Anisotropic conductive film & flip-chip bonding for low-cost sensor prototyping on rigid & flex PCB

Serguei Stoukatch[1], Nicolas André[2], Thibault Delhaye[2], Francois Dupont[1], Jean-Michel Redouté[1], Denis Flandre[2]
[1]Microsys lab, Department of Electrical Engineering and Computer Science, Liege University, Seraing, Belgium
[2]Institute of Information and Communication Technologies, Electronics and Applied Mathematics (ICTEAM), Université Catholique de Louvain, Louvain-la-Neuve, Belgium
e-mail: serguei.stoukatch@uliege.be

***Abstract*—We developed a low-cost process for assembling versatile sensors without expensive, thick metal finish on rigid and flexible PCB using anisotropic conductive films (ACF) flip-chip (FC) process. This allows a lower temperature budget than conventional FC assembly. The ACF FC process requires no expensive set up, is quick to implement and suits perfectly for sensor prototyping and low-scale manufacturing. The process was directly applied to assemble the bare die of a CMOS strain gauge sensor on flexible PCB without compromising its integrity.**

Keywords*— *low-cost flip-chip assembly; anisotropic conductive films; sensors assembly on flex; assembly methods for prototypes.

I. INTRODUCTION

Since its introduction for electronics manufacturing, flip-chip (FC) technology made enormous progress to meet demands for IC scaling [1] and higher device performance [2]. Initially the main drivers were performance and miniaturization [3], then later, the technology became cost effective [4] and reliable [5]. Meanwhile most developed FC technologies [6] are not directly applicable for low-scale manufacturing of e.g. prototypes or proof-of-concept (POC) demonstrators. Such devices are key tools for universities, research organizations and startups to prove an idea in a quick and low-cost way.

In response to that, in this paper*, we have reviewed known FC techniques and methods. In section III, we adopted them for assembly of fully functional prototypes and demonstrators. In section IV, we applied adopted process for assembling an original Si strain gauge sensor.

II. TEST MATERIAL

UCLouvain develop different sensors for e.g. mechanical stress [7] and pressure [8] based on a CMOS SOI platform. The sensors are versatile in functionality, but from assembly point of view, they share several common features: i) Si wafer fabrication, ii) die area between 2x2 mm^2 to 5x5 mm^2, iii) low number of I/Os (i.e. less than 12 input/output terminals), and iv) a low interconnect density. The main requirements for the assembly of such sensors are a low cost, a short delivery lead-time and a full functionality (i.e. maintaining integrity and performance).

To develop the required bonding technique, we firstly used a special designed test die and corresponding PCB to test quality and continuity of electrical contacts and tracks. The test chip features 12 pads of 250 x 250 μm^2 that are connected in pairs through thin Al conductive tracks. A photo of the test die is presented on figure 1 (left).

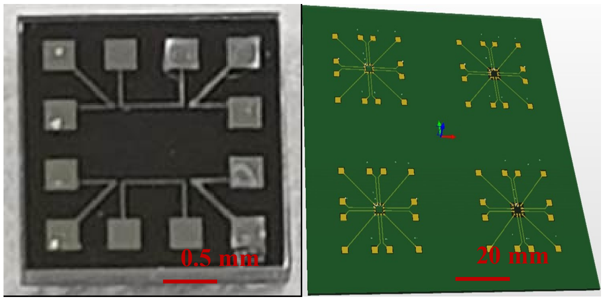

Fig. 1. Top view for the test die (left) and top angle view for the test PCB (right).

The die bond pads are made of evaporated 99.99% pure Al of 0.76 µm thickness and have no expensive metal finish such Ni/Au plated [9] or stud ball bumping [10] as commonly used for FC assembly. Microsys ULiege designed a test carrier with a corresponding footprint that matches bond pads on the test die. In case of successful die-to-PCB interconnect, it forms daisy chains that can be easily measured. The test carrier of 100 x 100 mm^2 has two PCB types. The rigid PCB (fig. 1, right) is 0.8 mm thick FR4, with Cu of 18 µm-thick, landing pads and measurement terminals are electroplated Ni/Au ENIG (3 µm Ni and 0.05 µm Au). The flexible PCB is processed on 25 µm polyimide PI, 18 µm thick Cu and 25 µm polyimide coverlay film. The copper landing pads and measurement terminals are chemically plated Ni/Au (3-5 µm Ni and 0.02-0.05 µm Au).

