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Redefining the Test Equipment Supply Chain: The Open Architecture Revolution

Redefining the Test Equipment Supply Chain: The Open Architecture Revolution

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ABSTRACT

As the automated test industry begins embracing the open architecture environment, equipment suppliers and their customers will need to evolve equipment development methodologies to fully benefit from the emerging business model.

The development of standards in the equipment industry allows suppliers to share in the cost of establishing basic infrastructural framework elements, releasing valuable resources to focus on development of distinctive, value-added technologies and services. Already a very competitive and financially unhealthy industry, the test equipment market will benefit from lowering the cost to deliver solutions to their customers. As a result, end users will benefit from increased innovation, more valuable capital assets, and reduced re-engineering.

Open architecture has evolved from vision to reality with the release of the Semiconductor Test Consortium's OPENSTAR[*] specification to the industry. With open standards, end users now have the ability to strategically manage the sustainability and extendibility of their fleet through a pipeline of module developments with traditional equipment suppliers and third-party developers for hardware and software solutions. With a more stable capital equipment fleet, end users can eliminate the cost and resource investments related to re-engineering and maintaining multiple solutions for similar problems and concentrate on improving their test processes, developing strategic supplier relationships, and innovating breakthrough technologies.

This paper illustrates the transformation of the supply chain to leverage the benefits of an open architecture. We focus on the structural challenges faced by the test equipment industry, demonstrate why the steps that have been taken are insufficient, and how open architecture can benefit the supply base as well as the customers.

INTRODUCTION

Semiconductor devices are among the most complicated structures designed and manufactured by humans and are becoming more complex with each passing moment. Regardless of this complexity, customer requirements demand that device incoming failure rates be measured in the 100s of defects per million or less. In the semiconductor manufacturing process, the test step is critical to this demand; it is pivotal to containment of defects and the product quality seen by the end customer.

Test is accomplished using highly automated test equipment that is designed to achieve highly accurate and repeatable results with high defect coverage and extremely high throughput. The fundamental test challenge is to execute the smallest number of measurements that cover the largest number of potential manufacturing defects in the shortest time possible. Typical test times are measured in the low seconds for devices of well over 10 million transistors.

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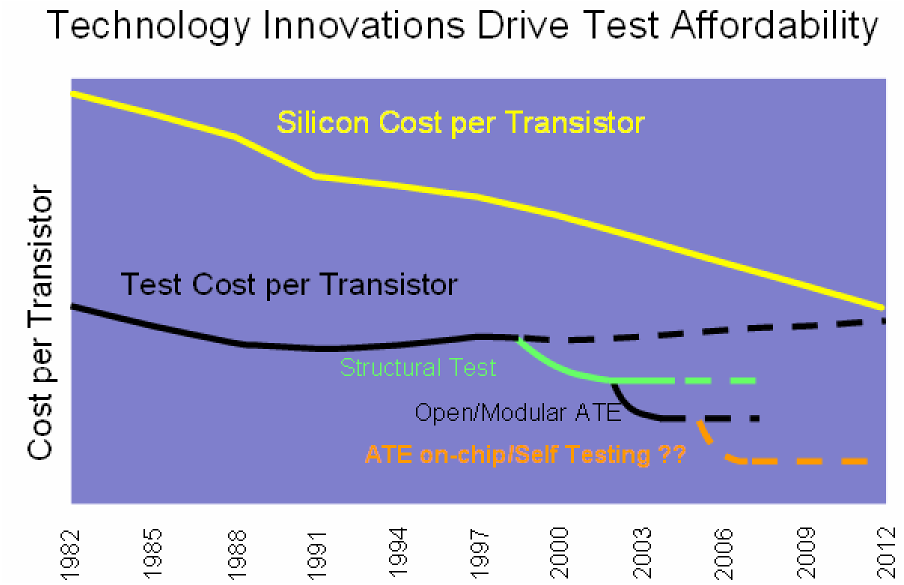


Figure 1: Historical cost per transistor [10]

