Metallization Effects on GaAs Microstrip Line Attenuation

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Abstract—**The transmission line losses of plated gold GaAs microstip were investigated from 5 to 30 GHz. Experimental attenuation coefficients were extracted from quality factor measurements of 50 Ω straight microstrip resonators. The measured attenuation coefficients for plated gold microstrip were found to be 38% higher than previously published data on evaporated gold microstrip, and 44% higher than Computer-Aided Design (CAD) simulations. Empirical bulk resistivities were found that correctly characterize GaAs plated line losses for CAD models. This paper indicates that GaAs microstrip line attenuation cannot be completely characterized by dc resistivity alone, and that empirical microstrip parameters are needed for accurate CAD modeling.**

I. Introduction

Equations describing the electrical characteristics of microstrip are widely available. Many of these equations have been incorporated into microwave nodal circuit simulators to increase the modeling accuracy of Monolithic Microwave Integrated Circuits (MMIC). However, the equations model the microstrip transmission line as a homogeneous conductor with a constant resistivity across its thickness. Most MMIC microstrip transmission lines on GaAs are not homogeneous in nature and are incorrectly modeled in the CAD programs. These differences cause the microstrip electrical response to be simulated incorrectly at microwave frequencies.

Plating is the most common deposition process for the large amounts of gold used for MMIC transmission lines. GaAs foundries prefer plating over other methods, such as evaporation, because it is a less expensive foundry process. Gold plate does not adhere well to GaAs, so a thin layer of alloy metal, commonly called 1st Metal, must be deposited on the substrate surface as an adhesion material under the plated gold [1]. The combination of both metallizations is referred to as 1st metal/gold plate in this paper. The plating process produces microstrip lines that are composed of multimetallizations, which cause differences to be seen between the modeled and measured behavior. This paper found that the microstrip attenuation coefficient was most prominently affected. The error was compounded by the fact that the metallizations are not usually produced coincidentally in the plating process. Better correlation with CAD modeling is shown by evaporated gold microstrip which is much more expensive to fabricate [2]. This indicates that the performance of microstrip is largely dependent on the process used to create it.

This paper details the use of 1st metal/gold plated lines to show that CAD models do not adequately simulate the most common method of microstrip deposition in MMIC's. From measurement of half-wave resonators, experimental attenuation coefficients were extracted and compared to modeled data. Empirical microstrip parameters were determined so a better correlation between CAD simulations and measured data would result. The empirical parameters facilitate MMIC design through accurate CAD characterization of gold plated microstrip at microwave frequencies. Better CAD models lead directly to lower design iterations.

Manuscript received April 13, 1992; revised December 10, 1992.

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IEEE Log Number 9209356.

II. Materials and Measurement Methods

Goldfarb and Platzker have previously extracted attenuation coefficients from evaporated gold microstrip [2]. Their results showed good correlation with CAD simulations. A comparison was made with these results by using their procedure to extract the attenuation coefficient of 1st metal/plated gold microstrip. The attenuation coefficient for microstrip was extracted from quality (Q) factor measurements of lightly coupled straight half-wave resonators. The resonators were constructed with 50 Ω microstrip measuring 69 μm wide and 6.8 mm long, as shown in Fig. 1. The microstrip was processed on 100-μm thick undoped GaAs. The resonator's fundamental resonant frequency was chosen to be approximately 7 GHz. This allowed four resonances to be measured in the 5–35 GHz range.

Fig. 2 is a Scanning Electron Microscope (SEM) photograph showing the 1st metal/gold plate composition. The bottom layer was 1st metal composed of an Au/Pt/Ti alloy that is used both for adhesion to the GaAs surface and as a gold diffusion barrier. It was evaporated on the substrate to a thickness of 0.78 μm. Gold was plated on top of the 1st metal to a thickness of 4.68 μm. The width of the plated gold has a step-in for processing alignment. The SEM photograph shows the plating of the gold caused the surface to have a roughness that is not seen in the evaporation process used to deposit the underlying 1st metal. A profilometer measured the plating's rms surface roughness, called SRuff in some CAD programs, to be 0.1 μm. This measurement is not extremely accurate due to the softness of the gold, but can be used to approximate the surface roughness of the plating. RF losses in CAD simulations are calculated using the dc bulk resistivity of the metal which was measured to be 2.56 $\mu\Omega \cdot$ cm for the 1st metal/gold plate. EEsof products use the parameter RHO which is dc bulk resistivity normalized to gold. RHO for the 1st metal/gold plated line was calculated to be 1.05 from the dc measurements.

