Important Considerations in the Design of Solderless Electronic Assemblies

Joseph Fjelstad
Darren Smith
Seattle, WA
joe@verdantelectronics.com

Verdant Electronics
AllWin Group
North East, MD
DarrenSmith3214@gmail.com

Abstract

Soldering has been a key process step in the manufacture of electronic assemblies since the earliest days of the electronics industry, it is also one of the most challenging processes to control and predict and a major source of defects and failure. For several years, the elimination of solder from the electronic circuit assembly manufacturing process has been suggested as a potential way to sidestep solder technology's many shortcomings. Elimination of solder can in fact be relatively easily accomplished by simply reversing the manufacturing process. That is, rather than building printed circuits and then placing components and soldering to them together, it is here proposed that boards containing components, with the component's planar terminations exposed on the surfaces of said component boards, have circuits applied to them using PCB build up technologies which are now well established in the PCB industry. By bypassing the soldering process, the resulting assemblies offer significant benefits and improvement potential in terms of cost, reliability, security and environmental friendliness among others.

While the manufacturing infrastructure to build such structures is fundamentally in place and ready to go, the design approach, mentality and some tools which are presently available are less ready. This paper will examine, by way of demonstration, the challenges associated with designing SAFE (solderless assembly for electronics) products. In the paper, a current product board is redesigned using all preferred case design rules which include, a fundamental grid pitch for all components resulting in a design which is substantially smaller than the original design and yet which are less challenging to the circuit manufacturer than most current leading edge designs. The paper will identify the limitations of current design tools relative to executing such designs and offer suggestions as to how those tools might be improved to make the manufacture of solder free electronic assemblies easier. It will also describe and suggest novel ways of integrating passive devices into such electronic assemblies to further conserve space and improve performance.

Introduction

Cost reduction has been a cornerstone of electronics manufacturing since the earliest days of the industry and has allowed for the proliferation of electronic devices of every imaginable type to satisfy consumer demand for ever more functional and useful products. This objective has been achieved both by economies of scale and as well by making products that are smaller and lighter, thus reducing waste. Corporate bottom lines have also been served by making products both at higher yield and more reliable, the latter of which is one of the pillars of customer retention. Reliability is thus unquestionably one of the important cornerstones of electronics. Unfortunately, the industry has been hobbled since 2006 by EU mandated restrictions (RoHS) on the materials used in electronics manufacture. The greatest impacts have been felt by the unnecessary elimination of lead from electronic solder. This was followed by a highly questionable demand for the elimination of haloids from flame retardants used in traditional PCB laminates. Since the legislation was introduced, the general electronics industry has been beset with a host of new challenges in its effort to comply. Failure mechanisms, both new and old, have surfaced which demand solution and the industry suppliers and manufacturing technologists have worked diligently to remedy those vexing faults through the development of a wide range of new materials and equipment for both board manufacture and assembly, along with modifications to the processes used in the manufacture and assembly of printed circuit boards.

Most of the problems which have confronted the electronics manufacturing industry have related to the solder assembly process. Lead-free solders were advertised early on as a drop-in replacement for traditional tin lead solders, however field experience proved this not to be the case. The tin rich alloys along with the higher temperatures which were required for assembly cause the industry to scramble for solutions to such problems as champagne voids, poorer wetting, brittle solder joints, copper dissolution, tin whiskers, head in pillow, greater vulnerability to damage caused by explosive outgassing of absorb moisture in packages among others including cleaning of baked on fluxes following the high temperature assembly process. Leadfree solder also had spillover effects on the PCB laminate material itself as manufacturers experienced delamination and degradation of the resins used in traditional circuit construction. One more recently encountered problem is a phenomenon referred to as pad cratering wherein resin beneath the copper land to which a component is attached is actually torn loose from the surrounding resin breaking through the copper and causing an open.

In this environment, an alternative approach to manufacturing electronic assemblies has been conceived and is presently being developed. The new method in simplest form is one which eschews the use of solder and is predicated on the use of aluminum substrates which house fully tested and burned in components to create what can be best described as a component board wherein the terminations of the components are proximately planar with the surface of the substrate. In subsequent processing the component board is first coated with an insulating material and then circuits which interconnect the components are applied using buildup technologies. An example of a solderless test vehicle assembly made of aluminum is shown in Figure 1.

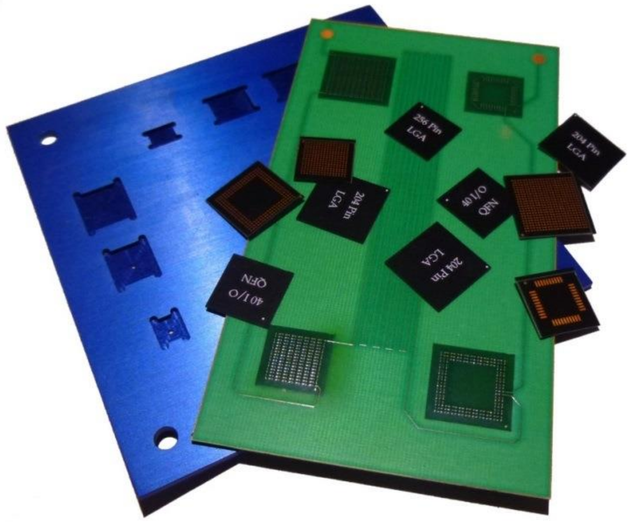


Figure 1. Aluminum is a viable alternative to customarily used laminates when solder is not used to make interconnections between components and circuits. Aluminum is unique in that its surface can be anodized creating an insulation layer of alumina which can be colored and sealed. All components shown have a purposely selected 0.5mm contact pitch for design reasons which is discussed in the body of the paper.

The balance of this paper will describe in more detail the processes used in the manufacture of such product and equally what considerations a design must consider when choosing to approach such designs. The paper will also identify and enumerate the numerous benefits that can be derived by what is fundamentally a reversing the manufacturing process. That is by building up circuits on what can be best described as a “component board” rather than placing and then soldering components on circuit boards.

Basics of a “Reverse Manufacturing” Process

To those skilled in the art of electronics assembly, the goal of eliminating solder from the electronics manufacturing process may seem at first like a “fool’s errand”. The infrastructure is set in place and traditional methods are deeply entrenched in the psyche of electronics industry. Presently billions of dollars are spent annually on materials, processes and equipment used for electronic assembly. Additional hundreds of millions are spent trying to identify and repair the inevitable faults that are inadvertently created by an assembly process that is inherently weak and made weaker by lead free solders and the higher temperatures required for their processing. The elimination of solder could allow manufacturers to either pocket those billions or turn some of the increase profits to their customers through more competitive pricing. It is arguably ad worthy goal but how exactly can it be done?

Following is a description of a novel process which bypasses completely the soldering process in accordance with precepts which are consistent with what has come to be known in industry as the Occam process [1], [2]. The process is a subset of technologies which fall under the general umbrella term of SAFE an acronym which stands for either “solderless assembly for electronics” or “solder alloy free electronics”.
SAFE manufacturing it will be shown is simpler than traditional circuit manufacturing and having fewer steps and lower capital equipment requirements, the cost must logically be less than present methods.

There are a number of different prospective approaches to making an electronic assembly without solder and these have been described in earlier work. [3] For this paper, the discussion will be limited to manufacture using an aluminum carrier.

The first step in the process is carried out by placing electrically tested and burned in electronic components (test and burning in of components before assembly is deemed vitally important) onto an aluminum carrier plate/housing. The use of tested and burned in components is considered critical for any product built using the method but it is deemed even of greater importance for high reliability applications. One note, worthy of mention at this point, is that the components do not need to be provided with either a solder ball, solder coating or a solderable finish. This should make the components both less costly and more reliable as they bypass the high temperature soldering process.

The actual placement of components can be performed using traditional pick and place equipment. The resulting structure is fundamentally a “component board” wherein the terminations of the components are visible and substantially planar to the surface of the carrier structure. The components can be placed on one or both sides.

Aluminum is deemed a highly attractive choice as a circuit substrate owing to a combination of different properties which include a coefficient of thermal expansion which is reasonably close to that of copper, dimensional stability which exceeds that of FR4, relative lightweight, good thermal spreading capability and low cost. As evidence, at the time of writing, aluminum is roughly $2 per kilogram while FR4 in quantities of 2000 kilograms coming out of China runs around $6 per kilogram [4]. It is also worth noting that aluminum comprises 8.3% of the earth’s crust and is highly recyclable positioning it among the most sustainable of all current circuit substrate choices.

Turning attention back to the steps in the exemplary process being here described (as stated earlier, there are a number of suitable and similarly useful prospective variations on the process). First a sheet (or sheets) of aluminum is prepared with cavities wherein components will be placed. Because the substrate is solid metal the cavities can be created by any of a number of steps including chemical machining, mechanical machining, and laser cutting and punching. The substrate could also be embossed or cast with the cavities if desired.

Aluminum is a unique metal in that it can be anodized a process which converts the surface to aluminum oxide, also referred to at alumina. Also a conductive material, aluminum can also be coated electrophoretically with a plateable insulating material making the exposed surfaces nonconductive. Such techniques are commonly used in the coating of a wide range of metals used in products of every imaginable type from toys and household appliances to automobiles and space craft.

The cavities which receive the components are ideally formed such that the depths will match the components’ height so that when components are placed into their assigned cavities with leads facing up, the lead terminations will be flush with the surface to facilitate further processing.

Following secure placement of the components, processing methods traditionally used for the manufacture of HDI buildup boards are carried out on the surface of the component bearing aluminum assembly to produce circuit patterns with the interconnection between components. The circuit pattern interconnection being achieved by copper plating of both the circuit features and the vias which interconnect component leads to those circuit features at desired locations. Figure 2 illustrates the basic steps.

Another advantage of note at this point, from both design and manufacturing perspectives, is that unlike soldered devices, only those component leads requiring connection need be provided with vias. In addition, the vias are smaller than the traditional solder lands so more surface area is available for circuit routing. This will be discussed in more detail later.

While the use of bare die is possible, and to reinforce the preferred approach to constructing the assembly, IC components are ideally provided at packaged and tested devices. Where size reduction is desired, CSPs are very well suited. Again, packaged devices are preferred because packaged IC devices are much more easily tested and burned in. Equally important from a design perspective, packages offer an important feature in that they have standardized lead patterns and physical outlines making the design process simpler. This is especially true if a single derivative lead pitch is used for all components (e.g., 0.5mm yields lead pitches of 0.707, 1.0,… etc.). Additionally, at the present time, nearly all packaged IC components use copper as the base metal for interconnections which is advantageous for more than just that one reason alone, as will be shown.

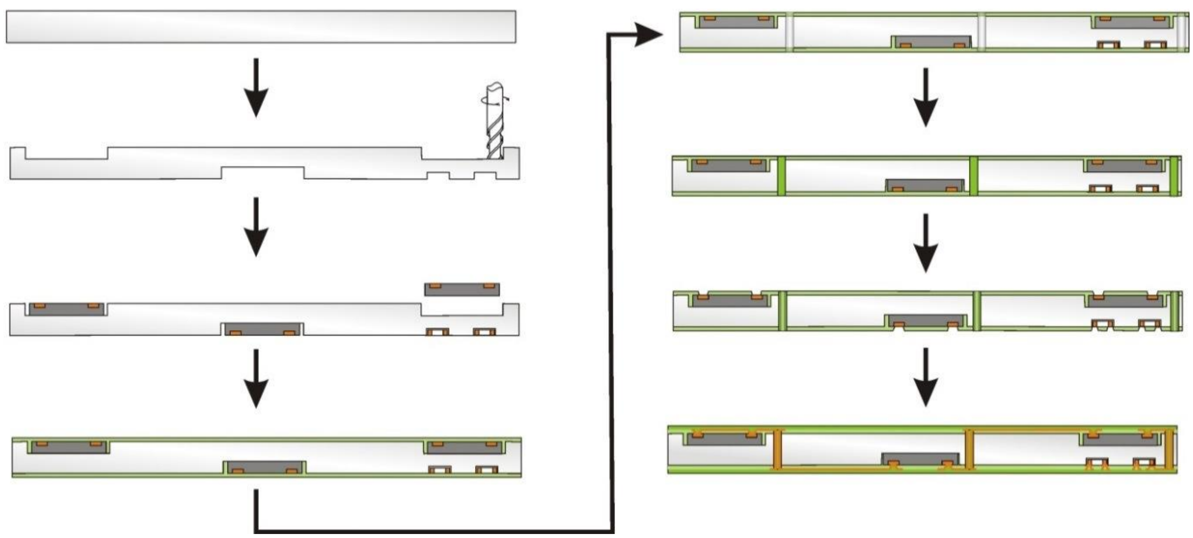


Figure 2. The basic process steps for double sided aluminum circuit assembled and interconnected without solder are illustrated. From the top left, aluminum material is provisioned with cavities by milling (as illustrated), etching or embossing, wherein components are placed and then coated with an insulating material. Holes are drilled and then filled with insulating material, the re-drilled. At the same time vias are formed to access component terminations. The circuit pattern is then plated and circuits sealed after last layer is complete leaving open feature required for interconnection and power (open features not illustrated). The metal core can serve both as heat spreader and power or ground layer.

After the components are placed and affixed permanently on one or both sides of the aluminum carrier plate, layers of insulation are applied to one or both surfaces of the metal sheet covering the components. At this point, the assembly can be processed as if it were a standard rigid printed circuit with high density build-up layers on one or both sides, using lasers to drill holes down to access component terminations and commonly practiced plating and imaging processes to create the circuits. A difference is that a fill step with an insulating material may be required if through holes have expose metal. However, if coated with epoxy, this may not be necessary. One caveat for those circuit manufacturers considering exploring processing circuits of this type is that if the aluminum is untreated, the edges need to be sealed to prevent contamination of subsequent processing chemistries that will be used in manufacture. While additional processing steps can be performed if desired and or required this assembly could be in some applications considered complete. The overall number of processing steps is obviously significantly reduced from those required for traditional processing of printed circuit assemblies.

While the foregoing has described a relatively simple structure the longer range potential of these novel aluminum circuit structures is impressive and limited more by imagination than the technology. One such example is illustrated in Figure 3, wherein two circuitized aluminum component carriers with components on both sides and having vias connecting them are placed face to face using a mezzanine connector system. The number of layers possible could be quite large and the finished structure could resemble an aluminum “brick” when complete. Also illustrated for consideration is the potential provision of optical channels in the assembly for making interconnection between components on an assembly as illustrated or to the edge if it is so desired. This is a particularly interesting prospect for designers because optical ports are commonly provided on the bottom of the electronic packages which contain optoelectronic devices.

Beyond the aforementioned potential in creative design, there is also possibility, in certain cases, to use relatively thin aluminum base material or to thin the base material in predetermined areas. The thinner aluminum structure or predefined areas could allow the developer to permanently form the final assembly into a desired shape, opening up new possibilities to a challenging product design or application for the clever product designer.

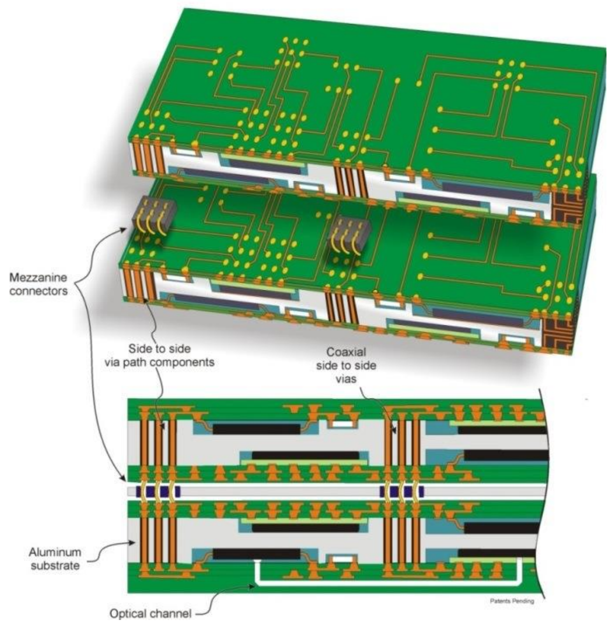


Figure 3. Solderless aluminum assembly structures can potentially be stacked and interconnected and even "bolted" together using mezzanine connectors to create "aluminum brick" which might simultaneously solve a range of problems related to both performance by creating shortest path routing and the thermal challenges which often accompanies higher performance. Note that optical interconnection opportunities also exist as optical ports are commonly provided on the edges and/or the bottom of optical devices making provision of stable optical channels.

Designing Solder Alloy Free Electronic (SAFE) Assemblies – Discussion and Practical Demonstration

The elimination of solder offers some significant advantages in both the design process and in the finished product. While SAFE assembly technology can improve density, improve yield, improve performance, reduce layer counts such advantages come at the price of greater attention to detail and greater discipline. An explanation and closer examination is here offered.

First, while decreasing assembly size can be accomplished by placing components closer together using SAFE design protocols, such actions can cause thermal management problems especially when higher power (i.e. hotter) components, in the range of 1-3 watts, are employed in a design. Thus shrinking an electronic assembly increases the thermal management challenge, this is where aluminum substrates begin to look attractive. Presently used PCB laminates are good electrical insulators but poor thermal conductors making hot spots and potential localized thermal degradation of the laminate a real possibility.