Test equipment cost versus performance has been an on-going debate between semiconductor manufacturers and equipment suppliers. Semiconductor manufactures face an environment of shrinking device Average Selling Prices (ASPs) and time-to-market windows. This drives the need for just enough capability to test a particular device, with low capital and sustaining costs, available early enough to learn how to use the equipment effectively ahead of initial device silicon. The cost focus of manufacturing has driven development of a variety of low-cost equipment solutions over the last five years. This, combined with the fact that manufacturing tools represent the majority of the total equipment sold, has caused dramatic changes in the Total Available Market (TAM) and Return on Investment (ROI) of the equipment industry. Equipment suppliers face an environment of revenue constraints that has resulted in poor balance sheets and high research and development costs.

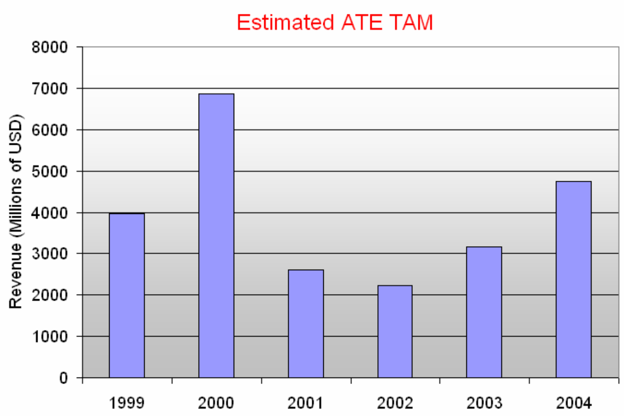


Figure 2: Estimated automated test market size [8,9]

In 2004, the test equipment industry represented a $4.8B industry where six major suppliers, each representing at least 5% Market Segment Share (MSS) garnered approximately 93% of the market. The TAM has been flat to down in four of the past five years and is 33% smaller than in 2000 as shown in Figure 1. Over this same period, Research and Development (R&D) investment has remained relatively flat, which has caused a disproportionate and unsustainable ratio of R&D as a percentage of revenue. These fundamental trends are not expected to change over the next several years which implies that business as usual may be catastrophic for one or more of the major equipment suppliers. Suppliers need to identify new methods to leverage development investment across many devices and customers and recover that investment as quickly as possible.

In this paper, we address a fundamental paradigm change that is emerging within the industry, a shift toward open architecture test equipment. Open architecture has the potential to reduce R&D costs while protecting Intellectual Property (IP) and innovation, and to increase productivity by targeting investment in new capabilities rather than re-engineering. The trends that enable this transition are described and the future landscape of the industry is discussed.

EVOLUTION OF THE TEST EQUIPMENT DEVELOPMENT MODEL

There are many different methodologies that are utilized to identify defects within a device. At a high level, these methodologies fall into one of two categories: functional and structural test. Functional test emulates the end use environment that would be seen by the device in the final application; tests replicate the actual function of the device, such as a system “boot” cycle in the case of a microprocessor. Structural test utilizes special structures that are included in the design to provide enhanced controllability and observability of internal device nodes; structural tests are specially written to disturb specific fault locations in the design and bear no relevance to actual device function. Each method has important implications for the capability of the test equipment: a functional tester typically needs to match the device performance while a structural tester may have significantly lower performance than the device.

Test plays three specific roles in the life of any device:

1. Product development uses test equipment to verify and guarantee device design functionality and performance.
2. Wafer probe is a test step that is done immediately following fabrication while the devices are still in wafer form. The wafer probe process step is driven by business decisions rather than product quality (with the exception of known good die requirements). The value of wafer probe is in the reduction of scrap costs from two sources: rapid data feedback to reduce misprocessing due to fabrication excursions and early identification of defects to reduce downstream processing costs of defective material. These savings opportunities must be balanced by careful management of the cost of the wafer probe process. Process cost can be reduced through many techniques, some of which may result in a reduction of test coverage at this step, by identifying fabrication excursions as early as possible.
3. Final test is done after the device has been packaged, typically as far downstream in the process as possible to minimize the risk of introducing defects after test. Final test is responsible for all remaining defects to ensure end-customer quality.

