A MICROWAVE PROBE SYSTEM

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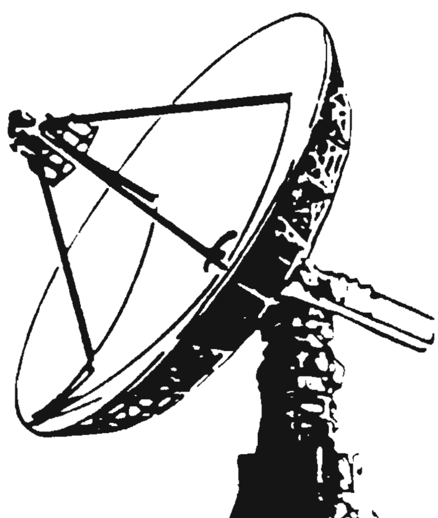


HEWLETT PACKARD

A MICROWAVE PROBE SYSTEM

The objective of this presentation is to demonstrate a method for microwave testing of unpackaged devices and circuits using probes for rf and dc connections.

CONTENTS

- Probe System Concept
- HP Probe System Description
- Measurement Capabilities
- Enhancements and Limitations

We will cover both the general requirements for probed testing at microwave frequencies and the specifics of how a high frequency probe system can be built.

PROBE SYSTEM CONCEPT

- What is it? What can it do?
- Why Probe?
- Why High Frequency?
- Performance Requirements.

Let's begin with an overview of the probe system discussed in this presentation, what it can do, and why its capabilities are so valuable.

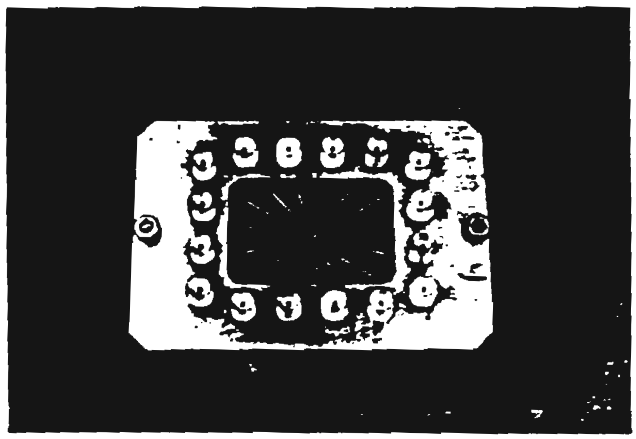
The probe system to be described is simply a means of temporarily connecting instruments to an unpackaged circuit for testing. It is especially useful for rapid, on-wafer testing of IC's and discrete devices. Its biggest contribution is its high frequency capability, which is about 100 times better than commercial IC probers. Similar systems have been used at several HP divisions for gain, S-parameter, noise, and distortion tests at frequencies up to 5 GHz.

PROBE SYSTEM— WHAT IS IT?

- Connection Method
- For Discretes, IC's, Hybrids
- On-Wafer Testing
- >5 GHz Capability
- An Example, Not HP Product

To preview what will be shown in detail later, the heart of the probe system is a large sapphire (or alumina) thin-film circuit called the 'probe card' or 'probe substrate'. Miniature probes protrude through a hole in the center of the probe card to contact the circuit being tested. The probes are permanently attached to microstrip lines on the probe card, which lead to coaxial connectors in a frame around the periphery.

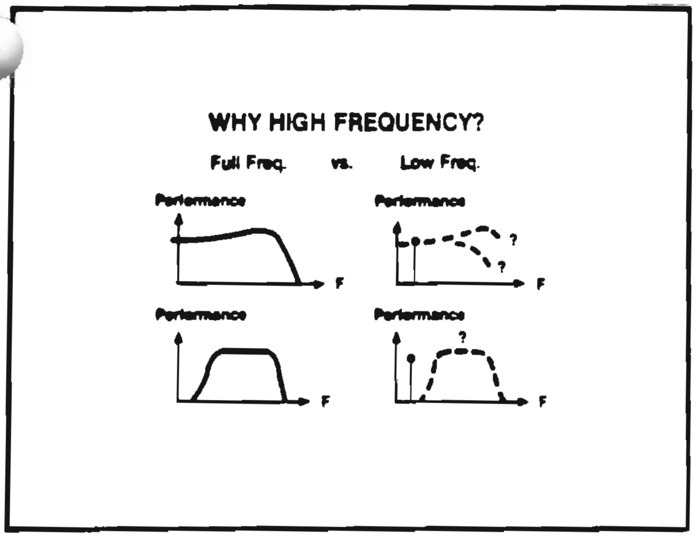
MICROWAVE PROBE CARD



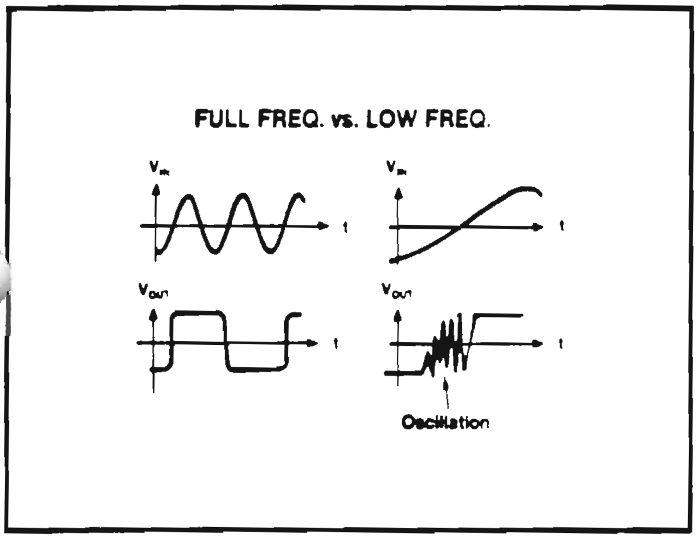
Testing with a probe system can dramatically improve productivity. With a wafer stepper and automated test equipment, entire wafers can be tested at operating frequencies without operator intervention.

