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RPPR Final Report
as of 05-Nov-2018

Agency Code:

Proposal Number: 66153ELST2 **Agreement Number: W911NF-15-C-0019**

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Report Date: 30-Aug-2017 Date Received: 03-Nov-2018
Final Report for Period Beginning 03-Nov-2014 and Ending 30-May-2017
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Begin Performance Period: 03-Nov-2014 **End Performance Period:** 30-May-2017
Report Term: 0-Other
Submitted By: Robert Weikle Email: weikle@dmprobes.com
Phone: (434) 996-01020000
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 2 **STEM Participants:** 4

Major Goals: The objective of this program was twofold: (1) to design, prototype, and commercialize differential on-wafer probes for characterizing devices in the 140—220 GHz and 220—320 GHz bands, and (2) to engineer the geometry and material of the micromachined probe tip to enable robust, consistent, and low-resistance electrical contact to devices with various contact pad metallizations, including gold and aluminum. Although the differential probe measurement capability described above currently did not exist above W-band (75—110 GHz)prior to this effort, it was widely recognized as a critical need for the future development of terahertz science and engineering.

The primary technical goals of this phase II STTR program were:
1) to exploit the flexibility afforded by micromachining fabrication technology to design and fabricate robust probe architectures suitable for measuring broad classes of devices that have non-standard geometries ? with primary focus on two-terminal and differential-mode devices that are not readily amenable to coplanar waveguide media. The frequency bands selected for the differential probe development were WR-5.1 (140—220 GHz) and WR-3.4 (220—320 GHz), corresponding to a region of the spectrum where there is significant current interest for engineering and scientific applications.

2) to apply lithographic processing and deposition techniques to realize engineered micromachined probe tips that retain their electrical and mechanical integrity over thousands of measurement cycles and consistently provide low-resistance (below 100 mOhms) contacts to devices and test structures utilizing various metallizations, such as gold and aluminum.

3) to evaluate and assess the robustness, reliability, and ultimate performance of differential on-wafer micromachined probes utilizing engineered contact tips.

Accomplishments: A pdf document detailing the accomplishments of this project has been uploaded as part of this final report.

Training Opportunities: This project involved a number of graduate research assistants pursuing research at the University of Virginia, in addition to research staff who received training in a variety of technical areas, including (1) microfabrication and micromachining, (2) electromagnetic simulation and design, (3) scattering parameter characterization and calibration, and (4) mechanical testing. The personnel receiving training under this effort (and supported by the program) are listed below:

1. Michel E. Cyberey, Ph.D. and principle scientist at the University of Virginia
2. Chunhu Zhang, Ph.D. student and graduate research assistant, Univ. of Virginia
3. Linli Xie, Ph.D. student and graduate research assistant, University of Virginia
4. Benjamin Gonzalez, M.S student and graduate researcher, Univ. of Virginia
5. Naser Alijabbari, Ph.D. student and graduate research assistant, Univ. of Virginia

Results Dissemination: The accomplishments achieved under support of this program have been disseminated through the technical literature, including IEEE symposia proceedings and technical journals. In addition, differential probes developed under support of this program are being prepared for delivery to Teledyne Scientific, Inc. where they will be employed to characterize amplifiers and other IC's being implemented with Teledyne's InP HBT process.

A list of publications resulting from this work are listed below:

D.R. Daughton, M. Bauwens, J. Bluestein, E. de Rijk, M. Favre, A. Lichtenberger, N.S. Barker, R.M. Weikle, J.L. Hesler, C. Rowland, E. Bryerton, D. McLean, and S. Yano, "Cryogenic temperature, 2-port, on-wafer characterization at WR-5.1 frequencies," 2016 IEEE International Microwave Symposium Proceedings, San Francisco, CA, 3 pages, May 2016.

R.M. Weikle, II, C. Zhang, S. Hawasli, S. Nadri, L. Xie, N. Scott Barker and A.W. Lichtenberger, "Terahertz Diode Arrays and Differential Probes based on Heterogeneous Integration and Silicon Micromachining ," (invited) 12th Internat. Conf. on Device Packaging, Proceedings, International Microelectronics Assembly and Packaging Society (IMAPS), Scottsdale, AZ, 4 pages, March 2016.

C. Zhang, M.F Bauwens, M. Cyberey, L. Xie, N.S. Barker, R.M. Weikle, II, and A.W. Lichtenberger, "A Micromachined Differential Probe for On-Wafer Measurements in the WM-1295 (140-220 GHz) Band," 2017 IEEE International Microwave Symposium Proceedings, Honolulu, HI, pp. 1088-1090, June 2017.

B.D. Gonzalez, M.F. Bauwens, C. Zhang, A.W. Lichtenberger, N.S. Barker, and R.M. Weikle, II, "A 0 - 40 GHz On-Wafer Probe With Replaceable Micromachined Silicon Tip," IEEE Microwave and Wireless Components Lett., vol. 26, no. 2, pp. 110-112, February 2016.

C. Zhang, M.F. Bauwens, N. Scott Barker, R. M. Weikle, II, A.W. Lichtenberger " A W-band micromachined on-wafer probe with integrated balun for characterization of differential circuits," IEEE Trans. Microwave Theory and Tech., vol. 64, no. 5, pp. 1585-1593, May 2016.

N.S. Barker, M.F. Bauwens, A.W. Lichtenberger, and R.M. Weikle, II, "Silicon-on-insulator substrates as a micromachining platform for advanced THz circuits," (invited), Proceedings of the IEEE, Special Issue on Terahertz RF Electronics and System Integration, pp. 1105-1120, June 2017.

