High-Temperature RF Probe Station For Device Characterization Through 500°C and 50 GHz

Zachary D. Schwartz, Alan N. Downey, Samuel A. Alterovitz, and George E. Ponchak

Abstract—A high-temperature measurement system capable of performing on-wafer microwave testing of semiconductor devices has been developed. This high temperature probe station can characterize active and passive devices and circuits at temperatures ranging from room temperature to above 500°C. The heating system uses a ceramic heater mounted on an insulating block of NASA shuttle tile material. The temperature is adjusted by a graphical computer interface and is controlled by the software-based feedback loop. The system is used with a Hewlett-Packard 8510C Network Analyzer to measure scattering parameters over a frequency range of 1 to 50 GHz. The microwave probes, cables, and inspection microscope are all shielded to protect from heat damage. The high temperature probe station has been successfully used to characterize gold transmission lines on silicon carbide at temperatures up to 540°C.

***Index Terms*—Microwave measurements, RF probing, high temperature, coplanar waveguide, SiC.**

I. Introduction

There is a growing need for sensors and communication circuits that operate at high temperatures (500°C and above) for aircraft engine development and monitoring during flight. Interest has also been expressed in high-temperature electronics for use in the harsh environments of interplanetary exploration, telemetry during mining operations and oil exploration, and in conjunction with advanced systems for consumer automobiles [1-3]. To realize this need for high-temperature electronic systems, devices have been fabricated using wide bandgap semiconductors such as silicon carbide (SiC) with a targeted operating temperature of 500 to 600°C. However, the microwave properties of these devices often change drastically with temperature [4], so any designs that are intended to be used in such an environment must be characterized at high temperatures. It is possible to package the device under test (DUT) and characterize it in an oven, which is acceptable for reliability, lifetime, and DC testing. However, for RF and microwave circuit design that requires accurate modeling of active and passive components, it is usually not possible to establish a calibrated reference plane at the DUT terminals within a package, thus accurate models cannot be developed. In addition, the characteristics of the package will vary over a 500°C temperature range and would have to be accounted for during analysis of the data. An RF probe station allows devices to be probed on-wafer quickly and effectively with a known plane of reference.

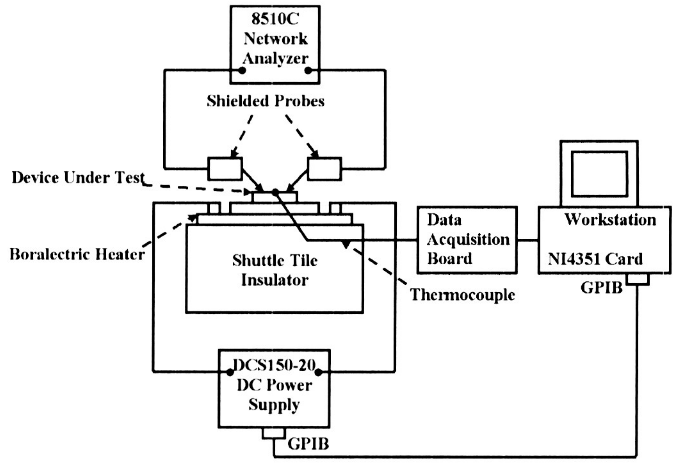


Fig. 1. Block diagram of high-temperature probe station system

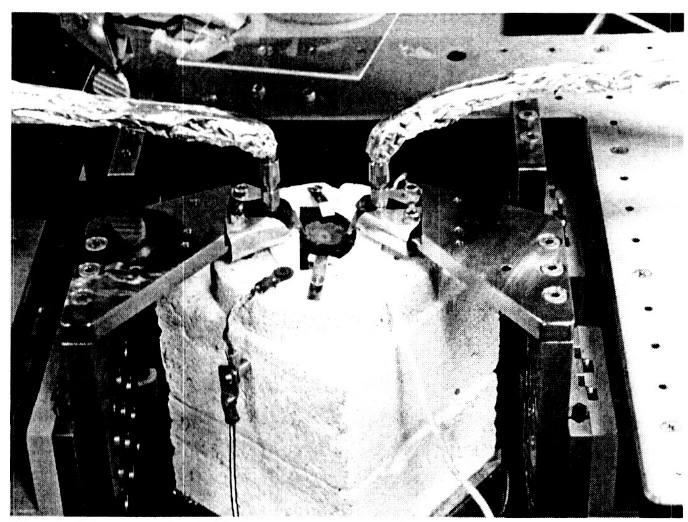


Fig. 2. Photograph of high-temperature probe station, including shuttle-tile insulating chuck, ceramic heater, and shielded probes and cables.

