Accuracy and Repeatability of Automated Non-Contact Probes for On-wafer Characterization

Cosan Caglayan*, Georgios C. Trichopoulos, and Kubilay Sertel
The ElectroScience Laboratory, The Ohio State University
1330 Kinnear Rd, Columbus, OH 43212
E-mail: {caglayan.1, trichopoulos.1, sertel.1}@osu.edu

***Abstract*—We present significant performance improvements of non-contact probes for the mmW and sub-mmW device characterization. Repeatability and accuracy of the measurement setup is studied using an automated non-contact probe system and compared with conventional contact-probes. Owing to the planar, non-contact nature of the new setup, only 2-axis automated positioning is required, as compared to typical 3-axis manipulators, including precise contact-force control used in commercially available systems. We demonstrate repeatability studies for the 140-220 GHz band using a precision servo system, which can be fully automated using a software-controlled aligner for wafer-scale measurements. This fully-automated system also allows for periodic re-calibrations that are typically required for reliable sub-mmW measurements.**

I. Introduction

The demand on ultrafast integrated circuits (ICs) for the sub-millimeter wave region continues to grow as key applications, including medical and securit imaging, high-speed communications, spectroscopy, are being adopted in practice. In particular, effective development of sub-mmW devices (e.g. diodes, transistors, passives, mixers, etc. operating above 300 GHz) require reilable and accurate, on-wafer metrology approaches to enable device testing at the intended operation frequency. However, this has become a challenge due to much smaller feature sizes at such high frequencies. Currently, contact probes are the state of the art for testing at sub-mmW frequencies up to 1.1THz [1]. This technology is primarily based on aggresive scaling of coplanar contact probes that are widely used in microwaves. Scaling requirements of contact probes result in high manufacturing and repair costs, as well as extreme fragility. For example, if the contact force between the probe tip and test wafer is not controlled precisely, this can result in poor repeatability or fast deterioration of the probe tips [2]. In an effort to circumvent such fundamental drawbacks, we recently proposed non-contact probes based on

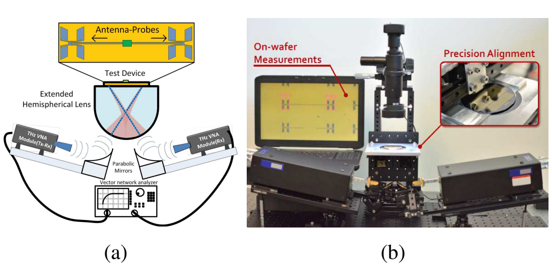


Fig. 1. (a) Illustration of the non-contact probe setup for on-wafer characterization in the THz and mmW bands (b) Photograph of the non-contact probe setup prototype

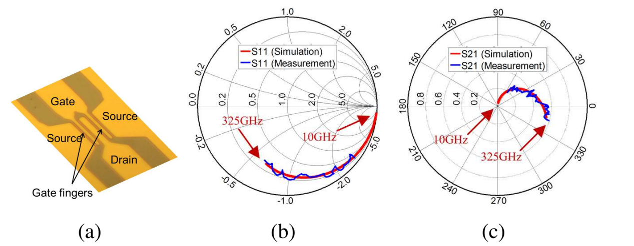


Fig. 2. Non-contact characterization of cold HEMT external parasitics: (a) Micrograph of the on-chip HEMT layout, (b) Smith Chart representation of the measured reflection (S_{11}) (c) Smith Chart representation of the measured transmission coefficient (S_{21})

efficient, quasi-optical coupling of the test signals into and out of the coplanar environment of the test device [3]. The concept is illustrated in Fig. 1(a) where a pair of diagonal horn antennas and a high-resistivity hemispherical Silicon lens is utilized for the quasi-optical wireless link. Effective coupling into the co-planar waveguide (CPW) environment is achieved using broadband, butterfly shaped double slot antennas integrated with the test device. These on-wafer antennas act as virtual probe tips and the measurement signals are quasi-optically focused onto the input and output ports of the device under test using Gaussian-like beams, as illustrated in Fig. 1(a).

A single test die or a complete test wafer can be characterized by placing the respective test structure over the hemispherical lens allowing for two isolated signal links between input and output ports. Since only the position of the test wafer is varied to collect the calibration and measurement data, the quasi-optical link is kept unchanged. As such, the non-contact test-bed can be automated easily by incorporating servo controlled precision manipulators instead of manual micromanipulators, as shown in Fig. 1(b). A relatively simple, software-controlled, commercially-available servos suffices to implement fully-automated measurements. In this work, we investigate the accuracy and repeatability of the non-contact test bed operated with servo-controlled manipulators and demonstrate the performance of fully-automated, on-wafer sub-mmW measurements for the first time.