Honors and Awards: During the course of this project, a number of participants have received honors and awards that are attributable in part to the progress and results arising from the accomplishments achieved on this effort. These include

1. N. Scott Barker, elevated to Fellow of the IEEE (effective January 2018)

2. Robert M. Weikle, II, elevated to Fellow of the iEEE (effective January 2018)

3. Linli Xie (GRA supported in part by this project), IEEE Instrumentation and Measurement Society Graduate Fellowship. Awarded in 2017 for his work on integrating Schottky diode sensors into micromachined on-wafer probes.

Protocol Activity Status:

Technology Transfer: The two primary items to report for technology transfer are listed below:

1. A differential probe for the WR-5.1 band is being prepared for delivery to Teledyne Scientific, Inc. for use in the development and characterization of differential circuits, amplifiers and IC's using Teledyne's InP HBT process. The probe provides a means of direct measurement of these circuits that, otherwise, would be difficult to achieve and require valuable real estate to include an on-chip balun.

2. A patent is in the process of being filed on using planar Schottky diodes as a standard for on-wafer electronic calibration. A paper is also being prepared on this effort which aims to address issues with measurement repeatability associated with probe skating and placement. This issue is significant at submillimeter wavelengths where movement of a few microns can correspond to 10's of degrees in electrical length. Electronic calibration eliminates the requirement to move and reposition probes during calibration, thus eliminating a major source of measurement uncertainty. Although not a direct or explicit objective of this STTR contract, this effort grew out of that work and is a direct consequence of developing calibration procedures for characterizing differential on-wafer probes.

PARTICIPANTS:

Participant Type: PD/PI
Participant: Robert Mason Weikle II
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Co-Investigator
Participant: Nicholas Scott Barker
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Co PD/PI
Participant: Arthur Weston Lichtenberger
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N

Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Michael Eugene Cyberey
Person Months Worked: 9.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Chunhu Zhang
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Linli Xie
Person Months Worked: 9.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Staff Scientist (doctoral level)
Participant: Naser Alijabbari
Person Months Worked: 9.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Benjamin Gonzalez
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

RPPR Final Report
as of 05-Nov-2018

Final Report
STTR Contract: W911NF-15-C-0019

Name of Contractor:	Dominion Microprobes, Inc. 1027 Stonewood Dr, Charlottesville, VA 22911-5771
Project Title:	Micromachined Probes for Measurement and Characterization of Terahertz Materials and Devices
Proposal Numbers:	A2-5780
Contract Number:	W911NF-15-C-0019
Contract Line Item Numbers:	N/A (No-Cost Extension)
Contract Performance Period:	December 1, 2015 –April 30, 2017
Period of Performance;	December 1, 2016 – January 2, 2016
Total Contract Amount:	$943,911.49
Amount Paid by DFAS to date:	$943,911.49
Total Amount Expended to date:	$943,911.49
Number of Employees on Project:	2
Report Authors:	Robert M. Weikle, II and Matthew F. Bauwens Dominion Microprobes, Inc.

Work Completed for the Project:

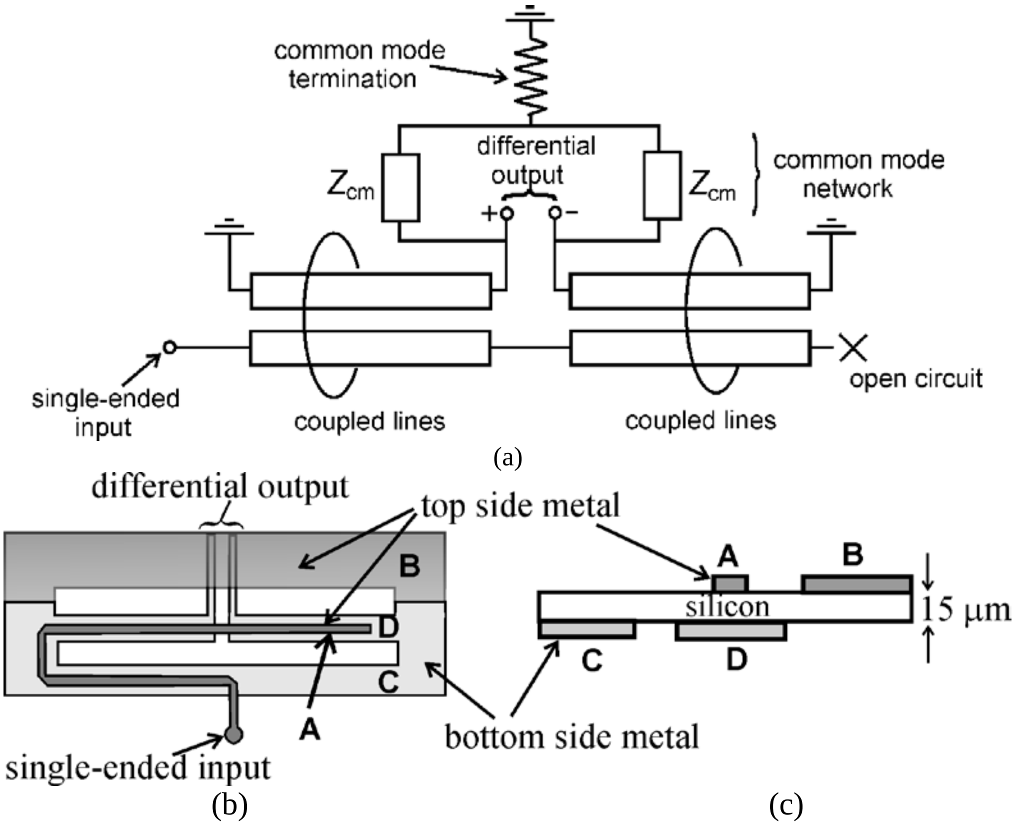
The design and processing of the differential probes supported under this contract were successfully completed, and a set of WR-3.4 and WR-5.1 micromachined differential on-wafer probes have been fabricated and tested. A summary of the design and characterization of these probes is provided below. In addition, progress on engineering the tips of the micromachined probes to improve robustness and reduce contract resistance when measuring devices with oxidized (aluminum) pads is reported.

