SEMI E113-1102
SPECIFICATION FOR SEMICONDUCTOR PROCESSING EQUIPMENT RF POWER DELIVERY SYSTEMS

This specification was technically approved by the Global Metrics Committee and is the direct responsibility of the North American Metrics Committee. Current edition approved by the North American Regional Standards Committee on July 21, 2002. Initially available at www.semi.org October 2002; to be published November 2002. Originally published November 2001

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1 Purpose

1.1 Process plasmas are used throughout the semiconductor industry for the etching and deposition of thin films. The majority of the process chambers use RF power to produce and sustain the plasmas. Because the reliability and repeatability of the plasma directly impacts wafer-processing results, RF power delivery systems are a key element of semiconductor manufacturing technology. The accurate and reproducible performance of the entire RF power generation system, including the RF influenced parameters of the plasma, must be within commonly accepted tolerances.

1.2 Design criteria for RF reliability and repeatability demand standardized testing and evaluation of the performance of the RF power delivery systems and control instrumentation on a chamber. Not only must the subsystems (i.e., the generator, cable assemblies, matching network, chuck/coil) be characterized, but the performance of the integrated system must also be characterized over the intended operating range.

1.3 It is the intent of this standard to provide RF power delivery specifications for semiconductor processing equipment that leads to improved system and subsystem performance. It outlines performance criteria as well as required documentation that must be supplied with the system or subsystem components. The goal of the document is to provide the specifications needed to produce a well-characterized RF power delivery system, where stability, repeatability, and important electrical parameters such as delivered power, current/voltage, and the impedance of the system can be determined within the operating space.

2 Scope

2.1 This document specifies the minimum performance criteria for RF equipment used in the semiconductor industry. It does not address specific test methods or procedures for performance verification.

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

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

2.3 This specification applies to semiconductor processing equipment RF power delivery systems whose power is directly used to produce and sustain the plasma.

2.4 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.

2.5 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 limitations prior to use.

3 Limitations

3.1 This standard is meant to address 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 intended to be a performance specification and is not intended to address design issues related to safety, which are covered elsewhere in the SEMI Standards.

3.3 This standard is not meant to address pulsed-power RF systems.

4 Referenced Standards

4.1 *SEMI Standards*

SEMI E10 — Specification for Definition and Measurement of Equipment Reliability, Availability, and Maintainability (RAM)

SEMI E78 — Electrostatic Compatibility - Guide to Assess and Control Electrostatic Discharge (ESD) and Electrostatic Attraction (ESA) for Equipment

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SEMI E114 — Test Method for RF Cable Assemblies Used in Semiconductor Processing Equipment RF Power Delivery Systems

SEMI E115 — Test Method for Determining the Load Impedance and Efficiency of Matching Networks Used in Semiconductor Processing Equipment RF Power Delivery Systems

4.2 *IEEE*[1]

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

4.3 *MIL-SPEC*[2]

MIL-C-17G — General Specification for Cables, Radio Frequency, Flexible and Semirigid

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

NOTE 1: Unless otherwise indicated, all documents cited shall be the latest published versions.

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 *cable assembly* — the section of cable (transmission line), including the connectors, used to connect various parts of the RF power delivery system.

5.2.2 *electrical length* — the length of the cable assembly at the operating frequency expressed in terms of degrees, where one wavelength at the nominal operating frequency is equal to 360°.

5.2.3 *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.

5.2.4 *matching network load impedance* — the impedance of the load to which the matching network is matched.

5.2.5 *power efficiency* — the power efficiency of a matching network is defined as the power exiting the network (output power) divided by the power entering the network (input power).

5.2.6 *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.

5.2.7 *RF applicator/interface* — the part of the chamber where the RF system is terminated. This interface can either be a chuck (driven electrode) or the coil/antenna part of a plasma source.

5.2.8 *load Q* — the quality factor, Q, of the load is defined here as the magnitude of the reactive part of the load divided by the real part of the load. For example, a load impedance of 2 – j20 ohms would have a load Q of 10.

5.2.9 *matched load* — 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°. In other words, the load is considered matched if the reflection coefficient is no greater than 0.032 at any phase angle.

5.2.10 *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.

5.2.11 *tap point* — for some systems, partial tuning of the matching network is achieved by switching in a combination of fixed tuning elements, such as different values of capacitors. The tap point is defined as the position of the switch(es) that connect or disconnect tuning elements in the matching network circuit.

5.2.12 *RF system* — the RF system is defined as the combination of the generator, matching network, chamber interface, and the associated connecting cable assemblies that are specific to a particular tool/chamber.