II. Accuracy and Repeatability of Automated Non-Contact Probes

A key feature of non-contact probes is the effective radiative coupling of the test signal in and out of the device under test without resorting to electrical contact with the device wafer. To do so, we use wideband planar antennas integrated with the

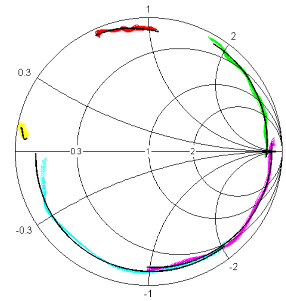
CPW device environment. As illustrated in Fig. 1(a), the incident beam radiated from the horn antenna at the to VNA input port is focused upon the "on-chip" probe antenna at the input port of CPW line. The hemispherical lens is used to achieve a tight focus (with approximately $\lambda/3$ in diameter) on the probe antenna. The test signal received by the on-chip antenna feeds the CPW environment of the test device. Subsequently, transmitted signal that may be attenuated or amplified by the test device is re-radiated out of the opposite on-chip antenna, enabling transmission parameters (S_{12}, S_{21}) measurements. Moreover, the signal reflected by the device couples back to the input port via the same optical path as the incident beam, enabling reflection (S_{11} and S_{22}) measurements. The incidence angle between optical axis and receiving/transmitting antenna beams is kept small, ensuring effective coupling into the planar antennas at broadside. We also note that relatively high refractive index of the high-resistivity silicon lens allows for much smaller on-wafer antenna sizes, minimizing chip space required to fabricate the virtual probe tips.

As an initial demonstration of the non-contact probe setup for device characterization, we recently studied a high electron mobility transistor (HEMT) layout to model its external parasitics. A SOLT-type on-wafer calibration is performed using well-known offset-short and thru standards. As seen in Fig. 2, there is excellent agreement between the full-wave simulations (HFSS) and non-contact measurements over the entire 90-325 GHz, spanning 3 successive waveguide bands. We note that the quasi-optical alignment of the non-contact probe setup was kept the same and only the frequency extenders were replaced to collect the data, illustrating the modularity of the proposed setup.

III. Repeatability Performance of Non-Contact Probes

Following the above initial demonstration, we next focus on identifying and quantifying the main sources of non-repeatable errors in the non-contact probing process. It is expected that the virtual probe tip placement under the beam spot will slightly differ for each of the calibration, as well as test device measurements. The placement relies on the precision of the alignment of the virtual probe tip under the microscope. Moreover, this probe alignment is also limited by the manipulating precision. As such, manual placement of the virtual probe tip under the marked beam spot better than 1 micron is not typically possible in both of the manipulation axes. However, this precision can be significantly improved using a software-controlled automated test-bed.

In addition, the instrument drift is another source of measurement error. Due to temperature sensitivity of the electronic components used in multipliers and mixers in VNA frequency extenders, they exhibit varying degrees of magnitude and phase drift over time, mainly due to fluctuations in the environment. For our current 2-port configuration in the WR 5.1 band, 3% of magnitude drift and $\pm 4^\circ$ phase drift over 1 hour time span is specified according to the manufacturer (Virginia Diodes Inc.).



(a)

Re-measured Calibration Standards (after initial calibration)	Worst Case Phase Dev. (deg)	Worst Case σ_{mag}/μ_{mag} (%)
Short(ref)	0.5270	1.1070
Short+62um	1.1269	1.0731
Short+124um	0.8022	0.9091
Short+186um	1.1079	0.7856
Short+248um	1.0455	1.6172

(b)

Fig. 3. 1-port repeatability of semi-automatic non-contact probe test bed in WR 5.1: (a) Smith Chart scatter plot (colored) of re-measured standards, black lines representing the ideal response. (b) Worst case phase and magnitude deviations tabulated for each standard.

The following experimental procedure was implemented to study the 1-port repeatability of our non-contact probe system: After an initial on-wafer calibration, the "standards" feature set, which consists of 5 offset short CPW lines and a through standard, was measured 25 times over a time span of 1.5 hours in typical laboratory conditions. The Smith Chart representation of the collected 25 measurements is shown in Fig. 3(a) as a scatter plot. As seen in Fig. 3(b), the worst case phase deviation is about 1° and the worst case magnitude deviation is 1.6%. According to manufacturer specifications, 1-port stability of the frequency extenders in the WR5.1 band is expected to be 5 times better than the 2-port configuration. As seen in this example, the measured repeatability of the non-contact probes, which is the combined effect two factors discussed above, is indeed very close to the instrument limitations. In a fully automated test-bed, repeatability is expected to further improve compared to semi-automatic version presented here.

IV. Conclusion

An initial study on reliability and repeatability of non-contact probes is presented. 1-port repeatability performance was calculated and shown to be very close to instrument drift, which demonstrates the effectiveness and ease of use of the non-contact probes. Owing to relatively simple, quasi-optical non-contact nature of this new approach, the non-contact probe system is cost-effective and free from fragility and wear/tear issues of traditional contact-based probes. Most importantly, they can be easily automated to enable large-scale wafer-level multi-port characterization of on-chip devices and ICs in the mmW and sub-mmW frequencies.

References

[1] M. Bauwens, N. Alijabbari, A. Lichtenberger, N. Barker, and R. Weikle, "A 1.1 THz micromachined on-wafer probe," *2014 IEEE MTT-S International Microwave Symposium (IMS)*, pp. 1–4, June 2014.

[2] T. Reck, L. Chen, C. Zhang, A. Arsenovic, C. Groppi, A. Lichtenberger, R. Weikle, and N. Barker, "Micromachined probes for submillimeter-wave on-wafer measurements part I: Mechanical design and characterization," *IEEE Transactions on Terahertz Science and Technology*, vol. 1, no. 2, pp. 349–356, November 2011.

[3] C. Caglayan, G. Trichopoulos, and K. Sertel, "Non-contact probes for on-wafer characterization of sub-millimeter-wave devices and integrated circuits," *IEEE Transactions on Microwave Theory and Techniques*, vol. PP, no. 99, pp. 1–11, 2014.