Conventional, commercially available thermal wafer-probe stations are used to evaluate microwave devices across a controlled temperature range and have a typical upper limit of 200°C [5, 6]. Stand-alone thermal heating chucks are available with an extended upper temperature range of 300 to 400°C [7]. To effectively characterize devices at temperatures up to and surpassing 500°C, a custom probe station is needed. In the past, custom probe stations have been developed to test devices under other extreme environments, such as cryogenic temperatures as low as 37 K [8]. To meet the need for high-temperature microwave device characterization, the authors have designed a probe station to operate at temperatures through at least 500°C [9].

This paper describes a high-temperature probe station that is simple in design, but quite suitable for microwave characterization. For the first time, a full description of the system is given, including heating stage, temperature controller, and probe shielding. Also presented are data on the repeatability of measurements at high temperature, the calibration procedures, and a discussion on the system and probe reliability. Finally, the results of a measurement of a coplanar waveguide (CPW) from room temperature through 540°C are given.

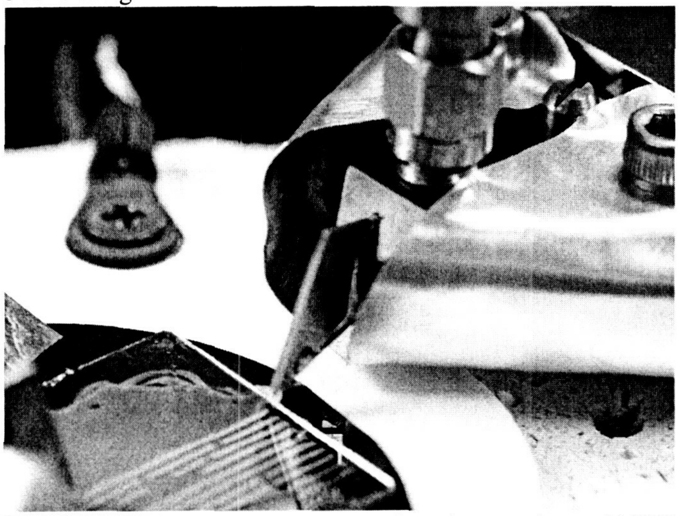


Fig. 3. Photograph of shielded microwave wafer probe measuring a gold CPW line on SiC.

II. System Description

A block diagram of the high temperature probe station is shown in Figure 1. The system consists of the ceramic heater mounted on NASA shuttle tile insulator, DC power supply, PC-based data acquisition and temperature controller, microwave probes, a microscope, and a network analyzer.

The heater is a Boralectric model ceramic heater produced by GE Advanced Ceramics and is rated to 1800°C. The heater is fixed atop a 15cm block of shuttle tile insulating material and DC power is supplied via the screw connections. The power supply is a Sorensen DCS 150-20 capable of sourcing 3 kW and is controlled via a General Purpose Interface Bus (GPIB) connection. At room temperature, the heater has a resistance of 24 Ω; this value drops to 13 Ω at 500°C. To maintain a steady-state temperature of 500°C, the heater requires 150 watts of power, or a DC supply current of about 3.4 amps. A K-type thermocouple is mounted on the surface of the DUT and held in place with a small spring clip to provide temperature readings to the laboratory computer. The heating stage can be brought up to 500°C in less than three minutes and will cool to a safe temperature of 50°C in less than ten minutes with no external cooling apparatus. The use of a small fan significantly speeds the cooling process, but was not used during DUT characterization. A photograph of the heater and insulating chuck are shown in Figure 2.

The heating system is controlled from a Windows computer running National Instruments' LabView software. The computer is equipped with both a GPIB interface card to control the DC power supply and a National Instruments' NI4351 data acquisition card to collect thermocouple data. The software program calculates the required heater current using a proportional-integral-differential (PID) feedback control algorithm. At low temperatures (under 200°C) the standard deviation of the controlled temperature is better than 0.5°C. At temperatures above 350°C, the standard deviation increases to a value that is typically between 0.8 and 1.2°C.

Because of the intense heat radiated by the ceramic heater at temperatures above 300°C, a typical microwave probe cannot be used. A specially made high temperature probe by GGB Industries is used [10]. These GGB Industries Picoprobe ground-signal-ground (GSG) probes were manufactured with two custom modifications; a copper heat sink was affixed to the micro coax leading to the tungsten probe tips and reflective tape was added to the bottom of the probe body to help reduce the heating effects. As a further precaution for use at elevated temperatures, the authors have wrapped an additional thin layer of shuttle tile insulator and a heavy foil heat shield around the plastic body of the probes, as shown in Figure 3. The coaxial cables are the 2.4mm UTiFLEX model with swept right angle bends, manufactured by Micro-Coax [11]. These cables have been wrapped in an additional glass-fiber insulating sleeve and a foil heat shield and are connected to the microwave probes. A Pyrex shield is held in place close to the microscope lens, about 10cm above the heating surface, to protect the microscope from radiated heat. The 15cm thick insulating shuttle tile block replaces the regular wafer chuck in this system. The rest of the system is a standard RF probe station operated with a vector network analyzer (VNA).

