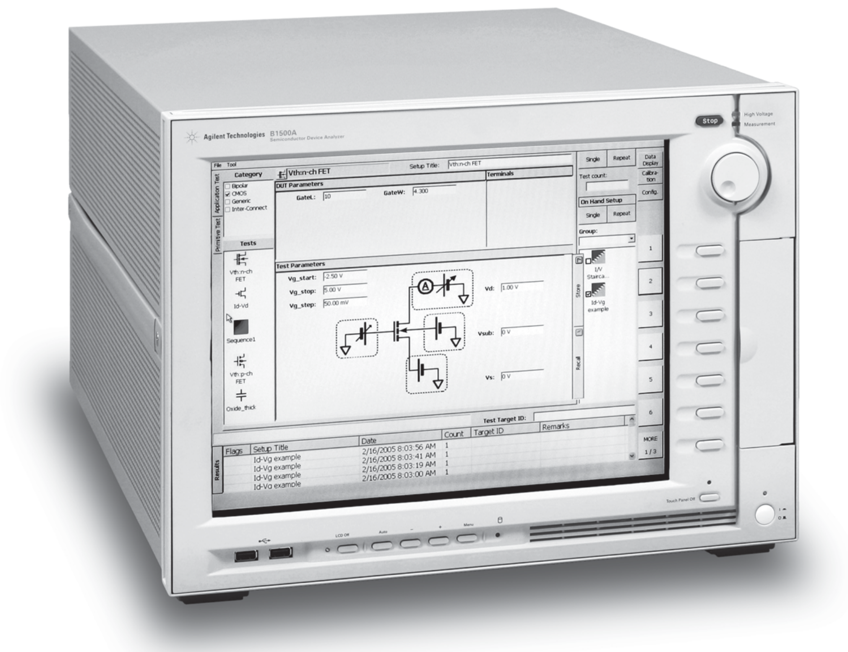
Measuring CNT FETs and CNT SETs Using the Agilent B1500A

Application Note B1500-1

Agilent B1500A Semiconductor Device Analyzer

Introduction



Exotic carbon nanotube (CNT) structures have generated a great deal of interest in the scientific community. There are many potential applications for CNTs, but much of the current focus in nanotechnology research is centered on electrical component structures, such as the CNT field effect transistor (FET) and the CNT single electron transistor (SET).

The Agilent 4155C and 4156C have been the de facto industry standard instruments for semiconductor device characterization for many years. In addition, they are very effective tools for nanotechnology device characterization. However, the new Agilent B1500A Semiconductor Device Analyzer is also an excellent instrument for analyzing the electrical properties of nanotechnology devices, and it has added benefits not found in the 4155C and 4156C.

The content of this application note is based on a study conducted by Professor K. Matsumoto of Osaka University. In his study Professor Matsumoto focused on how chirality determines the electrical properties of CNT FETs and CNT SETs, using the 4156C Precision Semiconductor Parameter Analyzer as the measurement tool. The new B1500A would have worked equally well for this study, and the B1500A offers added benefits, among which is an application library that contains the application tests necessary to perform these measurements.

CNTs have also been studied as materials for ultra large scale integration (ULSI) interconnection because they can support extremely high current densities (1000 times larger than those of Cu), and CNTs possess very high thermal conductivity (10 times greater than that of Cu). CNTs also show promise as the electrical source in field emission displays, and a close relative, the carbon nano-horn, shows potential as a material for constructing fuel cells. The B1500A is an excellent tool for characterizing these fundamental CNT structures.

CNT electrical properties are determined by chirality

CNTs can behave as either conductors or semiconductors. Behavior is dependent on their chirality, which is determined by the holding angle and diameter of the nanotube. The patterning of CNTs has been successfully controlled using patterned catalysts and chemical vapor deposition under the influence of an electric field.

Figure 1 shows a scanning electron microscope image of a CNT FET structure, which exhibits 10 times higher saturation performance.

