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IEEE Standard Test Methods for Measurement of Electrical Properties of Carbon Nanotubes

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IEEE Standard Test Methods for Measurement of Electrical Properties of Carbon Nanotubes

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Approved 8 December 2005

IEEE-SA Standards Board

Abstract: Recommended methods and standardized reporting practices for electrical characterization of carbon nanotubes (CNTs) are covered. Due to the nature of CNTs, significant measurement errors can be introduced if the electrical characterization design-of-experiment is not properly addressed. The most common sources of measurement error, particularly for high-impedance electrical measurements commonly required for CNTs, are described. Recommended practices in order to minimize and/or characterize the effect of measurement artifacts and other sources of error encountered while measuring CNTs are given.

Keywords: carbon nanotube, electrical characterization, high-impedance measurement, nanotechnology

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Introduction

This introduction is not part of IEEE Std 1650-2005, IEEE Standard Test Methods for Measurement of Electrical Properties of Carbon Nanotubes.

This standard covers recommended methods and standardized reporting practices for electrical characterization of carbon nanotubes (CNTs). Due to the nature of CNTs, significant measurement errors can be introduced if not properly addressed. This standard describes the most common sources of measurement error, and gives recommended practices in order to minimize and/or characterize the effect of each error.

Standard reporting practices are included in order to minimize confusion in analyzing reported data. Disclosure of environmental conditions and sample size are included so that results can be appropriately assessed by the research community. These reporting practices also support repeatability of results, so that new discoveries may be confirmed more efficiently. The practices in this standard were compiled from scientists and engineers from the CNT field. These practices were based on standard operating procedures utilized in facilities worldwide. This standard was initiated in 2003 to assist in the diffusion of CNT technology from the laboratory into the marketplace. Standardized characterization methods and reporting practices creates a means of effective comparison of information and a foundation for manufacturing readiness.

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IEEE Standard Test Methods for Measurement of Electrical Properties of Carbon Nanotubes

1. Overview

1.1 Scope

This standard provides methods for the electrical characterization of carbon nanotubes (CNTs). The methods will be independent of processing routes used to fabricate the CNTs.

1.2 Purpose

There is currently no defined standard for the electrical characterization of CNTs and the means of reporting performance and other data. Without openly defined standard test methods, the acceptance and diffusion of CNT technology will be severely impeded. This standard is intended to provide and suggest procedures for characterization and reporting of data. These methods will enable the creation of a suggested reporting standard that will be used by research through manufacturing as the technology is developed. Moreover, the standards will recommend the necessary tools and procedures for validation.

1.3 Electrical characterization overview

1.3.1 Testing apparatus

Testing shall be performed using an electronic device test system with measurement sensitivity sufficient to give a measurement resolution of at least ±0.1% (minimum sensitivity at or better than three orders of magnitude below expected signal level). For example, the smallest current through a CNT can be on the order of 1 pA (10^{-12} A) or smaller. Therefore, in this case the instrument shall have a resolution of 100 aA (10^{-16} A) or smaller. Additionally, due to the various impedances encountered in nanoscale measurements, the input impedance of all elements of the test system shall be at least three orders of magnitude greater than the highest impedance in the device. Commercial semiconductor characterization systems with the capability to characterize CNT materials and devices typically have input impedance values of 10^{13} Ω to 10^{16} Ω, which is a recommended suitable range.

This test method requires that the instrumentation be calibrated against a known and appropriate set of standards [e.g., National Institute of Standards and Technology (NIST)]. These calibrations may be performed by the equipment user provided the calibration is performed using the recommended calibration procedure called out by the equipment vendor or as a service by the equipment vendor. If calibration is not performed against a known CNT reference or known device, then the basic instrument operations (e.g., voltage, current, and resistance) shall be calibrated against some method traceable to a NIST (or similar internationally recognized standards organization) physical standard. Recalibration is required according to the instrument manufacturer's recommendations, when the instrument is moved, or when the testing conditions change significantly (e.g., temperature change greater than 10 °C, relative humidity (RH) change greater than 30%, etc.).

