# ANOMALIES OBSERVED IN WAFER LEVEL MICROWAVE TESTING+

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## ABSTRACT

Wafer level testing of GaAs MMICs is fast, reliable and can be very accurate. However, two anomalies have been observed in the course of developing planar wafer level standards. The first involves a low frequency characteristic impedance change of microstrip and coplanar waveguide transmission lines. This effect, which is due to conductor loss of the transmission media, can result in improper/inaccurate calibrations and measurements. The second anomaly results from resonant coupling of the microwave probe itself into adjacent structures on the wafer. This can occur during calibration or measurement and results in extreme inaccuracies at the resonant frequencies.

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## INTRODUCTION

At the present time, wafer level probing is being used extensively by MIMIC Phase 1 contractors as well as by the GaAs MMIC industry in general. The measurement is fast, low cost and has the promise of high accuracy. Unfortunately, there have been no traceable planar standards upon which to base these measurements. Because of the wide usage for modeling and performance verification, the largest part of Ball Communication Systems Division's (BCSD) MIMIC Phase 3 program has been directed toward developing planar wafer level standards on GaAs that are NIST traceable. The objective of this portion of the program was to analyze planar standards/calibration techniques and develop a NIST traceable interim planar verification kit for wafer level measurements over the frequency range of 0.045 - 26.5 GHz. This work has led to an increased understanding of the loss and impedance of transmission line structures on GaAs and methods of calibration and measurement of monolithic integrated circuits at microwave and millimeter wave frequencies. During the course of this work two significant anomalies in wafer level testing have been observed and studied. These two phenomena are the following:

1. Large changes at low frequencies (<5 GHz) in the characteristic impedance and effective dielectric constant of microstrip and coplanar waveguide transmission lines,

2. Resonant frequency coupling from the microwave probes into adjacent structures on the wafer being tested.



## LOW FREQUENCY EFFECTS

The low frequency effects of the microstrip and coplanar waveguide transmission lines were first predicted by incorporating conductor (metal) losses into a full wave analysis of these planar transmission lines. This rigorous formulation was based on a magneto-quasistatic analysis for the calculation of the surface resistance and frequency dependent internal inductance of the thin film conductor to obtain the equivalent surface impedance, Zs. A modified full-wave eigenvalue problem for the propagation characteristics of the microstrip was formulated in terms of an integral equation expression for the boundary condition, E(J)=ZsJ, on the equivalent impedance surface (1), (2). The modeled effect is shown in Figures 1 and 2 for the characteristic impedance and effective dielectric constant, respectively, of a 50 ohm microstrip transmission line on 100 um thick GaAs. Both lossless (spectral domain analysis) and lossy (rigorous full wave analysis) values of characteristic impedance and effective dielectric constant are predicted. These modeled results (2 um thick gold metallization) indicate that both characteristic impedance and effective dielectric constant increased dramatically at frequencies below 5 GHz.

This effect was also observed experimentally as depicted by the measurement data of Figures 3 and 4. The data shown in Figure 3 was calculated during the TRL calibration procedure from data measured on the microstrip thru and line standards (3). The effective dielectric constant of the microstrip transmission line that is plotted in this figure agrees very well with the predicted values. The increase in the effective dielectric constant (propagation constant) at low frequencies is attributed to the conductor loss of the thin film metallization that is typical of that used on monolithic microwave integrated circuits. The reflection coefficient, S11, data of Figure 4 was measured on a lumped thin film planar resistor. Calibration at the wafer level was also performed using the Thru-Reflect-Line technique with planar standards on GaAs. Although the thin film load was 57 ohms (DC measurement), it appears to be only 57 ohms at frequencies > 5 GHz. Lower values are indicated by the data for frequencies < 5GHz. The calibration impedance was assumed to be a constant 50 ohms by the measurement data display. However, the actual calibration impedance is set to the characteristic impedance of the transmission line (by the TRL calibration procedure) which is increasing as the frequency is decreased below 5 GHz. The data also suggests that the deviation of the imaginary part of the characteristic impedance is significant as well as that of the real part.