Figure 2 shows two drain IV curves through a CNT channel, taken by sweeping the drain voltage. Depending on the chirality of the CNT, these devices can be made to show either CNT FET behavior (left) or resistive behavior (right). This illustrates how critical the control of chirality is to the electrical performance of the CNT device. One variation of the simple CNT is the single wall CNT (SWCNT), which can be created by varying the deposition conditions. This application note focuses on the SWCNT, and all subsequent references to CNT devices in this application note refer to SWCNT devices.

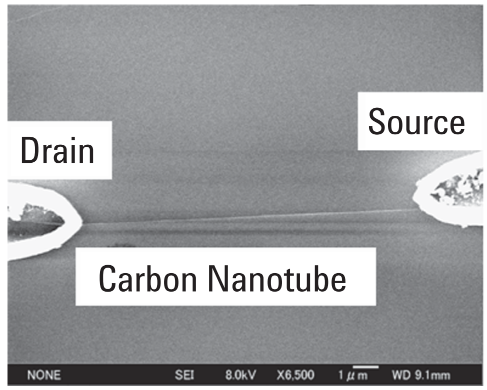


Figure 1. Scanning electron microscope image of a CNT FET

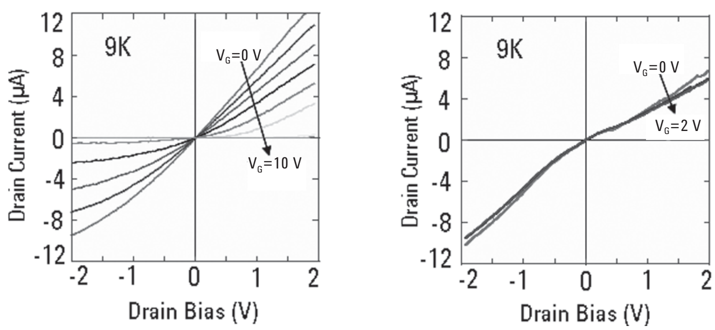


Figure 2. Two drain IV curves showing CNC FET behavior (left) and resistive behavior (right).

Combined low-current measurement and nanotechnology research capabilities

An instrument with stable low-voltage and low-current measurement capability is essential for the study and characterization of nanotechnology devices. There are two essential factors necessary to establish a good nanotechnology test environment: a suitable measurement instrument; and a low noise test environment. In addition to basic measurement performance, user-friendly hardware and software interfaces are also important for achieving an extremely high level of efficiency in research work.

Figure 3. Agilent 4156C Precision Semiconductor Analyzer

Measurement instruments

Agilent offers two instruments that are well suited for nanotechnology measurement, the Agilent 4156C Precision Semiconductor Parameter Analyzer and the Agilent B1500A Semiconductor Device Analyzer, which are shown in Figures 3 and 4 respectively.

Figure 4. Agilent B1500A Semiconductor Device Analyzer

The 4156C has a fixed configuration, with four source/monitor units (SMUs), two voltage monitor units (VMUs) and two voltage source units (VSUs). These measurement resources satisfy the vast majority of parametric characterization needs. The 4156C also has an interactive front panel with a combination of fixed hardware keys and soft keys, which provide an easy-to-use compact operating environment.

The B1500A, in contrast, is modular and supports a variety of SMU measurement modules, as well as a capacitance measurement unit (CMU). Figure 5 shows rear view of the B1500A with measurement modules inserted. SMUs supported by the B1500A include high-resolution, medium-power, and high-power. The B1500A also supports an atto-sense and switch unit (ASU).

