Nondestructive Variable Temperature Materials Characterization for Semiconductor Research

With the continuing demand for higher computing performance, significant research is being aimed at characterizing novel materials for semiconductor use. Characterization of carriers as well as unwanted impurities in materials will continue to be an important step in the development of next-generation semiconductor devices. Various measurement techniques for Hall conductivity, carrier concentration, and mobility measurements, as well as Raman and x-ray spectroscopy, help to understand these materials. However, many commercially available technologies offer limited utility because they do not account for material responses as a function of temperature, or their magnetic fields are fixed, so it is impossible to differentiate mobilities and carriers.

Many measurement platforms also do not allow for noninvasive characterization of wafer-scale materials or they require labor-intensive bonding and packaging, making them impractical in current semiconductor materials testing environments. New approaches to nondestructive measurement for early stage, temperature dependent materials characterization are needed.

Temperature and early-stage materials characterization

Analyzing at low temperatures is a common method for isolating specific material phenomena. Characterizing at variable temperatures can also yield important insights into underlying conductivity mechanisms. In particular, the cryogenic environment reduces the inherent noise of electronic materials, lessening its impact on measurements. Certain carrier transport properties are easier to detect at low temperatures as well.

In some semiconductor materials, free carriers can be “frozen out” at cryogenic temperatures while the intrinsic carrier concentration or activation energy can be determined from the temperature dependency of the carrier density. Knowing the material’s mobility and temperature dependence can also help identify concentrations of impurities and gauge potential saturation transconductance.

Continuous wave terahertz

For more than 20 years, researchers have used terahertz frequency spectroscopy for materials characterization. The energy of terahertz waves is low enough to couple to the free carrier motion in semiconductors. As a noncontact, quasi-optical technique, terahertz spectroscopy is ideal for characterizing the conductivity of bulk semiconductors, ultrathin epitaxial layers, and buried thin films in pre-device stage heterostructures.

Terahertz spectroscopy at cryogenic temperatures can expose properties not apparent at room temperature and allows carrier concentration and semiconductor mobility to be tuned. However, most commercially available THz systems lack the necessary cryogenic and magnetic environments required for targeted semiconductor materials research, and if they do have them, THz energy is usually generated outside the testing environment. With these optical cryostat-based systems, THz beams must pass through windows—reducing signal power and causing spectral distortion—and their optics are difficult to align, which can lead to repeatability issues.

However, all of this is changing with improvements in how THz energy is generated and applied to materials under test. Newer con-
Continuous wave (CW)-based THz spectroscopy systems place the optics inside the cryostat. CW-THz spectroscopy uses two distributive feedback lasers tuned to slightly different wavelengths. Mixing the light emitted by the lasers results in an intensity-modulated (with 0.2 to 1.5 THz modulation frequency) IR light source that is transmitted to fiber-coupled photomixer devices. Each photomixer contains a planar, broadband antenna patterned on an ultrafast photoconductive substrate and centered on a silicon dome lens. THz generation and detection is achieved with the IR light by modulating the conductance of the antenna with an integrated, semiconducting photoswitch. The cryogenically compatible THz emitters and detectors are contained in an insert that fits the narrow bore of a high-field magnet, in close proximity to tested materials. THz transmission spectra are acquired at temperatures from 5 to 300 K, and up to a 9 T magnetic field. Dome-shaped emitters and detectors are mounted on thermally stable, optical stages that maintain THz alignment while measurements are taken at variable temperatures.

**Case study: CW-THz magneto-spectroscopy**

A researcher exploring new growth methods for a particular semiconductor already employs a host of conventional optical spectroscopy techniques to characterize materials, such as x-ray spectroscopy to gather information about crystal structure and UV-visible technologies to determine the band gap. THz characterization can augment the information derived by conventional optical measurements, particularly when trying to determine temperature-dependent conductivity.

Traditionally, by calculating the transmission and reflection from each interface of a wafer, the THz-frequency, complex-valued refractive index is extracted from the THz spectra of the material. The contribution of free carriers to the permittivity is then modeled with a simple but fairly accurate Drude model. However, in the absence of a magnetic field, extracting the electronic material parameters requires knowledge of both carrier type and band mass from other techniques.

