Evolution of impedance-controlled coaxial test sockets and IM material application

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As the speed or frequency of semiconductor integrated circuit (IC) chips increases continuously, the test socket and contactor industry has been driven to develop new technology solutions for testing IC packages at higher frequency. Many advanced sockets and contactors have been developed during the last decade to address the requirements from high-speed IC chip makers. Generally, there are two basic approaches for high-speed IC test sockets, one with shorter contactors in order to reduce the socket's electric transmission path, and another with an impedance-controlled coaxial structure to match the impedance of contactors to tested IC chips and test boards. For example, the spring probe, one of the primary contact technologies used in IC chip testing, has become increasingly shorter, with the working length reduced from more than 6mm down to ~2.5mm over the last 15 years. On account of the mechanical limitations in spring probe size reduction, impedance controlled sockets with coaxial structures have become another valuable solution for testing high-speed IC chips with success. This paper will introduce the basics of coaxial structures and impedance matching, evolution of coaxial test sockets, and the application of IM (insulated metal) material in this structure.

Technical challenges in test socket applications

It is well known that signal discontinuity in transmission lines and interconnects (or contacts in test sockets) can affect the signal integrity (SI) performance when testing high-speed IC chips. This discontinuity is mainly caused by mechanical features in the interconnect that may result in impedance change vs. the IC chip. To achieve the best SI performance in IC chip testing, it is required to maintain constant impedance within the test socket, such as 50Ω, which matches that of the IC chip's impedance. However, because of the limitations of mechanical features, it is hard to control the impedance of traditional plastics used in test sockets. One common approach to maintain constant impedance or achieve controlled-impedance is a coaxial structure that has been widely applied in transmission lines and some interconnects. Application of coaxial structure in IC chip test sockets began about 15 years ago. Since then, various coaxial structures have been developed in the test socket industry.

The basic theory of coaxial structure for controlled-impedance can be expressed as the formula below and **Figure 1**:

$$Z_0 = \frac{138}{\sqrt{\varepsilon_r}}\log_{10}\frac{D}{d}$$

Where,

Z_0: Impedance;
ε_r: Relative dielectric constant
D: Dielectric layer outside diameter (or grounded metal body cavity internal diameter); and
d: Conductor or contactor diameter.

Following the formula, the impedance of the coaxial structure is affected mainly by signal conductor (or spring probe as an example) diameter and the dielectric constant of the dielectric material between the spring probe and grounded metal. **Figure 1** shows air as the dielectric medium—notice its low dielectric constant ($\varepsilon_r = 1.0$). Most coaxial transmission cables use composite insulation material with higher dielectric constants (ε_r ~2.0). If using a lower dielectric constant, the thickness of the dielectric layer can be thinner to accommodate a larger metal conductor diameter for better current capacity. The grounded metal body cavity inner diameter (ID) (equal to the cavity internal diameter) is mostly determined by the distance between two probes, or pitch, in the IC device package. Using spring probes as an example, in order to have more stable performance and improve manufacturing feasibility, a larger diameter "d" is expected. With a fixed impedance, such as 50Ω, and a pitch of 0.8mm, the signal pin diameter is 0.3mm in air ($\varepsilon_r = 1.0$). If a higher dielectric constant material is used, such as $\varepsilon_r = 2$, the signal probe diameter "d" will be 0.22mm to achieve a 50Ω impedance. Therefore, selecting an interface dielectric material with a small dielectric constant is always preferred in an impedance-controlled coaxial structure.