The scattering parameters were measured with the use of a wafer probe system. A two-port calibration was done to the tips of the wafer probes. The resonant frequencies were found by using a broad sweep across the 5–35 GHz range. The resonance peaks were then measured individually to ensure high resolution for the Q-factor measurement. The attenuation coefficients were extracted from these measurements in the same manner used by Goldfarb and Platzker [2]. This procedure also de-embeds the effects of the feed structure and coupling gaps. Using a wafer probe system demonstrates the feasibility of putting the microstrip test structures on production wafer test areas. This allows for constant production monitoring of the foundry's microstrip attenuation without damaging the wafer's other MMIC circuits. Measured data can be given back to the design engineer for empirical CAD modeling in future MMIC designs.

The attenuation of microstrip can be extracted from the measurement of the insertion loss and 3 dB bandwidth at the structure's resonances. The experimental error in the attenuation is dependent on the frequency resolution and measurement accuracy of the network analyzer. The resonant peaks were measured at no more than 5 MHz steps, and the insertion loss accuracy of the network analyzer for the lightly coupled resonators was shown to be a worst case of 1 dB over the 5–30 GHz test range. The error due to these factors was calculated in the same manner as the evaporated data, and was included with the measured results [2].

The modeled attenuation was determined by using EEsof's LineCalc. LineCalc models microstrip in the same way as the CAD programs Touchstone and Libra. The thickness used in the simulation was 5.46 μm, which was the total thickness of all the 1st metal/gold plate metallization layers. The modeled width of the microstrip was

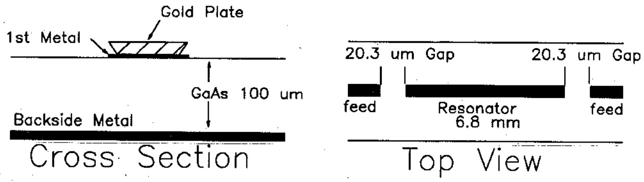

Fig. 1. Microstrip resonator geometry.

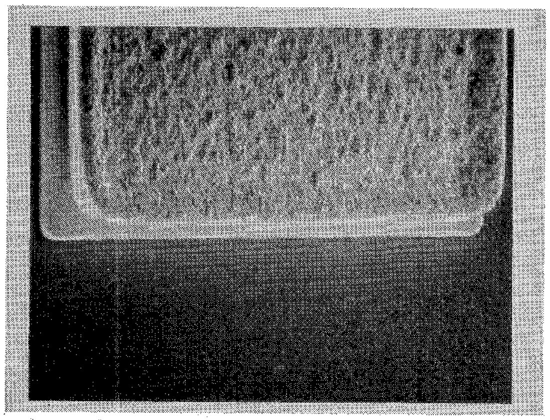

Fig. 2. SEM photograph of 1st metal/plated gold microstrip.

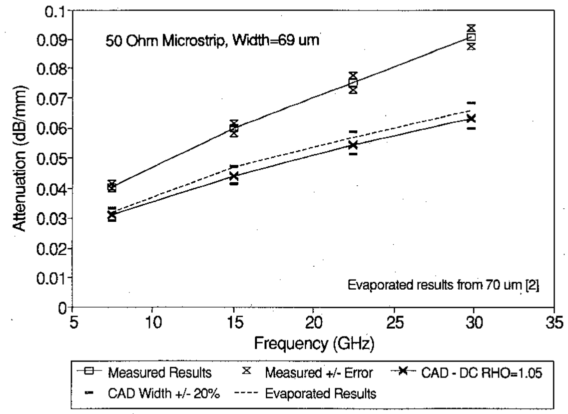

Fig. 3. Measured and CAD attenuations of 69-μm-wide 1st metal/plated gold microstrip lines.

the width of the 1st metal layer. However, there was a small 1.5 μm step-in for processing alignment. The SEM photograph also showed that the plating buildup grew wider at the top, which is typical of the plating process. This may change the "effective" width of the microstrip, so the CAD simulations used a width of 69 μm $+/-$ 20% to show the potential spread of the attenuation coefficients.

The simulated attenuations were tuned to measured data in an attempt to get good correlation. In order to determine which microstrip parameter to adjust, the experimental attenuations were separated into loss components. The major loss components can be divided into three categories: conduction, dielectric, and radiation. Each component has a different frequency dependency [3]. In terms of attenuation (dB/length), conduction losses are proportional to the square root of frequency, dielectric is proportional to frequency, and radiation losses are proportional to frequency cubed. The contributions due to each frequency can be derived by curve fitting the attenuation coefficients of the microstrip to those frequency dependencies. The loss component that contributed most to the attenuation was used for the empirical modeling.

