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Test System Is Key to Practical Applications of Nanotechnology

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To assure high reliability, Nanomix, Inc. tests FETs based on carbon nanotube technology at the wafer level, and packaged nanotube sensors under simulated use conditions.

Sensor Production

Nanomix, Inc. of Emeryville, CA was the first company to launch nanoelectronic detection devices to market, and continues to develop its ***Sensation™*** carbon nanotube (CNT) technology for high value diagnostic and monitoring applications. These currently include respiratory gas monitoring devices, and liquid-media biomolecule detectors for a wide variety of applications.

Typically, Nanomix sensors are based on CNT network FETs produced on six-inch silicon wafers using the chemical vapor deposition process and certain proprietary methods. In some cases, flexible substrate and spray coating are used. The CNT network is coated with a functional layer that interacts with the chemical or biological analyte of interest. Interactions between the functional layer and the analyte result in a measurable change in the electrical characteristics of the FET. (See ***Figure 1***.) The nanometer-scale diameter of a CNT and its chemical and electrical properties allow ultra-sensitive detection. The resulting sensors are small in size, with low power consumption.

During production, testing is done at the wafer level to evaluate the basic characteristics of the FETs. After FETs are functionalized, the packaged devices are exposed to target analytes, and their detection characteristics analyzed.

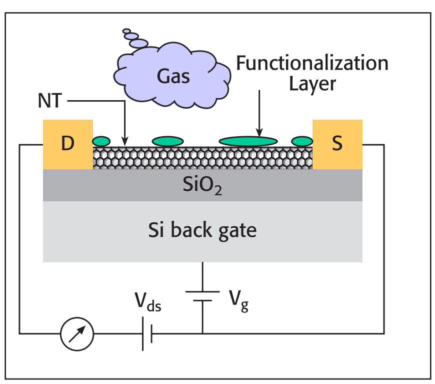

Figure 1. Electrical diagram of a CNT-network FET in a gas sensor.

Wafer Level Testing

In wafer level testing, I_d-V_d and I_d-V_g measurements are taken at various stages of production. The tests are conducted on actual devices and special test structures. The test equipment includes a semi-automatic prober, Keithley Model 2400 SourceMeter® instruments, a Model 7002 switch matirx with 7011C multiplexer cards, and a PC that provides all sequence control.

Testing takes place on a wafer prober without exposure to the target analyte. Analysis of the test results, such as gradients of certain characteristics on a wafer map, may be used for fine tuning of various stages of the development process. A QC test regimen is used during production for wafer disposition and die selection.

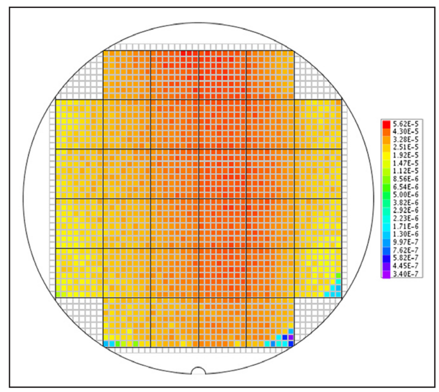

Figure 2. Wafer map example. A user is able to click on the image and view the I-V trace and calculated characteristic values for a particular device.

Typically, FET characteristics such as as Gmin, Gmax, transconductance etc. are calculated from the raw I_d-V_g data. The raw data and the calculated characteristics are uploaded to a production database. The engineers can generate histograms and interactive wafer maps (see ***Figure 2***) from the database using proprietary software, inspect the maps for uniformity and compare different types of devices that are present on the wafer. If necessary, statistical analysis is performed on multiple wafers or within a wafer.

Sensor Assembly Testing

Testing of packaged CNT-network FETs, and chemical sensors using those FETs, may take place inside environmental chambers.

Usually the analyte gas mixture is supplied by one of the custom gas delivery systems (GDS), developed at Nanomix, through special manifolds attached to the test fixture boards. The devices under test (DUTs) have various package configurations. The number of DUTs can vary from one to over a hundred. After devices are loaded onto appropriate test fixtures, they are exposed to analytes and changing environmental conditions during testing. This may also require monitoring with additional reference sensors.

Depending on the tests being run, DUTs may require uninterrupted bias voltage, typically between 5mV and 500mV. Device conductances may range from 1 microsiemens to 100 millisiemens, depending on design and fabrication method.