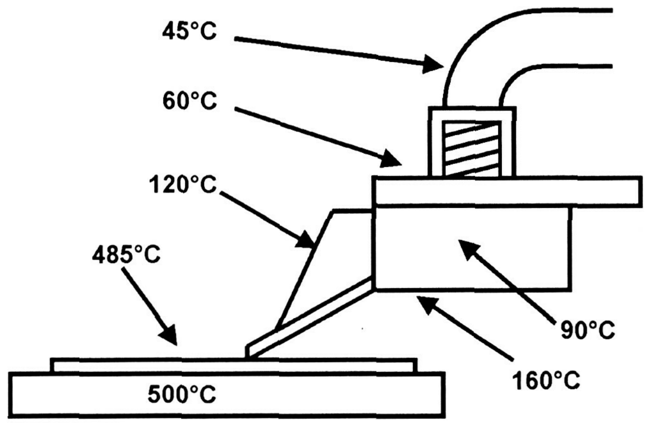


Fig. 4. Measured local values of temperature of the microwave probes and cables, with the heater at 500°C

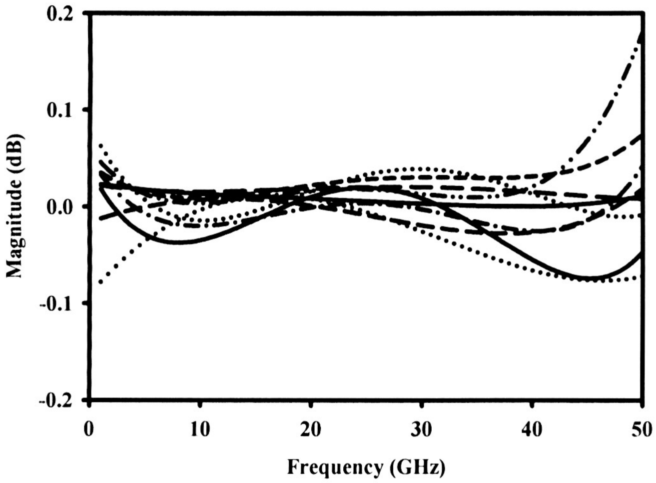


Fig. 5. Magnitude of S_{21} for two microwave cables connected in a thru configuration and suspended above the heating surface from 30 to 430°C in increments of 50°C.

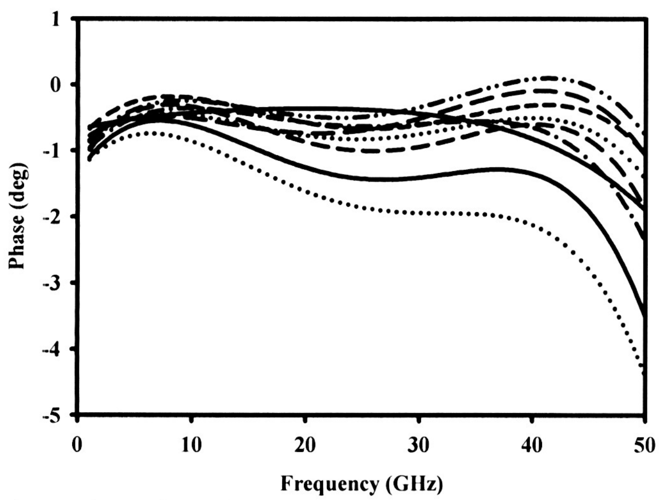


Fig. 6. Phase of S_{21} for two microwave cables connected in a thru configuration and suspended above the heating surface from 30 to 430°C in increments of 50°C.

III. HEATING EFFECTS ON THE SYSTEM

A. Probe Station At 500°C

The temperature at various points of the probe station was measured to determine the effectiveness of the heat shielding. The heater was held at a constant 500°C with one thermocouple while a second thermocouple was moved around the instrument. The top of the SiC wafer, which was the DUT, registered 485°C, while the Pyrex glass shield protecting the microscope lens was 65°C. Temperatures were also measured on the bottom (160°C), side (90°C), and top (60°C) of the microwave probe shielding, as well as the copper heatsink (120°C) and the connecting end of the coaxial cable (45°C), as pictured in Figure 4. Throughout the high temperature tests, the shuttle tile block could be moved by hand and stayed cool to the touch.

