Groundbreaking Achievements in Over-Temperature mmW Broadband Characterization of Semiconductor Devices

As semiconductor technology continues to push boundaries, the demand for accurate and reliable over-temperature characterization techniques becomes paramount. In this technical paper, we delve into the challenges of over-temperature characterization and present innovative solutions that address these challenges. Leveraging the capabilities of Anritsu VectorStar ME7838G 70 kHz–220 GHz broadband VNA, we have developed cutting-edge hardware and software solutions for on-wafer broadband characterization [1]. This paper showcases our industry-first 220 GHz TITAN™ Probe and it highlights the capabilities of SENTIO® and QAlibria® prober control and calibration software, respectively. The integrated solution enabled automated on-wafer system calibration with NIST multiline TRL and MPI's TMRR calibration and precise broadband device characterization over a wide range of temperatures. Through detailed examples of InP HBT device under test (DUT) characteristics, we demonstrate the effectiveness and reliability of our solutions.

Fig. 1: Anritsu VectorStar ME7838G 70 kHz–220 GHz broadband VNA integrated with the MPA TS3500-SE system.

CHALLENGES OF OVER-TEMPERATURE CHARACTERIZATION

Over-temperature characterization in semiconductor testing presents significant challenges. Probes and system drift can impact measurement accuracy, necessitating careful monitoring and compensation. Specialized calibration techniques are required to address temperature-induced variations, ensuring precise calibration across the temperature range. Calibration verification becomes even more crucial to maintain measurement integrity. Innovative hardware design, calibration techniques, and verification protocols are necessary to overcome these challenges and achieve accurate characterization.

Probes and system drift

RF probes can experience drift due to temperature expansion. As the temperature changes, the materials composing the probe can expand or contract, causing mechanical stress and altering the probe's electrical properties. This drift can lead to measurement inaccuracies and inconsistent results. Furthermore, it's important to note that the measurement system can also be affected by drift, not just due to temperature but also overall stability. Factors such as the stability of the vector network analyzer (VNA) and the phase stability of the RF cables used in the setup can contribute to measurement drift. Ensuring proper calibration and monitoring of these components is essential to mitigate the impact of drift and maintain accurate RF measurements.

Calibration at each temperature point

A crucial technique we employ is calibrating at each temperature point, and our calibration software effectively manages this process. The software provides an intuitive step-by-step guide that assists the user in executing a meticulous calibration procedure. Users can follow the software's instructions to take the necessary steps for a robust and accurate calibration. This approach guarantees that the calibration accounts for temperature-induced variations and enables precise measurements at different temperature points, enhancing the reliability and consistency of our characterization process.

Calibration verification

Equally crucial is the availability of tools that facilitate calibration verification. To maintain confidence in the calibration process, we have developed advanced verification tools that enable users to assess their calibration accuracy. These tools comprehensively analyze and compare measured results against reference standards or known values, allowing engineers to validate the calibration's effectiveness. By incorporating rigorous data verification into our workflow, we ensure the calibration's integrity and enhance our measurements' reliability, ultimately leading to more accurate and meaningful characterization data in the shortest time possible.

ISOTHERMAL BROADBAND MEASUREMENTS AND CALIBRATION

Broadband measurements and calibration are critical in semiconductor testing. They comprehensively explore device behavior and verify device model parameters in a wide frequency range, ensuring the final product performance optimization and specification at its true operation frequencies.

Accurate calibration corrects systematic errors, enhancing measurement data accuracy. It ensures precise and repeatable data, supporting accurate data analysis and the right results interpretation.

The extraction of compact model parameters and the validation of IC designs require data acquisition over a wide temperature range, typically from -40 °C to +125 °C or even higher. This requirement adds another dimension to the complexity of characterizing broadband mmW devices. Advanced integrated probe systems and sophisticated RF calibration software that support advanced calibration techniques can greatly simplify this task.