Product development is highly dependent on functional- and specification-based test methods, demanding the highest performance and typically most expensive equipment. Wafer probe and final test may contain a combination of structural and functional tests; the selection and implementation of these tests determines the complexity and cost of the required equipment. The investment structure of the industry faces the fundamental challenge that the highest cost and investment intensive equipment has a very small market potential (product development). The lowest cost equipment serves the largest market, but lower margins starve the R&D requirements of leading-edge technology. Further, semiconductor manufacturers typically demand that the same platform service all purposes in order to increase engineering productivity.

The rapid pace of advancement for the Device Under Test (DUT) has meant that the equipment designer was constantly faced with providing a capability that actually processed information faster than the DUT, but had to be constructed out of older generation technology. The significant performance disadvantages of the available components meant performance would need to be derived by architectural innovation. These architectural innovations typically resulted in sharp increases in equipment complexity.

In the 1990s, a typical new platform design required more than 100 hardware and software development engineers, an investment of $50-100M, and a 24-36 month cycle time. This investment and time-to-money scenario resulted in a tool capital cost of several million dollars and the need to sell several hundred tools to generate reasonable profit margins. In this generation of equipment, individual platform designs were targeted to match customer market segments to partition the test problem and reduce equipment design complexity. This resulted in the traditional memory, mixed signal, and logic test platform delineation.

Equipment design was approached from the system level, with little to no consideration given to feature growth. Design tradeoffs driven by practical cost, resource, and manufacturability considerations resulted in the selection of custom ASIC design for critical circuits and off-the-shelf components for basic functions. The ability to encapsulate tester functions was limited by the low integration density of available components and the practical limitations of Printed Circuit Board (PCB) sizes.

The complex and interwoven nature of the equipment design generated highly proprietary systems, requiring an intimate knowledge of the circuits and interconnects (Figure 3). The equipment was targeted at a very narrow capability window and delivered just-in-time. In the end, the customer spent several million dollars for each tool and typically experienced poor reliability, highly complex diagnosis, with limited extendibility to meet future requirements.

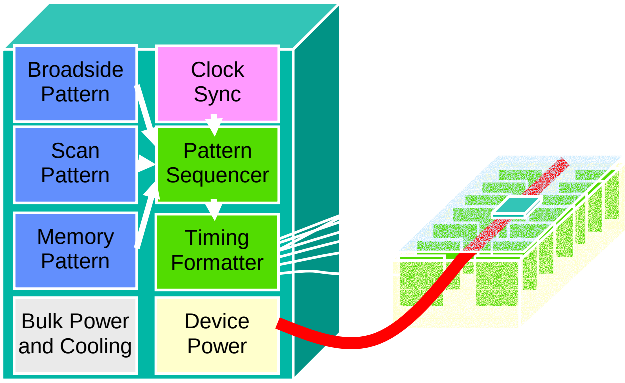


Figure 3: Traditional test equipment architecture

Moore’s Law stipulates that the number of transistors available to design on a chip will double with every new process node. At the same time, the transistor switching speed increases. This rapid change in device design complexity and performance when combined with the nature of test equipment development represents a capability gap for design verification and product manufacturing. Further, the rapid obsolescence of the equipment creates a significant cost barrier due to the need to replace the entire manufacturing fleet with each new device design; a cost barrier significant enough to make or break the product.

In today’s design and manufacturing environment the traditional equipment development model breaks for several fundamental reasons.

1. Device design time is continuing to shrink while equipment design cycle time for a new platform has remained essentially flat.
2. Device design complexity is increasing and product segments are collapsing, making the traditional device-type-based test partitioning obsolete–a single device now requires all of the capabilities that have traditionally been partitioned between distinct test platforms.
3. Device performance is increasing at a pace that makes new test equipment obsolete almost before it can be delivered, challenging the ability to achieve a reasonable return on invested capital.
4. Platform conversion costs are a significant portion of any equipment selection decision and represent a barrier to entry for new suppliers.
5. No single platform is capable of meeting all of the needs of the market, or in many cases even a single customer. Further, most customers are unwilling to align with a single supplier due to concerns over the business impacts of eliminating competition in a highly proprietary market.