Another reason components are normally placed further apart than need be in a design is because room must be left to facilitate flux removal and cleaning beneath the components after soldering. In addition, there is need to provide space for the removal and replacement and/or rework the components when problems related to the soldering process inevitably arise. This is largely obviated with a properly designed SAFE assembly. In contrast, any attempt at using normal lead free solders with an aluminum circuit board would likely yield poorly with many cold joints and/or thermally damaged components.

Layer count reduction is another easily achieved benefit with a safe assembly. There are a number of reasons for this. First, there are no solder lands required. Interconnection to component terminations can be achieved by a simple plated microvia. Moreover, when the designer uses components which have all of their terminations on a common grid pitch, the routing of circuits can get much simpler. In this regard, one can look to the work of scientists and engineers at the University of Arkansas in there development of their Integrated Mesh Power System (IMPS). The technology developed for multichip modules in the 1990s. The patented [5] approach allows for the designer to create the equivalent of 4 metal layers using just 2 metal layers. It is illustrated in Figure 4.

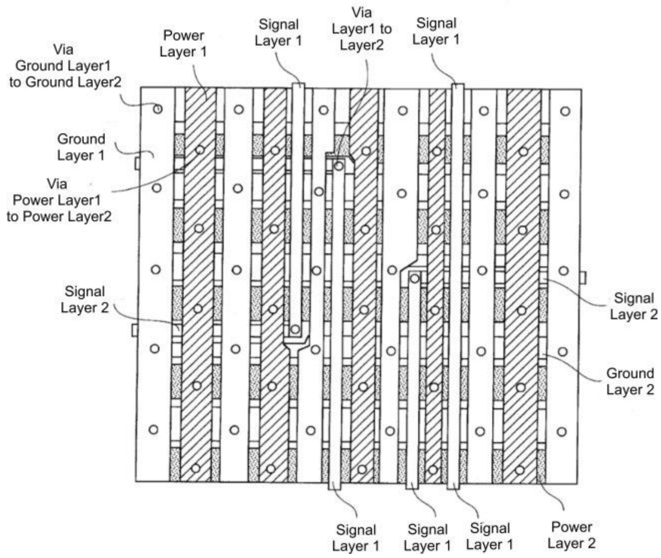


Figure 4. The patented Integrated Mesh Power System (IMPS) developed at the University of Arkansas allows a designer to interconnect in 2 metal layers that which would normally require 4 metal layers.

As alluded to earlier, such an approach benefits significantly from the use of a common grid pitch. While the pitch can be arbitrary, 0.5mm pitch is recommend because it is the lowest practical pitch for most SMT assembly. As for component types, two types stand out as being best suited to the technology, fully tested and burned in land grid arrays (LGA) and quad, flat, no lead (QFN) devices. These type devices are also among the favorites for designers. The QFN and LGA devices have added advantage of having no solder balls making them inherently very planar and nominally more reliable because they have bypassed the high temperatures required for solder ball attachment. Moreover no solderability protective coating is required. One addition benefit bestowed to the designer is the ability to make his product board thinner. This is because solder balls often account for as much as half of the thickness of ball grid array components, regardless of their lead pitch. This is illustrated in Figure 5

Figure 5 At any given lead pitch, solderless assembly methods can significantly reduce layer count by freeing up routing space as illustrated on the right. The approach provides freedom to use nearly any position within the BGA matrix for routing objects; traces & vias". For example, while via in pad is good. Via wherever (e.g. on pad, off pad, overlapping pad) is even more effective. This added flexibility in routing compliments the trend toward the dominance of ASICs & other System-On-Chip devices. That is it offers more flexibility for more signal pairs, more accordion routes (length matching), shielding, wave guides, etc. Note also that solder balls often makes up half of the overall height of a mounted package, thus a much thinner assembly is possible.

By way of analogy it is suggested that the designer approach the design with a "graph paper" mentality. That is that he or she place all component pins on a grid which is a multiple of five – 0.1mm, 0.5mm, 1.0mm, etc – and always routing with appropriately sized vias. This allows for an increased usage of real estate which climbs to asymptotically approach "full utilization" of available real estate. In contrast with the current design approach and methodology, employing random device pitches & oddly numbered via geometries & design rules, then layering in routing & placement grids in inches rather than staying metric, much real estate is wasted due to “white space” generated by constantly adjusting to grids & pitches that have no mathematical relationship to each other.

To illustrate the potential efficacy of SAFE assembly a demonstration design effort was undertaken. It was decided to use a current product board which had been laid out using best current practices. The centerpiece of the design was a 442 pin FPGA at 0.8mm ball pitch. The dimensions were 140mm X 100mm. The redesign carried out according to the precepts of company and SAFE protocols and using a 0.5mm lead pitch LGA resulted in an assembly 30mm X 40mm overall foot print. The actual area required was significantly less. Which required just 6 metal layers for routing. The redesign yielded a 6 layer rigid flex circuit is ~70% smaller in terms of total area and capable of being folded into an assembly which can occupy a foot print which is less than 20% of the original design with minimal increase in assembly height. Though the density of aluminum is higher than FR4, (FR4=1.8 gr/cm3, Al=2.7gr/cm) the total weight of the assembly is projected to be ~55-65% less than the original. Moreover, the rigid flex structure is amenable to the separation of digital and analog circuity and thus the potential for better control of the energy created by analog devices and power supplies. Interestingly, the design rules for layout do not in any way challenge current manufacturing practices. Minimum lines and spaces were held to 50 micrometer (2 mils) and only two via diameters were employed.

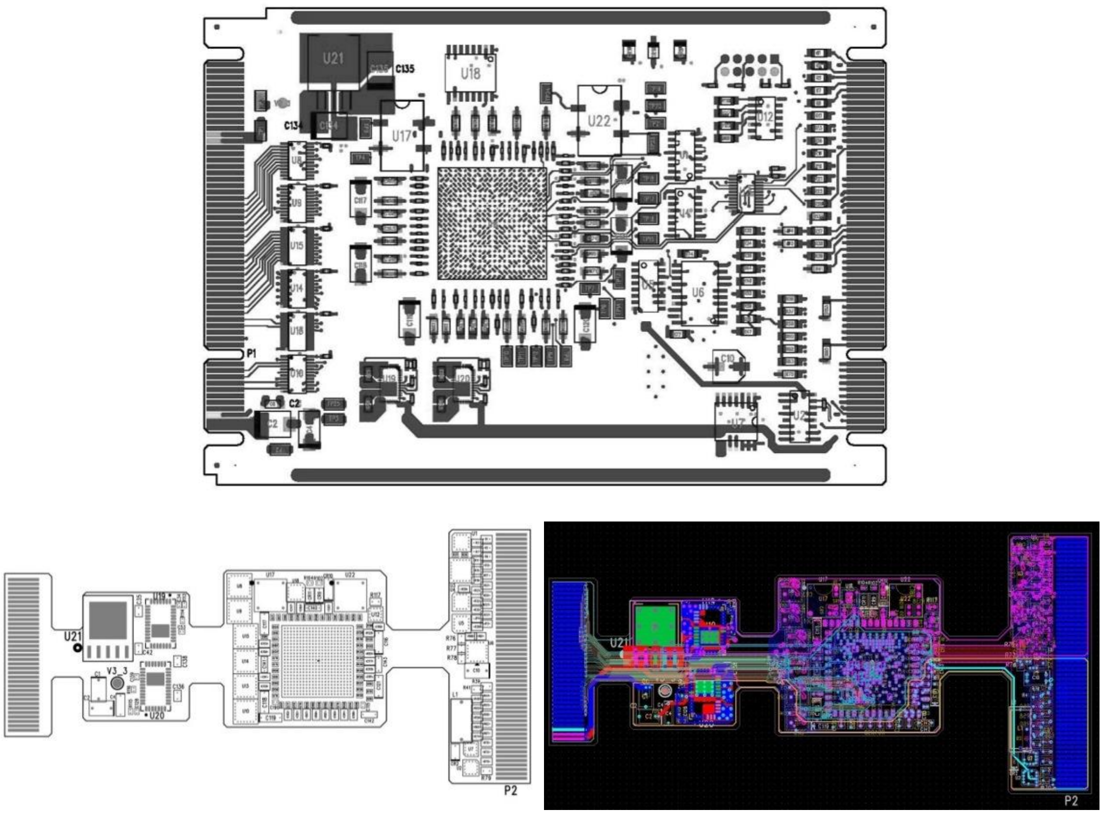


Figure 6. Above, shown to relative scale, is a comparison of an original circuit design using traditional manufacturing methods and a redesign of the same product board using company design principles, including selection of components having terminations on a common grid pitch of 0.5mm. The original design (above) was a 12 layer rigid multilayer circuit. The redesign assembly (shown bottom left) yielded a 6 layer rigid flex circuit is ~70% smaller in terms of total area and capable of being folded into an assembly which can occupy a foot print which is less than 20% of the original design with minimal increase in assembly height. Though the density of aluminum is higher than FR4, (FR4=1.8 gr/cm3, Al=2.7gr/cm) the total weight of the assembly is projected to be ~55-65% less than the original. Finally on the bottom right is a composite of the layers and routing of the resulting much more compact rigid flex redesign.

A primary objective of the SAFE layout approach is to use exclusively internal layers for component placement. Components may assume either a right-side-up or an up-side-down orientation Most CAD tools construct PCB footprints (decals, patterns, etc) to reside on either the top or bottom of the PCB. Flipping a part from top to bottom creates a mirror image of the pattern with CAD objects assigned to the bottom layer.

What is required for efficient component placement & manipulation are CAD parts & commands which change the placement layer, with a switch to indicate whether a mirrored version is being implemented or not; often referred to as Live Bug vs. Dead Bug orientation.

In summary, the design of an electronic assembly using company principles and the SAFE manufacturing approach can provide powerful advantages where there is desire to reduce the size of an electronic assembly while creating a more reliable assembly and one which can provide many additional benefits. It is believed that it has been arguably shown that there are clear benefits from solderless assembly in terms of making designs smaller. Such designs, it is also believed, will prove much more reliable than current approaches using solder for assembly. However, SAFE assemblies also offer a number of electrical/electronic benefits. Following are some of the more important ones.

First, where connections are required they can be made directly to terminations on component lands. In addition, the point of interconnection can be made without benefit of a large pad. This can reduce local parasitic capacitance. Elimination of the pad also frees routing space, allowing for a reduction in total layer count as has been shown and this further reduces cost. (see again Figure 5) If proper planning is used in choosing components of a common grid pitch (e.g., 0.5mm) the integrated power mesh system (IMPS) design layout approach may be employed, thus making layout simpler, speeding up the process by requiring less design spins and reducing layer counts while improving signal integrity. Moreover, with proper preparation, the aluminum core can serve as power or ground as mentioned earlier. This makes it possible to provide both power and/or ground immediately adjacent to every component.

There is as well the potential to employ in the future a novel and patented [6] but still prospective approach to the fabrication and inclusion of certain discrete devices especially with respect to small low power resistors such as are often used for terminations. The method which involves the creation of resistors in situ, could further reduce the size and component count for such assemblies. As illustrated in Figure 7 the concept is predicated on simply dispensing resistive inks into the via cavities which expose the package terminations. The resulting resistor's value in Ohms could be easily tailored by altering the ink formula, via diameter and depth. The method was originally conceived for use with soldering but the high temperatures of soldering were a concern as there was potential risk of the plating breaking away from one of the surfaces to which it was interconnected. With the prospect of there being no high temperatures encountered during assembly, it is a method deemed worthy of further investigation.

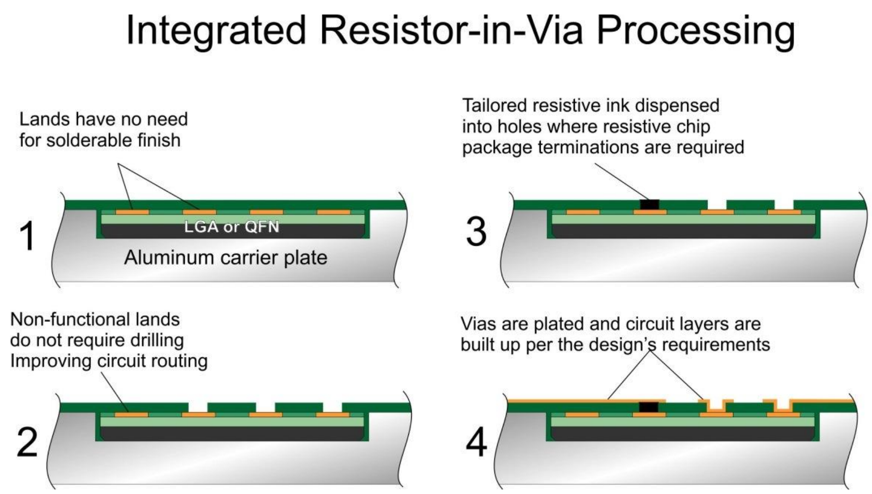


Figure 7. Resistors can be created directly at the point of need in company processing as illustrated by the process above. Note also that component leads do not require a solderable finish. In addition, nonfunctional lands on the package do not require processing, thus opening up real estate for circuit routing.

As a final point with respect to design advantages, a completed assembly can also be relatively easily provided with final metal plating after the assembly is completed. This step would make the entire assembly a fully metal jacketed one, exclusive of the external areas necessarily left open to allow access to external I/O points such as connectors. Such assemblies would be EMI and ESD immune as the body could be a grounding as well as a shielding finish. Moreover, except in the aforementioned areas required for I/O connections, a metal finish is fully hermetic and an impermeable moisture barrier. Finally the high thermal conductivity of a full metal jacket over a circuit assembly could also serve well the needs of thermal management.

Advantages of SAFE Aluminum Circuit Assembly Design

Beyond the structures just described, there are an impressive number of additional advantages to the design and manufacture of electronic assemblies that do not use solder to make interconnections, especially those circuit structures made with aluminum. However, the advantages of products manufactured using SAFE techniques also circumscribe the full range of benefits normally considered desirable for any electrical or electronic product. Following are brief discussions of those benefits:

A. Assembly Size and Weight Reduction

The size and weight of an electronic assembly are critical design factors in products of every kind. The benefits can be enjoyed across the entire spectrum of manufacturing, distribution and customer use. More devices can be built with less material, more devices can be shipped in a container. Smaller devices occupy a lesser amount of shelf space in warehouse as well as at retail stores. Lighter weight devices cost less to ship. No doubt the reader can think of more on their own.

B. Thermal Benefits of Aluminum Substrates

When aluminum is used as the component carrier, it becomes by default a heat spreader which is an integral part of the assembly. This allows the designer to address thermal concerns early on rather than at the end of the process. Given the inverse relationship between long-term reliability and the number, temperature extremes and durations of the thermal exposures a component experiences, having a built-in thermal management solution is an intrinsic value-added feature.

C. Mechanical Performance Improvements

Mechanical performance is another area of vital concern in aerospace electronics. Shock and vibration are commonly encountered by deployed aerospace mission electronic assemblies. With the assembly methods as are proposed here, the electronic components are fully encapsulated in the aluminum assembly and thus they become part of an integrated whole.

While not entirely immune to the effects of shock and vibration, the combination of their embedment combined with the elimination of solder, shock and vibration concerns are significantly mitigated as the mass of the components is moved from the surface, where the physical vibrational micro-warping of the assembly can fatigue solder joints, to the inside of the assembly with low mass copper circuits above them for interconnections.

Beyond shock and vibration mismatches in the CTE (coefficient of thermal expansion) of substrates and surface mounted component has long been a concern as thermal cycling during operation can also fatigue solder joints. In this regard it is worth noting that aluminum and copper are relatively well matched in terms of their CTEs. (Al = 22ppm/°C, Cu = 18ppm/°C), which reduces the potential stress on interconnections; moreover, the materials expand predictably in all directions, whereas reinforced laminates have CTEs that may vary in X, Y and Z dimensions, sometimes quite appreciably (e.g., X ~20ppm/°C, Y ~23ppm/°C and Z ~80ppm/°C).

With respect to vital electrical interconnections between components and circuits, microvia technology, which is an integral element of the proposed structures, has been proven superior to solder joints. Even though microvias have a solid and growing reputation for reliability, because of the high temperatures required, lead-free soldering can and has induced in process via failures.

D. Design Security

Not just military and aerospace designs are considered sensitive. Many commercial designs also desirably need to be made secure and resistant to tampering and/or easy device removal for reapplication in another design by counterfeiters. The military was highly sensitive during the Cold War, when potentially dual use electronics, such as microprocessors were sold into the Communist Block in electronic systems. To combat this, such devices were often glob topped with an epoxy before export, making their removal and reuse impractical if not impossible. With that in mind, it is noteworthy that the manufacturing approach suggested in this paper, offers a design security benefit that may not be immediately obvious to many product developers.

The methods employed obscure the components used in fabrication, making tear-down and reverse engineering of a product much more daunting and difficult for those wishing to understand what might differentiate the product in hand with previous competitive products. This benefit extends to all kinds of electronic products, from simple consumer to military and aerospace products. Once again, the assembly approach makes it much more difficult for unscrupulous individuals to extract and reuse components, injecting them into the supply chain as counterfeit devices [7]. This latter point is one of the more recent and bigger challenges facing those seeking to procure reliable military and aerospace electronics.

