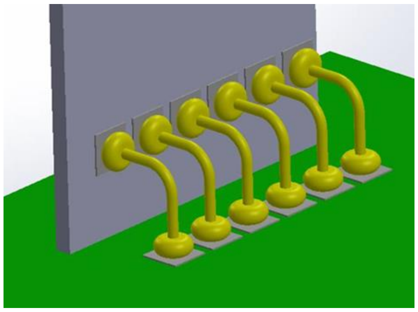

Fig. 1 : Vertical wire bonds

In this example, it would be nearly impossible for a traditional ball bonder to perform the connections. Very specific pivoting fixturing should be involved. If laser welding assisted wire bonding could be a solution, printing those wire bonds could also be an elegant manner to solve the issue. The way to print wire bonds in this example would be a two-step process. The first step would be to create a non-conductive bridge between the two pads with an ink like polyimide. The second step would be to print the wire bonds with a conductive ink. The wire bonds are then supported by the polyimide. The aerosol jetting process enables printing on a surface that is not flat, because of its non-contact nature.

The printing of wire bonds could also offer an advantage for device designs with multiple layers, and crossing, superimposed wires. On a development side, it would permit to vary wire dimensions on demand, without requiring any new spools, capillaries, wedge tools or clamps. Finally, a recent research suggests that printed wire bonds have lower transmission losses and better impedance matching for high frequency applications.[3]

II. Experiment

A. Samples description

Two types of samples were produced for this experiment. Both types used the same inks. The polyimide ink that was used is the ethanol-based PI-AJ from UTDots. This ink is intended to be used as an insulator between connections. The silver ink that was used is the HPS-108AE1 from Novacentrix, which is mainly DI water-based. This ink is intended to be used to create conductive patterns.

The first samples were polyimide ink dots and silver ink lines printed on various surfaces to assess the adhesion through Deep Thermal Cycling (DTC). The surfaces tested were: silicon dioxide, pure aluminum, gold and polyimide ink (for the silver ink lines only). The dimensions of the polyimide ink dots were: 850µm diameter by 4µm thick. The silver ink lines were 1mm long, 100µm wide and 50µm thick, with an average overspray of 20µm. The extent of the overspray can be seen in Fig.2.

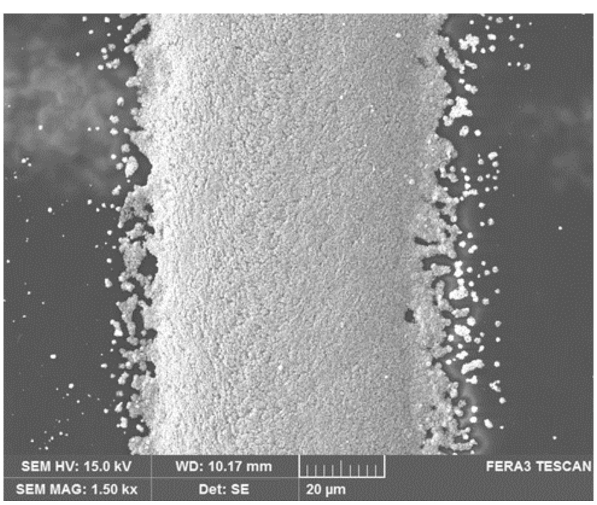

Fig. 2 : Chemical contrast view of the silver ink lines overspray

The second type of samples were a simulation of printed wire bonds. Gold plated flat cavity ceramics (28LCC from Kyocera) were used as the substrate. The cavity was filled with a non-conductive epoxy, the Optocast 3408 from EMIUV, to prevent the time-consuming process of filling it with polyimide ink. In fact, polyimide ink will be best printed in thin layers to avoid cracking. Silver ink lines were then printed onto the epoxy from opposite pin leads. An insulation layer was added on top of the printed lines. This layer was polyimide ink for two samples and the previously used epoxy for two others. Crossover lines were finally printed on top of the insulation layer, again from opposite pin leads, to create an array of superimposed printed wire bonds. Each side of the leads was shorted together with H20S (EpoTek) silver filled conductive epoxy to facilitate the reliability testing setup. The samples can be seen in Fig.3.