Major Accomplishments

WR-5.1 (140—220 GHz) Differential Probe Design and Measurement Results

A. DESIGN AND LAYOUT

Design of the WR-5.1 (also designated as WM-1295) differential probe is based on a previous proof-of-concept implementation developed for W-band. The critical feature of the probe is an integrated Marchand balun that generates a differential output from a single-ended input. The fundamental balun architecture, shown in figure 1(a), incorporates an integrated thin film resistor to suppress any common mode signal that may be generated due to imbalances in the physical balun or the device under test.



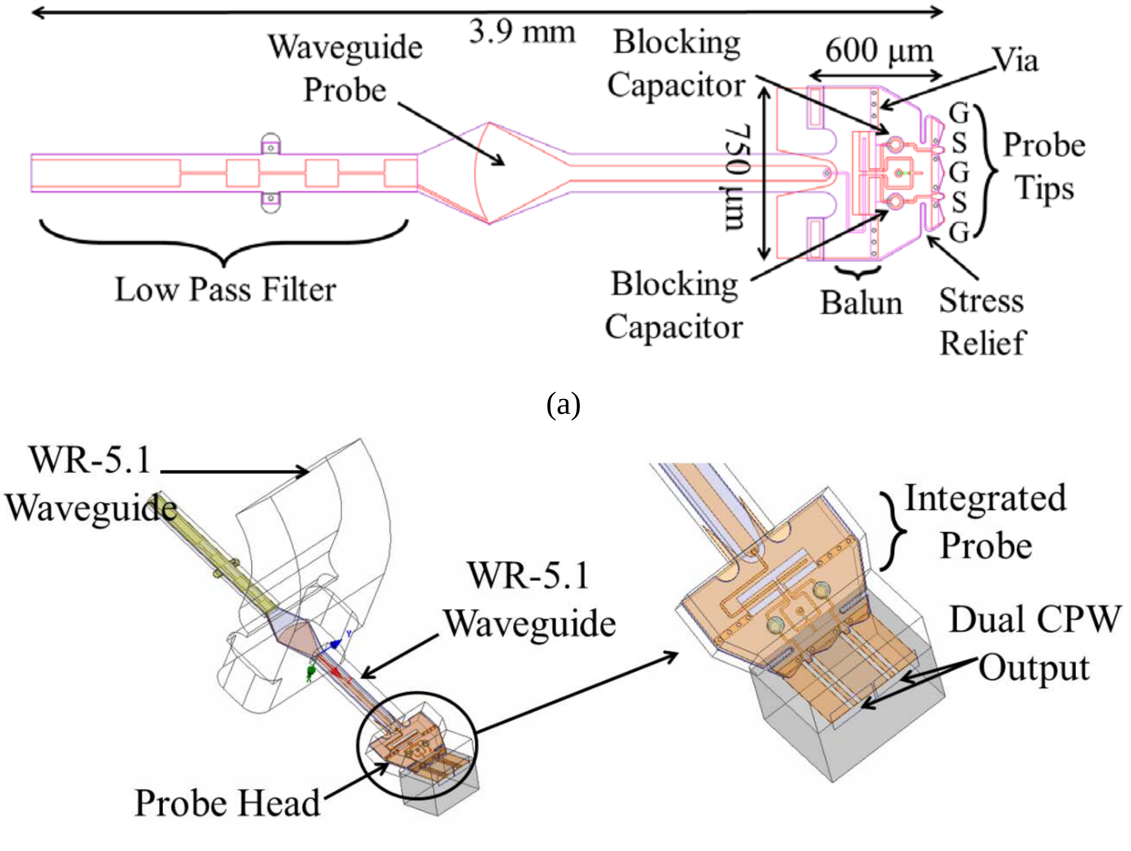
(a)

(b) (c)

Fig. 1.(a) Design of the probe Marchand balun with common mode termi-nation. (b) Top view and (c) side view of the asymmetrical balun layout.

To be compatible with the geometry of a micromachined on-wafer probe, an asymmetrical two-sided balun layout was developed for this work and its geometry is shown in figure 1(b). The single-ended microstrip input (metallization layer A) feeds a pair of coupled transmission lines (metallization layers C and D) that lie on the opposite side of the 15 μm thick silicon substrate. The output coupled lines feed the differential microstrip output (with ground plane metallization B). Figure 1(c) shows a side view of the balun metallization.

As the differential microstrip outputs of balun design are electrically connected to ground, a pair of dc blocking capacitors are included in the design to permit measurement of devices requiring bias. Following the blocking capacitors, the outputs are routed to the probe tips and the com-mon-mode termination network. The implemented probe design has a five-tip G-S-G-S-G version (S – "signal", G – "ground"). The probe tip ground contact is implemented using vias from the microstrip ground plane to the probe tip metallization.