Stimulating semiconductor materials at THz frequencies and in high field can reveal interesting properties that other techniques miss. For example, with InSb and other high-mobility materials, CW-THz magneto-spectroscopy can determine the cyclotron resonance condition in these materials. Band mass can be directly measured by mapping out the field dependence of the cyclotron resonance frequency shift while the resonance linewidth can provide an estimate of material mobility.

For many larger band mass carriers, where a THz-frequency cyclotron resonance condition cannot be easily met, THz magneto-spectroscopy can still reveal carrier type and mobility. Owing in part to the circularly polarized nature of CW-THz emission, electrons and holes behave differently in a magnetic field and result in an asymmetric (with field) permittivity of the material. As shown in Fig. 2, P-type silicon exhibits strong absorption in the THz band at negative fields and enhanced transmission at positive fields. Conversely, N-type materials show strong absorption at positive fields. Efforts are currently underway to develop a mobility extraction algorithm from field dependent CW-THz measurements.

**Moving to the device stage**

Nondestructive cryogenic testing can also play an important role later in the development cycle, such as when it is necessary to perform measurements on fabricated, on-wafer samples. Once research advances to the point of device construction, a cryogenic probe station enables multiple contact points for device biasing and signal measurement on a flexible, variable-temperature platform. The task of dicing fully fabricated wafers and bonding wire to the dissected piece for device characterization is no longer required, as in a conventional cryostat. Repositionable, micro-manipulated probes are used instead, eliminating the need for large, fixed-wire contacts and enabling multi-
ple structures to be sampled on a wafer. In a probe station chamber, test structures can be tens of microns in size (such as for the high-speed pHEMT device measurement application described later in this article) or up to tens of millimeters in size for measuring Hall structures.

Measuring devices in the vacuum chamber of a probe station offer advantages as well. The variability in measurements caused by humidity, condensation, and other environmental factors can be eliminated. Electronic properties of some materials, such as organic semiconductors, can be significantly affected by surface contamination, and when measured under ambient conditions, electrochemical leakage currents can obscure sensitive current measurements. However, once the device is evacuated in a probe station, measurement conditions can be restored. Additional options are available in cryogenic probe stations for materials and devices where surface contamination must be avoided. For example, high-vacuum options are used to reduce the base pressure in the chamber; in the advanced stations, the sample stage can be maintained near room temperature during cool down of the radiation shields so that residual gases are cryopumped away from the sample space.

Also, when used in conjunction with sophisticated mobility spectrum analysis software tools, vertical magnetic field probe stations can be valuable for studying multilayer or multi-carrier semiconductor Hall samples (such as multiply doped materials and heterostructures) by segregating the mobility spectrum for each carrier species. By identifying individual carriers, users can verify doping effectiveness, correct for unwanted impurities during growth, and control quality during various manufacturing stages.

**Case study: Cryogenic probing identifies off-state breakdown**

Off-state breakdowns in pseudomorphic high-electron-mobility transistor (pHEMT) devices result from the complex interplay of material properties and device geometry. Because gate-drain breakdown limits the maximum power handling capability of these devices, this effect has been a topic of interest since the inception of pHEMT device architectures. Several physical mechanisms for the breakdown have been proposed and each has distinct temperature dependencies that can be used to discern the dominant mechanism in a given device architecture. Variable temperature, on-wafer, transport measurements were performed on a commercially available GaAs pHEMT used in RF applications.

Three distinct gate leakage regimes are identified in the temperature-dependent gate current for fixed source-gate voltages in Fig. 3. Above 210 K, the nonmonotonic temperature dependence of the gate current is indicative of a thermionic field emission mechanism. Below 150 K, the gate current is independent of temperature with a source-gate voltage dependence, which suggests the barrier conduction is dominated by tunneling transport. Between 150 and 210 K, the observed temperature dependence of the gate current indicates an intermediate breakdown mechanism, perhaps defect-assisted tunneling.

**Conclusion**

Semiconductor research is becoming increasingly important to the development of higher-performing electronics and computing technologies. Terahertz spectroscopy bypasses the limitations of other characterization techniques by enabling nondestructive measurement under variable temperature and high magnetic field conditions. It is in these environments that researchers can learn the most about novel materials.

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