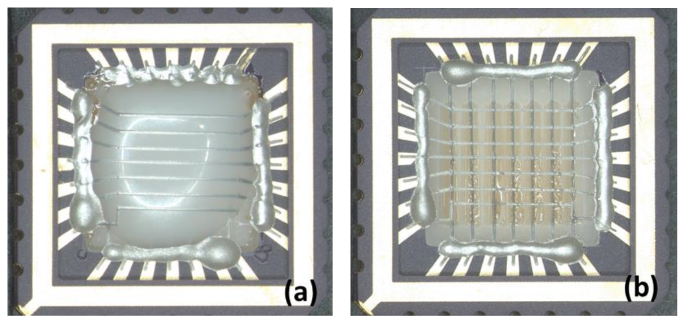

Fig. 3 : Printed wire bonds array with (a) epoxy and (b) polyimide

The adhesion of the samples is first addressed by a qualitative tape test at room temperature. This is a screening of the samples so that only good samples go through reliability tests. The tape that was used is an ESD high temperature polyimide Kapton tape with silicone adhesive.

B. Aerosol Jet method

The samples were printed with an Optomec Aerosol Jet ® HD Decathlon machine. Because of their different viscosities, the polyimide and silver ink were not printed through the same head system. An ultrasonic deposition head was used for the polyimide ink and a pressure deposition head was used for the silver ink. The difference of the two printing systems lies into the ink atomization method. In fact, the aerosol printing process starts with the ink to be printed stored into a recipient, called an atomizer. The ink may be diluted into its solvent: in the case of this experiment it was either ethanol (polyimide ink) or deionized water (silver ink). The ink is atomized into very fine particles within this bubbler. The atomization method can be ultrasonic or by the pressure of an inert gas (nitrogen). In the case of the pressure system, the ink droplets then travel through a Virtual Impactor that sorts the particles that are too big.[4] This will make for a more even printing and will prevent clogging. The atomized stream is then finally focused through the deposition head nozzle, with the help of a sheathing gas (nitrogen) to obtain well-defined patterns and minimize overspray.

C. Reliability Tests

The samples printed on various surfaces were tested for adhesion under thermal shock conditions. The test was performed into an *Espec ETS13-5SW* dual environmental chambers. The applied profile is shown in Fig. 4.

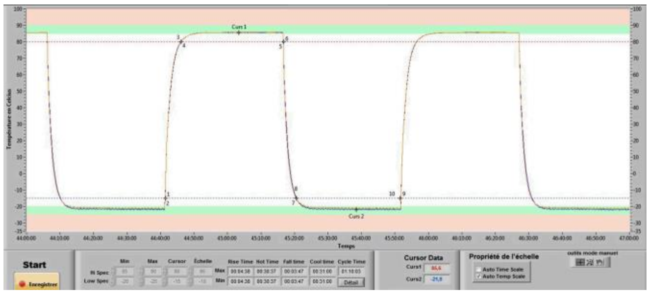

Fig. 4 : Deep Thermal Cycling Profile

The chambers were profiled so that all samples were exposed to -20°C and 85°C for a dwell time of 30 minutes respectively, with a tolerance of 5°C on the minimal and maximal temperature. The transfer time between the two chambers is less than 5 seconds. Since there is still few published examples of reliability testing on additive manufacturing, the DTC test was inspired by a publication from S. Lungen, 2018 [5]. The test was, however, only carried on for 1000 cycles, with visual inspections for defects after 250, 500, 750 and 1000 cycles.

The printed wire bonds samples were tested for silver electromigration under biased HAST conditions. The test was performed into a pressurizable environmental *Espec TPC-432ZM* chamber. The test conditions were: 110°C, 85%RH, 3.6V applied voltage for 264h. The samples were visually inspected and electrically tested at room temperature at 66h, 132h, 198h and 264h. The ceramics were placed into custom sockets, so that the samples could be biased. Fig 5. Shows the electrical diagram of the setup.