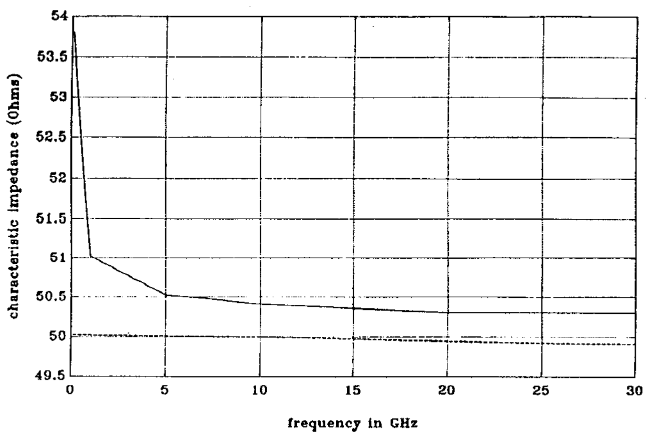


**Figure 1:** The characteristics impedance of a microstrip line increases at lower frequencies due to the conductor loss.

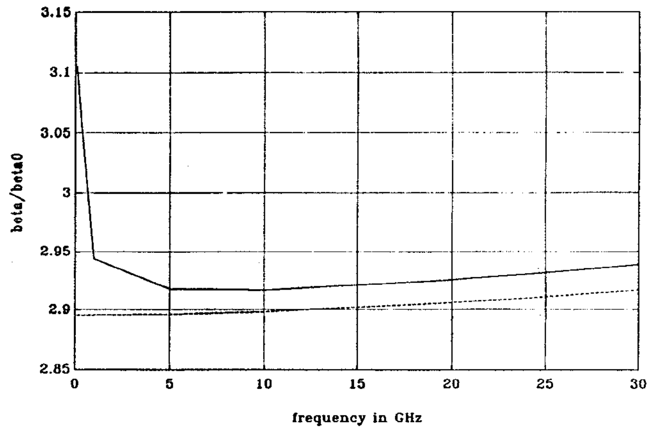


**Figure 2:** The propagation constant of a microstrip line increases at lower frequencies due to the conductor loss.

## PROBE COUPLING

The second anomaly was observed in the development of microstrip planar standards on GaAs. Resonant type behavior, spikes at repeated frequency intervals, was seen in the measurement data of insertion loss in transmission lines after calibration.

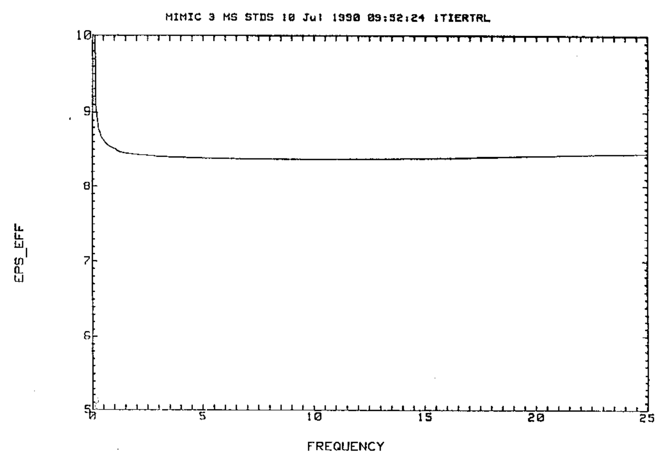


**Figure 3:** The measured effective dielectric constant of the microstrip transmission line on GaAs increases at low frequencies.