E. Reliability Improvement

Product reliability is key to a company's reputation. Unfortunately, it is not easy to assure with the complexities of the current manufacturing paradigm using solder. Reliability is the product of the many decisions made relative to all the important processing factors and functional elements of an electronic assembly. Considerations which must be taken up and acted on include the electrical, environmental, thermal and mechanical performance requirements placed on the final product in its application. The many design and production benefits enumerated and discussed in this paper so far, combined with the very important benefits that can be obtained by simply sidestepping the high-temperature lead-free soldering process required today, significantly improve the prospects of making highly reliable electronic assemblies. To this point, it is worth repeating what was mentioned earlier and that is that the soldering process is typically the largest cause of defects in assembly and that solder joints are the most common sites for failure of electronic interconnection systems.[8],[9] Moreover, in a solderless electronic assembly, concerns over tin whisker formation, a topic that has returned to prominence in recent years and which has been implicated by NASA reliability engineers as a most likely cause of failure of a number of satellite missions, is completely mitigated by the elimination of solder from electronic assembly.

As a final note on the topic in this brief discussion of reliability, conductive anodic filaments (CAF) [10], which is the growth of conductive fibers between adjacent vias in reinforced materials and tin whiskers [11] are obviated by the ability to use homogeneous, unreinforced materials and elimination of solder respectively.

F. Regulatory Compliance

Commercial products seeking world acceptance require compliance to the EU's RoHS legislation. While the aerospace industry is largely exempt, it is also de facto impacted by RoHS legislative mandate to eliminate lead from solder used in electronics. That mandate has proven very costly to date running to billions of dollars of waste [12], the materials and processing approach as described, which are designed to eliminate use of solder, automatically complies with RoHS. The finished structures described are fundamentally all-copper interconnection systems built on aluminum bases. On a finished product, only the surface sites required for making electrical connection to the other system elements, such as switches, connectors and the like, need to have a contact finish.

The key point and take away is that since neither copper nor aluminum is considered a problem, both the RoHS and REACH concerns should be obviated provided the other materials selected and used in the assembly are compliant. Additionally, the material declaration process is greatly simplified. These same benefits hold true relative to the use of conflict materials which is of growing concern among increasing numbers of both governmental and non-governmental organizations (NGOs) as the structures completed as described are completely devoid of any proscribed or sanctioned materials. In short, the assemblies described allow a product to much more easily pass regulatory scrutiny.

G. Environmental Friendliness

During the last few decades, concern over the environment has moved steadily into the consciousness of government officials, business leaders and the consuming public around the world. The term social responsibility is also often used to describe the concern; however, the fact that the industry makes products that impact the environment at the lowest possible level has become increasingly important. With that in mind, consider an electronic structure constructed principally of a material which is desirably and easily recycled, such as aluminum. Moreover, there is the significant amount of energy that is used in traditional manufacturing in component and assembly preparation and in the soldering process, which can be saved when solder is not used. Finally, as suggested earlier, additional energy savings can be found by obviating need for all of the process steps leading up to and following the soldering process.

4. DISCUSSION

It has been argued here that there are many advantages to making aluminum circuit assemblies in the manner described. Even so a recurring question is often raised by thoughtful and/or concerned/skeptical reviewers. Specifically the question is: "How does one test and rework such assemblies?" That question is perhaps best addressed with a separate question: "If the process is executed properly and the components are not subjected to thermal extremes, why is there a need to test and rework?" The simple fact is that most electronic assembly problems are related to the inherent weakness of the soldering process and solder joints failure remains a leading cause especially when there is shock or vibration experienced [13].

Moreover, below 0.5mm lead pitch, which is where the component roadmap trends are headed, assembly yields drop off appreciably, even with multiple preassembly inspection steps implemented and/or applied. The EMS industry has come to accept the weakness of its assembly and cleaning processes even as it strives to constantly improve them, making marginal improvements through new materials and equipment and as a result has come to also expect that rework and repair are a natural part of the manufacturing process. This acceptance carries with it what can be best described as a self-defeating ingrained attitude and results in the manufacturing having to continually carry out a process that might otherwise be made unnecessary. In short, if the components are fully tested and burned-in and the processes used are properly controlled, the final product should be high-yielding, provided the design is inherently valid and robust. The limits of reliability of future electronic products could well be better defined by IC reliability than the reliability of the circuits and plated vias that are used to interconnect them.

5. Conclusion

In summary, the global electronics industry will in the future, and with great certainty, require electronics which offer the highest level of reliability, especially if the industry hopes to serve the needs of poor peoples in developing nations who can ill afford to buy lower reliability products when they have very low wages and limited means. They deserve, and must have, both low cost and high reliability. The aluminum circuit structures which been described in this paper are relatively simple to design and eminently possible to manufacture and environmentally safe. Such assemblies can be easily produced using well-established manufacturing infrastructure tools, equipment and processing techniques which are simply reordered to make highly useful electronic products suitable for use in everything from consumer to high-reliability automotive, medical, military and aerospace products. The limits are likely to be defined more by the imagination of the designer than the limits of the fundamental technology which has been described.

References

[1] Fjelstad, J. “Reversing the Electronic Assembly Process”, Semiconductor International, Vol 32 No. 13 pp 24-28 December 2009

[2] Fjelstad, J "Environmentally friendly assembly of robust electronics without solder", Circuit World, Vol. 34 Iss: 2, pp.27 – 33 2008

[3] http://www.ipcoutlook.org/pdf/past_present_future_solderless_smta.pdf

[4] W. Callister and D. Rethwisch, Appendix C, Fundamentals of Materials Science and Engineering An integrated Approach 3rd Edition. Wiley (2007)

[5] US Patent No. 6,388,200

[6] US Patent No. 7,049,929

[7] Lowry, R., “Counterfeit Electronic Components – An Overview” Oneida Research Services White Paper (http://www.ors-labs.com/pdf/MASH07CounterfeitDevice.pdf)

[8] Lee, D., “What Can No Longer Be Ignored In Today’s Electronic Designs” SMTA Chapter Meeting Presentation, Jan 2008 (http://www.laocsmta.org/archive/Jan_2008_Plexus_Presnetation.pdf)

[9] Engelmaier, W., “Reliability Issues for Printed Circuit Boards in Lead-Free Soldering” SMTA Presentation Archive (http://www.smta.org/files/Englemaier_Opening.pdf)

[10] Karavakis, K and Bertling, S, “Conductive Anodic Filament (CAF) - The Threat to Miniaturization of the Electronics Industry” MEPTEC Journal, Number 4, pp 24-27, 2004

[11] NASA Metal Whiskers Web site http://nepp.nasa.gov/whisker/

[12] Buonpastore, P., “Survey: RoHS Costs at Over $32 Billion” PC Design and Manufacturing Magazine, April 2008 (http://pcdandf.com/cms/magazine/95/4572)

[13] de Maio, D. “High-frequency vibration tests of Sn-Pb & lead-free solder joints” Proceedings IEMRC/TWI Technical Seminar: Developments in Interconnection, Assembly and Packaging, December 2008.

Important Considerations in the Design of Solderless Electronic Assemblies

Joseph Fjelstad
Verdant Electronics
Seattle, Wa

Darren Smith
AllWin Group
North East, MD

“The reasonable man adapts himself to the world; the unreasonable one persists in trying to adapt the world to himself. Therefore all progress depends on the unreasonable man.”

-George Bernard Shaw-

"Maxims for Revolutionists”(1903)

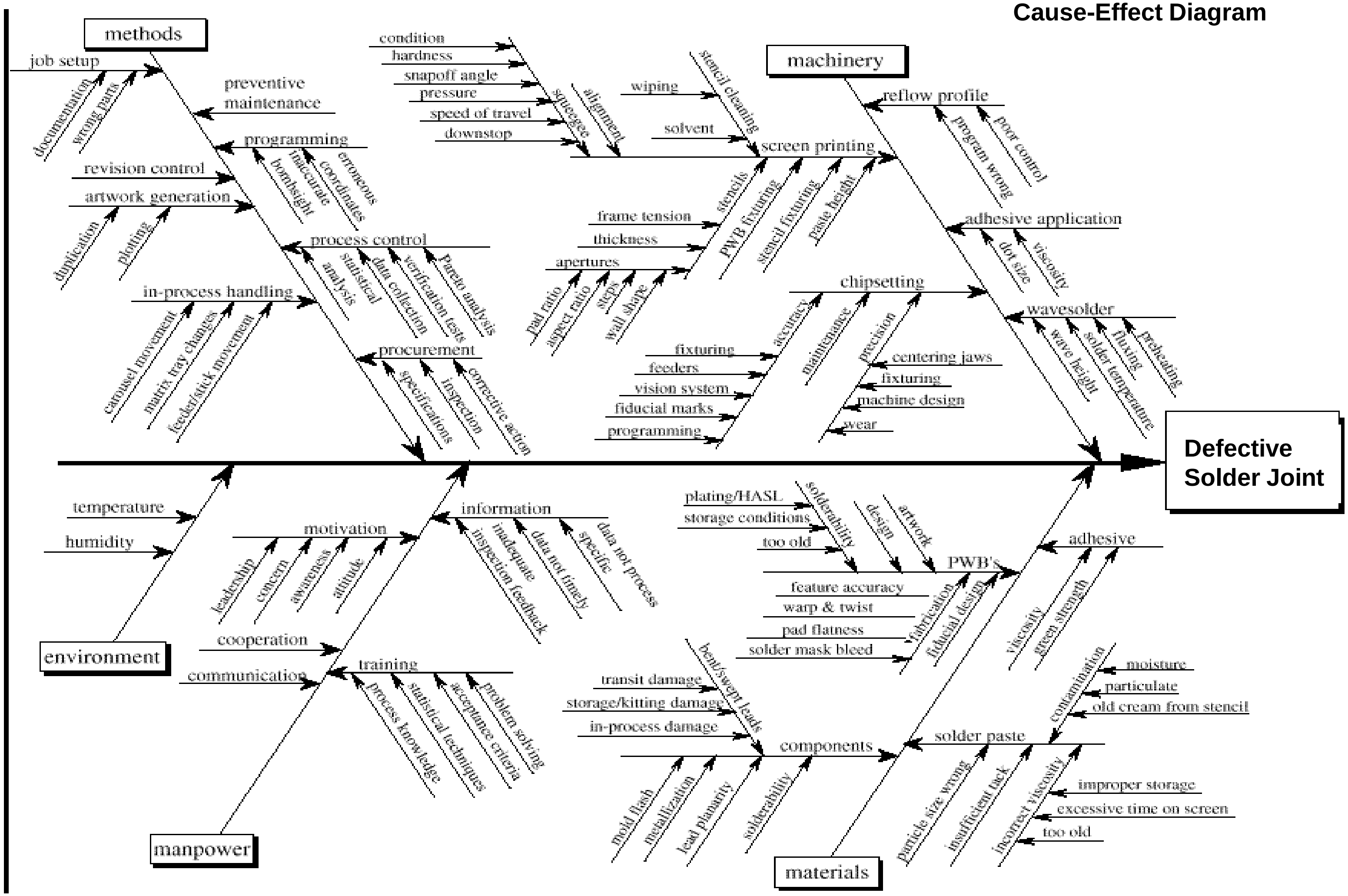
Solder - Lynchpin & Limiting Technology

- Soldering has long been a fundamental process used to perform mass assembly of electronic components
- Soldered interconnections are also commonly the limiting factor in product reliability thus improved approaches to interconnection are required to meet future requirements in a sustainable manner
- While solder made possible reliable electronic interconnections in the past with tin-lead alloys, lead-free solder is a wildcard with a thus far checkered reputation.
- The higher temperatures required and higher material and operating costs of lead free are impediments

Solder - Lynchpin & Limiting (cont.)

- There are as well intrinsic problems with solder, especially lead-free and as device contact pitch drops the limitations of solder are becoming increasing apparent.
- Presently industry journals are filled with articles on the problems of solder and prospective solutions:
  - Opens, shorts, non wetting, voids insufficient solder, excess solder whiskers, popcorning, head in pillow, pad cratering, black pad, poor cleaning beneath low standoff components, etc…
- The list things to manage and control in the soldering process is long and involved…

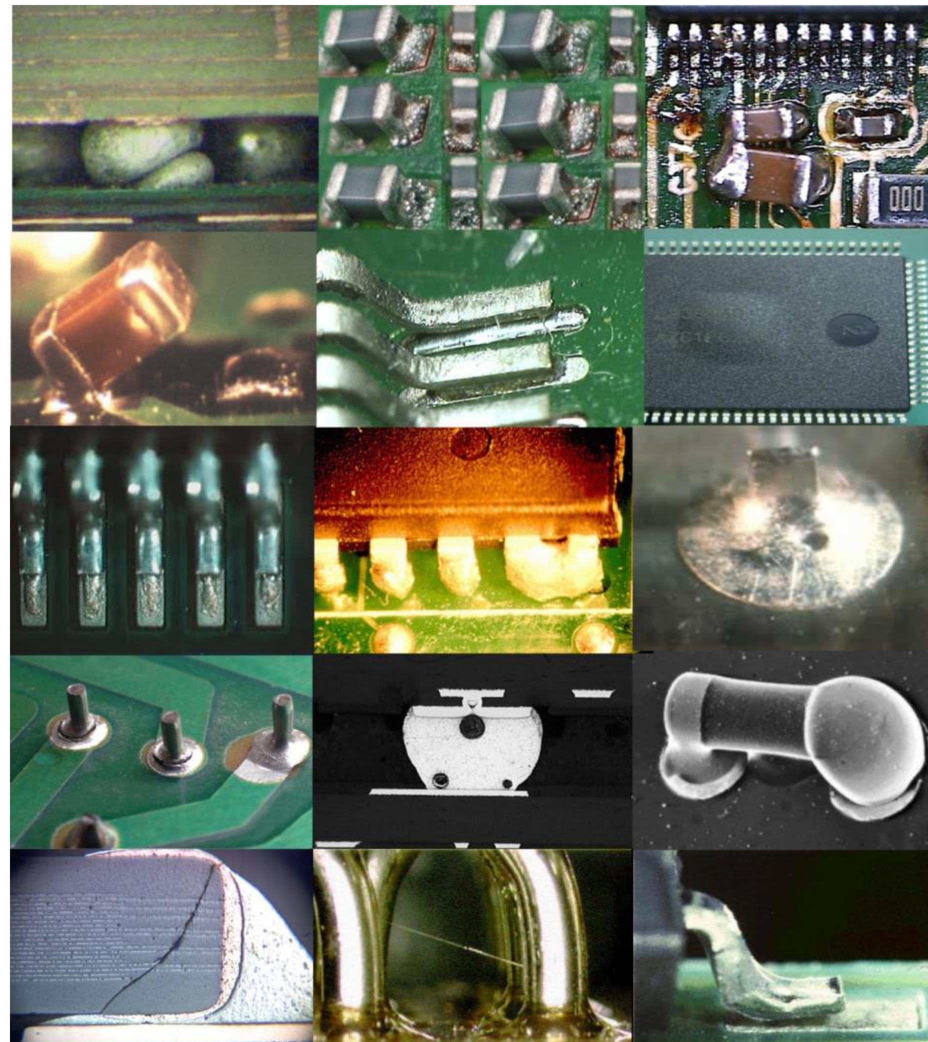
Soldering Fishbone Diagram



Source: Interphase Corporation

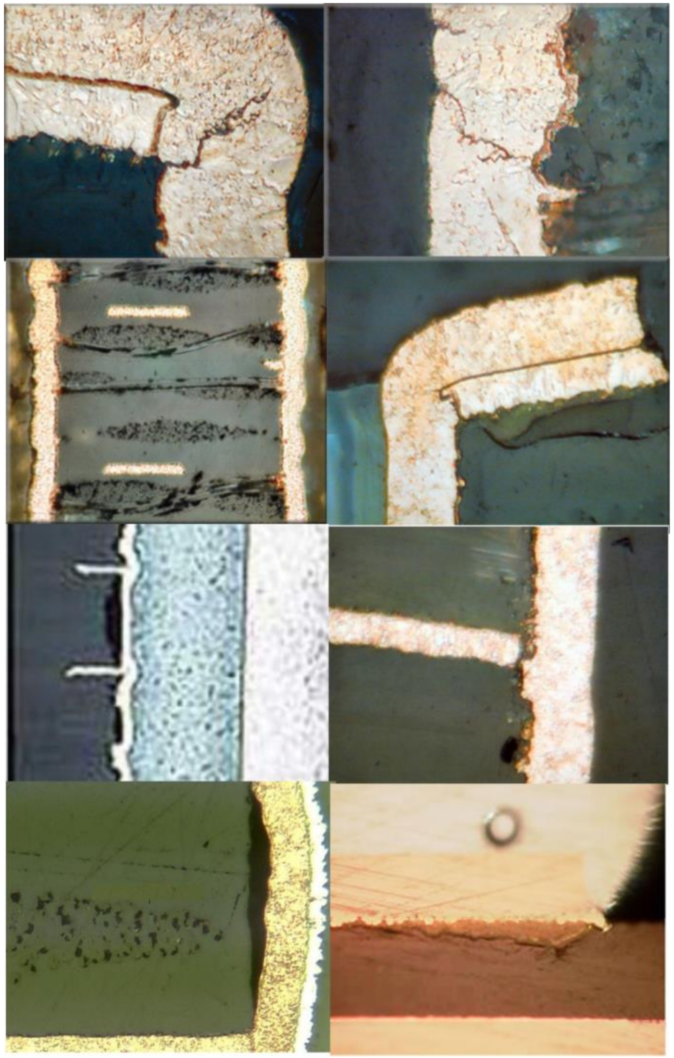
The Growing Number of Solder Related Defects