WHY PROBE?

- Can be Highly Automated.
- Full Freq. Testing of Every Chip.
- Greatly Reduce Rework of Hybrids.
- Rapid Feedback on Process or Vendor.



Full frequency testing eliminates marginal chips, and can dramatically improve yields at later stages of assembly. For bandpass circuits, low frequency testing may be worthless. ("Performance" could refer to gain, output power, return loss, relative harmonics, signal-to-noise ratio, etc.)



Some digital circuits require a fast risetime input, and will not function properly with a low frequency input (making them the digital counterpart of the analog bandpass circuit). As risetime requirements drop into the nanosecond range for circuits like GaAs prescalers, traditional probing methods are no longer adequate.

HIGH FREQ. PROBE REQUIREMENTS

- Constant Impedance
- Minimum Probe Inductance
- Very Short Ground Returns
- Minimum Crosstalk
- Low Impedance Supplies

High frequency probe measurements overcome the preceding problems. But what makes a good high frequency probe system? Performance and versatility are two key ingredients. Performance requires controlled impedances and minimum parasitics.

Probe locations are generally not adjustable on RF/microwave systems. To get maximum use from each probe card, it is valuable to allow each probe to be used for dc and/or rf; this simple structure also makes probe card construction straightforward. Probe spacing of less than 100 microns is required for some IC's. And the test system should accommodate large wafers or large hybrid circuits.

PROBE VERSATILITY

- DC and/or RF on Every Probe
- Large Wafer/Circuit Sizes
- High Density of Probes
- Probe Card Easy to Change

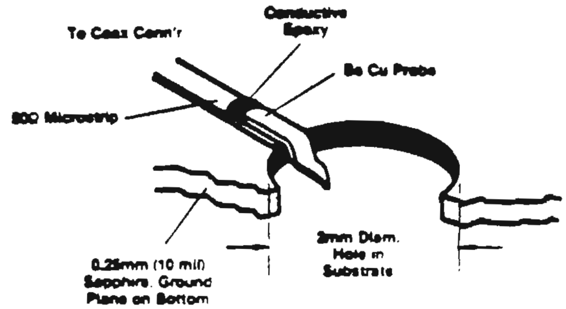
The probe system example to be described achieves both versatility and high performance--it has been used to 5 GHz and above for on-wafer testing. The 'probe card' is a thin-film sapphire or alumina circuit, rather than a printed circuit board. Some of its characteristics are listed in this slide.

HP PROBE SYSTEM

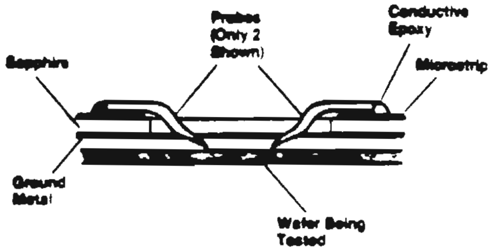
- 1mm Probe Length, 0.7nH
- 0.25mm Thin-Film Test Card
- 50 Ohm Microstrip Lines
- An Example; Not a Product Due to Custom Nature

Here is a detail showing how probes are mounted. Probes have been fabricated both by turning, on a miniature lathe, and by chemical etching. Tips are sharpened by electropolishing in 85% phosphoric acid with +5V bias applied to the probe. They are then plated with 50 micro-inches of gold.

DETAIL OF ONE PROBE

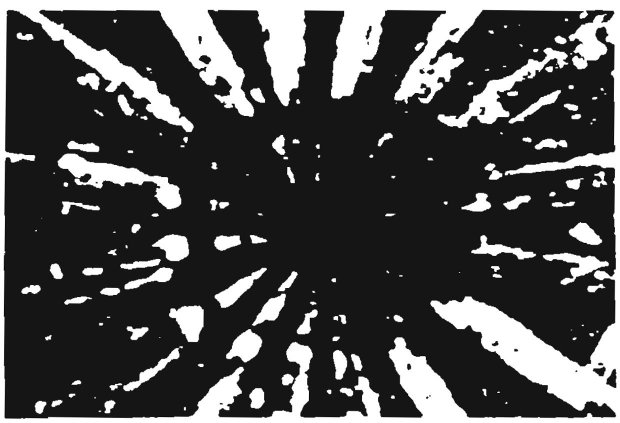


SIDE VIEW OF PROBES



A small bending jig is used to form the probes to the shape shown. If the probes are chemically etched parts, then strips of 20 or more probes can be bent (and sharpened) simultaneously. During assembly, probes are aligned by hand under a microscope to contact the pads of the type circuit to be tested. Tacky conductive epoxy holds the probes in place. After curing, a layer of non-conductive epoxy (not shown) is added over the probes for extra strength.

TOP VIEW OF PROBES



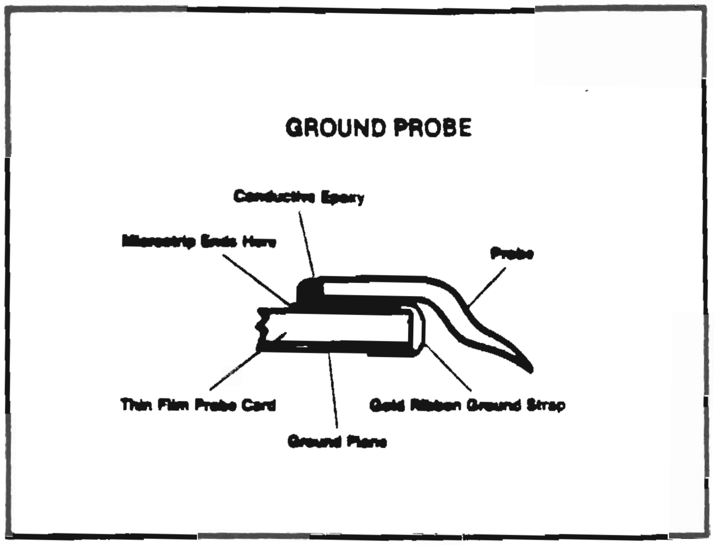
Here is a typical probe card, shown contacting a GaAs integrated circuit. Higher magnification is normally used during testing, so that the circuit under test may be examined visually.

