Inkjet printing: gaining competitive advantage

By Luca Gautero, Simon Donkers, Wouter Brok [Meyer Burger]

The semiconductor industry is giving attention to inkjet printing to gain benefits from its features. Inkjet business presents a less capex intensive alternative for patterning when compared to, for example, a lithographic step. Moreover, on the operational expenses side, materials are efficiently used. Especially, back-end-of-line (BEOL) and integrated circuit (IC) packaging profit from the digital patterning of encapsulations (permanent or temporary), or by using interconnects with appropriate types of materials (see the sidebar, “Background,” for additional discussion).

Inkjet printing offers a contactless, direct application of functional materials to substrates with topology. The height of features can span up to hundreds of micrometers. This additive process allows the creation of precisely controlled patterns on a scale in the tens of micrometers. Equipment manufacturers are either specializing in servicing a single application with inkjet printing technology (e.g., ceramic tiles industry), or providing a versatile and adaptable platform targeting many different applications.

The versatile and adaptable platform approach combines modules, carefully selected or designed, to enhance the desired inkjet capabilities. Thanks to this matching effort, the technology reaches a broad application range. Consequently, inkjet tools are commonly not standardized for specific application requirements. This situation is especially relevant for the semiconductor industry, where inkjet equipment manufacturers and early adopters are transferring existing manufacturing processes to this additive technology. The key elements to create a success story with inkjet printing are the application, its corresponding functional ink, and the printer.

Equipment characteristics

Inkjet positions itself as a digital technology for lines/spaces (LS) in the 50/50µm region. This range is of interest for packaging technology like flip chip, which holds most of the manufacturing worldwide [1,2]. To achieve such a result with three sigma confidence, all the error components need to be in control. A skillful identification of these components is crucial in a design for quality. A coarse division of the error components identifies them as printhead, ink and motion. Printhead and ink related errors are normally evaluated together as drop placement error. This can be managed by selecting a suitable printhead and a jetting ink formulation. These choices, however, are limited by process needs related to the application. The drop placement error alone can contribute up to 20µm (3sigma). Motion is then divided in accuracy and precision. These latter numbers are normally given by the equipment manufacturer, which are driven by equipment design.

For multi-layer prints it is important to accurately position each print pass relative to already existing structures. The approach of the graphical market is to control the error budget by printing registration marks in the sideline of pages and between prints. Visible offsets between color channels are then corrected as they appear on the printed result. This implies that the first products in each batch are scrapped for alignment, and that an area within each print needs to be reserved for registration marks.

In stark contrast, a first-time-right design is chosen for functional applications. An accurate and precise motion system is combined with a camera-based alignment system. This system ensures repeatable performance already at the first print. High-resolution encoders are used in the motion axis to ensure high repeatability. Encoders are only one part of the solution; the other part, an accurate machine base, ensures the straightness and perpendicularity of the axis. As part of the calibration, a proper mapping, which highlights differences between the motion encoders and absolute print locations, is made. These inspections, reoccurring at every tool produced, ensure and allow for continuous control and improvement.

A tool is typically designed around the incoming substrates. The graphical market has optimized for sheet-to-sheet or roll-to-roll (R2R) printing. Therefore, according to constraints introduced by these two types of substrate, graphical printers are optimized for low cost of ownership and fast throughput. For the functional printing market, each type of substrate and ink brings its own particular design constraints. The optimal way to deal with these constraints is to adapt the machine to them. Equipment modularity is therefore a key design specification. Figure 1 shows three examples of machine design concepts, to illustrate various possibilities.

For the semiconductor industry, two distinct machine designs are developed. The...
first relates to the silicon wafer shape: e.g., the machine presents a single round substrate carrier (Figure 1a). As mentioned above, camera(s) and the motion platform ensure an accurate print position. Throughput can be increased with multiple printheads, reaching up to the width of the substrate. By design, the assembly allows for easy maintenance of each printhead and the calibration of its position, to enable control of the error budget.

The second semiconductor-inspired design, which relates to lead frames and panels, presents a chuck and a moving printhead assembly (Figures 1b and 1c). Figure 1b, which shows how the chuck design follows the substrate specifications, holds a single substrate or carrier of substrates. This configuration is preferable for high-mix/low-volumes (HMLV). Compensation for inaccuracies on account of small board deformations due to previous processing can be accomplished for each substrate. The optical inspection system quantifies deformations and dynamically modifies the print image to match the unique shape; such an approach boosts yield (Figure 2). Figure 1b is an ideal implementation for printing a solder mask onto large PCBs where the deformations are common.

