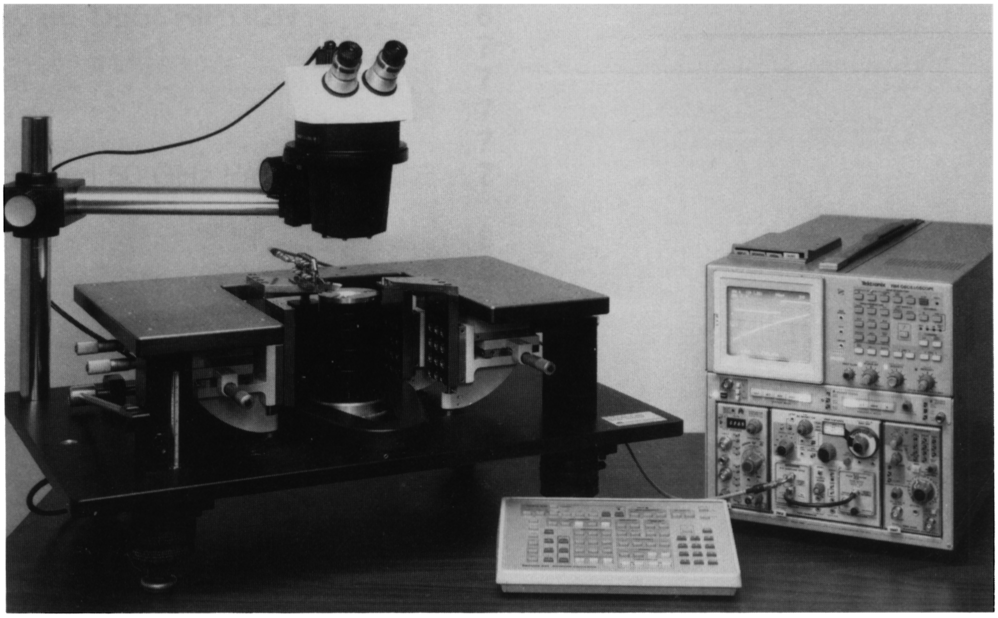
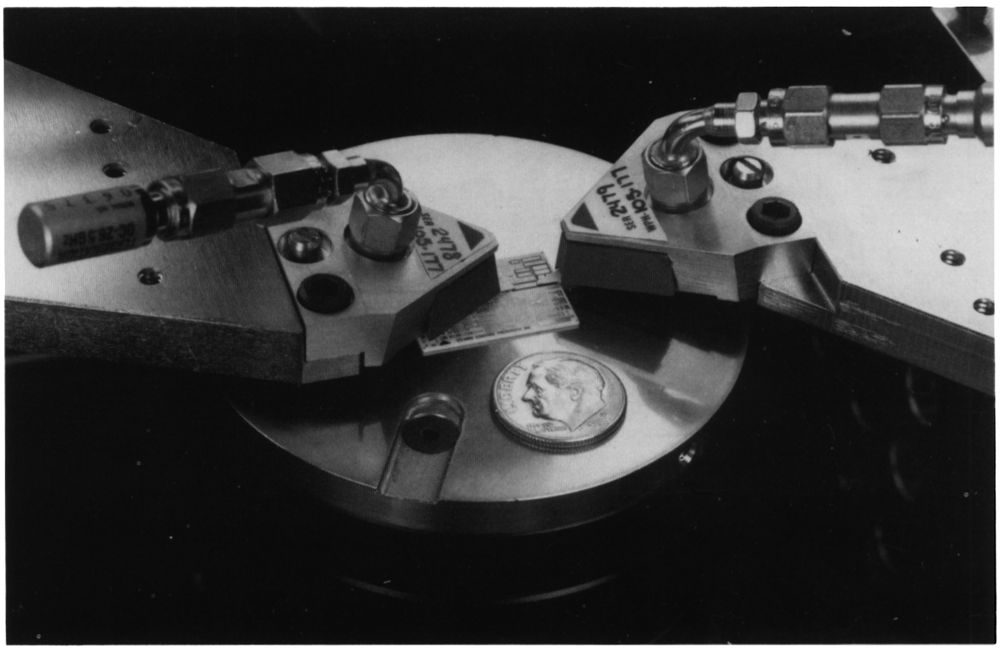
HIGH FREQUENCY WAFER PROBING





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INTRODUCTION

Making high speed, on wafer or substrate measurements has always been challenging because the signals are so easily distorted during acquisition. Probe impedance, lead reactance, probe placement, and mechanical contact, etc. present the major barriers at multi GHz frequencies and sub nanosecond rise times.

This application note introduces a new small structure and wafer probing technique in a system consisting of the Tektronix 7854 14GHz Waveform Processing Oscilloscope and Cascade Microtech wafer probe. The system successfully meets the challenge of making high-speed, on-wafer or substrate measurements. It addresses the major obstacles at these multi GHz frequences such as sub-nanosecond rise times — probe impedance, lead reactance, probe placement and mechanical contact. It provides ease of use, vastly improved accuracy and better repeatability when compared to traditional device test fixtures.

Since the die on wafers are physically very small, two criteria must be met to assure accurate parameter measurements: first, the measurement tool must mechanically and electrically match the device's physical test requirements; second, connection between measurement equipment and the device must be carefully controlled both electrically and mechanically to avoid distortion. Small geometry, very high frequency die, line and probe impedance must be carefully monitored.

