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WHITE PAPER

Non-destructive Hall measurement environment facilitates novel device R&D

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Hall measurement systems are invaluable research tools for electronic materials and device characterization, providing quantitative data on carrier type, concentration, and mobility, as well as measurements related to resistivity, *I–V* curves, and other useful information. Understanding the underlying transport mechanisms of a material provides insights into its potential for use in new device applications.

Sample preparation for Hall measurements can be a time-consuming process. Conventional Hall measurement techniques generally require a small, dedicated sample with hard-wired electrical connections. This typically entails destruction of at least part of the sample and prevents repeated measurement of the same structure at different stages of device fabrication. In addition, while Hall systems generally offer measurement at a range of temperatures, their sample environments may not be ideally suited to materials that react quickly in atmosphere. In these cases, a different measurement platform is indicated.

Recognizing the need for non-destructive testing of wafer-scale materials, and with an eye toward providing improved environmental control for Hall measurements, Lake Shore has been working to integrate its vertical field-equipped cryogenic probe station platform with its Hall measurement instrumentation. This type of configuration makes for easier sample preparation and enables measuring of multiple structures in a single experimental session, as well as providing the ability to repeat measurements of Hall structures at progressive steps in the formation of devices co-located on the wafer.

Since carrier densities and transport mechanisms change with temperature in very specific ways, a range of Hall measurements starting at cryogenic temperatures are typically taken. Cryogen-free refrigeration and advancements in thermally compliant cryogenic probe design now enable automated variable temperature measurement runs while ensuring consistent contact quality. The probe station's tightly controlled vacuum environment accommodates materials that are reactive to air and those that require initial warming to drive out moisture. Finally, the probe station platform allows the researcher to easily reconfigure the attached instrumentation in order to make any other (non-Hall) electrical measurements required while the sample is still in the environment.

Easy sample handling

In conventional Hall measurement systems, sample preparation usually involves dicing a wafer into appropriately sized pieces and attaching wires by soldering, wire bonding, or, if all else fails, conductive epoxies. Soldering and wire bonding can be especially tricky with high-bandgap materials like SiC, while sensitive materials like organics can be damaged in the process. The use of a probe station platform eliminates the need to attach wires to the sample, significantly speeding sample prep and avoiding any damage to the sample. Instead, four or six micromanipulated probes are individually positioned as needed once the sample has been installed in the sample chamber.

The probe station provides a large sample stage that can accommodate multiple individual samples and is ideal for handling wafer-scale samples (in the case of the Lake Shore system, up to 51 mm in diameter). In the typical case where the device developer has patterned a variety of different test structures on the same wafer, the repositionable probes can shift from measuring one Hall structure to the next without affecting the overall sample environment. Transport characteristics can be quickly confirmed at the current stage of device development, and the wafer remains intact for subsequent processing steps (see Figure 1).

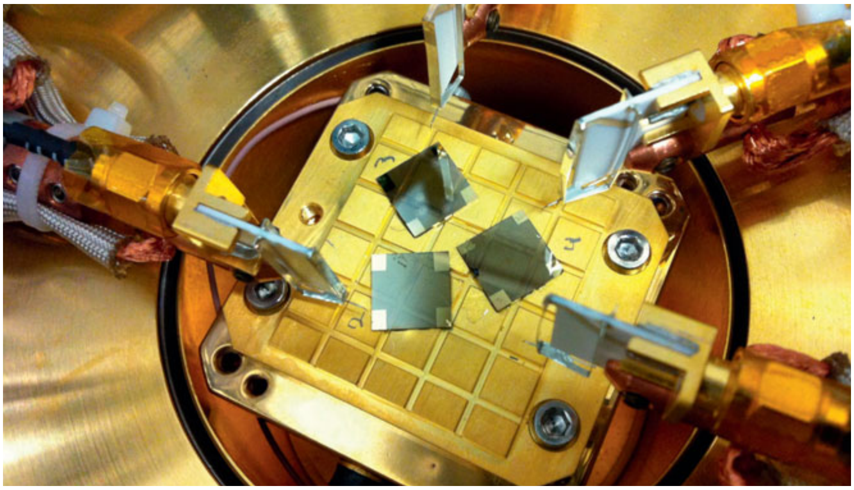

Figure 1. A probe station sample stage can hold multiple samples, and repositionable probes simplify the process of measuring multiple Hall structures.