A paradigm change was needed in equipment development to enable cost-effective engineering and production test without sacrificing leading-edge capability. The key to achieving this change was the significant advancements in circuit integration levels to provide encapsulation of equipment function into a practical physical space. This has enabled a transition to test instruments and the concept of a universal slot equipment architecture. This architecture creates a generic slot definition: all test instrument functions can then be designed to fit within that slot. The result is a platform infrastructure that may remain fixed over an extended period of time while significant new capabilities are introduced in the form of new instrumentation.

Current-generation test equipment is based on this universal slot architecture. The infrastructure has been reduced to power distribution, cooling, and communication, based on fixed, generic budgets on a per-slot basis (Figure 4). Instrumentation can be populated as needed, plugged into any slot, and integrated into the existing software environment. The result is a highly modular, configurable tester with minimal retraining to add new capabilities.

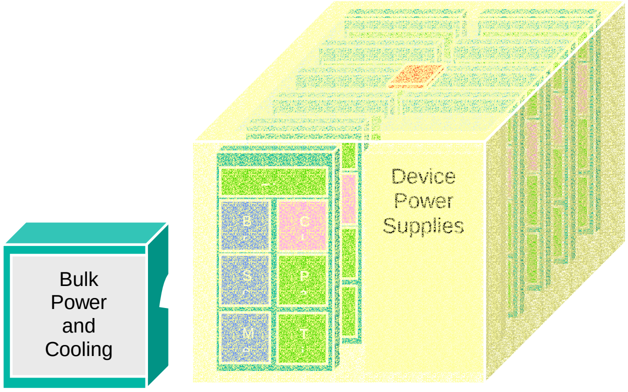


Figure 4: Universal Slot Test Equipment architecture

This architecture enables the user to purchase just what is needed, driving significant increases in equipment re-use and associated capital cost savings while also minimizing the training and transition costs associated with a new platform. The supplier need only develop the incremental capabilities, focusing resources and investment while reducing new capability design cycle times.

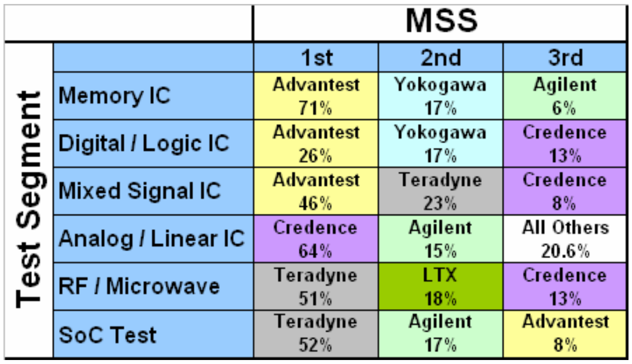
The transition to the universal slot architecture has been a significant step for the industry, necessary but insufficient to address many fundamental issues that remain.

1. Where does the customer go to find instrumentation to support specific device test requirements when the supplier is unwilling or unable to provide it at a competitive cost?
2. Most universal slot architectures lack fundamental market differentiation outside of the breadth of instrumentation available to support them. Continued investment in several competing slot definitions is inefficient and unproductive.
3. Few universal slot architectures have been defined sufficiently to stand the test of time. Keeping the shape and color the same while requiring full replacement of all of the infrastructure and instruments misses the target, even if the software environment remains somewhat stable.
4. Each individual platform has unique facilities requirements that can cost factories millions of dollars in retrofit costs when changes are required to add capacity or adapt to changes in product mix.
5. Each individual platform still has a unique programming interface, user model, and maintenance model that carries a significant investment in training, core competency development, and management business systems.