III. ASSEMBLY PROCESS DEVELOPMENT

For chip micro-packaging with our target objectives, we selected a FC technique using anisotropic conductive films (ACF) that works well both on rigid and flexible PCBs. This requires relatively lower process temperature (120-200°C, with optimum at 140-160°C) [11] than conventional FC methods (e.g. lead-free soldering at 260°C [12]) and is less costly than other low-temperature bonding methods as In-Au [13]. Lower thermal treatment temperature and overall duration are essential requirements for assembling sensitive sensors on flexible circuit carriers. Thermal treatment can potentially affect sensors performance [14] and degrade flexible PCB [15]. The resulted assembly will have some

---

* The work was supported by the Microsystème_ULg Microsys project, funded by the Wallonia (Belgium), and the Micro+ project co-funded by the European Regional Development Fund (ERDF) and Wallonia (Belgium).

978-1-7281-6801-2/20/$31.00 ©2020 IEEE

degree of flexibility, at least ACF FC interconnect doesn't restrict required bending of flexible PCB. In contrast to isotropic conductive adhesive (ICA) FC method [16], ACF FC technique requires less processing steps, and no expensive post-processing such an underfilling for example. The ACF FC is conceptually simple and comprises the following process steps: ACF lamination to PCB, die to PCB alignment, and finally bonding die to PCB.

We selected heat-bondable, electrically conductive adhesive film ACF 7376-10 manufactured by 3M™ [17]. It is easy to procure, low cost, originally designed for a display bonding of minimum bond pad area of 0.10 mm^2, about 0.5x0.2 mm^2. Other specially dedicated ACF (e.g. from [18] or [19]) for die direct FC bonding on PCB and flex circuitry are an order of magnitude more expensive and difficult to procure in small amount required for prototyping. Moreover, the latter ACF tapes have a limited self-life that typically amounts to 6 months. These were important requirements in our choice. The ACF 7376-10 is 40 µm thick and protected by polyester liner of 50 µm thickness. The unbonded film is consists of a thermoset-elastomer and thermoplastic adhesive matrix randomly loaded with conductive particles, gold plated polymer of 10 µm diameter, average. These particles allow interconnection of circuit lines through the adhesive thickness, but are spaced far enough apart to be electrically insulating in the plane of the adhesive. The ACF lamination optimized process steps are following: a) ACF square of 5x5 mm^2 placed on the PCB mounting area, b) PCB heated to 90°C, c) weight of 100 g applied on the ACF square for 10 seconds, d) finally the protective liner removal from the ACF. It is important to confirm that an entire ACF matrix transferred and evenly bonded to the PCB mounting area.

To perform ACF FC bonding we used a submicron die bonder FINEPLACER lambda system from Finetech [20], further in the text called a fineplacer. The fineplacer is a die-and-FC-bonder for high precision up to 1 µm post-bonding accuracy die attach. The system is PC controlled, has a relatively low cost and widely used for prototyping and low-volume production. The fineplacer initially picks up a die from a trey, then aligns the bond pads on the die with corresponding landing pads on the PCB. Finally, the bond head brings the die in a direct contact with the receiving PCB and simultaneously apply force and heat to perform a permanent bonding.

ACF FC bonding optimization was focused on defining a process window. For that, we fixed the FC bonding time (30 s), while the bonding force and the bonding temperature were variable. The initial criteria of "bonding" or "no bonding" was a mechanical integrity. If the die does not hold to the PCB, the assembly is immediately marked as "no bonding". If the die remains permanently bonded to the PCB, then the assembly undergoes an electrical characterization.

The bonding temperature was explored in the range starting from 100°C to 200°C, the bonding force is in range of 0.4 kgf to 3.2 kgf. That corresponds to pressure of 0.98 to 7.85 MPa applied on the die during bonding process. We put a temperature boundary of 200°C in our experiments to limit thermal induced stresses in the assembly. We were also looking for lower temperature as conventional assembly process. There was also limit of 3.2 kgf on bonding force (pressure of 7.85 MPa), to avoid applying an excessive pressure on silicon die. The bonding process window is presented on the fig. 2.

