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The Evolution of ICT: PCB Technologies, Test Philosophies, and Manufacturing Business Models Are Driving In-Circuit Test Evolution and Innovations

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Abstract
Many manufacturers employ one or more In-Circuit Test (ICT) systems in their PCB manufacturing facilities to help them detect manufacturing process and component defects. These "bed-of-nails" electrical test systems are highly valued for providing the qualities of simple program generation, high fault coverage, fast test throughput, low false fail rates, and exceptional diagnostic accuracy as compared to other available test and inspection techniques.

Advancements in PCB technologies, along with changing test philosophies and manufacturing business models in recent years have created new and diverse requirements for manufacturers of in-circuit test systems. Particular challenges that ICT manufacturers have had to address include the erosion of test point access in certain product sectors; the progression of ultra-low voltage components; the variable test requirements of different product applications; the varying test philosophies of different market segments and different manufacturing regions; and the demanding throughput requirements of high volume production facilities.

This paper highlights how in-circuit test systems have evolved in recent years to include innovations and advancements to address these challenges and trends. Topics that will be covered include boundary scan and functional test integration strategies; advancements in vectorless test techniques; incorporation of limited access electrical test techniques; test strategy analysis tools; high accuracy pin drivers and sensors; concurrent test throughput improvement options; scalable test performance capability architecture; and program development accelerators.

The paper describes how these new ICT advancements contribute to lowering overall manufacturing test costs by improving the fault coverage, reliability, and throughput of in-circuit production tests.

Introduction
When in-circuit test systems were first introduced in the late 1970's, the world was a different place. Printed Circuit Board Assemblies (PCBAs) used through hole technologies, spacing between pins was typically 100 mils, components were only placed on a single side, the largest components rarely had more than 14 pins, the prevalent voltages used to power the boards were 5, 12, and 15 volts, manufacturing occurred in the highly industrialized regions where the products were consumed and manufacturing test consisted primarily of the execution of complex and time consuming functional tests.

The introduction of in-circuit test systems revolutionized the PCB manufacturing process by changing the test paradigm from testing the functionality of the board to testing the functionality of the parts along with the integrity of the assembly process. In-circuit test systems accomplished this by using a bed-of-nails test fixture to make electrical contact to every net on the PCB allowing each component to be individually stimulated and measured. With such electrical test access and innovative guarding and voltage forcing techniques - which allowed each component to be tested individually without the influence of its surrounding parts - ICT systems could quickly detect shorted and open pins, missing components, incorrect analog component values and tolerances, and faulty digital component logic. The theory behind in-circuit testing is that manufacturers can be confident that the board will operate correctly if they verify that all the components are operating correctly and have been properly assembled.

The real breakthrough with in-circuit testing was the benefits it provided compared to traditional functional tests. The complexity of test generation was greatly simplified because test developers no longer had to understand the functionality of the board and could automatically generate programs in days that used to take weeks. The quality of the test coverage improved with ICT as well because direct access to every net eliminated the functional test complexity of trying to propagate faults from internal nets to externally observable test points. Finally, in-circuit test systems provided faster test throughput and exceptional diagnostic accuracy that were not possible with functional tests. All these benefits resulted in fast adoption of in-circuit test systems and they quickly eclipsed complex functional test systems and became the test system of choice for most high volume manufacturers.

In-circuit test systems have had to evolve throughout the years to keep up with the demands of ever-changing PCB technologies, the advance of global manufacturing capabilities, and the diversity of testing philosophies for different product and market segments.

Addressing Erosion of Test Point Access

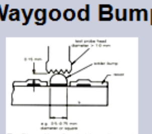
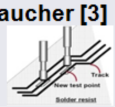
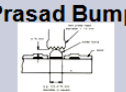
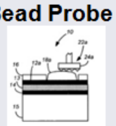
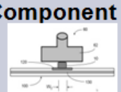
The cornerstone of traditional in-circuit testing has been the ability to gain electrical test access to all of the nets on the PCB using electrical test probes. In-circuit test providers use comprehensive CAD analysis and probe placement solutions to analyze circuit board designs and generate wiring instructions that fixture fabricators use to assemble bed of nails in-circuit test fixtures.

