

Flip-chip interconnects based on single metal-coated polymer spheres

Van Long Huynh
Department of Microsystems
University of South-Eastern Norway
Horten, Norway
Van.L.Huynh@usn.no

Knut E. Aasmundtveit
Department of Microsystems
University of South-Eastern Norway
Horten, Norway
Knut.Aasmundtveit@usn.no

Hoang-Vu Nguyen
Department of Microsystems
University of South-Eastern Norway
Horten, Norway
Hoang.V.Nguyen@usn.no

Abstract: *In microelectronics packaging, minimizing thermo-mechanical stresses is crucial to achieve high reliability. This paper presents a novel approach for flip-chip interconnects, utilizing individual metal-coated polymer spheres at a low bonding temperature. The method involves selectively depositing individual conductive particles onto a polydimethylsiloxane (PDMS) carrier and then transferring the particles to electrical pads on substrate using Ag sintering followed by die placement and introducing underfill material. The deposition process achieved a high yield of 98.8% on the PDMS carrier, while the transferring process resulted in well-defined ink dots with a yield of 96.2%. The sintered Ag formed good bonds between the particles and electrical pads, leading to moderate interconnect resistance (as low as 0.57 Ω). This work has demonstrated the feasibility of interconnects based on a single metal-coated polymer sphere with low thermo-mechanical stress induced, thanks to the low bonding temperature (140 °C) and pressure (0.1 MPa) as well as the mechanical compliance of polymer particles.*

Keywords—*Flip-chip interconnects, particle deposition, Ag sintering, low bonding temperature*

I. INTRODUCTION

In recent years, the miniaturization and increased integration of electronic components have become crucial factors for the advancement of electronics [1–3]. It is because electronic devices continue to shrink in size while simultaneously exhibiting enhanced functionalities, allowing for new applications in demanding environments, such as wearable and implantable devices. Electronic packaging, in particular interconnection technology, has thus been governed by a growing demand for high interconnection density, ultra-fine pitch capability, and high reliability.

Various flip-chip technologies have been developed and employed in the last decades [2–9]. These technologies include solder micro bumps, copper pillars with solder caps, direct metal-metal thermocompression bonding, solid-liquid interdiffusion (SLID) bonding, and electrically conductive adhesives (ECAs). Micro solder bumps enable high-density and fine-pitch interconnections ($\leq 130 \mu\text{m}$) while possessing self-alignment capabilities between solder bumps and metal pads. Solder reflow occurs at peak temperatures of 230 °C (eutectic bumps) or 260 °C (lead-free bumps) [2–4]. Copper pillars with solder caps utilize a smaller solder volume to prevent bridging between bumps, allowing for ultra-fine pitch capabilities (40 - 130 μm). A typical Cu pillar with a shallow Sn-3.5Ag solder cap is reflowed at 320 °C [5–6]. Direct metal-metal bonding has been explored for extremely fine pitch interconnects by directly joining two pure metal surfaces. For example, Cu-Cu thermocompression bonding enables interconnection pitches below 30 μm but requires a bonding

temperature exceeding 350 °C [8]. SLID bonding has gained attention due to its ability to utilize different substrate interfaces at lower bonding temperatures compared to metal-metal compression bonding, while allowing the use of joint materials in high-temperature environments [7].

When materials with different coefficients of thermal expansion (CTE) are bonded at such elevated temperatures and subsequently cooled down, thermo-mechanical stresses will arise within the package. Metallic joints typically lack mechanical compliance, limiting their capabilities to absorb the stresses generated by the thermal mismatch. Consequently, thermo-mechanical failures, particularly fatigue fractures, can occur in the package. The use of ECAs, including anisotropic conductive adhesives (ACAs) and isotropic conductive adhesives (ICAs), facilitates simplified processing and reduces bonding temperature. Nevertheless, ultra fine-pitch capability has impeded the implementation of ECAs across diverse applications. As a result, there is an increasing demand for interconnection technologies that provide compliance, (ultra) fine-pitch capability, low bonding pressure, and low bonding temperature.

