SEMI E115-0302[E] (Reapproved 0309)
TEST METHOD FOR DETERMINING THE LOAD IMPEDANCE AND EFFICIENCY OF MATCHING NETWORKS USED IN SEMICONDUCTOR PROCESSING EQUIPMENT RF POWER DELIVERY SYSTEMS

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[E] This document was editorially modified in May 2002 to correct an error. A change was made in § 1.1.

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1 Purpose

1.1 The purpose of this document is to define a test method used to determine the load impedance and efficiency of matching networks used in RF power delivery systems for semiconductor processing equipment.

2 Scope

2.1 This document specifies the testing procedures and test equipment required for determining the load impedance and power efficiency of a matching network based on the positions of the tuning elements in the matching network.

2.2 The primary focus for this specification is semiconductor processing equipment including, but not limited to, the following tool types:

- Dry etch equipment,
- Film deposition equipment (CVD and PVD).

2.3 This standard does not address any safety or performance issues related to RF emissions or electrical codes (e.g., Underwriter's Laboratory, Inc. (UL), the National Electrical Code (NEC®), Federal Communications Commission (FCC)). It is the responsibility of the users of this standard to conform to the appropriate local codes and regulations as applied to this type of equipment, some of which are covered by referenced documents.

NOTICE: This standard does not purport to address safety issues, if any, associated with its use. It is the responsibility of the users of this standard to establish appropriate safety and health practices and determine the applicability of regulatory or other limitations prior to use.

3 Limitations

3.1 This standard addresses RF Matching Networks used in RF systems that primarily operate in the frequency range of 0.2–100 MHz. It does not address higher frequency RF systems or microwave systems.

3.2 This standard is meant for analyzing matching networks that are designed to operate at fixed frequency with a 50-ohm input impedance.

3.3 International, national, and local codes, regulations and laws should be consulted to ensure that the equipment and procedures meet regulatory requirements in each location.

4 Referenced Standards and Documents

4.1 *SEMI Standard*

SEMI E113 — Specification for Semiconductor Processing Equipment RF Power Delivery Systems

4.2 *IEEE Standards*[1]

IEEE-STD-383 — IEEE Standard for Type Test of Class 1E Electrical Cables, Field Splices, and Connections for Nuclear Power Generating Stations

1 Institute of Electrical and Electronics Engineers, IEEE Operations Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, New Jersey 08855-1331, USA. Telephone: 732.981.0060; Fax: 732.981.1721; http://www.ieee.org

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4.3 *Military Standards*[2]

MIL-PRF-39012D — General Specification for Connectors, Coaxial, Radio Frequency

5 Terminology

5.1 *Abbreviations and Acronyms*

5.1.1 *CVD* — Chemical Vapor Deposition

5.1.2 *PVD* — Physical Vapor Deposition

5.1.3 *VSWR* — Voltage Standing Wave Ratio

5.2 *Definitions*

5.2.1 *complex conjugate load impedance* — the complex conjugate load impedance has the same real part of the load impedance and the negative of the reactive part of the load impedance. For example, the complex conjugate of a load impedance of 2.0 − j20 ohms would be 2.0 + j20 ohms.

5.2.2 *device under test (DUT)* — the matching network to be tested.

5.2.3 *harmonic frequency* — the harmonic frequencies are defined as integer multiples of the fundamental frequency. For example, the second harmonic of 13.56 MHz is 27.12 MHz.

5.2.4 *"L" type matching network* — this type of network consists of a tuning element that is connected to ground, which is often a variable capacitor, and another tuning element that is in series with the output connection. The series section of the "L" matching network typically consists of an inductor and a capacitor, one of which is variable.

5.2.5 *load and tune position* — for some matching networks, the tuning elements are referred to as the *Load Position* and the *Tune Position*. This terminology is common for "L" type matching networks, which have a tuning element that is connected to ground and another tuning element that is in series with the output connection. The *Load Position* corresponds to the tuning element that is grounded and is associated with matching to the real part of the load impedance. The *Tune Position* corresponds to the tuning element that is in series with the output and is associated with matching to the reactive part of the load impedance.

5.2.6 *load impedance* — the load impedance is the impedance to which a matching network is matched.