The industry is in transition. Current platforms that are based on this architecture are being marketed as sufficient to sustain customers for many years to come. If this is the case, one would theorize that the market for platform sales must eventually saturate and reach some steady state size (or at least as close as can be expected for such a cyclical industry). If platform sales saturate, and this is the value proposition of the supply base, then there is a significant business model challenge looming that will challenge the economic structure of the test equipment industry beyond what it already faces today.

THE OPEN ARCHITECTURE OPPORTUNITY

Coming out of the largest downturn in semiconductor history, the major test equipment suppliers are generally laden with poor balance sheets, unhealthy R&D ratios, and gloomy growth forecasts. Despite the high ratio of R&D spending, even the largest ATE vendors cannot be "everything to everyone" as demonstrated by the MSS disparity shown in Figure 5.



		MSS		
		1st	2nd	3rd
Test Segment	Memory IC	Advantest 71%	Yokogawa 17%	Agilent 6%
	Digital / Logic IC	Advantest 26%	Yokogawa 17%	Credence 13%
	Mixed Signal IC	Advantest 46%	Teradyne 23%	Credence 8%
	Analog / Linear IC	Credence 64%	Agilent 15%	All Others 20.6%
	RF / Microwave	Teradyne 51%	LTX 18%	Credence 13%
	SoC Test	Teradyne 52%	Agilent 17%	Advantest 8%

Figure 5: ATE market segment share [9]

In the past year many industry experts, like Gartner Dataquest, have predicted further market consolidation beyond the 2004 acquisition of NPTest by Credence, due in part to the disparity between the R&D required to develop new systems and the total available market.

In the early eighties, Dan Hutcheson of VLSI Research developed an equation that theorized how many suppliers a given market can sustain. Conceptually, any given market can only support a certain number of suppliers depending on the R&D required to develop a product and the total available market. The hypothesis provides valuable insight into the alarming health of the test equipment industry as it helps illustrate one of the fundamental problems in the marketplace: redundant and unjustifiable R&D.

Applying this equation, we estimate that the ATE industry can sustain three or four major suppliers (depending on assumptions) *without government or industry consortia intervention*. Currently, the test equipment industry consists of six major suppliers that have lost a combined total of approximately $4.2B since 2002. Although most of these companies returned to profitability in 2004, due in part to the 50% market growth, most analysts are predicting a steep TAM decline over the next two years. If this decline occurs, further consolidation is inevitable, if the fundamental cost structure of the industry cannot be reduced substantially.

The Open Architecture Initiative, begun in 2002 by Intel and currently represented by the Semiconductor Test Consortium (STC), put forth the concept of a standardized infrastructure architectural definition as a basis for combining instrumentation from multiple suppliers into a common platform. The goal of this effort is to leverage standards at the instrument interface level (power, cooling, communication, and device interfacing) to focus R&D on what customers actually pay for–the ability to test their devices.

The STC has turned this concept into reality through definition of the OPENSTAR architecture and has published a set of related instrument standards (available at http://semitest.org/site/About/Specifications* that are available to the industry. OPENSTAR leverages a universal slot architecture, focused on defining the interfaces to allow interoperability without stifling innovation or increasing the risk of intellectual property exposure. Focusing precious R&D resources on intellectual property development and sharing infrastructural development costs across the industry will lower the cost to develop new products and allow for a more healthy industry balance sheet.

Despite the current significant (and unsustainable) level of R&D funding, no single supplier has been able to provide the entire spectrum of test capability. Open architecture enables suppliers to focus on their areas of core competency to deliver value while enabling the customer to minimize the platform diversity that their engineering teams and factories must manage. Of critical importance is the realization that the infrastructure standards enable a diverse industry environment as shown in Figure 6. Such an environment comprises several vertically oriented system Original Equipment Manufacturers (OEMs) that provide complete development, integration, and sustaining services; as well as more horizontally oriented services suppliers who are focused on instrument development, qualification, integration, logistics, and field support.