(a)

(b)

Fig. 2. (a) Chip geometry of the differential probe with integrated balun network and ground-signal-ground-signal-ground tip configuration. (b) Finite element model for analyzing the RF performance of the probe

Figure 2(a) shows a rendering of the complete integrated probe chip layout. The chip is approximately 3.9 mm long with a pitch of 100 μm between contact tips. A waveguide probe couples the single-ended input from WM-1295 (WR-5.1) rectangular waveguide to a feed transmission line that exits the probe housing to the integrated balun. The probe head includes the balun circuitry and clamping metallization that supports the probe when it is mounted in the seam of the split-block waveguide housing. Electro-magnetic simulation of the probe chip utilizes the finite-element package HFSS using the model shown in figure 2(b). The geometry of the probe is adjusted to maximize return loss and coupling from the (single-ended) wave-guide port to differential outputs on dual 50 Ω coplanar transmission lines on a high-resistivity silicon substrate.

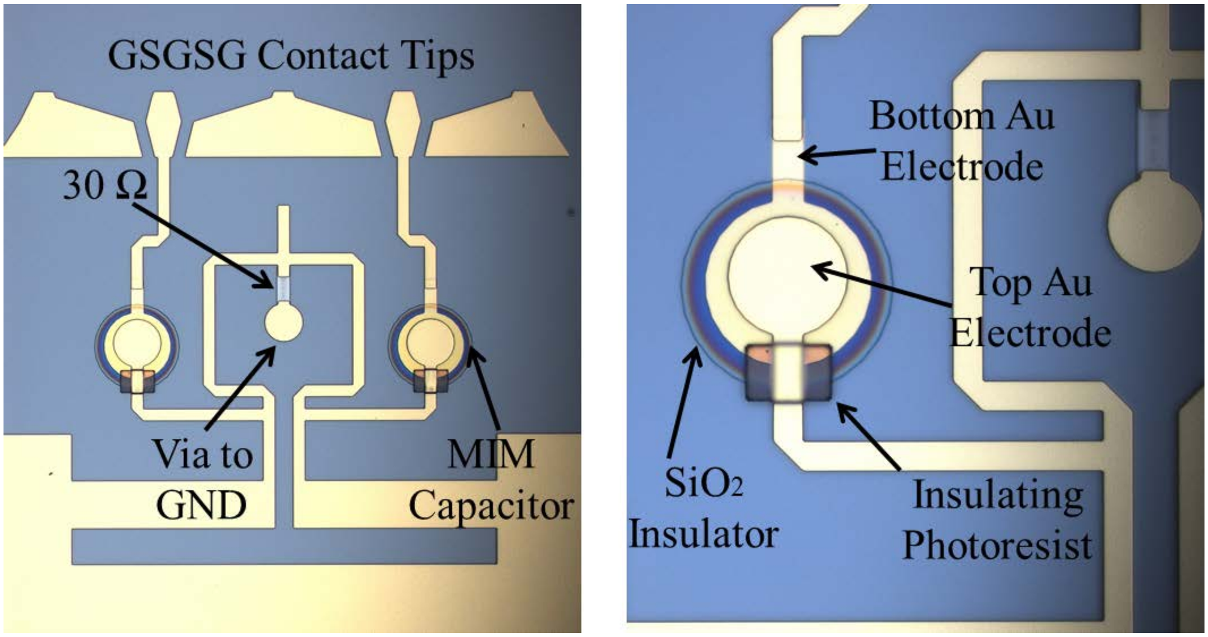
Mechanical performance of the probe head geometry is assessed using the ANSYS finite-element simulator to determine the deflection and planarity of the probe tips when subjected to a typical contact force during on-wafer measurement (10 mN per tip). Through these simulations, it was found that the relatively wide pitch between probes tips (100 μm) resulted in bowing of the probe head when the tips are under these typical loading conditions. This bowing brings the central tip contacts approximately 1 μm out of plane with respect to the outer contract tips, thus preventing simultaneous contact with all pads of the device-under-test. To mitigate this effect, stress-relief slots are incorporated into the probe head near the contact tips (noted in figure 2(a)). It was found through both simulation and experiment that these slots reduce bowing of the probe chip significantly and permit contact of DUT's with all probe tips without excess force or overdrive of the probe.

B. FABRICATION PROCESS

The probe chip fabrication is based on micromachining of a silicon-on-insulator (SOI) wafer with 15 μm thick Si "device" layer. Metallization and vias for the passive circuitry are formed with standard lithographic and etching processes documented in the technical literature. As the probe design utilizes circuitry lies on both sides of the probe chip, the thick "handle" silicon and buried oxide layer of the SOI wafer are removed after the initial topside processing is complete. For this step, the SOI wafer is mounted to a temporary carrier. Processing for the back-side circuitry is completed after the handle removal.

Details of the probe head geometry after metallization, formation of the thin film resistor and fabrication of the dc blocking capacitors are shown in figure 3(a). The common mode termination is realized as a titanium thin film resistor 8 μm wide by 24 μm long) using vacuum sputtering techniques. The integrated capacitors have a thin-film parallel-plate geometry with sputtered SiO2 (0.36 μm thick) as the insulating layer. The diameter of the top electrode (figure 3(b)) is 40 μm and the capacitance, extracted from on-wafer measurements of test structures with the same capacitor geometry, found to be 0.2 pF.

After formation of the probe circuitry shown in figure 3, the probe chip geometry is defined lithographically and formed using an "extents" reactive ion etch. The final step in the process is removal of the temporary carrier and re-lease of the individual probe chips. Images of the completed top and back sides of a five-tip differential probe chip are shown in figure 4.



(a) (b)

Fig. 3. (a) Image of the probe tip after finishing all front-side processes, showing the balun layout, common mode termination resistor, and dc blocking capacitors. (b) Image of the blocking capacitor geometry.