In developmental test scenarios the main objectives are sensor characterization and direct comparison of different fabrication methods through statistical analysis of measured parameters. In both development and production, a major test concern is high-throughput measurements of multiple devices over time.

In order to streamline testing and analysis, the DUTs are arranged in test groups, a technique known as blocking in experiment design. A test group may be composed of nominally identical devices, or conversely, some devices may be intentionally different. The device identification information (such as wafer, die location, package pinout, functionalization type etc.) is entered only once and used for all experiments with the test group. All devices in a group are exposed to the same testing and storage conditions, and the same sequence of tests, which reduces the possibility of mistaking unknown factors for intrinsic differences between devices.

Original Test System Design

Initially, the Nanomix test system was composed of custom designed DUT fixtures, onboard multiplexers, and current preamplifiers, all of which were interconnected with ADC and DAC boards. Test control was accomplished with a PC running LabVIEW®.

However, test fixtures were large, complicated, difficult to maintain and troubleshoot, supported only 40-pin DIP packages, and could not operate reliably at higher than room temperatures. When multiplexing the measurements, maintaining a constant bias voltage on all devices was impossible. Moreover, measurements had a limited range and insufficient resolution, with cycle times that were considered excessive. Test control was also becoming quite difficult due to test complexity and the need to quickly accommodate changing requirements. As a consequence, making changes on the fly required maintaining multiple software versions.

New System Improves All Test Parameters

To overcome these limitations, Nanomix developed an automated test system called Zephyr. One of the main challenges was the flexibility required to handle multiple package types and test conditions. Simple passive test fixtures were built to house several different types of DUT packages. These are connected to the test system over 1.5m twisted-pair DB25 cables and the fixtures can be placed in the environmental chamber. (Test fixtures and cables are inexpensive and easy to make.) With this hardware, DUTs can be heated or cooled individually.

Figure 3. One of the Zephyr measurement system installations

An important benefit of the Zephyr system is its flexibility. It is designed to work with different measurement equipment configurations as tests demand. One typical application (***Figure 3***) uses a Keithley switch matrix with two multiplexer cards, one Model 2400 SMU and one Model 2602 SourceMeter System, and a custom Trigger Link adaptor. More complex tests, or those with a larger number of DUTs, may employ additional switch matrices, switch cards, and SMUs.

The test executive software is written in Java and is platform independent (current version includes only Windows drivers for serial ports and GPIB, but adding new drivers is trivial). Instruments from multiple vendors are supported. The tests are programmed using a specialized script language, which is based on XML. Using the supplied schema, script files can be written in an editor with autocompletion, syntax checking etc. The script files can also be source-controlled, which makes it possible to track changes, or go back to earlier versions if necessary.

The flexibility of Zephyr software is due to loose coupling between the following features:

- The test script determines the sequence and timing of all switch and measure operations, which encompass both DUT and reference measurements, as well as heater control and certain gas delivery system control functions. This approach is known as domain-specific programming language.
- Test script settings such as device addresses, voltage levels, test duration, measurement frequency etc., can be modified for every test run and every installation without any changes to the script itself.
- Instrument control provides low-level implementation of communication interfaces shared by all scripts. Instruments from multiple vendors are supported. All instrument adapters use the same application programming interface (API), making instruments generally interchangeable with only minor (if any) changes to the script. One such instrument adapter collects target values from the GDS.
- The software facilitates DUT and test group identification. The application can use test group data to convert generic measurement names specified in the script to specific device names.
- The script does not handle data output explicitly; instead, the application sends measurement data to every active data output component, which stores or displays relevant data in a specific format. These components also use a certain API

and can be controlled by the user.

Some tests take advantage of the Test Script Processor (TSP™) built into the Keithley 2600 Series system. The TSP scripts, which are based on a widely used programming language, can range from just a few commands to a large set defining sophisticated test functions. Note that these scripts are quite different from the Zephyr scripts mentioned above. However, if necessary, it is possible to upload and run a TSP script on the Keithley 2600 System using Zephyr software.