In most semiconductor technologies, making wafer measurements prior to die packaging is most desirable and cost effective. Packaging high frequency devices is in itself very expensive; it is thus important to avoid packaging devices with unknown performance. Testing after die packaging adds additional expense, since high performance packages may cost as much or more than the chip.

Conventional probing methods, however, often distort rise time and bandwidth measurement results, requiring measurements after die packaging where fixtures with coaxial connections can be used for signal acquisition. But results from fixture measurements include distortions caused by packaging — lead and bond wire inductance, for example. The resulting measurements may mask actual chip performance, making accurate die performance process control difficult.

The Tektronix 7854 Waveform Processing Oscilloscope and Cascade Microtech wafer prober answer the above pre- and post-packaging distortion problems, making direct measurement of wafer devices or substrate structures and verification of circuit performance prior to packaging both accurate *and* practical.

MEASUREMENT SYSTEM REQUIREMENTS

Two basic measurement system requirements are timing or propagation delay and impedance.

Timing Measurements

Timing measurements on high speed circuits often require a precision of better than 50 picoseconds. Rise time, settling time, fall time and propagation delay measurements with picosecond accuracy must be made. For these timing measurements, use the Tektronix 7854 Waveform Processing Oscilloscope with 14 GHz waveform acquisition plug-ins (7S11 Vertical Amplifier, S4 Sampling Head, and 7T11A Sampling Sweep Unit).

Impedance Measurements

Time Domain Reflectometry (TDR) techniques profile the device's input, output and power supply terminal impedance. Programs in the Tektronix 7854 Waveform Processing Oscilloscope compute reflection coefficients to better than 0.001 and provide time resolution to a mere 10 picoseconds. When making impedance measurements use the 7854 TDR configuration (7S12 TDR/Sampler, S6 Sampling Head and the S52 Pulse Generator Head).

A general purpose system can be configured in the 7854 for both timing and impedance measurements, as shown in Figure 1.

SUPPORTING FIXTURE CONSIDERATIONS

When providing signals to and from the die on wafer, two major issues must be considered. They are *electrical fidelity* and *mechanical support*. The electrical challenge entails maintaining a controlled impedance to the device under test while reducing the conductor size. The mechanical mounting must assure accuracy, repeatability and rigidity to overcome stiff coaxial cables.

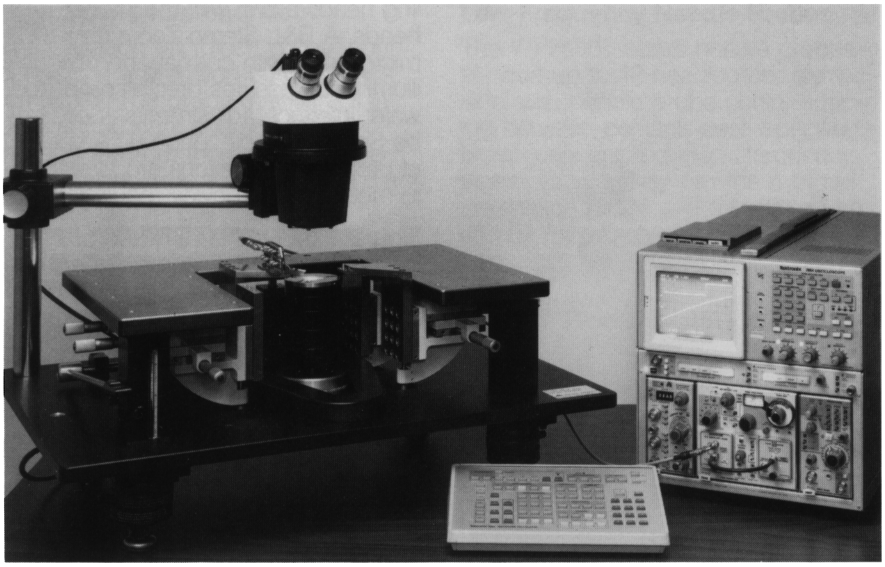

Figure 1. General purpose wafer probe station.

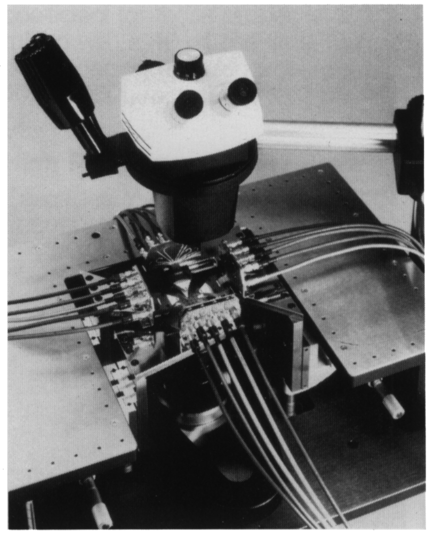

Figure 2. Model 42 probe station.

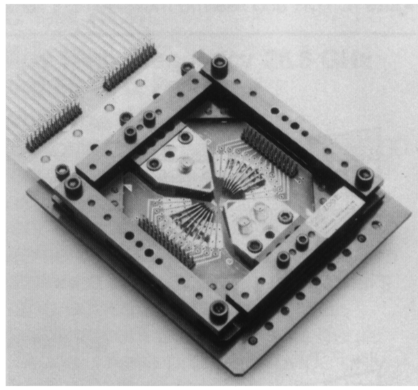

Figure 3. Solid probe card.

