PCB007 PRESENTS



January 2015

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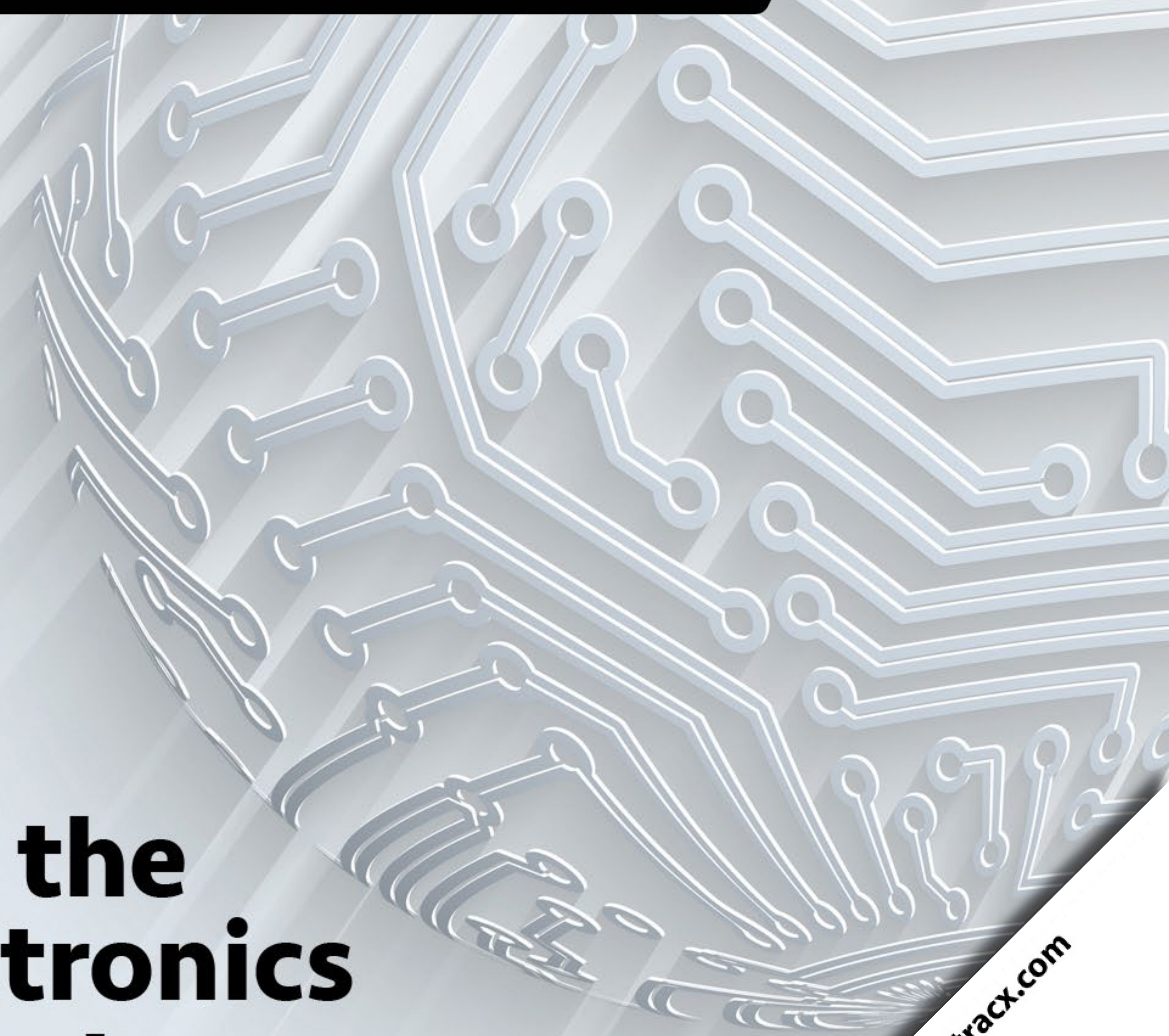
**3D Printing & Structural Electronics**



# Can the Electronics Industry Use 3D Printing?

*by Arjen Koppens, pg. 12*

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# January Featured Content

## 3D Printing & Structural Electronics

3D printing is happening, and it's happening fast. What could this mean for PCB manufacturing and structural electronics? This month's feature contributors explore the 3rd dimension.



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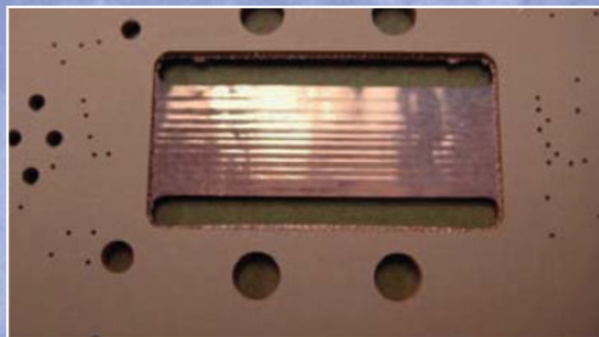

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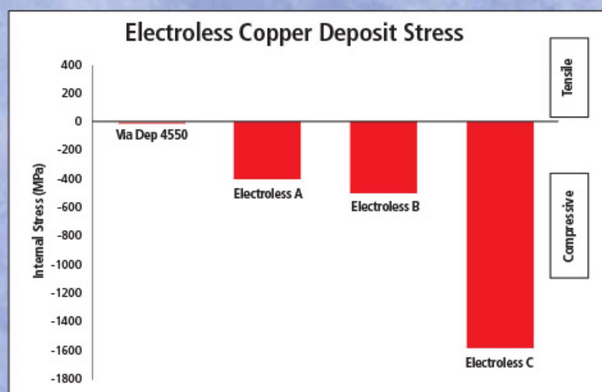


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# CONTENTS

# The Tipping Point

**by Ray Rasmussen**
I-CONNECT007

A recent Qualcomm customer survey on the product development efforts around printed electronics determined the tipping for this technology is 3–5 years away. That message was part of a presentation given by a company exec during the IDTechEx printed electronics conference last November in Silicon Valley.

I pulled this definition off of Wikipedia: a tipping point is "the moment of critical mass, the threshold, the boiling point."

I have been covering the printed electronics industry for over a decade. I've read plenty of forecasts pointing to an eminent explosion in low-cost electronics all centered on PE technologies. I've also written in past columns about Gartner's Hype Cycle , which describes the path new technologies take as they move from concept to unrealistic market expectations with lots of investment (the hype), to a collapse and consolidation and then to an established market. Gartner explains it better here.

If you look at Figure 1, I'd say we're currently on the Slope of Enlightenment, headed to the Plateau of Productivity.

As I've espoused the virtues of PE technology and its potential to disrupt the PCB world as we know it, I've also been challenged by some of the industry's top professionals who believe I'm way overstating the potential impact on PCBs. Naka (Dr. Hayao Nakahara) has promised to roll a peanut with his nose from New York to San Francisco if the printed electronics industry begins to displace a majority of the PCB industry. If you believe the Qualcomm survey results, then the good news is that Naka has 3–5 years to strengthen this arms and shoulders,

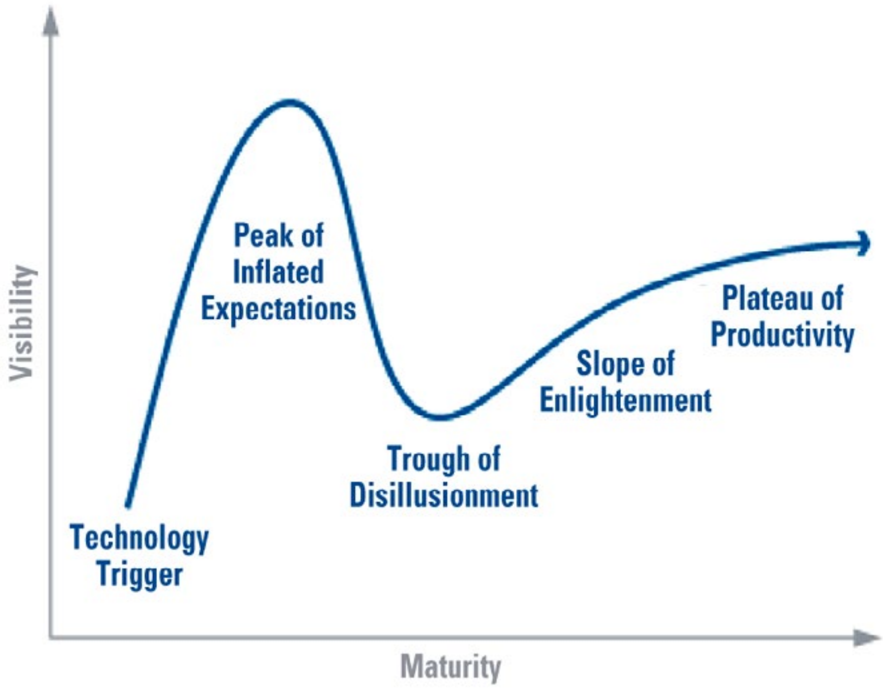



Figure 1: Gartner's Hype Cycle. (Source: Gartner Research)

which he'll need on his journey to the West Coast. Kneepads would also be recommended. But there's a lot more going on, which is why I believe that major change for our industry is on the horizon.

What many people miss is that it's not printed electronics that's driving this change. Companies aren't going to replace a PCB with PE, but they are going to redesign their products in ways which, in part, are enabled by printed electronics. There's a lot more energy going into the end products, of which PE is only a part of the story, as you'll see. PE is one of the enablers but it's not going to drive the market. It's the market that's driving printed electronics. I think that is what people don't understand. They tend to look at printed electronics as a direct replacement to the PCB, and scoff. It is the markets that printed electronics enables, which will drive its development. And each year, as PE becomes more capable, more companies will choose PE and all it enables over static PCBs. Keep reading.

These new markets will drive the PE industry forward at an ever-increasing rate. The capabilities of the technology will advance faster than that of traditional PCBs and therefore, seemingly overnight, blow by the PCB industry. PE will not likely ever be in direct competition with PCBs. Once OEMs start using PE solutions (interconnects) and structural electronics (see below) to build their products, game over.

### The Drivers: the Electronification of all Things

Over the last few years, the IDTechEx show has been expanding with some complimentary offerings on topics that include: 3D printing; energy harvesting and storage; internet of things (IoT); wearable technology; and super capacitors. To get a sense of these emerging technologies you should make the trek to one of these conferences. Spend a couple days listening to the speakers and walking the show floor. There's a lot going on. If the potential of PE wasn't real, this show would have died out years ago. Instead, hundreds of Silicon Valley engineers attend the courses, talk to exhibitors, and network with their peers. And globally, there are dozens of shows and conferences from major industry groups addressing these topics. What's happening is definitely for real.

By looking at these additional offerings from the conference, you can start to see where printed electronics is headed. There's a monster industry developing. And, what has started out slow, focused on low-cost products, will quickly jump into all markets, making just about everything you can think of smarter. And looking at PCBs, the PE technologies for making circuits are getting really good. Very, very fine lines are producible in high volume using many different techniques. The paper companies talk about PE using thermal paper, roll to roll. Printing presses are now producing multilayer circuits (as predicted) on the fly, printing conductors and insulators back to back. Inkjet printers are getting really good along with the inks and substrates. But again, you can't just look at the PE capabilities and match them up to a PCB. I believe there will only be a very short span of time when they actually intersect. We're seeing some of that, now.

**Structural Electronics**

As I mentioned earlier, there is something new, currently being called structural electronics. It has been talked about in theory for years and in the past, been done in the form of molded circuits, but this specialty market segment is poised for growth, soon. The marriage of 3D (also not new, but now taking off) and printed electronics can provide distinct advantages to those OEMs willing to take the plunge. It seems inevitable that all products will incorporate structural electronics at some point. That's the way it's all headed. You won't build a product by integrating the electronics into it. We may see structural electronics added to the IDtechEx conference next year, as a standalone, as more companies seek to meld electronics into everything. This is bigger than most of us can get our minds around.

Here's an excerpt from a news item we published back in November:

*Structural electronics involves electronic and/or electrical components and circuits that act as load-bearing, protective structures, replacing dumb structures such as vehicle bodies, or conformally placed upon them. It is of huge interest to the aerospace industry which is usually the first adopter, the automotive and civil engineering industries, both with compelling needs, but its reach is much broader even than this. Electric cars badly need longer range and more space for the money, and in civil engineering, corrosion of reinforced concrete structures and tighter requirements for all structures, including early warning of problems, are among the market drivers for structural electronics.*

You can read more about this rapidly evolving market here.

If you do some digging you'll find much more on this topic. The Internet of Things, which promises to connect everything with very inexpensive (or, not so inexpensive) electronics built into and onto just about everything you can imagine, is changing the game. A crude example is the integration of sensors into the pillars, surfaces and joints of a bridge. Before the bridge even shows a sign of a problem, the sensors have detected an anomaly and that information is transmitted to the builder, the architect, the engineers, and more. In this scenario, the surface sensors could weigh trucks as they pass and give a real-time traffic count and even collect solar energy, the joints would track ground tremors, etc. The sky's the limit on what's possible. Now, think of everything out there where failure is not an option and you can see what's driving this. The military/aerospace and medical, along with transportation companies are driving this hard. They have the most to gain, initially.