This work presents a novel approach that leverages selective deposition capability of single metal-coated polymer spheres (MPS) to individual interconnects, while utilizing low bonding temperature and low bonding pressure through a sintering method. By employing a low bonding temperature, the thermo-mechanical stress within the package can be significantly reduced. Additionally, the use of MPS enables the absorption of stresses arising from thermal expansion, vibration, or shock during operation, thanks to the elasticity of the polymer core. Previous techniques employed for depositing MPS onto electrical pads have involved various approaches such as applying electric field, magnetic field, dry or wet dispensing, and the utilization of mesh canisters [9–12]. Nonetheless, these methods have encountered limitations in terms of controlling the quantity and placement of the deposited particles. The advancement of the method proposed in this work is presented and discussed.

II. EXPERIMENTAL

A. Overview of assembly process

Fig 1 provides an overview of the assembly process proposed in this work. The process includes four primary steps: i) fabrication of a particle carrier (Fig 1a); ii) deposition of conductive particles onto the fabricated carrier (Fig 1b); iii) transferring and subsequently sintering the deposited particles to electrical pads on substrate using Ag sintering

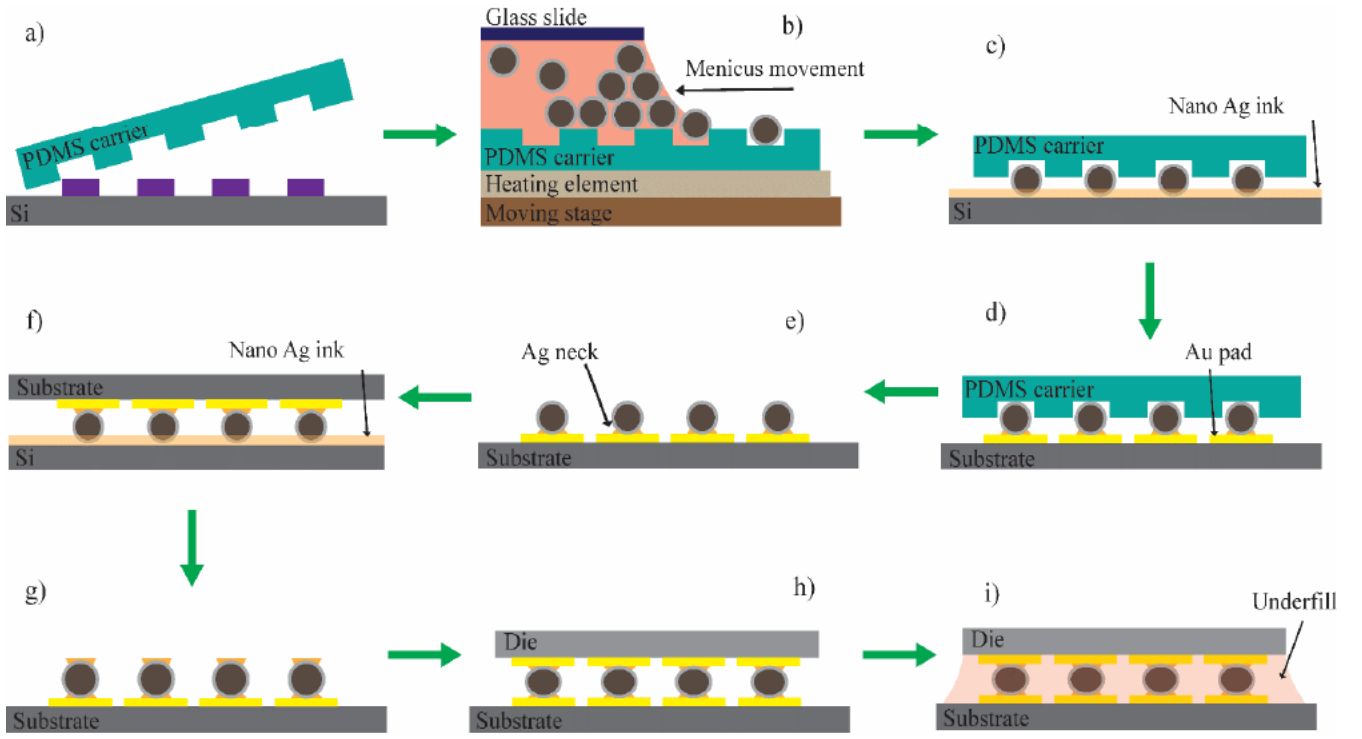


Fig 1. Assembly process for single particle-based interconnects using low-temperature Ag sintering. (a) Fabrication of PDMS carrier with particle traps. (b) Deposition of conductive particle on predefined traps using capillarity-assisted particle assembly. (c), (d), and (e) Deposition of Ag ink and the first Ag joint on substrate using Ag sintering. (f), (g), (h), and (i) Additional ink deposition for the second Ag joint on glass die and the final bonding.

