The benefits of inkjet printing of functional materials are multiple and obvious. First of all it is an additive manufacturing technology. Many structures in today’s (electronic) products are made with lithographic and thus subtractive technology while they could be printed directly. Cost of ownership analyses have shown that cost of capital equipment and labour for coating, exposure and development can be reduced significantly, while the reduction of chemicals and waste streams only add to this. A cost reduction potential of over 50% has been reported.

While manufacturing cost is always a strong driving force in the electronics industry, the time to market gain that is to be reaped by avoiding masks and screens and printing directly from a digital file, is an important factor too. Furthermore, inkjet is capable of depositing very homogeneous blanket coatings, precisely printing a wealth of materials (for example conductive, dielectric, adhesive, resist, sensing, biological, pharmaceutical and optical materials), and forming both very thin and flexible layers and 3D structures. Because of these reasons we experience an increasing acceptance of inkjet technology in both the organic and printed electronics industry and traditional electronics manufacturing industries (such as solar, PCB, display, semiconductor) as well as in biomedical and pharmaceutical applications.

Complete process flow

The wide variety of materials, industries and applications give rise to an obvious market requirement: modularity. Every application dictates its own specific substrate size, accuracy, post-processing, handling mechanism, and, as we will see later, reli-
ability enhancing functions. Instead of completely redesigning every inkjet printer as a bespoke tool, an important design rule is to use standard building blocks that help avoid non-recurring engineering cost and engineering risk. The starting point is a range of base platforms with different footprint and substrate sizes that are compatible with typical substrates in the display, semicon, PCB or solar industry. These are complemented with the optimal print head for the application and e.g. UV, photonic, or NIR based post-processing modules for curing, sintering or drying. Finally, the tool is to be integrated into the overall factory process flow with automatic handling based on off-the-shelf robot or conveyor solutions.

**Throughput and reliability**

An important design consideration is the number and type of print heads to be integrated. While an increasing number of heads generally improves throughput and adds redundancy, it also adds cost and can in fact hurt print reliability. Redundant nozzles and heads that only print at irregular intervals are showing much lower life expectancy than nozzles that are continuously printing. To determine the optimal number and type of print heads, a sophisticated model is used which takes the product layout and dimensions, the print resolution, the maximum jetting frequency of the head and ink combination, the print speed, the motion profile, the print strategy, and the handling overhead into account.

A very important aspect which is often overlooked in the R&D and proof-of-principle stage is reliability. Against the many benefits of inkjet printing stands the risk that nozzles may fail at unpredictable instances. And, where this is less of a problem for graphical applications, a failing nozzle may impair the functionality of a printed device. Fortunately there are many ways to deal with this.

Starting at a fundamental level, it is key to understand the mechanisms behind nozzle failure. Although the piezo actuators in the print heads don’t have an infinite lifetime and print head suppliers are typically conservative in their life time specifications, the main reason for failure is often not the head itself but the interaction with the ink.

Drying of the ink at the nozzle plate, deposition of particles from the ink, nozzle plate pooling (build-up of liquid material on the nozzle plate) and gas bubbles are the main factors that affect jetting stability. There is an important role for the ink supplier in formulating an ink with intrinsic long term reliability characteristics. Typically a monomer (non-solvent based) UV curing ink is less prone to drying effects. The same is true for hot melt inks that are jetted at high temperature. For solvent inks, it comes to selecting the right solvent/co-solvent system that is a compromise between fast drying of the ink on the substrate, and limited drying on the nozzle plate. When determining the optimal solvent system, one has to take the printing environment into account as well. Humidity and temperature of the environment around the print head may have a serious impact on the drying behaviour of the ink. The choice of dispersants and surfactants that help to keep particles dispersed in the ink and that dictate spreading of ink on the head are obviously very important too. It is very important to test an ink/head combination for long term stability before embarking on laying out a printer configuration. Drop watch and printing tests can quickly give an indication of ink stability and especially start-up effects or latency is a good indicator. Latency of a nozzle is the number of pulses needed before a first droplet is jetted after resuming printing. If there is a drying or particle settling effect during the time the head is not printing, it will take a few pulses before the first droplet is ejected. This effect is an indicator for potential reliability problems, but also shows up in the print result in the form of blurry edges. Experienced ink formulators are often capable of finding the right composition, so it is important to work with the right material partners and involve them in an early stage.

**Error-forgiving print strategies**

Nevertheless, ink formulation is a matter of compromises and nozzle failure cannot always be avoided. The next resort is then to search for error forgiving print strategies. In a multi-pass strategy there are possibilities to apply specific nozzle allocation strategies that hide the effect of nozzle failure. Whenever a layer or pattern is built up from the droplets ejected from a multitude of nozzles, the effect of one nozzle failing is just a slight and local reduction of the deposited material volume and doesn’t mean that the functionality of the layer is destroyed.

Fortunately nozzle failure is not irreversible. Excess ink or particle build up on the nozzles can be removed, which restores the original jetting characteristics of the head. Maintenance functionalities such as purging and wiping are therefore very important modules in an inkjet printer. Again, just like the number of print heads, maintenance schemes have to be optimised, as mechanical rubbing against wiping material may cause wear and tear and purging cycles consume both ink and time. Some processes remain working at very high yield with only one purge/wipe cycle per day, while others need maintenance cycles after every few products. Additionally it may be needed that all nozzles are kept jetting. During printing this requires advanced revolving nozzle allocation schemes to make sure that redundant nozzles are also used for printing and do not get clogged because they are just sitting idle.

Although the print strategy may be forgiving for nozzle failure and proper regular maintenance is key, it is often essential to monitor the state of the print heads. The most elegant solution is to use piezo sensing based self-diagnostic features that are available on some print heads. Unfortunately, only few of the industrial print heads on the market have this feature. The alternative is then to use vision systems to look at the jetting process or at the printed result. With today’s sensitive CMOS cameras and readily available computing power it is possible to...
scan a large number of nozzles in a short time and diagnose the stability of not only drop presence, but also speed, direction and volume. Taking these parameters into account, corrective head maintenance can take place in a feedback loop instead of scheduling this at regular intervals. This optimises throughput, reduces print head wear and corrects nozzle deviations before they develop into complete failure of the nozzle.

**Conclusion**

Driven by increasing maturity of application know how and quickly growing availability of good inkjet materials, the industry is adopting functional inkjet printing. In order to guarantee high throughput production at an industrial yield level, a lot of attention has to go into the design of the inkjet printing equipment. While it all starts with an equipment engineering effort needed to configure the right form factor tool including the handling and post-processing modules, the more important and less tangible part of configuring an inkjet tool is in the translation of the product requirements and ink characteristics into an optimal head choice and maintenance scheme. This part involves strong interaction with the ink vendor, process know-how and development by the customer and equipment supplier and often materialises in the form of software. It is often overlooked, but absolutely crucial for reliable production.