IDTechEx said this recently:

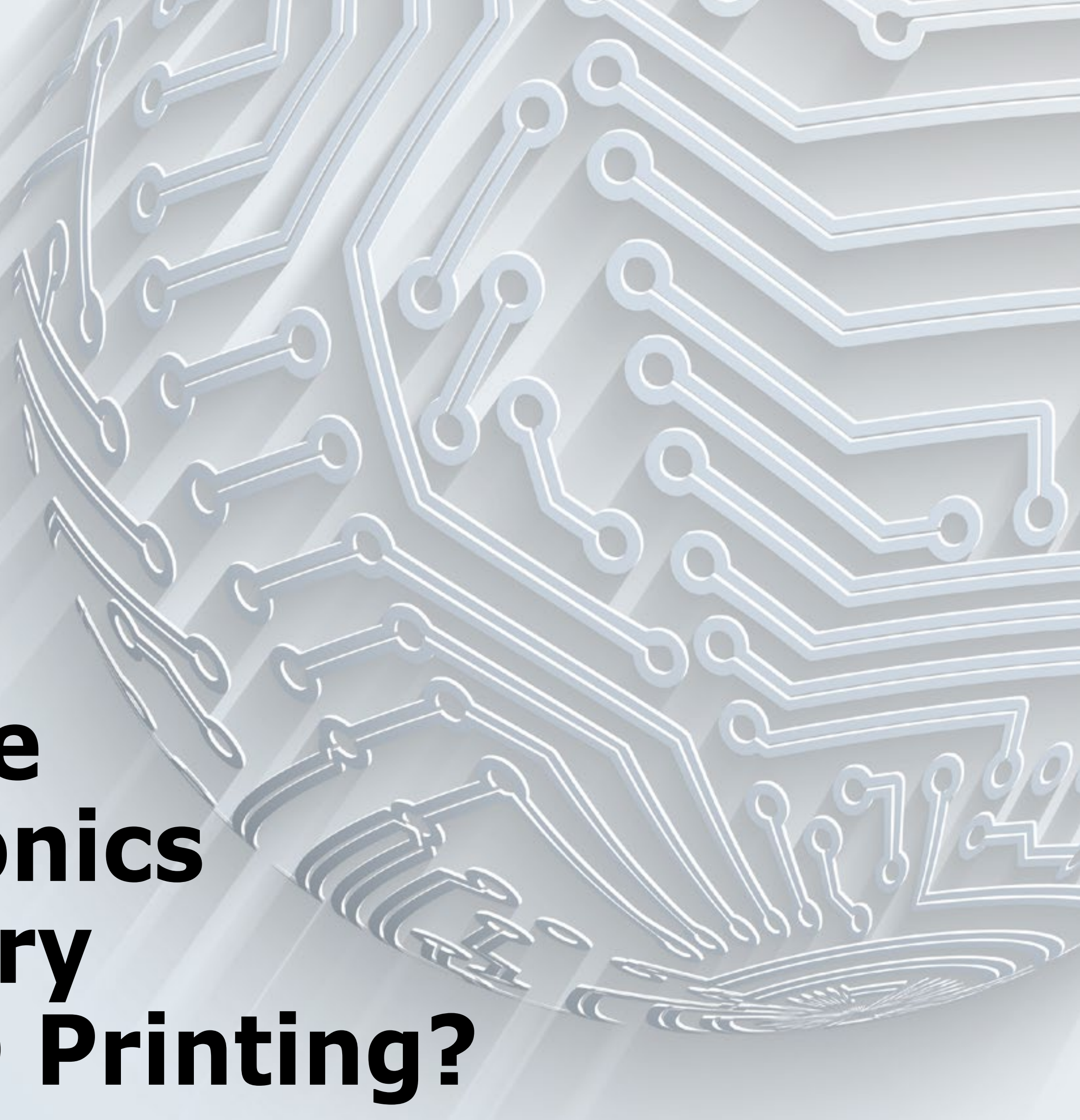
*Nonetheless, the big picture is structural electronics taking over from a century of joining components together and putting them in a box. Now is the century of electronic and electrical structures with a very different value chain.*

Read more here.

When we talk about electronic products today, they are usually in a class by themselves, as add-ons bringing intelligence to some piece of equipment, as mentioned above. Soon, everything will be an electronic product to some degree, which will have a structural component, or vise versa: roads, bridges, walls, floors, ceilings, tires, pots for plants (as I look around my office), fireplaces, lamps, desks, water and sewer pipes—you name it. That's where this is heading.

I hope you enjoy this month's topic. **PCB**

Ray Rasmussen is the publisher and chief editor for I-Connect007 Publications. He has worked in the industry since 1978 and is the former publisher and chief editor of *CircuiTree Magazine.* To read past columns, or to contact Rasmussen, click here.



# Can the Electronics Industry use 3D Printing?

**by Arjen Koppens**
DIMA GROUP B.V.

Most of today's electronic products consist of traditionally made parts: plastic molded housings containing PCBs with soldered THT and SMT components. In many cases, even the design of a product is based on the electronics that should fit inside! Shouldn't it be the other way around? Shouldn't the electronics be a part of the design based on ergonomics and aesthetics?

The only way to establish this is by somehow placing the electronics inside the design. This dictates that the substrate on which the components should be placed would be the inside of the designed housing itself. Since most housings are of a 3D shape, the components might need to be placed under an angle, but moreover, the interconnections between the components can no longer be on a separate piece of FR-4 material.

Also, if we look at the advanced 3D chip packaging level, interconnects are an important driver. This holds for through-silicon vias (TSVs) for chip stacking, but also for other interconnects steps like redistribution layers and solder bumps. Especially in applications with a low number (<100 mm-2) of relatively large features (10–100 µm diameter) with high aspect ratio (up to 1:10), conventional plating processes are slow and become cumbersome with increasing aspect ratio, thus becoming cost-ineffective. Hence, industrially feasible, alternative direct-write processes are of interest for advanced interconnects.

A general trend in IC manufacturing, driven by ever-increasing performance and form factor requirements, is that chips are becoming more and more integrated into very thin packages. Integration takes place at the chip level, on silicon interposers, and also by integrating ultra-thin chips into foil based devices.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| Method | Dimensions reported | Curing/ plating required |
|---|---|---|
| Plasma technology | 200–2000 µm | No |
| Ink jet/micro-dispensing | 20–100 µm | Yes |
| Aerosol jet (LENS) | 10–50 µm | Yes |
| Laser induced forward transfer (LIFT) | 1–10 µm | No |

Table 1: Overview of existing direct-write approaches.

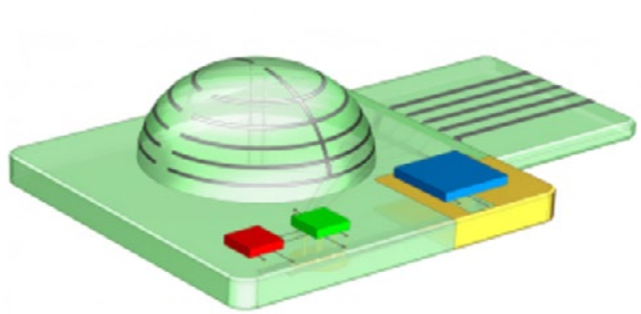

Figure 1: Example of 3D printed electronics.

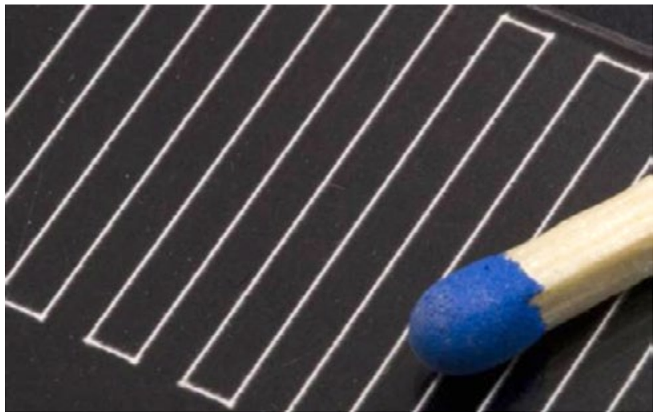

Figure 2: Printed interconnects.

Such integration requires new interconnect strategies like TSVs, through-mould vias in wafer-level packages, redistribution layers for chip-scale ball grid arrays, and all kinds of hybrid approaches to integrate thin silicon chips into foils or laminates. All these applications share the problem that existing industrial patterned metallization approaches are either costly or lack accuracy.

Traditionally, in IC manufacturing, a combination of sputtering and electroplating is the technology of choice. To create a pattern, the plating process has been combined with one or more lithographic masking and etching steps. Altogether, this combination of processing steps makes this a costly approach, especially when series are small. Further, novel packaging and interconnect approaches typically require metallization at enhanced aspect ratios (e.g., in TSVs, which leads to an even stronger cost increase). At the same time, the total area coverage of the structures is often relatively small. Finally, novel packaging approaches are not always compatible with wet processing.

Direct-write technologies can form a low-cost alternative approach to create interconnects by eliminating mask and etch costs as well as by being more efficient at low area coverage and high aspect ratio.

All kind of techniques have been developed to print interconnects. Existing direct-write technologies are summarized in Table 1. In most cases, either a metallic ink or paste (typically containing nano-particles) is used or an ink containing precursor for electroless plating. Metallic inks containing nano-particles require a thermal or photonic treatment to achieve sintering, hence electrical conductivity. Plating precursors need an electroless plating step to create the actual track. Hence, such precursor printing only solves part of the problems associated with the conventional approach.

In general, the approaches listed in Table I are well established technologies (except for LIFT) and many amongst them are incorporated in industrial processes like PCB production, solar cell production or electronics packaging. To be able to write structures compatibly with advanced IC packaging approaches, a deposition resolution of 1–5 µm is required. As can be seen in the table, this is at least a factor of 10 smaller than most of the existing direct-write figures. Only the LIFT technology shows the potential to overcome this limitation.

Laser-induced forward transfer uses a laser to shoot small droplets of conductive material from a carrier onto a substrate, as shown in Figure 1.

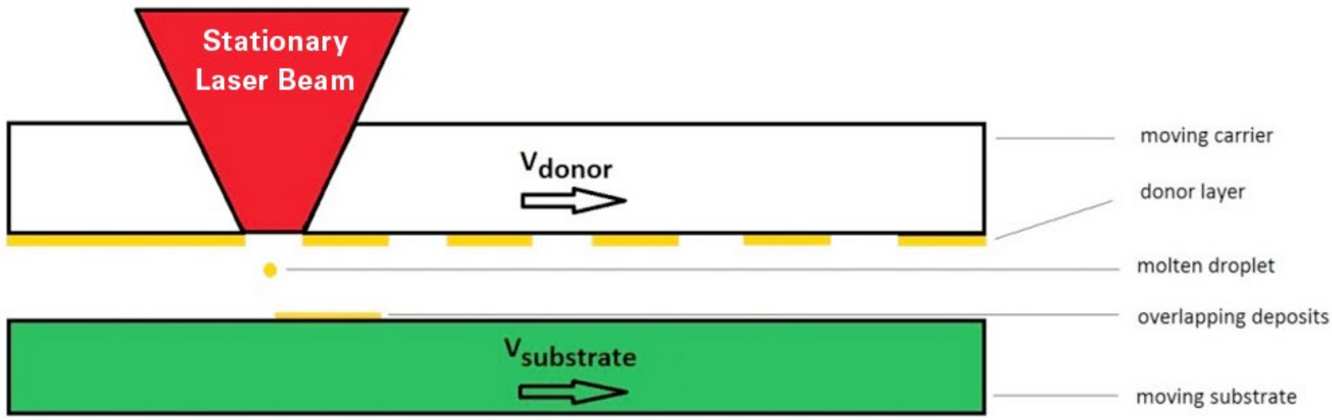


Figure 3: Graphic explanation of LIFT process.

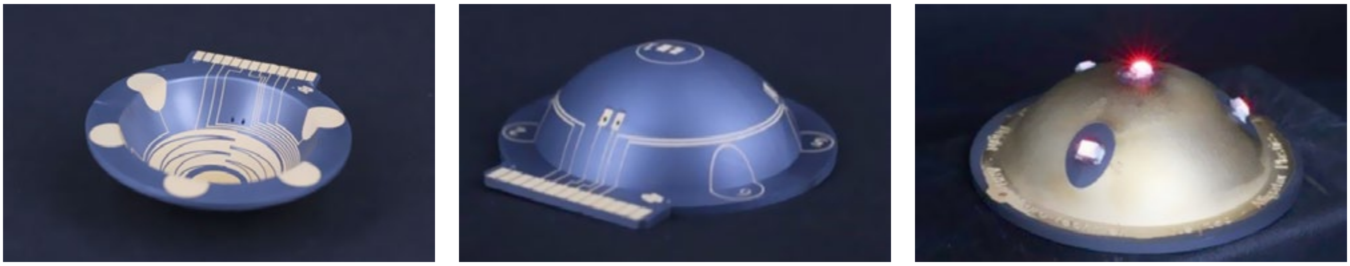

Figure 4: 3D MID examples (far right shows a functional 3D MID).

Note that the deposition size is typically smaller than the hole in the donor layer. Further, the substrate and the donor both move with respect to the laser beam, each with their own velocity. This is needed in order to create overlapping deposits which form a conducting line.

Inkjet printing can be used in electronics packaging as interconnections between electronic components. Conductive inks and dielectric inks are used when substituting traditional PCBs with inkjet-printed interconnections. Although both organic and inorganic inks can be used for conductive purposes, at the moment inorganic inks offer better conductivity. Inorganic ink consists of metal nano-particles and organic solvent which make the ink printable.

Aerosol jet printing is another material deposition technology for printed electronics. The process begins with atomization of an ink, which can be heated up to 80°C, producing droplets on the order of one to two microns in diameter. The atomized droplets are entrained in a gas stream and delivered to the print head. Here, an annular flow of clean gas is introduced around the aerosol stream to focus the droplets into a tightly collimated beam of material. The combined gas streams exit the print head through a converging nozzle that compresses the aerosol stream to a diameter as small as 10 microns.

The jet of droplets exits the print head at high velocity (~50 meters/second) and impinges upon the substrate. Electrical interconnects, passive and active components are formed by moving the print head, equipped with a mechanical stop/start shutter, relative to the substrate. The resulting patterns can have features ranging from 10 microns wide, with layer thicknesses from 10s of nanometers to >10 microns. A wide nozzle print head enables efficient patterning of millimeter size electronic features

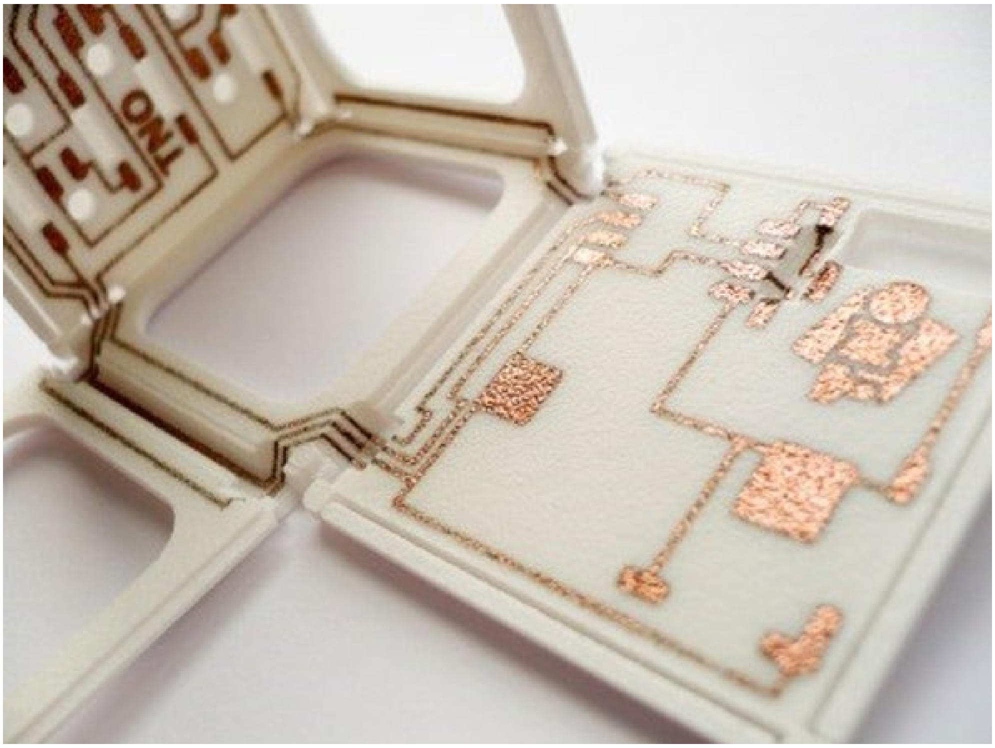


Figure 5: 3D printed copper tracks.

and surface coating applications. All printing occurs without the use of vacuum or pressure chambers and at room temperature. The high exit velocity of the jet enables a relatively large separation between the print head and the substrate, typically 2–5 mm. The droplets remain tightly focused over this distance, resulting in the ability to print conformal patterns over three dimensional substrates. Despite the high velocity, the printing process is gentle; substrate damage does not occur and there is generally no splatter or overspray from the droplets. Once patterning is complete, the printed ink typically requires post-treatment to attain final electrical and mechanical properties.