B. Heating Of The Coaxial Cables

The effect of heat on the characteristics of the coaxial microwave cables was investigated. Two Micro-Coax microwave cables, complete with their additional heat shielding, were calibrated using open-short-load standards. The cables were then mounted 7cm above the ceramic heater with a thru connector, which is the same height the cables are during the regular RF measurements. A thermocouple was attached to the heat shield on one cable to monitor its temperature during the test. The heater temperature was swept from room temperature to 425°C in 50°C increments. A thru measurement was recorded at each temperature for the cable configuration. The peak temperature of the cables was 45°C, recorded when the heater was set to 425°C. As shown in Figure 4, 45°C is the temperature of microwave cables when connected to the probes during a normal measurement with the heater at 500°C. The results are shown in Figures 5 and 6. The change in S_{21} was minimal, registering less than 0.2dB in magnitude and 3° in phase, agreeing with the manufacturer's published specifications [12].

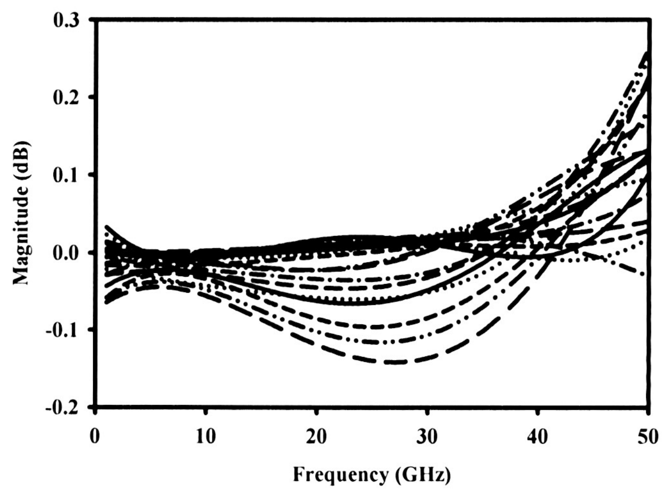


Fig. 7. Magnitude of the reflection coefficient for an open-circuit microwave probe suspended above the heating surface from 30 to 540°C in increments of 30°C.

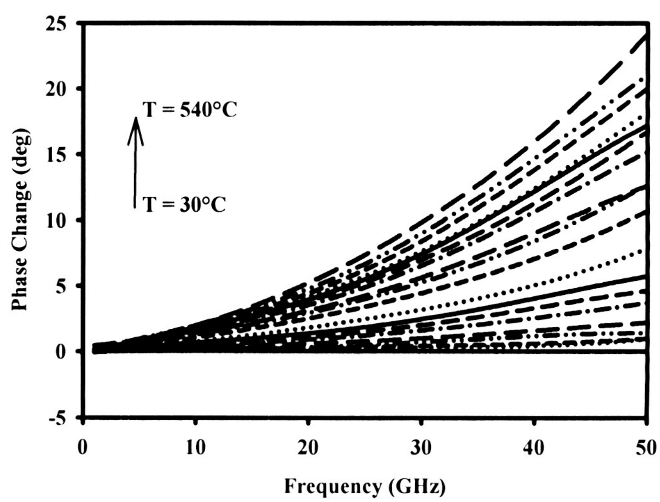


Fig. 8. Change in phase of the reflection coefficient for an open-circuit microwave probe suspended above the heating surface from 30 to 540°C in increments of 30°C.

C. Heating Of The Microwave Probes

The effect of temperature change on the microwave probes and cables combined was also measured in two separate experiments. First, one shielded microwave probe was calibrated using an open-short-load calibration standard. The probe was then suspended above the ceramic heater with the probe tip about 2mm above the heater's surface. The temperature of the heater was swept from room temperature to 540°C in 30°C increments. At each temperature, a one-port measurement of the open-circuited probe was recorded. The magnitude and phase of these open-circuit measurements are shown in Figures 7 and 8.

In the second experiment, the microwave probe was calibrated and then lowered onto a gold ground plane mounted on the heater's surface. A one-port measurement was made of the short-circuited probe in 30°C intervals to 390°C. The magnitude and phase of these short-circuited measurements are shown in Figures 9 and 10.

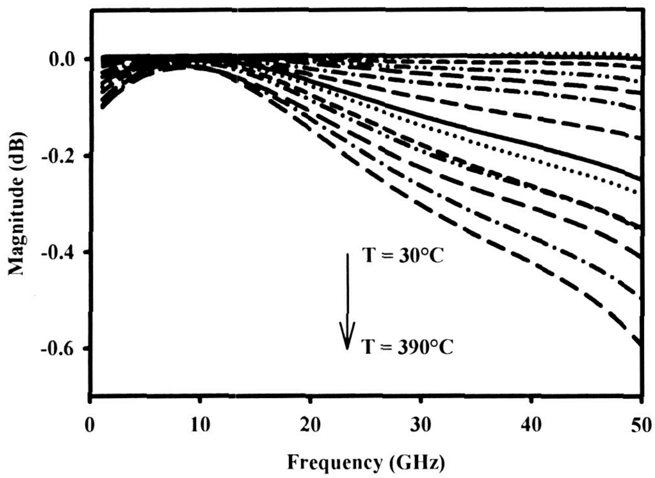


Fig. 9. Magnitude of the reflection coefficient for a short-circuit microwave probe grounded to a gold plane mounted on the heating surface from 30 to 390°C in increments of 30°C.

