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On-Wafer Testing Verifies IC Performance and Process Yield

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This tutorial presents some of the key issues involved in the initial post-fabrication testing of integrated circuits used in high frequency applications

More than ever, RF, microwave, optical and high-speed digital products are being developed with custom, semi-custom or application-specific integrated circuits as the primary active device. To verify that these devices work as designed, the first testing is performed by probing the new devices directly on the wafer, before dicing and packaging.

On-wafer testing of devices operating at GHz frequencies presents a unique set of challenges, compared to basic DC or low frequency functional testing. The two primary issues are the performance of probe itself, and calibration of the test system. Of course, issues that affect all wafer probing systems are also of concern. These include reliable contact of the probe tip to the wafer test points, accurate positioning of the probes, plus capturing and storing measurement data.

Why On-Wafer Measurements?

Nearly all integrated circuit wafers are probed for some basic performance verification, often just a set of key DC measurements. At a minimum, these measurements confirm that the ICs are functional, and that the fabrication process has been carried out more-or-less successfully.

This basic probing also provides insight into the yield of the wafer. Individual die that fail DC testing are marked with an ink dot, or indicated on a wafer map, so they are scrapped when the wafer is diced to avoid the cost of packaging known bad die. If the number of failures is higher than expected, it may be an indication of a problem with the fabrication process, the wafer or the handling and test systems.

The next level of on-wafer testing is 100% testing. For RF and microwave ICs, this may be an extended range of DC tests and moderate-frequency analog tests that do not require specialized microwave test systems.

Finally, a full set of tests over the full range of operating frequencies and input/output conditions may be specified, verifying the performance of each die that will be packaged, or bare die that will become part of an integrated subsystem. This type of testing is the main focus of this tutorial article.

There are other purposes for on-wafer testing, as well:

Sorting the die by performance is one test objective. All die are not identical, even on the same wafer. Variations in materials and the fabrication process result in a range of performance. An accurate and repeatable test system can sort the individual die into performance categories. The manufacturer often has different part numbers and specifications for devices with various levels of performance, although they are fabricated on the same die using the same process. Gain, noise and bandwidth measurements allow the better (and premium priced) die to be separated from the normal or below normal performing die.

Often, manufacturers will place test circuits on the wafer, in addition to the production die. Often, these are quality control reference devices to evaluate the fabrication process, both wafer-to-wafer, and at various locations on the same wafer. They may also be test die—for new circuits, or for variations in the fabrication of existing devices.

These special test circuits require test stations in the laboratory, in addition to the automated production test systems. These test die are usually measured manually, with units that place the die under a microscope, where the engineer or technician can position the probes at the desired locations.

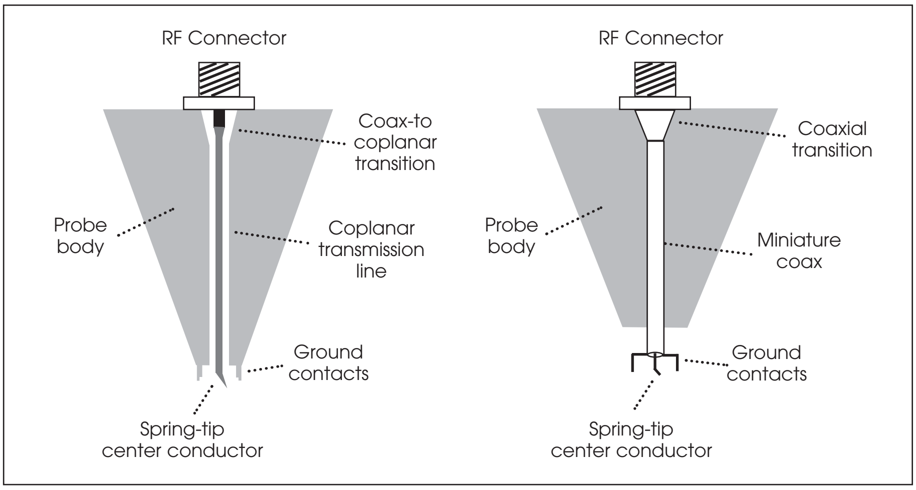

Figure 1 · Wafer probe basic construction. On the left is a coplanar probe, which has the highest frequency response. On the right is a probe with a coaxial RF transmission line.