Increasingly it is becoming more challenging to find probe placement solutions that provide full electrical test access to all the nets on the PCB. This is because shrinking packaging technologies, greater IC integration and functionality, higher pin counts, faster I/O speeds and reduced product footprints have lead to ultra-miniaturization. To support this trend, manufacturers are designing increasingly complex high density interconnect boards that make use of blind and buried vias, smaller tracks with tighter spacing and with less copper available on the board surface for electrical test access. This trend is more pronounced for high volume consumer products which place a premium on small size, fast performance, and low power consumption.

One way that designers and fixture fabricators have addressed these challenges is through the use of more advanced probe technologies. Traditional ICT probe technology which consists of a small probe contacting a larger test pad target on the Unit-Under-Test (UUT) is restricted to a target diameter of .024 inches with center spacing of .0395 inches between probes. New highly accurate probe fixturing technologies developed by the fixture fabricators are available that make it possible to design ICT fixtures that can reliably contact test points as small as .012 inches with pitch of .020 inches. [1]

To provide access to even smaller test points, manufacturers can use what are called micro-access test technologies. Instead of using a small point test probe in the fixture to contact a large test pad on the board, micro-access test technologies use a large head test probe in the fixture to contact a small test point on the board. Micro-access test technique concepts have been around since the 1990's and Table 1 describes the general concepts behind 5 different implementations. Micro-access technologies allow manufactures to get electrical test access to test points that are as small as the signal traces themselves; however, their use is only viable on signal traces that can be accessed from the top or bottom layer of the UUT and the micro-access test points must be spaced appropriately to avoid conflict with the large head probes that are used in the test fixture.

Table 1 – Micro-Access Comparison Matrix

Micro-Access Technique	Date	General Concept	Benefits	Considerations
Waygood Bump [2] 	1990	Place small solder bumps on test pads and contact them with large head probes	Improves probing accuracy by targeting small solder bumps with large test probes rather than large test pads with small test probes	Size of test pad may hinder performance and probe placement for high speed/high density PCB designs
Vaucher [3] 	1996	Open small apertures in solder mask above signal traces and contact them with deformable tipped probes	Allows direct access to signal traces with special probes that do not require solder bumps	Contact reliability depends on deformable probe performance
Prasad Bump [4] 	1997	Same as Waygood Bump, except proposes that solder bumps be placed on significantly smaller test pads	Better suited than Waygood Bump for high speed signals and high density interconnect designs	Smaller test pads and solder bumps may reduce mechanical performance
Bead Probe [5] 	2003 + 2007	Place small solder bumps directly on signal traces through open apertures in solder mask and contact them with large head probes	Also good for high speed signals and high density interconnect designs	Licensed technique limits which test equipment Mfgs can use / Less robust mechanical performance
Test Access Component [6] 	2007	Place small conductive Surface Mount Components directly on top of signal traces and contact them with large head probes	Very robust mechanical performance compared to other Micro-Access techniques	Need to place extra SMT component which can add costs

Despite the advances in ICT fixturing technology, manufacturers sometimes find it challenging to get complete physical test access to the boards they are testing. The effectiveness of the ICT solution diminishes as physical test access is lost, so some ICT test systems have evolved to augment physical test access with virtual test access techniques. Table 2 shows the reduced access tools that are available on some ICT test platforms.