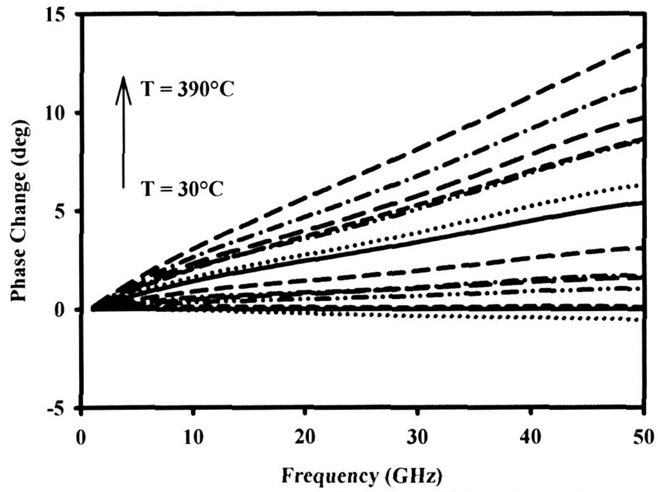


Fig. 10. Change in phase of the reflection coefficient for a short-circuit microwave probe grounded to a gold plane mounted on the heating surface from 30 to 390°C in increments of 30°C.

For the open-circuited probe measurements, the change in magnitude is minimal—less than 0.3dB at most temperatures and frequencies. There is a greater variation in the magnitude of S_{21} for the short-circuited probe, but this is due to the increase in resistivity of the gold ground plane with increasing temperature. The phase of both the open- and short-circuited probes, however, increases dramatically as the heater temperature increases. The magnitude of the RF characteristics of the probe and cable do not appear to be affected by increasing the temperature through 540°C but the phase increases with temperature and must be corrected during calibration as described in Section IV. Lastly, because the phase characteristics of the microwave cables did not change with temperature, this measured increase in phase is due to the RF probes.

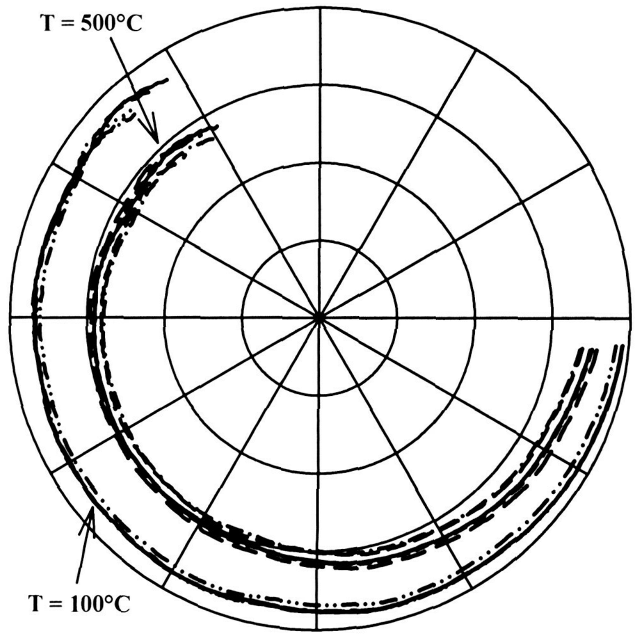


Fig. 11. Polar plot of S_{21} for repeated measurements of a 6700μm CPW line at 100°C (outer group) and 500°C (inner group) from 1 to 50 GHz.

D. *Repeatability Of High-Temperature Measurements*

The repeatability and consistency of microwave measurements at elevated temperatures is critical to accurate device characterizations. To investigate the repeatability of these measurements, two microwave wafer probes were mounted on the probe station, shielded, and connected to the network analyzer with a pair of shielded coaxial cables. A two-port, multiline thru-reflect-line (TRL) calibration was performed at room temperature, using the NIST Multical software [13], to prepare the probe station. The probes were lifted and the heater temperature was brought up to 500°C and allowed to stabilize. The probes were then lowered and a 6700μm long CPW line was measured. The probes were again raised and the temperature was lowered to 100°C. The probes were set again, and the same CPW line was re-measured. The temperature cycling was repeated five times to determine the repeatability of the on-wafer measurements at elevated temperatures. The results of these measurements are shown in Figure 11. The standard deviation of magnitude and phase were calculated for the measurements of S_{21} at both 100°C and 500°C. The deviation in magnitude was 0.08dB at 100°C and 0.23dB at 500°C. The standard deviation of the phase measurements was the same at both temperatures, increasing linearly with frequency at 0.10°/GHz. The system shows good repeatability and it is likely that much of the error is due to wear on the probe pads of the DUT at high temperature as opposed to unwanted degradation in the microwave characteristics of the measurement system.

