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Introduction

Put simply, the goal of this book is to enable the reader to go into the lab and make better RF measurements. During the course of designing RFICs and MMICs, much revolves around the RF data. It is presented to the engineering staff to validate a computer-aided design. It is used to iterate *integrated circuit* (IC) mask layouts used by the foundry. It guides the designer's overall RF understanding. All of these directly impact the design's cycle time and cost, and shortening this cycle is the surest way to product success.

The beginning of this chapter introduces the topics covered in subsequent chapters. Chapters are ordered in a building-block fashion, with each chapter laying the foundation for the[1] next. Understanding the basic composition of an RF test system is the first building block. To this end, the second part of this chapter details the essential elements in an RF test system. The three fundamental elements are: the test system interface to the *device-under-test* (DUT) (either coplanar probes or a test fixture); the VNA; and the connecting cables.

1.1 Topics Covered in This Book

1.1.1 Calibration

To ensure the validity of the measured data, the test equipment must be calibrated. Calibration serves to quantify the degree of error in a test system. Chapter 2 explains the errors found in an RF test system and how they can be mathematically removed by applying error models. Different methods of RF calibration are available, each based on measuring a set of standards in place of the DUT. At the end of Chapter 2, a list of common tips and tricks helps the reader put into practice the calibration concepts presented.

1.1.2 Coplanar Probes

Physically contacting the DUT, the coplanar probe becomes the final link in the RF test system to the wafer. Chapter 3 discusses the construction and RF characteristics of coplanar probes, beginning with coplanar waveguide theory. Training in their proper use develops habits that enhance the probe's accuracy and lifetime. The configuration of the coplanar probe depends on the die's layout of its probe pads, as well as the die's RF function. The coplanar probe has its own unique set of calibration standards. Chapter 3 examines the electrical issues to consider when using and designing these standards.

Another style of RF probe, the membrane probe, is well suited for high-volume testing and is discussed in Chapter 4.

1.1.3 High-Volume Probing

High-volume RF testing is the domain of manufacturing assembly. Issues surrounding high-volume testing are distinct from those in the lab, where individual die are manually probed one at a time. Test speed is the central issue driving the design of manufacturing test systems and, to some degree, the design of the product. Chapter 4 describes a typical high-volume test setup, focusing on the membrane probe. Analogous to the coplanar probe, the membrane probe is the RF interface from the test system to the DUT. Because of the speed of the die moving through the RF test system, unique issues arise.

1.1.4 Test Fixtures

Typically the final product is not a bare die but one that has been wire-bonded and packaged. For packaged die, the best RF interface to the test system is a test fixture [1] (see Figure 1.1). The ideal test fixture has [2] the following characteristics:

- No loss and no electrical length;
- Flat frequency response;
- Perfect impedance match between the test system and DUT ports;

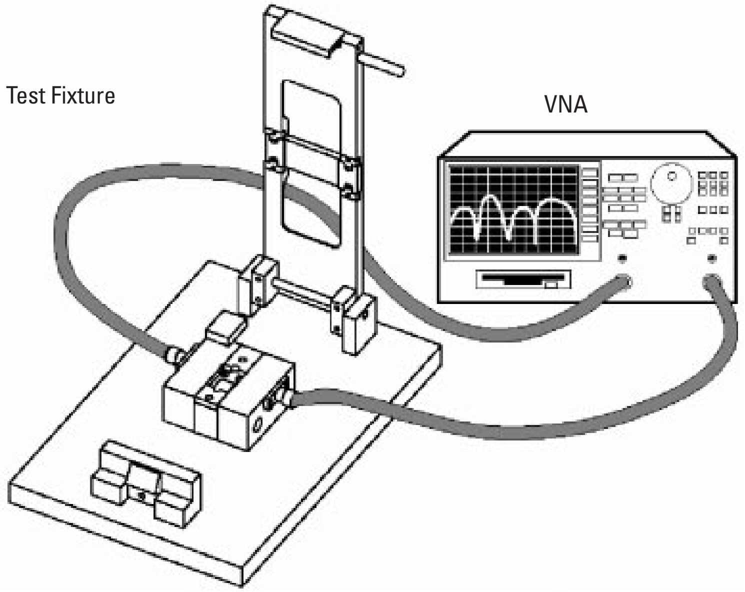

Figure 1.1 An RF test fixture and VNA for measuring packaged devices.

- No crosstalk between the fixture's input and output ports;
- Fast, easy, repeatable connections.