1.3.2 Probing systems

Probing systems will be selected that have demonstrated the ability to provide data that is consistent in nature and can be confirmed at various experimental labs. Probe tips will be chosen that were shown to be appropriate for the testing platform. In an effort to mitigate the potential for erroneous data, procedures should be followed to ensure that the probe tips are clean of contaminants. Therefore, probe tips must be stored in an environment that is devoid of contaminants and they must be handled following stringent procedures during nanotube characterization to minimize contamination.

1.3.3 Measurement techniques

1.3.3.1 Ohmic contact

Ohmic contact with a CNT is required in order to make the appropriate measurements.

Ohmic contact, as defined in the semiconductor industry, is a metallic-semiconductor contact with very low resistance that is independent of applied voltage (may be represented by constant resistance). To form an *ohmic* contact, the metal and the semiconductor materials must be selected such that there is no potential barrier formed at the interface (or the potential barrier is so thin that charge carriers can readily tunnel through it). Ohmic contacts show a linear correlation between current flowing through the contact and the voltage drop across this interface.

Non-ohmic contacts are evident when the potential difference across the contact is not linearly proportional to the current flowing through it. This type of contact is often known as a *rectifying* or *Schottky* contact. Non-ohmic contacts may occur in a low-voltage circuit as a result of non-linear connections.

1.3.3.1.1 Suggested methods to check for ohmic contact

Several methods are suggested in 1.3.3.1.1.1 and 1.3.3.1.1.2 to check for ohmic contact and methods to achieve ohmic contact.

1.3.3.1.1.1 Change source-measurement ranges

When using a semiconductor characterization tool to verify for ohmic contact, changing the source and measurement ranges can detect an ohmic contact condition. A normal condition would indicate the same reading but with correspondingly higher or lower resolution, depending on whether the instrument was up- or down-ranged. If the reading is significantly different, this may indicate a non-ohmic condition. Note that non-linear behavior may be attributed to the device.

1.3.3.1.1.2 Create an *I-V* sweep such that it crosses zero

When using a semiconductor characterization tool to verify for ohmic contact, a quick test to determine ohmic contact is to perform an *I-V* sweep through zero. If the sweep response crosses through zero, an ohmic contact has been achieved. If the sweep response does not cross zero, there is a high probability that there is a non-ohmic contact condition, indicative by a high resistance measurement. The response may be a horizontal line indicating an open condition and a high resistance. The sweep response may also be non-linear and not cross through zero, also indicative of a non-ohmic contact condition.

1.3.3.1.2 Minimizing non-ohmic contact conditions

To minimize non-ohmic contact behavior, use a contact material appropriate for CNTs, such as indium or gold. Contact material is selected to minimize the potential barrier between materials, which is typically achieved by matching the work functions of each material. Make sure the compliance voltage on the instrumentation is high enough to avoid problems due to source contact non-linearity. To reduce error due to voltmeter non-ohmic contacts, reduce ac pickup by using shielding and appropriate grounding.

1.3.3.2 Low resistance measurements (<100 kΩ)

When electrically characterizing CNTs and systems when *I-V* characteristics result in resistances of less than 100 kΩ, the force current, measure voltage (FCMV) method using the four-wire (Kelvin) connection scheme is recommended. As shown in Figure 1, the test current (*I*) supplied by a current source is forced through the resistance (*R*) through one set of test cables, while the voltage (*V*) across the unknown resistance (*R*) is measured through a second set of leads connected to the voltmeter. Although some small current may flow through the voltmeter leads (sometimes referred to as sense leads), it is usually negligible (typically much less than 1 pA) and can generally be ignored for all practical purposes. Since the voltage drop across the sense leads is negligible, the voltage measured by the measurement unit is essentially the same as the voltage across the unknown resistance (*R*). Note that the voltage-sensing leads should be connected as close to the device under test (DUT) as possible to avoid including the resistance of the test leads in the measurement.