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A controlled environment

The probe station environment has tightly controlled parameters of vacuum, temperature, and magnetic field. A vacuum chamber, capable of sustaining pressures of 10^{-5} Torr and below, offers an advantage over conventional Hall measurement systems. Materials can be warmed in vacuum prior to measurement to drive out any residual moisture. Reactive materials can be measured in an environment that minimizes atmospheric exposure and resulting contaminations. Cryo-pumping techniques resulting from creating temperature differentials within the probe station drive contaminants from the sample space.

Variable temperature Hall measurement experiments are commonly used to reveal specific changes in transport characteristics. At cryogenic levels, carriers can be identified by their activation energies and provide clues to predominant transport mechanisms in materials. Hall measurement at these low temperatures is especially helpful in understanding the frequency response of the material or device. A cryogen-free refrigerator and cryogenic temperature controller ensure reliable closed-loop management of sample temperature over a broad range. For best thermal accuracy, probes and probe arms need to be thermally anchored to the sample stage, while use of radiation shielding reduces the amount of stray thermal energy impacting the sample.

Specialized, thermally compliant probes (such as Lake Shore's ZN50R-CVT) enable automated measurement over a wide temperature range. These probes are designed to maintain consistent contact with the material despite thermal expansion of the sample, eliminating the need to manually adjust position as experiment temperature rises and allowing for continuous variable temperature Hall measurements.

The high field superconducting magnet of the probe station (capable of around 2 T) facilitates advanced quantitative carrier analysis. For material with a mobility of 5000 $cm^2/(Vs)$ or higher, the presence of multiple carrier species in a sample can be determined. This is particularly useful for resolving individual carrier mobilities and densities in quantum wells and high-electron-mobility transistors (HEMTs).

By employing specialized software, such as the Lake Shore QMSA package, properties of majority carriers and other carrier mechanisms of a multicarrier sample material can be accurately identified and analyzed. The software can segregate the mobility spectrum for each carrier species in multilayer structures, and is particularly useful where it is necessary to obtain magnetic field- and temperature-dependent information for the separate carriers within a material. Hall coefficient and resistivity can be measured at different magnetic field levels and then correlated to a unique mobility spectrum. This multicarrier measurement analysis can be very helpful for troubleshooting designs, for instance, materials fabricated in R&D environments and to evaluate deposition products in quality control applications. Without a QMSA type of analysis, researchers are left with performing fixed-field Hall measurements that extract carrier properties in bulk, limiting their utility as an analysis tool.

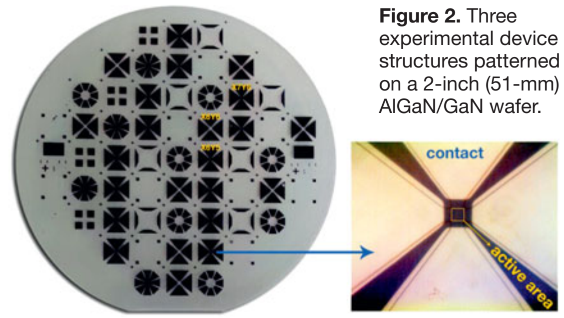

Figure 2. Three experimental device structures patterned on a 2-inch (51-mm) AlGaN/GaN wafer.

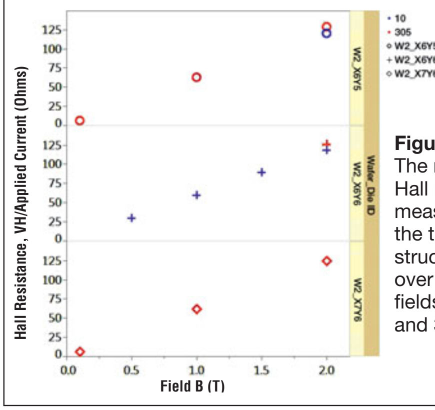

Figure 3. The results of Hall resistance measurements of the three device structures taken over a range of fields at 10 K and 305 K.

Example research application

Favorable results have been achieved in testing of HEMT devices. Considered highly promising for high-speed communications devices and applications, HEMT devices use a lattice-matched heterojunction between donor and acceptor compound semiconductors. Early HEMTs were largely fabricated using GaAs (gallium arsenide) substrates; advancing research is pursuing other semiconductor materials. In operation, the HEMT forms a two-dimensional electron gas (2DEG) layer that contains the mobile charge carriers and provides conduction for the device. With the aid of QMSA analysis, researchers have found a number of interesting properties for these devices, including significant differences in carrier mobility with temperature change and unexpected differences in majority and minority carrier mobility. Hall coefficient and resistivity have been measured at different magnetic fields up to 2 T and then correlated to a unique mobility spectrum.