5.2.7 *load impedance simulator* — the Load Impedance Simulator is a device that presents a load impedance to which a matching network can match. Details of a typical Load Simulator can be found in the Related Information section of this test method.

5.2.8 *matched input impedance* — a matched load impedance is defined as typically having a magnitude of 50 ± 3.3 ohms at a phase angle of up to ±3.8 degrees. In other words, the load is considered matched if the reflection coefficient is no greater than 0.032 at any phase angle.

5.2.9 *matching network* — the device used to transform the impedance of the load (chamber/chuck) to match the impedance of the generator/cable assembly, which is typically 50 ohms.

5.2.10 *power efficiency* — the ratio of the power exiting the matching network divided by the power entering the matching network.

5.2.11 *S-parameters* — the scattering matrix used to describe a network. The reflection coefficient is the S11 parameter and the transmission coefficient is the S21 parameter.

5.2.12 *tuning element position* — the position of the tuning element is defined as the output voltage or output encoder value that corresponds to the position of a variable tuning element in a Matching Network. For example, the voltage from a rotary potentiometer on the rotating shaft of a variable capacitor (the "Tuning Element") would be referred to as the capacitor's "Position." In this example, the position/voltage corresponds to a certain shaft location or position.

2 United States Military Standards, Available through the Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, PA 19120-5099, USA. Telephone: 215.697.3321

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6 Test Apparatus

6.1 *RF Vector Network Analyzer* — The Network Analyzer is used to measure the load impedance and efficiency of the matching network. The Network Analyzer requires vector capability so that both the magnitude of phase of the reflection coefficient and transmission coefficient can be measured at the operating frequency. The Network Analyzer shall have an up-to-date calibration per the manufacturer.

6.2 *Coaxial Output Adapter* — An adapter to convert the output connection of the matching network to a standard coaxial interface is required for some of the tests.

6.3 *RF Adapters and Terminations* — Various adapters may be necessary to convert between different types of coaxial connectors (e.g., type N to type HN adapters, etc.). All adapters used shall have the same nominal characteristic impedance as the system, which is typically 50 ohms. For some measurements, additional coaxial cable assemblies are used. These cable assemblies shall also be of the same nominal characteristic impedance as the system. Standard terminations are also used, such as shorts, opens, and precision 50-ohm loads.

6.4 *RF Load Impedance Simulator* — A device that can be attached to the output of the DUT to act as a load for the DUT is required for some of the measurements. The load simulator shall have an impedance range to match a minimum of 80% of the tuning space of the matching network to be tested.

7 Safety Precautions

7.1 Work should be conducted in accordance with local safety requirements and test device manufacturer recommended safety procedures. The tests described in this document involve using low output power test instrumentation (typically less than 10 milli-Watt).

7.2 The area immediately surrounding the Test Setup shall be keep free and clear of unnecessary equipment and materials.

8 Test Setup for Determining Load Impedance and Efficiency

8.1 Two test methods are described for analyzing matching networks. The first method for determining the load impedance and efficiency measures the complex conjugate of the load impedance and then corrects for the matching network losses to determine the load impedance and efficiency. A schematic of the Test Setup is shown in Figure 1. The method uses a Network Analyzer to measure the reflection coefficient, which is related to the load impedance, and the transmission coefficient, which is related to the efficiency. The Test Setup for this approach consists of the Network Analyzer, the matching network to be tested (DUT), coaxial test cables, and the appropriate adapters (if any) to connect the DUT to the Network Analyzer.

8.2 The second method for determining the load impedance and efficiency uses a Load Impedance Simulator attached to the output of the matching network. A schematic of the Test Setup is shown in Figure 2. The Test Setup for this approach consists of the Network Analyzer, the matching network to be tested (DUT), the load simulator, coaxial test cables, the appropriate adapter (if any) to connect the DUT to the Network Analyzer, and the appropriate adapter to connect the load simulator to the DUT.

8.3 Prior to making any measurements, the Network Analyzer shall be turned on and allowed to warm up before the testing is to take place. This time will allow for electronics to come to a stable operating condition for the measurements.