Cascade Microtech provides a variety of mechanical probe head supports. The Model 42 probe station, shown in Figure 2, features continuously variable adjustments in all directions: each individual probe head is variable in X, Y, and Z planes; the wafer stage is also continuously variable in X, Y, and Theta direction. The station is mounted on air cushions allowing freedom from base vibrations. Similar probe stations are available from Cascade for probe usage on autoprobers.

If the application calls for a fixed probe position for a specific die footprint, as in production, a solid probe card is used, providing mechanical support for the probe heads. This card is factory aligned to fit particular die or die family, and can be used in almost any automatic probe station. Figure 3 shows a typical probe card.

Interconnect Cables

If long cables are used, the overall bandwidth is reduced by cable skin effect losses; this reduced bandwidth, however, is not normally compensated for by the measurement instrument. Therefore, using short, high bandwidth cables or no cables is preferable. All cables are rated in terms of frequency response and insertion losses. Consequently, choose higher bandwidth and lower loss cables in these applications (e.g., <3 dB loss at 12 GHz).

Making a high frequency interface to the die on wafer requires that all components have at least the minimum bandwidth performance for the measurement.

The Oscilloscope

Our TDR set-up consists of the Tektronix 7854 14 GHz Programmable Oscilloscope along with the 7S12 TDR sampling plug-in and S-6 Sampling Head. This combination is ideal for TDR measurements directly on the wafer or substrate. For propagation delay measurements, two 7S11's with S-4 Sampling Heads and the 7T11A should be used. These sampling heads allow usage with sampling head extenders, Tektronix part number 012-0124-00 (3 foot length) and 012-0125-00 (6 foot length). Sampling head extenders reduce or eliminate cables entirely and let you bring the sampling head input right to the wafer probe.

The Probe Station

The Cascade Microtech Model 42 probe station, ideal for either application, consists of a rigid and precise mounting platform for the wafer under test and microwave probes. The station's large, stable work surface allows easy mounting of samp-

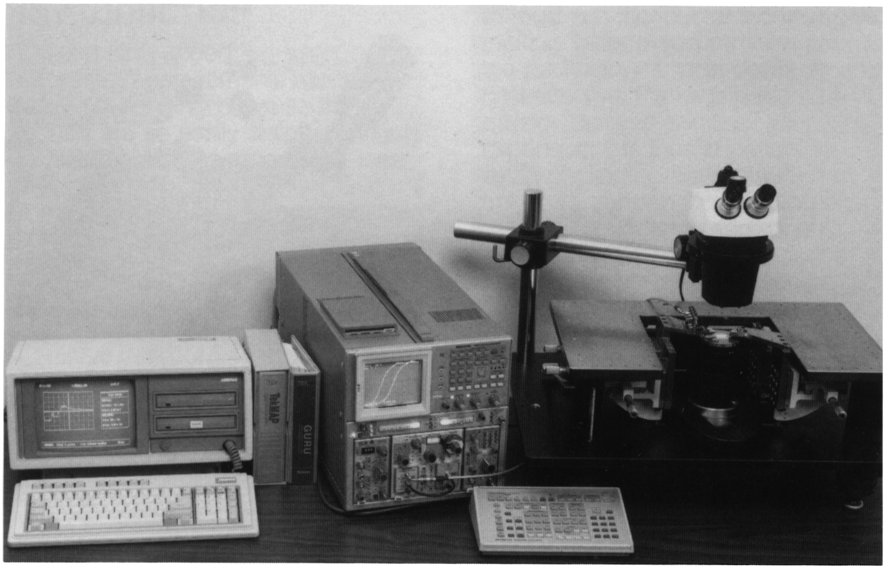

Figure 4. TDR and *risetime* measurement setup with PC controller.

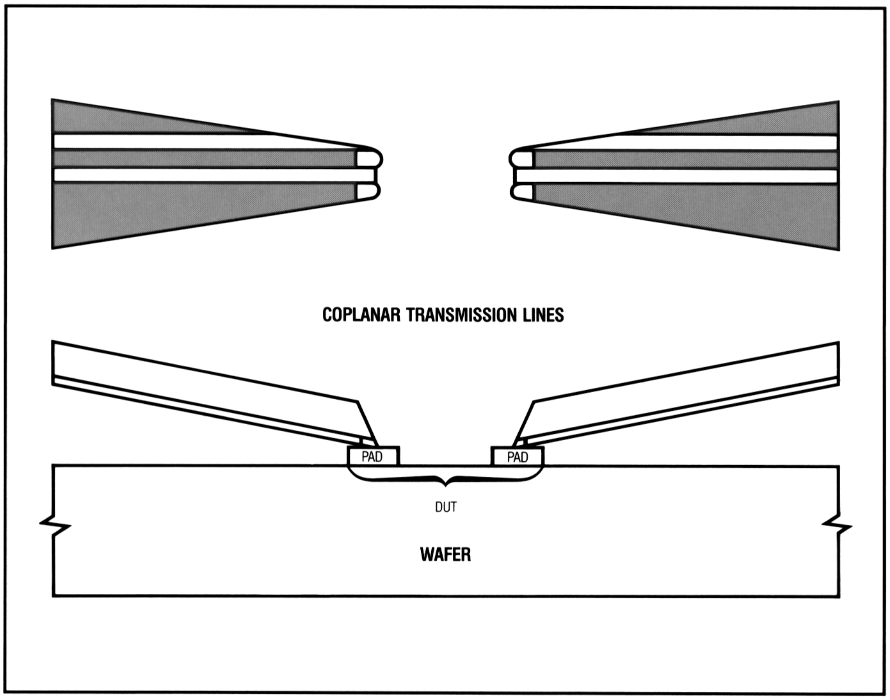

Figure 5. Model of GH_Z wafer probe *coplanar* transmission line.

ling heads along with the probe heads. A B&L Stereo Zoom (tm) 1070 microscope with coaxial and oblique illumination assures precise probe-to-wafer interface adjustments. (See Probe Selection Table, page 8.) A variety of probe configurations are available to meet specific device requirements.