Opens and Shorts
Insufficient Solder
Excessive Solder
Solder Cracking.
Tin Whiskers
Poor Wetting/Dewetting
Voids
Blowholes
Cold Solder Joints
Brittle Solder Joints
Head on Pillow
Graping
Tomb Stoning
Component Cracking
Popcorning
Solder Balling
Misregistration
Insufficient Cleaning Under Devices

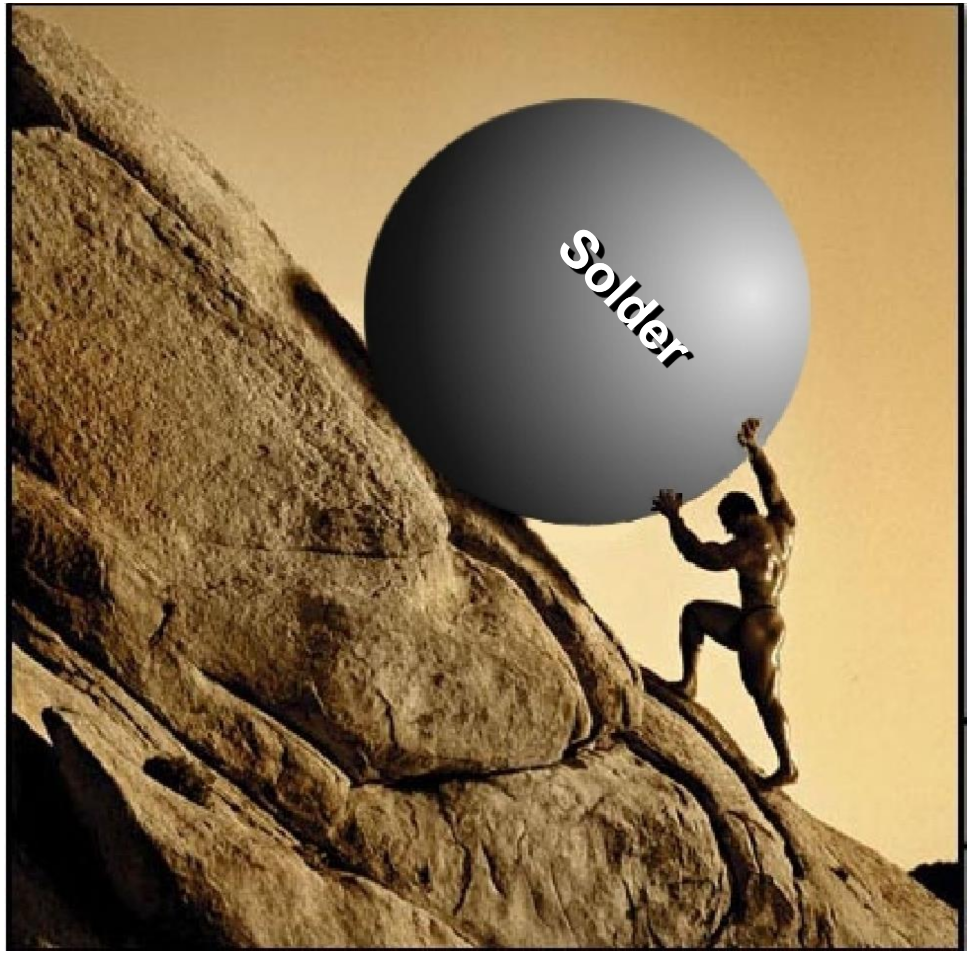


Soldering Process Related PCB Defects

Corner Cracking
Barrel Cracking
Post Separation
Hole Wall Pull Away
Resin Recession
Delamination
Pad Cratering
Decomposition



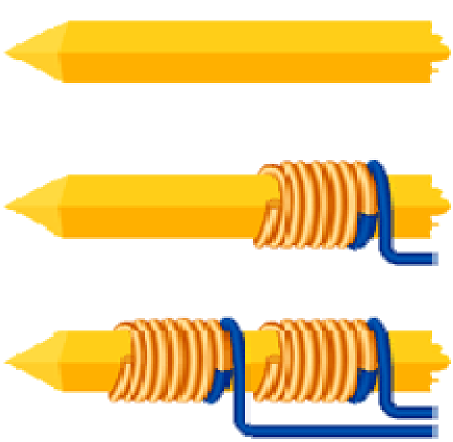
The Punishment of Sisyphus



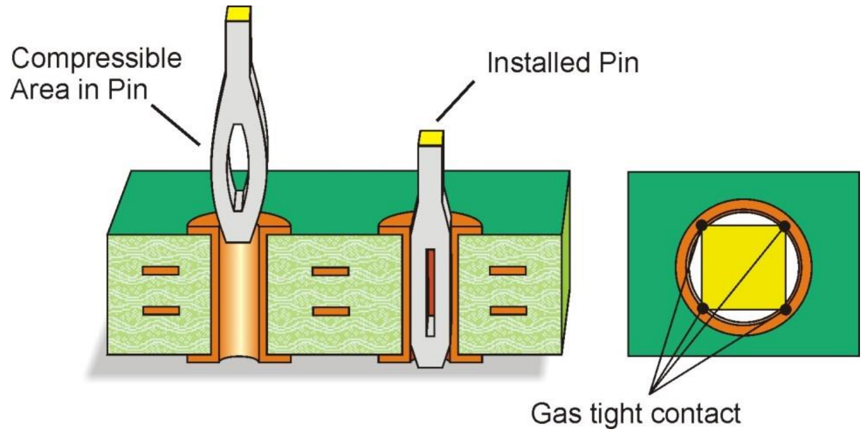
The PCB–Foundation of Electronics

- Electronics assemblies require substrates to support both the circuitry and the components which are interconnected thereon.
- Traditional substrates are composites of tailored organic resins and a reinforcing material and the most common of all is FR4 which is comprised of epoxy and glass cloth.
- Assembly is accomplished by placing components on circuit boards and then soldering them in place to make using wave or reflow methods to make electromechanical connections
- Complexity has been continually increasing but the soldering process is pressing up against the wall of practical limits.
- New circuit structures and methods will be required to meet the challenges of future generation products and they may well be produced without the use of solder.

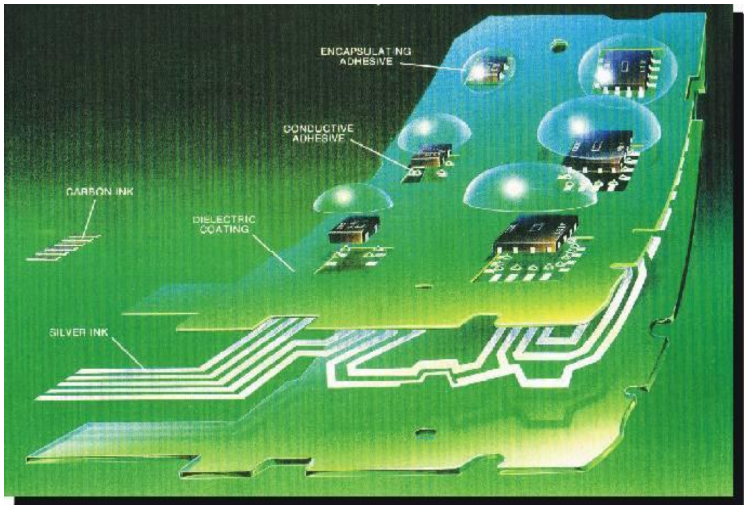
Solderless Assembly Methods



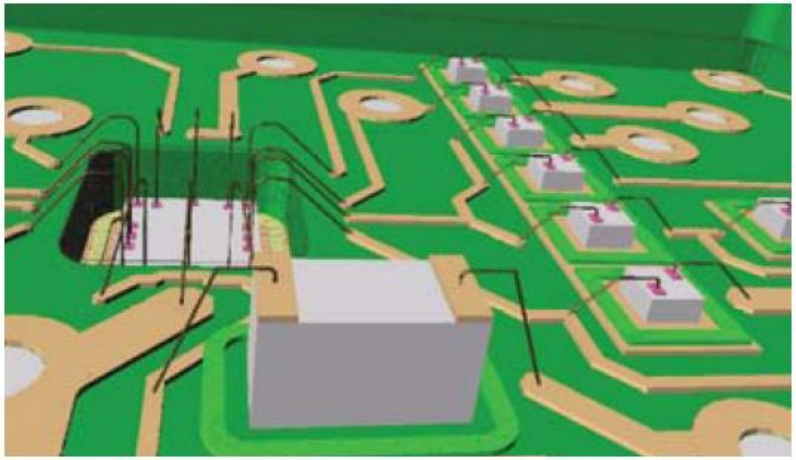
Wire wrap



Press fit

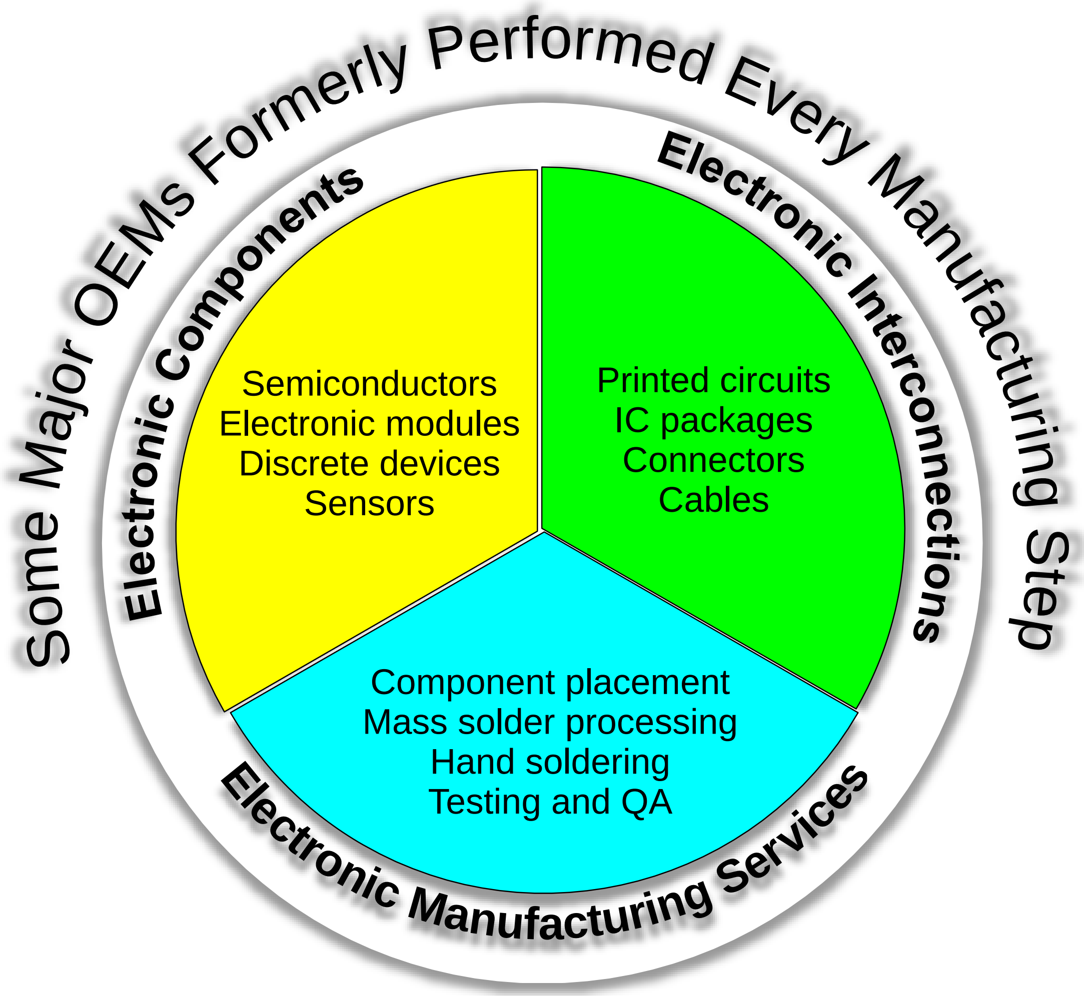


Conductive composites



Wire bond / Stitch wire

Current Electronics Industry Model



Electronics Manufacturing Steps

Design PCB Assembly	Fabricate PCB (multilayer)	Assemble PCB
1. Create schematic	1. Verify RoHS compliance	1. Procure components
2. Indentify components	2. Cut core laminas to size & tool	2. Verify RoHS compliance
3. Layout circuits	3. Clean and coat with resist	3. Verify component solderability
4. Validate signal integrity	4. Image and develop resist	4. Verify component MSL number
5. Validate design DfM	5. Etch and strip resist	5. Kit components
6. Validate design DfR	6. Treat exposed copper	6. Procure PCBs
7. Validate design DfE	7. AOI or visual inspect layers	7. Verify RoHS compliance
	8. Cut B-stage to size and tool	8. Verify PCB solderability
	9. Lay up core and B-stage	9. Verify PCB High Temp capability
	10. Laminate	10. Design solder stencil & purchase
	11. X-ray inspect (optional)	11. Develop suitable reflow profile
	12. Drill (stack height varies)	12. Track component exposure (MSL)
	13. Desmear or etchback	13. (Rebake components as required)
	14. Sensitize holes	14. Position PCB & stencil solder paste
	15. Plate electroless copper	15. (monitor solder paste)
	16. Clean and coat with resist	16. Inspect solder paste results
	17. Image an develop resist	17. (height and skips)
	18. Pattern plate copper	18. Dispense glue dots (optional)
	19. Pattern plate metal resist	19. Place components
	20. Strip plating resist	20. Inspect for missing parts
	21. Etch base copper	21. Reflow solder
	22. Clean and coat with soldermask	22. Repeat Steps 13-18 if two sided assy
	23. Image and develop	23. (second set of fixtures required)
	24. Treat exposed metal (options)	24. Perform hand assembly as required
	25. Solder, NiAu, Sn, Ag, OSP, etc.	25. (odd sized or temperature sensitive)
	26. Electrical test	26. Clean flux from surface and under
	27. Route to shape	27. Verify low standoff devices
	28. Package	28. Test cleanliness
	29. Ship	29. Underfill critical components
		30. X-ray inspect soldered assembly
		31. Identify shorts, opens, voids, missing
		32. Electrically test
		33. Rework and repair as needed
		34. Package
		35. Ship

Reversing the Assembly Process to Eliminate Soldering

1. Position & bond various tested components on a temporary substrate or permanent metal or organic carrier in up or down position depending on base

2. Encapsulate/coat the tested components in place

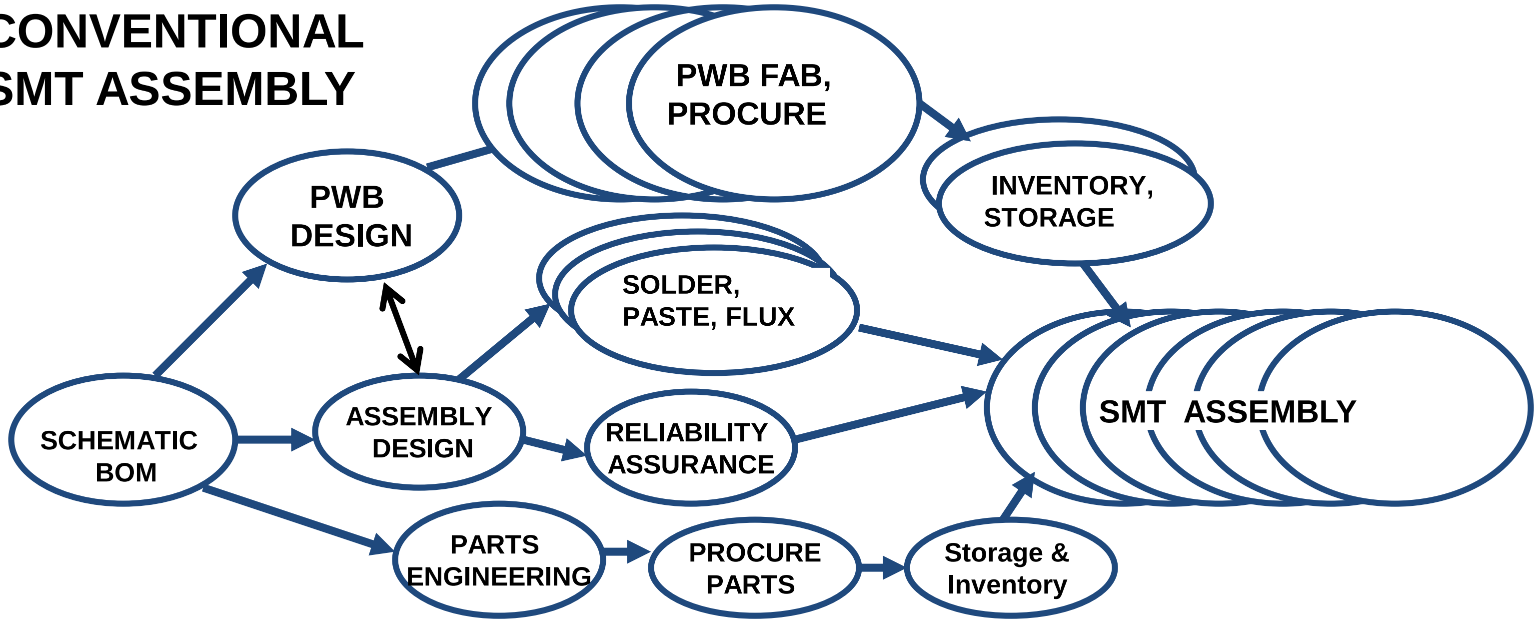
3. Expose terminations (multiple options)