The seamless integration of modern single-sweep broadband vector network analyzers, such as the Anritsu VectorStar ME7838G 70 kHz–220 GHz broadband VNA, with the MPI TS3500-SE probe system featuring the IceFree-Environment™ option, broadband TITAN™ Probes T220A, and SENTIO® embedded QAlibria® calibration software, along with automated probe-to-pad alignment, contact quality, data consistency, and calibration accuracy verification enables unattended broadband device characterization across the entire frequency and temperature ranges (Fig. 1).

IceFreeEnvironment™

MPI's IceFreeEnvironment™ is a ground-breaking feature that revolutionizes testing capabilities by enabling simultaneous testing with MicroPositioners and probe cards over an extensive temperature range. This innovative design offers significant advantages, including a shortened signal path, making it an ideal choice for demanding applications such as mmW (millimeter wave) and load-pull testing.

Thus, the RF probes directly mounted on the VNA frequency extenders can be used for over-temperature device characterization, including a negative temperature range with minimal insertion loss guaranteed and the maximal measurement dynamic range possible (Fig. 2). This feature especially benefits researchers and engineers working on advanced semiconductor technologies, where precise and reliable measurements at extreme temperatures are critical.

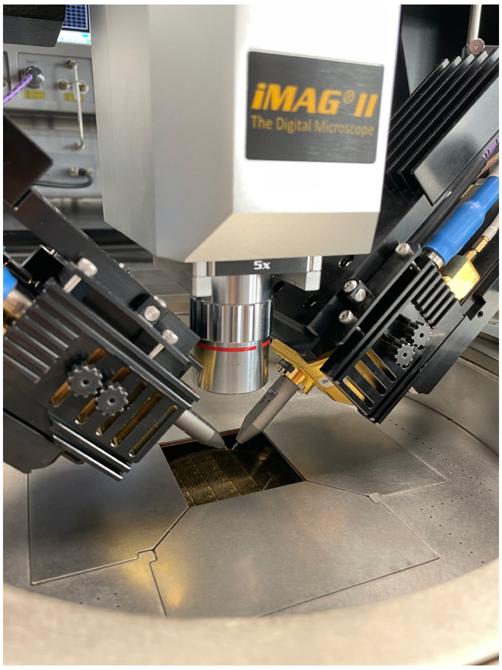

Fig. 2: MPI TITAN™ Probes T220A and the IceFreeEnvironment™ option.

Importance of the on-wafer calibration for broadband isothermal device characterization

Conventional device characterization campaigns are undertaken at frequencies below 110 GHz. The wafer-level measurement system is calibrated to the RF probe tip end using commercially-available calibration standards, such as MPI's AC-2 calibration substrate. A second-order error-correction step then follows the calibration procedure, the de-embedding of the device infrastructure parasitics, and the difference in the calibration and measurement environment.

As the measurement frequency increases, the probe-tip calibration and de-embedding errors increase. To address this issue, complex de-embedding methods must be employed with multiple steps and five or more de-embedding dummies [2]. Moreover, temperature-gradient calibration errors increase. These are the errors caused by the temperature differences of RF probes during the calibration step (standards are kept close to room temperature on a thermally-isolated AUX chuck) and on-wafer measurements of the DUT at its test temperature. The probe-tip calibration becomes impractical for mmWave device characterization beyond 110 GHz, particularly at typical extreme temperatures like -40 °C and +125 °C. The on-wafer calibration solves this challenge. It ensures that RF probe temperature remains unchanged between calibration and DUT measurement steps.

The key advantages of the on-wafer calibration approach are:
- Standards and the DUT are at the same temperature. Therefore, the temperature of the RF probes remains constant during calibration and measurements. As a result, the temperature gradient calibration residual errors are eliminated.
- Calibration standards and the DUT share the same interface and measurement environment. Thus, the calibration reference plane can be located at the DUT terminals, making the de-embedding step obsolete. The measurement accuracy of the DUT is drastically increased.

Custom calibration standards are specific to semiconductor technology, device type, and layout. Hence, calibration software should support simple and intuitive management of different calibration standards and their mechanical and electrical characteristics. QAlibria® standard database implements the xml file structure, open for easy editing and modification at any time. The SENTIO® Standards Navigator module makes navigation across the calibration chip as easy as ever (Fig. 3).