3D MID technology (moulded interconnect devices) is another way to create an electrical interconnect inside a moulded plastic housing. An electrical conductive circuit is created by means of two-shot moulding or by laser activation patterning. After this step the structures are metallized through an electroless plating process and become conductive. After the circuitry is created the conventional SMT machines (stencil printing, pick & place and reflow ovens) can make sure that components are added to the part.

Things can get even more interesting when we change our conventional way of thinking! What if we first placed the components inside the housing and then printed the interconnects? In that case we would not need the reflow process either! It would, however, be beneficial to be able to print copper interconnects without a post treatment. Plasma technology could be a good option in this case. This kind of technology could revolutionize manufacturing processes for sensitive surfaces under atmospheric pressure. Cold active atmospheric plasma encompasses a multitude of applications in the industries like solar, semiconductors and could become a substitute technology for 3D MID. Plasma technology however still needs some extra attention to be able to create fine-pitch tight tolerance interconnects.

What needs to be considered as well is the placement of the components. In case we create the electrical circuitry inside the housing and the shape is three-dimensional, we need to be able to place components in a three-dimensional way. This also means that we need to be able to apply solder paste or glue in a e3D way as well. If we could first place the components and then print the conductive copper tracks, there might even be a need to change the design of certain components that have their connections or heat sinks on the bottom side.

What advantages can these changes bring the electronics industry? Besides having a product designed for purpose and not just to fit the electronics, there are some major cost advan-

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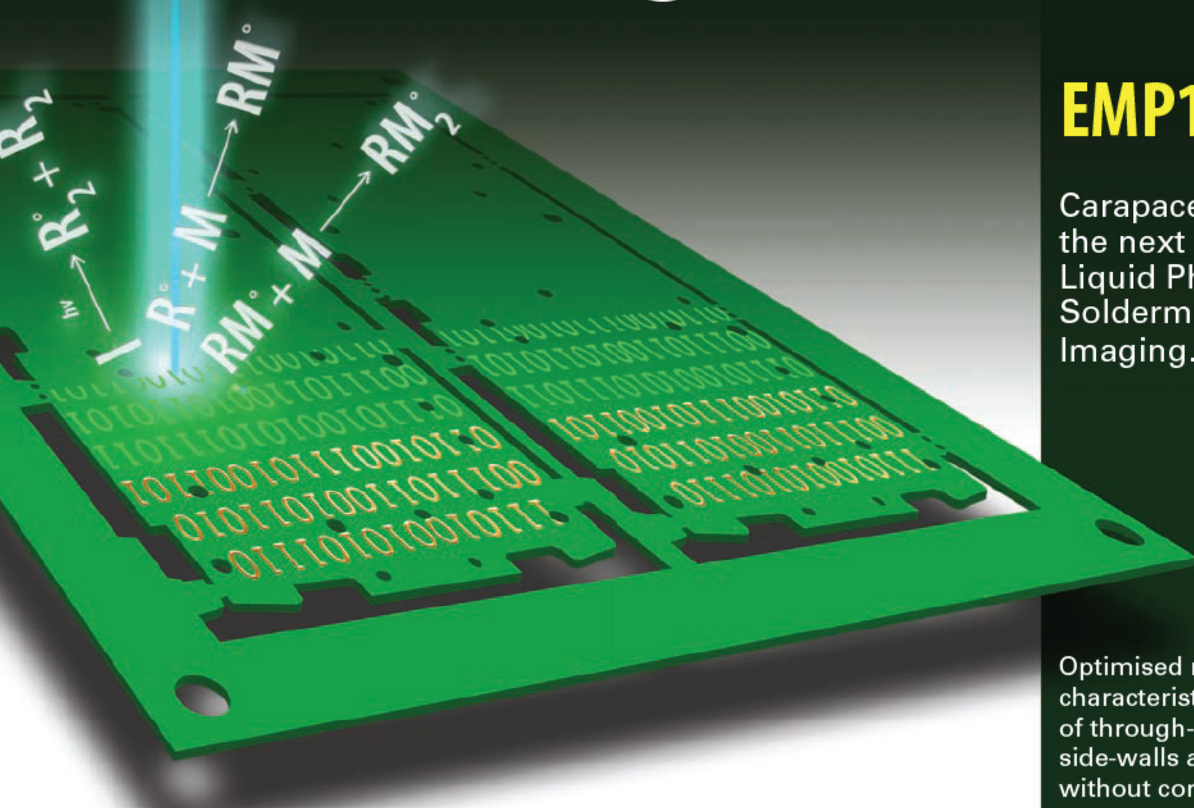

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tages. If the interconnects can be printed inside a housing, there is no more need for a printed circuit board. This is not only a cost-saving advantage, but also an environmental advantage. Furthermore, the assembly steps of integrating the PCB into a housing is no longer needed, which is another cost-saving argument. If some of the components can be part of the printed interconnects, then these components are no longer needed as conventional THT or SMT components. If we could first place components and secondly print the copper interconnects, no more solder paste would need to be applied and no reflow process would be needed either. The solder paste, however, probably needs to be replaced by a gluing process to hold the components in place especially if components will be placed in a three-dimensional way. Reducing production steps could lead to faster production cycles. This is especially true if this process could simplify a current complex sub-assembly, but for sure it will lead to a reduction of floor space and energy cost.

Several very interesting features should be thoroughly investigated for the electronics industry, as well as the mechanical segment. The next steps are pushing the technical limits and challenging the industry. TNO, a research institute in The Netherlands, has started with a strategic research program on the topic of 3D printed electronics to develop new techniques and further develop existing techniques in close cooperation with the electronics industry and its partners. We expect that due to fast developments in 3D printing, the technology will mature in the coming years into a cost-effective approach for electronics industry. **PCB**

Arjen Koppens is sales manager at DIMA Group B.V.

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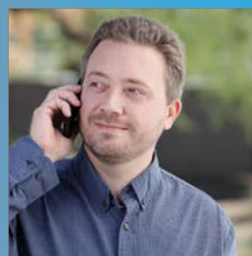

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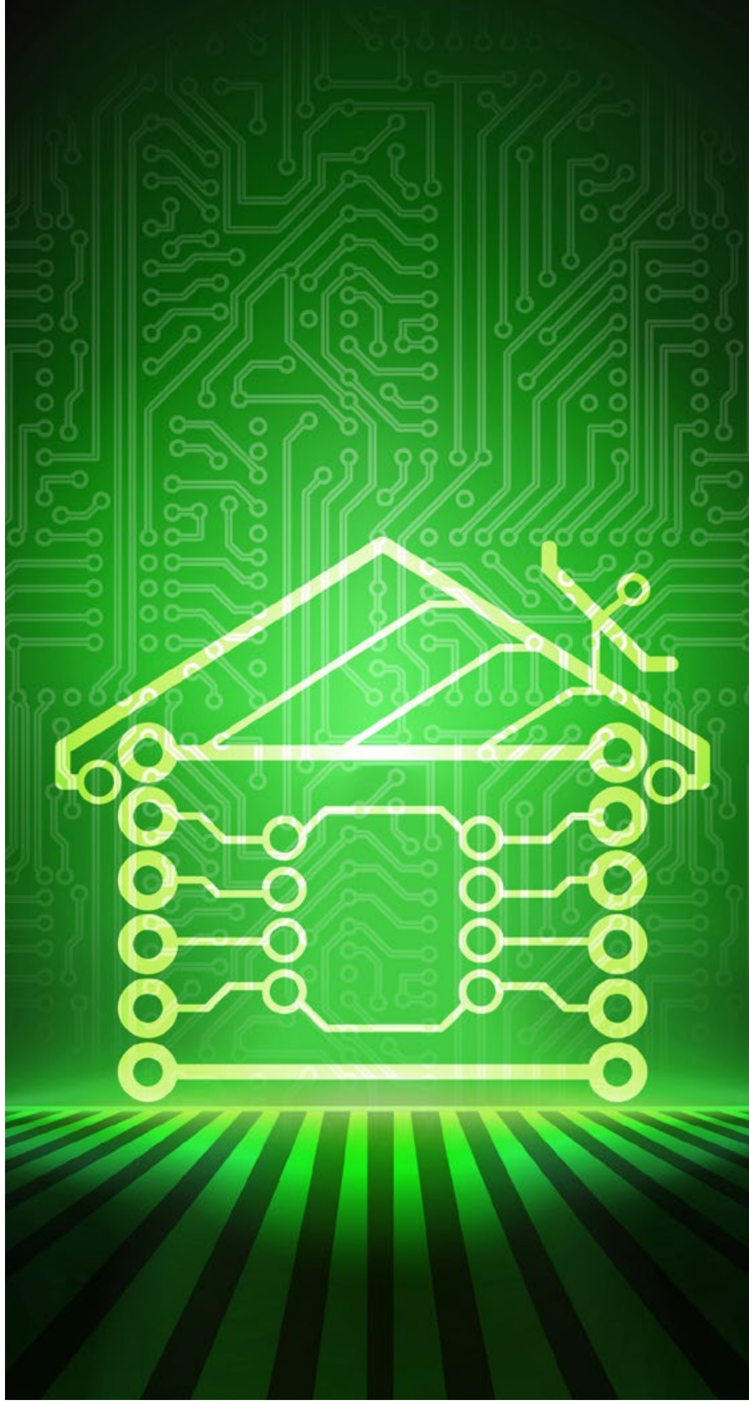
# Opportunities for 3D Printed Structural Electronics

**by Dr. Jon Harrop**
IDTECHEX



3D printing refers to the physical construction of an object from a digital description through the selective deposition of material. Today's 3D printers have many limitations, but the boundaries are being pushed and exciting developments are continuously being made. One of the most promising recent developments in the world of 3D printing is multimaterial printing, not least because it is the key to the emergence of 3D printed electronics. Today's commercially available multimaterial 3D printers are limited to providing a variety of mechanical characteristics such as rigidity as well as color and transparency, but the seemingly simple inclusion of UV curable conductive inks could make these machines capable of manufacturing objects that contain conductive traces.

This is naturally regarded by many as a direct alternative to traditional PCB manufacture and, in many respects, not a very good one. The logical application for 3D PCBs plays to the traditional strengths of 3D printing: rapid prototyping. However, the ability to lay down conductive traces inside a 3D object has far more potential. There is no longer any requirement to use flat designs. The added design freedom has the potential to greatly simplify circuit layout but will require a new generation of software tools. Furthermore, the natural evolution of this design freedom is the ability to embed electronics in the structure of anything. This is known as structural electronics.

Structural electronics is one of the most important technological developments of this century. It forms a key part of the dream, first formulated 30 years ago, of computing disappearing into the fabric of society. It also addresses, in a particularly elegant manner, the dream of Edison in 1880 that electricity should be made where it is needed. Structural electronics is often biomimetic—it usefully imitates nature in ways not previously feasible. An example of this

is giving an aircraft or a car something resembling a nervous system. Structural electronics effectively takes no space because it is integrated into something that was already there, achieving this by adding little weight to the integrated structure. However, in the world of electronics and electrics, the design rules change as we move from component selection and circuit design to functional design. Product development has additional objectives.

3D printing may well prove to be the enabling technology that brings structural electronics to the masses. For almost 30 years the 3D printing industry has viewed their technology through the eyes of the mechanical engineer. Hundreds of millions of dollars in R&D have been invested in improving mechanical properties such as strength and precision. Only in the past three years has this begun to change. Two big names in the world of 3D printing, Stratasys and Optomec, collaborated on a project to assess the feasibility of using Optomec's aerosol jet technology to deposit not only conductive traces but even sensors onto the curved surfaces of an object 3D printed using thermoplastic extrusion by a Stratasys machine. The University of Warwick developed the first usefully-conductive 3D printable thermoplastic filament called Carbomorph and used it to 3D print flexible sensors. Google developed 3D printable conductive inks in collaboration with 3D Systems for their modular mobile phone project and used them to 3D print computer-optimized antennas as part of the module shells. Inventables published an article describing a simple way for hobbyists to prototype PCBs by injecting conducting pastes into channels within 3D printed parts. None of these techniques have caught on yet, but the momentum behind 3D printed electronics continues to grow. To understand where 3D printed electronics might succeed it is necessary to first understand the applications of structural electronics and the competing technologies that might solve the same problems.

"A piece of MRI machine cannot be swapped out easily because there are so many wires to disconnect, reconnect and test. 3D printed electronics might just be the ideal solution to this problem. The housing of the MRI machine could be 3D printed with all of the wiring integrated into it as conductive traces."

Modular wiring is perhaps the application closest to printed circuit boards. After all, traditional PCBs have taken us a long way from using individual cables to connect everything. But wherever devices and equipment resort to using cables to connect PCBs there is the potential to provide a modular wiring solution. For example, GE Healthcare is the world's leading MRI scanner manufacturer and, despite the extensive use of PCBs in MRI machines, they have a lot of problems with wires. The wiring inside an MRI machine is not modular. A piece of MRI machine cannot be swapped out easily because there are so many wires to disconnect, reconnect and test. 3D printed electronics might just be the ideal solution to this problem. The housing of the MRI machine could be 3D printed with all of the wiring integrated into it as conductive traces. The slow speed of 3D printing is a non-issue when you are manufacturing 100 devices per year. The ability to cost-effectively manufacture individual objects or runs of less than 1,000 would make a 3D printed electronics solution the ideal platform for startups to launch new electronic devices such as Internet of Things or wearable devices. Although many more exciting applications of structural electronics exist none is perhaps as well suited to 3D printed electronics as modular wiring.

Smart skin is another application of structural electronics. Like a nervous system in a human body, sensor networks scattered across the body of a vehicle, such as an aircraft fuselage, will record and transmit essential data concerning the structural health of the vehicle. One solution is to turn the entire body of the vehicle into a printed circuit board. This idea is particularly popular in the aerospace industry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which, interestingly, is no stranger to 3D printing having been using it in production for well over a decade. For example, NASA developed open coil arrays as aircraft vehicle sensor arrays that double as lightning conductors on composite airframes that otherwise lack the ability to conduct lightning (Figure 1).

However, wide area circuit boards are not the only way to solve this problem. EADS Innovation Works and Vienna University of Technology used a wireless sensor network with power obtained via energy harvesting, a solution that would not benefit from 3D printed electronics.

Severe, unpredicted corrosion of reinforced steel concrete in bridges, tunnels and buildings calls for strengthening retrofit with embedded sensors. In Japan they spin carbon fiber around the support structure and embed in polymer with sensors as a smart skin. Printed electronics may well prove to be a competitive way to manufacture these wide area circuit boards in the future.