4. Interconnect terminations by additive or semi-additive board fab methods, combinations or alternative direct interconnection methods. Layers required will normally be less than for standard approaches do to the lack of need for solder connection lands

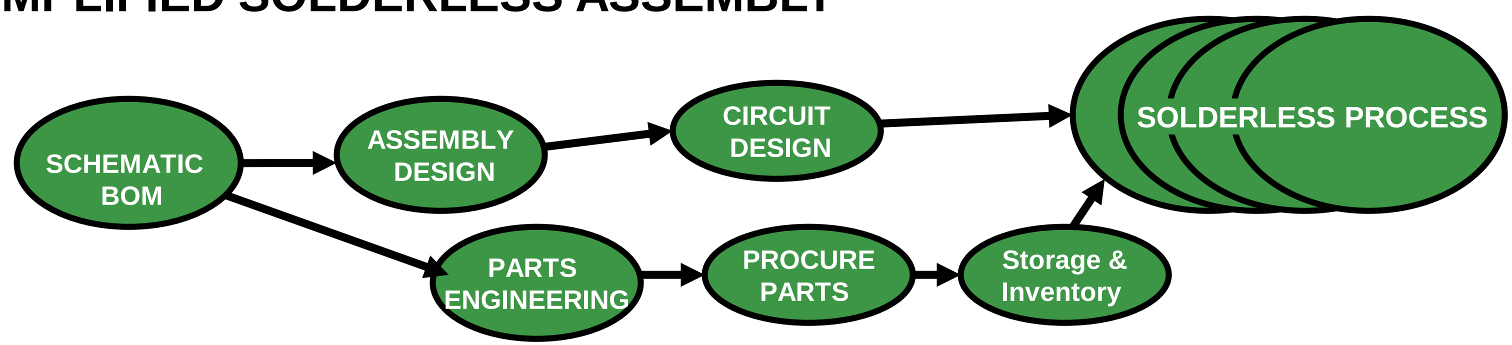
Electronics Manufacturing Alternative

Design PCB Assembly	Fabricate PCB (multilayer)	Assemble PCB
1. Create schematic 2. Indentify components 3. Layout circuits 4. Validate signal integrity 5. Validate design DfM 6. Validate design DfR 7. Validate design DfE	1.–11. [redacted] 12. Drill (stack height varies) 13. Desmear or etchback 14. Sensitize holes 15. Plate electroless copper 16. Clean and coat with resist 17. Image an develop resist 18. Pattern plate copper 19. Pattern plate metal resist 20. Strip plating resist 21. Etch base copper 22. Clean and coat with soldermask 23. Image and develop 24. Treat exposed metal (options) 25.–26. [redacted] 27. Route to shape 28. Package 29. Ship	1. Procure components 2.–4. [redacted] 5. Kit components 6.–18. [redacted] 19. Place components 20. Inspect for missing parts 21.–23. [redacted] 24. Perform hand assembly as required 25.–31. [redacted] 32. Electrically test 33. Rework and repair as needed 34. Package 35. Ship

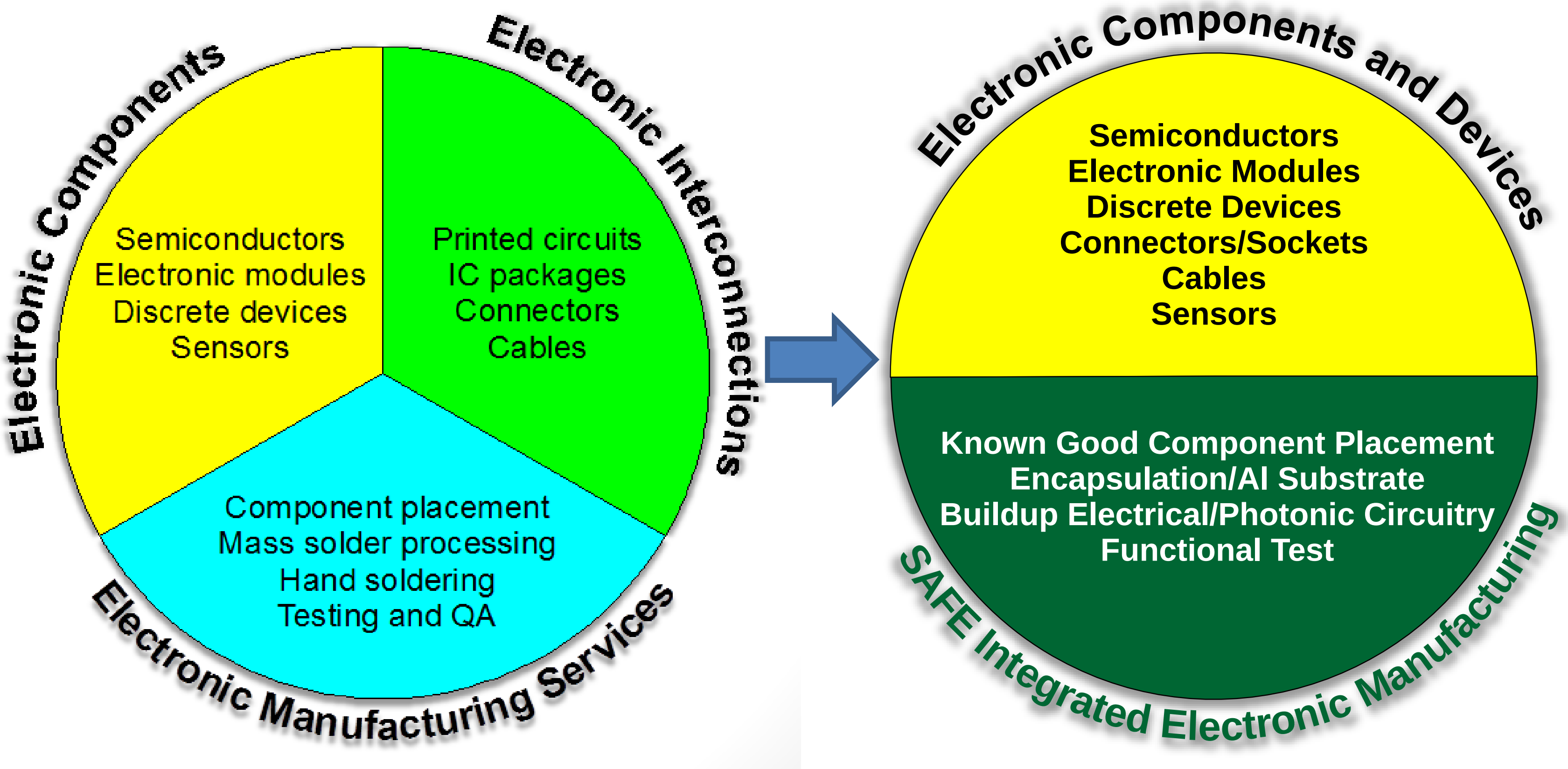
CONVENTIONAL SMT ASSEMBLY



SIMPLIFIED SOLDERLESS ASSEMBLY



Simplified Supply Chain



Aluminum – An Attractive Substrate Choice

Aluminum has **many attractive attributes** which make it an appealing circuit substrate alternative…

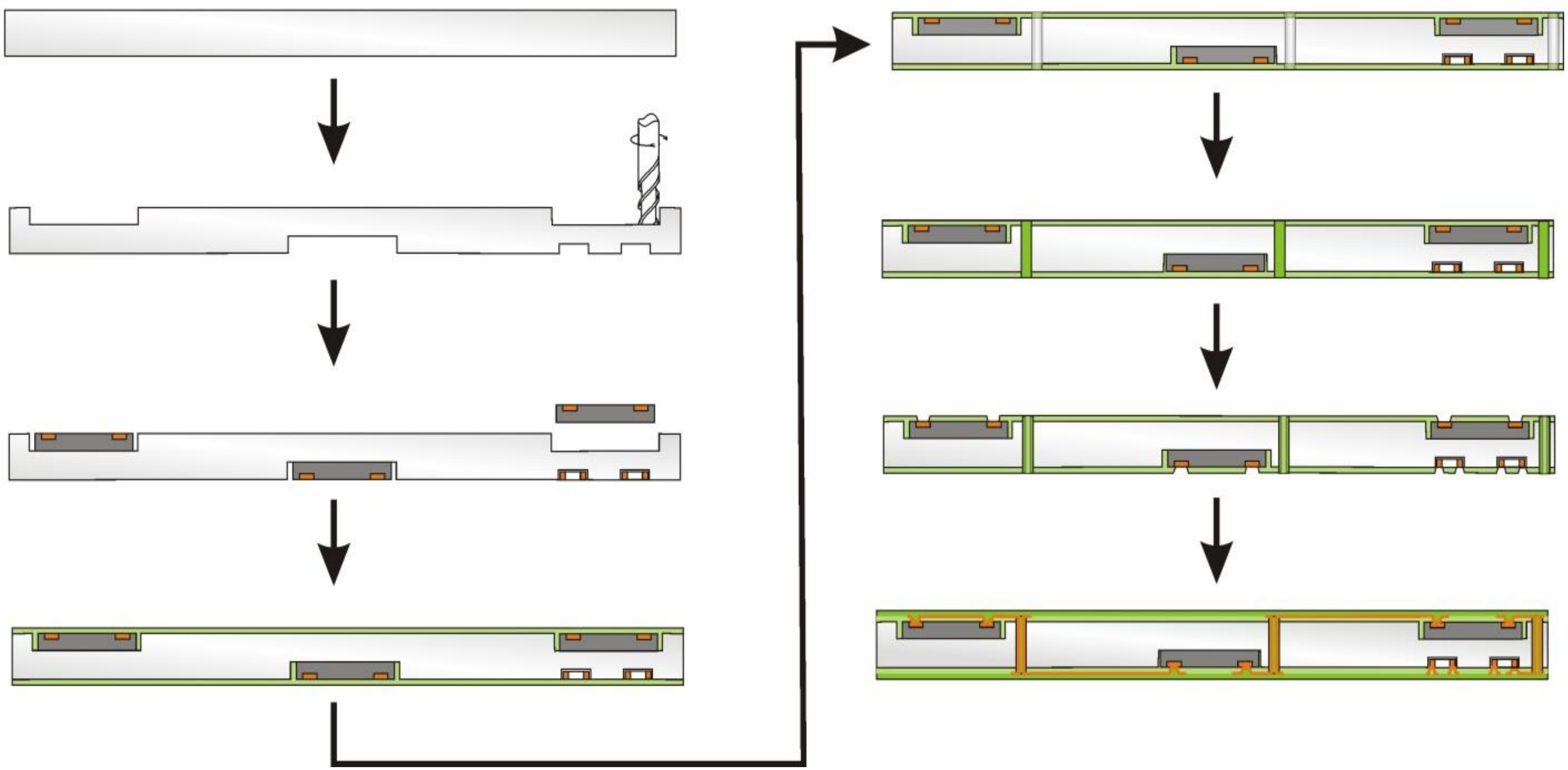
It is:

- **Abundant**: 3rd most common element (8.3 % of Earth's crust)
- **Nontoxic**/Environmentally friendly
- **Low cost**: $2.00/kg, $0.98/lb, $.015/mil/sq.ft.
- **Good thermal conductor** (~200 W/mK)
- **Relatively light we**ight (2.8g/cc vs 1.85 for FR4)
- **Dimensionally stable**
- **Good CTE** that approximates copper (22 vs 18 ppm/C)
- **Easily processed** (machined, punched, chemically milled)
- **Anodizable** to form an alumina (Al_2O_3) surface layer
- **Electrophoretically coatable** with epoxies or enamels

What Limits the Use of Aluminum?

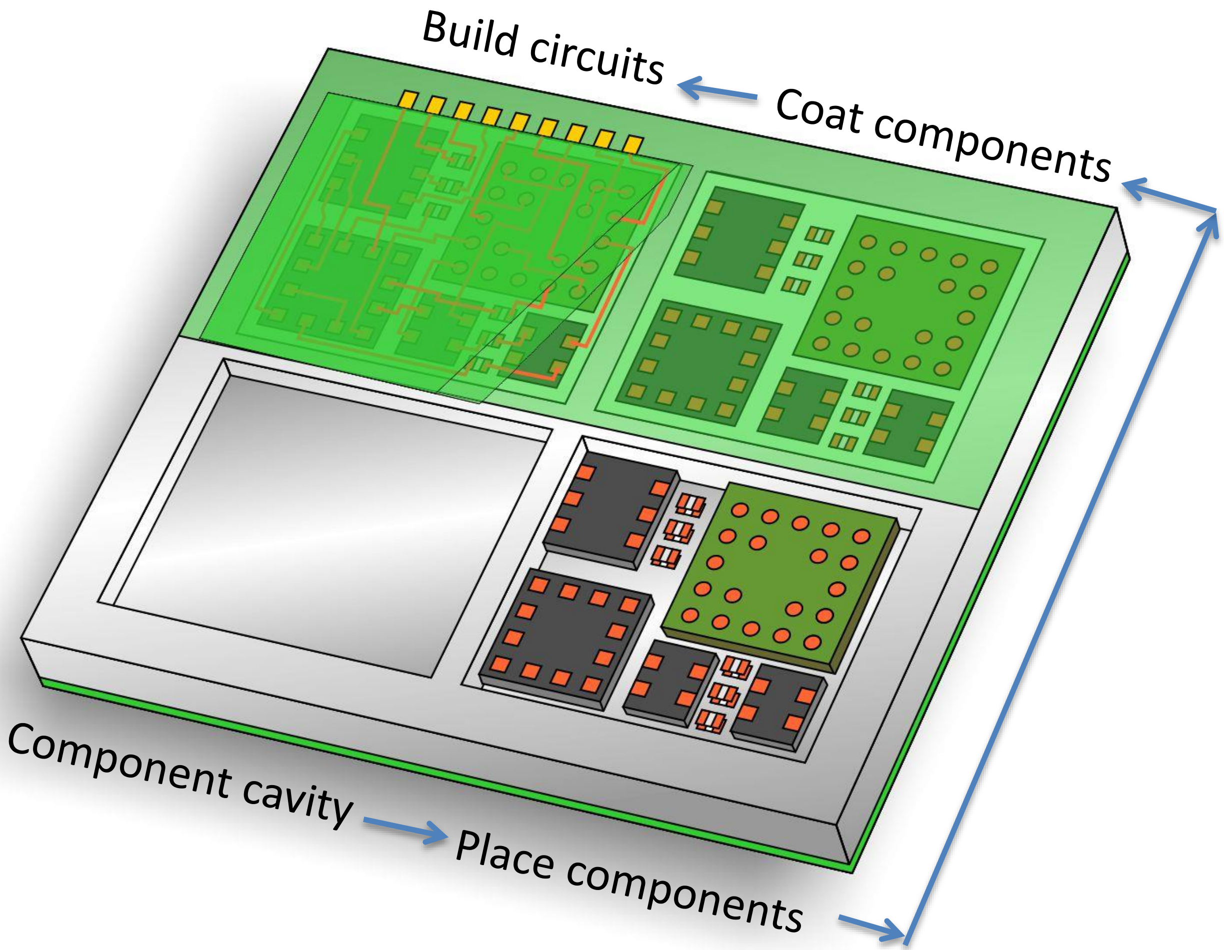
- Aluminum has be used in only a relatively few applications for a few compelling reasons, most notably is its high thermal conductivity which makes soldering challenging to difficult in the best of cases and nearly impossible in others.
- Good thermal conductivity increases the risk of the assembler forming cold joints on the one extreme and thermally damaging components at the other if dwells are excessive.
- Thus with some notable exceptions, such as for LEDs most designers have determined it is easier to use traditional laminates and then solve the thermal management issues associated with the assembly upon completion.
- Aluminum can be used effectively if the designer is willing to think differently about the process of assembly, specifically by reversing the process and instead of placing components on circuit boards, building circuits on component boards…

Aluminum Process Example

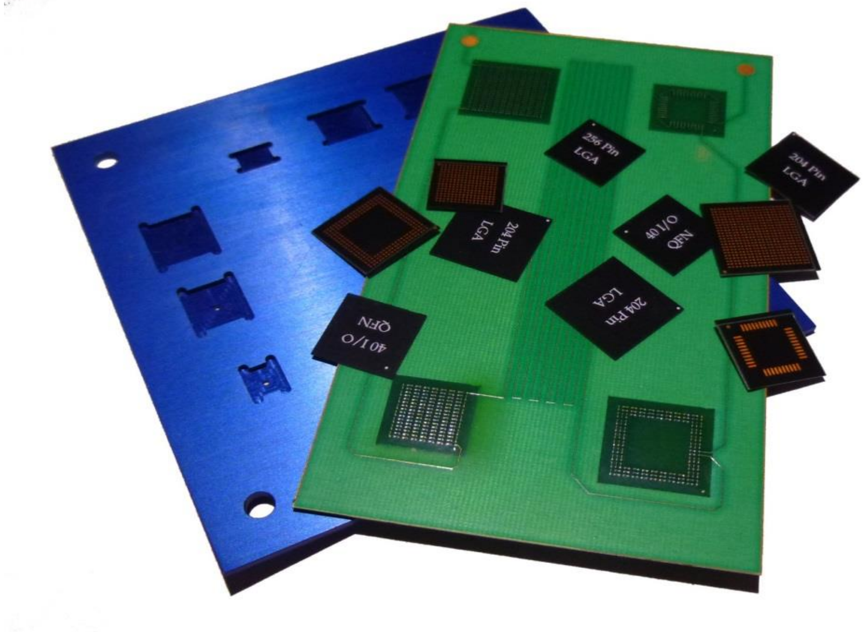


Patented

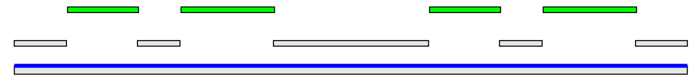
Processing Sequence



Aluminum Test Circuit Manufacture



1

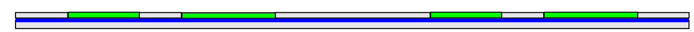


Prepare daisy chain parts and aluminum layers. Top layer has holes to contain parts Bottom layer is coated with pressure sensitive adhesive. Both layers have tooling holes

2

First laminate aluminum pieces and then place components

3



Press to level

4

Coat with suitable material (e.g. polyimide film, solder mask, etc.

