

RF requirements and spring probe development for semiconductor test

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The vast array of semiconductor applications translates into an equally diverse set of challenges for test engineers. However, there are two constant drivers that permeate the industry: smaller pitches and higher signal integrity. High bandwidth signal paths and low-inductance power delivery are essential for testing the next-generation of RF devices.

Several factors can impact signal integrity, such as contactor and performance board design, and material selection. However, a successful test strategy must start with consideration of contact technology used to interface the device lead. Spring probes are the technology of choice for most applications when considerations also include mechanical attributes such as reliability and wear, as in high-volume test applications. An effective spring probe design must address the balancing act between electrical and mechanical performance. Developing a spring probe capable of 40Ghz+ bandwidth (@ -1dB) while providing adequate spring force and compliance, not only involves extensive electrical and mechanical simulation, but also advanced manufacturing techniques.

RF device requirements

Many of today's devices require RF consideration during the test hardware development phase. The wireless evolution has given rise to a vast array of devices that transmit, receive and convert high-frequency RF signals. Many electronic products we use in everyday life require multiple RF devices to make communication to the outside world possible. The RF device chain includes low-noise amplifiers, filters, analog-to-digital converters, RF switches, and power amplifiers. Additionally, the variety of protocols make the number of unique devices astronomical. For instance, wireless networks have several devices depending on the protocol: 802.11a, b, g, n, and ac. Some of these devices

operate at 2.4GHz and others that operate at 5.8GHz. Smartphones include LTE, GSM, WCDMA, HSDPA, and EDGE basebands, that operate just under 1GHz to 4GHz. WiFi devices operate at 2.4GHz and 5.8GHz, while Bluetooth® devices operate at 1GHz and 2GHz. Wireless networks are now including more device technologies than ever before to accommodate the technology needs of the Internet of Things (IoT). Printers, cameras, tablets, appliances and cars are incorporating RF devices to allow wireless communication of data, current status, and warning conditions. Industrial, scientific, and medical wireless networks are commonplace and critical to efficient system performance and monitoring. All of these applications depend on RF semiconductor devices to function.

RF requirements of today's devices range from sub -1GHz (i.e., < -1GHz) up to 86GHz. In the future, devices are expected to reach Terahertz speeds. Besides the sheer speed of RF devices, there are other requirements that make testing a major challenge. These include low noise figure, precise impedance matching, and efficient power delivery. Because of the small amplitude of input signals and power efficiency requirements, it's critical to deliver clean and accurate signal inputs to RF devices.

Power amplifiers are either matched-impedance or low-impedance. Often they require external matching components selected to tune them to specific frequencies of operation. Today, power amplifiers have 20dB of gain with 50% efficiency in band. Soon they will require double the gain with 70% efficiency. Low-noise amplifiers (LNAs) receive extremely small signal levels and must decipher the signal from background noise. To do so requires a very low noise floor or low noise figure value (1dB and below today). Soon LNAs will need to be more sensitive, including noise figure values of <0.25dB.

Test results can limit the specifications

that can be published for an RF device. Ideally, RF devices must act as if they are soldered into the end application while in the test environment. For example, if the test environment is noisy, then it may limit a noise figure specification. If an end application or evaluation board results in a noise figure of 1.0dB, but the test environment noise figure is 1.5dB, then the published specification for the device will have to be 1.5dB. If a competitor can test in a lower noise environment and reduce the specification guard band, then a customer's comparison of the specifications on paper may limit the market available for the device manufacturer. For this reason it's essential to have a transparent interconnect from the test equipment to the device under test (DUT) during high-volume semiconductor test. The spring probe design is critical to achieve transparency. Impedance match, high isolation, and low inductance are necessary to keep the spring probe from being the performance bottleneck in many of today's RF test applications.

Critical design features

The design features of the spring probe are very important, but not the sole contributor to RF performance. It's also critical to choose the proper probe design for the given package configuration. Package features that must be considered to apply the proper spring probe design are the pitch of the package, the type of the package, and the ground locations. A spring probe that is transparent for one package might be a bottleneck for another package. The diameter of the spring probe, the spacing between spring probes, and the socket material type are all variables that impact the impedance, insertion loss, and inductance of the spring probe.

A spring probe that is matched to 50Ω at 0.5mm pitch will have a higher impedance at 1mm pitch. Historically, spring probe mechanicals resulted in a slightly higher impedance than ideal for

single-ended applications and a slightly lower impedance than ideal for differential applications. Attempting to achieve the desired impedance leads to increasing spring probe diameters for single-ended applications and decreasing spring probe diameters for differential applications—a contradictory requirement that may exist in the same device/package.

Today's pitches are such that flat probe technologies provide the best compromise of impedance in both single-ended and differential applications. The spacing of fine-pitch BGAs and QFNs provide optimal 50Ω match, and the smaller effective diameter of a flat probe vs. a barrel probe increases the impedance providing a better 100Ω impedance match for differential signaling. Ideally, spring probes would be designed for the application and the probe diameter would change based on the ground signal configuration, pitch, and signaling methodology (differential vs. single-ended). Practically speaking, this is impossible. High-volume manufacturing efficiencies would be impacted by the variety of probe types and the resulting maintenance challenges. At the mechanical level, spring diameters and force requirements push designs past safety factor limitations to achieve the geometries required for electrical performance.