Another application of structural electronics is building integrated photovoltaics (BIPV). This refers to products designed either to substitute for conventional building materials or to be installed flush on a building surface with minimal disruption of the underlying and surrounding building architecture. BIPV is one of the mostly watched segments of the photovoltaic industry, but it is far from mainstream. The BIPV market development is impeded by the existence of standardised solar panels that have become a commodity having decreased in price drastically. So far BIPV products are produced on a smaller scale. Sales are growing as architects and building specifiers look for more aesthetic ways to use solar energy and sales propositions are starting to take such forms as solar tiles and walkable PV roofing. Over the last few years, there has been a proliferation in the market of rigid BIPV panels designed to function as roofing tiles and, in some cases, exterior wall cladding. These include large, interlocking, weather-tight BIPV tiles that mount directly onto the

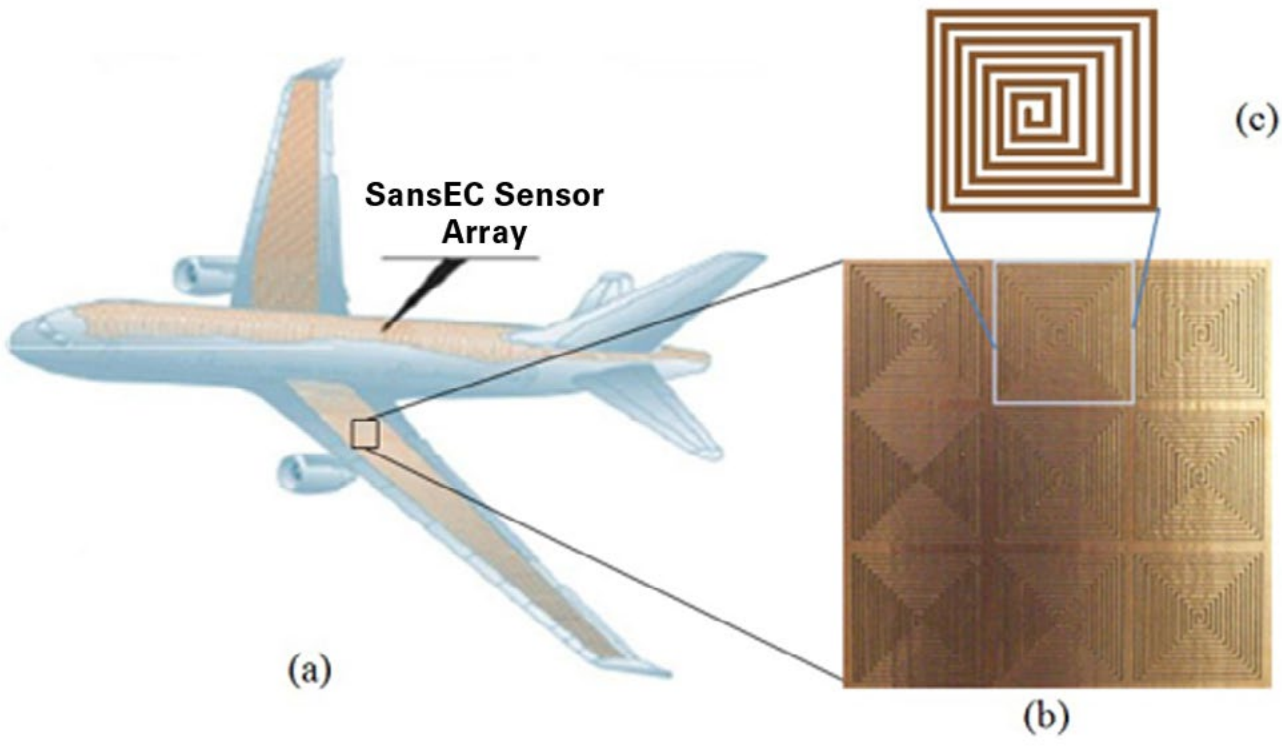



Figure 1: NASA Sans EC open coil arrays (a) placed on aircraft (b) as array of laminar open circuit coils and (c) the shape of a typical coil used. (Source: NASA)

sub roof or walls, generally substituting for an entire roof, as well as smaller BIPV tiles or slates that substitute for individual or small numbers of conventional shingles, tiles, or slates and can interlace with the conventional material units. The rigidity of these products permits the use of traditional crystalline silicon (c-Si) PV cells and indeed c-Si PV dominates this market. Due to the high production rates and low design complexity, this kind of application does not play to the strengths of 3D printed electronics.

The move to hybrid and pure electric vehicles such as e-cars calls for major weight and volume reduction to reduce cost and increase range (Figure 2). Also needed is replacement of batteries because they need to be replaced well within the life of the vehicle and at great cost.

In-mold electronics (IME) are processes by which capacitive sensor switches and other rigid replacements for components with moving parts are made in the molding process for greater reliability, lower cost, reliability, better appearance, space saving, etc. IME is the logical next step for in-mold decorating (IMD). IME is often combined with printed electronics. The high production volumes required by the automotive industry are better suited to IME than 3D printed electronics.

Figure 2: Car with printed organic light emitting diode OLED lighting on outside and inside of roof and printed photovoltaics over the outside generating electricity.

Printed electronics is the additive form of manufacture of electronic and electrical circuits and components in 2D (i.e., very thin and typically on flexible substrates). It is used for wide-area electronics such as flexible photovoltaics and for large numbers of fairly small circuits.

Printed electronics will become a huge business because it is often lower in cost and/or superior in performance to conventional electronics, examples of the latter being lighter weight, robustness, fault tolerance and thinness. In addition, some printed displays need no electricity unless the image is being changed—useful in signage—and others have unprecedentedly good viewing angle and vibrancy of colours.

Metamaterials are artificial materials engineered to have properties that may not be found in nature such as negative permittivity, magnetic permeability and refractive index resulting in acoustic, optical and electromagnetic capabilities. The honeycomb structure often used lends itself to being a lightweight structural component. The sum of the parts, not the parts themselves, determines how the material behaves. Do not have to be uniform in their structure which makes you able to change the properties of each individual metamaterial allowing you to make it go around corners or turn around. Able to make objects invisible to light, microwaves, earthquakes, etc., due to the ability to control of acoustic or electromagnetic radiation. Potential applications include remote aerospace applications, sensor detection and infrastructure monitoring, smart solar power management, public safety, radomes, high-frequency battlefield communication, terahertz components and lenses for high-gain antennas, improving ultrasonic sensors, and even shielding structures from earthquakes and laminar telephoto lenses. Metamaterials are a possible application of 3D printed electronics, particularly for longer wavelengths such as microwave or radio.

The potential benefits of structural electronics are substantial. Making better use of the void spaces in modern vehicles and other applications can clearly result in significant space savings. Fiat believes that cars, with about half their weight in bodywork and half in circuits and comfort facilities could save about 20% in weight by merging some of these into structural electronics. For a pure electric car that means a precious 20% range increase. New circuits such as telematics and vibration harvesting can also be designed into the structure saving even more weight without requiring any extra space. Pervasive wide area electronics such as photovoltaics over the whole airframe of an aircraft and sensing in places previously inaccessible has clear benefits in terms of energy efficiency and safety. Although supercapacitors require more weight and size per unit charge compared to batteries they are better suited for embedding inside structural components due to their superior lifespan. Thus structural electronics may allow us to tap the other benefits of supercapacitors including reliability, fast charge and discharge, ability to be fully discharged for safe transit and in an accident. A typical car employs around 50 tactile switches and four rotary switches, both being relatively unreliable. For example, the overhead console of a car with switches, lighting, etc., can be made much thinner, shaped and solid state with a saving of up to 40% in cost, weight and space and potentially an increase in reliability, including better waterproofing. Structural electronics also has the potential to reduce up-front costs compared to traditional approaches.

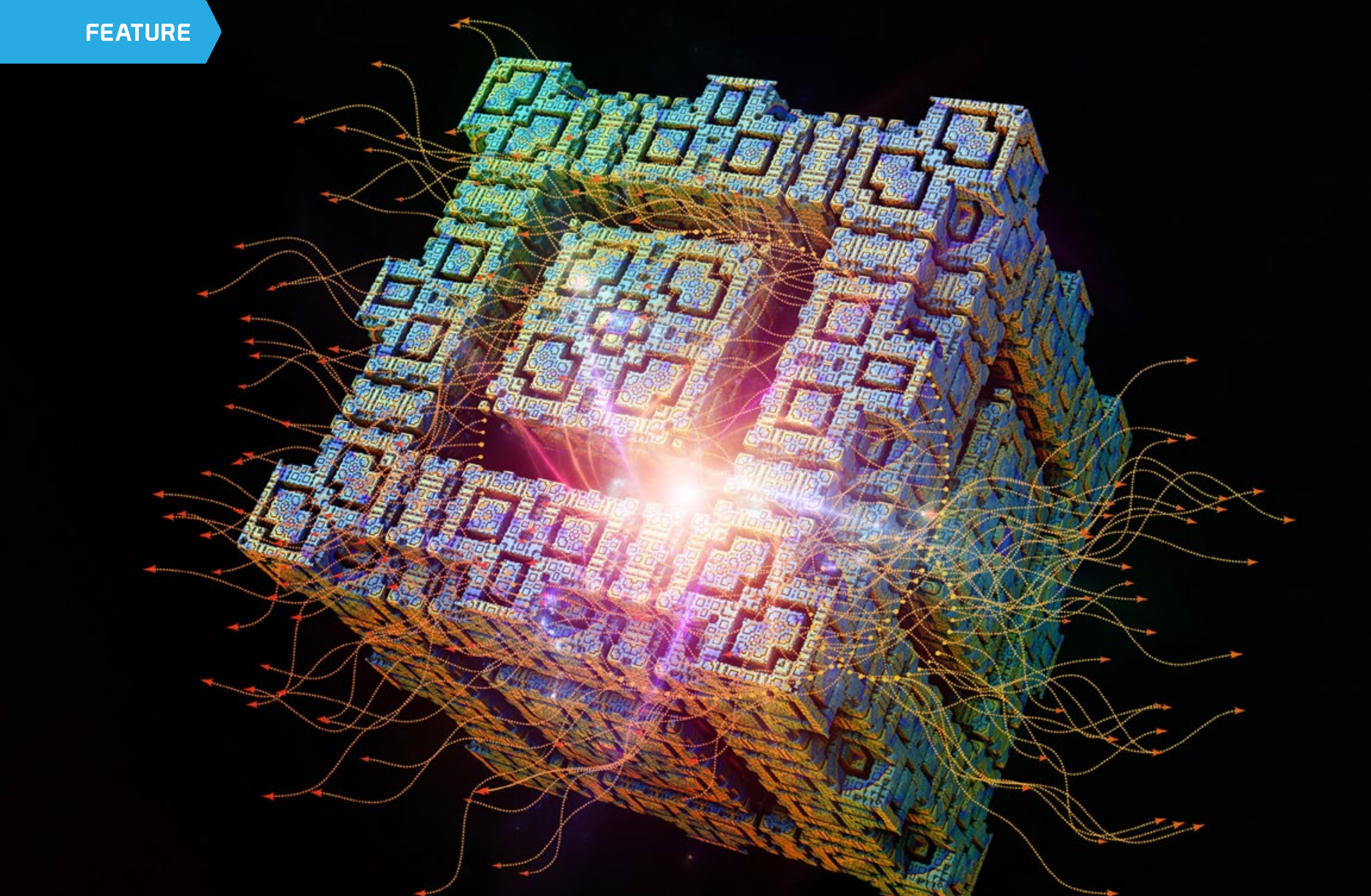
"Structural electronics needs to be designed into a structure such as a bus or a train when it is at the early conceptual stage. SE is often impracticable or too expensive as retrofit."

On the other hand, many challenges must be overcome if structural electronics is to fulfil its potential. Structural electronics needs to be designed into a structure such as a bus or a train when it is at the early conceptual stage. SE is often impracticable or too expensive as retrofit. Thin film, printed and other flexible forms of electronics are less efficient than bulk initially making it impracticable or too expensive to add more to compensate (e.g., more photovoltaics, supercapacitors or lithium-ion batteries). Flexible photovoltaics are much less efficient. Most forms of structural electronics will be costly, at least to begin with. Devices such as batteries that swell and shrink in use are difficult to contain in a structural material and when, after their relatively short life, they fail and need replacement, the whole structure will need to be replaced, probably uneconomically and costing much time and effort. Moving parts such as electric traction motors, internal combustion engines, fuel cells and pumped refrigeration are out of reach, at least for now.

In conclusion, 3D printed circuits are likely to become commercially available in 2015 and printers that can manufacture them are likely to become commercially available by 2018. Initial applications will include prototyping traditional PCB designs and embedded modular wiring inside 3D printed objects. Early adopters will include PCB designers, start-ups entering into areas like wearables and the Internet of Things and industries that manufacture their products in small volumes such as MRI scanners and the space industry. In the longer term, 3D printed electronics may well become a competitive solution to a broader range of problems but that will require a great deal of time and effort as the technology is embryonic today. Functional materials such as dielectrics and semiconductors may be directly 3D printable one day but existing technology is ready to make the substantial leap into a world of PCB islands in a 3D printed sea of conductive traces.

Discover how structural electronics will create a $97 billion market by 2025 in the new IDTechEx report [Structural Electronics 2015–2025: Applications, Technologies, Forecasts](). **PCB**

Dr. Jon Harrop is a director at IDTechEx.



# How 3D Printing Will Impact PCB Fabrication

**by Karl D.D. Willis, Ph.D.**
AUTODESK

There has been much talk in recent years about 3D printing, a type of additive manufacturing that has been used to create everything from plastic toys and trinkets to high-end industrial prototypes.

In the near future, we will enter an era where electronic devices "join the club" and are printed, rather than assembled. They will be fabricated layer-by-layer as a single object, rather than assembled from separate mechanical, electrical, and optical parts.

Unlike today's devices that house PCBs within a separate shell, 3D printing will enable electronics to be embedded entirely within the structure of the device itself.

Let's take a closer look at how we will get to this stage, and the implications it will have for PCB manufacturers.

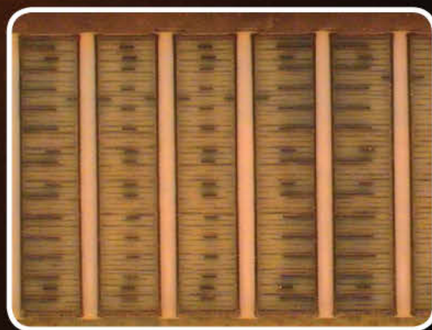
**Development No. 1: 3D printing Software**

When we talk about 3D printing, we're really talking about several different pieces of a puzzle: hardware (the 3D printer), software (used to prepare 3D models), and materials (the stuff that a printer is able extrude, jet, bind, cure, or sinter—plastics, ceramics, and other materials).

Autodesk's Spark is an open 3D printing platform that makes it easier for hardware manufacturers, software developers, materials scientists, product designers, and others to participate in and benefit from this technology. Spark encourages all members of the 3D printing industry to move additive manufacturing technology forward and push the boundaries of 3D printing.

**Development No. 2: Materials Innovation**

One of the key barriers for 3D printing has been a lack of innovation on the materials front. Fortunately, recent advances in materials science have enabled the combination of high-conductivity inks with standard 3D printing plastics.



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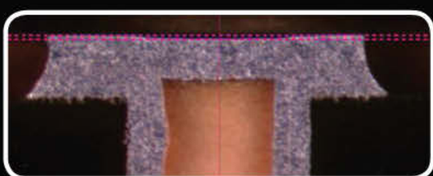

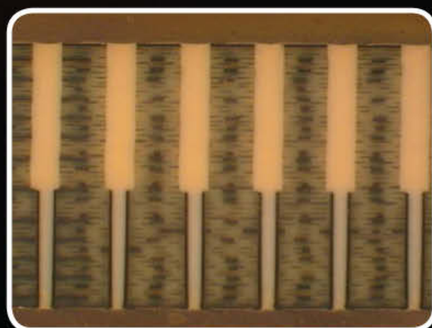

THP®-100DX1 (HTG)

Voxel8, a Massachusetts-based startup, has made intriguing progress in this area, bringing novel materials to 3D printing. Their materials allow them to print embedded conductors, wires, and batteries into the normal matrix materials of 3D printing.