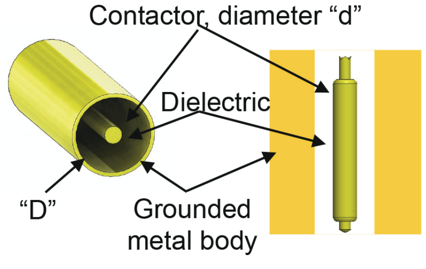
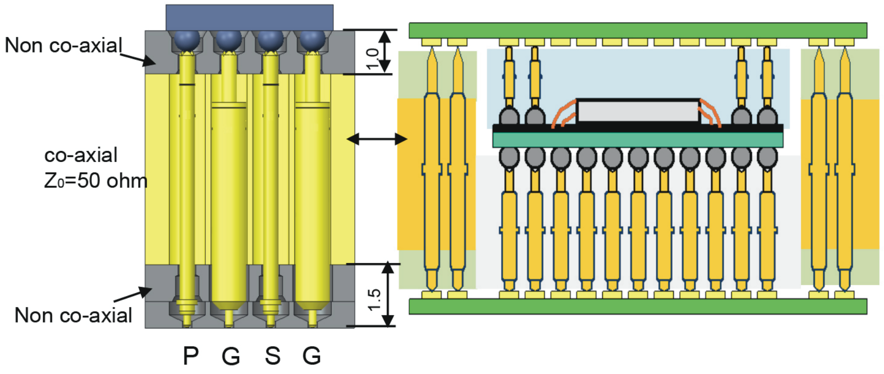


Figure 1: An ideal coaxial structure.

Theoretically, the impedance-controlled test socket structure should follow **Figure 1**, and have a spring probe with a diameter of "d" surrounded with dielectric material (air or insulation material) and grounded metal shield with a diameter of "D." The correlation between "d" and "D" must be represented as in the formula to achieve the required impedance. This ideal impedance-controlled structure is feasible and widely used in long signal transmission wires. But it is not possible to apply this ideal structure in package test sockets on account of a couple of challenges:

1) How to hold the signal pin in the center of the socket's cavity while retaining its position, without movement, over thousands of compression cycles in an IC chip test environment; and
2) How to insulate the power pins from a metal body, avoiding electric shortage, while maintaining mechanical stability.

Because the impedance-controlled test socket concept with coaxial structure was proposed many years ago, much development effort has been spent to solve



a. Sandwich coaxial structure b. Coaxial structure in PoP test socket

Figure 2: A sandwich coaxial structure and its application (P – power, S – signal; G - ground).

these challenges. Although various concepts have been proposed, only a few are applied in high-volume testing environments today including those that will be introduced here.

Evolution of the impedance-controlled socket with coaxial structures

A sandwich coaxial socket structure is the most commonly used impedance-controlled design. As shown in Figure 2, the sandwich coaxial socket has three layers: top and bottom layers made of high-strength insulating composite materials, and a middle layer consisting of a metal body. The middle layer has a coaxial pattern structure for signal pins to have impedance-controlled functions. The top and bottom layers retain the signal and power pins providing mechanical stability. The dielectric layer in the signal pin cavity is air, which has a dielectric constant of ~1.0, the minimum achievable dielectric constant. Following the impedance calculation formula, the signal probe diameter "d" is usually very small, in the range of 0.20~0.3mm for a pitch in the range of 0.6~1.0mm. One advantage of the sandwich coaxial structure is its well-grounded metal layer. Usually, a thicker middle metal layer can be used for better constant impedance. This sandwich coaxial socket structure is commonly used in package-on-package (PoP) device testing as the return path from an upper fan-out printed circuit board (PCB) to the bottom test board (shown in Figure 2b).

Obviously, the major weakness of the sandwich coaxial socket described above is the non-coaxial structure in the top and bottom plastic composite layers. As shown in the impedance distribution of the sandwich coaxial socket in Figure 3, the middle metal coaxial layer has a well-controlled 50Ω impedance, while the top and bottom layers have unmatched impedances. The actual impedances of the top and bottom layers may be predicted by SI simulation during socket design and are determined by a variety of factors including the composite materials selected, pin structure, and cavity dimensions.