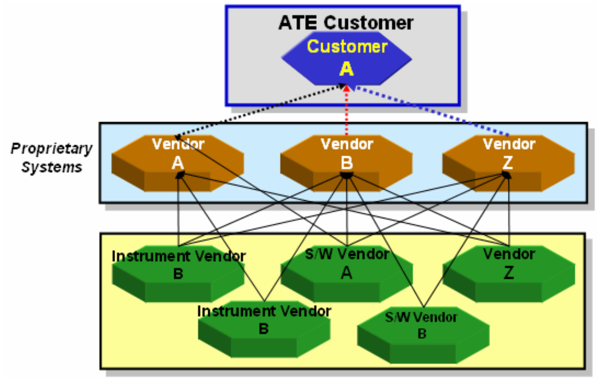


Figure 6: Traditional ATE supply chain

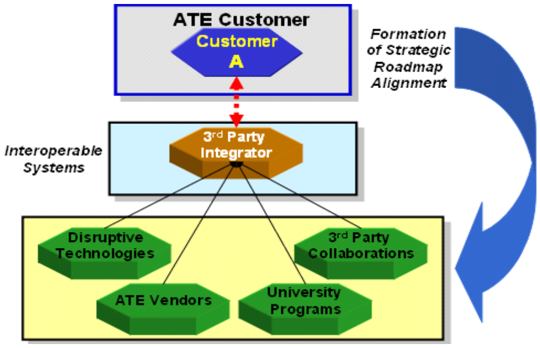


Figure 7: Open architecture supply chain

As depicted in Figure 7, the ATE user can strategically utilize and collaborate with Tier II suppliers to acquire optimal factory solutions. This mixture of vertically oriented solutions with cost-effective and efficient development of lower-volume, customer-specific solutions is a key enabler to increased innovation with decreased R&D costs. Customers can leverage a wide array of suppliers including university research, individual instrument suppliers, as well as traditional test equipment supplier offerings while providing a consistent infrastructure and training requirement. Open architecture permits customers to develop strategic technology pipelines while maintaining the ability to incorporate disruptive technologies into the existing test infrastructure.

At the heart of a horizontally oriented market is the need for instrument qualification and system integration services. Customer requirements for well integrated and sustainable test equipment have not changed. The ability to deliver this type of solution has been the strength of the traditional test equipment suppliers, but at the cost of proprietary, closed architectures. The ability to provide well-integrated systems containing instrumentation from multiple suppliers that can be efficiently maintained and serviced in the field is a core requirement of a successful open architecture.

The system integrator function offers several specific value-added services to the equipment as listed below. Note, however, that this is far from a complete list as the highly scalable and configurable nature of open architecture equipment, while solving many problems, will produce new challenges and exacerbate existing ones:

1. Design support for new instrument developers to lower the barrier to entry and simplify the learning curve.
2. Development services to simplify instrument software integration and check-out in the full system environment.
3. Qualification and certification services to verify that instruments conform to the hardware mechanical and interface standards.
4. Confirmation of interoperability with other instrumentation.
5. Electro-mechanical infrastructure sourcing and integration.
6. Specific system configuration integration, verification, and sales.
7. Worldwide support for complete systems post sales, including logistics, spares, service, and applications.

In this model the integrator could be either one of the vertically integrated OEMs (modeled after the traditional test equipment supplier) or a non-traditional horizontally focused third party. These services differentiate the integrator or OEM and enable higher operating margins than acting as a pure play distributor, where the customer is required to integrate each of the individual system components. Due to the steep and critical nature of product ramps and relatively limited user expertise, customers will typically not accept the additional risk associated with integration in house.

Beyond the opportunities evident in equipment development, standardized slots allow the equipment infrastructure to further embed itself within the factory facilities. Customers will find that asset management becomes focused on the instruments rather than at the system level as it is today. This represents an order of magnitude increase in business system complexity and opens the door for many value-added services including configuration management, instrument reliability and maintenance history tracking, spares depots, and field support for applications and maintenance.