For its test application, Lake Shore used its Model 8425 DC Hall measurement system with integrated cryogenic probe station to measure 2DEG materials on a 2-inch (51-mm) AlGaN/GaN patterned wafer (Figure 2). In this application, temperature-dependent behaviors were measured on three various sized device structures patterned on the same wafer, with Hall resistance as a function of applied field measured during one experimental session (no QMSA analysis was used for this 2DEG characterization). Figure 3 shows the results of the Hall resistance measurements over a range of fields for the devices. Blue data points show measurements at 10 K, while red data points show measurements at 305 K. The linear behavior of the Hall resistance versus field indicates that this material may have possible future use in sensing applications. □

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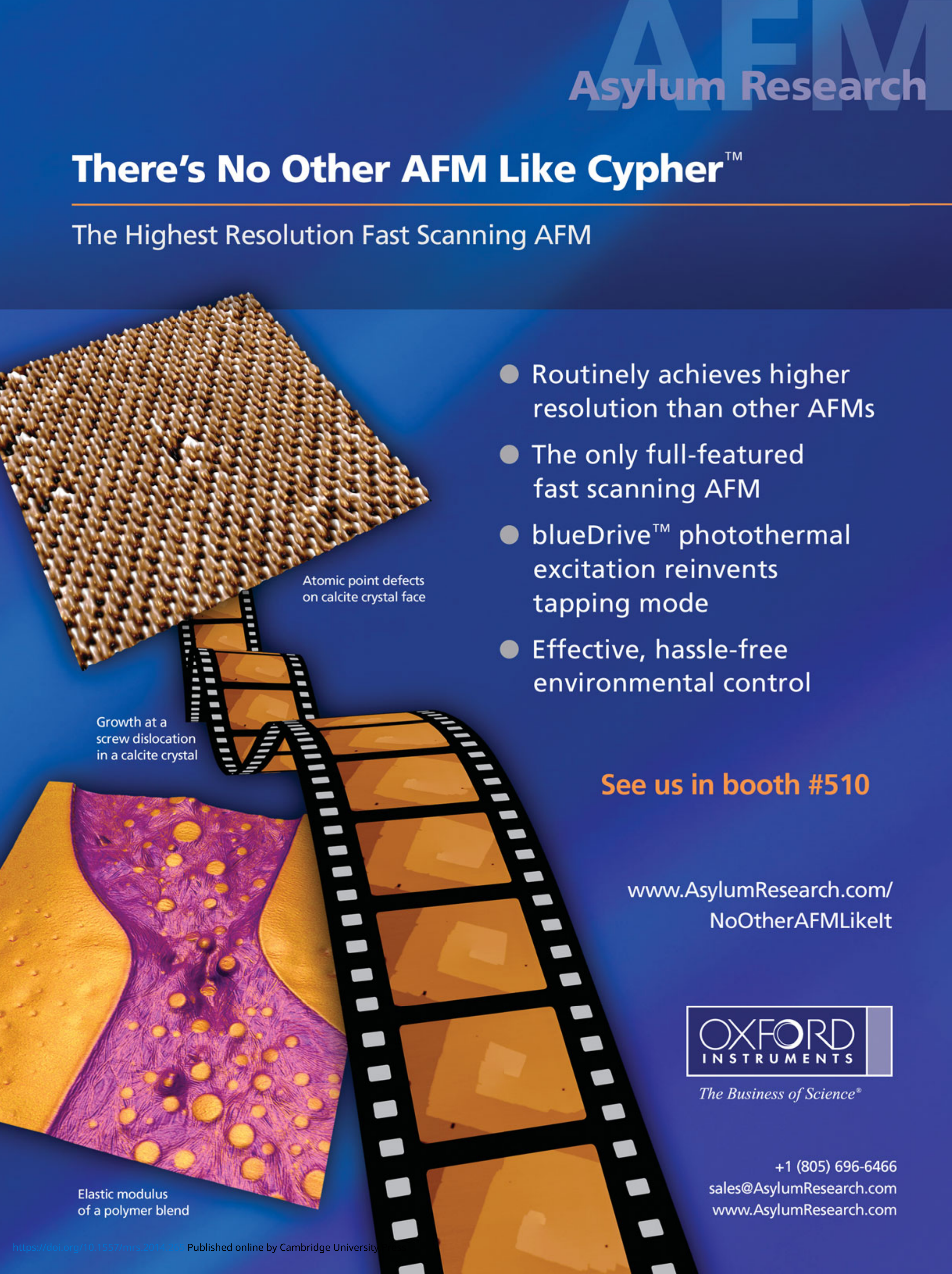

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