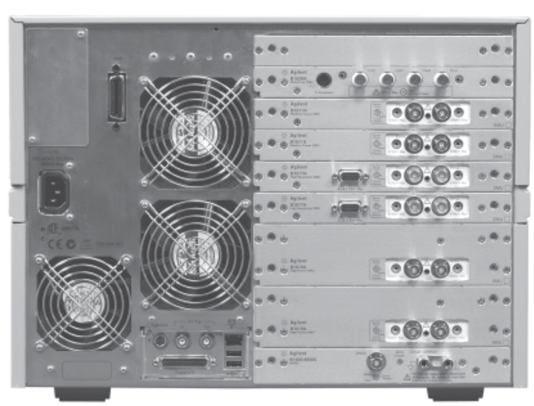


Figure 5. Agilent B1500A rear view with measurement modules inserted.

B1500A modules can provide the following measurement and forcing capabilities: current

Combined low-current measurement and nanotechnology research capabilities (continued)

measurement resolution down to 100 aA: (1×10^{-16} A); current force capability up to 1 A; voltage measurement resolution down to 0.5 µV; and voltage force capability up to 200 V.

The CMU covers a range from 1 KHz to 5 MHz. Accurate CV and DC measurements are easily achievable for specific output pins by using the switching capabilities of the SMUs and CMU.

The B1500A includes Agilent's Windows®-based, user-friendly EasyEXPERT software interface and a front touch panel, as shown in Figure 6. In addition, the B1500A comes with more than 100 semiconductor-related application tests. Users can select an application test and immediately execute the test. The B1500A software will automatically calculate the desired DUT parameters. Application tests can be run with or without modification but, if modification is required, users can treat an application test as a template and easily customize it with a few simple mouse clicks.

When a unique nanotechnology application test is required, a new test library can be created and easily shared among test group members. Since the application test concept is solution-based (as opposed to hardware based), it is very easy for other group members to utilize the new test library. Group members do not have to understand the details of the measurement setup in order to use the application tests.

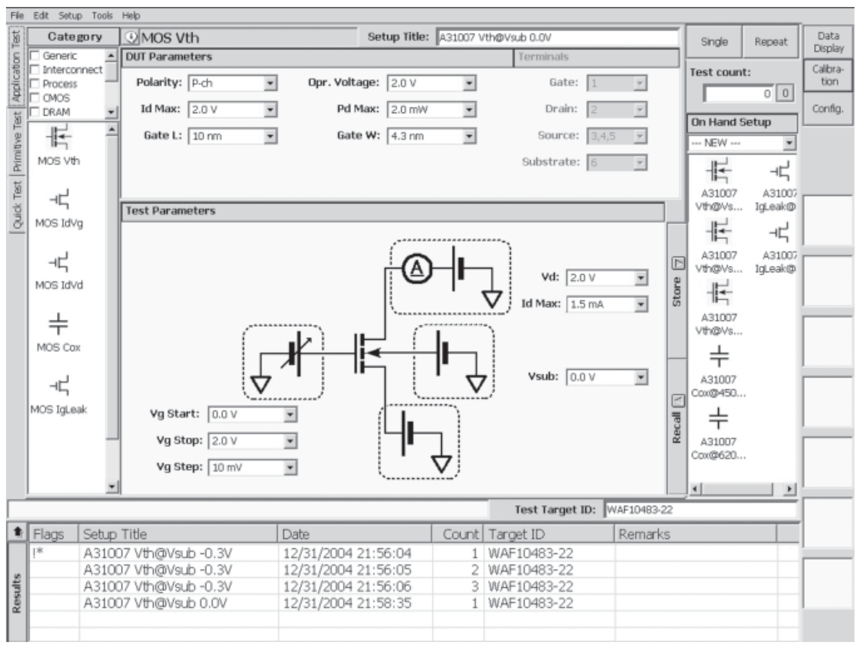


Figure 6. B1500A EasyEXPERT Windows-based, user-friendly software interface.

Low-noise test environment

When performing nanotechnology measurement and characterization, grounding and shielding are essential for obtaining accurate low-current and low-voltage measurements. Figure 7 shows an example of a shielding box around the SMU connections and device under test (DUT). The DUT, which in this example is a CNT FET, must reside in a compact shielding box that is properly grounded to the circuit common of the SMUs via the outer ground shield of the triaxial cable. The shielding box prevents outside electrical noise, magnetic noise, and optical noise from reaching the DUT.