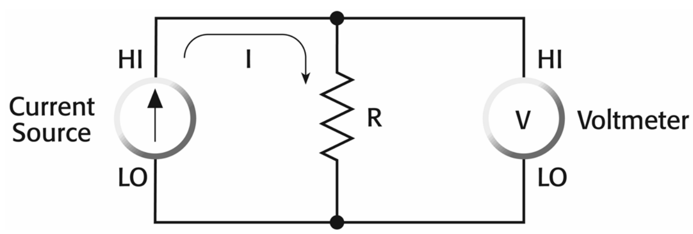

Figure 1—FVMC configuration for low-impedance devices

When a source-measure unit (SMU) is configured to source current (“I-Source”) as shown in Figure 2, the SMU functions as a high-impedance current source with voltage limit capability and can measure current (“I-Meter”) or voltage (“V-Meter”). The compliance circuit limits the output voltage to the programmed value. For voltage measurements, the sense selection (local or remote) determines where the measurement is made. In local sense, voltage is measured at the “FORCE” and “COMMON” terminals of the SMU. In remote sense, voltage can be measured directly at the DUT using the “SENSE” and “SENSE LO” terminals. To achieve a true four-wire Kelvin measurement, the SMU should be configured for remote sense. This method eliminates any voltage drops that may be in the test cables or connections between the SMU or PreAmp and the DUT.

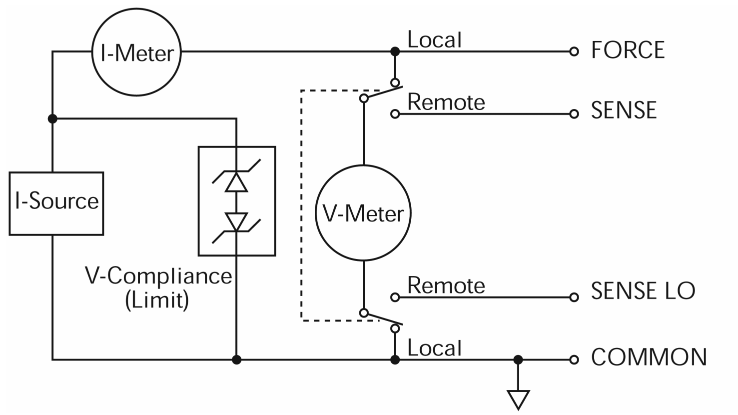

Figure 2—Remote and local sensing configurations

1.3.3.3 High resistance measurements (>100 kΩ)

When electrically characterizing CNTs and systems when *I-V* characteristics result in resistances greater than 100 kΩ, the force voltage, measure current (FVMC) method (sometimes referred to as the *constant-voltage method*) is preferred. To make high resistance measurements using the FVMC method, an instrument that can measure low current (see 1.3.1) and a constant dc voltage source are required. The basic configuration of the constant-voltage method is shown in Figure 3.

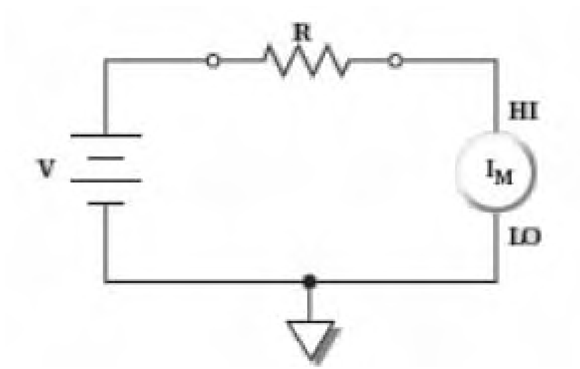

Figure 3—FVMC configuration for high-impedance measurement

In this method, a constant voltage source (V) is placed in series with the unknown resistance (R) and an ammeter (I_M). Since the voltage drop across the ammeter is negligible, essentially all the voltage appears across R. The resulting current is measured by the ammeter and the resistance is calculated using Ohm's Law ($J = \sigma E$) (see Equation (1) in 5.3.2.2).

— High resistance can be a function of the applied voltage, which makes the constant-voltage method preferable to the constant-current method. By testing at several voltages, a resistance versus voltage curve can be developed and a "voltage coefficient of resistance" can be determined.