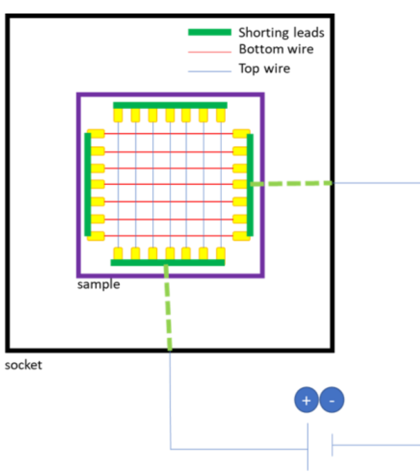

Fig. 5 : HAST electrical setup

Both reliability test environmental chambers are run with DI water. They are placed into a lab that is not controlled as a clean room, so the samples were exposed to ambient air contamination.

III. Results and discussion

The pretest adhesion tape test left samples unchanged with no delamination observed.

A. The adhesion test

Throughout the DTC test of the printed ink samples on various surfaces, the samples were taken out for visual inspection at 250, 500, 750 and 1000 cycles. No sign of further cracking, fatigue or delamination could be observed at any point during the stress, for both, polyimide and silver, samples. The cracks present at time zero on some dots of polyimide ink into the aluminum and silicon dioxide substrates remain unchanged during testing. Pictures of a polyimide dots presenting cracking at time zero and at every checkpoint are showing that in Fig.6.

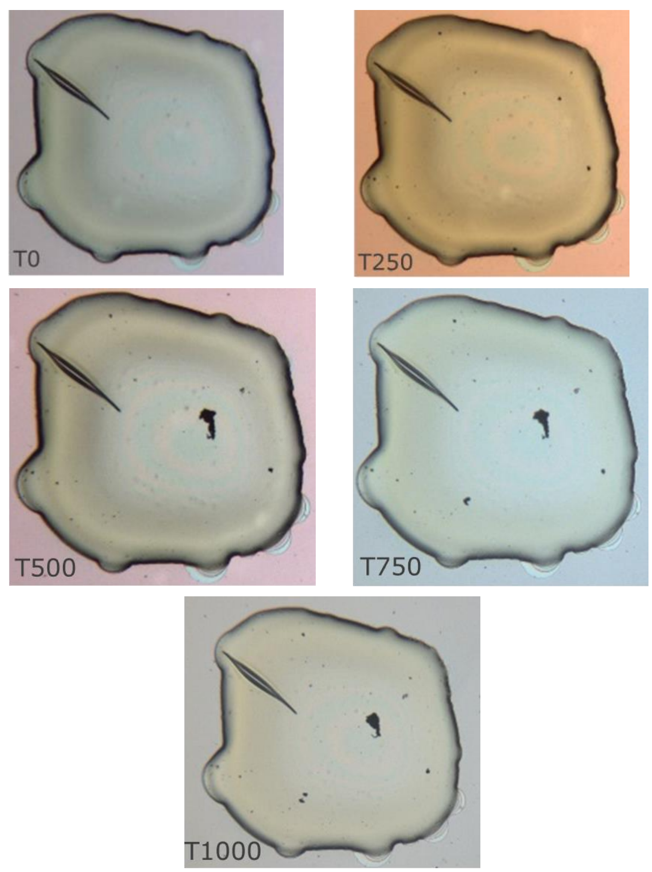

Fig. 6 : Cracking remains unchanged throughout DTC on polyimide ink dot

Surface corrosion was observed on the silver ink lines after the test. The Fig. 7 is showing a silver ink line partially covered with surface corrosion at 750 cycles of DTC.