SMU outputs coming from the device analyzer are triaxial cables and are attached to the shielding box wall with triaxial connectors. To minimize noise, the outer common ground of the triaxial cable must be connected to the shielding box, and the middle guard line should be routed with the center force line to a point as close to the DUT as possible. The measurement signal from the triaxial connector is routed to the DUT using a low-noise coaxial cable. The middle guard signal of the triaxial cable must be connected to the outer conductor of the coaxial cable, as shown in Figure 8. The guard connection inside the shielding box protects the measurement signal from noise sources that might exist in the shielding box (such as those generated by vibration). It also eliminates stray capacitance effects that can slow the measurement response of the system. It is also desirable to surround the back gate with the guard, as shown in Figure 7, when applying a gate bias from the substrate.

To interface the triaxial cable with the coaxial cable through the shielding wall the Agilent 16495J connector plate can be used, as shown in Figure 9.

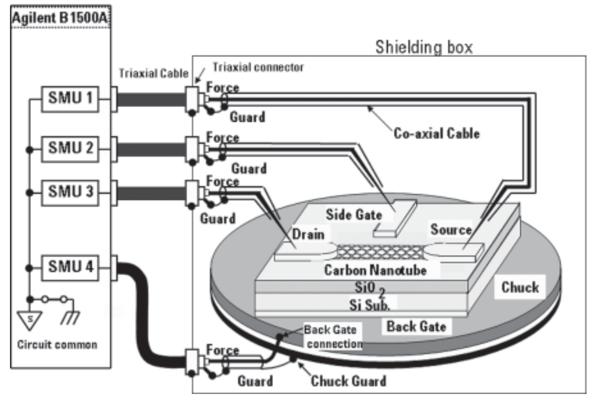


Figure 7. Example of a shielding box protecting SMU connections and the DUT.

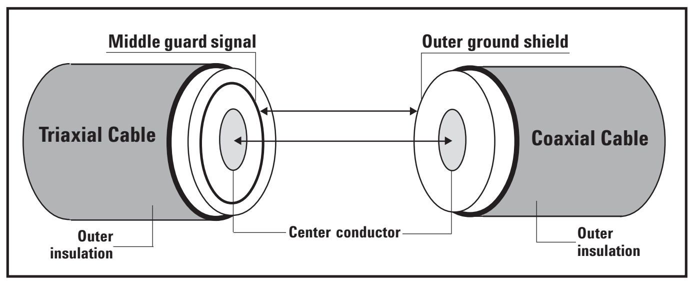


Figure 8. Middle guard signal of a triaxial cable connected to the outer ground shield of a coaxial cable.

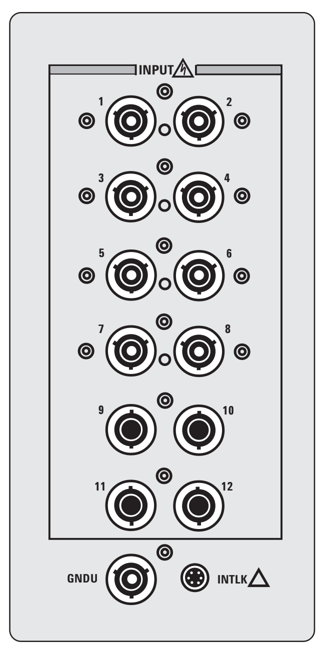


Figure 9. Agilent 16495J connector plate for interfacing a triaxial cable through a shielding wall.

Single electron transistor measurement performance

With special chemical treatment, CNT FETs can be made to exhibit SET performance even at room temperature. When a nanoscale multi-dot CNT is divided by defects, the drain current exhibits oscillation as shown in Figure 10.