PROBE CIRCUIT MODIFICATIONS

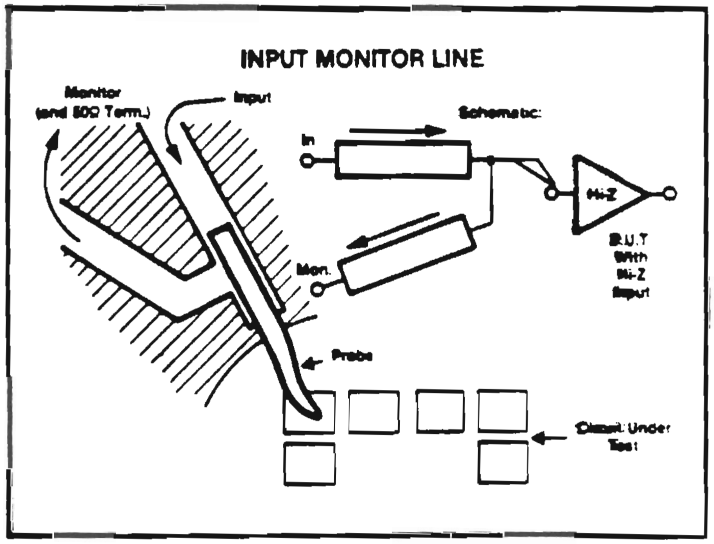
- Ground Probes
- Input Monitors
- Non-50Ω Loads
- Power Supply Bypassing

There are a number of variations on the simple 50-ohm transmission-line connection to a circuit under test. Each may be useful or necessary in certain cases, and each requires some modification to the thin-film probe card. The most common variations are shown here and discussed in the following pages.

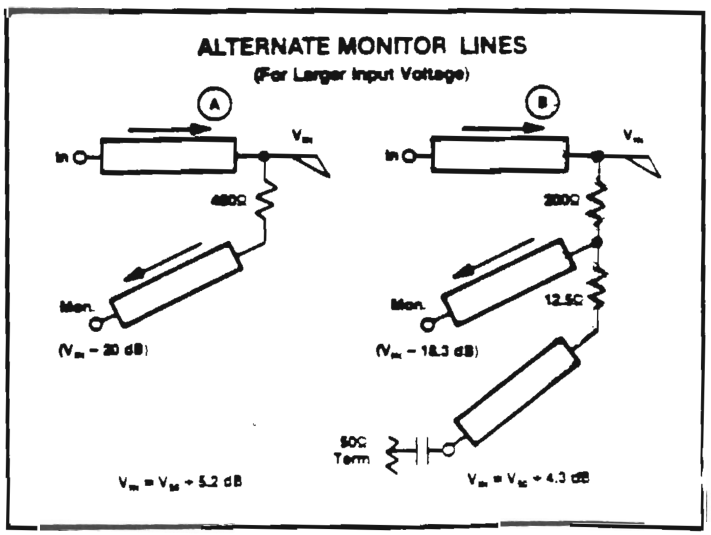
Many circuits require a low impedance ground connection. The method shown here provides a ground inductance of about 0.8 nH, roughly double that of a 0.5-mm long wire bond. High gain circuits, and those operating above 2 GHz, may require multiple ground probes for accurate characterization. They may also require separate ground pads on the chip under test for various portions of its circuitry.



An input monitor line can be useful when the circuit under test has a high input reflection coefficient. Without a monitor, input voltage can only be calculated, and the calculation requires that S_{11} (magnitude and phase) be measured first. For example, the voltage of a perfect open circuit (without a monitor) is double the voltage that the source provides into a 50 ohm load. A monitor line can be used to measure the input voltage directly, eliminating the need to measure S_{11} for calculating voltage.



The type of monitor line shown above also provides a 50 ohm termination for the input line, which is usually desirable for minimizing measurement errors. However, it is possible to take advantage of the open-circuit voltage-doubling effect to get a larger input voltage than the source provides into 50 ohms; two methods are shown here. (B) is less susceptible to mismatch errors on the monitor line. Bias T's on all lines (not shown) allow dc bias to be applied to the input.