The Probe System

A wafer probe must perform a number of difficult mechanical tasks while maintaining excellent high frequency electrical performance. The simultaneous requirements include:

- Reliable contact to the wafer
- Repeatable performance when relocated to another contact point
- Small tip size to allow multiple probes and minimize interaction with die (capacitive coupling)
- Constant impedance through the probe body to the tip (low VSWR)
- Low RF loss
- Sufficient bandwidth for the desired frequency range (plus harmonics as required)
- Convenient connection to test equipment
- Probe tip easily visible through a microscope for accurate manual positioning

As you can see, these are a challenging set of requirements, but they have been successfully achieved by probe manufacturers. As an aside, the mechanical and electrical issues for wafer test probes have many similarities to the requirements for disk drive read/write head systems.

Most probes use either coaxial or coplanar waveguide construction for the transmission line between the probe tip and the RF connector. Figure 1 is a simplified diagram. Note the tapered configuration of the probe housing to achieve the smallest practical dimension at the tip.

Coaxial probes offer excellent VSWR performance and straightforward construction of the probe, while coplanar probes have the widest bandwidth, but require more complex and precise physical construction of the probe. Both types or probes are in common use.

Test Equipment Calibration

In addition to the probe itself, the quality of the measurement also depends on an accurate and reliable calibration of the test equipment through the probing setup. Classic microwave calibration procedures can be used, remembering that the interface between the probe tips and the wafer substrate may not be as consistent as a coaxial connector.

Calibration methods include the well-known TRL (thru-reflect-line), OSLT (open-short-load-thru) and LRM (line-reflect-match) techniques. In this case, the calibration standards will differ from typical microwave measurements, although commercially available calibration standards are available for wafers, as they are for connectorized or waveguide test fixtures. In some cases, the user may wish to have custom calibration standards that match a particular wafer type and contact style.

In any case, the calibration must be made at the probe tips in order to completely de-embed the entire measurement interconnect system. In general, coplanar type probes will exhibit the least discontinuity at the point of contact, providing the most trustworthy calibrations.

Even with the most careful calibrations, measurement errors are quite possible, due to subtle differences between the calibration setup and the actual measurement. One such change is the alteration of the electromagnetic fields around the probe's coplanar line, caused by its placement over the wafer substrate. The conductive and dielectric properties of the region surrounding the probe may be significantly different from the calibration setup. In this case, a custom calibration standard that closely mimics the probe/wafer alignment may be necessary.

All microwave measurement calibrations require certain cautions. The time between calibration and measurement must be small, to avoid the effects of drift. Increasing error versus time for microwave measurements is well established. Also, the most critical calibrations and measurements should be repeated, to minimize results affected by an occasional misalignment or poor contact of the probe tips. This is, after all, a sensitive mechanical process.

Data Management

As noted earlier, wafer probing may be used for sorting and grading die, as well as for pass/fail testing (yield). Over a longer period of time, the accumulated data should be analyzed for trends in performance and yield that may indicate problems with the fabrication process. The data can also be used to compare processes at different fabs, and to provide a baseline for pre- and post-packaging performance and yield.

In short, all measured data is useful at more than one level.

Future Developments

As frequencies increase, maintaining consistent performance of a wafer probing test system becomes more difficult. Although commercial probes are available for applications to 220 GHz or more, there may be better methods for on-wafer testing of higher-frequency devices.

Among the techniques being explored are solder bumps as test contacts—the same as used for packaging or placement of a die directly on a circuit substrate. The larger surface area of solder bumps has the potential for reducing the magnitude of the discontinuity between the contact and the die, which should result in better measurements.

Advanced researchers are considering on-chip test circuitry and self-test functions that are part of the semiconductor fabrication process itself. New pad developments to accommodate future generations of packaging may allow for easier test access to the chips, as well.

For now, wafer probing is an essential part of the RF/microwave/high-speed integrated circuit manufacturing process. On-wafer testing provides data that cannot be obtained by any other method. And, as more products are developed for implementation as RFICs/MMICs, the importance of on-wafer testing will continue to grow.