The oscillation observed in the I-V plots of the drain current illustrate a Coulomb blockade within the Coulomb gap
($V = e/C$, e : electron charge 1.6×10^{-19})
caused by changes in the number of trapped electrons in the island of the multi-dot structure. The irregularity of these oscillations may come from the multi-dot structure. Theoretical calculations put the total capacitance of this SET at about 0.2 aF (2E-19F) and the Coulomb energy at 400 meV. This corresponds to an island approximately the size of a sphere 1 nm to 2 nm in diameter.

This Coulomb energy corresponds to a temperature of approximately 5000° K, so it is possible to detect the transfer of a single electron, even at room temperature, through the change in the SET performance.

This type of behavior is especially important for sensors, and it is one potential application for this device.

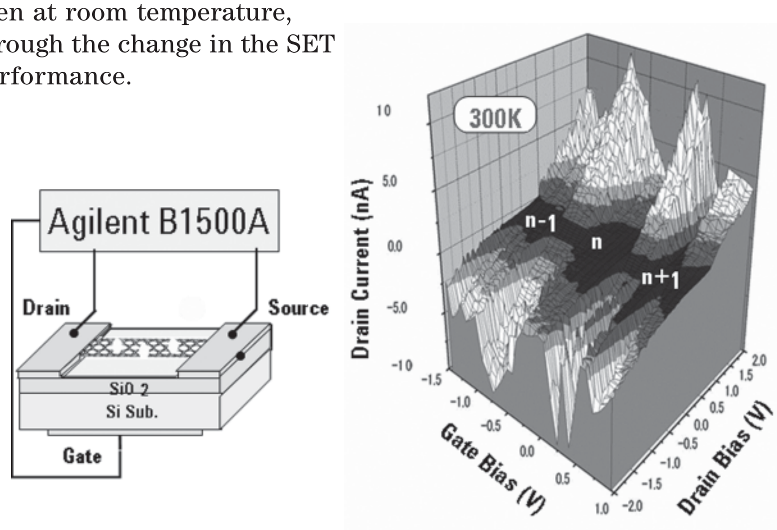


Figure 10. Oscillation observed in the I-V plots of a drain current illustrate a Coulomb blockade within a Coulomb gap.

Measurement of multiple IV curves using the Agilent B1500A Analyzer

In Professor Matsumoto's study, the number of measurement points in the IV curves of the SET was 10,000. For a measurement with this many points, the B1500A would be a good choice because it is very easy to transfer this sort of data into other Windows-based applications. In addition, the B1500A software environment supports automated measurement sequencing and data handling through a GUI utility, which eliminates the need to write a special program to perform this task.

Both the 4156C and the B1500A can be controlled using Agilent FLEX commands and whatever programming language the user prefers. Agilent provides a VXI*plug&play* driver for both instruments, which gives you an easy to use, high-level programming interface for your software environment. The VXI*plug&play* driver can be used with Visual BASIC, C/C++, National Instrument LabView, and Agilent VEE.

Summary

This application note presents an electrical measurement solution for CNT FET and CNT SET characterization using the Agilent B1500A and Agilent 4156C analyzers. These instruments can measure unique electrical performance in nanotechnology devices, and they can even detect a single electron transfer at room temperature.

The Agilent B1500A Semiconductor Device Analyzer and the Agilent 4156C Precision Semiconductor Parameter Analyzer are shown to be suitable choices for the electrical measurement and study of nanotechnology devices.

Agilent gratefully acknowledges Professor K. Matsumoto of Osaka University and his group for the CNT FET and CNT SET data.

References

K. Matsumoto, S. Kinoshita, Y. Gotoh, K. Kurauchi, T. Kamimura, M. Maeda, K. Sakamoto, M. Kuwahara, N. Atoda and Y. Awano Jpn. J. Appl. Phys. Vol. 42 (2003) pp. 2415-2418

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