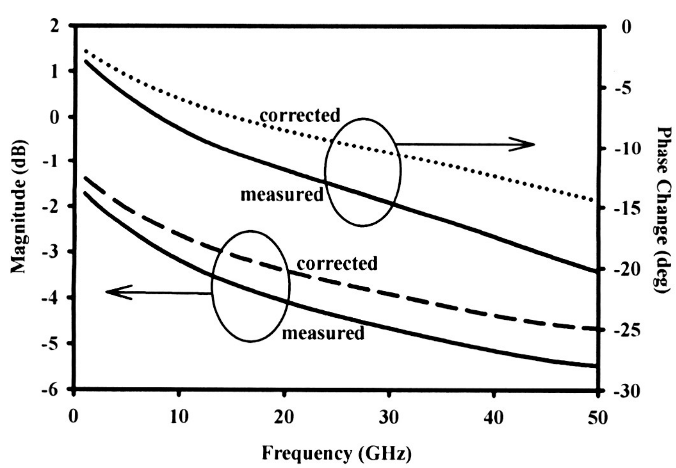


Fig. 12. Magnitude and change in phase of S_{21} for a gold CPW line on SiC at 360°C. The data is shown both as measured and after corrections have been applied.

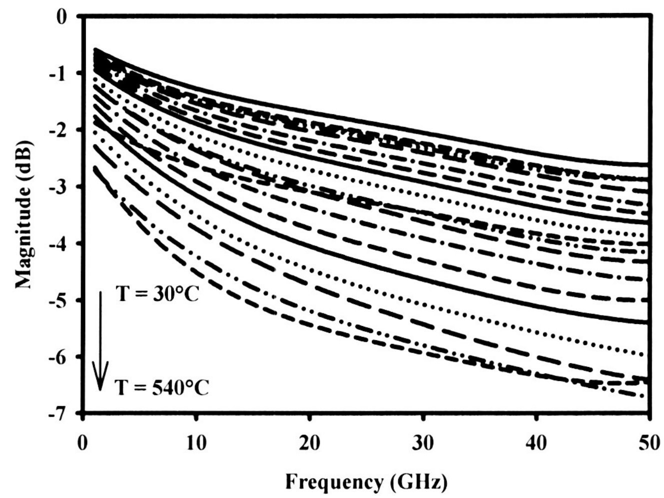


Fig. 13. Magnitude of S_{21} for a gold CPW line on SiC from 30 to 540°C in increments of 30°C, corrected for the effects of heating within the measurement system.

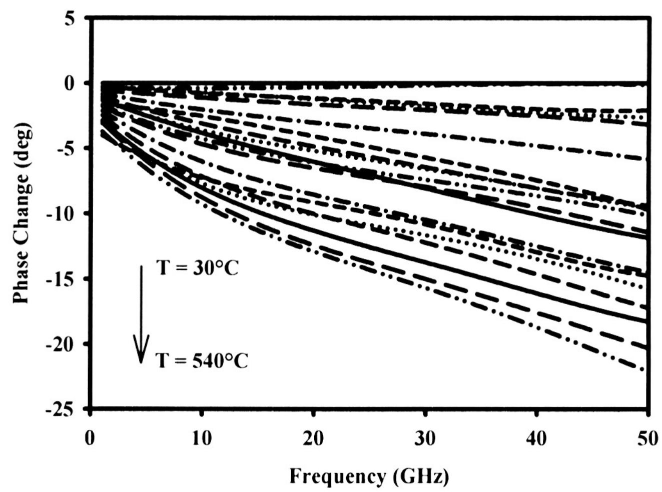


Fig. 14. Change in phase of S_{21} for a gold CPW line on SiC from 30 to 540°C in increments of 30°C, corrected for the effects of heating within the measurement system.