Table 2 – Limited Access Tools Augment ICT

Technique	Description	Benefit
Boundary Scan / Embedded Test	Many boards today have components with built-in testability features like boundary scan that can be activated during in-circuit testing to run board self tests or provide virtual access to signals on the board when the ICT system does not have physical test access.	Detects faults on nets that do not have physical test access. Uses ICT resources and board testability features in concert for maximum test effectiveness. Consolidates tests on single manufacturing test solution.
Combined BSCAN + Framescan [7]	Combines BSCAN and capacitive opens test techniques. BSCAN devices provide digital stimulus, probe sensor plate in fixture detects stimulus signal.	Identifies open pins on connectors, sockets and IC devices that do not have physical test access.
Indirect Testing	Indirect stimulus of inaccessible pins through low value resistors or buffers on the board.	Allows ICT system to indirectly test nets that do not have direct physical test access using physical nails on the other side of low value resistors and buffers.
Cluster Testing	Groups of two or more components are tested as a single entity to verify proper operation	Allows testing of functions like RC Networks and filter circuits without access to all pins in the cluster.
Functional Test [8]	Application specific circuit board functional tests are executed using add-on functional test instrumentation.	Some ICT systems have ability to plug in industry standard PXI instrumentation which allows ICT to be integrated with functional test in a single test stage.
Adaptive Test Generation	Intelligent test generators and device models are designed to automatically adapt to circuit constraints and missing test access.	Faster test generation and program debug; less time modifying tests to account for different wiring configurations.
Distributed Test [9]	Intelligent analysis tool that can analyze test access, objectively report fault coverage, model alternative test strategies, and recommend optimal test strategies based on manufacturer preferences.	Simplifies the task of understanding ICT fault coverage and the alternative inspection methods that could be used to detect defects other than ICT.

The tools highlighted in Table 2 extend the capabilities of the ICT system allowing manufacturers to still maintain high fault coverage even on boards that do not have full physical test access. It must be noted however that the tradeoff for using these tools is often an increase in programming complexity, less accurate diagnostics at the repair station and longer test execution times. Given these tradeoffs, it is in the best interest of designers and manufacturers whenever it is possible to provide physical test access to every pin they can.

Addressing Ultra Low Voltage Technologies

As Moore's Law predicted, the number of transistors in integrated circuit packages has approximately doubled every two years over the last two decades. The greater the number of transistors in a package the more power it requires. The amount of power a transistor requires is calculated using the formula ***Power = Frequency x Capacitance x Voltage***^{2}. Designers have discovered that the most effective way to reduce the power requirements for their products and satisfy the reduced power consumption and environmental concerns of their customers is to lower the voltages at which they operate. As a result, many boards now contain devices that operate with a combination of low voltage logic levels of 1.8V and below.

The challenge for many in-circuit test systems is that their pin electronics were originally designed when 5V was the predominant logic technology and many of them do not have the required accuracy to test these ultra low voltage components accurately, reliably, and safely.

Some in-circuit test systems have evolved to address this low voltage testing challenge by updating their digital pin electronics with dramatically improved drive and sense accuracy (as low as 15mV). Other capabilities added to ensure safe and reliable testing include real-time backdrive current measurement and control features (to prevent devices from being harmed by electrical over-stress conditions); automatic driver verification (to guarantee that drivers reach their programmed logic levels); dual-level sensor thresholds (to ensure device output drivers are within published specifications); and programmable per-pin logic levels (to support devices that require multiple independent logic levels). [10]

In-circuit test systems equipped with these advanced digital test capabilities can confidently perform powered-up digital testing of the latest low voltage technologies. However, if manufacturers are using in-circuit test equipment that do not have these advanced digital test capabilities they may not be able to reliably or safely test low voltage components , or they be forced to resort to unpowered vectorless test strategies of their low voltage digital parts which are slower, more expensive, and less comprehensive. [11]

Addressing Diverse Test Requirements

In addition to evolving to meet the technology requirements previously described, manufacturers of ICT systems have had to evolve to meet the shifting testing philosophies and business economic drivers of their customers. ICT vendors have struggled to satisfy the demands of different manufacturers who specify different requirements for their ICT systems and who have different expectations as to what they need the system to do.

The factors that drive these expectations include:

- PCB complexity - simple or complex board; low or high pin count; full or limited test access?
- Product cost – low margin consumer product; high cost server, communication, or military/aerospace board?
- Reliability & Regulatory obligations – what safety standards are required for automotive, medical, and industrial equipment?
- Manufacturing strategy – Outsourced vs internal manufacturing; multi-site manufacturing; frequent manufacturing location changes?
- Product volume and mix – high mix/low volume; dedicated high volume production lines; automated vs operator driven operation
- Manufacturing skill levels – experienced vs inexperienced developers and operators; trained vs un-trained personnel

All these factors combine to place conflicting demands on ICT systems. Low margin manufacturers demand low cost ICT; manufacturers of high reliability, highly complex products demand high fault coverage and high pin count capacity; untrained operators demand simple and easy to use operation; highly skilled test engineers demand powerful programming capabilities; high volume manufacturers demand ever higher test throughputs; manufacturers using outsourcing business models demand equipment compatibility. To further complicate matters for ICT vendors different market segments and different geographic regions implement different test philosophies.