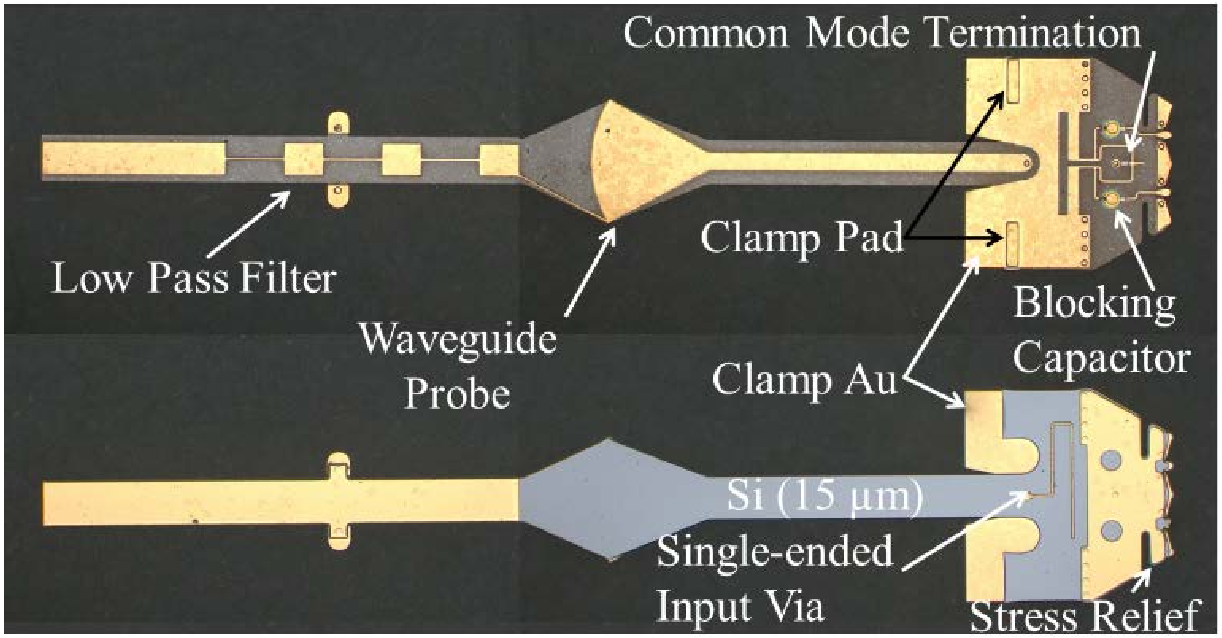


Fig. 4. Top side and bottom side geometry of the micromachined probe head. The probe design shown has a ground-signal-ground-signal-ground tip configuration.

C. CHARACTERIZATION

Performance of the WM-1295 differential probes is evaluated by extracting the mixed-mode scattering parameters from measurements of a set of on-wafer calibration standards, following the procedure detailed in previous reports. Each on-wafer calibration standard consists of dual coplanar short-circuited transmission lines with different offset delays. The dual delayed short-circuited lines can be viewed as a set of independent terminations at the balanced ports of the probe, and measurement of a minimum of seven standards permits the mixed mode scattering parameters of the probe to be found. A set of nine standards are measured to provide redundancy and improve estimation of the mixed-mode scattering parameters.

The differential probe scattering parameters, extracted from the measurement process described above are shown in figure 5. Insertion loss from the single-mode input to the differential output (Sds) is approximately 3 dB across the full WM-1295 band, while the return loss for the single-ended (Sss), differential (Sdd), and common-mode (Scc) signals are all better the 10 dB. Cross-coupling from the common to single-ended (Scs) and common-to differential (Scd) modes are near -30 dB over most of the band.

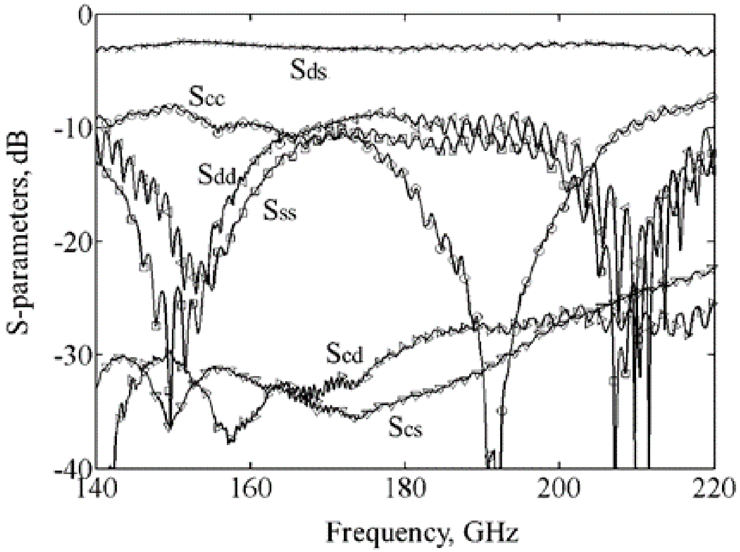


Fig. 5. Measured mixed-mode scattering parameters of the differential probe over the full WM-1295 frequency band.

D. SUMMARY

The design, fabrication, and characterization of an integrated micromachined probe for differential measurements in the 140—220 GHz frequency band has been accomplished for first time. Performance of the probe is comparable to that demonstrated for differential probes operating at lower frequency bands. In addition, implementation of the probe highlights the advantages of silicon as a suitable platform for heterogeneous integration of millimeter-wave circuits, devices, and micromachined components. The probe described above is currently being prepared for delivery to Teledyne Scientific, Inc. where it will be used to characterize a differential amplifier being developed with Teledyne's InP HBT process.

WR-3.4 (220—325 GHz) Differential Probe Design and Measurement Results

A. DESIGN AND LAYOUT

The WR-3.4 differential probe design is based on a scaling of the WR-5.1 design described above. These probes were fabricated on 15 μm silicon and images of the front and back sides of the final probe are shown in figure 6.