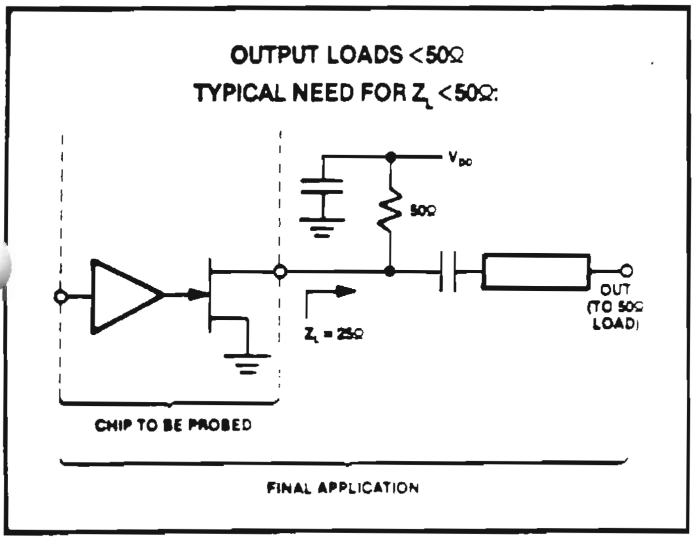


WHEN TO USE MONITORS

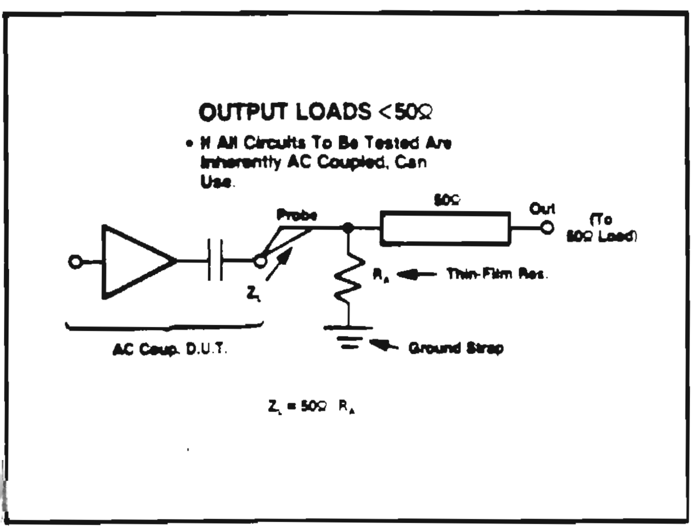
Appropriate When S_{11} Is Not Measured

Accurate V_{IN} Data For High Refl. Coeff. Inputs

If S_{11} is going to be measured, then don't use a monitor line. A monitor would shunt the input and affect the S_{11} measurement; and a monitor is not needed, since input voltage can be calculated from S_{11}. If S_{11} is not measured, a monitor line can provide a direct measurement of input voltage.

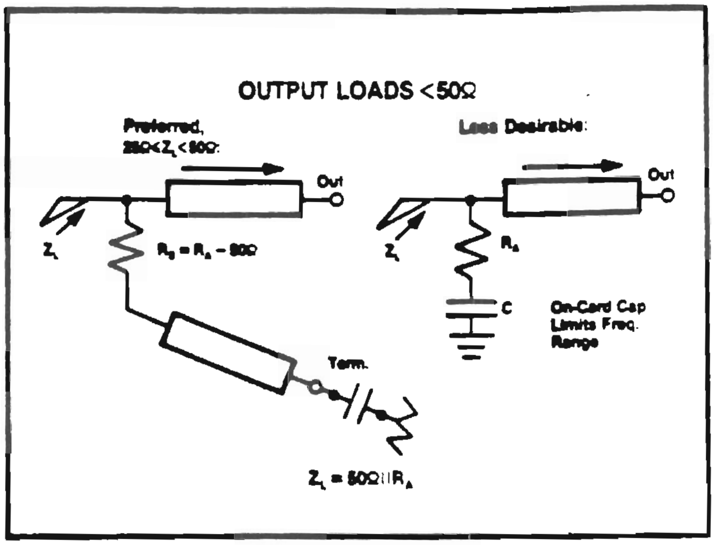


Some applications involve a load impedance less than 50 ohms, like the 25 ohm load in the case at left. If the chip is probed with a 50 ohm load, it may exhibit up to 6 dB more small-signal gain than in the 25 ohm application (depending on the S_{22} of the circuit under test). A gain correction factor could be applied. Or the probe circuit could be modified to present the desired load impedance, as described below. Accurate tests of parameters like saturation, distortion, or logic swing may require such a modification.



If all circuits to be tested are ac coupled, then, of course, a shunt resistor directly to ground could be used to lower the load impedance. For dc coupled outputs, such a resistor might dissipate excessive power (0.5W for 50 ohms and 5V bias), and complicates the measurement of circuit dc currents and voltages.

Two methods for providing loads lower than 50 ohms without affecting dc biasing are shown here. The one at left is more flexible, in that the ac coupling of the shunt resistor is external; the frequency range can be changed by changing an external bias T. This method is limited to loads between 25 ohms (for R_B=0) and 50 ohms, unless additional 50 ohm lines are used. Neither method guarantees a good reverse termination on the output line; that would require a more complex circuit, unless R_A in parallel with S_{22} of the device happens to be near to 50 ohms.



In other cases, a load impedance greater than 50 ohms may be desired. Examples are circuits designed for 75 ohm systems, and applications involving chip-to-chip interconnects without controlled impedance transmission lines. Diagnostic probing of internal circuit nodes--nodes that are not externally connected in the final application--is another case where a higher impedance is desirable.

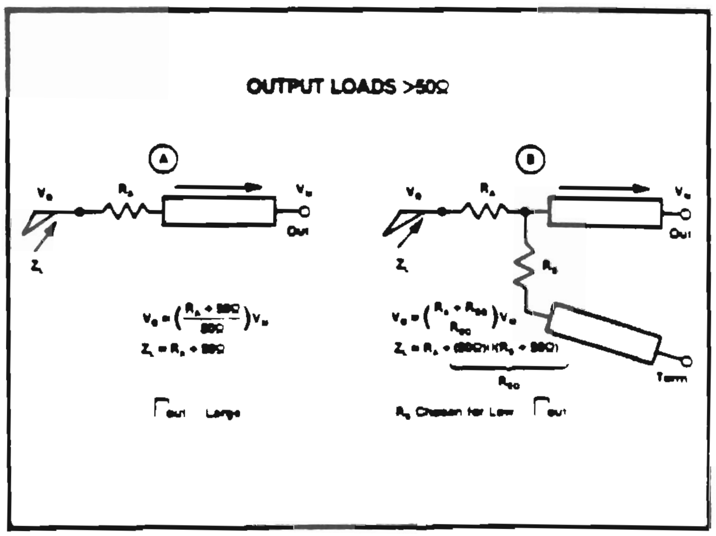
NEED FOR Z_L >50Ω

- Systems w/ Z_o >50Ω
- Chip-to-Chip Interconnects in Same Package, R_L >50Ω
- Probing Internal Circuit Nodes

Here are two methods of providing a load impedance greater than 50 ohms. Method B, on the right, gives greater measurement accuracy by providing a reverse-terminated output line. R_B is chosen so that

$$(R_B+50\text{ ohm}) \,||\, (R_A+S_{22DUT}) \approx 50\text{ ohm}.$$

(The equality is not exact because S_{22} usually is a complex value; also, S_{22} varies from chip to chip.)