(Fig 1 c, d, and e); iv) die placement and final bonding (Fig 1f, g, h, and i).

B. Design of test samples

The fabrication process of silicon substrates and glass dies followed the layout design shown in Fig 2. The dimensions of the substrates and dies are $7 \times 7 \text{ mm}^2$ and $3 \times 3 \text{ mm}^2$, respectively. The test samples consist of four Kelvin structures located at four corners to monitor interconnect resistance. In addition, three daisy chain structures, each consisting of 18 interconnects, are placed at the central area. The electrical pads and tracks were deposited using sputtered Cr/Au (10 nm/100 nm). The X-Y dimensions of each pad is $150 \times 150 \mu\text{m}^2$. The interconnection pitch for the pads is $200 \mu\text{m}$ for the Kelvin structures, and $200 \mu\text{m}$ and $175 \mu\text{m}$ for the daisy chains.

C. Fabrication of PDMS carrier

The PDMS carrier with particle traps was designed to match the position and dimensions of electrical pads on the substrate. First, a Si master mold was fabricated by photopatterning SU-8 photoresist (Kayaku Advanced Materials). PDMS liquid (Sylgard 184 kit Dow Corning) with a 10:1 ratio of prepolymer to cross-linker was then poured onto the SU-8 master mold and cured for 2 hours at 80°C . The cured PDMS carrier was then peeled off from the mold to allow for particle deposition (Fig 1a).

D. Particle deposition on PDMS carrier

The experimental setup for depositing conductive particles has been described in previous work [14]. In short, a droplet ($20 \mu\text{l}$) of colloidal Ag-coated polymer spheres ($40 \mu\text{m}$ in diameter, Ag thickness of 120 nm, supplied by Conpart AS, Norway) in 0.01 wt.% polyethylene glycol tert-octylphenyl ether (Triton X-100, VWR Chemicals) was injected between

the moving PDMS carrier and the fixed glass slide (Fig 1b). The velocity of the carrier was controlled by a syringe pump (Chemyx Mirco), and the temperature was maintained at 27°C using a thermal control module. The carrier with deposited particles was collected when the droplet reached the end of the carrier.

E. Transferring particles to substrate

A thin layer of nano Ag ink (Silverjet DGP 40LT-15C, Advanced nano products) was spin-coated on a Si wafer at 1500 rpm. A semi-automatic flip chip bonder (Finetech, FinePlacer Pico) was used for ink deposition and bonding process. Particles deposited on the carrier were brought into contact with the ink layer and subsequently aligned with the electrical pads on a substrate (Fig 1c, d). A temperature of 140°C was applied in 2 minutes to form the first Ag sintered necks between the substrate pads and particles (Fig 1e).

F. Die alignment and final bonding

Sintered particles on a substrate were deposited with an additional Ag ink layer on top by dipping in an ink film spin-coated on a Si wafer (Fig 1f, g). A glass die was immediately picked and placed on the prepared substrate, followed by the second sintering of Ag ink at 140°C for 2 minutes (Fig 1h). A bonding force of 1 N was applied during the second sintering process. Finally, epoxy underfill was introduced between the glass die and Si substrate followed by curing at 140°C for 10 minutes while maintaining the applied bonding force (Fig 1i). In this work, five samples were bonded using the same bonding profile and characterized.