Figure 4 shows the TDR and rise time measurement setups. Either setup benefits from a GPIB controller and TekMap software. This software takes full advantage of the 7854's waveform processing capability, providing the waveform processing and data processing desired in automatic wafer probing applications. Three currently available software packages are the S42P101 Communications and Control Software, S42P202 TEKMAP Time and Amplitude Measurement Software for the IBM PC/XT/AT or compatible computer, and the S42H202 7854/HP Series 200 Time and Amplitude Measurement Software.

This system demonstrates the expanded capabilities achieved when adding high frequency probing equipment, extending the measurement instrument performance to the device under test.

CASCADE MICROTECH PROBE DESCRIPTION

Cascade supports applications ranging from low frequency to very high frequency 50 GHz probes. Low frequency probes are conventional needle type probes. Medium frequency probes (up to 15 GHz) include multi-contact types allowing up to 44 contacts per die with 24 controlled impedance input or output ports, eight bypassed power supply contacts and 12 ground contacts. Very high frequency probes (26.5 GHz and 50 GHz) support two through five contacts per die or device side.

High Speed Interconnects

The Cascade Microtech probe input consists of a precision 50 ohm SMA connector. The probe maintains this constant 50 ohm characteristic impedance from the relatively large SMA connector to the very small die contacts on the wafer, typically spaced from four to ten mils apart — to ensure accurate test results by minimizing reflections.

At the heart of the Cascade probe is a special transmission line which adapts the SMA coaxial connector to the small die pads on the wafer and thus provides the interface between the measurement system and the wafer die.

As with all transmission lines, the key to accurate measurements is maintaining the characteristic impedance with minimal loss over the entire operating frequency, a relatively simple task in conventional large geometry transmission lines but a real challenge when combined with four mil spacing.

Cascade meets this challenge by gradually and precisely reducing the center conductor size from the SMA connector right to the very small probe tip. Then, by precisely reducing the center to outer conductor spacing, a constant 50 ohms is maintained. (See Figure 5.)

Contacting the die requires minute tip dimensions. To achieve this, a highly polished and carefully cut alumina substrate is used, a material ideally suited to this application due to its strength and insulating properties over the needed distance.

Low Frequency Needle Probes

The WPH-900 series needle probes support up to 12 needles per die side, with needle probe center spacing between contacts user- specified. Commonly applied in low-frequency wafer probing, they provide a broad application range and are offered by several manufacturers at relatively low cost.

Needle probe tips are often made of hard tungsten to insure long life and reliability. These probes work well to about 100 MHz with greater than 2 ns rise times; they suffer, however, from very high series inductance (about 10nH), and relatively high reflection coefficient (of nearly 200 mRho). Primary probe applications include DC control lines, bias voltage power supplies and low frequency compensation networks; due to limited high frequency range, probes should not be used as signal stimulus, output waveform measurements or even ground or power supply contacts when fast edges are being used.

Multi-Contact 14 GHz Probes

The WPH-700 series probes support measurements to 14 GHz with greater than 25 picosecond rise times. At these frequencies, a ground connection physically very close to the signal connection must be provided. One of the more popular applications is die power supply decoupling. The WPH-700 probehead decoupling provides power to the die from very low impedance, instead of highly inductive needles.

Since these probes can be customized, an excellent die to interconnect match is easily attained. Any contact may be specified as either a ground reference, a low impedance, high capacitance bypass power supply, a 50 ohm transmission line, or a 50 ohm signal line terminated in 50 ohm to ground or to a power supply. The worst case reflection coefficient for these probes is 80 mRho with a 40 ps rise time. Contact pitch spacing may range between 100 to 250 μm, with up to 8 contacts per side.

High Frequency 18 GHz Probes

Cascades' WPH-000 series of high frequency wafer probes cover the DC to 18 GHz frequency range. These heads are designed for a controlled impedance for microwave, clock and clock driver applications and rise times of 20 ps or greater. Contact spacing ranges from 50 to 1500 μm. These probes work very well in ECL, high speed silicon and digital GaAs applications. Their reflection coefficient is less than 50 mRho when measured with the Tektronix 7854 Waveform Processing Oscilloscope and 7S12 Time Domain Reflectometer (TDR).

Very High Frequency 26.5 GHz and 50 GHz Probes

When rise times as short as 13 picoseconds prevail, the WPH-100 series of Cascade probes provides the best solution. Ideally suited to very high speed waveform measurements, they provide first class performance when viewing the signal's rising edges and to monitor all measurement aberrations or degradations. These probes provide only single signal connection with a maximum of 5 contacts per probe head; their reflection coefficient,like the WPH-000 series probes, is less than 50 mRho. The WPH-200 series probes deliver a maximum bandwidth of 50 GHz and 7 picosecond rise time. Available only in a single ground-signal- ground probe contact configuration, this probe is normally used in millimeter wave on device probing.