— When an SMU is configured to source voltage ("V-Source"), the SMU functions as a low-impedance voltage source with current limit capability and can measure current ("I-Meter") or voltage ("V-Meter"). The compliance circuit limits the current to the programmed value. Sense circuitry is used to continuously monitor the output voltage and make adjustments to the V-source as needed. The V-meter senses the voltage at the "FORCE" and "COMMON" terminals (local sense) or at the DUT (remote sense using the "SENSE" and "SENSE LO" terminals) and compares it to the programmed voltage level. If the sensed level and the programmed value are not the same, the V-source is adjusted accordingly. Remote sense eliminates the effect of voltage drops in the test cables ensuring that the exact programmed voltage appears at the DUT.

1.3.4 Repeatability and reporting sample size

Sample performance between different devices may vary due to variations in the fabrication process. Additionally, it is critical to determine the repeatability of the reported results. When reporting sample size, the following criteria shall be used:

- If no sample size is reported, it is assumed that the data represent a sample size of exactly one (i.e., may not represent repeatable results).
- For sample sizes larger than one, the sample size is reported with the method of sampling (e.g., whether all devices were characterized, a randomly chosen fraction of the total sample set, etc.).
- A description of what the reported data demonstrate (e.g., average value, maximum value, minimum value, mean, standard deviation, etc.) is also required.

1.3.5 Reproducibility of measurement

CNT fabrication to date produces nanotube “bundles” of various populations. It is difficult to extract, for characterization purposes, a single nanotube. Often, for those purposes, a small bundle is extracted and placed on the “inspection table.” Ideally a single nanotube should be extracted; this may be impractical for general usage. For electrical characterization, the inspection table may be two electrically isolated pads on a common surface. Multiple sets of these pads on that surface provide a means of presenting a series of nanotube samples to the measurement system (MS) to generate sequential measurement data.

Electrical characterization of nanotubes can be obtained with an MS that contains an atomic force microscope (AFM)-like “probe station” and an *I-V* electrical instrument. Reproducibility is defined in SEMI E89 [B2]. Several factors can affect the nanotube measurement results, and their calculated “reproducibility.”

1.3.5.1 Nanotube measurement system reproducibility

Nanotube measurement system reproducibility can be established by measuring *I-V* values on several reference materials (not nanotubes). The availability of those materials, from NIST for instance, remains to be established.

1.3.5.2 Reproducibility of multiple measurements on the same device

Reproducibility of multiple measurements on the same device is currently impractical for nanotubes. Each bundle or nanotube is deformed by the measurement process, limiting the number of measurements (n) on that bundle to one ($n = 1$), since the deformation can change the electrical properties of the bundle.

1.3.5.3 Reproducibility of multiple measurements on like devices on a multi-pad surface

Reproducibility of multiple measurements on like devices on a multi-pad surface can be determined. Differences among individual bundle populations (nanotube count, nanotube type, juxtaposition, length, etc.) or among individual nanotubes can affect the reported results.

1.3.5.4 Reference materials

Reproducibility between like measurement systems can be established with reference materials. For the reasons above, reproducibility between like measurement systems with like devices on multi-pad surfaces is problematic. Yet establishing this is an important goal in the commercial interchange of nanotubes.

Considerable work remains to develop the following:

- Reference materials
- Measurement system configurations
- Techniques for extracting and mounting individual nanotubes
- Round-robin tests to establish within-lab and between-lab reproducibility data

1.3.6 Application of low-noise techniques

Generally, lower absolute voltage bias voltages cause smaller stress effects than higher absolute voltage biases. Depending on the device structure, this shifting may be reduced by ensuring that the DUT is properly grounded. This issue may be further improved if this grounding is through a low-impedance path to system ground.

In order for comparability between different device structures and eventual compatibility to other technologies [e.g., integration to conventional silicon integrated circuits (ICs)], sufficient information is to be given so that electrical fields (in V/cm) may be determined (if possible). Preferably, electrical field values are specified. In the absence of known or undetermined geometrical information, voltage information is given with information describing the difficulties in obtaining geometrical data.

Due to optical sensitivity of some materials, all measurements should be conducted inside a light-insulating enclosure that is preferably earth (safety) grounded. Optical isolation is recommended if exposure to ambient light causes a change of more than 1% from values obtained in the dark.

