Nano Testing for Future Electronics

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The engineering of functional systems at the molecular scale, nanotechnology refers to the applied part of nanoscience which typically includes the engineering to control, manipulate and structure matter at an atomically small scale. Nanotechnology as a field is nothing less than diverse, ranging from extensions of conventional device physics to new approaches based upon molecular self-assembly, from developing new materials with dimensions on the nanoscale to direct control of matter on the atomic scale.

The global market for nanotechnology was valued at about $20.1 billion in 2011, and reached about $20.7 billion in 2012, according to data from BCC Research. Total sales of nanotechnology are expected to reach $48.9 billion in 2017, after increasing at a five-year compound annual growth rate (CAGR) of 18.7%. Nanomaterials, according to the data, had sales of about $15.9 billion in 2012, and $37.3 billion in 2017.

The amount of money involved makes it clear that nanotechnology device development is an important goal. With this growing interest in nanotechnology and transition from a passive to active field, equipment is needed to test these devices before entering the marketplace. Testing is crucial. The challenge in nano research and developing technologies at the nano level focuses around signal levels. The physical size, or lack thereof, presents a low-level measurement challenge, and researchers want low-noise, high-quality, high-sensitivity test equipment for accurate measurements.

A large segment of development in nanotechnology is the electronics industry, which is increasingly designing materials and structures that are truly nanoscale. Source measurement units (SMU) are universal tools for doing voltage current characterization measurements, which is the starting point for any new material, including semiconductor type or nanoelectronic materials. SMUs, manufactured by companies such as Keithley Instruments and Agilent Technologies, are instruments that meet the low-noise, high-quality, high-sensitivity test needs for nanotechnology research.

Testing nanoelectronics for space

Nanomaterials, including semiconductor nanowires, graphene, carbon nanotubes and fullerenes, are in the forefront of a revolution in speedy electronics and other strong, lightweight structures. At Michigan State Univ., researchers are investigating an additional benefit of nanomaterials, increased radiation resiliency. This benefit could be conferred by more widely separated quantized electronic energy levels.

Through a series of beam time grants, Virginia Ayres, assoc. prof. of electrical and computer engineering at Michigan State Univ., and her collaborators utilize beams at the National Superconducting Cyclotron Laboratory to investigate interactions with nanomaterials and nanocircuits. These are primary beams of fully stripped relativistic heavy ions that are well calibrated in terms of their energies and particles per area. The energies accurately simulate the heavy ion component of space radiation, which is especially destructive for current state-of-the-art electronics. For its research, the team fabricates circuits using nanowires to simulate an ordinary transistor and investigates how they react in the beam environment. However, the transistor is not quite like the one that is in a computer, as it has a nano field-effect transistor design that relies on contact barrier manipulation instead of channel modulation to achieve on/off transistor functionality.

“We are the first group to run such nanocircuits under heavy ion radiation that simulates space radiation for fairly lengthy periods of time; up to a half an hour per circuit,” says Ayres. “And through our electronic performance testing, we have received information about what happens within the nanocircuit at the contact barriers and in the oxide layer as well as within the nanowire itself under bombardment conditions that simulate what electronics in space go through.”

To run such experiments, ordinary garden-variety test equipment won’t help. Because the researchers are running a field-effect transistor, they must source voltages to the circuit and the gate of the transistor. Most importantly, they must run these experiments in real time and record the currents that are coming back under conditions that can produce unexpected results, where the accuracy of every data point counts.

“Under the conditions that I work with, what I care about is low noise and steady sourcing, as well as picoamp-resolution current measurement capability,” says Ayres. “But I also need the ability to measure currents that are higher than that.”

The team studies transients and effects that could involve currents, which on the nanocircuit scale are quite large, around tens or hundreds of microamps. The team settled on Keithley’s Model 4200-SCS semiconductor parameter analyzer, a compact integrated system of multiple SMUs that both sources voltage and measures current.

As the challenge is to record everything that happens in real time, Ayres says the most challenging part in her research has been in connecting the pieces of the circuit all the way down to the nanoscale level. “Access to the laboratory’s test vault was not designed for the kind of test circuits we are doing, but we were able to design a test circuit that is embedded within what are commonly called ordinary dual in-line package—something you would plug into a breadboard,” says Ayres.

Electron beam lithography is used to “wire” the nano- field-effect transistor that uses a semiconductor nanowire less than 100 nm in diameter to micron-scale photo-lithographically fabricated contact pads. These are connected by ultrasonic wedge wire bonding to the individual pins of the dual in-line package. The package is then carefully impedance-matched and connected to the SMUs of the 4200-SCS. “Making these connections all the way to the nanoscale level requires care at every step,” says Ayres, “and Keithley SMUs help aid in this challenge by providing a low noise, high fidelity test platform.”

Developing measurement infrastructure

The development of measurement infrastructure that enables research into novel nanoelectronic devices and supports their manufacture is of great importance to the electronics industry. In the Nanoelectronics Group at NIST, research is conducted to advance the electrical and optical measurement science infrastructure necessary for innovation in future nanoelectronic and thin-film devices, and their component materials. While most researchers are trying to invent the next widget, the NIST team is inventing the measurement infrastructure that will allow the scientific community to research that widget and allow companies to manufacture it and monitor the process.