9 Test Procedure for Determining Load Impedance and Efficiency

9.1 Two test procedures can be used to determine the load impedance and efficiency of the matching network. The first method is designed for “L” type matching networks, where the losses are dominated by the loss resistance of the inductor that is in series with the load impedance. For the case where there are finite losses in the shunt capacitor, the capacitor losses can be lumped in with the inductor losses without introducing significant error (usually less than 0.5% for typical values of <0.1 ohms). Lumping the total losses into an overall series loss will also cause a slight shift in the reactive part of the impedance, but the magnitude of the shift is on the same order as the impedance measurement uncertainty and can be ignored.

9.2 The second method is designed for other matching network types and uses a load simulator to determine the load impedance and efficiency.

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9.3 *Test Method 1 for Determining Matching Network Load Impedance and Efficiency*

9.3.1 This test method shall be used for "L" type matching networks of the type shown schematically in Figure 1, where the losses in the network are dominated by the loss resistance of the inductor, RLOSS. The efficiency for this type of matching network is given as:

$$Eff = \frac{RLOAD}{RLOAD + RLOSS} \tag{1}$$

where *RLOAD* refers to the real part of the load impedance and *RLOSS* refers to the losses of the matching network.

9.3.2 For this type of network, the real part of the complex conjugate impedance, Re(*Zout**), contains the real part of the load impedance plus twice the loss resistance, *RLOSS*.

$$\mathrm{Re}(Zout^*) = RLOAD + 2RLOSS \tag{2}$$

9.3.3 The load impedance, therefore, is equal to the complex conjugate impedance less twice the loss resistance (along with the sign change of the reactive part of the conjugate impedance). For example, if the conjugate impedance is measured as 3 + j20 and RLOSS is determined to be 0.5 ohms, then the load impedance is 2 − j20 ohms.

9.3.4 The efficiency of the matching network and the loss resistance, *RLOSS*, can be determined by measuring both the transmission coefficient, S21, and the reflection coefficient, S11, in the Test Setup shown in Figure 1. Note that the reflection coefficient measurement, S11, is equivalent to measuring the complex conjugate impedance. If the matching network is considered as a test load with an impedance equal to the complex conjugate impedance, then the loss resistance is found by measuring the efficiency of the test load. This efficiency, *Effm*, can be expressed as

$$Effm = \frac{\mathrm{Re}(Zout^*) - RLOSS}{\mathrm{Re}(Zout^*)} \tag{3}$$

where Re(*Zout**) is the real part of the complex conjugate load impedance, *Zout**. The measured efficiency, *Effm*, can be determined from the S21 and S11 measurements (as shown later in this section). Thus, the measurements of Re(*Zout**) and *Effm* can be used to determine *RLOSS* as:

$$RLOSS = \mathrm{Re}(Zout^*) \times (1 - Effm) \tag{4}$$

and the load impedance and power efficiency of the matching network can then be determined from

$$Effc = \frac{\mathrm{Re}(Zout^*) - 2RLOSS}{\mathrm{Re}(Zout^*) - RLOSS} \tag{5}$$

$$RLOAD = \mathrm{Re}(Zout^*) - 2RLOSS \tag{6}$$

$$XLOAD = -\mathrm{Im}(Zout^*) \tag{7}$$

where *Effc* is the calculated power efficiency based on the measurement of Re(*Zout**) and *Effm*, *RLOAD* is the real part of the load impedance, and *XLOAD* is the imaginary part of the load impedance.

9.3.5 Calibrate the Network Analyzer at the desired operating frequency (e.g., 13.56 MHz). The Network Analyzer shall be calibrated for measuring the reflection coefficient at test Port 1 and for measuring the transmission coefficient at test Port 2 (see Figure 1) using the calibration kit provided with the Network Analyzer. This measurement requires measuring the S11 and S21 S-parameters and requires a full 2-port calibration. The calibration shall be performed at fixed frequency (continuous-wave operation) using the lowest bandwidth possible (typically 10 Hz). The calibration for each port shall include the additional test cables and any additional adapters.

9.3.6 After calibration of the Network Analyzer, the cable connected to Port 1 of the Network Analyzer shall be connected to the output of the DUT. The cable connected to Port 2 of the Network Analyzer shall be connected to the input of the DUT.