In practice, each of these points are met by the following:

- Keeping the fixture's amount of loss and phase errors << the system's measurement uncertainty;
- Making sure the DUT bandwidth << fixture bandwidth;
- The characteristic impedance Z_0 of the test system = the test fixture Z_0 = the DUT Z_0;
- The test fixture crosstalk << the DUT's loss or isolation;
- The measurement repeatability << the margin of the DUT test specifications.

Chapter 5 covers how to design an RF test fixture. In particular, it discusses the parasitic effects of the fixture on the DUT, as well as a detailed discussion of how to design RF transitions in the fixture. The often-challenging task of calibrating a test fixture is also included.

1.1.5 On-Wafer Characterization

Chapter 6 explains how to use RF coplanar probes to measure die on the wafer. The DUT is simply a thin film deposited on the wafer, too small to contact directly without disturbing it. Finding its RF behavior with coplanar probes requires probe pads and interconnecting lines. The discussion in Chapter 6 centers on how to de-embed the effects of the probe pads and interconnects leading to the DUT.

1.1.6 RF Test Systems

Moving beyond the DUT-to-coplanar probe interface, Chapter 7 describes the rest of the RF test system. The choice of test system depends on the RF quantity under study. Highlighted are three RF test systems and how to use them. These are a noise measurement system, a high-power RF test system, and a thermal (both hot and cold) measurement system.

1.1.7 Package Characterization

The package is an essential part of an RFIC or MMIC component. Its importance is often underestimated, neglected by the designer until the last moment. The package can have a demonstrable impact on the final product's RF performance. This chapter explores package testing, breaking the test fixture down section by section and explaining the RF aspects of its design. The chapter also covers techniques on how to characterize packages, both empty and with the die mounted inside. Calibration issues are discussed. The chapter ends by explaining how to characterize popular package styles.

1.2 Components of an RF Test System

The typical RF test system is composed of a VNA, RF cables, bias cables, and the interface to the DUT (see Figure 1.2). The interface is either RF on-wafer probes or a test fixture. The quality of the test system's RF performance depends on the VNA, the reliability of the RF cable and fixture connections, and the calibration quality.

Attempts at RF measurement fail when parts of the test system are corrupted by errors. At worst, these sources of error impede making any measurements. At best, the errors degrade RF measurement quality. This section details the components of an RF test system, highlighting where degradations may be found in the test setup and how to correct for them.

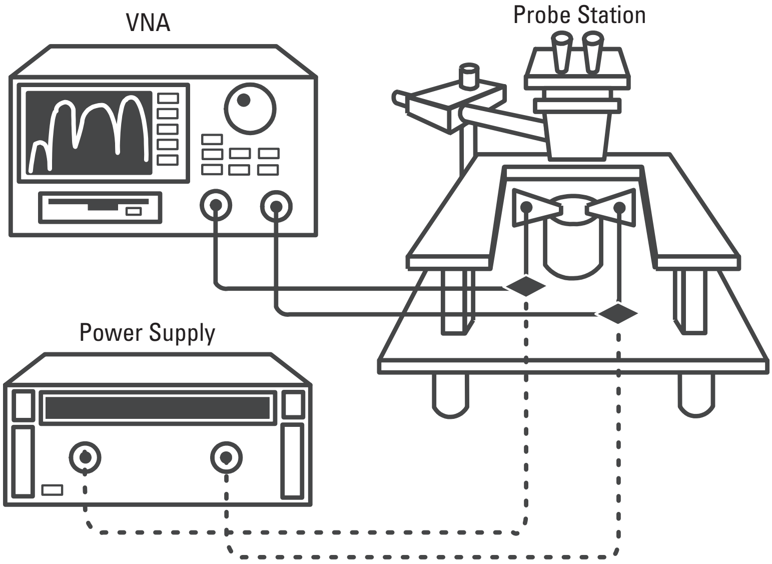

Figure 1.2 An RF test system for probing active devices on-wafer. The diamonds denote the locations of the bias tees.

1.2.1 VNA

Figure 1.3 shows the internal schematic of a VNA. An RF source drives either port 1 (P1) or port 2 (P2) of the DUT while the opposite port path is switched to the load R_L. The VNA is constructed with either three (a_0, b_1, b_2) or four (a_1, a_2, b_1, b_2) signal samplers.

In a three-sampler VNA, the switching between forward and reverse paths results in a different load being presented to P1 and P2. Yet the calibration equations assume the two paths have equal terminations. In reality, the two R_L loads are not identical, a source of error.