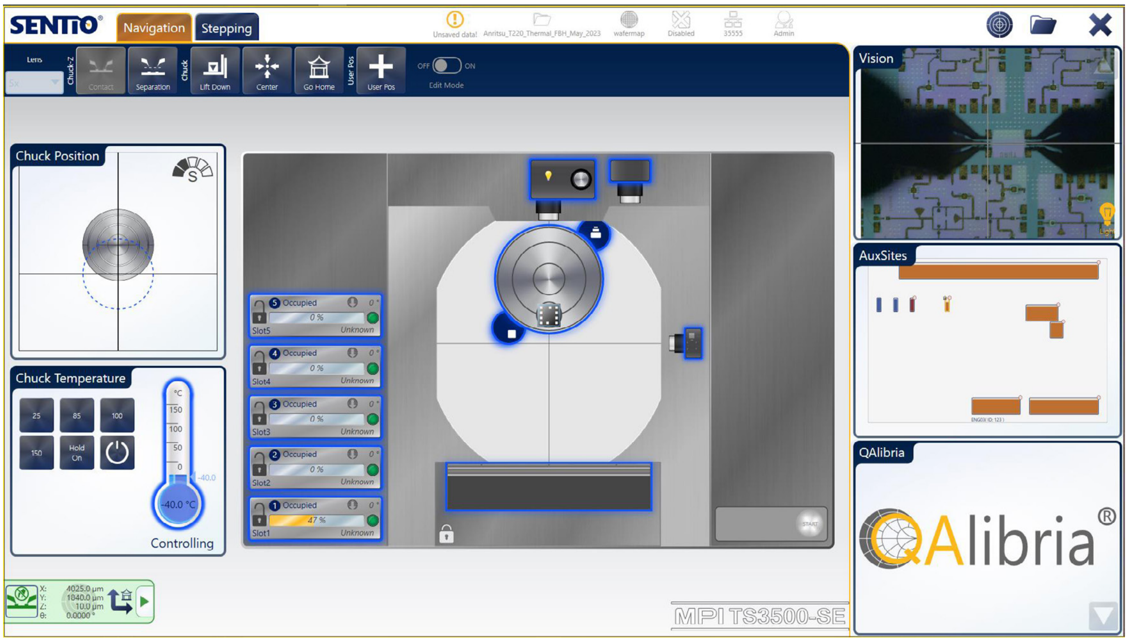

Fig. 3: SENTIO® Dashboard demonstrating the RF calibration configuration at -40 °C and with the on-wafer calibration standards.

ON-WAFER MTRL AND TMRR CALIBRATIONS

The NIST multiline TRL Calibration

The NIST multiline TRL calibration method is widely adopted by the industry for system calibration at mm-wafer and sub-THz frequency ranges. The key advantage of this algorithm over other methods is that the equivalent electrical models of calibration standards are not required. The NIST multiline TRL implemented in NIST StatistiCAL calibration software delivers the metrology-grated calibration and measurement results that can be used later the benchmarking. QAlibria® unique integration with NIST StatistiCAL engine enabled automated NIST mTRL system calibration in the lab environment [3].

Fig. 4: QAlibria® Dashboard configured for the NIST mTRL calibration with custom on-wafer standards.

As demonstrated in [4], the on-wafer NIST mTRL can be used successfully for system calibration over a wide frequency and temperature range with minimal effort. The experimental system was calibrated at each measurement temperature using the mTRL method and the microstrip transmission lines and highly-reflective elements (Open and Short) implemented in the InP HBT process (Fig. 4). Fig. 5 shows the propagation constant (the loss and the relative phase constant) extracted for the calibration transmission lines at the room temperature and the experiment's corner temperatures, -40 °C and +125 °C, respectively. The results ensure the accuracy and consistency of the calibration across the entire frequency and temperature ranges.