IV. Calibration/Deembed Routine

The VNA may be calibrated at each temperature to correct for temperature variation in the system. However, calibration at each temperature step would greatly increase the measurement time and the time that the DUT would have to be at high temperatures. Because most electronic parts degrade rapidly at high temperatures, the system is calibrated once at room temperature and then corrections are made to the data to account for the temperature effects on the system. The multiline TRL calibration establishes a reference plane at the middle of the 5000μm long thru line, or 2500μm from the probe pads. The line lengths are 5850, 6700, 8500, and 17500μm to completely cover the 1 to 50 GHz bandwidth, and the reflection is a CPW short circuit at 2500μm from the probe pads.

Two corrections are applied to the measured data to account for changes in the measurement system with increasing temperature. The first correction is due to the change in characteristics of the microwave coaxial cables and wafer probes as the heater temperature is increased. As shown earlier in Figures 7 and 8, the magnitude change due to the heating of probes and cables is negligible (less than 0.3dB) and is not corrected, but the associated change in phase is significant (as large as 25°). A quadratic function of temperature and frequency is fit to the measured phase change, giving the empirical function *h(T,f)*.

$$h(T,f)=10^{-4}\cdot(T-30)\cdot\left\{\begin{array}{l}\left[3.4439+2.9856\times10^{-3}(T-30)\right]\\+\left[2.4711-5.9781\times10^{-4}(T-30)\right]\cdot f\\+\left[8.7811\times10^{-2}+1.0851\times10^{-4}(T-30)\right]\cdot f^{2}\end{array}\right\} \quad (1)$$

This correction factor is subtracted from the phase of all measurements performed above room temperature to remove the phase shift associated with the warming of the microwave probes and cables.

The second correction arises from the change in the characteristics of the 2500μm long CPW feedlines between the probe tips and the original calibrated plane of reference at the ports to the DUT. After calibration at room temperature, the measured data reflects only the characteristics of the DUT. However, at an elevated temperature, the measurement is a combination of the room temperature DUT characteristics, as well as the change in characteristics of both the DUT and the CPW feedlines to the device. To determine the change in the 2500μm long CPW feedlines with temperature, a long delay line is measured in 30°C increments from 30°C to 540°C. The temperature dependent attenuation and phase change is assumed to be constant across the CPW delay line and the 2500μm long CPW feedlines, therefore the effect of the feedlines on the measured values can be deduced. This calculated error value is then added to the data measured for the DUT. With these corrections, the original plane of reference is restored at the ports of the DUT.

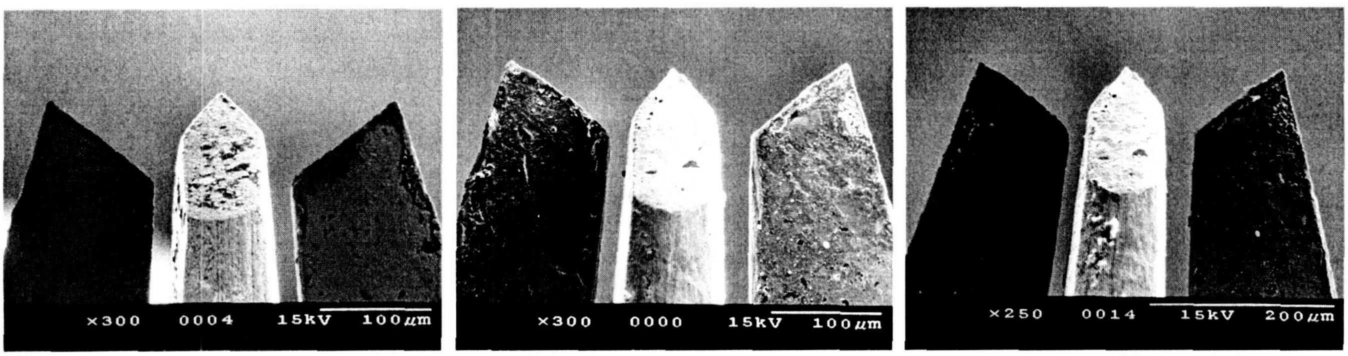
The complete correction of magnitude and phase data is as follows:

$$S_C(T)=S_M(T)\cdot\left[\frac{S_D(RT)}{S_D(T)}\right]^{\left(\frac{l_1}{l_0}\right)} \quad (2)$$

$$\phi_C(T)=\left[\phi_M(T)-h(T,f)\right]+\frac{l_1}{l_0}\left\{\phi_D(RT)-\left[\phi_D(T)-h(T,f)\right]\right\} \quad (3)$$