5.2.13 $MTBF_p$ — mean (productive) time between failures; the average time the equipment performed its intended function between failures; productive time divided by the number of failures during that time. Only productive time is included in this calculation.

6 Ordering Information

6.1 Semiconductor manufacturers may use this standard when procuring processing equipment to specify RF power delivery system performance and

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 website: www.ieee.org

2 Available from Naval Publication and Forms Center, 5801 Tabor Avenue, Philadelphia PA 19120 U.S.A website: www.dodssp.daps.mil/products.htm.

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documentation. The equipment suppliers may also use this document to specify the RF system components and subassemblies.

6.2 Orders for equipment in accordance with this standard shall include:

6.2.1 This specification number and date of issue.

6.2.2 Any certification showing passage of qualification tests required to be provided (optional).

6.2.3 Any test results required to be included in reports to be provided (optional).

7 Requirements

7.1 Semiconductor processing equipment shall be designed and built with a reliable RF power delivery system. The requirements defined in this specification address the integrated RF system as well as the following RF power delivery system components: the RF cable assemblies, the matching network, the generator, and the RF applicator/interface, as well as specific components of these assemblies or systems.

7.2 The mean (productive) time between failures ($MTBF_p$), as outlined in SEMI E10, of the generator, matching network, and the RF power delivery system as a whole shall be provided by the supplier, as well as the test method used to determine $MTBF_p$.

7.3 *RF Cable Assemblies (Transmission Lines)*

7.3.1 Many RF power delivery systems use RF cable assemblies to transfer power from the generator to the input of the matching network and, in some cases, from the output of the matching network to the process chamber (e.g., the chuck assembly). All cable assemblies shall adhere to industry standards for cables and connectors (e.g., MIL-C-17G, MIL-PRF-39012D, IEEE-STD-383) in terms of rated power/voltage/ current, allowed bending radius, expected variation in characteristic impedance, and attenuation at the expected operating frequency(s) for the specific cable type (e.g., RG-217, RG-218) per the cable manufacturer's specifications. SEMI E114 or an equivalent test method(s) shall be used to determine the electrical length, power dissipation (loss), and characteristic impedance of the RF cable assemblies.

7.3.2 The length of the cable assemblies used to connect portions of the RF power delivery system shall be specified in terms of electrical length at the nominal operating frequency, in addition to the nominal physical length. The electrical length shall be given in terms of degrees of phase shift. Variations in the dielectric properties (e.g., phase velocity, characteristic impedance) of the cable assemblies can cause the electrical length to differ between assemblies.

7.3.3 The electrical length of cables used between the matching network and the chamber (if any) shall be specified to within 0.25° of the standard electrical length value at the operating frequency for fixed frequency systems or at the midpoint frequency for variable frequency systems, for frequencies less than or equal to 13.56 MHz. For frequencies above 13.56 MHz, the length should be specified to a value (in degrees) equal to the frequency in MHz multiplied by 0.018 (e.g., the specification for 60 MHz would be $60 \times 0.018 = 1.1°$). For example, at 13.56 MHz, the physical length of typical cable (RG-217) corresponding to 0.25° of phase shift (0.5° of reflection coefficient phase shift) would be approximately 1 cm. This specification would result in impedance variations seen by the matching network of less than approximately 1 percent between processing chambers.

7.3.4 The length of cables used between the matching network and the generator shall be specified to within 1.0° of the standard electrical length value at the operating frequency for fixed frequency systems or at the midpoint frequency for variable frequency systems, for frequencies less than or equal to 13.56 MHz. For frequencies above 13.56 MHz, the length shall be specified to a value (in degrees) equal to the frequency in MHz multiplied by 0.074 (e.g., the specification for 60 MHz would be $60 \times 0.074 = 4.44°$). For example, at 13.56 MHz, the physical length of typical cable (RG-217) corresponding to 1.0° of phase shift (2.0° of reflection coefficient phase shift) would be approximately 4 cm. This specification would minimize the impedance transformation at the harmonic frequencies (10° of phase shift at the 10th harmonic frequency).

7.3.5 The expected power dissipation in the cable assembly(s) supplied with the system shall be provided as a function of the operating frequency(s) of the system. The amount of power transmitted through the cable assembly shall be given in terms of dB (decibels) and percentage. The relationship between dB and percentage is given as:

$$\text{Percentage} = 100 \times 10^{(dB/10)}.$$

For example, approximately 94.8% (–0.232 dB of loss) of the power at 13.56 MHz will be transmitted through a cable assembly made from RG-217 cable with a physical length of 15.24 meters (electrical length of 375.74°). In other words, 5.2% of the power is dissipated in the cable assembly at 13.56 MHz.