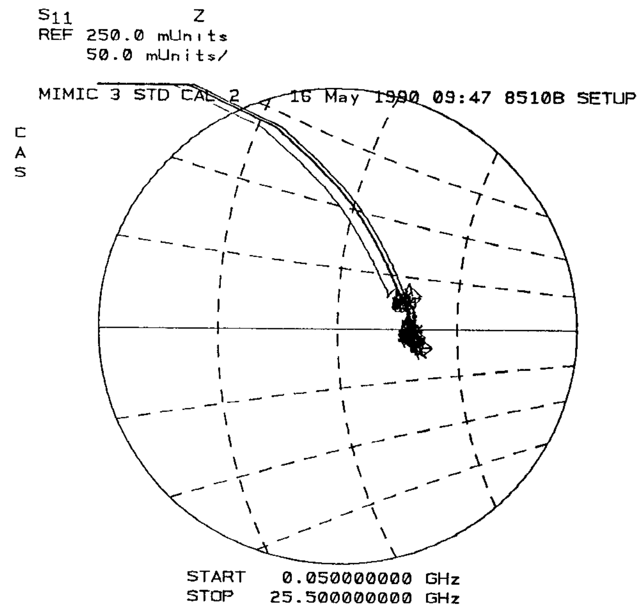


**Figure 4:** The impedance of a 57 ohm load is mapped into the microstrip transmission line impedance used in the TRL calibration.

This data is shown in Figure 5. This behavior has been attributed to resonant coupling of the CPW microwave probes into structures on the GaAs wafer that are adjacent (under the probes) to the circuit under test. The initial data was difficult to analyze due to a number of different coupling structures that existed on the wafers being tested. A model was subsequently developed that included coupling to these adjacent structures during test and calibration. The modeled behavior shown in Figure 6 agreed very closely to the measured results. These structures are microstrip lines which behave as sections of open ended transmission lines. These lines resonated at different frequencies and harmonics depending upon their respective lengths. This resonant coupling effect was observed to exist both near calibration standards and devices under test. These structures were typically spaced greater that 500 um (5 substrate thickness) away from the calibration standard or the device under test. Therefore it is believed that structure- to-structure coupling is not the dominant effect but that of probe-to-structure coupling.

This phenomenon is shown graphically in Figure 7. Due to the low probe to wafer angle (20 degrees), the unshielded probe tip area (approximately 3 mm from the probe contact tip) is in very close proximity to structures that are adjacent to the circuit under test. The tapered coplanar waveguide transmission line on the underside (wafer side) of the probe combined with numerous discontinuities along the probe board is prone to radiate heavily. The radiation is most probably due to slot-line modes that are excited by the discontinuities. It is believed that this resonant coupling from the probe to adjacent die on the wafer is the dominant mechanism that produced the observed anomaly.

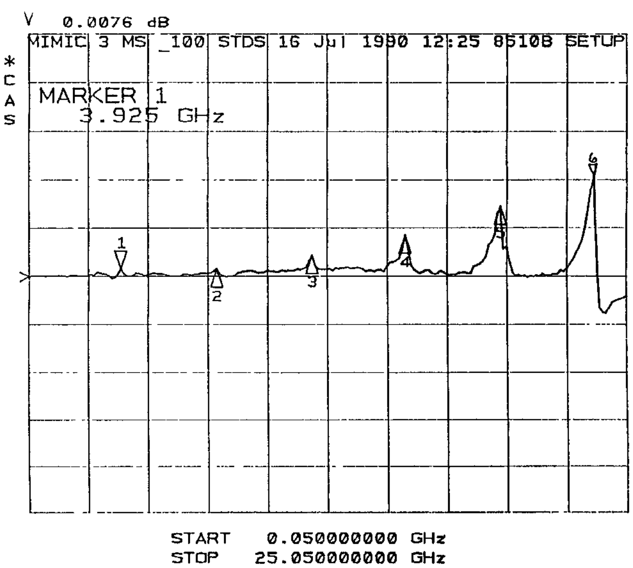


**Figure 5:** The resonsant behavior in the insertion loss measurement of a microstrip line is due to probe coupling into adjacent resonant structures during the TRL calibration procedure.