This type of breakthrough means the design and fabrication of 3D circuits is now possible, with multimaterial 3D printers presenting a large area of opportunity.

The result? When you press "print," you can create not only the physical component of the object itself, but also the sensing component that allows it to sense its environment, take action, and do things. As the Internet of Things gains momentum and creates more and more connected devices, this type of ability becomes increasingly important.

> "Circuit prototyping can be done incredibly quickly. Even more exciting is the ability to design and fabricate circuits that were not previously possible."

### Development No. 3: New Design Tools

Despite these advancements in 3D printing and materials, numerous challenges remain, not least of which is how to design conductive circuits in 3D.

Until now, the software for designing 3D circuits for use with 3D printing simply did not exist. New tools currently under development will let designers create 3D circuits integrated into CAD models, providing electronics and 3D printing enthusiasts with the ability to place components, route 3D traces, and fabricate their devices using multi-material electronics 3D printers.

Circuit prototyping can be done incredibly quickly. Even more exciting is the ability to design and fabricate circuits that were not previously possible. Wires can be routed in three dimensions to make compact circuits in arbitrary 3D shapes, components can be embedded inside prints to create very robust devices, and each circuit can be customized entirely.

### Implications for PCB Manufacturers

Thanks to these developments, many of the building blocks for advanced functional 3D printing are already in place.

This means that PCB manufacturers will no longer manufacture the PCB and the housing as separate objects. Instead they will design and fabricate both 3D objects with structural circuits embedded within.

Disruption within the PCB manufacturing space is likely to occur on several fronts, starting with designers rapidly prototyping circuits that can also be made as PCBs. Some of these prototype cases include:

1) Rapidly prototyping PCBs using 3D Printing before doing a PCB run. These circuits will be designed in conventional 2D board layout software, but translated into machine instructions that allow 2.5D printing of circuits on the desktop.

2) Rapidly prototyping hybrid electromechanical 3D structures before breaking out the design into PCBs and mass-producible parts. Think of this as a printed wire harness embedded into the structure of your physical 3D model. Instead of manually connecting wires, robust printed connections can be made between a PCB and components, such as buttons, displays, and sensors.

Further disruption will occur through the creation of designs that cannot be made as PCBs. Some of these end-manufacture use cases include:

1) **Hearing aids.** Hearing aids are predicted to be a $3.2 billion market by 2020. Their resale price is $36,000/ounce; compare that to gold ($1,300/ounce) or the iPhone 4 ($132/ounce). These are highly integrated electronics in a bespoke shape, and they must be robust, small, and with embedded electronics. All of these factors make them a natural fit with the new developments in 3D printing.

2) **Cellphone antennas.** Advances in 3D printing mean that cellphone antennas can be integrated into the mechanical structure of the

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phone itself, making them compact, robust, and low in signal attenuation. The Lewis Research Group at Harvard University, where Voxel8 spun out from, has demonstrated considerable performance benefits for 3D antennas.

3) **Structural electronics.** According to a recent report by IDTechEx, structural electronics—essentially, electrical components and circuits that act as load-bearing, protective structures—is predicted to be a $97 billion market by 2025. That means a world populated with everything from smart bridges that have sensors embedded into the concrete, to buildings with integrated photovoltaics.

What these use cases show is that designers will be increasingly manufacturing intelligent integrated devices instead of components for a larger assembly.

To take another example, the Mimo Smart Baby Monitor, a onesie-based baby monitor that sends breathing, temp, and sleep data in real-time to a parent's phone. Mimo can allow parents to have a warm bottle of milk ready when the baby wakes up, instead of having to wait. Because of its design, it's able to provide a much faster feedback loop. This may be a simple example, but it also applies to other products where performance can be rapidly increased based on a signal being disseminated where it's needed.

"Mimo is a real-world case study of how a real product is benefiting from new manufacturing technologies. 3D printed electronics will push this benefit even further by decreasing iteration cycles."

Mimo is a real-world case study of how a real product is benefiting from new manufacturing technologies. 3D printed electronics will push this benefit even further by decreasing iteration cycles. Robust, functional circuits can be created together with the object itself, entirely in-house.

### Democratization of Technology

Products like the Mimo show how much an entrepreneur with a smart idea can accomplish now that technology around design and manufacturing has been democratized.

In the old days, someone trying to assemble all of the internal circuitry and all of the physical components of a new product would likely need to hire a contract manufacturer to do that for them. When you can quickly and easily accomplish the same thing with a printer, you've fundamentally changed the ability for a small entrepreneur to innovate, rapidly iterate prototypes, and produce a real product.

### Conclusion

The fundamentals of how we fabricate electronic devices are changing. The traditional approach—manufacturing discrete components and then putting them together into a larger assembly of things—is giving way to new fabrication methods like 3D printing.

A platform like Spark can help accelerate innovation around 3D printing, and more importantly, to serve as a platform for making things. It connects digital content to the physical thing, incorporating not just additive manufacturing or 3D printing processes, but subtractive manufacturing, robotics, and circuitry.

3D printing is going to merge with the underlying circuitry to create things that have their inner working parts—including all of the electronics—embedded within the physical object. And we think that's going to fundamentally change what kind of products and devices can be created.

With the proper platforms and building blocks in place, we are excited to see how innovation around electronic designs continues to unfold. **PCB**

Karl D.D. Willis is principal research engineer at Autodesk.

# 3D Printing PCBs

**by Simon Fried**
NANODIMENSION LTD.

For anyone familiar with 3D printing and PCBs, it's difficult to imagine a future where PCBs are not 3D printed. 3D printing promises to make PCB manufacturing faster, easier and more innovative. It is only recently, however, that printed electronics (PE) and 3D printing technology have started to catch up with imagination. 3D printing is now at the stage where it is going from a fun, interesting approach to a serious contender that will change industries.

## An Introduction to the World of 3D Printing

It's a topic that has been in the news a lot recently, yet 3D printing, or as it's more properly known, additive manufacturing, has been around as a process for quite some time. The bottom line is that additive manufacturing nowadays comprises a range of different competing processes, including those that use heat, lasers, inkjet deposition or other techniques to add different materials, layer by layer, to build new or to add to existing objects. Each process has advantages and disadvantages in terms of precision, materials, end-product durability and flexibility in terms of the objects and shapes that can be supported. As a rule, there is a correlation between price, resolution and range of supported materials.

But 30 years ago, things were different. In 1984, Chuck Hull of 3D Systems Corp. developed the stereolithography (SLA) approach. Here, UV lasers cure liquid photopolymers into solid objects. Imagine a container of polymer liquid where a laser beams down from above and solidifies the surface layer. After each laser pass, the object is lowered a little. Each solid layer is then added to until, in the end, a complete object has been built, from the bottom up.

At the high end of 3D printing, the SLA process is still going strong and has been joined by Stratasys's sophisticated "polyjet matrix," an inkjet-based technology. HP has recently announced that it is joining the fray with its own approach to inkjet additive printing.

The 3D printers that are making their way into people's homes are generally of the thermoplastic extrusion kind. This approach generally involves a reel of plastic thread being heated and delicately squeezed into place. Some say

this can't technically be called printing, but is certainly bona fide additive manufacturing.

3D printing isn't just about printing plastic objects. The industrial uses for 3D printing are constantly expanding. There is a great deal of R&D dedicated to the materials that 3D printers can use. 3D printers are now printing or repairing fully functional mechanical and structural parts using a range of metals, alloys and ceramics. Biological structures are also printable using polymer and organic materials for body parts or pharmaceuticals. Large printers can print houses and developments in nanomaterials that allow 3D printers to print incredibly small objects just microns in size. However, it's not all serious. People are having a lot of fun with their 3D printers, printing chocolates, cakes, pottery, pizzas and candy.

In the end, it's clear that adopting 3D printing is essentially a question of deciding on the right additive printing process and developing printable materials that meet the requirements of the final product.

"There is no shortage of folks that want to 3D print electronics. Firstly, printers have to be able to print conductive traces, which is the domain of PE. This an advanced technological area in its own right that involves the development of conductive materials suited to a range of different substrates. Basic connections can be embedded in objects by 3D extrusion printers using conductive filaments."

### What Does it Mean for Electronics and PCBs?

There is no shortage of folks that want to 3D print electronics. Firstly, printers have to be able to print conductive traces, which is the domain of PE. This an advanced technological area in its own right that involves the development of conductive materials suited to a range of different substrates. Basic connections can be embedded in objects by 3D extrusion printers using conductive filaments. These contain conductive polymers, carbon nano-tubes or other conductive materials. The end result, using current technologies, is a low-resolution, point-to-point conductive trace that struggles to cope with the electrical requirements of professional circuits—fun for hobbyist printers of 3D objects.

For higher resolution and acceptable conductivity, more advanced printing solutions are required. The materials development world is abuzz with R&D for all manner of new materials and formulations across the whole gamut of 3D printing processes.

Inkjet and aerosol PE are turning to nano-inks. The nano-ink industry is currently providing formulations to meet this challenge in the form of various silver nano-particle inks. These inks are suspensions of nano-meter-sized silver particles that, after printing, need to be cured either chemically, or by light or heat. Once cured, the particles coalesce to form a conductive solid silver trace. The technology is now developed enough that silver nano-particles are emerging as a mature technological solution to printing electronics. That is not to say that all silver nano-particle inks are the same, nano-ink development itself is a very advanced field. Silver may be an expensive metal to use, but given that traces are so fine, not much is needed. The performance justifies the cost. Copper ink would be clearly preferable from a cost perspective but copper ink is not currently a mature enough technology. Copper is much harder to print with, because oxidation issues mean that the ink isn't as easy to make or use and the end results are not robust. Carbon nano-tubes and other exotic materials may well offer alternatives in the future also.

Are any companies actually printing PCBs? The ability to quickly print a two-sided PCB would certainly make life easier for many. Being able to say goodbye to etching and the myriad other stages required to quickly make a PCB at home would put a smile on anyone's face. These smiles are about to break out with the upcom-

ing launches of two new PCB printers. Voltera is a U.S.-based start-up that is about to launch a printer that prints conductive traces onto standard FR-4 substrates. Voltera's system can print 10-mil traces on both sides of pre-cut FR-4. Similarly, an Australian start-up, Cartesian Co., having completed a successful Kickstarter campaign, is preparing to launch a printer that also prints two-sided PCBs with similar trace specification to Voltera. Both of these companies aim to support a wide range of substrates including paper, textiles and plastics. So there certainly are companies launching PCB printers.

It is important to point out that printed electronics does not equal 3D printed electronics. By 3D printing standards, however, the world of proper multi-layer PCBs is a complex one. To 3D print electronics requires additional materials and different equipment. High-quality conductive traces are a must but so are three-axis capable printers and insulating structural ink.

On one hand PCBs are multilayered, which implies they are well suited to additive manufacturing. On the other hand, the multiple materials, conductivity requirements and exacting precision required present serious technological challenges.

What is the current state of truly 3D PCB printing? There are two types of 3D printing technology that can be expected to rise to the challenge. Optomec of Minnesota uses aerosol jet technology which is a bit like a super precise spray can. This approach allows for very precise printing of conductive inks, such as that for cell phone antennas. It is an approach that can print onto any geometry/shape but isn't currently being extensively used for printing the substrate itself.

Inkjet deposition is likely to be the first truly 3D printing process to provide professional multi-layered PCBs. To rise to the challenge of making proper multi-layer PCBs the conductive traces clearly have to be printed in such a way that they are precise enough, conductive enough and robust enough to do the job reliably.

“It is important to point out that printed electronics does not equal 3D printed electronics. By 3D printing standards, however, the world of proper multi-layer PCBs is a complex one. To 3D print electronics requires additional materials and different equipment. High-quality conductive traces are a must but so are three-axis capable printers and insulating structural ink.”

Having solved the printing of advanced inks to give precise conductive traces, the next step in order to 3D print a PCB is to print the substrate. For traditional rigid boards the substrate ink material needs to be inkjet printable as well as an excellent insulator and offer rigidity that is comparable to standard FR-4. Flexible boards are another field and require a different combination of substrate and conductive ink formulations. Each substrate requires its own ink specifications to ensure adhesion, precision and compatibility with the relevant ink curing stage.

If nano-materials can be engineered to meet the requirements of a PCB, the next challenge is how to manage the printer. The software has to be able to process Gerber files which are intended for a 2D manufacturing environment. This would allow the 3D printer to print the substrate to the required thickness, leave and fill holes where vias are required, and so on.

The only company currently dedicated to 3D printing complete multi-layer rigid PCBs is NanoDimension. Listed on the Tel Aviv stock exchange, the company is developing a 3D inkjet printer that will offer in-house rapid-prototyping of professional multi-layer PCBs. To this end, the company has formulated and makes its own nano-inks for the conductive trace and another proprietary nano-epoxy ink for the insulating layer. The company promises a trace width of 3–4 mils.

It is early days for the 3D electronics revolution, but it's clearly coming. If all of these elements, printer, inks, and software come together there is no reason that PCBs shouldn't be 3D printed. 3D printing can lead to dramatically faster in-house development, protect IP in development and maybe even inject a little more design innovation and creativity. As is the case in other industries, it is unlikely that 3D printers will replace efficient mass-production processes anytime soon. For prototypes and very small-batches, however, 3D printing may be just around the corner. Being able to print a prototype HD multilayer board in-house would certainly be a welcome development for many companies, both big and small.

Industrial scale 3D printing of a multilayer PCB is another matter. Mass production of PCBs by additive manufacturing won't be a reality for quite some time. It's probably as much as a decade away at least, if at all. Discrete stages of the PCB manufacturing process can be 3D printed however. Industrial digital printing of photoresist (Mutracx) is here today, as is 3D printing of solder mask (Camtek's Gryphon).

3D printing will likely affect the world of PCBs as it has other areas. First printers will deliver in-house prototyping solutions that change the way products are developed and, in the mid-term, 3D printing will begin to replace discreet stages of mass production. Whether 3D printing will completely replace traditional manufacturing processes remains to be seen. There are those that dream of a 3D printer that can print multi-material objects with completely embedded HD circuits and no traditional PCB at all. **PCB**

Simon Fried is VP, director & co-founder of NanoDimension Ltd.

## VIDEO INTERVIEW

### Two European Industry Giants Discuss Cooperation in China

***by Real Time with... HKPCA 2014***

I-Connect007 Guest Editor Bob Neves interviews Rex Rozario and Giovanni Tridenti about their collaboration in China with the formation of DSG in 2007.



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# Electronics Industry News
## Market Highlights

### [Global OE Market to Grow $75.82B in Coming Years]
The organic electronics market is expected to grow from $16.45 billion in 2014 to $75.82 billion by 2020 at a CAGR of 29%. This growth is heralded by the growing display applications for organic electronics market. The lighting applications for this market are also expected to grow rapidly in the coming five years.