LIMITS TO HI-Z LOADS

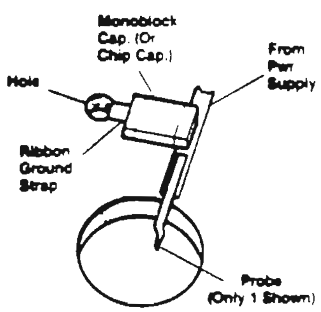
- Hard to Achieve Parasitic C_{SHUNT} <0.3 pF in Chip-to-Chip Interconnects; R_L<500Ω For F_{-3} ≥1 GHz
- Probe C_{SH}≈0.3pF Imposes Similar Limit For Probing

How large can Z_L be made in practice? The limit is determined by the parasitic shunt capacitance to ground. It is difficult to reduce this capacitance below about 0.3 pF, either in a real application or in this probe station. So

$$X_C = \frac{1}{2\pi f\ 0.3\text{pF}} \approx \frac{500\ \text{ohm GHz}}{f},$$

and this capacitive reactance limits Z_L. This means a 500 ohm load is usable to 1 GHz (its -3dB point), and a 5k ohm load to 100 MHz.

ON-CARD SUPPLY BYPASSING



The scheme at left can be used to provide bypassed, low impedance power supplies. However, it has the disadvantages of restricted frequency range (both low and high end), less generality than simple 50 ohm lines, and poor area efficiency which can limit the number of probes. Many circuits will work well with 50 ohm supply impedances, eliminating the need for the bypass capacitor. Computer simulation should be used to check the effect of 50-ohm supplies, and the possible need for multiple power supply and ground connections (for both probe testing and the actual application).

CONCLUSIONS ON SPECIAL PROBE & LINE CONFIGURATIONS

- For Generality & Low Volume:
  - —Define Standard Pad Locations, Incl. Ground
  - —Make All Lines 50Ω Except Ground Probe(s)
- High Volume or High Precision Test Requirements May Justify Unique Probe Cards

If a number of integrated circuits are being designed with similar chip sizes, then defining a standard bonding pad layout and ground location(s) can allow use of a single thin-film probe card for testing many or all of the circuits. This minimizes initial cost and test setup times. But it may not be possible with hybrid circuits, due to size and layout variations, or with circuits needing special test configurations.

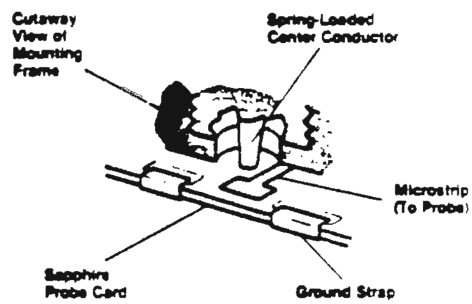
Other important probe system components include those listed here, which will be described next.

OTHER PARTS OF PROBE STATION

- Microstrip to Coax Transitions
- Bias T's
- X – Y – Θ Stage
- Microscope

A coax-to-microstrip transition ties the probe card to the measuring equipment and interconnecting coaxial cables. The electrical design must provide low return loss. The mechanical design is a challenge because the coaxial connector should not protrude below the thin-film probe card, to avoid restricting wafer size for the circuit being tested. The design shown here addresses both requirements.

MICROSTRIP TO COAX TRANSITION



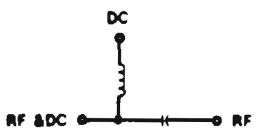
The reflection coefficient of this microstrip-to-coax transition is a very low -0.02, as measured with a time-domain reflectometer (TDR) having 40 psec risetime. Mechanically, the transition only protrudes below the thin-film circuit by the thickness of the gold ribbon ground straps, plus that of the thin metal clamps (not shown) which hold the thin-film circuit to the mounting frame.

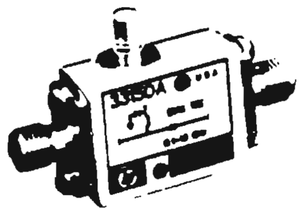
MICROSTRIP TO COAX TRANSITION
CROSS SECTION (ASSEMBLED)

Note—No Protrusions Below Test Card

BIAS T — MINI.
50 MHz – 18 GHz

CIRCUIT:





Bias T's combine dc biases and RF signals to the circuit under test. A 50-ohm termination on the RF port provides a controlled impedance for lines which do not carry RF signals. The bias T shown is specified from 0.1 to 18 GHz, and is small enough to be supported by a short semi-rigid cable from the coaxial connector in the probe frame.

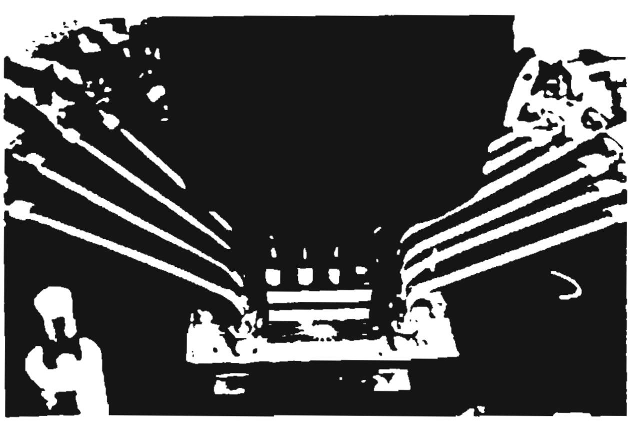
X – Y – Θ STAGE

- In-House Designs, Commercial Manual, & Commercial Wafer Steppers All Useable Interchangeably

MICROSCOPE

- Axial Illuminator & Zoom Desirable

The probe card described here has been successfully adapted to a number of wafer translation/rotation stages. The only modification required was for use with an automatic wafer stepper having limited Z-axis positioning accuracy. In that case, probes were designed to extend 0.5 mm below the thin-film probe card instead of the usual 0.25 mm, to reduce the amount of lateral skidding associated with the vertical position variations.