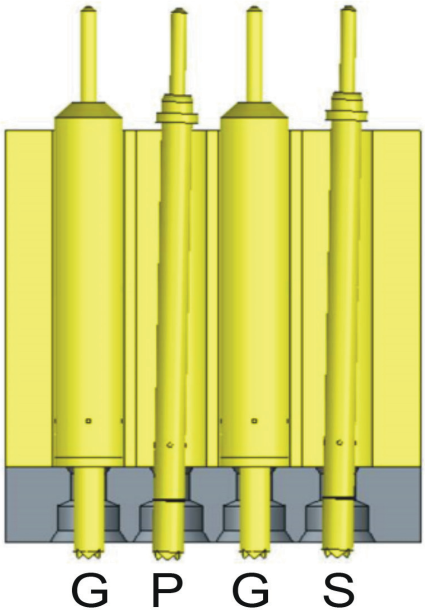


Figure 4: Signal (S)/power (P) pins status in assembly or maintenance.

Another weakness of the sandwich coaxial socket is poor manufacturing and maintenance feasibility on account of difficulties in retaining the spring probe's position. As shown in Figure 4, when the socket is placed upside down for assembly or maintenance, the signal and power pins are captured in the top layer cavity with limited thickness, which may cause the probe to move at an angle. The random tilting of signal probes in cavities affects socket assembly and probe replacement in the field. Increasing top layer thickness is one solution, but it will affect the signal integrity performance of the whole socket.

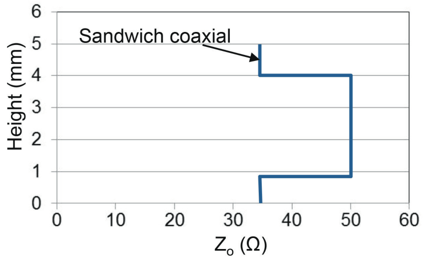


Figure 3: Z distribution in a sandwich coaxial (example).

Because of the challenges inherent in the sandwich coaxial socket, development efforts turned again to a full impedance-controlled coaxial structure. One solution to this challenge was developed by Smiths Connectors in the form of a patented socket material technology (IM, or insulated metal) and structure marketed under the trade name, DaVinci. This impedance-controlled coaxial socket features a metal body that is insulated on all surfaces, including top, bottom, and all signal and power pin cavities. DaVinci socket components are shown in Figure 5. A proprietary manufacturing process has been applied to generate a thin insulation layer on metal base components. This insulation layer ensures signal and power probes do not make contact with the grounded metal base material, while the ground probes are well-grounded by contacting metal cavity surfaces that are without an insulation layer. IM socket material is inherently very strong, which minimizes socket deflection generated by

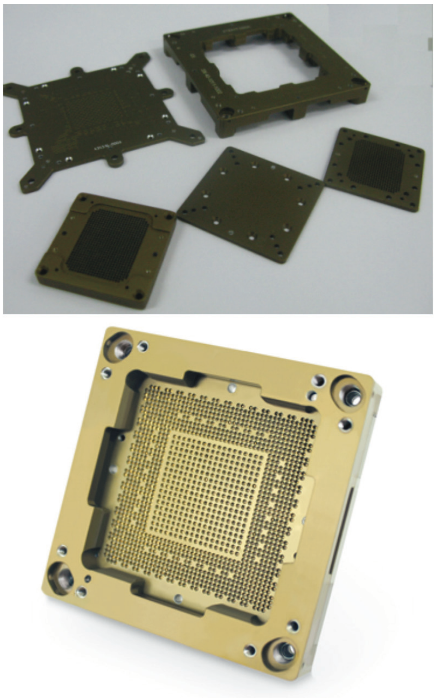


Figure 5: Insulated metal socket and components.

spring probe preload force when mounted on a test board. For example, plastic composite socket materials have a maximum deflection of ~50μm in a 0.8mm pitch, 1750 pin count design. Using IM material in the same socket structure results in a maximum deflection of only ~9μm, significantly less than composite plastics. Most plastic composite materials will shrink or expand with humidity variation, but IM socket material eliminates this concern and provides dimensional stability.