G. Characterization

The deposition of particles on the PDMS carrier was observed in real-time using an optical microscope (V12, Zeiss). The electrical resistance of individual interconnects

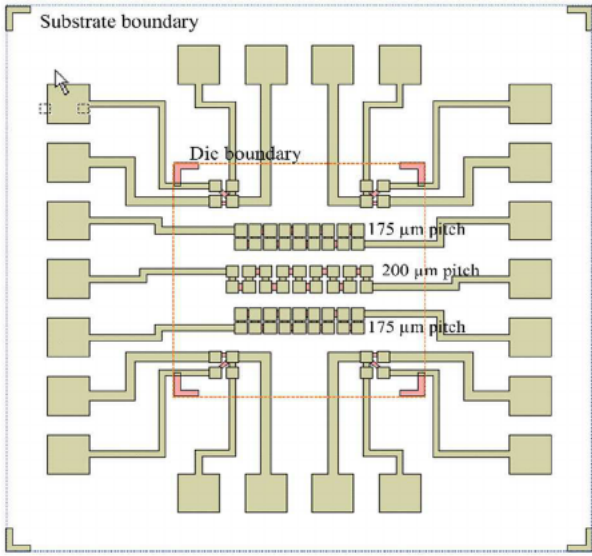


Fig 2. Layout of test sample consisting of Kelvin structures at four corners and three daisy chain structures located at center of the sample.

and daisy chains were measured by means of four-point probe and two-point probe, respectively, using a Keithley 2400 source meter. Cross-sectional microscopy was employed to inspect the deformation of conductive particles between electrical pads on dies and substrates using a scanning electron microscope (SEM SU-3500, Hitachi).

III. RESULTS

A. Fabrication of PDMS carrier and particle deposition

The PDMS carrier with particle traps was successfully fabricated using the replica molding method. The traps had dimensions of 50 μm in diameter and 20 ± 2 μm in depth. After deposition of MPS particles (as sketched in Fig 1b), 692 traps out of 700 were filled with single 40 μm Ag-MPS particles, resulting in a deposition yield of 98.8 %. Fig 3a shows the deposition of 8 particles on predefined traps for the daisy chain structure (175 μm pitch). The position of each deposited particle corresponds to an electrical pad on the substrate.

B. Transferring particles to the substrate using Ag sintering

Fig 3b shows the particles transferred from the PDMS carrier to the electrical pads after sintering at 140 $^{\circ}\text{C}$, exhibiting the formation of an ink layer between the particle and the electrical pad (Fig 3c). The conductive particles were successfully transferred to the pads while maintaining their arrangement. A shear test demonstrated the creation of ink dots with an ink diameter of 25 ± 5 μm between the particles and electrical pads (Fig 3d). The transfer yield, determined by counting the number of particles successfully transferred to the electrical pads out of the total transferred particles, was found to be 96.2%.

C. Die placement and electrical performance of bonded samples

During the second dip-coating of sintered particles on a substrate to a Ag ink film (Fig 1f), no particles were found detached from the substrate after contacting the wet ink. The results from the electrical characterization of bonded samples are shown in Table I. The resistance of individual interconnects located at the four-point probe structures ranged from 0.57 Ω to 0.74 Ω . The electrical resistance of both daisy

chains with pitches of 200 μm and 175 μm was measured to be 23.8 Ω and 24.3 Ω , respectively. The sintered Ag joint is characterized and shown in Fig 4, with the observation of the Ag neck between the particle and the electrical pad on the substrate.

TABLE I. ELECTRICAL RESISTANCE MEASURED AT THE FOUR-POINT PROBE STRUCTURES AND DAISY CHAINS

Bonding pad structures	Four-point probe	Daisy chains			
		175 μm pitch		200 μm pitch	
		Entire chain	Interconnect *	Entire chain	Interconnect
Resistance [Ω]	0.7 ± 0.1	23.8 ± 1.2	0.8 ± 0.1	24.3 ± 1.4	0.9 ± 0.1

*by using the geometry of the design and the table values for Cr and Au resistivity. Electrical resistance of all metal tracks included in the daisy chains with 175 μm and 200 μm pitch was calculated to be 9.8 Ω and 9.0 Ω , respectively.