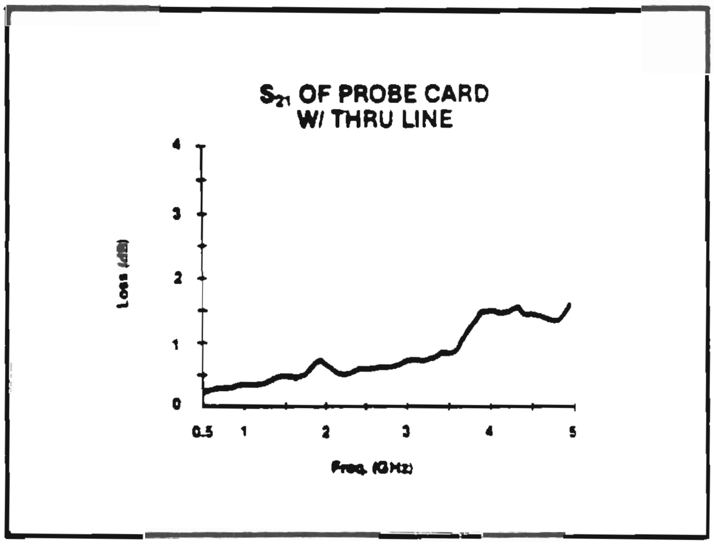
This photo shows a probe card mounted in a manual wafer positioning stage. The bright spot at the center of the card is light from the axial illuminator; the hole in the card and the probes are too small to be seen in this view. Bias T's are partially visible around the edges of the photo, supported by semi-rigid coax cables. This card has only 12 probes, rather than 16, which is the reason for the 4 unused connector locations at the front of the card.

Several aspects of probe system performance will be described next, followed by an example of a typical measurement.

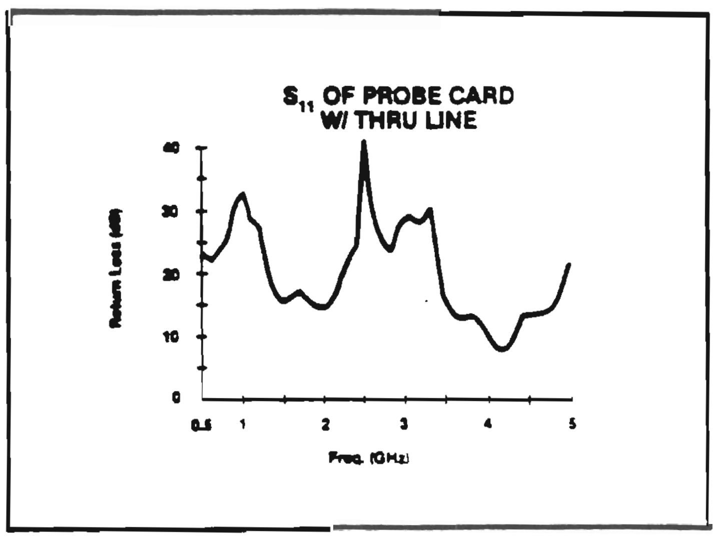
PROBE CARD PERFORMANCE

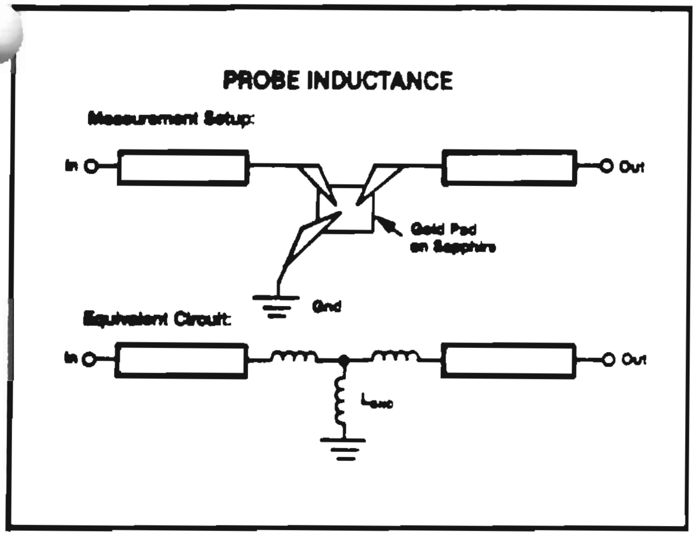
- S_{11}, S_{21} With Thin-Film Thru Line
- Probe Inductance
- Crosstalk
- Coax-to-Microstrip Mismatch
- Bias-T Effects
- Typical Measurement

One good test of the probe card performance is to probe a thru line. Here the thru line consists of a pair of 100-micron wide gold lines on a sapphire substrate. One line connects the input probe (no monitor) to the output probe. The second line connects the ground probe nearest the input to the ground probe nearest the output. Thru loss is reasonably low, even though the probes selected had the longest microstrip lines (about 6 cm total), and the loss of 15 cm of semi-rigid coax is included.

