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Test methods for measurement of electrical properties of carbon nanotubes

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TEST METHODS FOR MEASUREMENT OF ELECTRICAL PROPERTIES OF CARBON NANOTUBES

FOREWORD

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1650 (2005)	113/58A/FDIS	113/63/RVD

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

Sponsor

Nanotechnology Council Standards Committee
of the
IEEE Nanotechnology Council

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

IEEE Introduction

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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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