7.4 *Matching Networks*

7.4.1 Matching networks transform the impedance of the plasma load to match the impedance of the generator, which is nominally 50 ohms. The transformation is achieved by the use of various

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reactive components, such as capacitors and inductors, that "tune" the matching network by transforming the impedance at the output of the network to the input of the matching network. For a given frequency, there is a fixed relationship between the impedance at the input of the matching network and the impedance at the output of the matching network (the load impedance). In other words, the impedance to which the matching network is matched (the load impedance) can be determined if the transform properties of the network are known for a given frequency. Typically, there are two methods of impedance transformation. The first method uses a fixed frequency (e.g., 13.56 MHz) and variable tuning elements, while the second method uses a variable frequency and fixed tuning elements. Specifications for both methods are given below. SEMI E115 or an equivalent test method(s) shall be used to determine the load impedance and efficiency of matching networks that are designed to operate at fixed frequency with a 50-ohm input impedance.

7.4.2 For those systems that use fixed frequency operation, matching networks typically have two variable tuning elements, which are usually variable capacitors and/or inductors. These variable tuning elements typically have an output voltage or encoder value that corresponds to a certain value of the element (i.e., an output voltage will correspond to a specific value of capacitance or inductance in the matching network). The value of the output voltage or encoder value is referred to as the tuning element position. To obtain information on the operation and performance of the matching network, the tuning element positions must be provided as outputs.

7.4.3 For those systems that use variable frequency operation, matching networks typically have fixed tuning elements (no variation) or tap points between fixed tuning elements, and the frequency is varied to obtain the best matched condition. In some cases, the tap points are also varied for matching. To obtain information on the operation and performance of these types of networks, the operating frequency and the input impedance (or reflection coefficient magnitude and phase angle) shall be provided. For those systems that have variable tap points, the tap point position shall also be provided as an output.

7.4.4 For matching networks run at a fixed frequency with variable tuning elements, the load impedance shall be provided as a function of the tuning element positions. In addition, the efficiency of the matching network shall be provided as a function of the tuning element positions. The information shall be provided in tabular form. The increment of the tuning element positions shall be in steps equal to or less than 10% of the full range. For example, a voltage increment of 1 volt or less shall be used in the case where the full range of the tuning element position is 10 volts. A plot providing an example of the real part of the load transformed to 50 ohms by the matching network as a function of tuning element position indicator is shown in Figure 1 and a plot of the reactive part of the load impedance is shown in Figure 2. A plot of the power efficiency is shown in Figure 3. An example of data to be provided in tabular form is shown in Table 1. The required uncertainty of the magnitude of the impedance is ± 1.5%, the required uncertainty in the phase angle of the impedance is ± 0.35°, and the required uncertainty of the power efficiency is ± 2.0%. For example, a load impedance of 2.0 – j20 ohms would have an uncertainty in the real part of ± 0.15 ohms and an uncertainty in the reactive part of ± 0.32 ohms.

7.4.5 For matching networks run at a variable frequency with fixed tuning elements and/or tap points, the efficiency and load impedance as a function of its output parameters (frequency, input impedance, and tap point value (if any)) shall be provided. The information shall be provided in tabular form. The increment of the output parameters shall be in steps equal to or less than 10% of the full range. For example, if the operating frequency parameter is given as an output voltage, a voltage increment of 1 volt or less shall be used in the case where the full range of the output parameter is 10 volts. The required uncertainty of the magnitude of the impedance is ± 1.5%, the required uncertainty in the phase angle of the impedance is ± 0.35°, and the required uncertainty of the power efficiency is ± 2.0%.

7.4.6 The tuning element positions/values for each matching network (of the same type/model) shall be adjusted to provide consistent efficiency and matching network input impedance when the matching network is connected to a fixed load impedance. The load impedance used shall be one that is typically encountered by the matching network during processing and/or shall be an impedance that is near the mid-range of the tuning space (e.g., 2 – j20 ohms). A simple way to ensure network-to-network consistency is to adjust the tuning element positions/values to have consistent values between matching networks when connected to a common/fixed load impedance. The variation in tuning element positions between matching networks shall be less than 1% of full scale for a common fixed load impedance and shall be less than 2% of full scale over 80% of the operating range. For example, if the fixed load impedance is chosen such that the tuning element positions on matching network A are both 5 volts (for a 10 volt range), the tuning element positions for matching network B shall be within 0.1 volts of 5.0 volts.

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