Due to the high impedances and extremely low current values being measured, proximity of personnel, heavy machinery, or other potential electromagnetic/radio frequency interference (EMI/RFI) sources should be maintained as far away from the measurement system while in operation. This is of particular concern when measured voltages are below 1 mV or when current values are less than 1 µA.

2. Definitions, acronyms, and abbreviations

2.1 Definitions

For the purposes of this standard, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B1][1] should be referenced for terms not defined in this clause.

2.1.1 carbon nanotube: Phase of carbon, characterized by at least one plane of graphite, that is bent into a cylindrical shape.

2.1.2 chirality: Orientation of a chemical structure and its inability to be superimposed on its mirror image.

2.1.3 device under test: Sample attached to an apparatus for evaluation of a specific physical property, such as electrical resistance or *I-V* behavior.

[1] The numbers in brackets correspond to those of the bibliography in Annex A.

2.1.4 environmental condition: Real or artificial atmospheric conditions immediately surrounding the device under test. These values are to be measured as close to the device under test as possible, and performed in a manner that introduces minimal effect on the test environment.

2.1.5 FORCE: Source of known voltage or current applied to a device to be tested for a particular electrical property (such as resistance).

2.1.6 force voltage: Voltage source that is supplied by the instrument in order to bias a particular electrode.

2.1.7 ground chuck: Conductive platform on which the device under test is placed. This platform is typically electrically referenced to system ground.

2.1.8 Kelvin measurement: Four-wire electrical resistance technique that uses separate contacts for measuring voltage across a device from that used to apply a known current through the device. This separation minimized current flow through the voltage probes, which minimizes errors due to contact or lead resistance. Used for characterization of materials with electrical resistances comparable to or lower than the leads and contacts.

2.1.9 multi-wall carbon nanotube: Nanotube consisting of more than one concentric ring of carbon.

2.1.10 SENSE: Probes at which a voltage is measured across a device under test resulting from a known applied current. Typically used in four-wire resistance (Kelvin) measurements.

2.1.11 single-wall carbon nanotube: Nanotube consisting of exactly one ring of carbon.

2.1.12 transport properties: Physical property of a material or device that governs the behavior of an electrical charge passing through it.

2.2 Acronyms and abbreviations

ac	alternating current
AFM	atomic force microscope
CNT	carbon nanotube
CVD	chemical vapor deposition
dc	direct current
DUT	device under test
FCMV	force current, measure voltage
FVMC	force voltage, measure current
IC	integrated circuit
IEEE	Institute of Electrical and Electronics Engineers
MS	measurement system
MWNT	multi-wall nanotube
NIST	National Institute of Standards and Technology
RH	relative humidity
SEM	scanning electron microscope
SMU	source-measure unit
STM	scanning tunneling microscope
SWNT	single-wall nanotube
TEM	transmission electron microscope

3. Nanotube properties

There is considerable difficulty in measuring the critical dimensions of individual nanotubes. These dimensions are important to record since they strongly influence the observed electrical properties. If at all possible, measurements of these critical dimensions should be provided. Because of the fact that the dimension measurement instrumentation is presently operated near optimum performance, descriptions of the techniques used to obtain these dimensions should also accompany the measurement.

NOTE—In some instances, measurements of nanotube dimensions by AFM are complicated by its finite radius tip and could introduce error.[2]

A list of dimensions/descriptions and suggested characterization techniques follows:

— Multi-wall nanotube (MWNT) or single-wall nanotube (SWNT), transmission electron microscope (TEM)
— For MWNT, indicate if concentric tubes or side-by-side "ropes" of tubes, TEM
— Length of nanotube between electrodes, scanning electron microscope (SEM)
— Outside diameter, TEM, SEM
— Inside diameter, TEM
— Number of walls. TEM
— Defect density, TEM
— End-cap density within the tube (bamboo-like structure), TEM
— Chirality, scanning tunneling microscope (STM)

3.1 Single-walled nanotube

3.1.1 Method for processing and fabrication

Fabrication process information for SWNT is to be reported [e.g., carbon monoxide disproportionation, chemical vapor deposition (CVD), laser ablation, electric arc, etc.], along with descriptions of any post-growth treatments for chemical purification, disaggregation, chemical derivatization, or structural sorting.