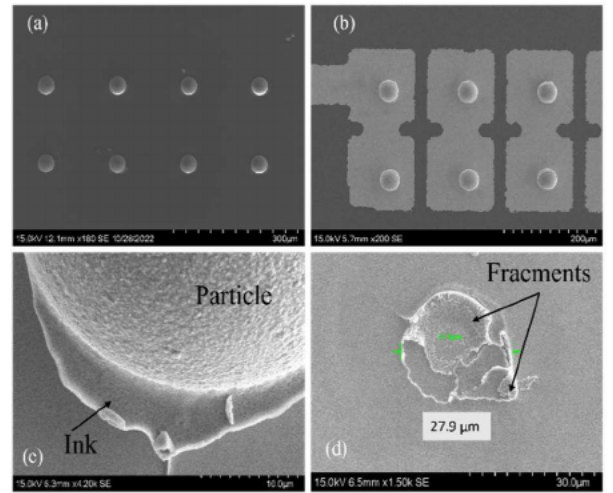


Fig 3. SEM micrographs of (a) particle deposition on PDMS carrier, (b) transferred particles on electrical pads with (c) formation ink dot between particle and pad before and (d) after a shear test.

IV. DISCUSSION

For depositing particles on PDMS carrier, the trap dimensions, particularly the trap depth, are important parameters. On one hand, a shallower depth results in particles being unable to stay in the traps (capillary forces smaller than droplet drag force). On the other hand, increasing the trap depth leads to the formation of particle clusters being deposited in a single trap [14]. Additionally, the trap depth defines the thickness of silver ink to be used in the ink deposition process since the deposited particles on the PDMS carrier come into contact with the ink. The thinner the ink layer, the less ink is deposited on the particles and the faster the evaporation of the solvent in the ink, thus, lowering the transferring yield. In contrast, if the ink is too thick, the surface of the PDMS carrier can be easily contaminated when contacting with thick ink. An optimal trap depth, approximately equal to the particle radius (~ 20 μm), allows for the deposition of a single particle with a high yield while leaving a reasonable gap (below 20 μm) for Ag ink deposition.

When the particles with deposited ink come into contact with electrical pads, they are deformed, and wet the pad surface, forming ink dots on the pads (Fig 3c). Fragments of

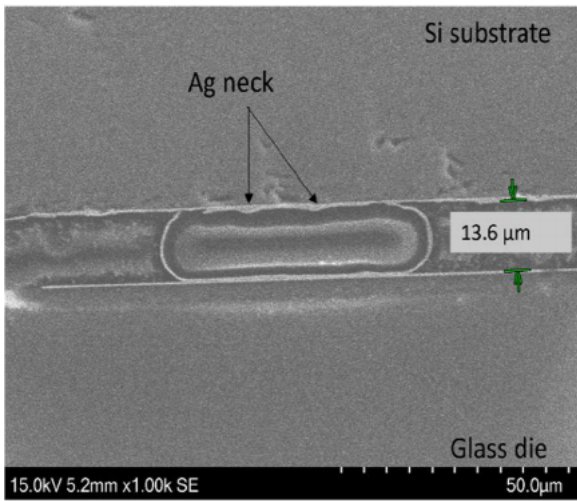


Fig 4. SEM image of cross-section at the four-point probe structure showing particle deformation with the formation of Ag neck

Ag shell on MPS were observed at the bonding interface after the shear test (Fig 3d), indicating that the sintered Ag induces a certain strength between mating particles and pads, although it is challenging to quantify. The sintered Ag plays a crucial role in effectively securing the particles onto the electrical pads, both during the detachment of the PDMS carrier and the subsequent ink deposition process.

The Ag neck was observed between the particle and the electrical pad on a substrate but not between the particle and the electrical pad on a die (Fig 4). This can be explained by the application of 1 N bonding force (corresponding to 14 mN/particle) during the second sintering. The applied force causes the particles to deform and expand, leading to an increased contact area with the electrical pads on the substrate. As a result, an overlap area with the sintered Ag is formed. However, in the case of particles in contact with the electrical pads on the die, the wet ink is drawn up along with the particle deformation. This leads to the formation of a thin sintered layer between the particles and the Au pads on the die.