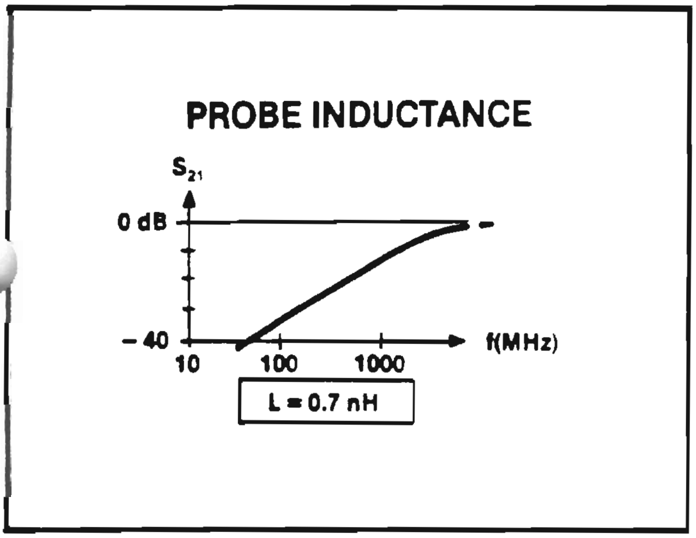


Return loss for the same configuration is greater than 14 dB to 3.5 GHz. These measurements were made with an 8409C Network Analyzer, calibrated at the ends of flexible SMA cables.





Probe inductance was measured as shown here. For confirmation, a similar measurement was made of the inductance of two probes in series (by using a monitor line connected directly to the input line at the input probe, instead of the output line shown here).



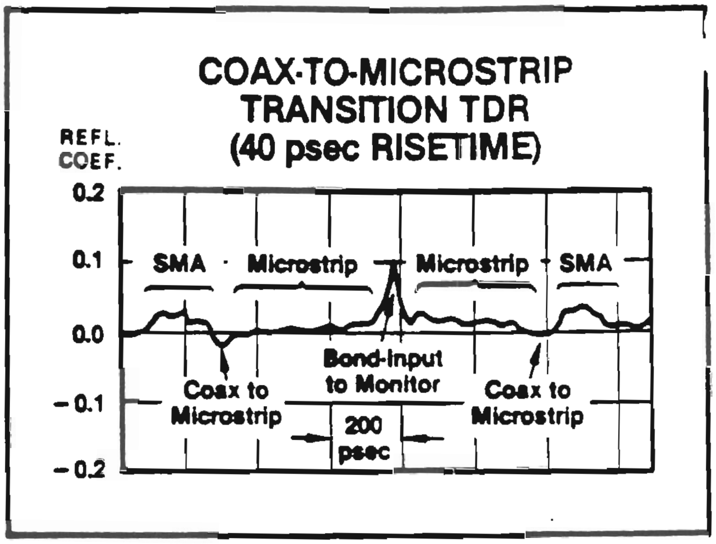
Both measurement methods gave a value of 0.7 to 0.8 nH inductance per probe. This is only about double the inductance of a 0.5 mm-length (20 mil) bond wire. For many circuits, this inductance will have minimal effect, or will be as low as the worst-case bond-wire inductance. For ground and power-supply connections, the inductance can be further reduced by using multiple bond-pads on the circuit under test and multiple probes in parallel (or else using independent probes for various parts of the circuit under test.)

CROSSTALK BETWEEN OPEN-CIRCUITED PROBES

Freq. (GHz)	Adjacent Probes (S_{21}, dB)	To Next After Adjacent (S_{31}, dB)
0.05	– 74	– 94
0.5	– 50	– 72
1.0	– 47	– 69
2.4	– 35	– 55

Crosstalk between probes is low enough to have little effect on measurement accuracy.

The time-domain-reflectometer (TDR) trace at left indicates the mismatch at various points along the probe circuits. The coax-to-microstrip transition has a reflection coefficient of -0.02, which is better than the SMA connector. The worst mismatch, near the center of this trace, is for a gold bond wire connecting the input and monitor lines (a direct connection on the thin-film circuit, as illustrated previously, would be better than a bond wire here).

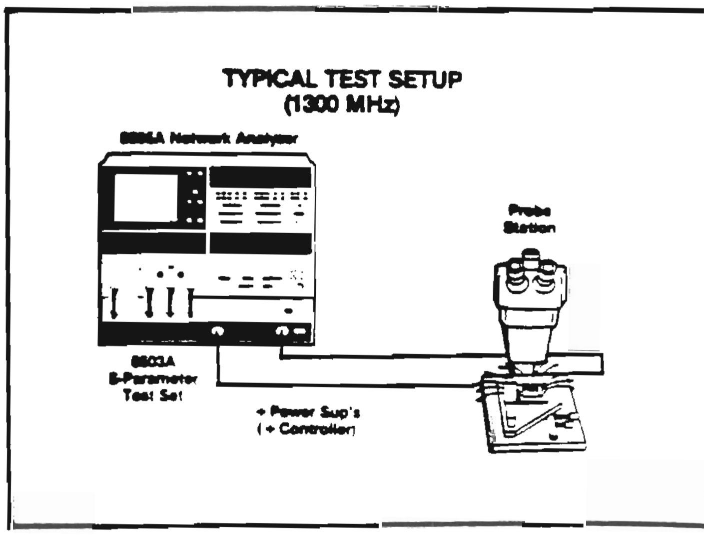


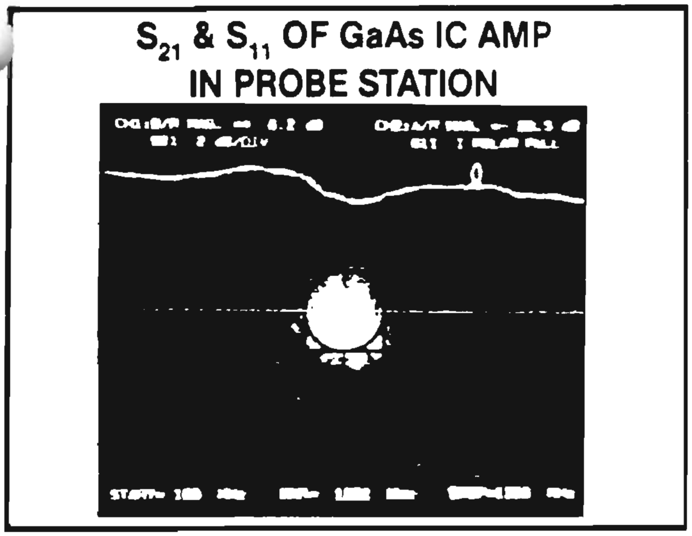
The bias T's have some effects on measurement range and accuracy, which may need to be taken into account.