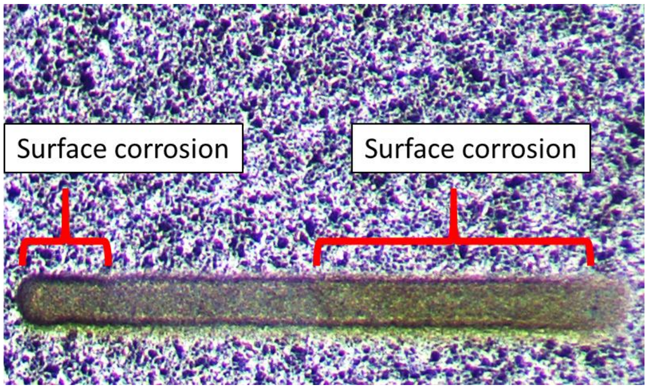

Fig. 7 : Surface corrosion on silver ink

This corrosion could also be observed on cross-sectioned samples of silver ink that remained in an uncontrolled atmosphere for some time. The corrosion was easily removable on the cross-sectioned samples by fine (2µm paper) polishing. This observation may lead to the conclusion that silver ink patterns may need to be protected from the outside when packaged into usable devices.[6]

B. The polyimide ink deposition challenges

The polyimide layer of the second group of samples for this test (Fig. 3 (b)) peeled from the epoxy. It is suspected that the thermal dilation of the epoxy (14ppm/°C) was too different for the polyimide ink layer. Pre-test cross-section on one sample also showed that the polyimide layer was uneven, causing the crossing silver lines to short. As a result, the shorted sample went through HAST unbiased. The uneven deposition of the polyimide ink could have been caused by many factors. The polyimide ink used had a very low viscosity (1 cP). It has a natural tendency to flow. The domed shape of the silver lines would have made it flow to the bottom, leaving a very thin or inexistent layer of polyimide on top of the silver lines to prevent them from shorting. This phenomenon is clearly seen in the cross-section view of Fig. 8.

Fig. 8 : Cross-section view of silver inks lines crossing over

The flowing of the polyimide ink could have been minimized by using a higher viscosity ink or by increasing the work stage temperature, so that the solvent of the ink evaporates more rapidly, preventing it from flowing. One would have to be careful, however, not to heat the deposited ink too rapidly, since defects such as pinholes or bubbles could appear into the printed layer.

C. The silver electromigration test

From the two samples, with epoxy as an insulation layer between the silver ink crossing lines (Fig. 3 (a)), one went through biased HAST with no problem and the other shorted as soon as the test conditions were reached. It, however, tested good at all checkpoints (after 66h, 132h, 198h and 264h). The checkpoints were done at room temperature conditions and no silver dendrites could be observed at visual inspection during the test. Fig. 9 shows the *in-situ* monitoring of the two biased samples during HAST. Module 2 (in orange) is the module that shorted during the test. The 5 starts along the curves are the point checks at each quarter, beginning and end of the test.

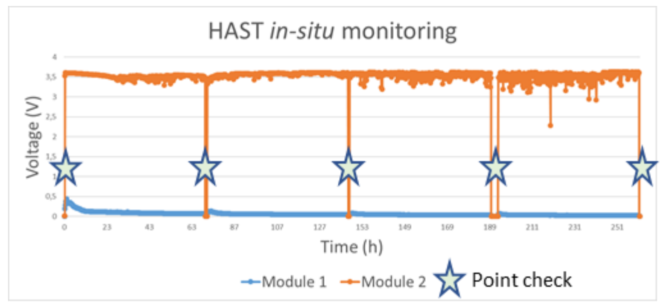

Fig. 9 : *In-situ* HAST monitoring

Since no precise observation of silver dendrites could be made at visual inspection, the shorting sample was taken to SEM (Scanning Electron Microscopy). This instrument enables very high magnification inspection, coupled with chemical contrast. It permitted an interesting insight on the failure mechanism. Fig. 10 is showing two neighbor silver ink lines that are crossing and on which was applied an electrical potential difference.