The estimated electrical resistance of individual interconnects in the daisy chains, with two different pitches of 200 μm and 175 μm , shows similar results. However, these results are slightly higher than the interconnect resistance obtained from the four-point probe measurement (Table I). This difference can be attributed to the contribution of probe contact resistance in the two-point probe measurements as well as uncertainties in the estimation of track resistance. The interconnect resistance achieved as low as 0.57 Ω is significantly higher than other metallic joint technologies (below 50 m Ω), such as micro solder [4], copper pillars with solder cap [16], direct metal-metal [8], and SLID bonding [7] as well as adhesive joints (ICA, ACA) [9], which typically exhibit resistances of 100-200 m Ω . However, while these metallic and adhesive joints require higher bonding temperatures and/or higher pressure over an extended period, the presented approach could be performed at a bonding temperature as low as 140 $^{\circ}\text{C}$ and a bonding pressure as low as 0.1 MPa. To reduce the electrical resistance of interconnects, one can use MPS with a thicker metal coating layer (resistance can be reduced by half if the coating thickness increases threefold, at the same deformation degree) [17]. Achieving finer pitch capability (below 100 μm) is potentially attainable by minimizing the distance between the

two closest deposited particles on the PDMS carrier, which can be as close as the particle diameter (40 μm).

V. CONCLUSION

We have demonstrated a new interconnection approach utilizing a single Ag-coated polymer particle for each interconnect. The single-particle interconnects were realized by selectively depositing particles on the PDMS carrier using capillary assembly, and then transferring the particles to mating electrical pads on the substrate and die using thin layers of Ag ink. Bonds between Ag-coated particles and mating pads were achieved by Ag sintering at 140 $^{\circ}\text{C}$ in short time (2 minutes) with low pressure (0.1 MPa). Occupancy rates of 98.8 % for the particle deposition on the PDMS carrier and 96.2 % for the particle transfer to the electrical pads were achieved. The formation of ink dots with well-defined ink dimensions was also accomplished. The resulting interconnect resistance ranged from 0.57 – 0.74 Ω . The measurements of interconnection daisy chains demonstrated reliable sub-ohm resistance across a large number of interconnects. The presented approach enables a low thermo-mechanical stress bonding technique with low bonding temperature and low bonding pressure.

ACKNOWLEDGMENT

The Research Council of Norway is acknowledged for the support to the Norwegian Micro- and Nano-Fabrication Facility (Norfab III, Project number: 295864). We thank Helge Kristiansen (Conpart AS) for providing conductive particles, Daniel Nilsen Wright (SINTEF MiNaLab) for general advice, Thai Anh Tuan Nguyen and Zekija Ramic (USN) for help with the lithography process.

REFERENCES

- [1] J. H. Lau, "Recent Advances and Trends in Advanced Packaging," *IEEE Trans. Compon. Packag. Manuf. Technol.*, vol. 12, no. 2, pp. 228–252, Feb. 2022, doi: 10.1109/TCPMT.2022.3144461.
- [2] S.-K. Kang, D.-Y. Shih, and W. E. Bernier, "Flip-Chip Interconnections: Past, Present, and Future," in *Advanced Flip Chip Packaging*, H.-M. Tong, Y.-S. Lai, and C. P. Wong, Eds., Boston, MA: Springer US, 2013, pp. 85–154. doi: 10.1007/978-1-4419-5768-9_4.
- [3] W. S. Tsai, C. Y. Huang, C. K. Chung, K. H. Yu, and C. F. Lin, "Generational changes of flip chip interconnection technology," in *2017 12th International Microsystems, Packaging, Assembly and Circuits Technology Conference (IMPACT)*, Taipei: IEEE, Oct. 2017, pp. 306–310. doi: 10.1109/IMPACT.2017.8255955.
- [4] S. L. Wright *et al.*, "Characterization of Micro-Bump C4 Interconnects for Si-Carrier SOP Applications," in *56th Electronic Components and Technology Conference 2006*, San Diego, CA: IEEE, 2006, pp. 633–640. doi: 10.1109/ECTC.2006.1645716.
- [5] J. R. Lee, M. S. A. Aziz, M. H. H. Ishak, and C. Y. Khor, "A review on numerical approach of reflow soldering process for copper pillar technology," *Int. J. Adv. Manuf. Technol.*, vol. 121, no. 7–8, pp. 4325–4353, Aug. 2022, doi: 10.1007/s00170-022-09724-w.
- [6] J. Li *et al.*, "Design of Cu nanoaggregates composed of ultra-small Cu nanoparticles for Cu-Cu thermocompression bonding," *J. Alloys Compd.*, vol. 772, pp. 793–800, Jan. 2019, doi: 10.1016/j.jallcom.2018.09.115.
- [7] L. Sun, M. Chen, L. Zhang, P. He, and L. Xie, "Recent progress in SLID bonding in novel 3D-IC technologies," *J.*