Now consider instead a low-mix/high-volume (LMHV) situation, in which incoming substrates are less prone to deformation and the speed given by the parallel performance of design C (see Figure 1c) provides high throughput. In Figure 1, the motion system offers correctly aligned substrates to the printing system. During this printing action, the alignment of the upcoming substrates is performed. Figure 1c is an ideal production machine, for example, in the photovoltaics market. There, throughputs higher than one thousand substrates per hour are essential. Although speed is key in this design, fragile substrates need to be handled delicately. These contradicting design constraints are fully satisfied by the two print lanes with multiple substrates each.

Synergies emerge by deliberately designing a printer around the requirements for the process. As a pragmatic example, inspection per substrate is designed into the machine to detect any print defects. These print defects can then trigger either maintenance, manual or automatic, or, when redundancy is designed into the system, an automatic change of printing strategy. If these actions are taken, later prints will therefore not be affected. Another design leverages the wait time of the substrate exchange to inspect the printhead performance. These two designs provide control on quality before and after each print. This assures that no print defects will be created.

Controls on printhead variation

Within the graphical market, printheads and inks are developed simultaneously over the years to assure an optimal print quality. For functional applications, obtaining an optimal end result is a shared responsibility among three players: material suppliers, equipment manufacturers, and device makers. Inks are tailor-made by material suppliers upon desired functional and jetting process requirements. Equipment is designed to accommodate substrates and offer large process windows for ink jetting. The device maker is the process owner, therefore central in the specification of both inks and equipment. The focal point of attention of these three players is the physical printhead. A printhead is integrated into the equipment and will drive the dispatch of material according to the manufacturing requirements.

Current state of the art printheads offer extensive control over the nozzle actuation waveform. This greater freedom comes with a larger process window to investigate for good printhead settings. Optimal performances of printing, which means a decrease in the drop placement error, are obtained by matching and optimizing ink to printing parameters such as pressure, temperature, and nozzle actuation waveform. When experiments and quality controls of the droplets, as they exit nozzles, are performed by a camera system with dedicated image recognition software (called a “drop watch”), the influence of any parameter become appreciable in a quantified, reproducible manner.

Figure 3 shows two examples of recorded droplet formation. Both of these examples show a collection of images recorded at a fixed time after jetting, while a single parameter of the nozzle actuation waveform has been varied. Figure 3a shows the harmonic behavior of the liquid in the nozzle chamber. This shows that with a fixed incoming voltage, a big difference in drop speed is a consequence of the pulse duration. Once the pulse duration is fixed, the pulse voltage offers fine control over the exact shape and speed.
of the droplet (Figure 3b). Aside from these two examples, a drop watch also allows the quantification of the process boundaries. They explore compatible jetting frequencies, investigate jetting uniformity, and inquire the time reliability of drop formation. With this information, the design of the machine, together with the process window, is made robust.

Drop watchers detect and quantify variation of the printhead. Variation of speed and angle among nozzles of a printhead, even within specification, can result in erratic performances. This knowledge helps to drive print strategies. These new inkjet strategies are achieved with comprehensive simulators (Figures 4a and 4b). These tools allow users to zoom into their print strategy down to the single drop level. When and which nozzle printed a drop is clearly displayed. With this detailed information, various strategies can quickly be sketched, reviewed and printed to find their effect.

The stepping of the printhead is a parameter in print strategies. In a multi-pass print, where the desired resolution (dot per inch, or DPI) is higher than the native printhead resolution (nozzle per inch, or NPI) and the stepping is one, the printhead passes over the substrate once, moves one pixel, and repeats (Figure 4c). Instead, a better approach is given by higher stepping numbers: the printhead shifts a few millimeters during passes, and an entirely different set of nozzles prints next to each droplet, thereby mitigating the printhead variations without throughput impact (Figure 4d).

Another print strategy could send the printhead over the same area multiple times to dispatch ink. In other words, multiple nozzles would be involved in printing that area (Figure 4e). The benefit is additional redundancy. Furthermore, the additional drying time offers more control over the layer formation. This strategy, in combination with the variable stepping, creates a much more diffuse drop placement pattern (Figure 4f).

**Digital revolution in action**

One of the advantages of inkjet printing is its digital nature, which makes each product unique, even in LMHV situations. Compensation for substrate rotation (Figure 1b) has already been presented. When multiple fiducials are available, digital correction can go much further as shown in Figure 2. This maintains a tight drop placement relative to the substrates, even if the substrate has significant deformations.