Probe selection table

	Band-width GHz	Reflection Coefficient mp	Available Pitch µm	Approx. Inductance pH	Application
Needle Probes					
WPH-9YY-XXX	NA	NA	NA	8000	DC control signals
Multi-contact Probes					
WPH-70Y-XXX-aaaaaaaa	≈10	80	100-250	100-300	High speed digital
Medium Performance Probes					
WPH-001-XXX G-S1	18	50	50-400	NA	Single ended
WPH-002-XXX S1-G	18	50	50-400	NA	Single ended
WPH-003-XXX S1-G-S2	18	50	100-750	60	Differential or Push Pull
WPH-004-XXX G-S1-G-S1-G	18	50	50-150	NA	Balanced
WPH-005-XXX G-S1-G	18	50	50-1250	NA	Single ended shielded
WPH-006-XXX S1+S1−	18	50	100-1500	NA	Differential or Push Pull
WPH-011-XXX G-S1-G-S2-G	18	50	100-250	20	Dual ended shielded
WPH-016-XXX G-S1+S1-G	18	50	50-150	NA	Differential or Push Pull shielded
WPH-017-XXX G-S1+X-S1-G	18	50	50-150	NA	Balanced shielded
WPH-018-XXX X-S1+X-S1-X	18	50	50-150	NA	Balanced unshielded
WPH-020-XXX G-S1-S2	18	150	100-250	250	Dual ended
WPH-021-XXX S1-S2-G	18	150	100-250	250	Dual ended
High Performance Probes					
WPH-101-XXX G-S1	26.5	50	50-400	NA	Single ended
WPH-102-XXX S1-G	26.5	50	50-400	NA	Single ended
WPH-104-XXX G-S1-G-S1-G	26.5	50	50-150	NA	Balanced
WPH-105-XXX G-S1-G	26.5	50	50-250	NA	Single ended shielded
WPH-116-XXX G-S1+S1-G	26.5	50	50-150	NA	Differential or Push Pull shielded
WPH-117-XXX G-S1+X-S1-G	26.5	50	50-150	NA	Balanced shielded
Highest Performance Probes					
WPH-205-XXX G-S1-G	50	50	50-250	NA	Single ended shielded

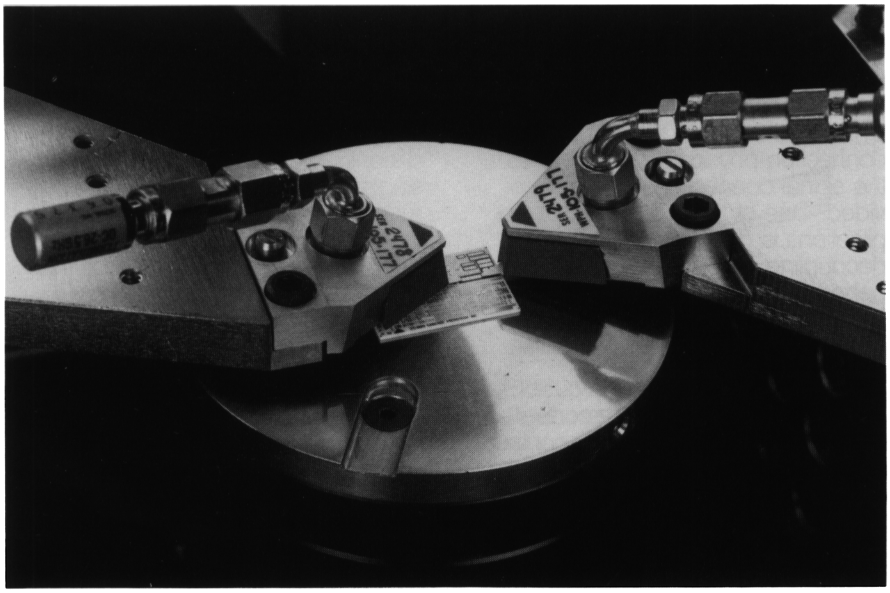

Figure 6. Probing an Impedance Standard Substrate (ISS).

MEASUREMENT EXAMPLES

Some simple measurement examples are shown here, including reflection and transmission accuracy verifications. The Cascade Impedance Standard Substrate (ISS) makes verification easy and accurate by allowing connection to nearly ideal 50 ohm transmission lines, opens, shorts, and 50 ohm terminations right at the probe tip. See Figure 6.

TDR measurements

While rise time measurements provide excellent time and amplitude information, they do not provide impedance and distance calculation results. A TDR (Time Domain Reflectometer) provides a means to derive both impedance and distance information. The equipment used for these measurements consist of the Tektronix 7S12 with the S-6 Sampling Head and S-52 fast rise pulse generator head. The TDR sends a fast edge to the Device Under Test (DUT) and measures the signal reflected back to the generator; each imperfection is easily located, since the time delay of the reflection implies the position of the discontinuity. A perfect measurement system would not introduce any reflections.

The Needle Probe TDR

The photo in Figure 7 shows a needle probe TDR measurement. The waveform shows an overall reflection coefficient of 200 mRho which translates to an impedance mismatch of −17 to +25 ohms. As a result, in high speed digital applications, the measured signal amplitude may not reach the 100% value if the pulse returns to the baseline level before the probe responds.