5

Access terminations on daisy chain parts by laser or photoimagin

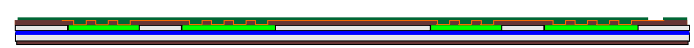
6

Electrolessly plate with copper and flash

7

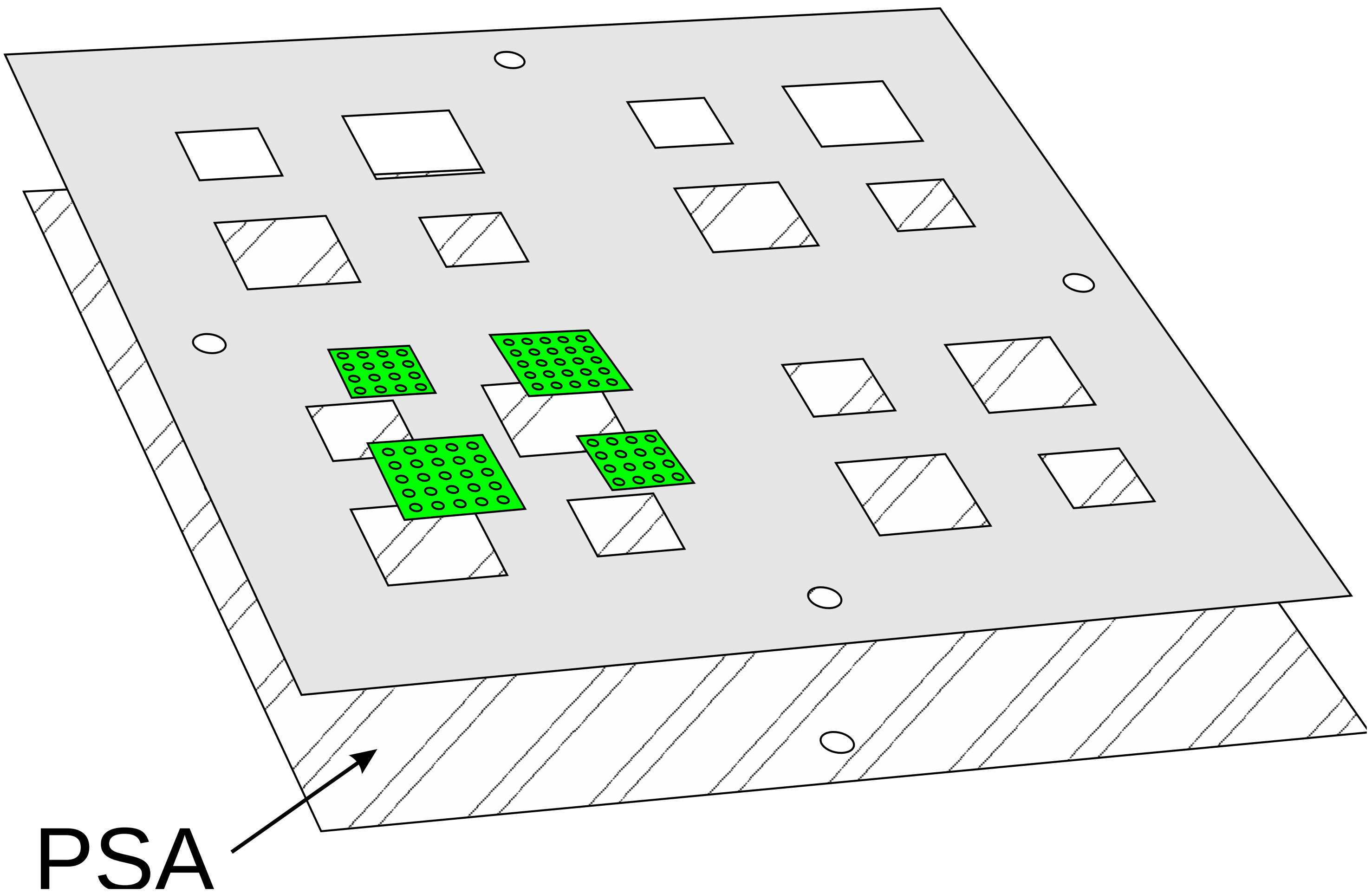
Pattern plate or print and etch

8



Coat exposed circuits with mask leaving open test contacts

Simple, low temperature processing…



Solder Alloy Free Electronics (SAFE) Infrastructure Exists Now

- Components can be placed conventionally
- More potentially useful materials available
  (Need not withstand leadfree soldering temperatures)
- Low pressure molding options available
- Numerous circuit processing options possible
- Semi-additive fabrication well established
- All copper interconnection system possible
- Appropriate for all classes of products including flex
- Testing and rework... Philosophical concerns?

Solderless Assembly Benefits

- **No PCB required**
  - No procurement, shelf life, testing, environmental related issues
- **No soldering required**
  - Multiple steps obviated, weak link eliminated, no high temp exposure
- **Reduced component concerns**
  - Leadless devices, MSL 1, all copper, no high temp damage, low profile
- **Increased product design security**
  - Component detail hidden
- **Integral thermal management**
  - Aluminum substrates – high conductivity and close CTE match to Cu
- **Enhanced reliability**
  - Simpler, temperature process, no solder joints, no CAF, ESD & EMI mgmt
- **Multiple novel structure options possible**
  - Stacked assemblies, rigid flex assemblies, optical pathways

Designing without Solder
Advantages and Considerations

Material Selection

Many options are possible…

- Low temperature processing opens doors to alternatives…
  - Polyester - Good electrical properties, low cost
  - Photoimagable soldermask – no laser required.
  - Thermoplastics – tailored properties possible
  - Inkjet printed polymers and conductors.

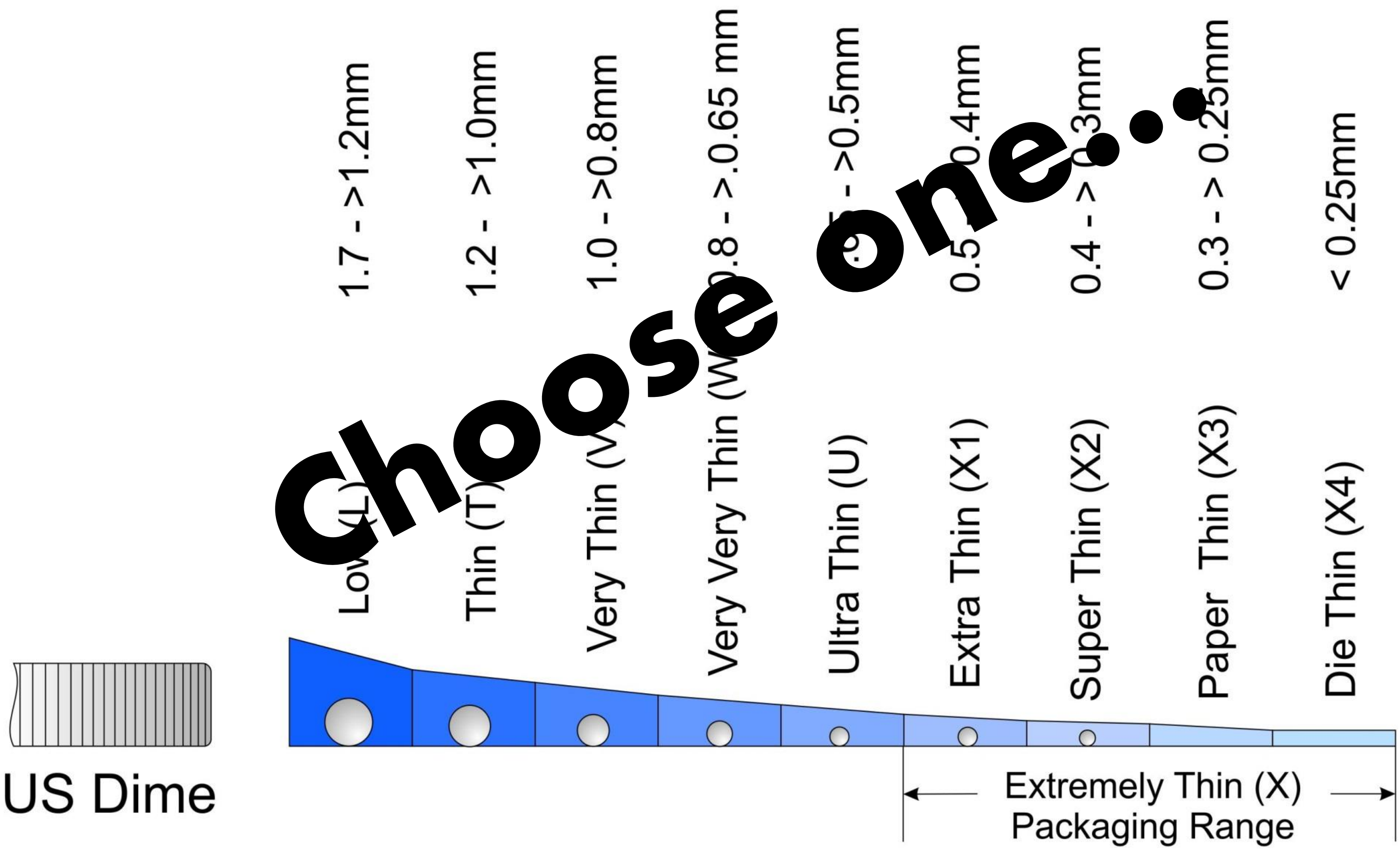
Component Selection

Ideally…

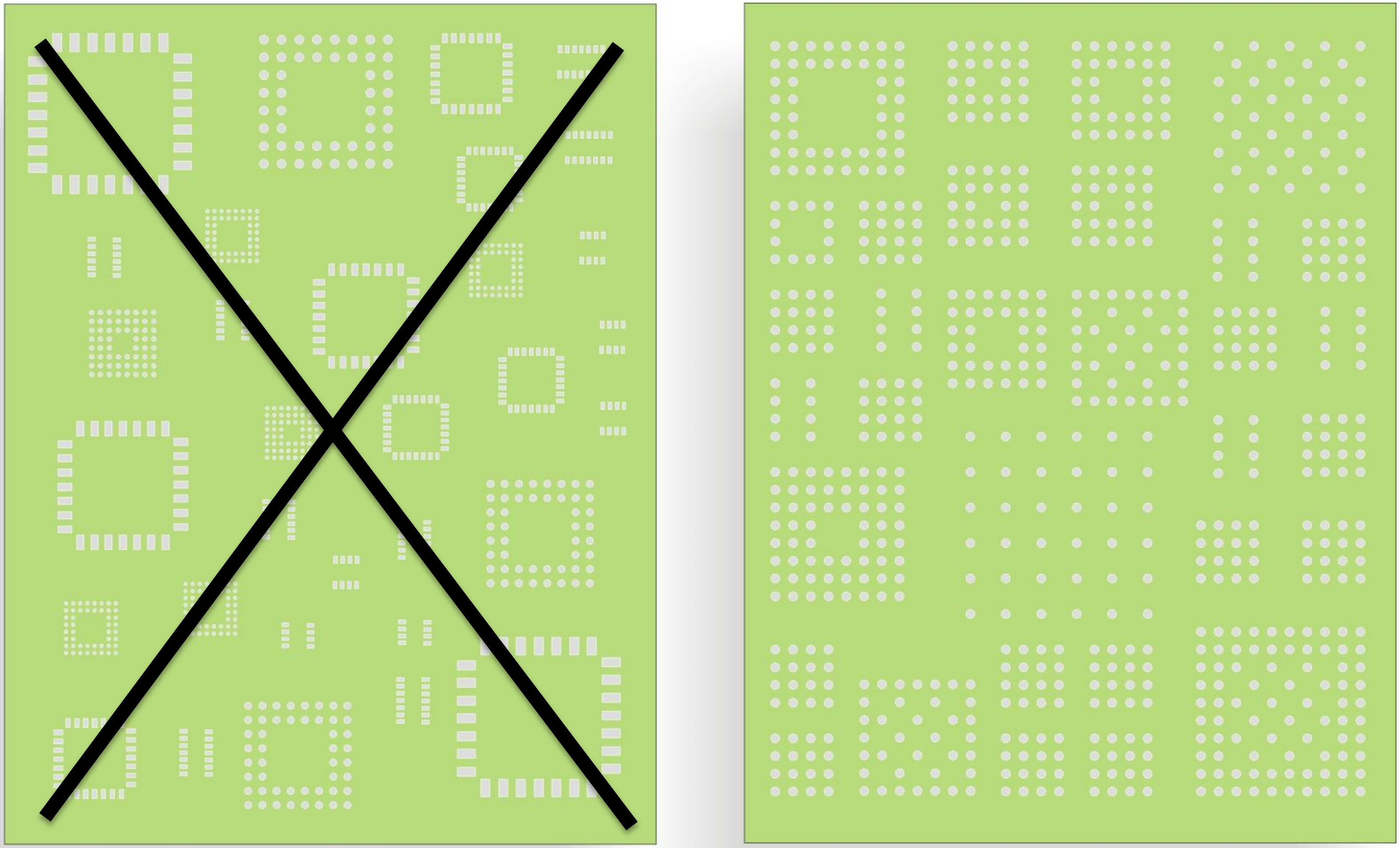
- only components with planar leads (LGA & QFN)
- only components with a common lead pitch (0.5mm) to reduce circuit layer count
- only components with a lead finish
- only burned in and tested components
- only components with a common height