When the RF signal is down-converted to an *intermediate frequency* (IF), harmonics arise. To avoid mixing products, some VNAs allow the user to set the IF filter bandwidth. Choosing a narrow IF bandwidth results in less noise. However, phase-lock between the RF source and *local oscillator* (LO) can be lost, skipping to the next harmonic (see Figure 1.4). In general, a narrow IF bandwidth lowers the noise floor, enabling the measurement of smaller signals. The improved sensitivity yields a lower measurement noise floor, a gauge of the smallest signal that can be measured.

The perfect VNA has infinite isolation between ports, infinite directivity, no impedance mismatches anywhere, and a flat frequency response. In

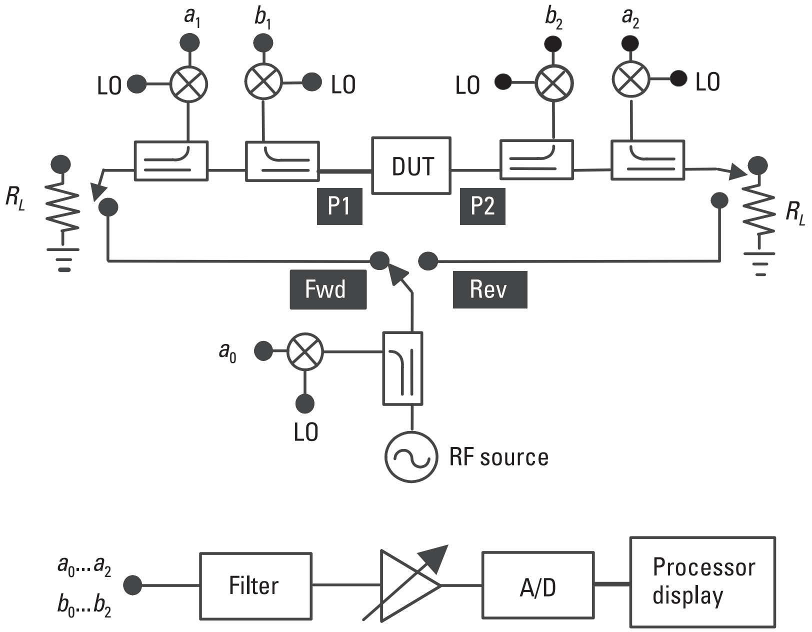

Figure 1.3 Block diagram of the vector network analyzer. A three-sampler VNA uses one coupler (a_0) to detect the incident signal, while a four-sampler VNA uses two couplers (a_1 and a_2). Reflected signals are detected using b_1 and b_2.

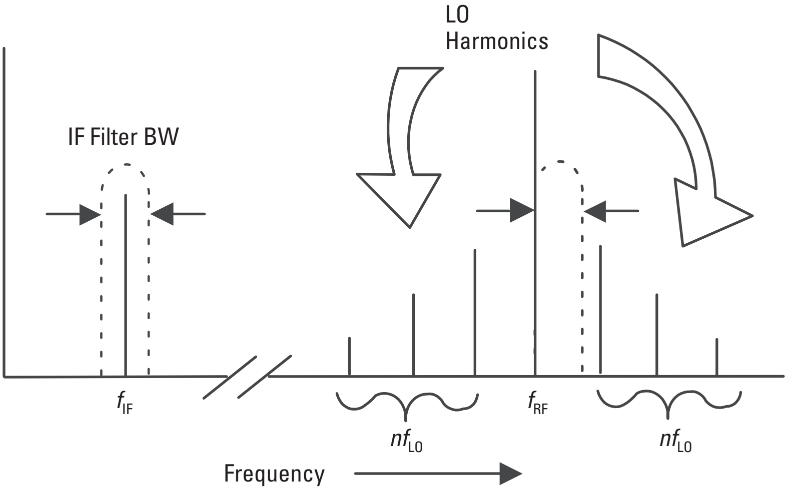

Figure 1.4 Harmonic mixing of the RF and LO sources inside the VNA. The dotted line shows the IF filter bandwidth (BW), while nf_{LO} are the harmonics around f_{RF}.

reality, the VNA's internal components are nonideal. To better understand the sources of error in the VNA, some key terms must be defined. *Directivity* is a measure of how well the VNA's couplers separate the forward and reflected waves. A high value of directivity is desirable. Poor directivity allows leakage of the signal into the coupled path. *Source match* is how closely the source path's R_L matches 50Ω, while *load match* is the quality of the load path's R_L termination. The two matches can be impacted by discontinuities between the RF source and the sampling paths. *Frequency response tracking* is how well the magnitude and phase of a signal passing through the VNA compares to (or tracks) the reference signal. This reveals the frequency response of the RF source and the internal samplers. *Transmission mismatch* is due to impedance mismatch between the test system's ports and the DUT's ports. *Isolation* is the leakage of energy between the test and reference channels inside the VNA. Leakage between transmitted and reflected paths within the VNA contaminates low-level signals.