The most recent feature added to the software is the ability to measure the I-V characteristics of the devices (***Figure 4***) without increasing the level of Zephyr test script complexity. This is achieved by adding a virtual instrument (or instrument adapter in Zephyr terminology) that returns a special type of measurement result, which is handled by the appropriate output components. Behind the scenes, the adapter uploads a custom TSP script to a Keithley 2602 unit at the beginning of a test,. For every measurement request from the Zephyr script, the adapter calls a function defined in the uploaded script, and transforms the returned data for further processing by the output components. Thus, a new type of measurements can take extensive advantage of hardware capabilities and be integrated seamlessly into the system.

About 10 Zephyr scripts are currently in use for various purposes. For example, one of the scripts used for DC measurements, with typical settings, measures 16 devices every 500ms repeatedly for several hours. The test duration or number of cycles is set by the operator and depends on the specific task. By taking advantage of the switch matrix and SMU capabilities, the Zephyr system has greatly increased test throughput. In certain applications that were possible with the old system, the cycle time was decreased by a factor of three, low-conductance accuracy improved by at least two orders of magnitude, and resolution by at least one order of magnitude.

In reference device tests of the current system with the Keithley Model 2602 set at one NPLC, the resolution limited by noise was better than 250pA, or 5 nanosiemens at 50mV. The accuracy for low-conductance devices was better than these values. For low-resistance devices, the accuracy was determined by cables and relay contact resistances and was approximately 1.5 ohms.

These characteristics, which are sufficient in this case, can be improved if necessary. For example, low-resistance accuracy can be greatly improved by using four-wire connections, which would require a special fixture and twice as many cables. Accuracy can also be improved significantly by adding a short to the test fixture and programming automatic correction in the script. Shielding fixture connection cables and the fixture itself could further decrease the noise. Triax connections may be used for very low-conductance devices.

Conclusions

Zephyr has now been in use for almost two years, and Nanomix has found it to be a highly scalable and flexible test system. Currently, there are multiple installations in various configurations. As indicated in the text, this system is used for packaged device testing. However, support for wafer-level tests and autoprober control is planned for future versions. This will replace older software and allow an upgrade of the autoprober measurement system from the Keithley Model 2400s to Model 2602, and further decrease test cycle time.

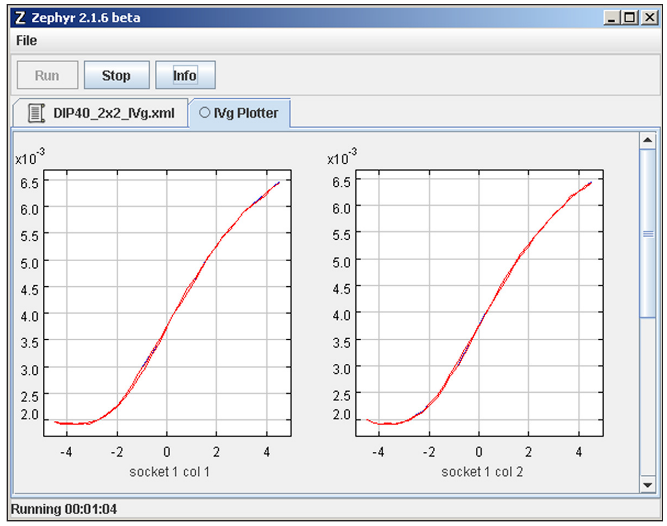

Figure 4. Zephyr application screen showing the real-time I-V_g plotter output component tab in the foreground.

In February of 2007, the Nanomix Quality Management System received ISO 9001:2000 and ISO 13485:2003 certification. Relying on simple test fixture design, standard measurement equipment, source-controlled measurement software and scripts contributed to the validation of the Zephyr Measurement System and overall certification of the company.

Although the system is used extensively, it is still a work in progress. The Zephyr software is planned to be released soon as an open source project at http://zephyr.sourceforge.net. All those interested in this project are encouraged to use and contribute to it.

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About the Author

Sergei Skarupo is the Senior Software Engineer at Nanomix, Inc. He studied electrical engineering at the Kiev Polytechnic Institute. As a software engineer, he has been involved in development and support of various medical, Internet, analysis, lab measurement, and other applications. He is the lead designer of Zephyr software and is currently working on expanding the capabilities of that and several other software applications, as well as on development of the respiratory monitoring devices. 5980 Horton Street, Ste 600 , Emeryville, CA 94608, 510-428-5337, e-mail: sskarupo@nano.com.

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