The team looks to correlate the final electrical properties of a device and the underlying physical properties of the materials and interfaces that comprise the devices. “We really want to know why the device behaves the way it does, and that will allow users to better optimize it,” says Dr. Curt Richter, group leader of NIST’s Nanoelectronics Group. “So we want to relate the intrinsic properties of the materials that comprise the device to the full device properties.”

The challenge in terms of characterizing nanoelectronics isn’t necessarily the electronic instrumentation. In fact, the biggest challenge is how to couple the electronics to a nanoscale device or nanoscale component materials. As a result, there is a great deal of effort in designing and creating specific test structures on chips that allow researchers to couple into the nanoscale structure, and also to properly extract the intrinsic properties of the materials.

“When you are talking about something that isn’t very many atoms across, it is difficult to couple this big piece of electronic equipment down to a nanometer scale device,” says Richter. “And we have the same challenge optically. It is the issue of how to couple the optics to devices that are much smaller than the wavelength of the optics and how to extract information from them.”

Noise is always an issue in nanoscale test measurements, and it is becoming more of an issue in nanoscale devices where single defects can cause large noise issues. To test nanoelectronics, researchers want low-noise equipment so they are actually looking at the intrinsic noise of the device.

Among the principal electrical measurements the team uses are low-current, low-noise direct current (DC) measurements to parametrically characterize nanodevices. In addition to carrying out a range of low-noise, low-current electrical measurements, they are pioneering unique methods that combine both electrical and optical measurements. By working with individual SMUs, the team gets the flexibility necessary for their measurement setups.

“We typically use SMUs in our research,” says Richter. “If we have a multi-terminal device, such as a transistor, we will have a stack of SMUs, one for each terminal. We will have an SMU for the source, another for the drain, yet another for the gate, and one for the substrate, if a substrate contact is possible.”

Often researchers simply use voltage sources for selected nanoelectronics measurements (such as applying a gate bias), but in research level devices, the NIST team finds it important to have a measurement of both the applied voltage and the current from a given contact. In nanoelectronic devices, even for contacts designed not to leak, there usually is some current leakage, and researchers must measure it. The NIST team finds that SMUs are a more powerful tool than just individual voltage sources or current sources, as researchers can have both numbers at every part of their device.

“It’s more powerful and it allows us to interpret our data better,” says Richter. “And when it comes down to understanding and interpreting the results of our measurements, it is important to truly understanding whether your measurement is correct or not. Complete information allows you to more easily debug the measurement system and optimize it when you are setting it up.”

Future nanoelectronics

When working with future nanoelectronics and nanomaterials related to electronics, it is important to measure their unique properties. Using a Keithley Model 4200-SCS SMU-based test system, a team of researchers led by Dr. Kang Wang, Distinguished Professor and Raytheon Professor at Univ. of California, Los Angeles, measures source currents and voltages as low as tens of nanovolts at different temperatures, from room temperature all the way down to 50 mK. The team also performs very sensitive experiments at the National High Magnetic Field Facilities at Tallahassee, Fla., as well as with many collaborators internationally. The team measures different properties in two areas: nanoscale magnetic materials and topological insulators. It is the team’s goal to help the semiconductor industry go beyond 2020, and as such researchers need to explore new materials, nanoscale devices and how those devices work together in a system. The years of scaled CMOS technology may slowly come to an end due to the increase of energy dissipation in continuing the scaling, among others.

To measure nanoscale magnetism, the team measures spin current and sees how the electron spin can torque a magnetic moment, making a switch or a memory device no less than transfer torque memory. The team also works on electric field control of metallic magnetism. “It used to be that you would have to pass current through a magnet in order to do something with magnetic properties," says Wang. "But now, in the last few years, one can use a low voltage to change or control the magnetic properties. This is a breakthrough as it enables the potential memory of many orders of magnitude in reduction of dissipation energy."

When performing measurements, the team looks to minimize noise, or to achieve a high-sensitivity measurement at the smallest signal at different temperatures, as affected by other parameters. But by doing so they must be able to detect the desired signal, which is often buried in the noise. Sometimes, capacitance problems of cables are important and so the team must minimize the length of the cables and put the SMU as close to the sample as possible to alleviate the challenge.

Integration time is also very important to the team as it affects the total acquisition time. "Obviously you want to get a lot of data as fast as possible as you can't afford to spend a whole day just on getting one data point," says Wang. So the team needs acquisition speed, but the noise becomes a factor. Coupled together, the team needs to understand the noise, acquisition time and how the sensitivity is related to the source temperature and resistance.

Where Wang's research direction will eventually lead to is a million-dollar question. "It will continue to be in nanoscale electronics and nanostructure devices and materials; however, as our research continues, it may develop into a new paradigm of the brain-like devices and systems, or referred to as neuromorphic devices and nanosystems," says Wang. As devices get smaller and smaller, the interactions of those devices and how to sort out those interactions and smaller signal effects is where Wang's research finds its home.