Proper operation of the VNA by the user is the easiest way to improve RF measurements. For instance, some VNAs allow the user to choose among the frequency sweep modes. The *step sweep* mode phase-locks the LO and RF synthesizers at each discrete frequency point, providing better repeatability. The *ramp sweep* mode phase-locks the LO and RF synthesizers at the first frequency point only. Further points depart from the initial phase-lock, causing phase drift to accumulate. Ramp mode has a faster test time but less measurement accuracy.

When the VNA processor display is set to a fine-enough scale, the once-flat trace shows fluctuations and spikes with frequency. A good example is the insertion loss measurement of a 50-Ω transmission line. What appears as a straight line on a 10-dB per division log magnitude plot looks jagged on a 0.1-dB per division scale. The jaggedness is a result of thermal noise and the noise figure of the amplifiers within the VNA. Averaging several measurements using the VNA's average feature improves the measurement. Next, remove the 50-Ω transmission line and attach 50-Ω loads to P1 and P2. The log magnitude of the insertion loss will give the VNA's noise floor, usually –70 dB or less.

1.2.2 LCR Meter

Instead of a VNA, an *inductance capacitance resistance* (LCR) meter is often used to measure chip components such as capacitors, inductors, and resistors. Common ones operate at 1 MHz, contacting the DUT with needle probes. Measuring at high frequencies can reveal parasitic effects that do not appear at 1 MHz.

Aside from operating at a low-fixed frequency, LCR meters do not allow flexibility of circuit design. The equivalent circuit is always assumed to be an inductor-capacitor-resistor (LCR) combination. With a VNA, the measured S-parameters can be fit to any circuit configuration.

1.2.3 RF Cables

RF cables connect the test system to the DUT. Quality RF cables exhibit minimal insertion loss and *voltage standing-wave ratio* (VSWR). To achieve this, the cable's dielectric core has a low dielectric constant and loss tangent. The outer diameter of the center conductor provides plenty of conductive surface, diminishing its inductance.

Two types of RF cabling, semirigid and flexible, are available. Semirigid cables have a solid aluminum or copper jacket over a semiflexible dielectric protecting a solid center conductor. In comparison, a flexible RF cable is a more complicated arrangement of plastic-encased, aluminum-braided shielding over a flexible dielectric that covers a stranded center conductor. In general, good RF cables have a flexible outer skin, are thin, and have a smooth conductor surface.

Flexible cables are more expensive than semirigid, but the added expense provides advantages. Turning semirigid cable around corners requires a miniature pipe-bender that resembles a plumber's tool. The signal phase changes when the cable is bent because the outer radius becomes larger than the inner. Microscopic cracks can occur in the solder from the cable to the connector, resulting in an unreliable ground connection. Low-loss, semirigid cabling allows more dynamic range for the VNA.

In both semirigid and semiflexible, bent cables will dent the dielectric, forming an impedance mismatch at the dent. Such mismatches present a discontinuity similar to connector adapters. Flexing a cable degrades S-parameter repeatability to no better than –40 dB (or less than 1% of the transmitted signal). Physical motion such as raising and lowering the probes off the wafer's surface flexes cables. The solution is to fix the cables to the probe station and move the wafer chuck up and down, resulting in repeatability better than –60 dB. The metal-to-metal connection of the cable's center conductor and the connector pin can create a nonlinear interface, leading to intermodulation distortion in mixer applications.

The following are some general tips when using high-frequency cables [3]:

- Keep the number of bends to a minimum.
- Make the bend radii as large as possible.

- Operate in a temperature-controlled environment.
- Use the minimum number of cables, ideally connecting the DUT directly to the test port.
- Minimize movement.
- Keep the cable length short to avoid noise at high frequency [4].

In general, changes in the environment cause changes in the cable's phase delay. Small changes in the cable's phase length and insertion loss can occur with temperature. Some manufacturers offer pairs of phase-matched cables with identical electrical length and insertion loss.

1.2.4 Bias Cables

In the lab, coaxial cables are often used to supply bias to the DUT. Although they are easily found around the lab, using coaxial cables to connect the DUT to the dc power supply has disadvantages. When current flows, a voltage drop occurs along the length of the cable. Also, current leaks through the dielectric between the coaxial center conductor and its outer shielding.

