Ultra-Precise Dispensing in 3D Packaging: A Seamless Shift from R&D to Production

Nina Szczotka[1, 2], Aleksandra Motyka[1, 3], Aleksandra Chudzyńska[1, 3], Mateusz Łysień[1, 3], Aleksandra Perczyńska[1], Anna Szczurek[1], Łukasz Witczak[1, 4], Piotr Kowalczewski [1], Aneta Wiatrowska[1]
XTPL S.A.
Stabłowicka 147, 54-066 Wrocław, Poland
Email: nina.szczotka@xtpl.com

Abstract

Additive manufacturing (AM) opens up a world of possibilities for creating next-generation electronics. However, employing AM technologies in microfabrication presents its own unique set of challenges. The ongoing trend towards miniaturization necessitates the printing of ultra-thin, high-density conductive interconnections in 3D packages and heterogeneous systems. In the presentation, we will showcase how the innovative technology of Ultra-Precise Dispensing (UPD) effectively addresses these challenges, how this microfabrication process is already used in advanced R&D and prototyping projects, and our current approach towards the use of the UPD approach in large-scale manufacturing.

Keywords
printed microelectronics, 3D packaging, 3D interconnections, high-frequency applications, Flexible hybrid electronics, Ultra-Precise Dispensing, nanomaterials, silver nanopaste, copper nanopaste, gold nanopaste

[1] XTPL SA, Stabłowicka 147, 54-066 Wrocław, Poland
[2] Department of Microsystems, Faculty of Electronics, Photonics and Microsystems, Wrocław University of Science and Technology, wyb. S. Wyspiańskiego 27, 50-370, Wrocław, Poland
[3] Institute of Low Temperature and Structure Research, Polish Academy of Sciences, Okólna 2, 50-422 Wrocław, Poland.
[4] Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wroclaw University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wroclaw, Poland

I. Introduction

Ultra-Precise Dispensing (UPD) is a versatile approach that enables the printing of microelectronic conductive and non-conductive structures on a variety of rigid and flexible substrates. This process facilitates maskless deposition of high-performance materials - highly-concentrated nanopastes. (https://xtpl.com/product/high-performance-materials/).
We begin with a description of three compatible materials: high-viscosity silver, gold, and copper nanoparticle-based pastes. This selection provides a wide array of potential applications for the UPD approach.

The CL85 Ag is a high-viscosity paste based on silver nanoparticles with an average diameter ranging between 35 and 50 nm. The paste is characterized by non-Newtonian behavior and its viscosity is between 1-2 million cP at a shear rate of 1.0 1/s. This enables ultra-fine and high-aspect ratio dispensing. The paste allows printing on vertical surfaces, rigid or flexible substrates with resolution ranging from 0.5 to 100 µm. High concentration (silver content: 82 +/- 2 wt.%) and rheological properties ensure the possibility of printing with a 1.5 μm nozzle and achieving electrical conductivity up to 50% of the bulk value. The unique non-clogging properties ensure a long lifespan, which translates into trouble-free use of the nozzle for over a month.

Designed for application in microelectronics, the Au nanopaste 90 is composed of nanoparticles predominantly in a spherical shape. Their average diameter is 35-55 nm. The developed paste formulation, allowing a high concentration of gold (solid content: 90 +/- 3 wt.%), ensures an increased amount of conductive metal dispensed in one pass of the printing head. Using the UPD technology, this nanopaste can be printed on various materials, including glass, PCB, and foils (e.g. PET, Kapton) with a conductivity of up to 27% on the printed structures. Thanks to the use of gold nanoparticles and specialized additives, the paste is specially dedicated to fine feature printing and deposition of electrodes for modern sensor applications.