Another benefit of inkjet printing is the high repeatability of material volume control. Inkjet printing repeatedly prints the same volume of active material on each substrate or specific location thanks to its digital nature. Active printed layers are accurately calibrated with the exact quantity of material needed. It is therefore a wise choice to create the active material on sensors, or to reach an extremely precise thickness for optical applications, with an inkjet tool.

**Productivity enhancements**

Material suppliers are continuously developing their inks to improve the performance and reliability. Also, printheads have ever more advanced designs, and are better equipped with features for higher stability. Still, drop watch features, as described earlier, are used in production environments. They quickly scan all nozzles’ drops for basic properties, such as speed and angle, which results in a performance map of the entire printhead. This can easily be used as an automated trigger to run preventive maintenance and prevent the occurrence of print defects.

Several printheads are available with ink recirculation possibilities. When ink is circulating, better temperature control and continuous ink change are achieved even when the printer is idle. Furthermore, any build-up of agglomerates or air bubbles is immediately removed to prevent nozzle clogging.

A well-known phrasal idiom for printheads is: “a working nozzle is a happy nozzle.” Production printers have an automated jetting sequence (jetting guard) to act during long inactive intervals. Ink flows, in the range of microliter/day, are enough to ensure that the printer functions reliably. With this guard set, the system is always ready to run production.

**Drop behavior on a substrate’s surface**

Functional inkjet printing is typically applied on impermeable substrates. Any printed volume will therefore be found on the substrate surface. Printing parameters will affect the way the drop is landing. After landing, the material will flow. The final extension of the solidified material on the surface depends on the curing process, solvent evaporation or simple solidification due to temperature decrease. These effects are intertwined with timing of drop placement, which is controlled by print strategy and machine design.

Referring to the above discussion, a particular example considers inks with low viscosity at room temperature and low surface energy. These deliver planar features, but conflict with precise pattern formation (Figure 5b). Advanced printing optimization

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**Figure 4:** Print strategy variations for a printing task that requires four passes. Droplets are colored by the nozzle firing them. a) Print image; b) Simulator overview of a detail of 4a; c) A zoom-in view of 4b showing each individual droplet. Drops highlighted per nozzle with different colors; d) Alternative stepping print strategy compared to 4c; e) Alternative multi-pass print strategy compared to 4c; f) Combining 4d and 4e.

**Figure 5:** Overview of lateral edge movement for two levels of ink viscosity (5a and 5b) in time without applying any active solidification method.
Background
The suitability of inkjet printing for the semiconductor manufacturing [S1] is best described by typical examples: dielectric inks offer passivation, isolation and protections; common applications are encapsulation, stress buffer on silicon dies, buffer rings, wafer edge protection and containment structures with high aspect ratio, like dams or fillings. Hot melts offer temporary masking for etching or plating of conductors. On lead frame substrates, isolation patterns for routed quad flat no leads (QFN) packages, solder mask, and roughening are typical examples of inkjet patterning. Conductive inks produce interconnects, antennas and passive components. Adhesive formulations enable wafer bonding and die attach. Print results are shown in Figure S1 for: solder flux (Figures S1a and S1b), BGA solder ball encapsulation (Figure S1c), solder mask on routed QFN (Figure S1d), 3D-printed dams (100µm walls, 500µm height) (Figure S1e), and printed adhesive patterns (Figure S1f) illustrate the capabilities of inkjet technology.

Sidebar reference

Figure S1: Typical print results for several applications.

Summary
Functional inkjet printing can reliably support applications with high accuracy and excellent process controls for the semiconductor industry. Suitable equipment and ink materials are commercially available and they are defining additive manufacturing innovation. Equipment manufacturers, material and printhead suppliers, as well as application owners, work together to leverage the unique benefits of inkjet printing. It is essential to apply the tools, strategies and methods detailed here to minimize the time to market.

References

Biographies
Luca Gautero is Product Manager of PiXDRO at Meyer Burger (Netherlands) B.V. with more than a decade of professional experience in equipment design for several sectors: photovoltaic, displays and semiconductors. His academic path includes a MSc at the Institut National Polytechnique de Grenoble (FR), and a PhD thesis in Micro and Nanotechnologies from the Ecole polytechnique fédérale de Lausanne (CH). Email: luca.Gautero@meyerburger.com

Simon Donkers is System Architect at Meyer Burger (Netherlands) B.V. with over 12 years of professional experience in inkjet printing. After his study of Applied Physics at Eindhoven U., he started as Process Development Engineer to assist customers starting in inkjet printing. Now he translates those customer wishes into machine designs.

Wouter Brok is Innovations Manager at Meyer Burger (Netherlands) B.V. and received his MSc and PhD degrees in Applied Physics at Eindhoven U. of Technology in the Netherlands.