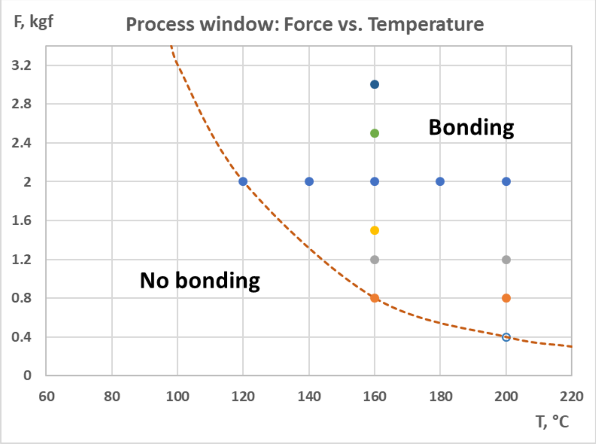

Fig. 2. Flip chip bonding process window.

We learned that there is no bonding below temperature of 100°C, the die does not stick to the PCB. The lower bonding temperature needs higher bonding force. The higher bonding temperature requires less bonding force, although there is a limit on it. There is no bonding below 0.4 kgf. We defined a relatively broad bonding window. The developed ACF FC bonding process that has relatively lower temperature process (120-200°C, with optimum 140-180°C) than conventional FC assembly (lead-free soldering at 260°C).

Examples of the test die ACF FC bonding to a rigid and a flexible PCB are presented on the figure 3.

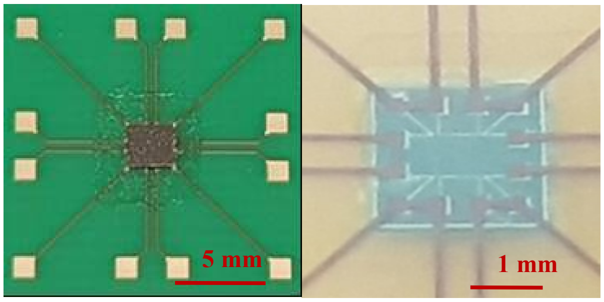

Fig. 3. Test die FC bonded to rigid PCB : top view (left) and to flexible PCB : back side view (right).

Resistance of each individual daisy chain is a combination of resistance of conductive tracks on PCB, on the test die and 2 FC joints. Electrical characterizations on each ACF FC bonded test sample comprises measurements of 6 individual daisy chains. The electrical characterizations clearly detect a failed joint, such as open FC joint or an abnormal high resistance of FC joint.

We performed failure analyses on the test samples with presence of failed joints using cross-sectioning method. The method is destructive and includes sequential polishing of the sample with set of sand paper of different grades. For a reference purpose we cross-sectioned also samples where we did not detect any failures using a backside microscopic inspection and the electrical test. On an electrically yielding sample (fig. 4, left) one can clearly see several gold particles form a joint between the bond pads on the die and the PCB landing pad. Whereas on failed joint (fig. 4, right) there is a gap between them and no gold particles.

Fig. 4. Cross-section view on ACF FC yielding (left) and failed joint (right).

IV. ACF FC ASSEMBLY OF STRAIN GAUGE SENSOR

The developed and successfully tested ACF FC technology on the test die and test PCB, was directly applied to assemble a SOI strain gauge sensor on flexible PCB.

The strain gauge sensor (fig. 5, left) was processed at UCLouvain using SOI platform. The test die has an area of 3 x 3 mm^2, is 0.3 mm thick and has five 0.76 µm thick Al bond pads without an expensive metal finish. Microsys ULiege designed a flexible PCB (fig. 5, right) of 7 x 9 mm^2 on 25 µm polyimide PI, with 18 µm thick Cu and 25 µm polyimide coverlay. The Cu landing pads and measurement terminals are chemically plated with Ni/Au (3-5 µm Ni and 0.02-0.05 µm Au).

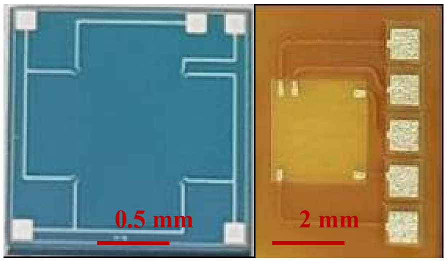

Fig. 5. Sensor die top view (left) and flexible PCB.

The strain sensor detection principle is based on the piezoresistive effect, i.e. electrical resistivity variations induced by an applied strain. These are quantified by the gauge factor (GF), that for Si is approximately two orders of magnitude larger than for standard metal lines. It depends on the Si p- or n-type doping and crystalline orientation. In the present case, the strain gauges are four n-type implanted monocrystalline resistors patterned into the silicon film of SOI wafer and connected as a Wheatstone full bridge. The configuration is optimized to monitor a surface that deforms as a membrane.