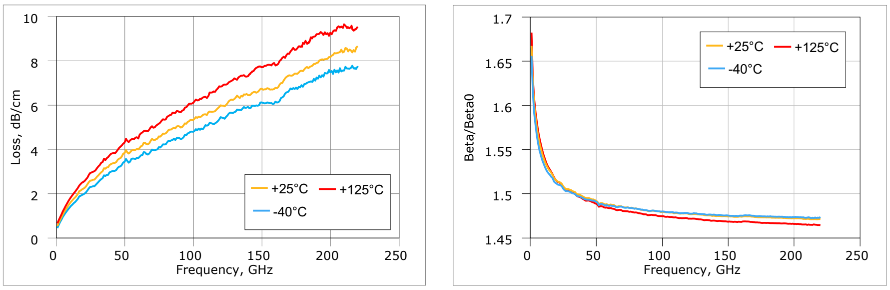

Fig. 5: The NIST mTRL calibration verification over the entire temperature range: extracted attenuation (left) and relative phase (right) constants of the transmission lines at -40 °C, +25 °C, and +125 °C.

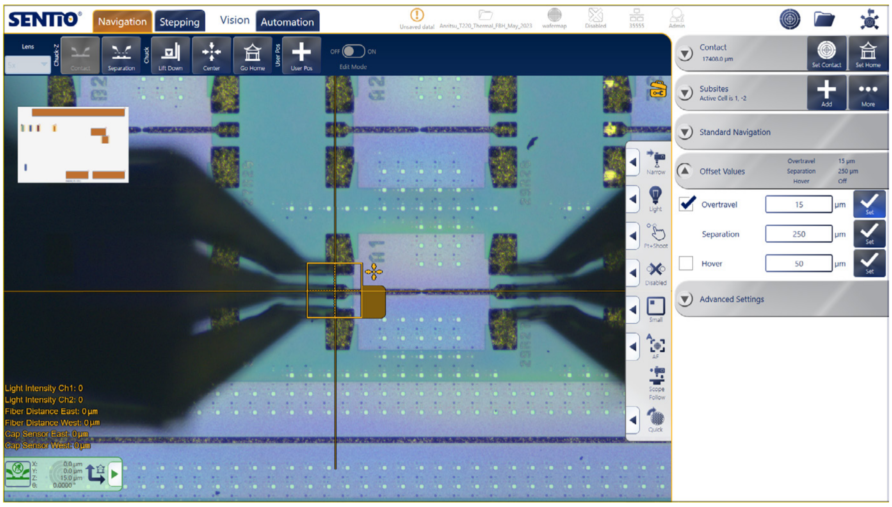

Fig. 6: TITAN™ Probes T220A in contact with the DUT, an InP HBT.

Example of the InP HBT Characterization

To demonstrate the calibration and measurement capabilities of the integrated system discussed above, a test transistor fabricated on an InP HBT process was used (Fig. 6). The device characteristics were evaluated at each temperature and under several bias conditions. First, the DUT was measured under „cold" operation mode, i.e., zero Volt bias at its base and collector. The DUT characteristics should remain unchanged across a wide temperature range under this operation mode. However, some minor variations of the DUT S-parameters observed during the experiment can be attributed to the impact of the temperature-dependent characteristics of the substrate dielectric (Fig. 7).

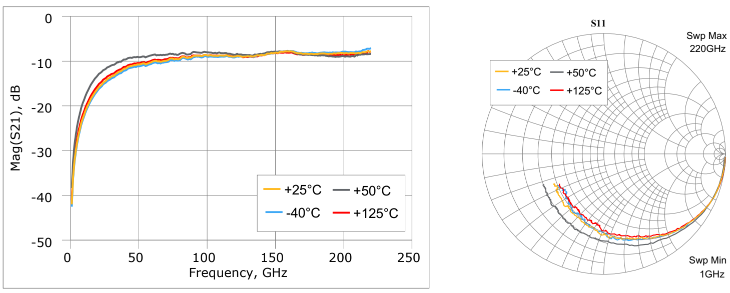

Fig. 7: Device measurement data acquired at -40 °C, +25 °C, +50 °C, and +125 °C in cold operation mode and corrected by the mTRL.