3.1.2 Structures

The SWNT structures are to be reported in as much detail as possible. This information may include the following:

— Nanotube length
— Nanotube diameter
— Nanotube chirality

3.1.3 Other properties

Other properties such as tube filling, open or closed tube ends, extent of chemical derivatization, etc., should be reported.

[2] Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

3.2 Multi-walled nanotube

3.2.1 Method for processing and fabrication

Fabrication process information for MWNT is to be reported (e.g., CVD, laser oven, electric arc, etc.), along with descriptions of any post-growth treatments for chemical purification, disaggregation, chemical derivatization, or structural sorting.

3.2.2 Structures

The MWNT structures are to be reported in as much detail as possible. This information may include the following:

— Number of concentric tubes

— Nanotube length

— Diameter of the outer nanotube

3.2.3 Other properties

Other properties such as tube filling, open or closed tube ends, extent of chemical derivatization, etc., should be reported.

4. Electrodes

The design and fabrication method of the electrode should be provided, such as electron beam deposition, focused ion beam deposition, patterned and vapor deposited metal, placement of the CNT on the testing contact, electrical characterization system probe tip, self assembly, etc. In addition to the electrode, the interface created between the electrode and nanotube, referred in this standard as weld, should be described by the following:

— Length of nanotube in contact with the electrode

— Width of nanotube in contact with the electrode

— Thickness of weld between nanotube and electrode

— Composition of the weld

— Fabrication technique of the weld if independent of electrode fabrication

4.1 Materials

The composition of the material used for the electrode should be reported [e.g., gold (Au)].

4.2 Method for electrode fabrication

The following information for electrode fabrication should be reported:

— Electron beam deposition process parameters

— Focused ion beam deposition process parameters

— Vapor deposition process parameters

— Substrate composition and surface characteristics prior to electrode fabrication

— Substrate surface treatment prior to and after electrode fabrication

— Any surface treatment between electrode fabrication steps, including chemical, mechanical, or any other enhancements used

4.3 Dimensions

The dimensions of the electrode are to be reported. At minimum, the following geometrical information is to be reported:

— Electrode length, l (in centimeters, micrometers, or nanometers)

— Electrode width, w (in centimeters, micrometers, or nanometers)

— Electrode thickness, t (in centimeters, micrometers, or nanometers)

5. Device characterization

5.1 Architecture design

The device structure shall be reported, including general device geometry, electrode placement, etc. At minimum, the following geometrical information is to be reported:

— Relation of the first electrode to substrate (whatever is sufficiently descriptive for accurate reproduction of the experiment)

— Relation of the second electrode to substrate (whatever is sufficiently descriptive for accurate reproduction of the experiment)

— Distance between the first electrode and the second electrode

5.2 Method for processing and fabrication

The following information for two terminal device fabrication is to be reported:

— Substrate composition

— Fabrication process

— Any surface treatment between device fabrication steps, including chemical, mechanical, or any other enhancements used

5.3 Standard characterization procedures

5.3.1 Guidelines for the characterization process

The following settings are to be chosen so that:

— Step size is small enough to give a minimum of ten data points per curve. Twenty-five or more points are recommended. Increased number of data points results in more accurate curve fitting and greater noise/outlier tolerance, and therefore more accurate parameter extraction. The number of points used for each measurement is to be reported in some clear fashion (e.g., start, stop, and step values; number of points measured, etc.).

— Values are to reflect the full expected operating range and/or demonstrate full device operating range.

— Range of chosen values accurately represents full device operating range. These values are chosen so that device behavior is shown for the full expected operating range.

— One probe is used per electrode, plus one shielded ground chuck connection that is in electrical contact with the substrate (“bulk”). If the measured resistance for any channel is less than 100 kΩ, two probes per electrode (one “force” electrode for current application and one “sense” electrode for voltage measurement) are used to minimize electrode and interfacial impedance errors (see 1.3.3.2).