- Alloys Compd.*, vol. 818, p. 152825, Mar. 2020, doi: 10.1016/j.jallcom.2019.152825.
- [8] S. Jangam *et al.*, "Fine-Pitch ($\leq 10\ \mu\text{m}$) Direct Cu-Cu Interconnects Using In-Situ Formic Acid Vapor Treatment," in *2019 IEEE 69th Electronic Components and Technology Conference (ECTC)*, Las Vegas, NV, USA: IEEE, May 2019, pp. 620–627. doi: 10.1109/ECTC.2019.00099.
 - [9] R. Aradhana, S. Mohanty, and S. K. Nayak, "A review on epoxy-based electrically conductive adhesives," *Int. J. Adhes. Adhes.*, vol. 99, p. 102596, Jun. 2020, doi: 10.1016/j.ijadhadh.2020.102596.
 - [10] M. W. Sugden, C. Liu, D. Hutt, D. Whalley, and H. Kristiansen, "Metal-coated mono-sized polymer core particles for fine pitch flip-chip interconnects," in *2012 IEEE 62nd Electronic Components and Technology Conference*, San Diego, CA, USA: IEEE, May 2012, pp. 218–224. doi: 10.1109/ECTC.2012.6248831.
 - [11] J. Tao, D. Whalley, and C. Liu, "Magnetic deposition of Ni/Au coated polymer core particles for flip-chip interconnection," in *2014 15th International Conference on Electronic Packaging Technology*, Chengdu, China: IEEE, May 2014, pp. 409–413. doi: 10.1109/ICEPT.2014.6922684.
 - [12] V. C. Duy, H.-V. Nguyen, H. Kristiansen, M. M. V. Taklo, K. E. Aasmundtveit, and N. Hoivik, "Immobilization of metal coated polymer spheres on Indium pads," in *Proceedings of the 5th Electronics System-integration Technology Conference (ESTC)*, Helsinki, Finland: IEEE, Sep. 2014, pp. 1–5. doi: 10.1109/ESTC.2014.6962800.
 - [13] D. N. Wright, B. D. Belle, and J. S. Graff, "Development of mechanically compliant flip chip interconnect using single metal coated polymer spheres," in *2019 22nd European Microelectronics and Packaging Conference & Exhibition (EMPC)*, Pisa, Italy: IEEE, Sep. 2019, pp. 1–7. doi: 10.23919/EMPC44848.2019.8951849.
 - [14] V. L. Huynh, K. E. Aasmundtveit, and H.-V. Nguyen, "Selective Deposition of Conductive Particles for Anisotropic Conductive Adhesive Interconnects," in *2022 IEEE 9th Electronics System-Integration Technology Conference (ESTC)*, Sibiu, Romania: IEEE, Sep. 2022, pp. 124–128. doi: 10.1109/ESTC55720.2022.9939469.
 - [15] J. R. Rumble, Ed., *CRC handbook of chemistry and physics*, 102nd edition 2021-2022. Boca Raton London New York: CRC Press, 2021.
 - [16] M. Volpert, D. Henry, D. Taneja, T. Chaira, A. Gueugnot, and F. Hodaj, "Cu pillar as interconnect for 10 μm pitch and below: Fabrication issues and assembly results," in *2018 7th Electronic System-Integration Technology Conference (ESTC)*, Dresden: IEEE, Sep. 2018, pp. 1–7. doi: 10.1109/ESTC.2018.8546408.
 - [17] M. Bazilchuk, S. R. Pettersen, H. Kristiansen, Z. Zhang, and J. He, "Electromechanical characterization of individual micron-sized metal coated polymer particles," *J. Appl. Phys.*, vol. 119, no. 24, p. 245102, Jun. 2016, doi: 10.1063/1.4954218.