Upgrade Your TECH[nowledgy] IPC APEX EXPO 2015

JEDEC Registered Package Thicknesses



Common Land Pitch Preferred

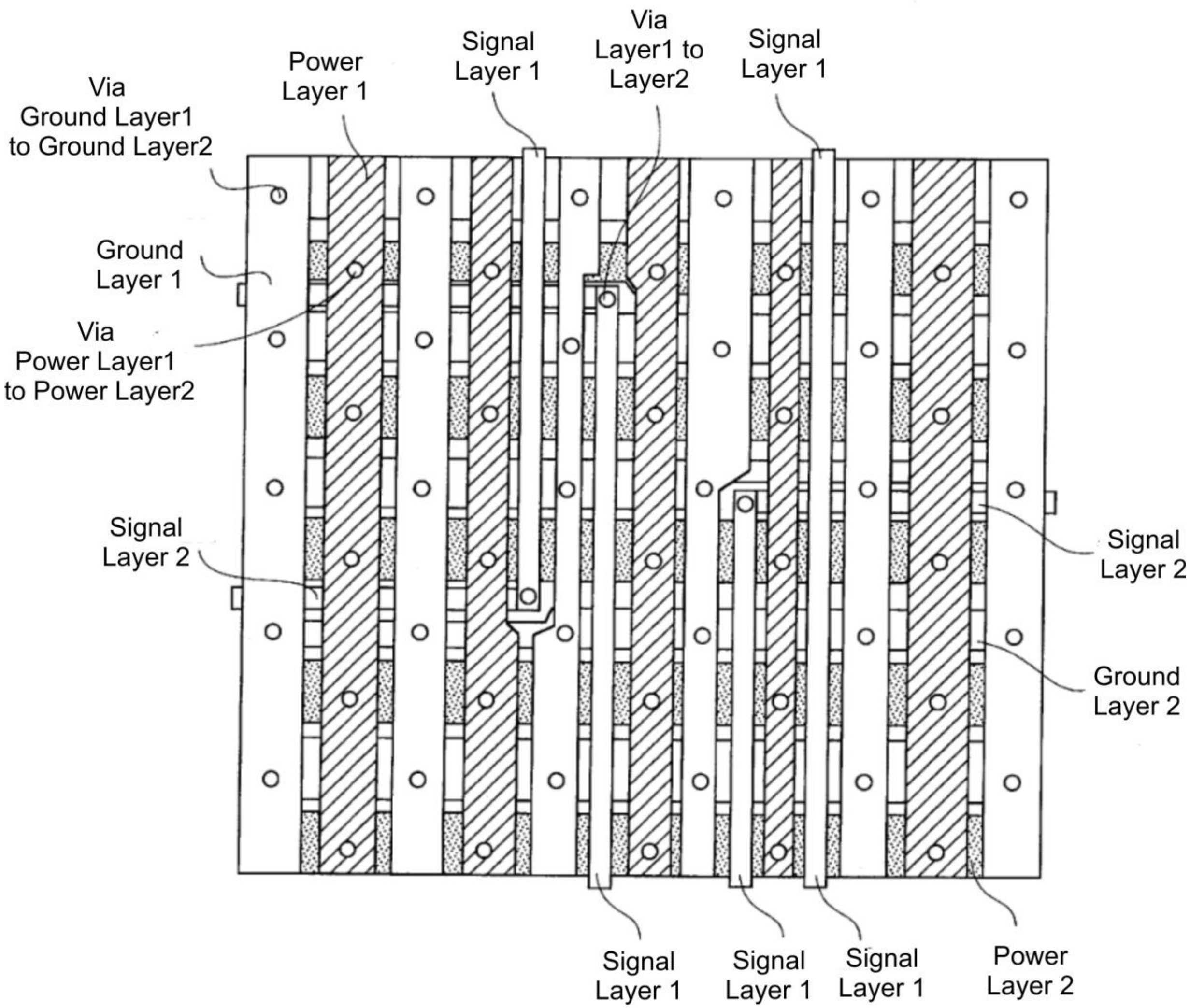


Circuit Routing Options

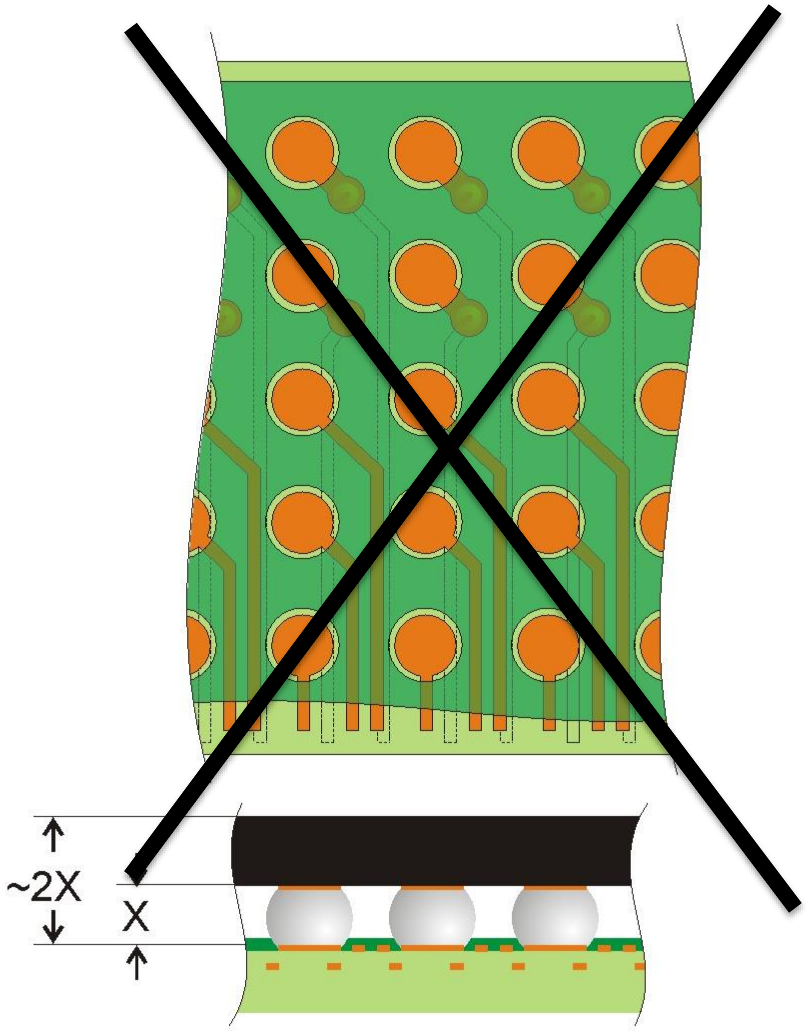
Ideally…

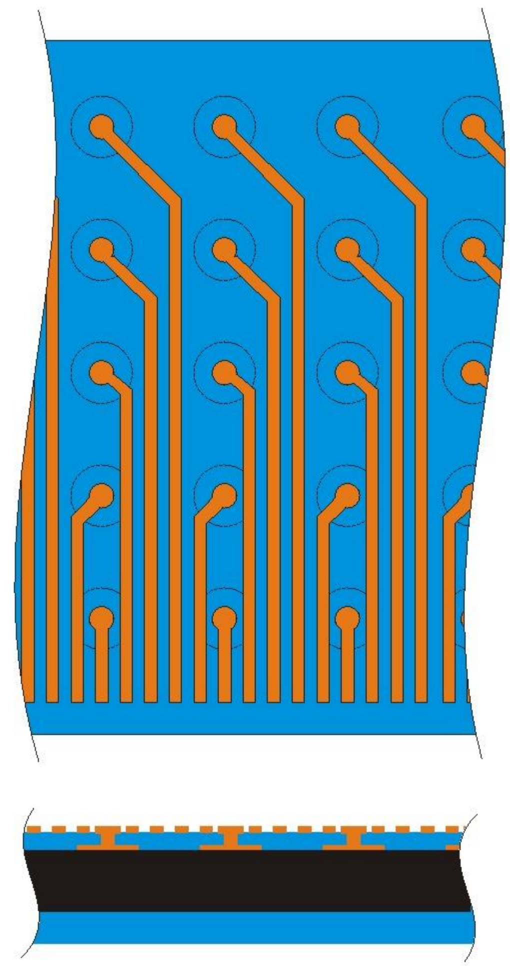
- Consider using Integrated Mesh Power System (IMPS) and standard grid components
- Land terminations can be vias only to improve routing
- Ignore terminations on non-functional lands
- Make layer to layer terminations using via to trace
- Consider using vias as resistors

Integrated Mesh Power System Design

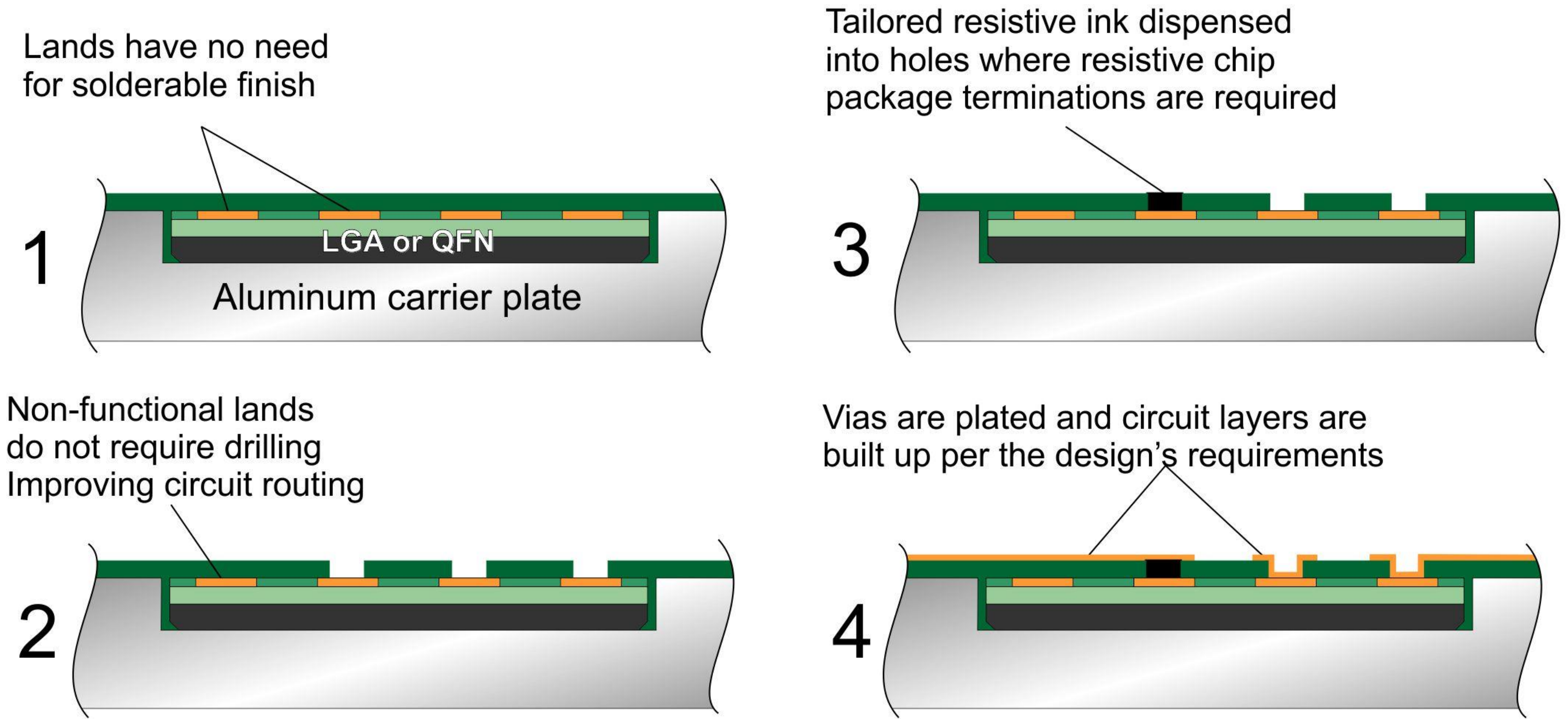


BGA Routing Advantage

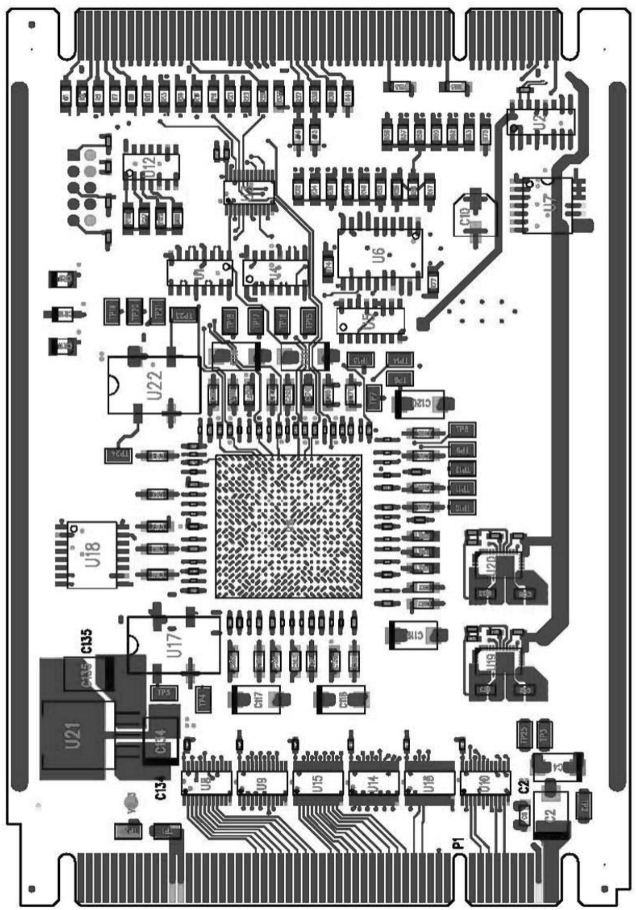




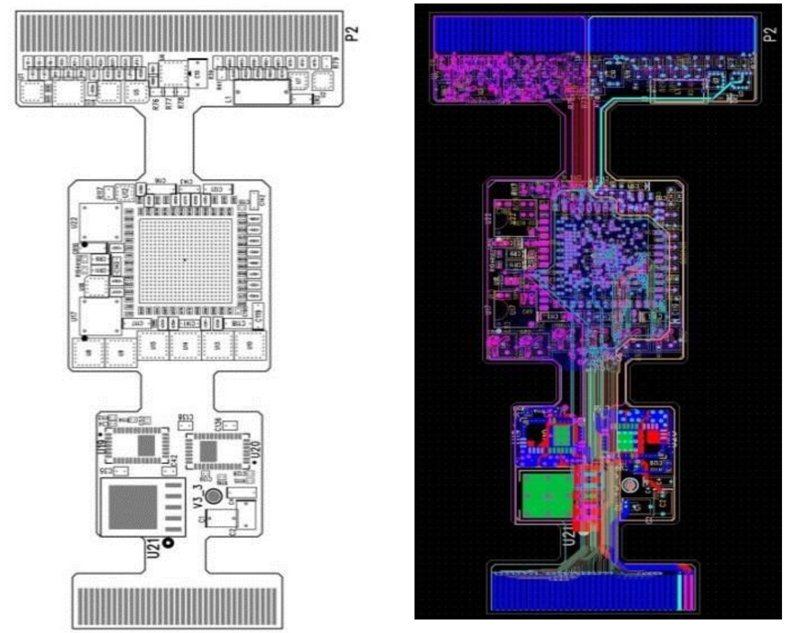
Integrated Resistor-in-Via Processing



SAFE Design Exercise

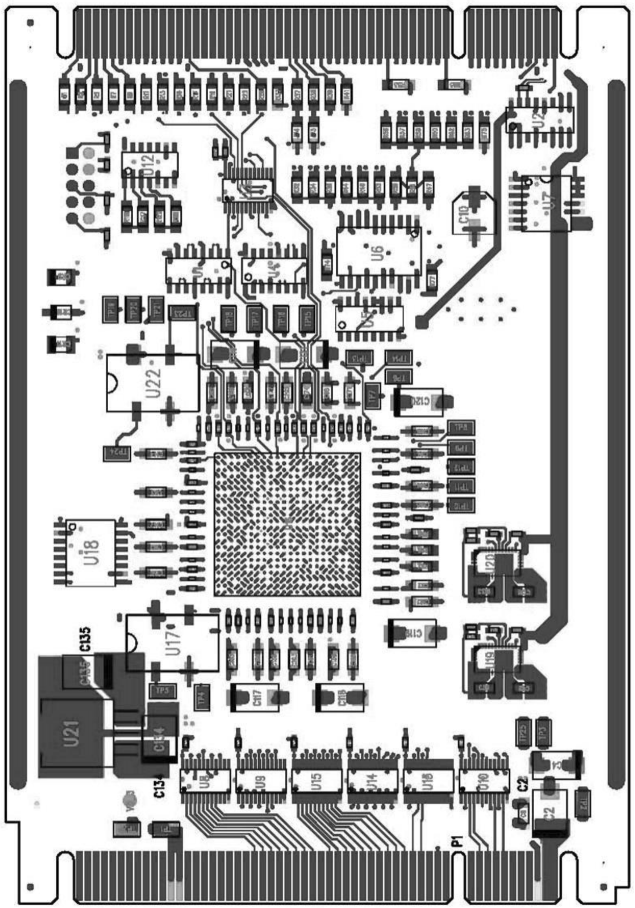


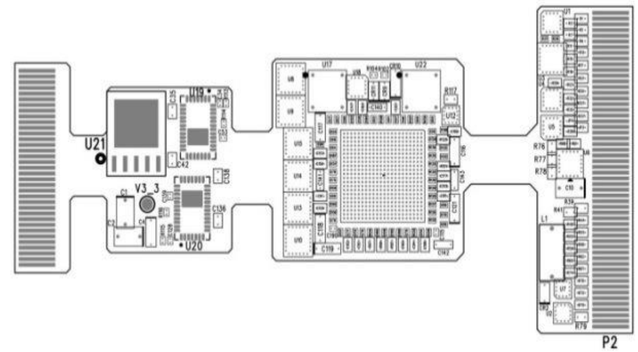
140 x 100mm 12 layer rigid board
442 FPGA 0.8mm pitch



6 layer Rigid-flex SAFE Assembly
~30mm X 40mm (when folded)
All components on 0.5mm pitch
50μm line/space with 50μm vias