After ACF FC bonding, each assembly was inspected visually using a 5x magnification microscope to check that there is no mechanical damage on the sensor die caused by FC bonding (fig. 6 left).

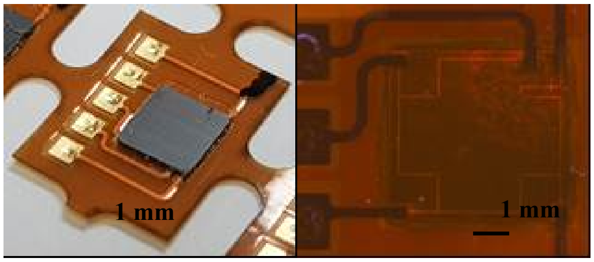

Fig. 6. ACF FC bonded die top angle (left) and backside view (right).

We also confirmed that the post-bonding accuracy is good and there is no sensor misalignment in respect to the PCB (fig. 6 right). It was easy to check using a 20x magnification microscope in a light reflective mode because the relative transparency of the flexible PCB. In order to confirm that the assembly has no failed FC joints such an open FC joint or an abnormal high resistance, we probed all assembled devices through the 5 measurements pads. The design allowed us on each assembly to measure one main chain and 4 individual sub-chains that forms the main chain. The resistance of the main chain at normal conditions such no stress and room temperature is 80±5 kΩ, and resistance of each individual sub-chain is 20±3 kΩ correspondingly. The contribution of an individual ACF FC joint that is typically less as 5 Ω, is negligible compared to the resistance of the chains that is in kΩ range. Meanwhile the test can detect failed ACF FC joint. The resistance measurement test may suggest that all ACF FC joints are functional and there is no damage on the sensor die caused by the FC assembly. The final functionality test using a dedicated equipment was performed at UCLouvain.

V. STRAIN GAUGE SENSOR FUNCTIONALITY TEST

To validate the ACF FC assembled sensor operation, a cyanoacrylate glue has been used to fix the assembly on a flexible metal beam also instrumented with a classical metal strain gauge. The beam is then deformed in a four-point bending machine at room temperature. Preliminary measurements with elongations up to 200 µstrains proved the sensor functionality, all ACF FC joints maintain an electrical contacts upon bending. We experimentally determined the GF of the full assembly , it is about 30, whereas the intrinsic GF of Si can be as high as 200. According to Comsol simulation, a maximum of 20% of the strain applied to the beam can be transmitted through 25 µm-thick PI and 10 µm-thick ACF stack, up to the Si chip. The observed reduced GF is then in reasonable agreement with simulation results. It can be further enhanced by measuring the precise thickness of the full stack including cyanoacrylate glue and fully calibrating the system before use. However the flex assembly has to trade-off for a lower gauge factor versus a higher stretchability. This can be considered as an advantage for applications requiring larger deformations than Si alone can withstand (i.e. a maximum strain of 0.2% before rupture).

VI. CONCLUSIONS

We developed a low cost assembly process for rigid and flexible PCB using ACF FC method on the test die without an expensive metallization. The developed ACF FC assembly process requires no expensive set up, is quickly to implement and suits perfectly for sensor prototyping. The process was directly applied to assembly a strain gauge sensor on flexible PCB without compromising sensor integrity. The developed technology can be easily scaled up to reach higher manufacturing volume.

REFERENCES

[1] A.A. Bajwa, S. Jangam, S. Pal, N. Marathe, T. Bai, T. Fukushima et al. “Heterogeneous Integration at Fine Pitch (≤ 10 µm) Using Thermal Compression Bonding”. In 2017 IEEE 67th Electronic Components and Technology Conference (ECTC), 2017, pp. 1276-1284.

[2] S. Gupta, W.T. Navaraj, L. Lorenzelli, R. Dahiya. “Ultra-thin chips for high-performance flexible electronics”. NPJ Flex Electron 2, 8 (2018). https://doi.org/10.1038/s41528-018-0021-5

[3] E. Beyne, "The 3-D Interconnect Technology Landscape," in IEEE Design & Test, vol. 33, no. 3, pp. 8-20, June 2016, doi: 10.1109/MDAT.2016.2544837.