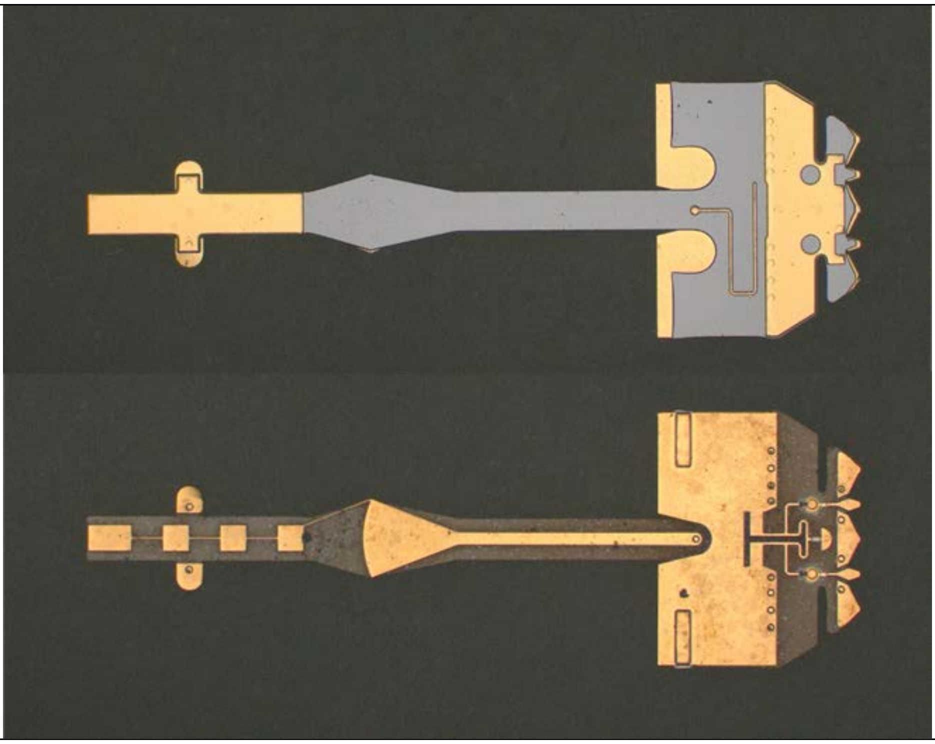
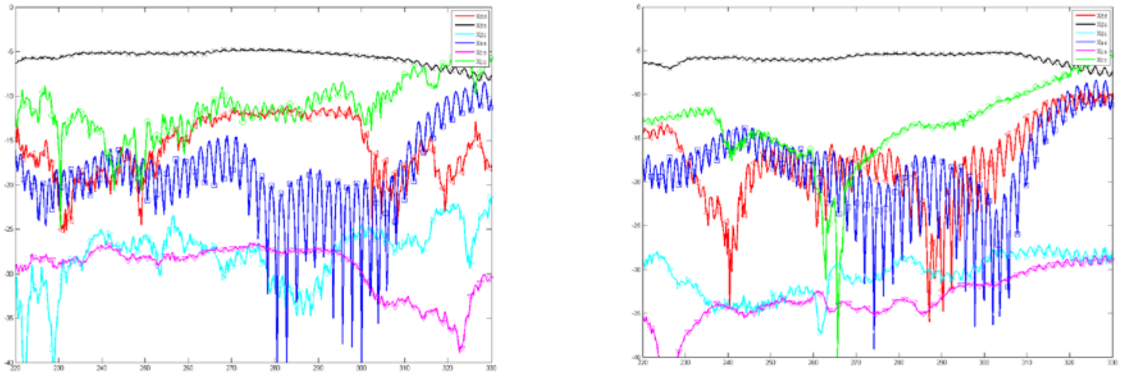


Fig. 6 The backside and frontside view of WR-3.4 differential probes with DC-blocking capacitors

B. CHARACTERIZATION

The scattering parameters obtained from the WR-3.4 differential probes (operating from 220 GHz to 325 GHz) are shown below in Figure 7. The probes exhibit a single-ended input to differential output insertion loss of approximately 6 dB, with a noticeable roll-off in performance above 300 GHz. The return loss for the differential and common mode reflections are generally better than 10 dB, with the single-ended input reflection better than 15 dB up to 300 GHz. Coupling between the single-ended input and common-mode output as well as the differential and common mode outputs are generally below -25 dB. Figure 7(a) shows the differential probe s-parameters extracted from measuring coplanar waveguide standards, while figure 7(b) shows the parameters extracted from microstrip transmission line standards. The two sets of extracted probe scattering parameters show comparable performance characteristics.