### Top 20 Global Semiconductor Sales Ranking for 2014
The top 20 worldwide semiconductor sales ranking for 2014 includes eight suppliers headquartered in the U.S., three in Japan, three in Europe, three in Taiwan, two in South Korea, and one in Singapore, a relatively broad representation of geographic regions.

### Smart Grid Infrastructure Gets $13.6B Investment from SEA
"Smart grid investment over the next decade will shift from North America and Europe to emerging market regions," said Ben Gardner, president of Northeast Group. "Southeast Asian countries are just beginning on the path of modernizing their electric infrastructure."

### Industrial Internet Sensors to See $20.1B in Revenue
In a newly released report from NanoMarkets, the firm predicts the value of Internet-connected sensors for industrial applications is expected to grow to $20.1 billion by 2019. This report also identifies and quantifies where the opportunities are for makers of these sensors and provides eight-year forecasts for a variety of industrial sensors types.

### Power Electronics Market Outlook Shows 9.6% CAGR
The Global Power Electronics Market 2014–2018 research report forecasts the industry to grow at 9.6% CAGR during 2013–2018. The global power electronics market can be segmented into five end-user segments: commercial, industrial, consumer electronics, transportation, and others.

### Wearable Technology to Continue Evolution
New research shows that wearable technology will evolve beyond its current ecosystem, which is very dependent on smartphone integration. New business models will develop that place wearable tech at the center of communications, applications, content, and commerce without the need for handheld devices of any type.

### APAC to Retain Growth in Nanotech-enabled Printing
BCC Research reveals the global market for nanotechnology-enabled printing technology is expected to grow at a projected CAGR of 17.7% over the next five years to total $31.8 billion by 2018. The Asia-Pacific region is the largest buyer of printing technologies and will retain growth through the forecast period with 17.3% CAGR and reach revenues of $20.2 billion.

### Bluetooth Low Energy Dominates Wearable Connectivity
"Wearables are about the quantified self, more than likely, communicated via Bluetooth to a smartphone to view the results and then possibly from there to a cloud-based service for aggregation and further analysis," states Nick Spencer, senior practice director, Mobile Devices at ABI Research.

### Critical Innovation Stage to Drive Cloud Services Market
Public IT cloud services spending will reach $56.6 billion in 2014 and grow to more than $127 billion in 2018, according to a new forecast from International Data Corporation (IDC). Among the factors driving public IT cloud services growth is the adoption of "cloud first" strategies by both IT vendors expanding their offerings and IT buyers implementing new solutions.

### 3D Printing Materials Market to Grow Significantl
The 3D printing materials market is expected to grow significantly in the next few years, due to high demand for 3D printing technology in various industries such as electronics, consumer products, automotive, aerospace, and medical.

COLUMN

KARL'S TECH TALK

# Signal Loss

**by Karl Dietz**
KARL DIETZ CONSULTING LLC

Signal loss (attenuation) in transmission lines can have a variety of causes[1].

- Radiative loss
- Coupling to adjacent traces
- Impedance mismatches
- Conductor loss
- Dielectric loss

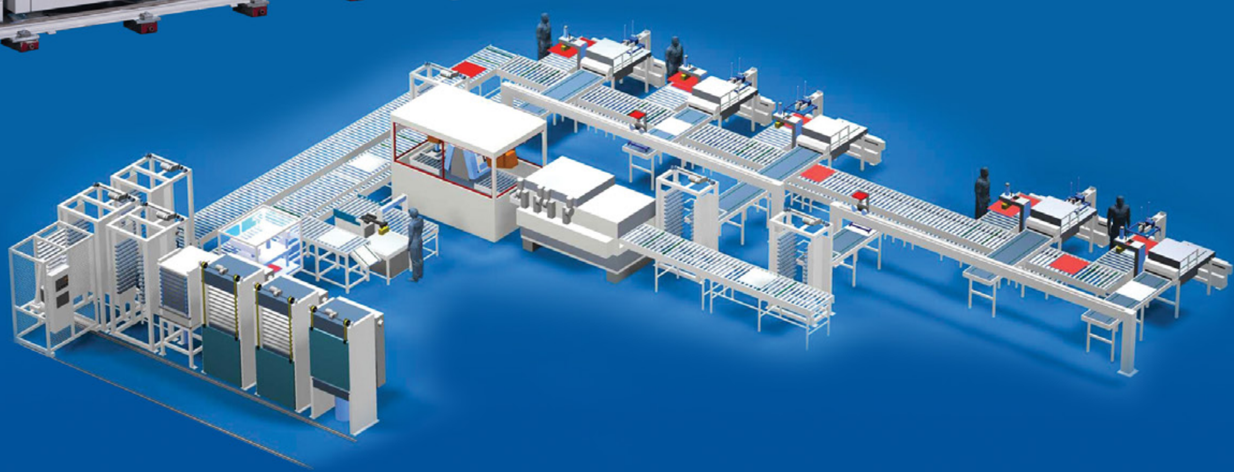
According to Reference 1, radiative loss is only a small component of loss contributors. Coupling to adjacent lines, on the other hand, can cause signal rise time degradation. It can be modeled quite accurately and proper circuit layout can minimize it.

## Impedance Discontinuities

Impedance discontinuities (i.e., variations or changes) along the transmission line cause signal degradation. The cross section of the conductor should not change along the transmission line. Such changes affect the impedance. They can be caused by plating height variation, or etch non-uniformity, or localized imperfections such as conductor "dish down" or "mouse bites."

Less understood is the change of the properties of the dielectric that contributes to impedance mismatch, namely the dielectric constant. Typical dielectric structures are glass weave, reinforced epoxy resins. Both the dielectric constant of the resin as well as that of the glass are bulk properties of the materials and are quite constant throughout the material. The dielectric constant of FR-4 resin is about 3.2 and the dielectric constant of glass is about 5.6. Since the glass weave reinforcement has a pattern, there are glass-rich and glass-lean domains in the dielectric. Therefore there are domains of higher and lower dielectric constant surrounding the signal path, which means the impedance changes along the signal path (i.e., there


BÜRKLE



are impedance discontinuities). If a transmission line runs parallel, and on top of a glass fiber strand, or along a resin-rich area between glass fibers, then the dielectric environments of these two lines are noticeably different, which unfortunately is the case most of the time as laminate is sheared parallel to the weave pattern, and conductor lines tend to run in the same direction. Angling the transmission lines relative to the weave pattern will improve the situation by randomizing the glass/resin concentration differences along the transmission path. References 2 and 3 have studied this problem area.

### Conductor Loss

Metallic conductors are characterized by their ability to conduct current, or the reverse—their resistivity. These resistivities can vary significantly. For example, the resistivity of copper is a low 1.7 µΩ.cm, whereas nickel has a resistivity of 7.4 µΩ.cm. Conductors with low conductivity cause high conductor loss. Conductivity is proportional to the conductor cross-section area and is inversely proportional to the resistivity. However, this is only a first approximation for the following reasons:

- A D/C signal is uniformly distributed through the conductor, as is the signal of a low frequency A/C signal. However, as the frequency of an A/C signal increases, the signal travels preferentially near the surface of the conductor, a phenomenon known as the skin effect. Thus, the effective conductor cross section for high-frequency A/C signals is the "skin depth," not the entire cross-section area. Skin depth is inversely related to the square root of the frequency, the material permeability and the material conductivity.
- Since the copper of the transmission lines are typically covered with a material other than copper (in the case of outer layers a final metal surface finish, and in the case of innerlayers a multilayer bonder), we must ask ourselves in which way do these materials affect conductor loss? This depends on their resistivity and the thickness of the coating. If we look at different final finishes that are in use, we note the following resistivities: Ag=1.6 µΩ.cm, Cu=1.7 µΩ.cm, Au=2.4 µΩ.cm, Ni=7.4 µΩ.cm, Sn=10.9 µΩ.cm, Sn/Pb=17 µΩ.cm, and electroless Ni (containing phosphorus)=55-90. This issue was addressed in the study of Reference 4. The author came to the conclusion that a thin deposit of immersion silver has no detrimental effect on conductor loss. electroless nickel/immersion gold (ENIG), on the other hand, worsens conductor loss which can become an issue with long transmission lines that are found on backplanes.
- A contributor to conductor loss can be the topography of the conductor. Conductors with rough surfaces are lossier than smooth conductors. This effect becomes more pronounced at high frequencies. References 5 and 6 have investigated this problem.

> "An ideal insulator, or dielectric, would not have any conductivity and would not attenuate the signal strength. However, due to the material properties of the insulating material, there is some dielectric loss, or loss tangent, or dissipation of the material (dissipation factor)."

### Dielectric Loss

An ideal insulator, or dielectric, would not have any conductivity and would not attenuate the signal strength. However, due to the material properties of the insulating material, there is some dielectric loss, or loss tangent, or dissipation of the material (dissipation factor). The end result is a leakage current through the dielectric that contributes to signal loss. The bulk A/C conductivity of a dielectric, according to Ref. 1, is a function of the signal frequency, the permittivity of free space ($E_0$), the relative dielectric constant ($E_r$) or dielectric constant for short, and the dissipation factor (or loss tangent) of the material. The dielectric loss is basically caused by the dipoles present in the insulating resins. When polymers have covalent bonds between different atoms (e.g., a bond between oxygen and carbon), these two atoms have what's called different electronegativities, which means that the electrons of the covalent bond are not equally shared by the two atoms. The atom with the higher electronegativity tends to attract more than 50% of the shared electrons, causing a partial negative charge on the oxygen, and a partial positive charge on the carbon. This (partial) separation of charges forms what is called a dipole, comparable to a magnet with its positive and negative poles. If these dipoles are exposed to an electromagnetic field, as is the case in a conductor surrounded by a dielectric, the dipole will line up in the direction of the electromagnetic field lines, assuming they have the mobility to do so. If the electromagnetic field flip-flops, as is the case with A/C current, the dipoles reverse direction (i.e., they flip-flop too). This flip-flopping of the dipoles in the dielectric basically amount to an A/C current flowing through the dielectric, the so called leakage current. As the signal frequency goes up, the dipoles switch faster, increasing the leakage current, but ultimately there are some spacial constraints to this motion and the dipoles may not be able to keep up. This is the cause of the frequency dependency of the dielectric loss. Given the factors that contribute to the bulk A/C conductivity of a dielectric (see above) we'd like to choose a dielectric with a low dielectric constant and a low-loss tangent. Such dielectrics either have no dipoles, or they have very weak dipoles in the polymeric structure, or they have dipoles with little mobility. As it turns out, low dielectric constant and low-loss tangent go hand in hand. Thus, we notice that polymers with a low dielectric constant such as PTFE (poly-tetrafluoroethylene) or hydrocarbons also have a low loss tangent. Unfortunately, they also tend to be more expensive that the higher dielectric constant and higher loss tangent epoxies. **PCB**

"If the electromagnetic field flip-flops, as is the case with A/C current, the dipoles reverse direction (i.e., they flip-flop too). This flip-flopping of the dipoles in the dielectric basically amount to an A/C current flowing through the dielectric, the so called leakage current."

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COLUMN

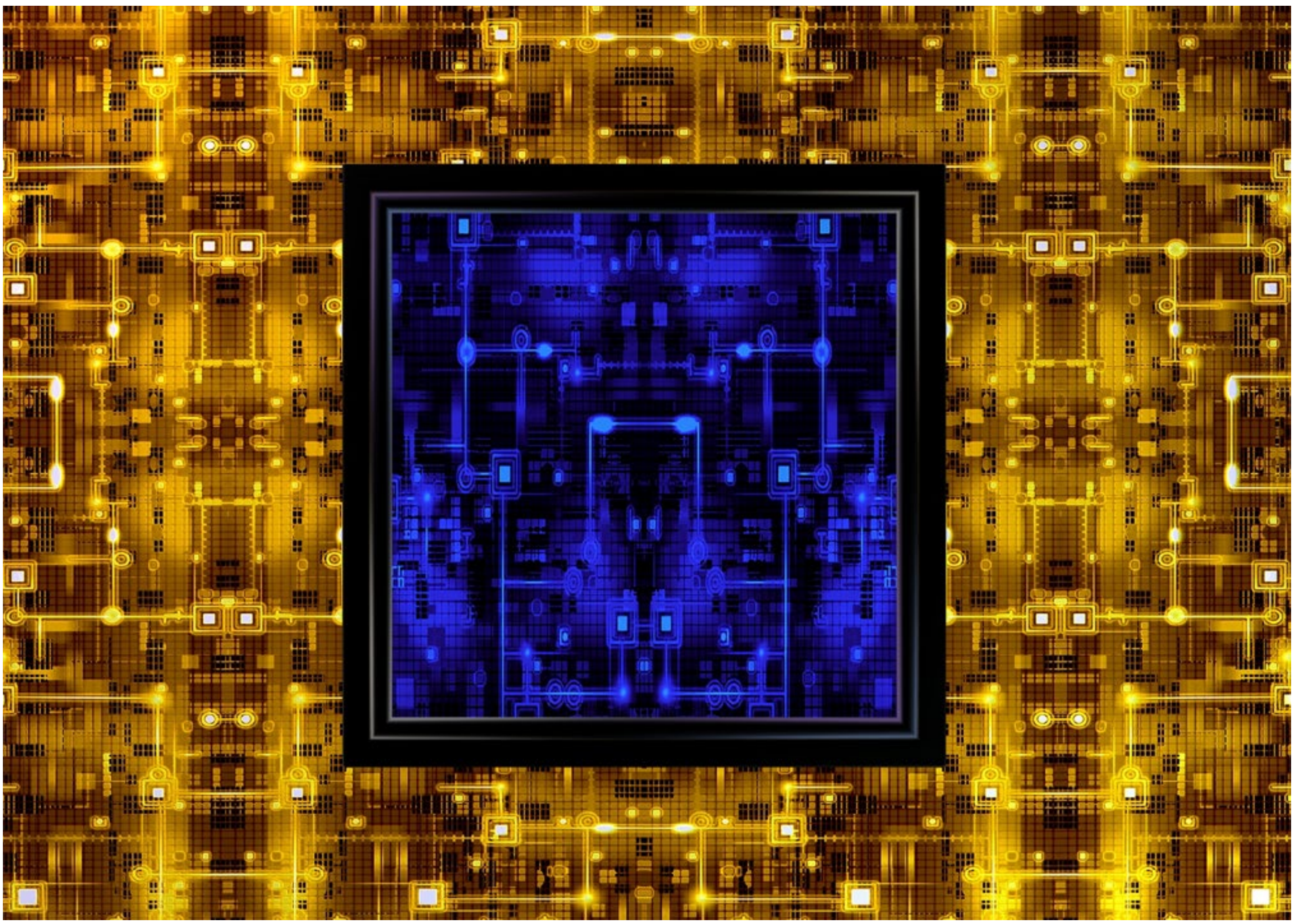
TROUBLE IN YOUR TANK

# Fine Lines and Spaces with Half-Etch Processes

**by Michael Carano**
OMG ELECTRONIC CHEMICALS

## Introduction

It is all about circuit density. If your customer or customers are pushing the envelope with respect to greater circuit densities, how are the fabricators adapting to these requirements? I do not want to oversimplify the task at hand, but there are a number of things one can do to improve the yields on finer lines. These include laser direct imaging, semi-additive processing, use of ultra-thin foils, and special processes. Another and perhaps lesser known application is termed "half-etch." Here the fabricator utilizes a specially formulated copper etching process to remove a minimal amount of copper. The goal is to remove the copper uniformly, but not completely from the surface as is performed during the final etch-process step. For example, by reducing 1 ounce copper foil (35 microns) down to ½-ounce or ¼-ounce, one maintains the adhesion of the original foil. In addition, the fabricator is presented with a much thinner substrate foil that can be easily etched during the final etch process. There are several good reasons for this approach:

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**FINE LINES AND SPACES WITH HALF-ETCH PROCESSES** *continues*

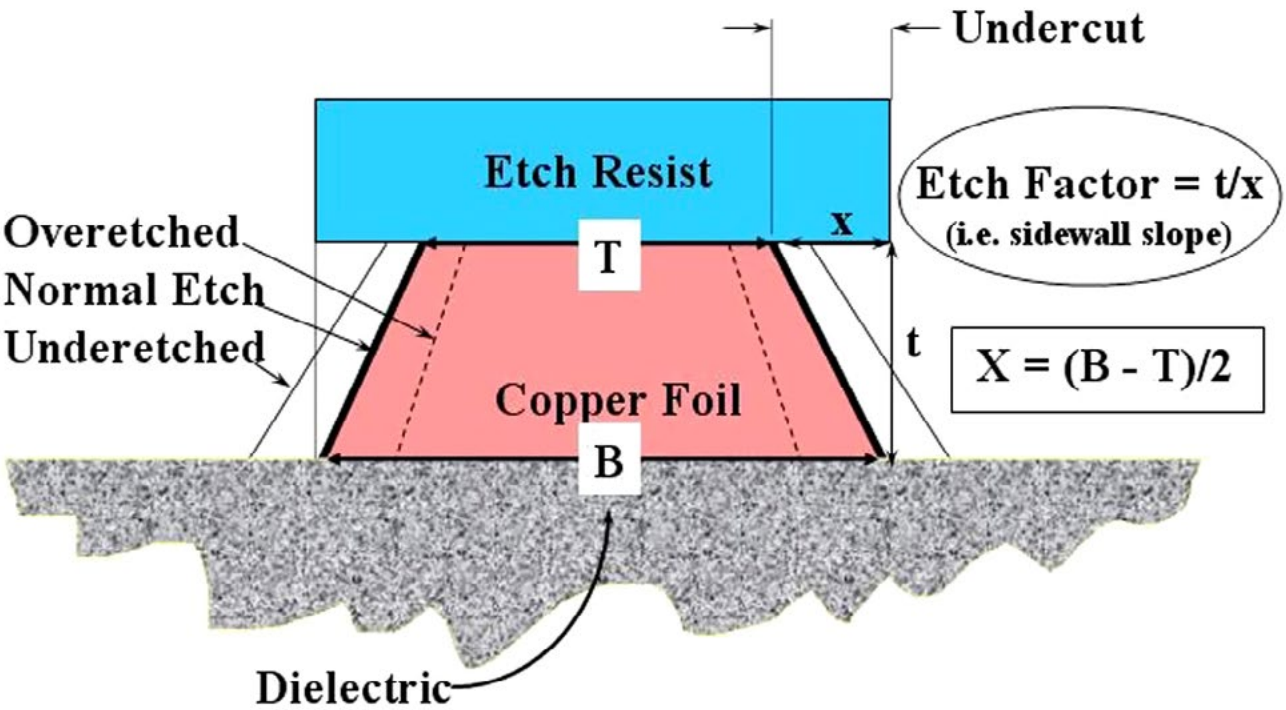



Figure 1: Example of etch factor and undercut. (Source: Dr. Karl Dietz)

1. Minimization of undercut and increase of fine line yields (Figure 1)
2. Ease of handling as opposed to working with ultra-thin copper foils
3. Adhesion of the half-etched foil is usually greater than the adhesion of the ultra-thin foil to the resin materials as well as the plated copper in the SAP (semi-additive process).

In subtractive etching, as the copper is etched down, there is lateral removal of the copper as well.

If one can minimize the amount of copper foil that must be etched (either through thinner copper foils, semi-additive processing, copper foil half-etch) undercut can be minimized and finer lines and spaces achieved.

It is well understood that the three most fundamental metrics of organic interconnections and substrates are imaging feature sizes, hole formation technology and size, and the plating types and thicknesses used for interconnections. These same parameters have been used for nearly four decades to quickly quantify the capability of a fabricator to profitably produce traditional boards. The ability to image conductor lines and, perhaps even more important, the insulating airspace between them, is considered a key characteristic. With surface mount components, a dramatic decrease in plated via hole diameter requirements occurred and, as a result, via holes have become simple vertical interconnections. Now, under competition from laser drilling, both drill bit and machine technology have driven mechanical holes' capability much smaller. When microvia technology was introduced in the mid-1990s, high-density interconnect really took hold into the mainstream of printed circuit fabrication.

### But What About Fine Lines?

True, the via, whether blind or through-hole, is critical for the board design. And with HDI technology leading the way to increased routing density, finer lines and spaces are required. While there are several means to achieve finer lines and spaces, the author will present the half-etch process for this month's Trouble in Your Tank.

| Test Parameters | Process Targets | Test Results |
|---|---|---|
| Reducing 25 boards from 12 µm to 3 µm | Residual layer thickness 3 µm ± 0.6 µm | Minimum: 2.6 µm |
| | | Maximum: 3.4 µm |
| Evaluation of the results on the basis of 1,250 measuring points | Cp related to 3 µm ± 20 % > 1 | Average: 3.0 µm |
| | | Standard deviation: 0.16 |
| | | CpK at 3 µm ± 20 %: 1.18 |
| | | Cp at 3 µm ± 20 %: 1.27 |

Table 1.

### Half-etch Process

This really is the drive for sub-35 micron lines. And the half-etch process is one way to achieve this goal. The basic concept of half-etch is to remove a set amount of copper from the surface in as uniform a fashion as possible. By etching the copper foil down to a lower thickness, the etch factor and resulting undercut are greatly reduced. Consequently, minimal copper is lost from the circuit trace. To ensure this operation is successful, both chemistry and equipment configuration designs are critical. First and foremost, etching chemistry should etch down in the Z-axis as fast as possible. Secondly, the etching equipment must be designed to move the solution across the copper foils uniformly.

With respect to the half-etch process, the etching chemistry should be designed to remove the copper in a controlled fashion, imparting minimal roughness to the remaining copper. I have found that the desired etch rate on the copper foil (whether HTE or ED foil) for the half-etch process is 0.10–0.25 microns per second (4–10 microinches per second, or 240–600 microinches per minute). One can achieve higher etch rates if desired. However, there needs to be a balance between chemical consumption, etch equipment compatibility and overall process control. Removing copper too fast could cause the heat to rise in the etching chamber. In addition, it is beneficial to process the innerlayer foils through an acidic cleaner that will remove chromate and mild soils prior to actually etching the copper. This helps to ensure a clean virgin copper surface that permits the etching chemistry to remove copper uniformly.

### Results

In Table 1 the results of production runs at a large volume fabricator are listed. The objective is to reduce the thickness of 12 micron copper foil to three micron. As shown, the results are consistent and uniform. The data points are gathered over several production shifts each week.

### Equipment

Equipment capability is a key part of process of half-etching. And the etching equipment must continue to evolve in order to improve quality and reduce labor costs. Horizontal etching equipment used for half-etch must prevent "puddling" on the top side of the layers. Failure to prevent puddling will lead to more copper being etched from the top side than the bottom.

### Summary

Half-etch technology is production proven in meeting high density circuitry requirements. Thinner copper is effective in achieving sub-35 micron lines and spaces due to the total copper thickness that must be etched. **PCB**

Michael Carano is with OMG Electronic Chemicals, a developer and provider of processes and materials for the electronics industry supply chain. To read past columns, or to contact the author, click here.

# PCB007 Supplier/New Product News Highlights

### Orbotech to Supply Direct Imaging System to Red Board

Orbotech Ltd. announces Chinese PCB manufacturer Red Board Ltd. has selected its latest direct imaging (DI) system, the Nuvogo 800, to increase productivity and accuracy in the production of its high-density interconnect (HDI) PCBs for mobile phones.

### Camtek's Gryphon Completes Beta Testing at Eltek

Camtek Ltd. announced today that its 3D Functional InkJet Technology system for PCB solder mask applications, known as Gryphon, successfully completed a beta testing phase at Eltek Ltd.'s site in Israel.

### Graphic PLC Selects Ucamco's Integr8tor

Graphic selected Ucamco's Integr8tor system for the quality, stability, reliability, and accuracy of its results, and for its compatibility with Graphic's existing Orbotech systems environment.

### Eurocircuits Purchases Ledia 5S DI from Ucamco

Eurocircuits, a leading European PCB prototype manufacturer, has purchased a Ledia 5S direct imager for its manufacturing facility in Eger, Hungary from Ucamco. Luc Smets, managing partner at Eurocircuits, explains, "We need state-of-the-art equipment to follow the rising demand of our customers, both in complexity and variety of orders. The Ledia will help us achieve our goal."

### ACE Adds Isola's Astra & I-Tera to Materials List

Accurate Circuit Engineering (ACE) is proud to announce the addition of Isola's Astra and I-Tera laminates to their list of standard materials. After extensive testing and several successful builds, ACE is pleased to add these lower cost replacements of many high-cost RF materials to their long list of standard laminates.

### Murrietta Circuits Debuts eSurface Line at Open House

With over 100 guests present at last week's open house, Murrietta Circuits unveiled its new eSurface Technology enabled line with startling results. The event successfully showcased the technology by running boards through its new eSurface-enabled line showing the attendees for the first time circuits boards with 2 mil lines and spaces in just a matter of minutes.

### Mentor: PCB Technology Leadership Award Winners

Continuing its tradition of promoting and recognizing PCB design excellence, Mentor Graphics Corporation has announced the winners of its 25$^{th}$ annual PCB Technology Leadership Awards. Started in 1988, this program is the longest running competition of its kind in the electronic design automation (EDA) industry.

### Atotech Unveils High Throwing Power Electroless Copper

Printoganth MV TP1 is Atotech's answer to increased electroless copper throwing power requirements of the IC substrate industry. The newly developed electroless copper bath provides highest throwing power (TP) into blind micro vias (BMVs) and especially into their wedges.

### Optiprint Employs Orbotech's NuvogoTM 800 DI System

After qualifying several relevant solutions, Optiprint found that the Orbotech's NuvogoTM 800 DI system best matched its strict production requirements. Optiprint specializes in the production of high-frequency, flexible, and flex-rigid boards. The company is also known for their specialty products including ultra-fine line boards, metal core multilayer, metal inserts, and more.

### Enthone Shanghai Earns ISO 14001, OHSAS 18001

The company's Shanghai Technical and Manufacturing Center recently received certification to ISO 14001 and OHSAS 18001 through the BSI. Bob Haskins, senior VP and Regional managing director, said, "We continue to be are focused on creating value for our customers through accelerated product innovation that addresses existing and emerging application requirements, operational execution, technical leadership, and industry expertise."

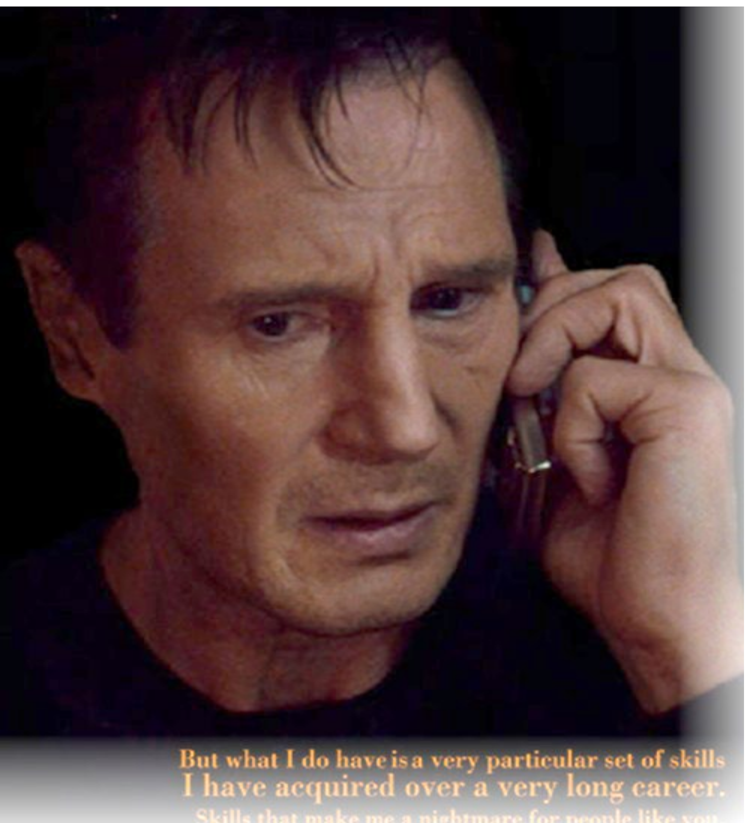
# Steve's Particular Skill Set for Today's Quality Professional

**by Steve Williams**
STEVE WILLIAMS CONSULTING LLC

In today's business environment, a top-quality executive in any organization needs to have a hybrid skill set that crosses many functions outside of quality: sales, marketing, operations, conflict resolution, human resources, and finance. It is a rare and unique person who can do all of this, well.

### Steve's Particular Set of Skills

One of the most important decisions a quality organization can make is the selection of its leader. This person will most likely be the face of the company with customers, suppliers, and your ISO registrar as the organization's ISO management representative. To differentiate yourself as a world-class organization, the skill set of your senior quality professional must go way beyond the requisite technical competencies called for in the job description.




In this column, I will be sharing with you a very particular set of skills—skills I have acquired over a lengthy career. These skills will make you a nightmare for any auditor looking to slap you with numerous findings. A person with this skill set will be able to elevate your organization—from the middle of the pack to the rarified air of the exceptional.

(As a side note, after seeing his 2008 blockbuster movie "Taken," I called my friend Liam Neeson and gave him hell for stealing my skill set quote for his Bryan Mills character!)

### My Particular Set of Skills

***1. Charismatic leadership***

The reason most quality systems fail is the lack of employee buy-in. The ability to successfully promote and sell the vision is the difference between success and failure.

***2. Political savvy***

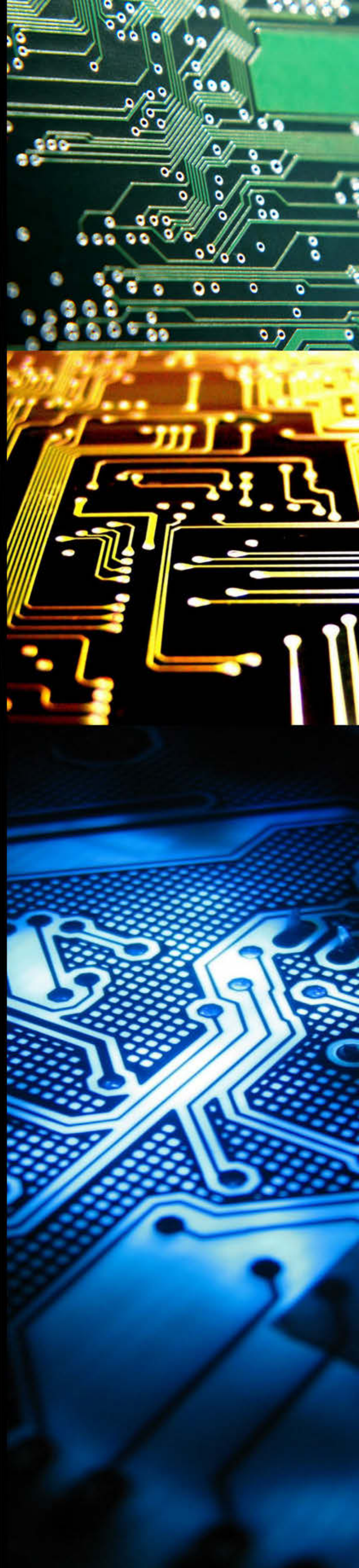
Politics are present in every organization; the key is to recognize it and manage it accordingly. Political crosscurrents will often distract and roadblock efforts to change the status quo.