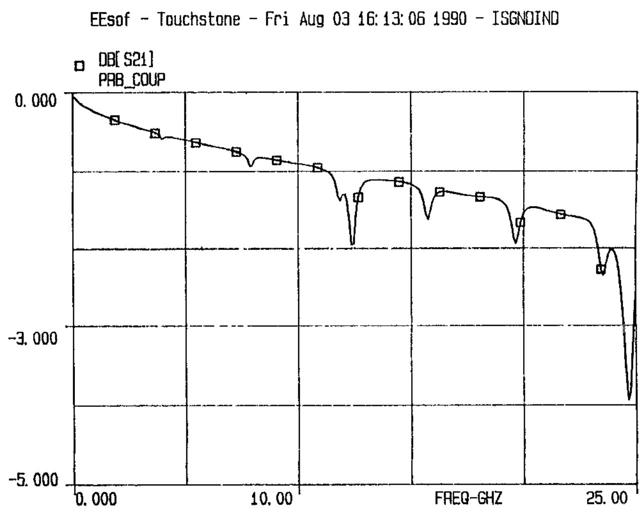


**Figure 6:** The resonant coupling behavior was modeled by coupling to three different length microstrip lines that were adjacent to the structures used in the TRL calibration.

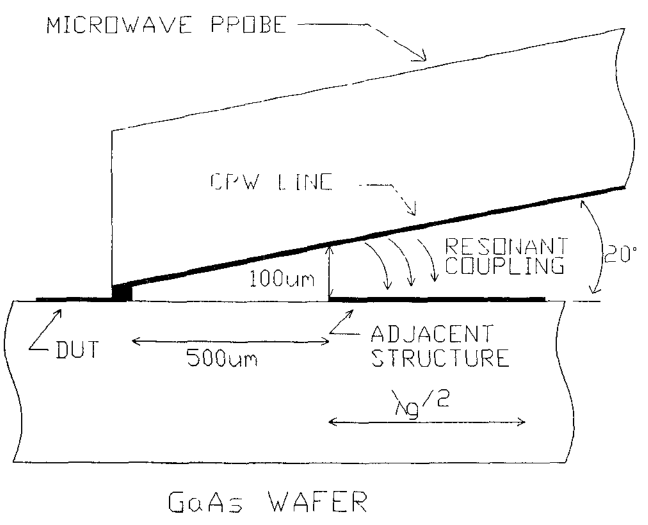


**Figure 7:** The unshielded portion of the CPW probe tip couples into adjacent structures.

## SUMMARY AND DISCUSSION

The effects that have been discovered can have significant impact on the measurement accuracy of wafer level testing of GaAs MMICs. Both of the observed anomalies are easily masked by the calibration procedure. Systematic and random errors will be generated if these effects are manifest during calibration. The low frequency change in characteristic impedance can be viewed as a systematic error in the calibration/measurement process if the reference impedance is assumed to be constant. The probe coupling effect can be viewed as a random measurement error when introduced during measurement or as a systematic error when introduced in the calibration process.

The low frequency increase in the characteristic impedance of microstrip transmission lines that has been observed is due to conductor losses. This conductor loss effect is not negligible at low frequencies (< 5 GHz) when the electric field completely penetrates the conductor metallization (i.e., the conductor thickness is less than the skin depth). The effect of the transmission line impedance variation can be removed in the error correction of automatic network analyzers by proper standard definition such that the measured data is mapped onto a constant impedance plane (50 ohms).

Due to the variability of adjacent structures and the resonant coupling of the microwave probes into these structures, the probe coupling effect can not, in principle, be corrected (random error). Therefore, this effect must be eliminated or minimized. The solution can be addressed at the probe in order to minimize its radiation or addressed from the GaAs wafer design/layout standpoint. The adjacent structures could moved away from the MMIC under test (which is not a practical solution), or the "Q of the resonant coupling" could be reduced. Preliminary work to reduce the "Q of the resonant probe coupling" by physically breaking the ground plane around individual MMICs appears to be successful.

## REFERENCES

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