The compromise between electrical and mechanical performance must always be considered when designing an RF spring probe. The attributes of flat probe technology allow spring probes to reach an acceptable balance point. Everett Charles Technologies' (ECT) ZIP™ 0 is an example of a flat spring probe architecture and is shown in Figure 1. The probe has very good RF characteristics and has been proven to provide high insertion counts. The external spring allows shorter test heights and lower inductance. The sliding



Figure 1: ECT's ZIP 0 RF spring probe.

contact surfaces keep internal resistance low while providing long insertion life. The flat components have only external surfaces resulting in a more uniform plating with better adhesion than tradition Pogo-style probes in which internal surfaces of a barrel must be plated. Additionally, the base material is resistant

to wear against rough and contaminated packages. Of course, a probe that meets all of the technical challenges will not be widely used if the cost is not within the window of acceptance. Therefore, the manufacturing process must support a low-cost probe, and the process must be robust and repeatable.

Developing a high-bandwidth spring probe solution

Architectural features of a spring probe profoundly affect its RF performance. When designing a spring probe, the goal is to hit RF targets on the first design. Simulation tools can be extremely valuable to predict, understand, optimize the results, and shorten the time-to-market. Equally important are RF measurements of the probe. Vector network analyzer (VNA) data is used to fine tune the probe models so that simulation results align with actual measurements. Once accurate models are in place, the probe's physical features can be adjusted to achieve desired performance levels.

Simulation. The simulation process begins by translating the physical design features of a spring probe into its equivalent electrical model. A precise model is essential to accurately simulate waveforms and predict RF performance. A 3D EM (electromagnetic) simulator is used for the design of complex RF electronic circuit elements, such as a spring probe. It simulates the magnetic and electric fields at many nodes in the model. The results can be viewed in the frequency and time domain through s-parameter extraction.

A successful simulation requires a practical mechanical model to accurately predict RF performance levels without simplifications that affect accuracy. The individual probe components and their interaction with one another must be modeled correctly. To do this, the design files from the mechanical design team are converted to standard ACIS text (SAT) format that is fed into the 3D simulation tool. Then key variables that have a direct impact on performance are incorporated into the model, such as dielectric material (in final application), loss tangent, height (path length), pitch (distance between signal and return paths), and material properties.

To more accurately represent the probe's performance in various digital and analog applications, different simulation configurations are modeled. Figure 2

shows an example of a GSG (ground signal ground) arrangement typically found in

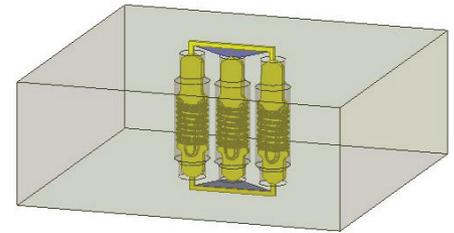


Figure 2: GSG configuration of ZIP 0 in 3D simulation.

high speed analog package designs. The GSG configuration is correlated to the VNA measurement.

VNA measurement. A vector network analyzer emits a sine wave voltage at each port and through the DUT. The VNA measures the amount of energy transmitted through the DUT and reflected by the DUT at different frequencies. It then provides these results in scattering-parameter (S-parameter) format from which we extract insertion loss, return loss, etc.

In addition to the VNA, the station needs several pieces of equipment to be effective: light source, microscope, a spring probe fixture that duplicates the contactor cross-section, two manipulators with x, y and z movement capability, and the CPW probes (coplanar waveguide contact) in different configuration, i.e., GS, GSG, GSSG, and SG. Figure 3 shows the probe station used in the lab.

Method. The setup for taking RF measurements of spring probes requires custom-designed fixtures and delicate handling of ESD-sensitive equipment (Figure 4). Test port extension cables and air coplanar probes are connected and

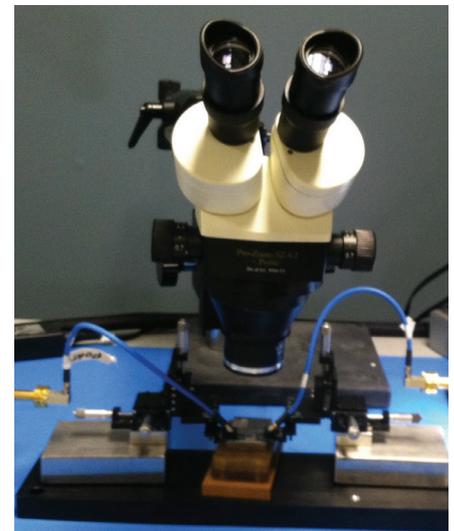


Figure 3: VNA probe station.

mounted to the VNA and probing station. The VNA is powered “on” in advance for temperature stabilization and it is set to the frequency domain of interest. A full 2-port SOLT (short, open, load, thru) calibration

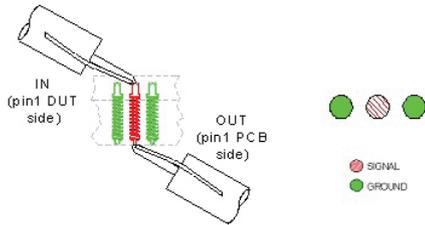


Figure 4: Setup for one-way through measurement of GSG configuration.

is performed on the VNA using the calibration substrate per the manufacturer's recommended procedures. After verifying the calibration, the spring probes are placed into the fixture in GSG configuration. The VNA probes contact directly to the spring probes to accurately capture the RF characteristics of the spring probes.