Additional opportunities will also emerge for fundamental changes in how instrumentation is valued and paid for. Rental or leasing options will be more cost effective and a lower risk for the customer as well as the capital owner. This enables customers to rapidly and cost effectively flex equipment capability to adapt to changing market dynamics and natural shifts in requirements from customer to customer, as technologies are phased out of one company and brought up in others. The interoperability of the modules will allow individual instrument designs to appeal to a broader customer base over a longer period of time, thereby deriving greater revenue per design.

Open architecture is the logical next step for an industry that is already converging towards proprietary implementations of fundamentally similar architectures. The traditional test equipment supply base is already facing difficulties differentiating their product based on architecture. The forecast longevity of these systems forces a business model change to focus on deriving revenue from incremental capability sales based on instrumentation. Open architecture is the logical end state where the platform and infrastructure are based on standards, and the supply base is focusing R&D investment on what customers are willing to pay for: value-added technology development and service delivery.

BENEFITS OF OPEN ARCHITECTURE

Open architecture creates many opportunities for the test equipment supply base and the customers, but the benefits need to be clearly defined. Transitioning into an open architecture marketplace radically changes how the supply chain is managed and the relationships between suppliers and customers. How can this be justified?

Historically, the ATE industry has been mired in an adversarial seller to buyer relationship. Customers requiring test solutions carefully canvas the industry to find the most optimized equipment to meet product cost of ownership and technical requirements while suppliers scramble to profitably meet cost and technical targets set by the buyer. Customers attempt to drive the cost-learning curve of their product environment into the supply base while suppliers struggle to justify the investment in new development. Neither side believes the positions taken by the other are reasonable, and in the end reach a stalemate of dissatisfaction where there are no obvious choices. Within the industry, pockets of “strategic” agreements have been put in place between customers and their suppliers, but customers constantly drive competition to minimize exposure.

The open environment allows such strategic alliances to take hold and provide the valuable ROI that they are intended to produce by driving competition to the instrument level. No longer does a customer need to hesitate over the selection of the platform based on concerns over whether it will be positioned to meet the requirements after several years of careful investment and deployment.

Admittedly, open architecture testers will struggle to show a dramatic cost of ownership improvement over competing current-generation proprietary solutions when an initial ramp of capacity is occurring. In this scenario, open architecture testers will provide a marginal cost-savings benefit (at best). The true value of open architecture is evident during the follow-on technology ramps and product mix transitions as investment becomes incremental with a high degree of confidence versus replacement.

Open architecture opens the door to many optimizations in which both the supply and customer base can benefit:

- ***Acquisition costs:*** Suppliers need only invest in the development of new technologies or compelling value-added extensions of existing solutions. R&D investment is lower for the supplier, and capital acquisition costs are lower for the customer, reducing time to money for both parties. Customers need only purchase the instrumentation needed to adapt to specific device requirements.
- ***Capacity management costs:*** By extending the life of the tester infrastructure and pushing the infrastructure into the factory, customers can efficiently flex capacity by shipping instruments instead of one ton testers. Testers require expensive and careful logistics

planning to locate the specific transport method able to deal with the size and weight of the complete system.