9.3.7 The tuning elements shall be moved to their minimum positions before the measurement is initiated. After all connections are visually inspected for proper contact and the Network Analyzer has stabilized, the value of the complex conjugate impedance (*Zout**), the magnitude of the reflection coefficient (S11), and the magnitude of the transmission coefficient (S21) shall be recorded.

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9.3.8 The efficiency when the DUT is viewed as a test load, *Effm*, is determined from both the reflection and transmission coefficients. The efficiency can be calculated by taking the ratio of the output power divided by the input power. The output power is simply $(S21)^2$ and the input power is $(1-(S11)^2)$.

$$Effm = \frac{(S21)^2}{1-(S11)^2} \tag{8}$$

Typically, the reflection and transmission coefficients are expressed in terms of dB (decibels). The conversion between dB and efficiency is expressed as:

$$Effm = \frac{10^{(\mathrm{S21\,in\,dB}/10)}}{1-10^{(\mathrm{S11\,in\,dB}/10)}} \tag{9}$$

For example, if the transmission coefficient is measured to be −10.2 dB and the reflection coefficient is measured to be −0.61 dB, then *Effm* would be 0.7288. The efficiency based on this measurement can then be used to calculate *RLOSS*, *Effc*, *RLOAD*, and *XLOAD* by using the equations previously shown. All of these calculated numbers using equations 3–6 shall be recorded, as well as the positions of the tuning elements of the matching network.

9.3.9 For the next measurement, Tune Position shall remain fixed, and the Load Position shall be increased by an increment equal to no more than 10% of the full-scale range of the tuning element position. For example, if the range of the tuning element is 10 volts, then the tuning element should be moved in increments of no greater than 1 volt. A smaller increment shall be used for the case where the incremental change in Load Position results in an incremental impedance change of more than 20% of the total impedance variation measured by the full-scale variation of the Load Position. For example, if the real part of the load impedance varies 15 ohms over the 10 volt variation of the Load Position, then a smaller Load Position increment shall be used if the real load impedance varies by more than 3 ohms between increments (0.2 × 15 = 0.3). After the tuning elements have been moved to their new values, the previous measurement steps shall be repeated.

9.3.10 After the Load Position has been varied over its entire range, the Tune Position shall be increased by an increment equal to no more than 10% of the full-scale range of the tuning element position. The Load Position shall be moved back to its minimum position and the above steps shall be repeated until the entire tuning range of the matching network is measured.

9.3.11 The data shall be recorded and then presented in both graphical and tabular forms. An example of a typical impedance range graph is shown in Figure 3 for the real load impedance and in Figure 4 for the reactive load impedance. An example of a typical efficiency plot is shown in Figure 5. An example of data presented in tabular form is shown in Table I.

9.4 *Test Method 2 for Determining Matching Network Load Impedance and Efficiency*

9.4.1 This test method shall be used for matching networks that are not necessarily dominated by a series loss resistance as in an ideal "L" type network. This method uses a Load Simulator(s) attached to the DUT and assumes that the DUT has two tuning elements. The Load Simulator(s) shall have a tuning range that will cover no less than 80% of the tuning range of the matching network. Details of a typical Load Simulator can be found in the Related Information section of this Test Method. The test method outlined here assumes that the Load Simulator(s) contains variable tuning elements with position indicators to allow the load impedance to vary. An example of a load simulator would be a matching network used in reverse, where the output of the DUT would attach to the output of another matching network.

9.4.2 Calibrate the Network Analyzer at the desired operating frequency (e.g., 13.56 MHz). The Network Analyzer shall be calibrated for measuring the reflection coefficient at test Port 1 and for measuring the transmission coefficient at test Port 2 (see Figure 1) using the calibration kit provided with the Network Analyzer. This measurement requires measuring the S11 and S21 S-parameters and requires a full 2-port calibration. The calibration shall be performed at fixed frequency (continuous-wave operation) using the lowest bandwidth possible (typically 10 Hz). The calibration for each port shall include the additional test cables and any additional adapters.

9.4.3 After calibration of the Network Analyzer, the test cable connected to Port 1 of the Network Analyzer shall be connected to the input of the matching network to be tested (DUT). The Load Simulator shall be connected to the

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