While IM socket material eliminates the risk of signal and power pins shorting to a grounded metal base, the DaVinci socket structure also incorporates signal pin retention features. As shown in **Figure 6**, a specific feature is added in the signal pin cavities to hold the signal pins. This allows the pins to align with package pads on the top side and test board pads on the bottom side. Precise alignment of signal pins within the cavity ensures that the probes maintain reliable contact through thousands of cycles in high-volume device testing environments, especially at high- and low-temperature testing. A plastic composite material with a low dielectric constant is used for the retention rings to minimize impedance differences between the ring and air gap sections.

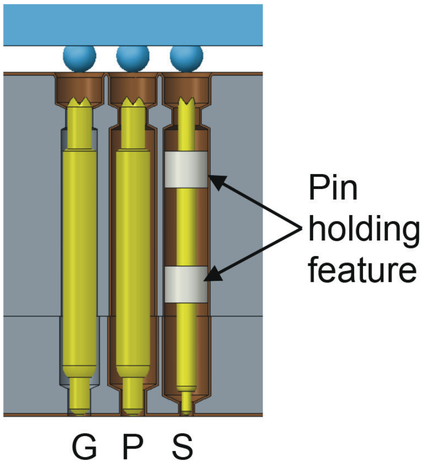


Figure 6: DaVinci socket structure.

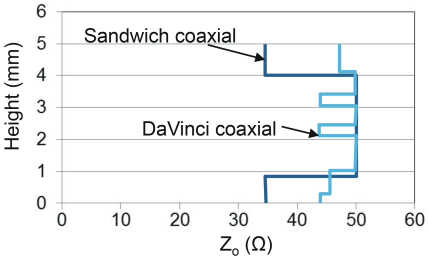
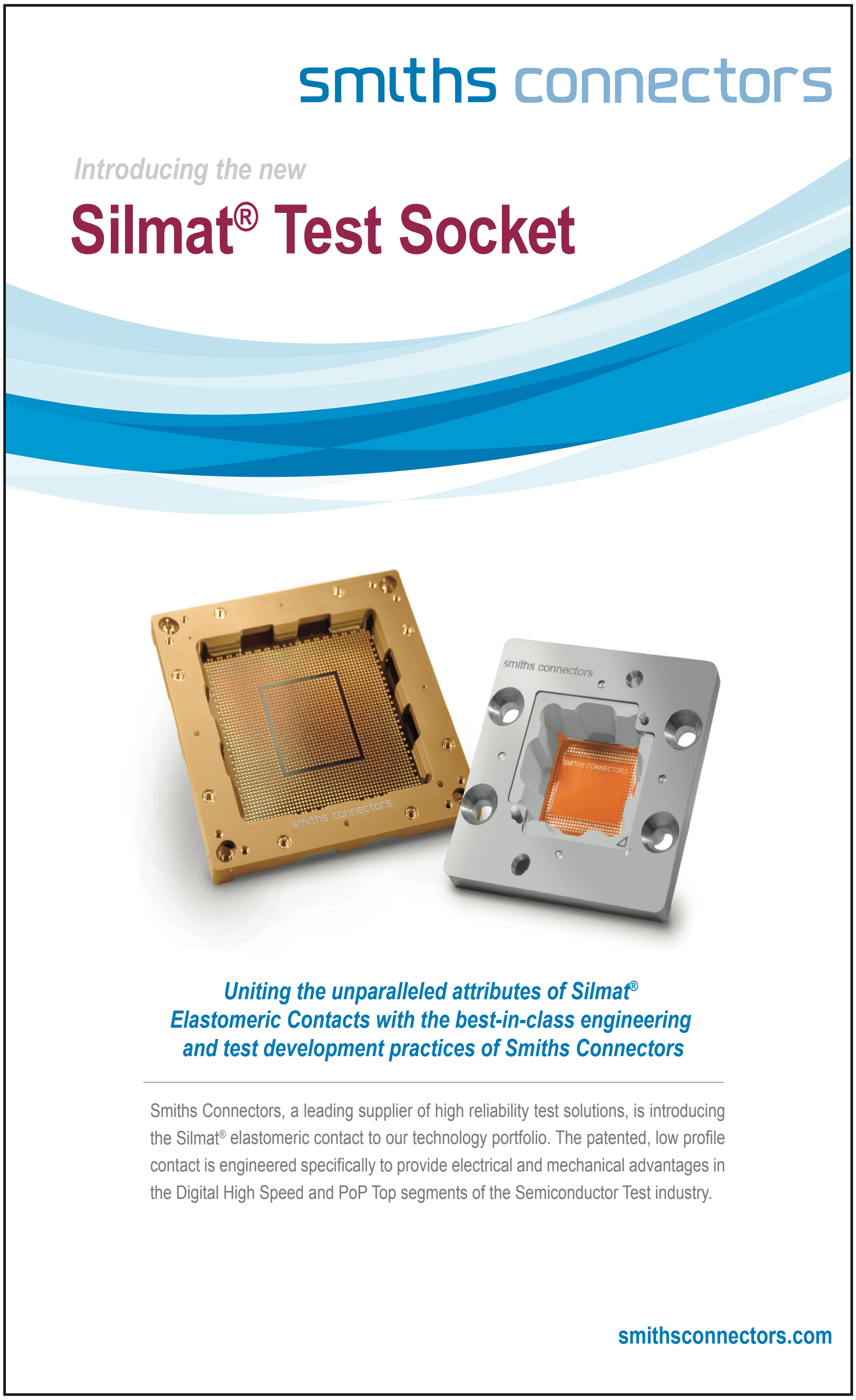