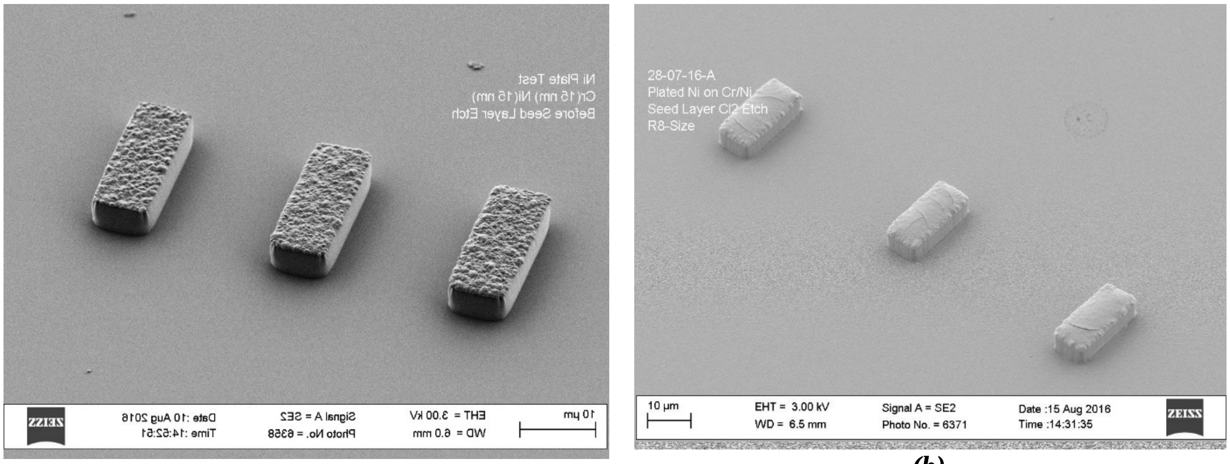
(a) (b)

Fig. 7. WR-3.4 differential probe scattering parameters extracted from measurement of (a) coplanar waveguide calibration standards, and (b) microstrip transmission line calibration standards.

Engineered Probe Tip Development

A second effort of this project was research on improving the contract resistance and robustness of the micromachined probe tips to permit low-resistance contact measurement on hard metal or oxidized pads, such as aluminum. To address this, we have formed up to 8-micron-wide Ni pillars on our standard Au plated probes, with the idea that the small pillars will break through the oxide on Al contact pads, allowing DC-biasing of active devices using aluminum metallization (and similar to the technique used by the Cascade Infinity probe). To evaluate the quality of the contact, We have probed an Al surface and measured the contact resistance of the tips. The 8 micron wide tips provide an order of magnitude better performance in terms of DC contact resistance compared to the nickel plated tips of a standard micromachined probe. However, these tips would eventually delaminate from the probe after a few contacts.

In addition, we developed a standardized testing procedure to evaluate the adhesion of Ni pillars plated on a substrate without need for the entire probe fabrication process. We first form the Ni pillars on a substrate (with seed layer/plated Au) through electroplating. This results in a substrate with Ni pillars on the surface (figure 8). We load this substrate into a probe station, and use a standard 'Ni-coated-tip' probe to repeatedly land on top of the plated Ni pillars. Using the computer controlled probe station, we can use a constant overtravel distance across different samples, the same as used when probing devices with the micromachined probe., This test roughly simulates the forces the Ni pillars must withstand during probing. With this process we can quickly evaluate the adhesion of our Ni pillars.



(a) ***(b)***

Fig. 8. (a) Nickel test pillars prior to the chlorine-based reactive ion etch. (b) SEM image of the pillars after the etch, showing rounding of the sharp corners and small cracks on the surface.

A number of processing approaches for defining robust Ni pillars on Si substrates such that when a contract force is applied to plastically deform the pillars, the maximum adhesion stress is not exceeded and the pillars do not delaminate from the substrate, have been investigated. Work continues on this effort at Dominion Microprobes and focuses on process development to integrate the nickel pillars into the standard probe fabrication process to improve robustness and reduce the contact resistance of micromachined probes when contacting hard or oxidized metal device pads.

As of the completion of this project, our process allows Ni pillars to be formed on Cr/Ni seed layers and we can form Au plated circuity on Cr/Ni seed layers. However, there still remains the question to how to remove the Cr/Ni seed layer. Commercially available Ni wet etches remove the Ni pillars and argon sputter etches have too slow an etch rate, at least with the conditions explored thus far in the process.

Removal of the seed Cr/Ni layer can be done with a chlorine (Cl) based RIE, however, this raises a number of issues. Cl etches Si, and the etch rate across a 2" wafer is generally not uniform. The perimeter generally etches more quickly, leading to the Si on the perimeter being exposed to the Cl plasma. We continue to work on characterizing the etch rates of Si in our standard etch processes to evaluate this approach. One concept that is being pursued is to stop on the Cr layer after etching the Ni seed layer in the RIE. If this is possible, we can try using a Cr wet etch to finish the etch and prevent the Si substrate from 'seeing' the Cl plasma. However, we do not yet know if a Cr wet etch will also remove the Ni pillars. The Cr wet etch chemistry does not etch Ni, but it is possible that it may undercut the 8-micron-wide pillars

The process described above continues to be developed, tested and evaluated with the aim of developing a final, robust process for incorporating hard-nickel pillars onto our probe contact tips (thus allowing the probes to be used for measuring devices with aluminum and other oxidized metal contacts).

Name of Contractor: Dominion MicroProbes, Inc.
1027 Stonewood Dr.
Charlottesville, VA 22911-5771

Project Title: Submillimeter-wave Load-Pull Measurement Systems

Proposal Number: A12a-T022

Contract Number: W911NF-15-C-0019

Contract Line Item Number: N/A (No Cost Extension)

Contract Performance Period: December 1, 2015 –April 30, 2017

Period of Performance; December 1, 2016 – January 2, 2016

Total Contract Amount: $943,911.49

Amount Paid by DFAS to date: $943,911.49

Total Amount Expended to date: $943,911.49

Number of Employees on Project: 2

Report Authors: N. Scott Barker and Matthew F. Bauwens
Dominion MicroProbes, Inc.