5.3.2 Reporting data

5.3.2.1 Reporting standards

The information that is reported with two-terminal devices is shown in Table 1.

Table 1—List of electrical parameters for two-terminal devices.

Characteristic	Standard symbol	Units
Electrical conductivity	σ	S/cm
Electrical resistivity	ρ	Ω • cm
Carrier mobility	μ	$cm^2/V \cdot s$
Density of charge carriers	N	cm^{-3}
Electron carrier density	n	cm^{-3}
Hole carrier density	p	cm^{-3}
Diode saturation current	I_S	A

5.3.2.2 Determination and reporting of electrical conductivity and resistivity

Electrical conductivity, and its reciprocal, electrical resistivity, are measured by the following two methods:

— FCMV (see 1.3.3.2), where a constant and known electrical current density, J, (in A/cm^2) is passed through the sample, and the resulting electric field, E, (in V/cm) is measured. Typically, the FCMV method is used for samples with a resistance much less than 100 kΩ, and shall use the four-probe Kelvin technique for sample resistances less than 1 kΩ. The Kelvin technique uses separate contacts for the applied current and the measured voltage potential, with the current contacts placed at the outside edges of the sample.

— FVMC (see 1.3.3.3), where a constant and known electric field, E, (in V/cm) is applied across the sample, and the resulting electrical current density flowing through the sample, J, (in A/cm^2) is measured. The FVMC method shall be used for characterizing samples with a resistance greater than

10 MΩ, and shall not be used for samples with a resistance less than 1 kΩ. The FVMC method uses two contacts only, placed at each end of the sample under test.

The electrical conductivity and/or electrical resistivity is derived from Ohm's Law, given in Equation (1), as follows:

$$J = \sigma E = \frac{1}{\rho} E \tag{1}$$

where

J is the current density

σ is the electrical conductivity

E is the electric field

ρ is the electrical resistivity

The current density, J, is equal to the current, I, (in A) divided cross-sectional unit area, A, (in cm^2) of the sample ($J = I/A$), and the field strength, E, is equal to the voltage potential, V, (in V) divided by the distance between the two voltage probes, L (in cm) ($E = V/L$).

NOTE—For a nanotube, the cross-sectional area may be difficult to define; therefore, current density, conductivity, and resistivity may require special definitions. In these instances, a definition for geometry should be provided.

Measurement of electrical conductivity or electrical resistivity shall be reported for two-terminal devices that show substantially linear behavior. These measurements also require ohmic contacts to the two-terminal device (see 1.3.3.1). If the two-terminal device is significantly non-linear, electrical conductivity and electrical resistivity data for the device generally cannot be derived.

For semiconducting or insulating samples, the electrical conductivity is typically reported. For metallic samples, the electrical resistivity is usually given.

5.3.2.3 Determination and reporting of carrier mobility and density of charge carriers

The carrier mobility (in $cm^2/V{\bullet}s$) and density of charge carriers (in cm^{-3}) can be determined by the Hall effect. In a Hall effect measurement, a known current density, J_x, (in A/cm^2) is applied to the two-terminal device in the *x*-direction. A known magnetic field, B_z, (in G) is applied in the *z*-direction. The Hall field, E_y, (in V/cm) is then measured across the two-terminal device in the *y*-direction. The number of conduction electrons is then calculated by Equation (2) as follows:

$$N = \frac{J_x B_z}{q E_y} \tag{2}$$

where

N is the density of charge carriers

q is the charge of an electron (1.602×10^{-19} C)

J_x is current density in the *x*-direction

E_y is the Hall field in the *y*-direction

B_z is the applied magnetic field in the *z*-direction

The sign of N determines whether electrons or holes predominate in the conduction process, with N positive if holes dominate, negative if electrons dominate.

N combined with the electrical conductivity, σ, (see 5.3.2.2) gives the carrier mobility, shown in Equation (3), as follows:

$$\mu = \frac{\sigma}{Nq} \tag{3}$$

where

μ is the carrier mobility

It is noted that the *carrier mobility* given in Equation (3) is different from the *field effect mobility* measured in field effect devices [such as field effect transistors (FETs)]. The field-effect mobility is affected by various device-level factors, and often deviates significantly from the carrier mobility.