High viscosity (ranging between 1-2 million cP at a shear rate of 1.0 1/s), concentrated (solid content: 83 +/- 2 wt.%), copper nanoparticles-based (average diameter: 35-50 nm) conductive paste serves as an advanced solution for microelectronic circuit printing and die-attaching. Like CL85, this copper analogue was engineered to fabricate ultrafine features, achieving 3 – 10 µm widths while maintaining high aspect ratios after a single pass of the printing head. The paste has the ability to be dispensed through nozzles as narrow as 3.5 µm, facilitating the deposition of uniform and homogeneous thin lines or dots on planar and as well 3-dimensional substrates. Despite its high viscosity, it enables precise control over the printing process, achieving printed features conductivity of up to 40% compared to bulk copper. The printed features can be as small as 1 um, and the maximum electrical conductivity achieved in this range is up to 50% of the bulk material.

Table 1. Characteristic values of pastes based on nanoparticles.

Nanopaste	Solid content [%]	Mean nanoparticles size [nm] (TEM)	Electrical resistivity [$\mu\Omega$*cm]
CL85	85 +/- 2	35-50	4.20 (250 °C; 40 minutes; Air)
Au90	90 +/- 3	35-55	8.13 (350 °C; 20 minutes; Air)
CuEx	83 +/- 2	35-50	3.42 (700 °C; 30 minutes; Nitrogen)

In our previous work, we delved into the physical fundamentals of the UPD process, the means to control it, and the synthesis of XTPL nanopaste CL85 [1]. In this paper, we will concentrate on the versatility of the UPD technology, considering both a broad spectrum of printable materials and use cases that are beyond the capabilities of other AM techniques. We will also discuss the transition from research and development use of the UPD approach to large-scale production, with the potential to become an industrial standard for microdispensing. In this paper, we will discuss three specific use cases:

1) 3D interconnections. Dispensing on 3D topographies for advanced packaging applications.
2) High-frequency applications. Dispensing structures for high-frequency signals, such as on-chip antennas and 5G/6G communication devices.
3) High-performance flexible hybrid electronics. Dispensing on flexible devices, like sensors with a wide range of feature sizes (from 1 to 50 µm linewidth).

High-performance flexible hybrid electronics is a field that combines the advantages of printed electronics and silicon technology. One of the key challenges in this area is the integration of semiconductor chips onto flexible foils. This is due to the challenges related to the reliability of the interconnection of a chip to the flexible substrate and the size of the rigid chip package, which influence the bending capabilities of flexible devices. Using XTPL's Ultra-Precise Dispensing system and technology, the electrical interconnections can be made directly from high-density chip electrodes to the substrate, not extending the rigid area by the package, area for wire bonds, interposer, filler, etc.

Samples created using UPD possess unique characteristics crucial for high-frequency applications. These include high surface smoothness, consistent linewidth, and uniform line space, all of which help to minimize signal losses. As a result, UPD holds a competitive edge over other additive manufacturing technologies, offering printed structures specifically tailored for signals above 300 GHz.

In early 2021, following a period of technology incubation and printing process optimization, the XTPL research and development team launched the first commercially available printing system for R&D and prototyping. This standalone equipment with UPD technology, primarily utilized by scientific institutes, universities, and corporate R&D departments, enables customers to work on new development projects involving innovative microelectronic devices. Recent publications from the users of R&D equipment (DPS, Delta Printing System) have showcased the versatility of UPD technology, with applications ranging from the fabrication of coplanar waveguide transmission lines [2] to the creation of printed Organic Field Transistors with high-resolution short channels [3], and the development of printed interconnections on flexible foils for ultra-thin chips [4]. Given its scalability, UPD technology holds promise as a preferred method for high-volume production.

Industrial implementations of UPD technology provide a reliable and cost-effective solution for manufacturing processes requiring microscale features and high throughput. Within the realm of industrial production, the UPD System has demonstrated its effectiveness in producing various microelectronic components, including 3D interconnectors, microLEDs, and the repair of next-generation displays. Its capability to achieve micron-level accuracy ensures the reproducibility of complex patterns, meeting the stringent demands of modern electronic manufacturing.