Historically, ICT vendors have addressed these conflicting demands with different classes of ICT systems. Manufacturing Defect Analyzers offered low price and simple test operation, but provided limited test capabilities and low fault coverage. High performance In-Circuit Testers offered extended test capabilities and high fault coverage, but were expensive and complex to program. In the middle were a variety of standard in-circuit test systems that offered more performance than an MDA class system at a lower price than high performance class ICT systems.

Given the different classes of test systems, many manufacturers now have production floors with multiple incompatible classes of ICT systems, often from different ICT vendors. There can be a hidden cost to this multi-system test strategy because it increases system training and service costs, increases program maintenance costs, and reduces flexibility in test equipment utilization.

If a manufacturer decides to only use an MDA class tester, then they may not be able to adequately test complex PCB assemblies due to its limited capabilities. On the other hand, if a manufacturer decides on a high performance ICT platform solution, it can be overkill for simple PCB Assemblies where the high performance ICT features are not always needed and the program development requires higher skilled operators.

To account for this dilemma, some ICT vendors have evolved their ICT test systems to be highly scalable to satisfy diverse test requirements in a single compatible platform that supports multiple pin board types and independent hardware options and software plug-ins that can be used to expand the capabilities of the tester. Figure 1 shows how this approach can be used by manufacturers to buy only the test capability they need and grow or reduce test capabilities without changing the tester. The benefits include lower training and programming costs because operators only have to learn one test system and develop one test program, higher equipment utilization rates because a single test system can be used for multiple test applications and higher equipment value because the tester can be configured as an MDA+ system all the way to a high performance digital ICT system. To facilitate test program compatibility and equipment utilization, the test executive on these ICT systems will adapt to run only those tests in the program that can be supported with the given hardware and software configuration of the target tester. No more need to create custom test programs designed for the configuration of each tester on your production floor!