THRU measurements are required for bandwidth and electrical delay analysis. OPEN measurements are required for capacitance analysis, and SHORT measurements are required for inductance analysis. When the VNA data is verified, it is imported into analysis software for S-parameters extraction. The S-parameters give a clear physical interpretation of the transmission and reflection performance of the device.

Correlation. Simulation results are correlated with empirical data based on the layout used on the measurement, (i.e., GS, GSG, GSSG or SG). The S-parameters are then extracted and compared in the 3D simulator software tool.

In order to match the VNA measurement, different modeling techniques are used in the 3D simulator tool. One technique involves modeling contact between probe components. It's critical to capture an accurate representation of the physical interaction between probe components under compression.

Impedance mismatch and cross talk (isolation) are two of the main concerns when designing a probe. Therefore, in order to get good signal integrity in designing a spring probe, we need a good understanding of the mechanical and electrical requirements of the test environment. Because the mechanical and electrical characteristics complement one another, considering them together yields

good results when testing any product. **Figure 5** shows the insertion loss of ECT's ZIP probe and compares measured to simulated. Correlation matches very closely over the entire frequency range. The low loss and high bandwidth confirm a well matched transmission line through the ZIP0 probes in typical applications.

Field Performance.

Simulating, optimizing, and measuring probe characteristics is important to bring a new spring probe product to market, but no amount of simulation or lab data can predict the performance in a high-volume production environment. Only customers can provide the essential final feedback that a design is successful. Shown in **Figure 6** is the RF performance of ZIP 0 compared to the competition. The result here includes the loss through the PCB, the probe and the device. The only variable compared in the figure was the probe technology used. This plot shows the benefits of the 40GHz ZIP0 probe are not only noticeable for extremely high-frequency applications, but can also be realized for lower frequency RF applications.

Summary

The number of devices that require high-speed test is expanding rapidly. Both mobility and consumer applications are leading the push toward increased RF performance and smaller form factors. These two elements form the basis of a balancing act between electrical and mechanical spring probe design requirements. Flat probe technology with its unique architectural features and manufacturing processes has shown to be an effective option to achieve high RF performance and mechanical reliability. The use of finely tuned 3D EM simulation tools are instrumental in designing a RF spring

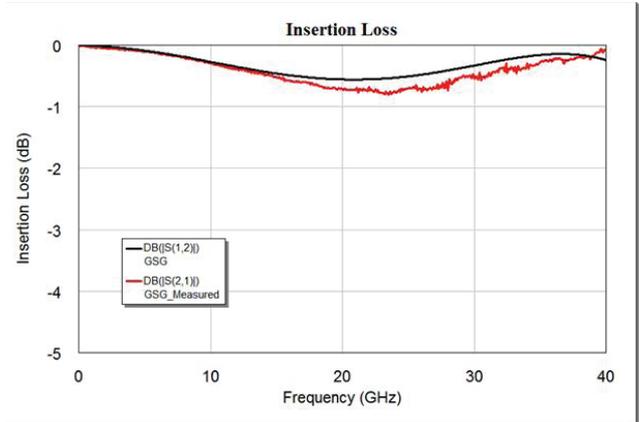


Figure 5: ZIP0 insertion loss, measured vs. simulation.

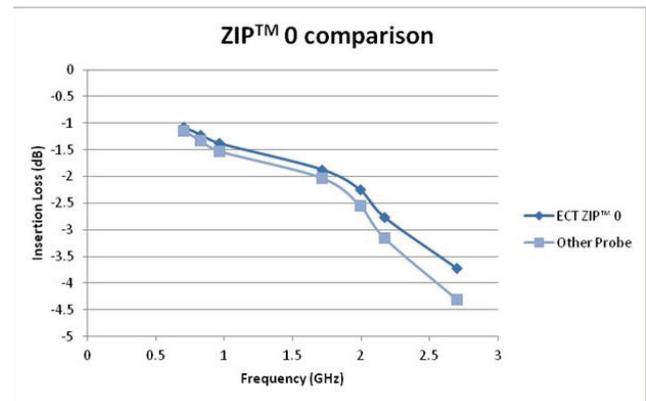


Figure 6: Field performance, ZIP0 vs. a competitor's probe.

probe. Accurate models predict performance and aid in defining the probe's mechanical features. Empirical measurement data validates performance and is used to make adjustments to the probe's simulation models. Through the use of simulation and empirical data, ECT has developed a reliable spring probe suitable for many of today's RF semiconductor devices.

Biographies

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