The versatility of UPD is evident in its compatibility with different inks, pastes, substrates, and applications allowing manufacturers to explore novel possibilities in designing and fabricating electronic devices on unconventional surfaces. This flexibility opens avenues for innovation in product development. As industries increasingly seek efficient and precise methods for producing miniaturized electronic components, UPD technology emerges as a frontrunner, promising enhanced productivity and reduced production costs. Its scalability further positions UPD as a competitive solution for mass production, facilitating a seamless transition from research and development to large-scale manufacturing.

II. Results

A. 3D interconnections. Dispensing on 3D topographies for advanced packaging applications

The booming electronics industry and the continued miniaturization of devices are driving the focus on designing and manufacturing smaller and more efficient devices. Consequently, the need for methods of making electrical connections, beyond traditional wire bonding, is growing. The previously described UPD technology [1] allows the printing process with high resolution of electrical interconnections, including printing on 3D topographies for advanced packaging applications. Printing such connections reduces:

- production costs,
- energy consumption,
- and the overall size of the device.

In addition it leads to an increase in:

- serial production of electrical connections,
- functionality,
- and areas of application of the UPD technology in the microelectronics market.

In this paper, we present the possibility of printing conductive lines (using CL85 Ag nanopaste) on the edge of substrates using UPD technology. Conductive paths of 500 µm width were made on glass/PI substrate, for which the parameters were used: printing pressure 4.5 bar, printing speed 0.3 mm/s, nozzle outer diameter opening 250 µm (Figure 1). The post treatment of printed structures was performed in the form of thermal sintering at 220 °C for 1 hour. The resistance value for the printed lines was around ~1 Ohm. Recently, Terry Wang et al (2024) presented the application of dispensing conductive electrical connections between electrodes on opposite sides of the substrate for a novel FOPLP (Fan-Out Panel Level Package) Structure with Chip First & RDL (Re-distributions Layers) for Automotive chip application [5].

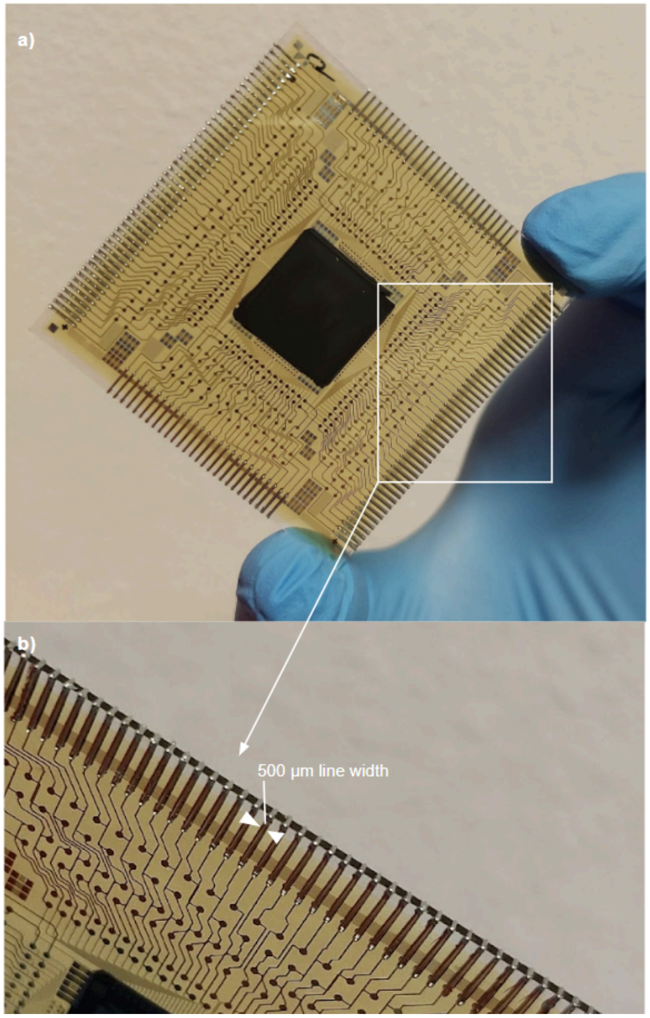

Figure 1. Top view (a) with the magnification (b) of silver conductive structures made on glass/PI substrate using UPD system and CL85 nanopaste. The line width is 500 µm.