- ***Utilization:*** As product test plans are developed to take advantage of this environment, the factory is able to rapidly adapt existing capacity to meet ever-changing volume mix requirements. Costly and time-intensive platform conversion steps can be eliminated. High utilization also frees up valuable factory space to alleviate existing bottlenecks and improve factory output per square foot.
- ***Upgrade costs:*** Most equipment purchases are driven by incremental testing requirements. Upgrades can be a fraction of the cost of a full system, but must be available within the platform. Open architecture lowers the risk that capability will not be or can not be made available to meet the need at the same time that it lowers the supplier investment in providing new capabilities.
- ***Factory efficiency:*** The cost of maintaining multiple test platforms arises from many sources: it ranges from the ability to guarantee that a given spare part is available to the ability of a particular operator to drive the equipment. The fewer the number of platforms, the more operationally efficient the factory becomes in terms of headcount and inventory expenses.
- ***Cost of spare line items:*** Due to the consolidated equipment base, the number and breadth of spare line items can be vastly reduced. No longer must duplicate instruments be stocked to provide essentially the same functionality simply because the platform they plug into is different.
- ***Training costs:*** Utilization of common platforms allows engineers and technicians to focus their training on new technology instead of the entire programming, maintenance, and operating procedures of a new platform. More important than the reduction in training cost is the fundamental improvement in engineer and technician expertise as they focus on fewer variables.
- ***Opportunity costs:*** The projects, developments, and opportunities that are lost due to the limitations of the existing test equipment model are substantial. Moving to a standardized platform infrastructure allows the customer to integrate the "slots" into the factory and make engineering and manufacturing test decisions based on how those slots are populated with specific instrumentation. This enables unprecedented flexibility to adapt the equipment to ever-changing device requirements without the need for costly and resource-intensive platform conversions.
- ***Maximizing ROI:*** Equipment suppliers will be able to focus their resources on the areas that customers truly covet: innovation, IP creation, and capability development. Liberating supplier resources from mundane platform tasks enables them to provide more value, delivering more services but at a lower cost, thereby increasing profit margins.
- ***Strategic relationships:*** Open architecture can eliminate the adversarial customer versus supplier relationship by lowering investment risk and enabling third-party support. These strategic alliances allow companies to define the key development areas, decide which technologies to pursue, and mature the process of transferring new technology to the factory. Where a customer roadmap diverges from its suppliers', the companies can strategically choose the opportunities in which to engage with alternate suppliers without severing or damaging the relationship (Figure 8).

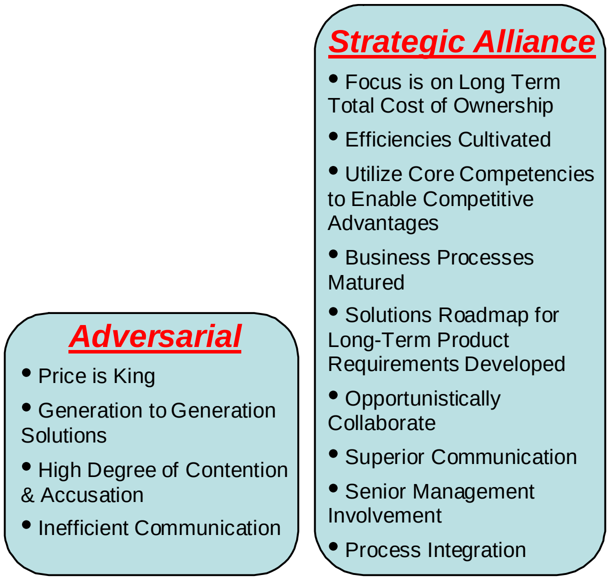


Figure 8: Supplier management shift

CONCLUSION

Economic indicators are beginning to challenge the traditional business model of the test equipment industry. The disparity emerging between the increasing operating and R&D costs of the supply base and the flat or decreasing total available market is not sustainable. There is little indication that there will be a significant increase in the size of the overall market in the near term; as a result the industry must look for opportunities to reduce cost while continuing to deliver cost-effective test solutions.

Initially with Intel's Open Architecture Initiative, and now in the Semiconductor Test Consortium OPENSTAR specifications, a shift from proprietary, monolithic equipment toward modular, scalable architectures and interchangeable instrumentation has been taken from vision to reality. OPENSTAR compliant equipment is now available on the market and a significant number of tools have been deployed in production.

Open architecture enables the supply base to focus investments on value-added services, intellectual property innovation, and product development. Further, it provides an environment where suppliers can focus on their areas of core competency to develop best-of-breed capability without being distracted by other portions of the test requirement that are necessary but outside of their expertise. No longer must every supplier be able to be everything to everyone.

The fundamental challenge in open architecture lies in the restructuring of the industry that a change of this significance entails. There are many opportunities for new value-added services as well as for traditional equipment suppliers. The industry is beginning to embrace change and make real progress in establishing new business models; this is a long-term strategic direction that will take many years to achieve.

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AUTHORS' BIOGRAPHIES

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