[4] I. A. Papistas, V. F. Pavlidis, D. Velenis: “Fabrication Cost Analysis for Contactless 3-D ICs”. IEEE Trans. Circuits Syst. II Express Briefs 66-II(5): 2019, p. 758-762.

[5] Cu pillar bump, seen on https://ase.aseglobal.com/en/technology

[6] M.J. Yim, J. Hwang, J.G. Kim, J.Y. Ahn, H.J. Kim, W.Kwom et al. “Highly reliable flip-chip-on-flex package using multilayered anisotropic conductive film”. Journal of Elec. Material. 33, 76–82 (2004). https://doi.org/10.1007/s11664-004-0297-1

[7] M. Al Kadi Jazairli, N. André, E. Tooten, B. Olbrechts, J.-P. Raskin, D. Flandre, “Ultra-low-power 130nm SOI CMOS smart sensor for in-situ mechanical stress in SiP and SoC applications,” IRSP 2016, 14th International Conference Reliability and Stress-Related Phenomena in Nanoelectronics, Bad Schandau, Germany, May 30 – June 1, 2016.

[8] N. André, T. Delhaye, M. Al Kadi Jazairli, B. Olbrechts, P. Gérard, L. A. Francis, et al., “Ultra-low-power SOI CMOS pressure sensor based on orthogonal PMOS gauges,” 22nd IMEKO TC4 International Symposium & 20th International Workshop on ADC Modelling and Testing, Iasi, Romania, Sept. 14-15, 2017

[9] J. Haberland, M. Becker, D. Lütke Notarp, Ch. Kallmayer, R. Aschenbrenner, H. Reichl, "Ultrathin 3D ACA FlipChip-in-Flex Technology", Device packaging conference, March 8-11, 2010, Scottsdale, AZ.

[10] Y. Kumano, Y. Tomura, M. Itagaki, Y. Bessho, “Development of chip-on-flex using SBB flip-chip technology”, Microelectronics Reliability, Volume 41, Issue 4, 2001, p.525-530, https://doi.org/10.1016/S0026-2714(00)00258-4.

[11] M.J. Rizvi, Y.C. Chan., C. Bailey, H. Lu, and A. Sharif, "The effect of curing on the performance of ACF bonded chip‐on‐flex assemblies after thermal ageing", Soldering & Surface Mount Technology, 2005, Vol. 17 No. 2, pp. 40-48. https://doi.org/10.1108/09540910510597492

[12] “Advanced Flip Chip Packaging”, Eds. Ho-Ming Tong, Yi-Shao Lai, C.P. Wong, Springer, 2013, 560 p., https://doi.org/10.1007/978-1-4419-5768-9.

[13] A. Vásquez Quintero, R. Verplancke, H. De Smet, J. Vanfleteren, “Stretchable electronic platform for soft and smart contact lens applications”. Advanced Materials Technologies, 2017, 2(8), 1700073.

[14] S. Stoukatch, F. Dupont, M. Kraft, "Low-Temperature Packaging Methods as a Key Enablers for Microsystems Assembly and Integration", CAS 2018, International Semiconductor Conference, IEEE-EDS, 10-12 Oct. 2018, Sinaia, Romania, p. 115-118, DOI: 10.1109/SMICND.2018.8539847.

[15] S. Stoukatch, Chapter 2. "Low-Temperature Microassembly Methods and Integration Techniques for Biomedical Applications", pp. 21-42, Book "Wireless Medical Systems and Algorithms. Design and Applications", Edited by P. Salvo and M.l Hernandez-Silveira CRC Press, 2016, ISBN: 978-1-4987-0076-4.

[16] A. F. Vasquez Quintero, D. Briand, and N. de Rooij, “Flip-chip integration of Si bare dies on polymeric substrates at low temperature using ICA vias made in dry film photoresist,” Journal of Micromechanics and Microengineering, vol. 25, no. 4, 2015.

[17] Electrically conductive adhesive films, seen on https://multimedia.3m.com/mws/media/643845O/3mtm-anisotropic-conductive-film-adhesive-7371.pdf

[18] Hitachi: Anisotropic Conductive Film, seen on https://www.hitachi-chemical.com/products_do_anisotropic_conductive_film_index.htm

[19] Telephus: Anisotropic Conductive Film: seen on https://telephus.en.ec21.com/Anisotropic_Conductive_Film_ACF--8672073_8673055.html

[20] Finetech products overview: https://www.finetech.de/products/rd-bonders/sub-micron-bonder/