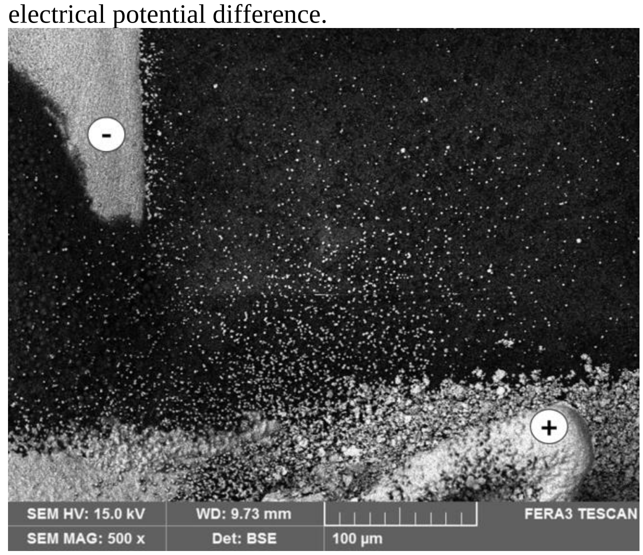

Fig. 10 : SEM picture of neighbor silver lines with overspray

The chemical contrasted picture shows the silver in white on its dark substrate. Even if a path is now clearly distinguishable between the two lines, the amount of overspray present could have been the right media for a fragile path to form under the right circumstances. The high temperature and humidity of the HAST could have been enough to create that path. Since no dendrite could be observed at any point, this path must have been dependent of the test conditions to be functional. Further experiments are planned to better understand this phenomenon. This observation makes the importance of reducing overspray of conductive patterns very relevant. In this case, the part tested good at room temperature, but failed under high temperature and humidity conditions. This could make devices that fail to work only under certain conditions.

Still under the SEM, the silver ink particles were inspected at very high magnification on a pre-test and a post-test HAST sample. The results can be seen in Fig. 11. The particles did not show evidence that the sintering of the silver was affected or did not sintered further during HAST.

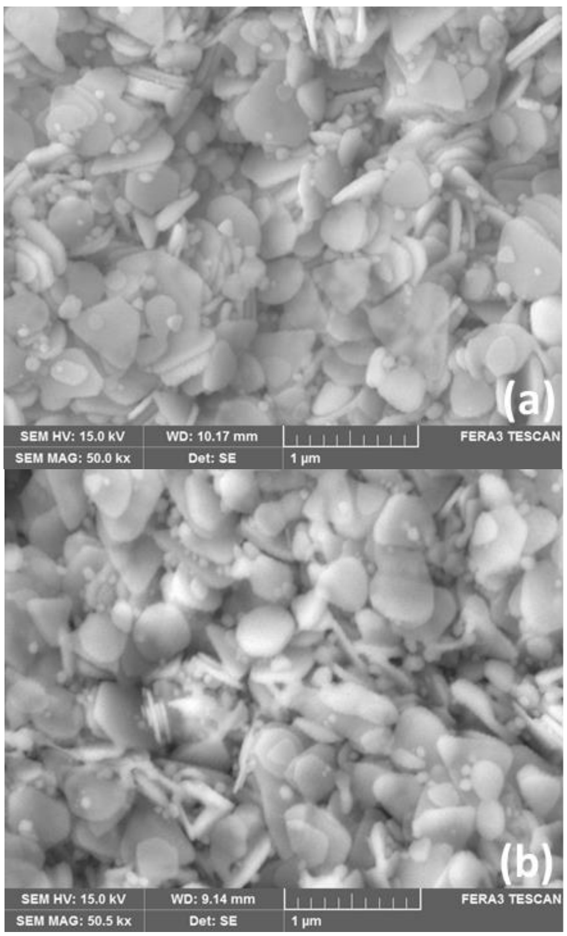

Fig. 11 : SEM picture of silver ink particles before (a) and after (b) HAST

IV. Conclusion

This study gives a starting point to commercially available inks for printed electronics that prove to be reliable. There are, however, many challenges that remain to be solved. The polyimide ink dispense and geometry of the lines shall be reviewed, including research on higher viscosity ink, higher work stage temperature and thick layer deposition cracking prevention. The conductive ink deposition process shall be improved to reduce overspray. This could be assessed by sheathing gas control and ink particles formulation. Finally, the reliability tests of this article are not the more severe of the industry, especially for the DTC test. Further tests shall be realized to fully evaluate this technology potential for consumer applications.

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