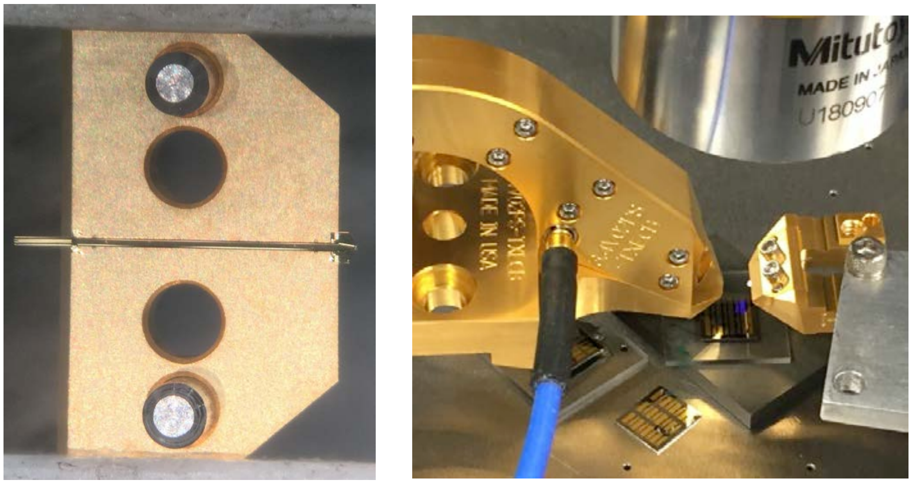
Work Completed and Scheduled for Project:

This project seeks to develop two load-pull measurement tools: 1) a passive load-pull measurement system for the WR-10 (75 – 110 GHz) and WR-3.4 (220 – 325 GHz) waveguide bands, and 2) an active load-pull measurement system that controls the impedance at the fundamental frequency up to 90 GHz as well as the impedance at the 2nd and 3rd harmonics (to 180 GHz and 270 GHz respectively). Over the past month, progress has been made in assembly of the active probe.

Summary of Results:

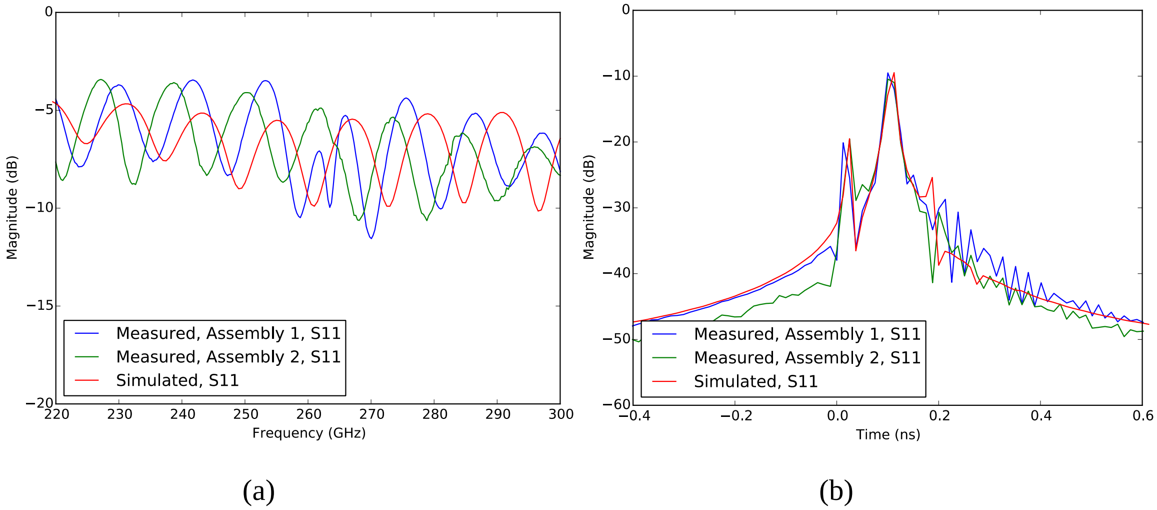
The micromachined probe chip and housing for this project were completed and are shown in figure 9. Figure 9(a) shows the micromachined silicon chip mounted into the split-block probe housing. The chip emerges from the probe housing near the bottom of the micrograph and terminates in 50 µm pitch GSG contacts. Near the top, the chip emerges from the housing and terminates in 100 µm pitch GSG beamleads for contacting the active InP chip.

Due to the beamlead output of the probe, it was not possible to directly characterize the S-parameters of the assembly. However, some information about performance was gathered through a one-port reflection measurement. The experimental setup is shown in Fig. 9(b). A calibrated WR-3.4 probe is mounted to the probe station on the left, while the load-pull probe assembly is mounted on the right. Both probes are landed on a 280 µm thru line and the reflection coefficient is measured using the WR-3.4 probe.



(a) (b)

Fig 9. (a) Micrograph of micromachined silicon chip mounted split-block probe housing. (b) RF test setup: WR-3.4 probe on the left, load-pull probe tip assembly on the right.



(a) (b)

Fig 10. RF measurement results of load-pull probe. (a) Reflection coefficient. (b) Time-domain response.

A simulation of this experiment is completed in HFSS and the results are compared with the measured data. The reflection coefficient magnitude and time domain response are shown in Fig. 10. The standing wave pattern in the reflection coefficient is due to the finite mismatch at each end of the 6.6 mm long transmission line channel. The comparable peak-to-peak amplitude and frequency separation suggest that the probe is operating as expected. Examination of the time-domain response, shown in Fig. 10(b) also suggest that most of the power is reflected from the same point. There is a small reflection near the reference plane (0 ns) which is the transition from the on-wafer CPW to the probe tip, but the majority of the reflected power appears to come from the open circuit GSG beamleads.

The active load-pull probe was delivered to the National Institute of Standards and Technology (NIST) for assembly with the integrated circuit (IC) designed by the NIST team and fabricated through the Teledyne Scientific indium phosphide HBT process. As of the date of this report, we have not received data on the progress at NIST in charactering the full load-pull system.