BIAS-T EFFECTS

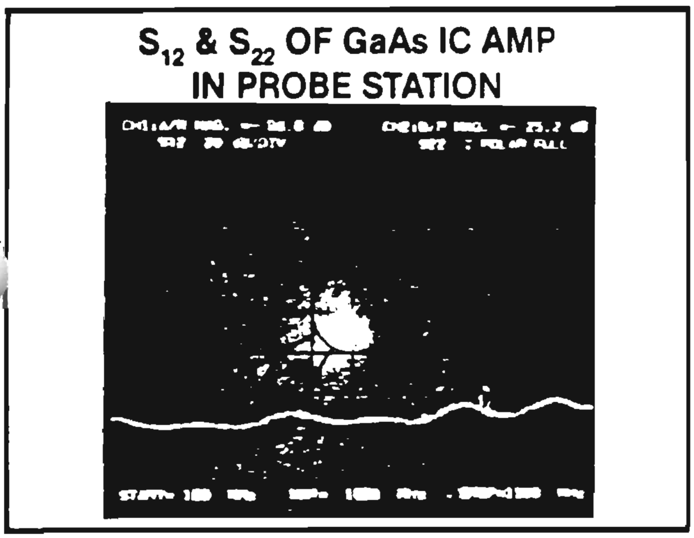
- 0.6 dB Inser. Loss at 8 GHz
- 4 Ohm DC Resistance
- RF Port ≥50 MHz (Substitute 10 kHz - 100 MHz Handmade Bias T's for Low Freq. Characterization)

Shown here is a typical test setup for measuring S-parameters with this probe station. DC connections and bias T's are not shown. Other network analyzers could be used, such as the 8754H26 for frequencies up to 2.6 GHz, or an 8410-based analyzer for higher microwave frequencies.

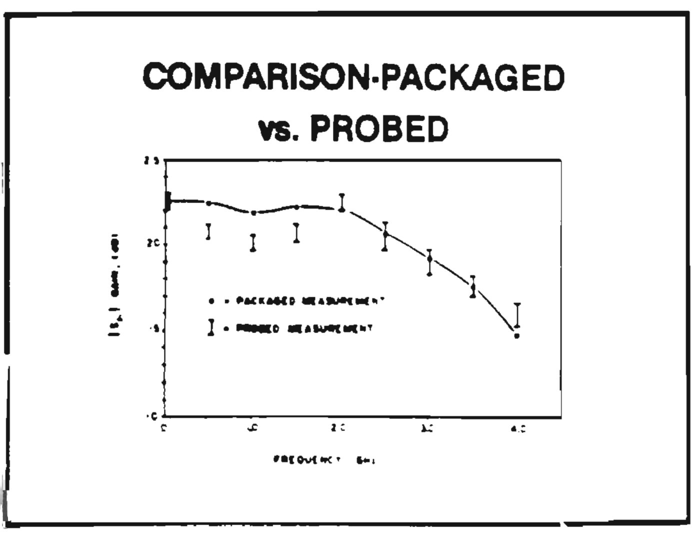




Here is measured data on S_{21} and S_{11} of a monolithic GaAs IC amplifier, obtained with the test setup of the preceding slide.



This data on S_{12} and S_{22} of the same device illustrates the low crosstalk of the probe station, which makes possible measurements of reverse isolation exceeding 80 dB up to 1300 MHz.



Amplifier IC's have been measured in the probe station and re-measured after being diced and mounted in a microstrip package. This slide shows a worst case comparison (bars represent measurement uncertainty). Three stages of this amplifier IC share a common ground probe, causing the 1 1/2 dB discrepancy between probed and packaged data.

The principal limitations of this probe system are the parasitic reactances and the number of connections possible. The reactances are orders of magnitude smaller than for commercial IC probe systems, and are as small as the parasitics in many final applications. Yet it would be desirable to further reduce the probe inductance, for characterizing low impedance devices like power FET's. And decreasing the parasitic capacitance to ground would allow higher impedance loads.

PROBE CARD LIMITATIONS

- Hi-Z Loads (0.3 pF Parasitic Probe Cap.)
- Probe Inductance (0.7nH)
- Number of Probes (16 to 22 for 1½" x 2" Card)

The number of connections is limited both by the number of coaxial connectors which can be fitted around the periphery of the thin-film probe card, and by the number of microstrip lines around the hole where the probes are mounted. The former constraint could be overcome by not restricting the coax connectors to the circuit periphery, or by using a larger thin-film circuit; the latter constraint can be partially addressed with tapered microstrip lines and longer, narrower probes, at the expense of higher inductance.

PROBE SYSTEM ENHANCEMENTS

- Larger Card, More Probes
- Lower Ground Inductance (Ribbon to Midpoint of Probe)
- Moveable RF Probe for Checking Internal Nodes
- Error Corrected Meas'ts to 18 GHz with 8409 Network Analyzer.

In summary, probe testing is rapid, cost effective, and well suited to automation. This presentation has illustrated a means of extending the technique to microwave frequencies, with emphasis on practical construction details and measured performance.

SUMMARY

- Circuit Probing Increases Productivity, Saves Money.
- Controlled Impedances and Low Parasitics Are Necessary for VHF, UHF, and Microwave Probing.
- The Probe Card Example Described Makes High Accuracy Meas'ts at Microwave Frequencies.