B. High-frequency applications. Dispensing structures for high-frequency signals, such as on-chip antennas and 5G/6G communication devices

Devices based on high-frequency signals facilitate the wireless identification and location of objects using electromagnetic fields. They enable fast and accurate entity recognition, finding applications in logistics, retail, healthcare, wearable technology, smart textiles, and other innovative sectors [3,6]. Recently, the global demand for this miniaturized technology has counted in billions per year in commercial and noncommercial items. Each of the tools processing high-frequency consists of antennas to send data and receive them back in a moment. However, the fabrication of antennas requires new strategies to improve the currently available materials and manufacturing techniques. Printable electronics have been identified as a potential method due to the advantage of fast prototyping and versatility process development with various materials on different substrates [7]. The UPD, as a groundbreaking printing technology, provides the solution with extreme precision at the micro and nanoscale for the creation of highly efficient and miniaturized antennas. This capability facilitates the production of much smaller objects without compromising their performance. Compared to traditional methods, such as screen printing or inkjet printing, they offer lower precision, making it challenging to achieve the same level of accuracy and detail. Moreover, the integration, with direct tunable deposition invented by XTPL, can be very promising in shortening antenna design cycles as this technique does not require a special mask for testing each iteration of new parameters. Techniques like photolithography offer high precision but are often more complex and costlier, potentially limiting their widespread adoption for antenna production. The summary of various antenna fabrication methods presented by Y. Xiong and Z. Qu [8] shows that the printing method is reaching the cost of a common FPC (Flexible Printed Circuit) antenna, which was considered the lowest-cost manufacturing technology at that time. UPD technology can be particularly beneficial in the fabrication of highly efficient antennas with complex geometries and optimal material properties, resulting in improved signal strength and range as well as reduction of the high-performance-material wastes. One of the main advantages of the presented method is the capability of printing on flexible substrates. UPD allows for the creation of durable and flexible elements that can be integrated into various surfaces, including textiles, thin films, and polymers. Methods such as Laser Direct Structuring (LDS) [9] or etching are typically limited to rigid substrates, reducing their applicability for flexible electronics. Our UPD technology offers significant improvement in terms of performance, size, cost-efficiency, and versatility, achieving new levels of functionality and integration in the fabrication of high-frequency components.

We proposed an antenna with a basic design made of silver nanopaste (85 wt% of solid content) for high-frequency signals operations. The choice of the conductive material is based on device constraints, such as operating frequency and process simplicity with continuous deposition. Here, UPD is adopted for maskless printing of specific highly concentrated architectures with no restriction to the substrates. Figure 2a demonstrates repeatable lines printed on PEN, using a nozzle outer diameter opening of 1.5 µm, with an average width of 3.3 ± 0.2 µm, for a total design width of > 1 mm and an average line separation of 0.7 ± 0.05 µm. High resolution connected with well-controllable movements introduces an upcoming method for precise design printing with no satellite droplets and improved uniformity in all three dimensions. In Figure 2b, we presented another set of silver lines printed on a glass substrate, using a nozzle outer diameter opening of 1.5 µm, with an average width of 1.3 ± 0.2 µm and an average line separation of 2 ± 0.1 µm. The obtained dimensions allow for miniaturization of antennas and shortening the fabrication time while preserving high throughput. Presented lines were obtained by using the printing speed of 0.02 mm/s and by applying 5 bar pressure, gaining maximum electrical conductivity in this range of around 40% of bulk silver. The post treatment of printed structures was performed in the form of thermal sintering at 150 °C for PEN and 250 °C for glass for 10 min to ensure full adhesion and achieve satisfactory conductivity. The UPD method allows for printing the structures of a thickness counted in nanometers, facilitating high aspect ratio objects. In this contribution, we presented a method of high-resolution printing without common defects and rigorous control over the printing dimension of concentrated lines for antenna applications