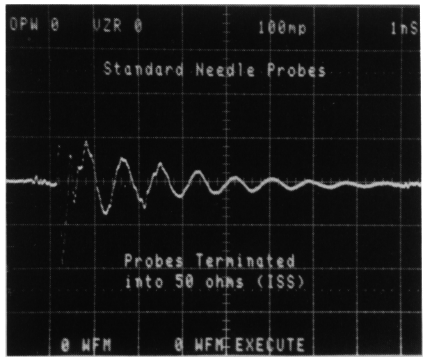

Figure 7. Needle probe TDR.

WPH-100 TDR

In contrast, Figure 8 shows a TDR measurement with the same set-up seen in Figure 7, with the needle probe replaced by the WPH-105 probe. This waveform shows a 20 mRho reflection coefficient, which is only a ±2 ohm impedance mismatch. This corresponds to a worst case ±2% measurement error due to the high frequency impedance mismatches. In practical systems, this is a second order effect.

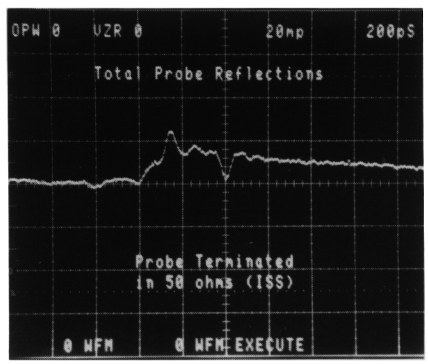

Figure 8. GH_Z probe TDR WPH-105 probe.

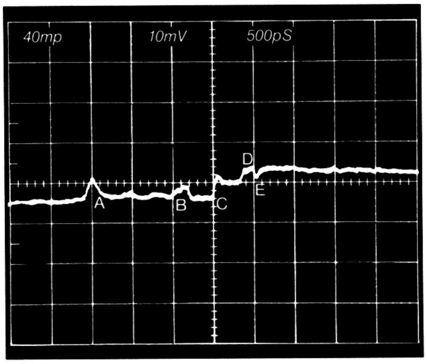

Figure 9. 40 picosecond TDR.

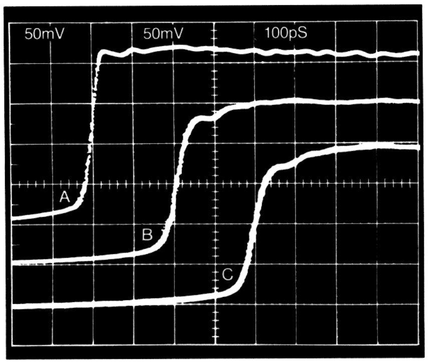

Figure 10. Transmission characteristics.

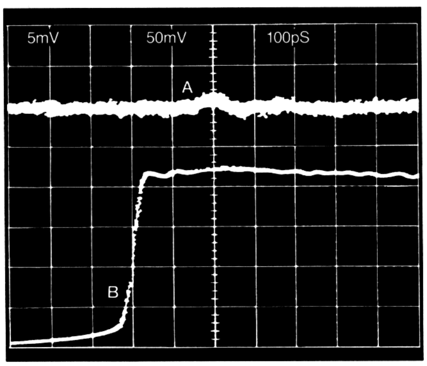

Figure 11. Worst case crosstalk.

Typical Time Domain Performance

In Figure 9, a 40 picosecond Time Domain Reflectometer (TDR) is used to measure the *reflection* of two probes (a Cascade WPH-001-04 and a WPH-002-04 probe head) contacting a through connection on the ISS.

The discontinuity at "A" is caused by a typical SMA connector on a semi rigid cable; "B" pinpoints where the semi rigid cable contacts the first probe head; "C" represents the discontinuity at the probe tips; "D" is the SMA connector on the second probe head; and "E" is the SMA termination.

In Figure 10 the same 40 picosecond step generator and sampler combination is used to measure the *transmission* characteristics of the pair of probe heads discussed above.

Here, "A" shows the input from the step generator. Trace "B" shows the same step after passing through two typical 5 nanosecond cables, 10 nanosecond total, with normal dribble-up and degradation in rise time apparent. Trace "C" shows the step after passing though a 5 nanosecond cable, through the pair of probe heads and out the other 5 nanosecond cable to the sampling oscilloscope. This demonstrates that the main degradation is just the frequency response of the cables connecting the probes. Taking the approximate rise time of trace "B" and "C" as 80 picosecond and 85 picosecond respectively, the rise time of the two probes together is:

$$tr = \sqrt{85^2 - 80^2}$$

= 28.7 picoseconds or about 14 picoseconds for one probe.

In Figure 11, the worst case crosstalk between the probes is shown. Worst case occurs when all probe tips (both grounds and both signals) are shorted together. In this example, both probe tips are contacting the 8x4 mil pad.

Typical wire needle probes have very high crosstalk above 1 GHz due to the inductance in the common leads. Figure 11 shows that the inductive spike "A" feeding through from the 40 picosecond 200 millivolt step "B" is only 1 millivolt amplitude. The Cascade WPH-003-xx probe head has 10 millivolt feedthrough in this test, corresponding to a common lead inductance of less than 60 picohenry.

Digital circuit rise times do not yet approach the rise times of available cables and printable transmission lines, so the need for waveshape correction is relatively minor. More important to the digital designer is the accurate measurement of propagation delays. Through connections for accurate delay calibrations with multi line probes can be built in the same style as two port ANA standards, with lines at enough different angle positions to make throughs between each pair of signal lines.