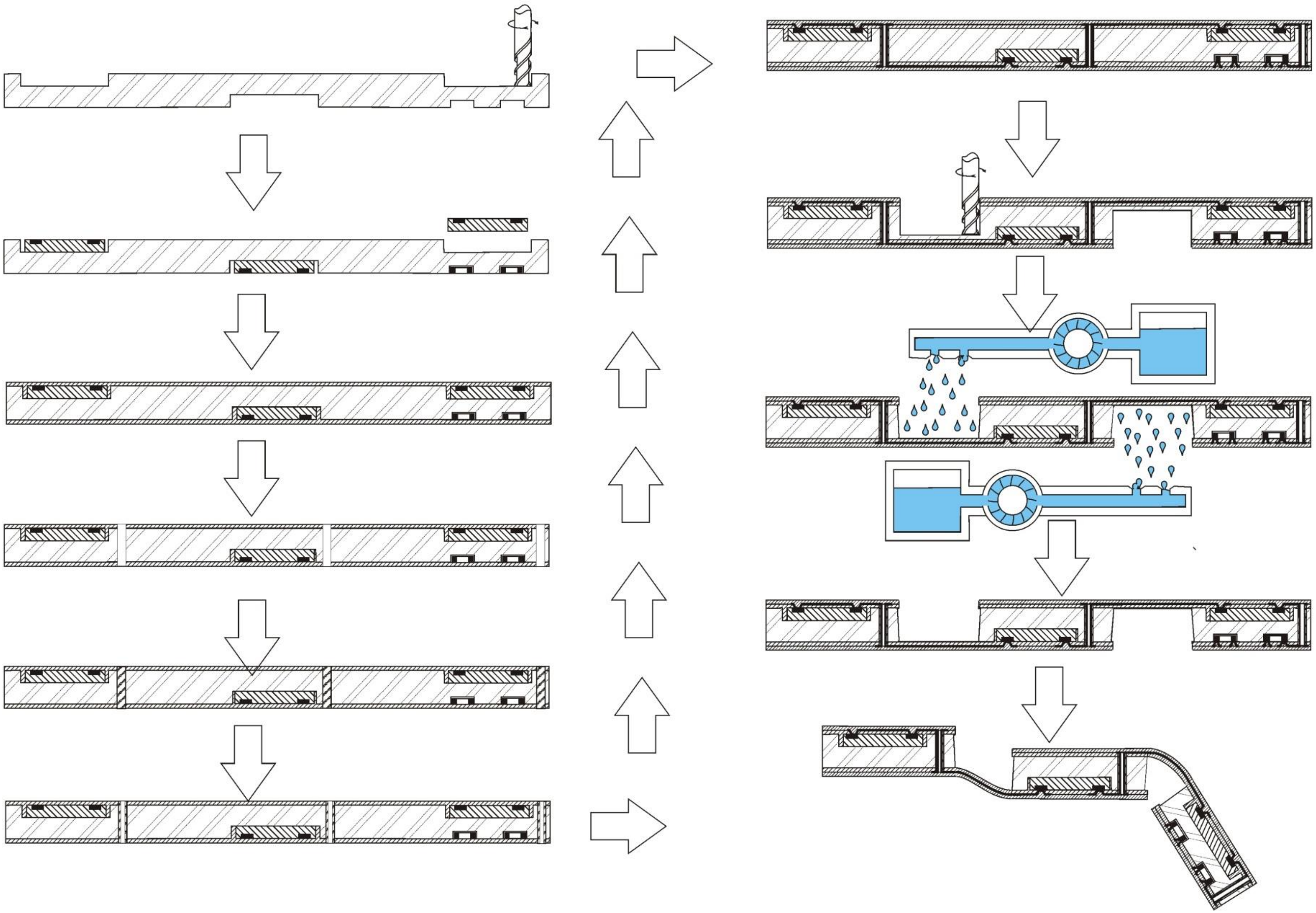
SAFE Design Comparison Details





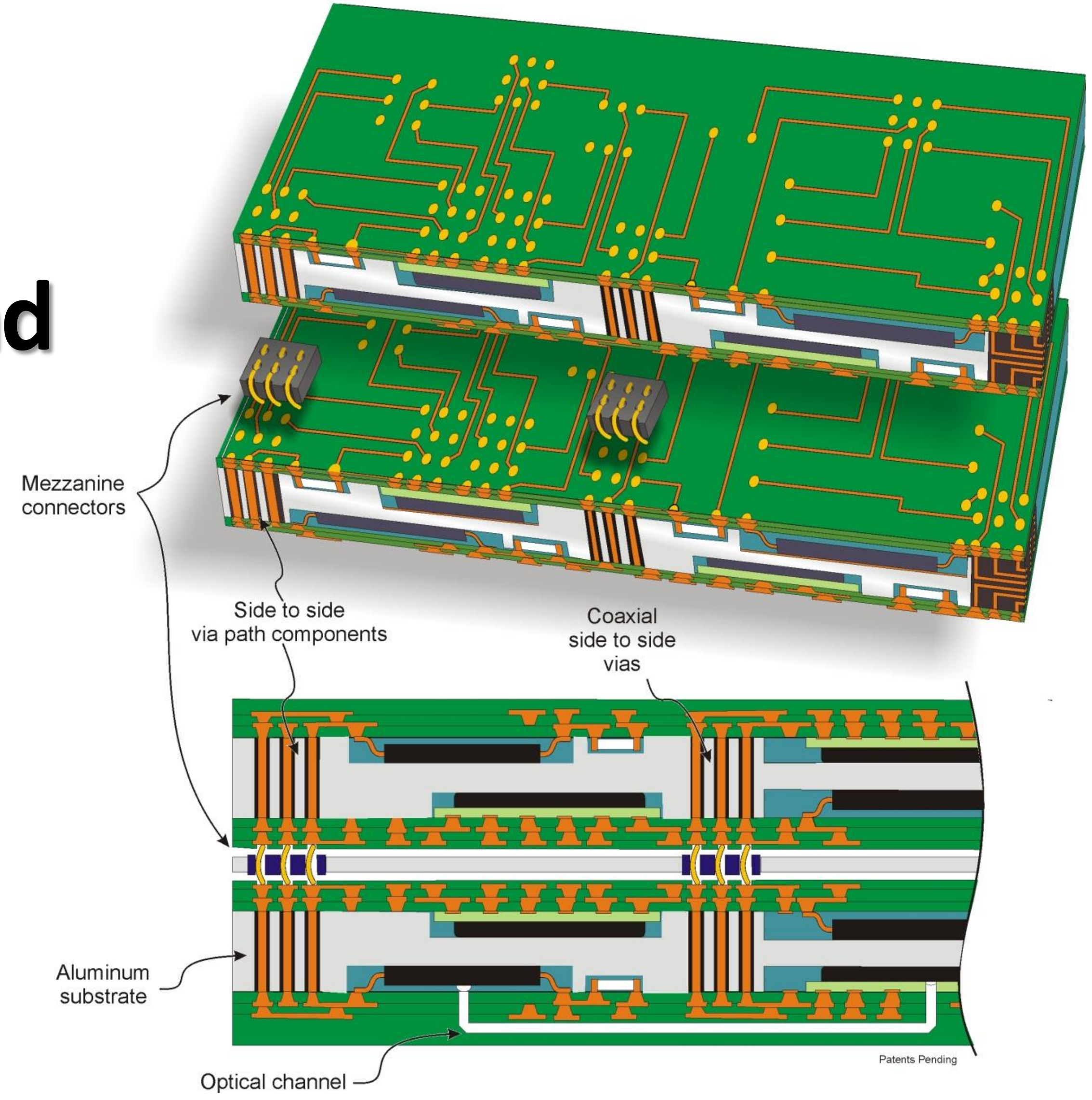
- Design is ~70% smaller in terms of total area
- Folds into an assembly with footprint ~20% of original design with minimal increase in height.
- Though the density of aluminum is higher than FR4, (FR4=1.8 gr/cm3, Al=2.7gr/cm) the total weight of the assembly is projected to be ~55-65% less than the original.
- Rigid flex structure is amenable to the separation of digital and analog circuity and thus the potential for better control of the energy created by analog devices and power supplies.

Aluminum Core Rigid Flex Assembly

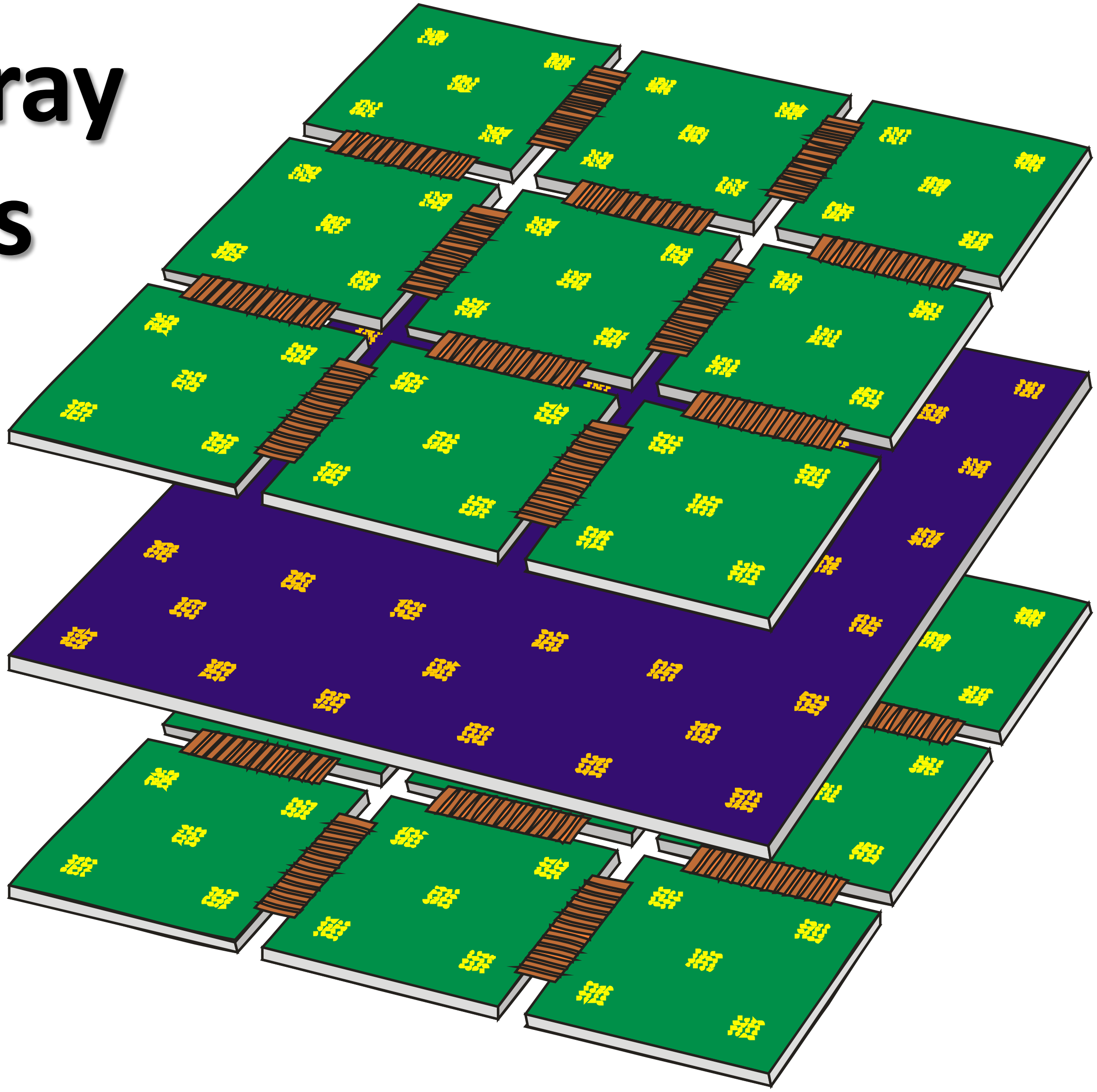


Structural Design Opportunities for Aluminum

Other Design Possibilities and Prospective Benefits

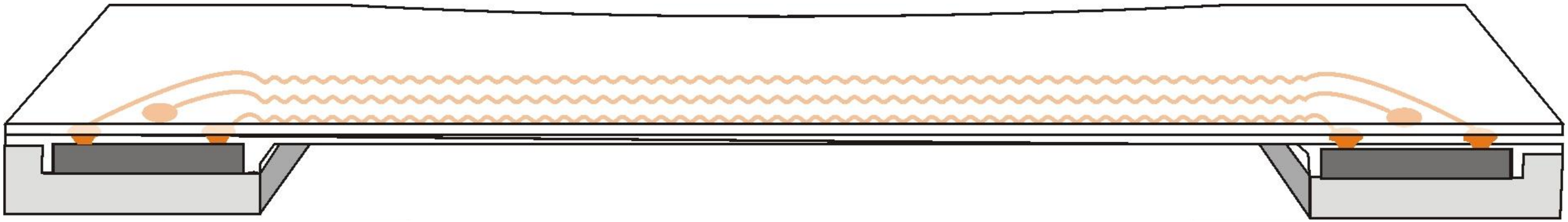


Modular Array Assemblies

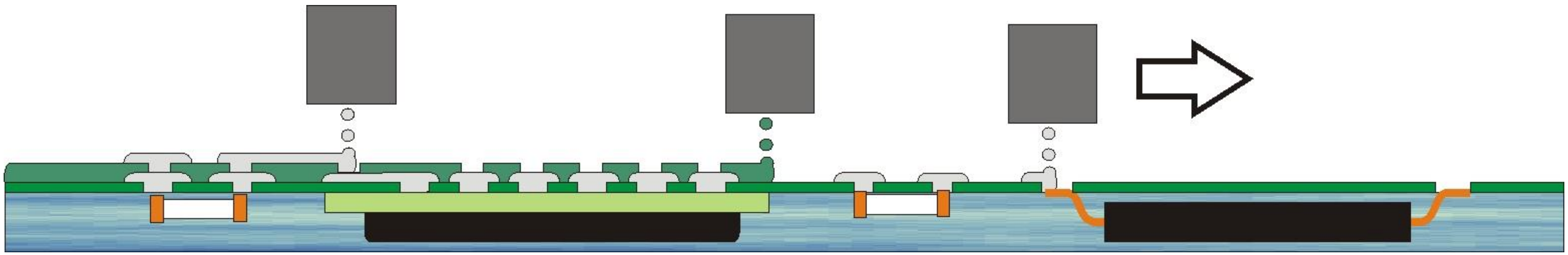


Out of Plane Stretching Methods from the Past

Solderless Stretchable Rigid Flex Circuit Processing

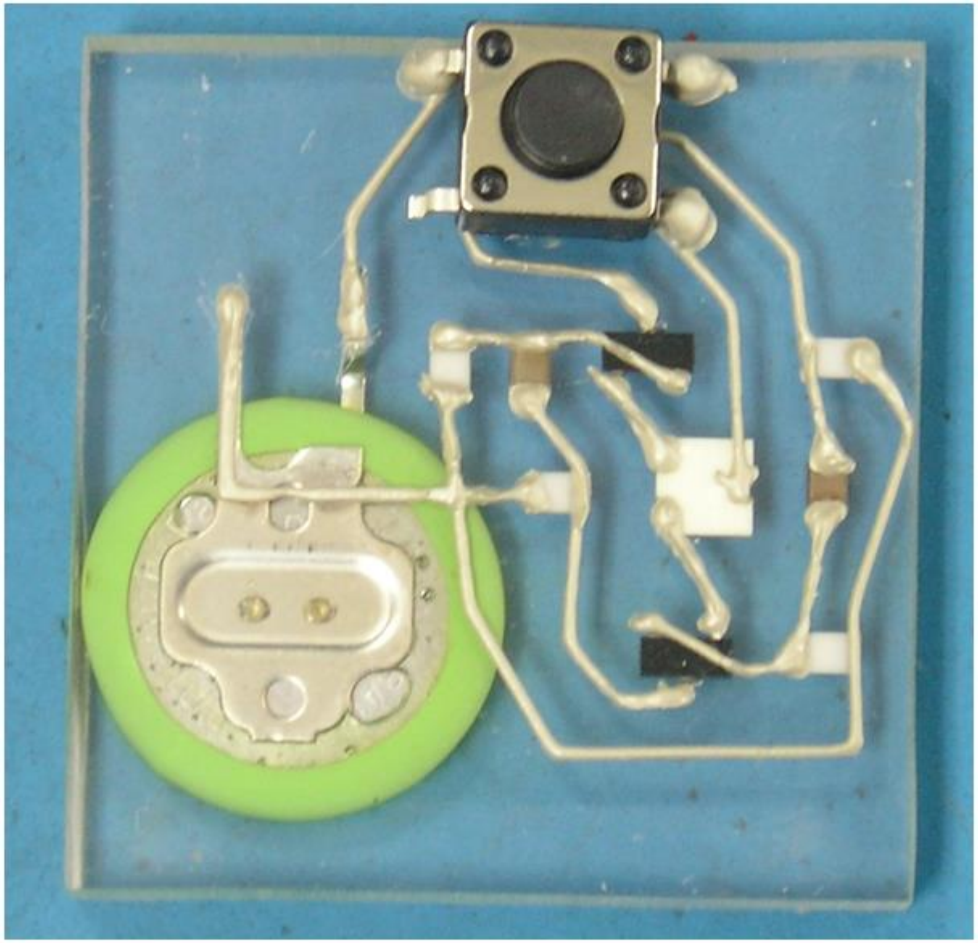


Direct Write Prototyping without Solder



With parts in hand, first prototypes could possibly be completed in hours rather than days, weeks or months

Printing Conductive Inks on Embedded Components



Printing stretchable inks on elastomer bases potential

What about testing...?

Testing is believed to be critical… Why?

- Most testing is predicated on the anticipation of manufacturing related defects and faults
  - Shorts and opens are accepted as facts of life
  - Lead-free assembly damage to assembly components
  - Thermal excursions reduce product life
- Current assembly technology has limits below 0.5mm pitch
- Simpler processes should yield higher and be more reliable
- The ultimate test is assembly turn on

Question…

Can time and money used for test be better allocated?

Summary

- Elimination of solder from the manufacturing process could, at once: increase design efficiency by opening up space for circuit routing while reducing the size and volume of the resulting assembly compared to traditional/standard methods
- Elimination of solder also obviates one to the major causes for failure of electronic products both in process and in use. It also would obviate most concerns related to RoHS
- Simplicity is at the center of the concept, but ironically, to achieve simplicity requires greater design and manufacturing discipline.
- Economics will ultimately dictate the methods used in electronic manufacturing

Thank you…