Figure 7: Impedance distribution comparison (reference only, varies with actual dimensions).

Performance comparison of coaxial sockets

A coaxial structure is typically incorporated in the design of an IC device test socket to optimize the signal integrity performance at high frequency through controlled impedance matching of the IC chip and test board. Generally, the impedance of an IC chip is 50Ω for single-ended and 100Ω for a differential pair of pads. The impedance distributions along the signal pin transmission sections is one indicator of coaxial structure SI performance. Consistent impedance around the required specification, such as 50Ω, is vital. **Figure 7** compares DaVinci socket impedance distribution with that of a sandwich coaxial socket. The sandwich socket has low impedances in nearly half of the signal



transmission path. The DaVinci socket has more consistent impedance distribution with only two points demonstrating slight impedance changes. These impedance variations in DaVinci can affect SI, but are controlled in the acceptable range of socket SI performance in IC testing. Performing this impedance distribution calculation ensures optimization of the coaxial structure. As mentioned above, selection of dielectric materials, probe dimensions and structure of probe retention features were optimized in the design stage, resulting in a more uniform impedance distribution while avoiding dramatic impedance fluctuations along the signal transmission path.

To verify SI performance of coaxial test sockets, extensive studies, including SI simulation and measurements, have been performed. One measurement uses a typical signal and ground pin pattern, shown in **Figure 8**, and an Agilent E8363B network analyzer with a 40GHz measurement range. It is well known that one approach for better test socket SI performance is to use short contactors or spring probes. To identify the SI performance improvement of a coaxial structure socket, a short probe with an electric transmission length of 2.8mm is selected as a comparison. The insertion loss (IL) and return loss (RL), as major SI performance parameters, are presented in **Figure 9**, identifying short probe, sandwich coaxial socket, and DaVinci coaxial structures. The SI performance summary of these curves is listed in **Table 1**. As shown in these curves, the DaVinci socket has the best SI performance among the three tested sockets with bandwidths of >40GHz at -1dB in IL and -10dB in RL. The short pin has better SI performance than the sandwich coaxial socket. However, the short pin socket SI performance is largely affected by socket material, pin maps, and pin structures, which cause many variations. One major limitation of the short pin is its low compliance, as minimal as 0.3mm, which may not be enough to cover total tolerances in package thickness and flatness in large packages.