Device Package Considerations

Die packaging plays a large part in high frequency die performance. Device packages typically use small bond wires for outside world connections to the lead frame. This bond wire, however, introduces series inductance, resistance, and additional stray capacitance which can severely limit die performance. Cascade probes offer the capability to measure the individual die both *before* packaging and then *with* the package, allowing designers to measure packaging effects with ease and greater accuracy. It is also possible to use these probes and test setups to measure the package performance directly.

Bond wire degradation

Figure 12 uses high speed probes for a TDR, showing that the difference between no bond wire and a 20 mil bond wire (shorter than usually practical), is about 60 mRho reflection or about 3 times as large as the probe reflection (Figure 13). The end result indicates that whatever the die response, typical bond wires distort high speed edges significantly.

Without the ability to measure the die independently, the designer might try to improve performance by compensating for package limitations, an expensive option due to the numerous design iterations. For instance, peaking a device driver for package limitations may solve the immediate problem, but may also result in serious manufacturing and yield problems, since wire bond inductances are not that repeatable and actual die performance is unknown.

Power supply Bypassing

Given the numerous problems facing the device designer, it's not surprising that powering a device is quite often forgotten in overall designs until testing time. Elaborate power supply designs incorporate feedback networks to regulate the dc output to a specified accuracy. This feedback network, however, can't respond nearly fast enough to the current demands when a device is trying to switch. The main reason: the physical location of the power supply relative to the device.

Power supplies tend to reside in racks many meters away from the device. Therefore, it is common practice to add decoupling or bypass capacitors to a fixture to supply the current demands until the power supply can respond. In effect, the power supply impedance is designed

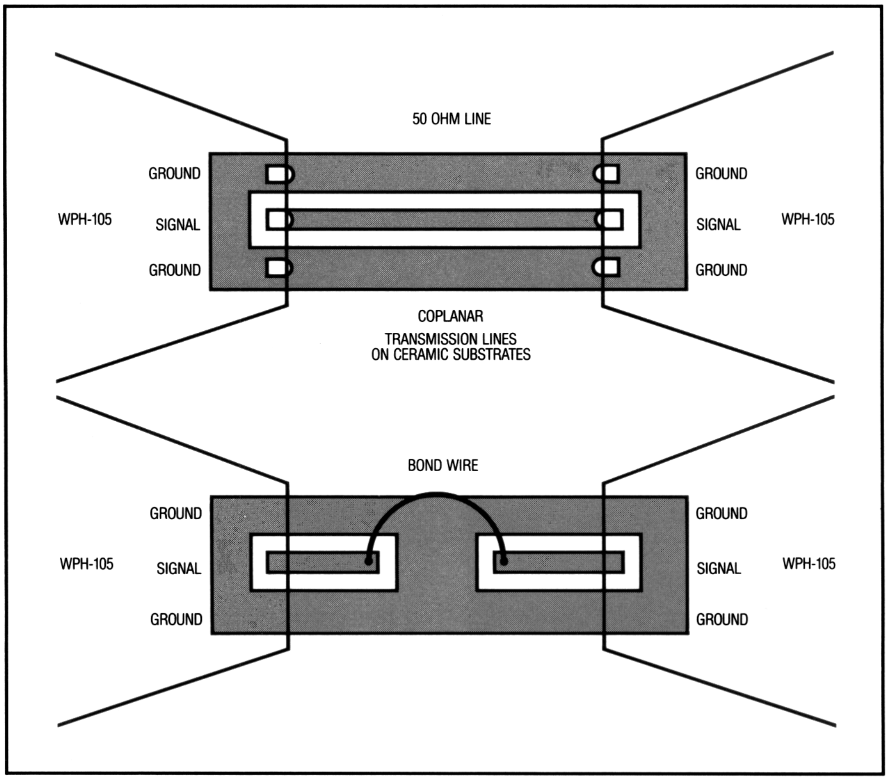

Figure 12. The bond wire model.

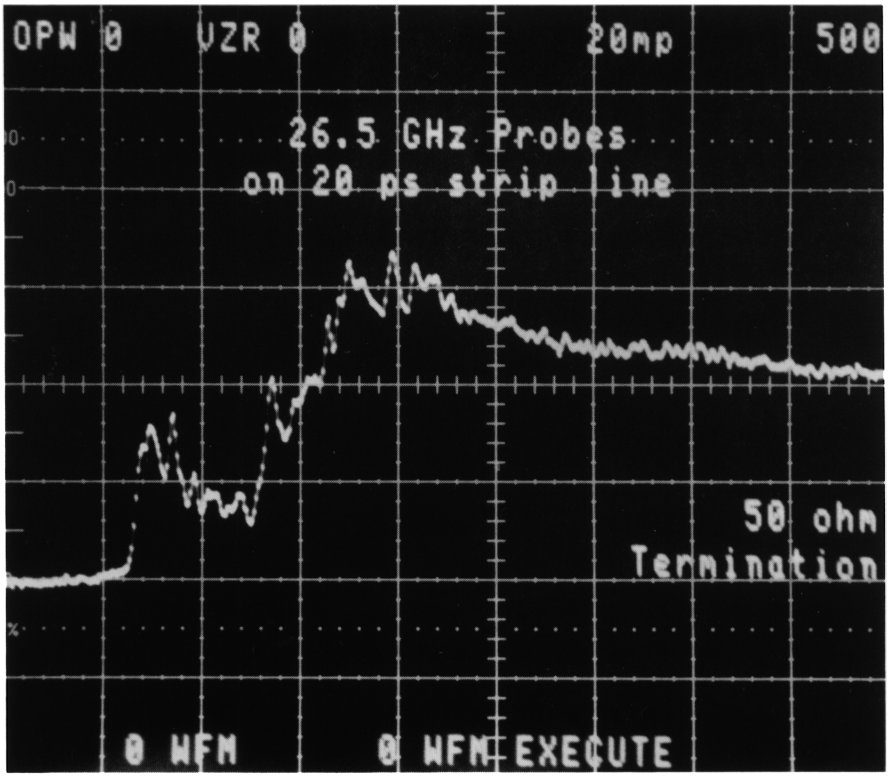

Figure 13. Bond wire TDR.