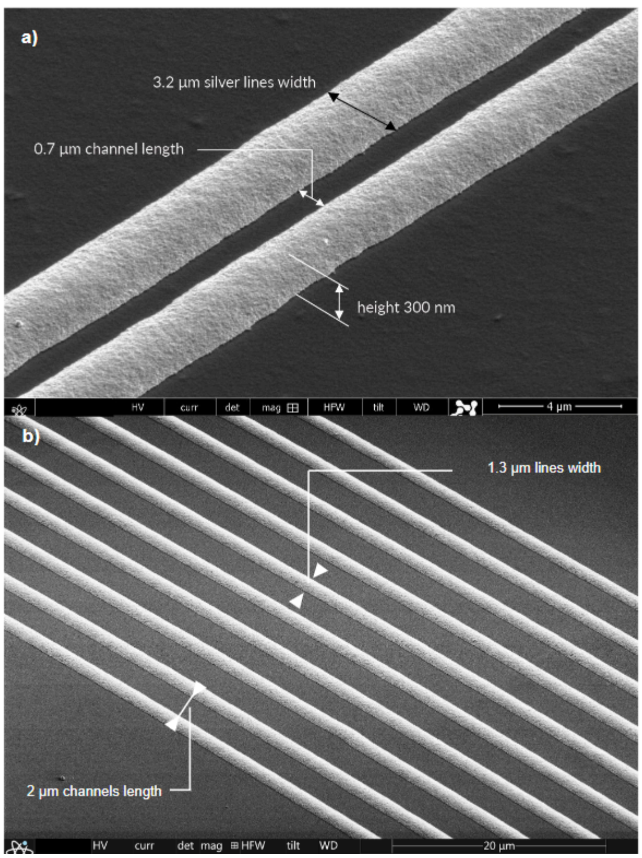

Figure 2. SEM images of silver conductive structures dispensed using UPD system and CL85 nanopaste on PEN substrate (a) and on the glass (b).

C. High-performance flexible hybrid electronics. Dispensing on flexible devices, like sensors with a wide range of feature sizes (from 1 to 50 µm linewidth)

Flexible hybrid electronics (FHE) represent a significant advancement in electronic manufacturing, merging traditional silicon-based electronics with flexible substrates. A crucial challenge in FHE development is the ultra-precise dispensing of materials onto flexible devices, such as sensors, displays, wearable electronics, and biomedical devices, which feature a wide range of line widths from 1 to 50 µm. Ultra-precise dispensing on flexible substrates requires a system capable of maintaining high precision and accuracy despite the flexible substrate's inherent variability and potential deformation. The UPD system excels in this application due to its (i) wide range of flexible nozzles, with outer diameters ranging from 1.5 to 20 µm, capable of dispensing feature sizes from 1 to 50 µm, (ii) ultra-precise pressure control unit, and (iii) high-stability metallic nanopaste. The integration of advanced dispensing modules, vision systems, pneumatic controls, kinematics, and optical components with substrate fixtures and environmental control mechanisms within the UPD system ensures accurate material dispensing, making it an essential tool for the production of high-quality FHE components.