The operation mode (measurements under biased conditions) demonstrated a strong dependency of the device characteristics on the temperature, as expected. The Fig. 8 presents the magnitude of the S21 (left) and S12 (right) of the device measured at -40 °C, +25 °C, +50 °C, and +125 °C. The device was driven at different bias points to demonstrate that it can provide a comparable gain across the wide frequency and temperature ranges. It is important to note, that the recommended base plate temperature should not exceed +50 °C. Nevertheless, the +125 °C DUT data are presented to demonstrate the capability of the measurement system.

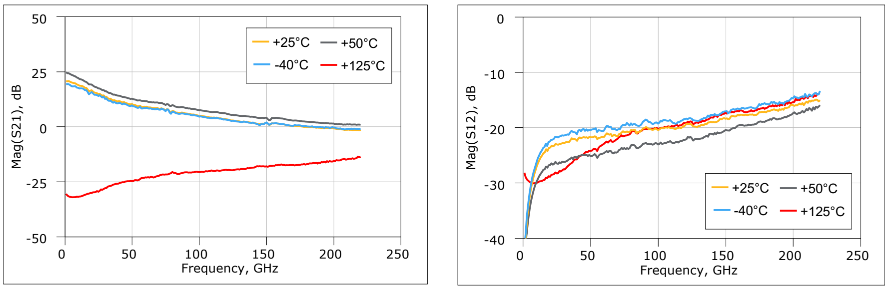

Fig. 8: Device measurement data acquired at -40 °C, +25 °C, +50 °C, and +125 °C under biased operation mode. Different bias voltages are used at different temperatures.

The TMRR Calibration

Typically, advanced probes systems used for unattended isothermal device characterization are equipped with programmable micro-positioners, such as TS3500-SE or TS2000-IFE and MPM80 from MPI Corporation, respectively. The mTRL calibration can be executed quickly and unattended. However, the mTRL calibration standards occupy the modeling chip's large real estate area, which might be unfavorable for several commercial semiconductor processes. TMRR calibration is a good alternative in such cases as it significantly reduces the space of the on-wafer calibration kit. In addition, it helps to complete the calibration process faster as only four standards have to be measured, and probe re-positioning is not required.

MPI's TMRR successfully calibrates the system at mmW frequencies even if the Load standard is asymmetrical and non-ideal (a typical scenario for the wafer-embedded resistors) [5]. With the precise characterization of the Load impedance, the TMRR-corrected data demonstrate a good agreement with the data, corrected by reference NIST mTRL (Fig. 9).

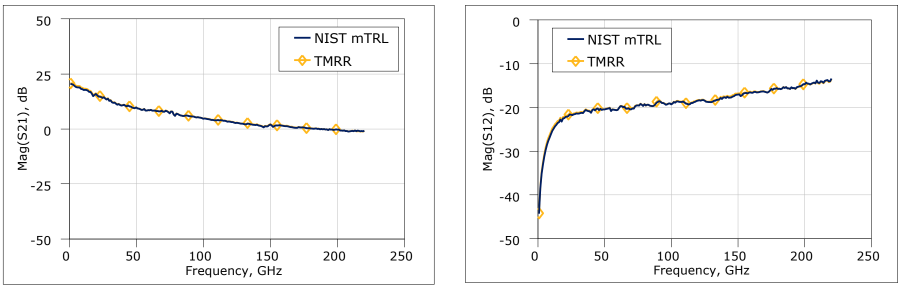

Fig. 9: Device measurement data acquired at -40 °C correct by the reference mTRL and the TMRR calibration methods.

CONCLUSION

The unique single-sweep broadband wafer-level measurement system demonstrated breakthrough calibration capabilities and unparallel measurement results of a test InP HBT in the frequency range from DC up to 220 GHz and the temperature range from -40 °C through +125 °C. The system integrates Anritsu VectorStar ME7838G 70 GHz–220 GHz broadband VNA with MPI TS3500-SE automated probe measurement system, 220 GHz TITAN™ Probe T220A, featuring on-wafer mTRL and TMRR calibration by SENTIO® and QAlibria® probe controlling and RF calibration software suits. Technology innovations implemented in the discussed system and software, RF calibration and measurement results set industry benchmarks for the next decade.

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