Applications demanding precision current levels below 1nA require triaxial cables. A triaxial cable has three concentric conductors: force/sense, guard, and common. Typically, the innermost conductor is either the force or the sense, the next conductor guard, and the outermost common (see Figure 1.5). Voltage is applied on the force and measured with the sense. Within the power supply is a unity-gain amplifier that drives the same voltage on the guard surrounding the force. For low-current measurements, presenting the same potential on the force and guard negates leakage between them as well as capacitance. Lengthening the integration time of the dc measurement overcomes the cable's capacitance charging time. A high-quality dielectric in triaxial cables results in femtofarads of capacitance between force/sense and common.

With low resistance and negligible current, the triaxial sense line precisely reads the forced voltage, thereby capturing any voltage drop along the force line. At the power supply end of the sense line, a high impedance prevents current from flowing into the power supply.

The common outer conductor Faraday-shields the cable from external *electromagnetic interference* (EMI). Well-built bias tees should be enclosed in a metal box that connects to common. This completely shields the bias path end-to-end from power supply to DUT. To eliminate all EMI, encase the DUT in the same manner of shielding and connect to the same common

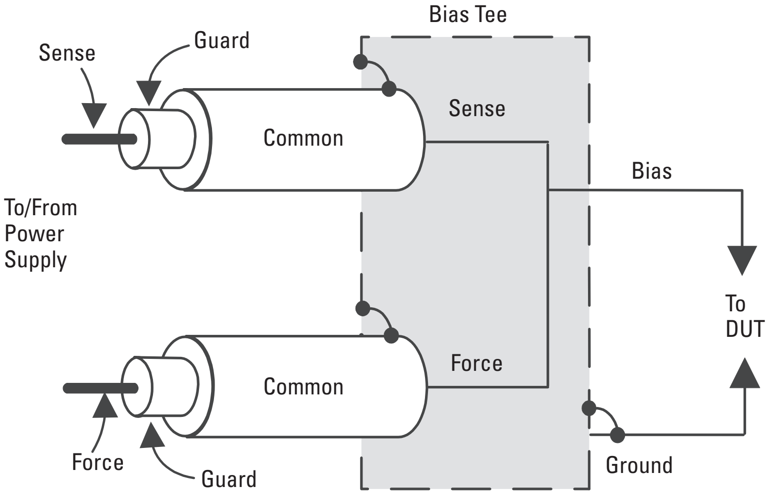

Figure 1.5 Force and sense triaxial cables. These connect to the DUT via a bias tee. In this configuration, the common also serves as ground.

(see Figure 7.2 in Chapter 7). With triaxial cables, the common is not necessarily ground. When the common is not ground, the DUT can connect to the power supply's ground using a separate cable.

Regarding its RF performance, the equivalent circuit of any coaxial or triaxial cable is a distributed series inductance with shunt capacitance. Long cables have large inductance, useful in blocking noise generated by a dc supply from getting into the RF channel. A practical advantage is that large inductance dampens amplifier oscillations. Conversely, high-inductance cables create undesirable ripple on the rising and falling edges of square-wave pulses. Solutions are either shorter cables with lower inductance or slowing the pulse's rise time.

1.2.5 Bias Tees

Active devices such as transistors and diodes require a voltage and current. Needle probes are commonly used to supply bias on-wafer. During an RF test, the problem becomes how to de-embed the RF effects of the needles. Not only do they have high inductance, needle probes will couple to other nearby probes. Attaching a bias tee to the input of an RF probe is a simpler way to supply bias to the DUT since the probe can simultaneously supply both RF and dc.

The bias tee is a three-port network. RF is fed into one port and dc into another, while RF and dc depart together from the third port. The dc input includes a lowpass network to keep the applied RF from disturbing the power supply and vice versa. Similarly, the RF input has a highpass network to keep dc from flowing into the VNA. Commercial bias tees are specified by their frequency range, RF power handling, and current rating.

1.3 RF Connectors

1.3.1 Connector Types

Common RF coaxial connector styles are 3.5 mm, *Subminiature A* (SMA), and *Amphenol Precision Connector–7 mm* (APC-7). The 3.5 mm and SMA are sexed while the APC-7 is not. The APC-7 is designed for the lowest *standing-wave ratio* (SWR) and has the best repeatability. Because they are small, the 3.5 mm and SMA have an advantage at higher frequencies. While the SMA and 3.5 mm appear identical, the SMA with its dielectric core operates to 24 GHz while the 3.5 mm with an air core extends to 34 GHz.