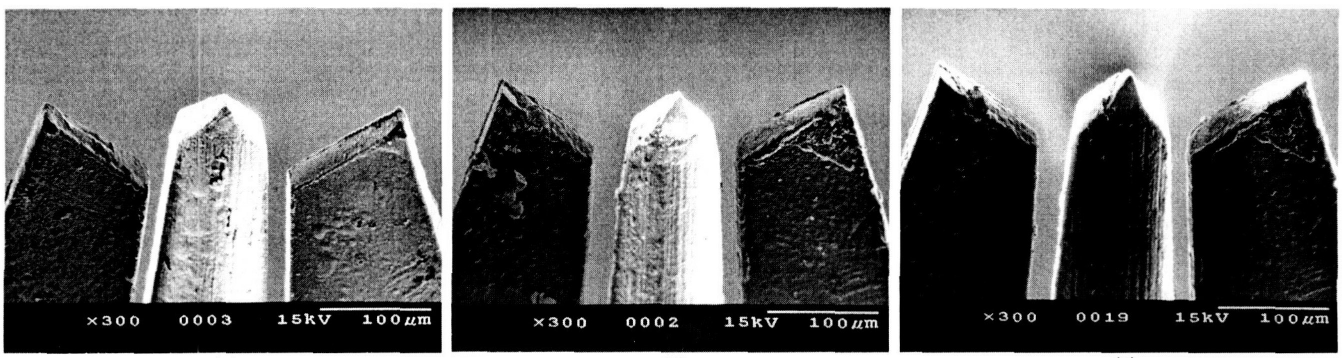
where:
$S_D(T)$ = measured magnitude of S_{21} for delay line at temperature T
$\phi_D(T)$ = measured phase of S_{21} for delay line at temperature T
$S_M(T)$ = measured magnitude of S_{xy} for DUT at temperature T
$\phi_M(T)$ = measured phase of S_{xy} for DUT at temperature T
$S_C(T)$ = corrected magnitude of S_{xy} for DUT at temperature T
$\phi_C(T)$ = corrected phase of S_{xy} for DUT at temperature T
T = temperature in °C
RT = room temperature, 30°C
f = frequency in GHz
l_0 = total length of transmission line, including feedlines (17500μm)
l_1 = total length of feedlines (5000μm)

These same correction factors are applied to all four s-parameters to yield data corrected for effects of heating within the measurement system.



(a) (b) (c)

Fig. 15. Scanning electron microscope pictures of the top side of the GSG wafer probes (a) before use, (b) after use, and (c) after cleaning.



(a) (b) (c)

Fig. 16. Scanning electron microscope pictures of the bottom side of the GSG wafer probes (a) before use, (b) after use, and (c) after cleaning.

V. Measurement Example

A set of CPW lines were fabricated on a semi-insulating 4H-SiC wafer from Cree [14]. The metal lines consist of 1.5μm gold on top of 200Å titanium. The CPW lines have a center conductor width of 50μm, a slot width of 25μm, and a ground plane width of 150μm [15]. The network analyzer was calibrated as described in Section IV. Measurements of two-port scattering parameters of the 17500μm long CPW line were then taken from room temperature to 540°C in intervals of 30°C. As a precaution, the probes were lifted during each increase in temperature and were set again after the temperature had stabilized. An example plot of the magnitude and change in phase of S_{21} at 360°C is shown in Figure 12, both before and after the corrections were applied. The complete set of corrected magnitude and phase of S_{21} are shown in Figures 13 and 14.

From the magnitude of S_{21}, it is clear that the transmission line losses increase with frequency and temperature, as expected. The phase of S_{21} decreases with the rising temperature, suggesting that the effective dielectric constant of the transmission line (ϵ_{eff} = 5.5 at room temperature) is increasing slightly with temperature. The results are very consistent though 450°C, and show no effect of degradation of probes, cables, or the line under test. Above 480°C, the effects of repeated probing— the pads on the 17500μm line had been probed 18 times by this point— became apparent. There were small holes in the gold probe pads and more force was needed to ensure contact to the pads, causing the last three measurements to scatter from the trend. This problem can be avoided by probing in larger intervals; probing in temperature increments of 50°C would cause significantly less damage to the probe pads.

The microwave probes were inspected before and after use with a scanning electron microscope. Aside from minor misalignment, the probe tips appeared to be structurally sound. A small bit of residue, presumably from the gold probe pads, had formed on the bottom side of the probes and the tips had discolored slightly at the highest temperatures. After cleaning the probe tips by dragging them across a piece of paper soaked in alcohol and realigning the tips, a second calibration was performed and the probes were useable for another set of measurements. Pictures of the probe tips before use, after use, and after cleaning are shown in Figures 15 and 16.

VI. Summary

A high-temperature probe station has been developed that is capable of testing microwave devices. The heating stage is well insulated from the probe station and heats and cools quickly to facilitate measurements at various temperatures. The microwave probes and connectors are shielded from the heating element and have been demonstrated to withstand device temperatures as high as 540°C. The heating system is controlled from a computer interface, while a network analyzer is easily connected to the probe station to perform temperature dependent microwave measurements.

Acknowledgements

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