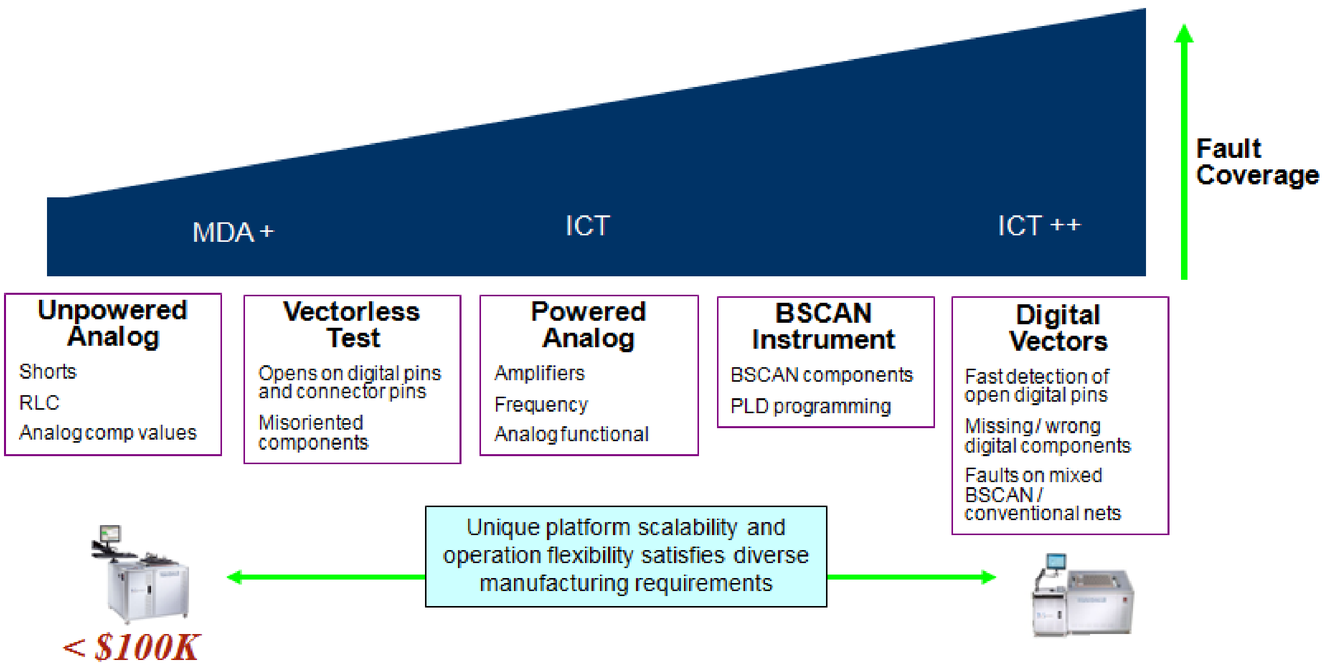


Figure 1 – Scalable ICT Platform Satisfies Diverse Manufacturing Requirements

Addressing High Volume Manufacturing Requirements

High speed assembly equipment continues to improve resulting in ever faster beat rates on the production line. The beat rate for today's high volume production lines is often less than 30 seconds. In-circuit testers can become the bottleneck in the production line when their test times exceed the beat rate of the assembly equipment and place a limit on the number of boards that can manufactured per hour.

When this happens manufacturers can choose to add additional test equipment to increase their test capacity or they can reduce test times by eliminating tests until the test time is below the target beat rate. Neither of these options is considered ideal as adding additional test equipment is expensive, requires extra test fixtures, and is not always possible because production facilities often have limited floor space. Eliminating tests requires extra program maintenance and reduces the amount of defects that can be detected by the ICT system.

A better approach is to increase the execution speed of the tester until it no longer is the bottleneck on the production line. Some ICT systems have evolved to support concurrent testing of more than one component at a time. This is accomplished by duplicating instrumentation in the test system so that the test executive can test multiple components in parallel (typically on boards manufactured as part of a panel). How concurrent test is implemented differs for different ICT vendors and the amount of concurrency depends on many factors, but ICT systems with concurrent test features can generally test 1.5 to 2 times faster than a standard ICT tester.

In addition to increasing the test execution speed, high volume manufacturers also try to reduce or eliminate the board handling times. This can be done on non-automated lines by using dual-well fixtures so there is no delay between testing boards, however the highest volume can be achieved by eliminating the test operator and placing the ICT system in an automated line. Some ICT vendors sell their ICT subsystems as standard 19” rack mount components so that they can be easily integrated into the automated handler solution that is preferred by the manufacturer.

Finally, some manufacturers provide test throughput analysis and optimization software that can modify test parameters to ensure that the test program is optimized for the fastest test throughput. This software reduces test times by an average of 15% and identifies test inefficiencies in the program that could be corrected to further reduce test times.

Conclusion

ICT systems have evolved to address the technology and business challenges of modern PCB manufacturing and their capabilities have advanced far beyond when they were first introduced. Reduced access test techniques, integration of boundary scan and embedded testability tools, advanced pin electronics capable of testing low voltage technologies, concurrent test capabilities, functional test capabilities, and scalable test system configurations have all combined to extend the life of ICT systems and make them one of the tools that is still most valued by high volume PCBA manufacturers.

Taking into consideration how the in-circuit tester has evolved since its introduction and all the electrical test capabilities that are now at its disposal that do not require actual physical test access, it may be time for the industry to stop categorizing these test systems as “In-Circuit Testers” because that name no longer reflects all the things that the tester has evolved to do.

It may be more appropriate to now start categorizing these versatile test systems as “Electrical Test Controllers” because the most capable ones can support in-circuit, boundary scan, PLD programming, cluster and functional testing techniques all in a single consolidated test platform.

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