1.3.2 Making the Connection

Repeatability and accuracy of RF/microwave connectors critically depend on alignment of the mating surfaces. APC-7 connectors are prone to misalignment of the spring-loaded center conductors called collets. With 3.5 mm and SMA connectors, the male center conductor pin fits snugly into the female contact fingers. At the same time, the two connectors' dielectrics contact along a flat plane. To make sure this occurs properly, periodically use a connector gauge to adjust the center pin length, usually just a few ten-thousandths of an inch. Similarly for the APC-7, the collets extend just enough for the two planes to make contact when properly tightened. Using a torque wrench ensures the mating planes make uniform contact without overtightening and crushing them together.

An air gap in the mating plane can arise, either due to a gap in the dielectrics or because of a gap between center pins. An air gap between male and female connectors manifests itself in the return loss (see Section 2.2 in Chapter 2). A dielectric gap or pin gap can contribute to inaccurate coaxial calibration.

Different-size connectors will sometimes mate mechanically but not electrically. For instance, SMA, 3.5-mm, and 2.92-mm connectors will all mate mechanically, but the electrical interface will exhibit a capacitive mismatch.

There are two types of female connector pins, slotted (the most common) and slotless. To mechanically accept male pins of various diameters, the female connector pin often has a slot cut in its diameter. Slotless female pins are more inductive and expensive than their slotted counterparts. Yet slotless female pins are more repeatable since their diameter does not change with the size of the male pin. While mating mechanically, a change in the diameter of the male pin will contribute to reflections.

1.3.3 Connector Care

When mating two connectors, always tighten the nut rather than rotate the cable. The center conductors grind and wear while turning, leaving metal filings to dirty the interface. Such metal filings or particles originate from the connector threads. Dirt collects in the connector cavities. The connectors are cleaned using a blast of compressed air or a soft cloth or swab dampened with *isopropyl alcohol* (IPA). Do not dip the connector into the IPA as dirt will collect in its crevices as it dries.

When tightening two connectors together, hard dirt particles caught in between will plow scratches into the dielectric, manifested as carved concentric rings in the dielectric mating surfaces. In contrast, storing connectors facedown results in straight scratches across the dielectric faces.

1.4 RF Connector Adapters

Adapters transition between connector types and genders. Because adapters often involve transforming between diameters, their design is important. Quality adapters generate little reflections. Sometimes both test ports can have the same gender connector, complicating calibration. A DUT with the same gender connector on both ports is referred to as a noninsertible device. In this case, the contribution of the adapter to the calibration must be removed [5, 6].

1.5 The Probe Station

Properly understanding the role of the RF probe in the test system requires a description of a probe station. To begin, the wafer is placed on a tall column, or chuck, slightly larger than the diameter of the wafer. A vacuum line runs through the probe station to the center of the chuck, securing the wafer on top. Rather than move the probes from die to die, the chuck moves the wafer from die to die. Z-motion raises and lowers the chuck height with respect to the probes.

The probes are fixed to micropositioners secured to the probe station. The micropositioners are precision micrometers, enabling fine movement in the *x*, *y*, and *z* dimensions. A single micropositioner can hold multiple dc and RF probes. The RF probe is usually mounted to a micropositioner whose placement accuracy is within 1 micron. Placing the probes in the exact same spot on the wafer or on the calibration substrate each time is a challenge and can be a source of measurement error. As the chuck is stepped across the wafer, the probe tips can lose alignment with the die's pads. One way RF probe misplacement manifests itself is on the Smith chart. For instance, a 5-micron misplacement of the probes on the calibration standards can result in ±11 pH in pad inductance (see Figure 3.11 in Chapter 3). Such detailed alignment becomes more important as the frequency increases.

Minute vibrations can cause the probes to vibrate on the DUT's pads during the RF test. To prevent this, the entire probe station should sit on a vibration table. Bellows in the vibration table suspend the station on a cushion of air, dampening floor vibrations.

Depending on the application, probe stations are designed either for sample probing in the lab or for manufacturing. In the lab, chuck movement and DUT measurement are manual operations. Conversely, RF probing on the manufacturing line demands speed, where a computer automates wafer loading, chuck movement from die-to-die, and RF measurement.

1.6 Summary

This chapter serves as an introduction to the components of an RF test system. These components will be referred to again as concepts are further developed in Chapters 2 to 9.

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