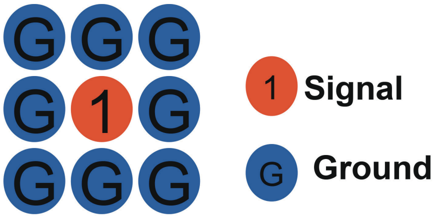


Figure 8: Pattern of SI measurement.

	IL, -1.0dB	RL, -10dB
DaVinci	>40GHz	>40GHz
2.15mm length pin	27GHz	27GHz
Conventional coaxial	19GHz	18GHz

Table 1: SI performance comparison.

Because of the limitations of coaxial structures, small diameter signal pins must be used in the test socket. There can be concern in using a small signal pin relative to its contact reliability over thousands of compressive cycles. **Figure 10** illustrates the performance of a signal pin with diameter of ~0.25mm tested over 500K cycles. The average contact resistance over 500K cycles is <60mohm with standard deviation of <16mohm. This is within the performance specification for signal pin performance in an IC package testing environment.

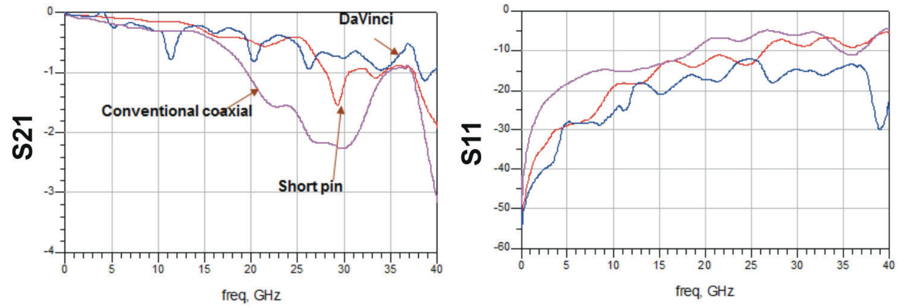


Figure 9: SI performance comparison: short pin and coaxial socket structures.

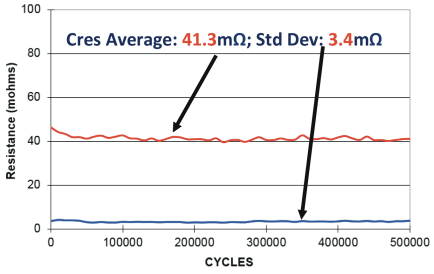


Figure 10: Signal pin 500K cycling test results.

Summary

For many years, developing optimal coaxial structures applied in IC package testing has been a major focus for many engineers working in this industry. Because of mechanical limitations and challenges, only sandwich coaxial sockets have been widely applied in high-volume IC package testing environments. The DaVinci socket utilizing IM material and a proprietary pin holding structure has several advantages:

1. Excellent signal integrity with over 40GHz bandwidth at -1dB (IL) and -10dB (RL).
2. Very rigid and high-strength metal material that minimizes deflection from preload, especially in high pin count packages (>2000 pins).
3. Reliable and stable signal pin performance over 500K compressive cycles on account of the solid dielectric pin holding feature inside the signal pin cavity.
4. A reliable insulated surface layer on the socket body and cavity holes that eliminates any electric shorting in applications.
5. Stable socket dimensions that remove concern about shrinking or expansion with humidity variations.

Extensive research has been performed to optimize coaxial socket structure with these patented technologies. Products incorporating the solutions presented in this paper have been extensively used in IC package test houses and have shown significant advantages to users.

Biography

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