For this purpose, three samples were prepared using two transparent substrates: slide glass and PET foil. This was because glass is a typical substrate for testing various formulations of materials, providing a benchmark with low surface roughness and PET as commonly available flexible foil for hybrid electronic applications. The UPD technology was used for printing complex designs with extended miniaturization of structures with metallic pastes. Figure 3a represents a replication of the pattern from Figure 3b bent using human strength. The sample was prepared on PET foil, using a nozzle outer diameter opening of 5 µm, with an average width of 5 ± 1 µm, for a total design of 2 mm x 0.5 mm and an average line separation of 10 ± 5 µm. The silver nanopaste provides good adhesion to flexible substrates under the thermal sintering conditions of 140 °C for 10 min. Figure 3b shows the optical image of the design acquired from silver material but prepared on glass substrate. Independently from the type of the underlying layer, in both examples, the dimensions were comparable, but the sintering parameters were different. Glass can resist higher sintering conditions; thus 250 °C for 15 min was adopted for good conductivity and stability. The last image on Figure 3c presents a structure based on gold lines printing for more advanced application of hybrid elections, where biocompatibility and non-toxicity is required. Obtained sets of structures are characterized by an average width of 10 ± 2 µm and an average line separation of 15 ± 5 µm. To receive proper durability and uniformity, the sample was sintered at 350 °C for 10 min. The gold paste is more rigorous with handling, nevertheless, the lifetime of the nozzle is extended compared to silver-based pastes. In all presented cases, the moving speed of the nozzle was set to 0.035 mm/s. The dispensing pressure was in the range from 1-2 bar and 5-7 bar for gold and silver nanopaste,

Table 2. The summary of three different methodologies of large-scale manufacturing using UPD systems

Methodology	Description	Advantages	Challenges
Multiple Single-Nozzle Systems on a Single Production Line.	Multiple UPD units, each equipped with a single nozzle. This configuration allows for simultaneous dispensing processes across many systems, significantly boosting efficiency.	- flexibility in process management, -independent calibration of each unit, - ease of troubleshooting and repair.	- requires more space on the production line, - necessitates synchronization of multiple units.
Multiple Nozzles in a Single System.	The UPD system can be equipped with multiple nozzles, enabling simultaneous dispensing from all nozzles at the same time. This approach increases efficiency without the need to install multiple separate units.	- saves space on the production line, - simplifies installation and system management.	- complexity in system design and calibration, - need to ensure uniform dispensing from all nozzles.
Multiple systems with Multi-Nozzle on a Very Large Production Line.	The combination of the above methods: multiple UPD systems with multiple nozzles on a single production line maximizes production efficiency.	- highest possible efficiency, - redundancy in the system (failure of one unit does not halt the entire production), - ability to handle very large production volumes.	- high installation and maintenance costs, - complex synchronization and system management, - need for advanced software to control the process.

respectively. The trials with various substrates facilitated the usability of the precise dispensing method on low-cost materials devoted to FHE.

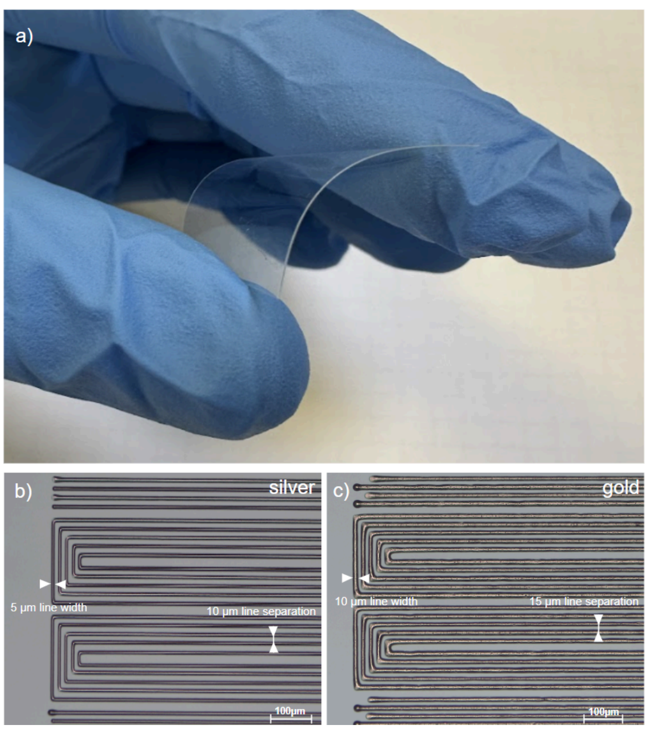

Figure 3. Macroscopic image of silver conductive structures made on flexible foil PET substrate using UPD system (a). Optical microscopic images of the structure of 5 µm line width and 10 µm line separation made of silver CL85 nanopaste (b) and the structure of 10 µm line width and 15 µm line separation of gold Au90 nanopaste (c).