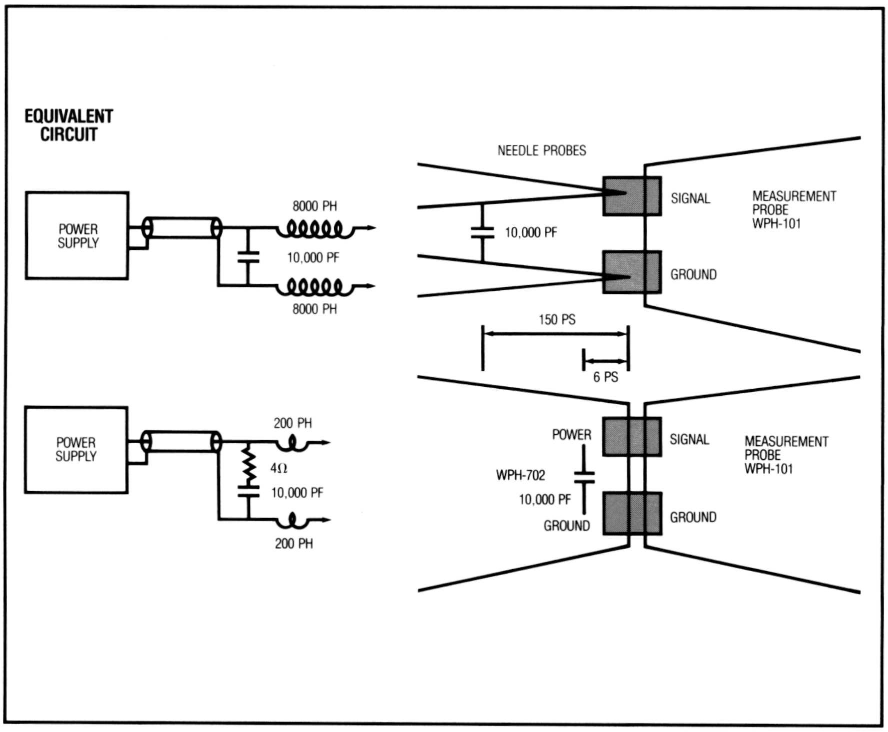

Figure 14. GH_Z power supply decoupling.

to appear as zero ohms. In most cases, because of capacitor's physical size limitations, this bypass network resides nanoseconds away from the device, still too distant to respond to sub nanosecond current transients.

The WPH-700 series probes can provide low impedance bypassing as close as 6 picoseconds from the device pad. The bypass networks provide the probe with constant low impedance at all frequencies and meet the requirement that the power supply impedance be as low as possible as seen from the device's power supply and ground terminals.

The setup in Figure 14 shows a TDR comparison between a pair of needle probes with a 0.01 μF capacitor bypass soldered within 300 mils of the probe head and a WPH-700 series power supply probe contact. A zero impedance power supply would appear to be a short circuit in high frequency measurements; the lower trace in Figure 15 is very close to a short circuit.

The TDR measurement shows the Cascade probe to be highly capacitive with low inductance at the probe tip. The overall impedance is about 4 ohms to dampen out very high frequency ringing which could occur from a high speed device's fast transitions. The result is a broad band non-resonating bypass network. On the other hand, the needle probe trace shows several nanohenries inductance prior to the probe becoming capacitive. The typical effect of such first order inductance is severe crosstalk due to a noisy die ground or power supply.

Four terminal Kelvin power

Another application benefit from the WPH-700 series probes is the ability to provide power at the probe tips through Kelvin or four terminal sense techniques. In those cases where a power supply voltage must be as accurate as possible, the probe itself can be included in the power supply feedback loop. This method compensates for interconnect resistance and contact resistance.

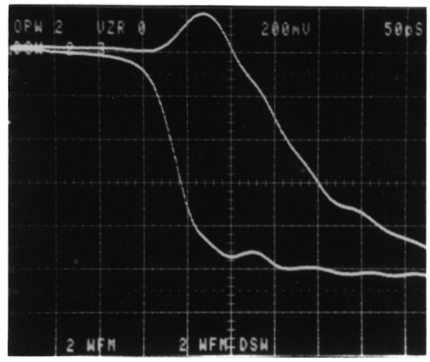

Figure 15. Power supply impedance.

SUMMARY

Wafer probing challenges can now be effectively addressed using state-of-the-art constant impedance wafer probes. A system combining these new Cascade Microtech probes with the Tektronix 7854 programmable Waveform Processing Oscilloscope now provides innovative and effective solutions to complex high frequency wafer and die performance qualifying requirements *prior* to actual device packaging.

ACKNOWLEDGEMENTS

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