***3. Sense of humor and the knack to know when to use it appropriately***

Humor works! Whether to defuse an uncomfortable situation, sell an idea or simply to add some levity to a tedious working session, the proper use of humor is priceless.

***4. Practical business sense***

With apologies to my good friend Phil Crosby, quality is NOT free. Any change to an exist-



ing system must fit and complement the overall organization's business practices.

***5. Marketing mindset***

Marketing is everyone's job. The quality leader should take every opportunity to sell the company's strengths and capabilities to both external and internal customers.

***6. Innate understanding of human nature***

People are creatures of habit and naturally resistant to change. Recognizing and managing this appropriately through the change process is critical.

***7. Ability to convert tribal knowledge into a sustainable system***

A company's black magic needs to be uncovered and incorporated into the system to avoid losing decades of experience, knowledge and know-how. The failure to capture this has resulted in more than a few catastrophic fails in companies that thought they were smart by offering early retirement to their most senior employees.

***8. Personality that fosters trust and confidence***

When making hiring decisions, personality is often undervalued. People have to trust their leader; as my favorite college professor John Houseman once told us, "We gain trust the old fashioned way: We earn it."

***9. Ability to motivate a workforce***

Once the workforce buys in to the change, it must be implemented and most of the work will need to be done by others. Typically, you either have this skill, or you don't; it is not a learned behavior.

***10. Cost/benefit mentality***

Understanding that every business process change has a cost, and the ability to do a cost/benefit analysis assures you are not spending a dollar to save a dime.

***11. Capacity to remain calm under extreme pressure***

This is the life of the quality professional; extreme pressure from all directions. Never let them see you sweat!

***12. Big picture vision***

This is critical not only from an organizational standpoint, but also from a customer perspective. With an irate customer, sometimes it truly is better to lose the battle in order to win the war.

***13. Motivational skill that inspires the best from others***

Take a lesson from my high school teammate Michael Jordan; as insanely good as he was, his team never accomplished anything until he learned to get the best out of everyone playing alongside him.

***14. Lean approach to continuous improvement***

It's OK to take baby steps; continued small incremental improvements will drive lasting improvement more than a few sporadic big-ticket gains.

***15. Talent to identify drivers of operational improvement***

The quality leader must have the ability to see how all moving parts of the company fit together and mesh, to be able to support overall operational improvement and drive change in the right areas.

In our business, what is emerging is a step-change in quality thinking and practices that clearly has an impact on the role of the quality professional. Today's quality leaders must look outside their own traditional sandbox and be their organization's champions in transforming to a culture of improvement, which requires *a particular set of skills.* **PCB**

Steve Williams is the president of Steve Williams Consulting LLC and the former strategic sourcing manager for Plexus Corp. To read past columns, or to contact Williams, click here.

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## News Highlights

### ACE Recertified as Northrop Grumman Preferred Supplier
ACE has held this prestigious certification for the last five years and is extremely honored to have again been certified by NGC's Supplier Quality Team.

### Eltek Suffers from Defense Sector Decline
Yitzhak Nissan, chairman of the Board and CEO, commented, "Eltek's revenues in the third quarter were still weak. We experienced a decline in the demand by the domestic defense sector for printed circuit boards manufactured locally. This decline was not sufficiently compensated by sales to the domestic civilian market. In addition, there was a reduction in orders received from the United States."

### Murrietta Recognized as Raytheon Three Star Supplier
After receiving their second 5 Star award earlier this year, another Raytheon division, Space and Airborne Systems, awarded Murrietta their 3 Star Supplier Excellence Award. The annual award was instituted to recognize suppliers who have provided excellent service and exceeded customer requirements.

### Invotec Enjoys Strong Demand from Space Sector
In addition to NADCAP and AS9100 Rev C accreditation, Invotec is one of the very few PCB manufacturers to have been awarded two separate ESA approvals: one for sequential rigid circuits and one for sequential flex-rigid circuits.

### Multicircuits Earns UL Cert for Bergquist Metal-clad Materials
Mike Thiel, director of Operations at Multicircuits, announces his company achieved UL Certification for a number of Bergquist thermal-clad materials including high temperature (HT) and multi-purpose (MP).

### PEC Debuts Contest to Spur Manufacturing Innovation
At a meeting of the President's Export Council (PEC), President Obama will announce nearly $400 million to help improve the competitiveness of American businesses and workers by spurring new manufacturing innovations and giving America workers additional opportunities to improve and expand their skill sets for middle-class jobs.

### Global Business Aviation Reaches Cruising Altitude
Global business aviation activity saw modest gains in Q3 2014, with 2% growth quarter-over-quarter and 2.2% growth year-over-year, according to JSSI's most recent Business Aviation Index.

### Security, Economic Concerns Fuel Military Radar Market
The worldwide market for military radar was worth US $6,900 million in 2012 and will reach US $8,440 million in 2019, registering a 2.9% CAGR during the forecast period.

### Military Radar Market Continues on Growth Trajectory
"The total number of radar shipments is forecast to grow at a CAGR of 4.1% through 2023, to reach 1393 units," notes Eric Higham, North American director for ADS.

### 2014-2024 Electronic Warfare Market Forecast
The global electronic warfare (EW) market is currently going through a period of growth, as many countries are realising its benefits and attempting to expand their capabilities therein.

# Challenges of Electrical Test

**by Todd Kolmodin**
GARDIEN SERVICES USA

Challenges to electrical test are many, but a few come to mind as the most challenging. What do you think they are? Here's what I think:

3. Pitch and density
2. Volume
And the #1 most challenging attribute to electrical test: soldermask!

In our arena today, we can solve pitch and density with flying probe machines, and volume with our grid testers, but the catalyst that is in the mix is that pesky soldermask! So why do I bring up that necessary process as a problem for electrical test?

Electrical test is an absolute science test based on mathematics and absolutes. Front-end systems rasterize the given data to absolutes. If the IPC, Gerber, and ODB++ data show the alignment of layers to the mask, it is an absolute measurement. There are no easements for registration. The test points are assigned to the product based on the absolute clearance allowed in the "Golden" data supplied in the CAD Reference.

But there is a disconnect.

To be blatantly accurate, it never happens. The phenomenon of via cap, via fill and zero-height via fill all come in to play to change the whole game regardless of what the OEM designed. Tolerances are never considered.

This specifically comes in to play when the OEM expects a certain type of test (i.e., IPC Class III) where mid-points are required, but they have also required via cap on only one side of barrels

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Figure 1: Landing pad encroachment.

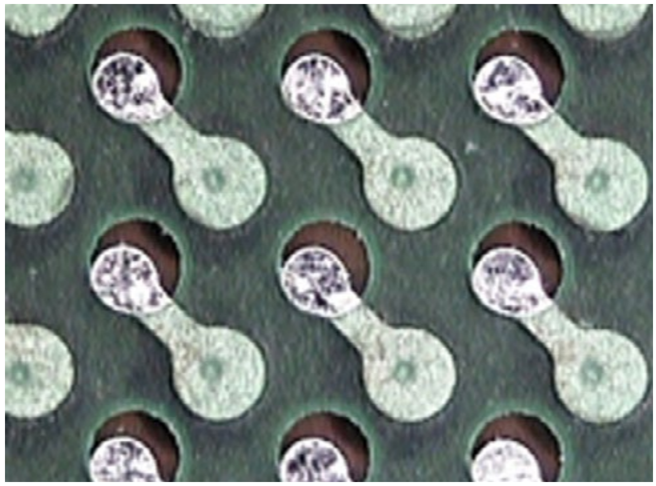

Figure 3: Mis-registration.

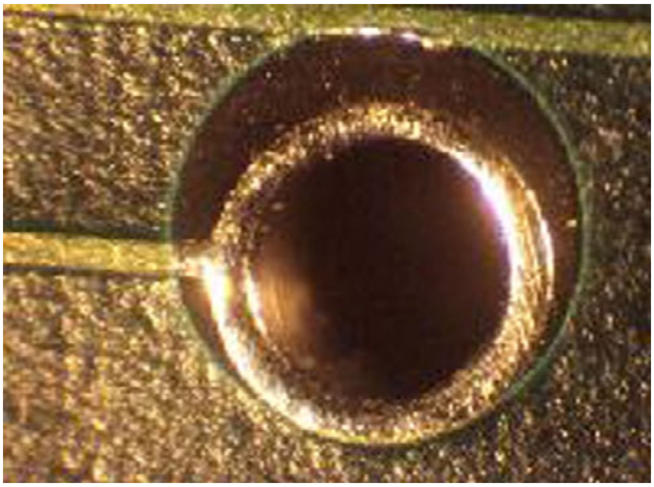

Figure 2: Mis-registration.

or required zero-height (ZHT) via fill. Although a valid process, the misnomer is that this can affect the opposing side of the PCB barrel from valid probing. The "squish" from this can encapsulate the barrel to the point that probing from the opposing side is invalid. So what is an electrical test engineer to do? Amendment 1 of IPC-9252A states that mid-points should be tested, but, according to Footnote 6, "When conductors are not covered by mask or via plug material." This is all fine when read literally. Mechanical processes in the PCB manufacture are not literal. Capping or filling the via from one side does not guarantee the accessibility of testability from the opposing side! Further, the issue of encroachment exists. If the encroachment is absolute, there is no issue, but introduce shift in any direction and the ET probing will be at risk. This is especially prominent when targeting larger PTH features where a flying probe cannot probe directly to the center of drill. Figure 1 illustrates an issue that ET must combat to accurately validate subtrates.

The systems will offset to the annular ring, but if soldermask is not registered as the CAD reference shows, there will be false "opens" reported and will stall the product due to MRB issues. This mis-registration is shown in Figures 2 and 3. If the OEM wishes the full Class III mid-point test it is advisable that they put stipulations on the ICT or mid-points they want tested. Recommendations are only allowing 50–75% squeeze from the opposing side when via filling based on aspect ratio while also not allowing encroachment on the landing pad on the side they wish probed.

These examples are somewhat relaxed from what are real challenges but you can see the flavor of what the issue is. **PCB**

Todd Kolmodin is the vice president of quality for Gardien Services USA, and an expert in electrical test and reliability issues. To read past columns, or to contact Kolmodin, click here.

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# News Highlights from PCB007 this Month

## 1 TTM, Viasystems Receive Second Request from FTC

TTM Technologies, Inc. and Viasystems Group Inc. announced they have each received a second request from the United States Federal Trade Commission for additional information associated with TTM's proposed acquisition of Viasystems.

## 2 Dragon Circuits Battles Industrial "Planned Obsolescence"

The company is announcing an ongoing effort to combat planned obsolescence. Vice President Rajan Babaria says, "I recently discovered complaints about an Asian-made cable (for a gimbal) that was designed to break easily, ensuring customers would have to repurchase after a just a few uses. Our team discussed it and had it redesigned and built with better, more durable material."

## 3 All Flex Invests in Capital Equipment

All Flex has improved its component inspection capability with the purchase of an inline cleaner and an automated optical inspection (AOI) system to handle flexible circuits with high volume components. The AOI has the latest optics technology that rapidly scans for placement accuracy and the inline cleaner has an advanced system that helps deliver defect free parts.

## 4 N.A. PCB Book-to-Bill Ratio Recovers in October

"Unusually strong growth in North American PCB orders in October is good news for an industry that has experienced declining sales for more than three years," said Sharon Starr, IPC's director of market research. "The impact can be seen in the book-to-bill ratio, which made a strong comeback this month, indicating that sales may begin to rebound by the end of the year."

## 5 Infineon Acquires 9.4% Stake in Schweizer Electronic

By investing into Schweizer, Infineon emphasizes its intention to jointly develop technologies for the integration of power semiconductors into PCBs and to tap the chip embedding market for high-power automotive and industrial applications.

## 6 Cicor Wins DeviceMed Award

The DeviceMed Awards were presented at the Compamed in Düsseldorf, the leading international trade fair for medical technology industry suppliers. Cicor came out on top in the Outsourcing Partner category.

## 7 South Korean FPCB Firms See Sharp Fall in Sales

In 2014, price decline continued to deteriorate, which led to a sharp fall in revenue of South Korean vendors. The implications of high-speed capacity expansion are high fixed costs, which would thus result in a plunge in profit margin.

## 8 Saturn Electronics Now UL Certified for Aismalibar IMS

The certification allows Saturn to UL stamp their products using the entire line of Cobritherm materials which includes ALCUP-G 1.3w, ALCUP 1.8w, HTC 2.2w, and HTC 3.2w. The company can now offer a high-quality European alternative the small group of IMS materials currently available in the North American market.

## 9 Candor Invests in Equipment from atg, Olec, Pluritec

Canadian high-technology PCB manufacturer Candor Industries announces it has improved overall production, speed, and capability through recent capital investments from atg, Olec, and Pluritec.

## 10 Aspocomp to Cease Operations at Teuva Plant

It was decided that a total of 34 personnel, consisting of 28 non-salaried and six salaried employees, will be made redundant and production at the Teuva plant will be closed down.

# EVENTS

For the IPC Calendar of Events, click here.

For the SMTA Calendar of Events, click here.

For the iNEMI Calendar of Events, click here.

For the complete PCB007 Calendar of Events, click here.

**2015 European 3D TSV Summit Enabling Smarter Systems**
January 19–21, 2015
Grenoble, France

**SEMI Arizona Tech Talk: INanoBio**
January 23, 2015
Chandler, Arizona, USA

**IPC Conference on Assembly and Reliability**
January 27, 2015
Ho Chi Minh City, Vietnam

**RockyMountain Expo & Tech Forum**
January 28, 2015
Denver, Colorado, USA

**IPC Conference on Assembly and Reliability**
January 29, 2015
Bangkok, Thailand

**SMTA Pan Pacific 2015**
February 2–5, 2015
Kauai, Hawaii, USA

**SEMICON Korea 2015**
February 4–6, 2015
Seoul, Korea

**MEDIX 2015**
February 4–6, 2015
Osaka, Japan

**LED Korea 2015**
February 4–6, 2015
Seoul, Korea

**2015 Flex Conference**
February 23–26, 2015
Monterey, California, USA

**IPC APEX EXPO 2015**
February 24–26, 2015
San Diego, California, USA

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# ADVERTISER INDEX



## Coming Soon to *The PCB Magazine:*

*February:*
**Surface Finishes**

*March:*
**Materials**

*April:*
**HDI**