5.3.2.4 Determination and reporting of non-linear behavior

For non-linear two-terminal devices where rectifying behavior is present.

For a *p-n* junction of *p*-type and *n*-type semiconductors in intimate contact, the Shockley equation (also called the ideal diode law) can be used to relate the reverse-bias saturation current to the carrier mobility, as given in Equation (4), as follows:

$$I_{\mathrm{S}} = Ak_{\mathrm{B}}T\left(\frac{C_{\mathrm{ep}}\mu_{\mathrm{ep}}}{L_{\mathrm{ep}}} + \frac{C_{\mathrm{hn}}\mu_{\mathrm{hn}}}{L_{\mathrm{hn}}}\right) \tag{4}$$

where

I_{S} is the reverse-bias saturation current
A is the cross-sectional area of the device
T is the temperature (in K)
C is the concentration of minority carriers in each semiconductor region
L is the diffusion length
k_{B} is the Boltzmann constant (1.381×10^{-23} J/K)

The subscripts *ep* and *hn* denote the electrons in the *p*-region and holes in the *n*-region, respectively.

For a metal-semiconductor junction (which forms a Schottky contact), the reverse-bias saturation current is given by Equation (5) as follows:

$$I_{\mathrm{S}} = ABT^2 e^{-\frac{\phi_{\mathrm{M}} - \phi_{\mathrm{S}}}{k_{\mathrm{B}}T}} \tag{5}$$

where

B is a constant value
φ_{M} is the work function of the metal
φ_{S} is the work function of the semiconductor
k_{B} is the Boltzmann constant (1.381×10^{-23} J/K)
e is the base of the natural logarithm

The current-voltage relationship (I versus V) of the rectifying two-terminal device is characterized by Equation (6) as follows:

$$I(V) = I_S\left(e^{\frac{qV}{k_B T}} - 1\right) \quad (6)$$

where
I is the device current
V is the device voltage

5.3.2.5 Reporting of environmental conditions

The environmental conditions present during device storage and characterization shall be reported with all electrical characterization data. Guidelines for environmental monitoring are detailed in 5.4.

5.3.2.6 Other reportable parameters

Table 2 lists other nonelectrical parameters that can be extracted and reported with electrical data. Reporting these parameters shall follow the terminology, symbol use, and units given in Table 2.

Table 2—Other nonelectrical parameters that can be reported

Characteristic	Standard symbol	Units
Thermal		
Thermal conductivity	K	mW/cm•K or W/m•K
Seebeck coefficient	S	µV/K
Mechanical		
Tensile strength	σ_{uts}	GPa
Young's modulus	E	GPa

5.4 Environmental control and standards

Device storage conditions from time of device fabrication to time of measurement shall be reported. Environmental conditions during device storage may significantly affect device performance. Changes in the storage and characterization environment could result in potentially significant variation in device performance. Therefore, diligent reporting of device storage and characterization environments is necessary for comparing or verifying data.

The environmental conditions driving the measurement shall be monitored and recorded for every measurement. Conditions are, at a minimum, to be recorded at the beginning and at the end of each experiment. However, real-time recording of the environmental conditions repeatedly and recorded with each data point is recommended.

The following environmental conditions must be monitored and recorded:

— Measurement atmosphere (e.g., ambient air, nitrogen environment, vacuum, etc.).

— Light illumination conditions and light exposure time (e.g., dark, UV protection, etc.). Also include change in lighting conditions, such as length of time sample was placed in dark after light exposure and before electrical measurement.

— Device temperature (measured to a resolution of at least 1 °C or 1 K, 0.1 °C or 0.1 K recommended).

— RH (to a resolution of 5% minimum, 1% recommended).

— Measurement duration, time of measurement (in order to assist in evaluating measurement artifacts due to very long lifetime effects).

Annex A

(informative)

Bibliography

[B1] IEEE 100™, *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition.[3]

[B2] SEMI E89, Guide for Measurement System Analysis (MSA).

[3] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).