III. From R&D to large-scale manufacturing

One of the primary challenges in transitioning additive manufacturing technologies from a laboratory setup to full-scale industrial production is achieving the necessary throughput. There are three primary strategies for scaling up the ultra-precise dispensing system to enhance production efficiency, as summarized in Table 2. :

First strategy is based on installing multiple single-nozzle UPD units on a single production line. Each unit, equipped with a single nozzle and individual ink or nanopaste reservoir (cartridge), operates concurrently, allowing simultaneous dispensing processes on multiple samples. This approach offers flexibility in process management, independent calibration of each unit, and ease of troubleshooting and repair. However, it requires more space to accommodate the increased number of units.

Second strategy is the multi-nozzle solution. A crucial feature of this solution is that each nozzle in the multi-nozzle printhead can be positioned independently. Furthermore, only selected nozzles may operate at any given time. Each nozzle also has its own cartridge, allowing for the use of different materials when printing a specific sample. This is particularly significant for the concept of all-printed devices, where both metals and insulators are required. Such high independence for each nozzle provides flexibility in designing device architectures and eliminates the need for any compromises in terms of capabilities and resolution compared to single-nozzle printheads. This method enhances efficiency without needing numerous separate units, saving space and simplifying installation and management. Nonetheless, it introduces complexity in system design and calibration, requiring uniform dispensing from all nozzles.

Last strategy, for very large-scale production, combines both methods. Installing multiple UPD systems with multiple nozzles on a single production line maximizes production efficiency, offering the highest possible throughput, redundancy in case of unit failure, and the capacity to handle large production volumes. This combination comes at a price of higher installation and maintenance costs. We also face the challenge of complex synchronization and the need for advanced control software. By scaling the UPD system in this manner, it becomes a versatile and efficient tool capable of managing production at various scales while ensuring the highest precision and control over the dispensing process.

IV. Conclusion

The development and implementation of UPD technology marks a significant advancement in the field of microfabrication for next-generation advanced electronics. This innovative technology addresses the critical challenges posed by the ongoing trend towards miniaturization, enabling the precise dispensing of ultra-thin, high-density conductive interconnections in 3D packages and heterogeneous systems.

Our exploration of UPD technology has demonstrated its versatility and effectiveness across a wide range of applications. From its ability to dispense high-resolution conductive lines on a complex 3D topographies to its suitability for high-frequency signal applications such as on-chip antennas and 5G/6G communication devices, UPD stands out as a robust solution that meets the stringent demands of modern electronic manufacturing.

The transition from research and development to large-scale manufacturing is a crucial step for any technology. In this contribution, we have presented three strategies to scale the UPD technology and ensure industrial viability. These strategies provide a cost-effective and reliable solution for producing microscale features with high throughput. It is a clear path for widespread use of microfabrication on an industrial scale.

Acknowledgment

We would like to express our gratitude to the entire team at XTPL S.A. for their continuous support and collaboration. Special thanks are due to the Polish Academy of Sciences and Wrocław University of Science and Technology for their engagement to industry PhD courses of Nina Szczotka, Aleksandra Motyka, Aleksandra Chudzyńska, Łukasz Witczak and Mateusz Łysień. We also acknowledge the resources provided by our partners, especially Industrial Technology Research Institute ITRI in Taiwan, which were instrumental in bringing this project to fruition.

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