III. Results and Discussion

The results for the measured and theoretical attenuation coefficients were calculated for the microstrip lines. Fig. 3 shows the attenuation coefficients for the 1st metal/gold plate using the dc RHO value of 1.05. For comparison, this graph also includes the attenuation for the evaporated gold microstrip measured by Goldfarb and Platzker. These data were taken from their 70 μm (50 Ω) microstrip graph [2].

It can be seen from Fig. 3 that the 1st metal/plated gold microstrip showed significantly more loss than both the evaporated microstrip and CAD models. The error bars clearly show that experimental error cannot account for this difference. At the fourth resonance (29.9 GHz), a 44% increase in microstrip loss was shown in the 1st metal/gold plate measurements over CAD models. At this frequency, the 1st metal/gold plate microstrip also showed about 38% higher losses than reported for evaporated microstrip. The CAD models show that there is not much spread in the attenuations due to a $+/-$ 20% change in microstrip width. It was concluded from these facts that both the widening of the gold microstrip inherently caused by the plating process and measurement error were not the causes of the attenuation differences.

The differences between the measured losses for plated lines and previously published evaporated microstrip attenuation must be attributed to the microstrip composition. CAD models assume that the microstrip geometry is a rectangular and homogeneous cross section of metal with a uniform bulk resistivity and surface roughness. The good correlation between the models and previous experimental results shows that metal evaporation on GaAs can create microstrip lines that are very close to the geometry that CAD programs simulate. However, the plating process produces multimetal transmission lines that did not show good correlation with modeled data. The major contribution to the differences was attributed to the nonhomogeneous metal cross section that gold plating creates. This causes the dc resistivity of the 1st metal/gold plate not to correctly quantify the attenuation of the microstrip line. The alignment step-in and the way the gold plating built up must also contribute to the modeling error, but not as significantly as the effect of multimetal layers.

IV. Empirical Simulation

The loss components for the 1st metal/gold plate measured results were derived from curve fitting the attenuation to its frequency dependencies. The results are shown in Table I. These values show that the conduction losses dominate the attenuation. Therefore, the microstrip metal resistivity was used to empirically correct for CAD errors. LineCalc's parameter RHO was varied so that the CAD attenuation matched the measured at each resonance. These empirical RHO values are shown in Table I and were more than twice as high as the dc measurements. The tuned RHO values varied with frequency, which was attributed to the changing current densities in each of the different metal layers. An increasing empirical RHO suggests that the more resistive 1st metal layers get larger current densities at the higher frequencies. Normally, RHO is dependent only on the measured dc resistivity of the homogeneous metal composing the microstrip. Gold plating is not a homogeneous metal, and therefore the losses of plated GaAs microstrip cannot be fully characterized with only the dc resistivity of the line. Therefore, an empirical RHO must be used to accurately simulate 1st metal/gold plate microstrip line losses.

TABLE I
LOSS COMPONENT SEPARATION FOR 1ST METAL/GOLD PLATE RESONATOR

Frequency (GHz)	Conduction Loss % of Total	Dielectric Loss % of Total	Radiation Loss % of Total	Empirical RHO value (Unitless)
7.502	91.8	8.0	0.2	2.02
15.004	88.2	10.8	1.0	2.19
22.472	84.7	12.7	2.6	2.28
29.860	81.0	14.0	5.0	2.50

To properly characterize the measured 1st metal/gold plate microstrip, a second-order polynomial was used to describe the frequency varying empirical RHO values. This allowed for simple and accurate empirical modeling to be achieved over the entire frequency range. The empirical RHO values shown in Table I were curve fitted to dc, frequency, and frequency squared components with the least squares method of curve fitting. This curve fitted equation should not be confused with the curve fitting used to separate the conduction, dielectric, and radiation losses. The separation of losses was used to determine which component contributed most to the attenuation. The equation for RHO is only a way to describe how the empirical RHO value changes over frequency.

The polynomial describing RHO can be inserted into the equation block of a CAD program. The equation empirically models 50 Ω gold plated microstrip lines between 5 and 35 GHz. The empirical bulk RHO equation shown below can be inserted into the equation block of a CAD simulator such as Touchstone [4].

$$\begin{aligned} \text{RHO} &= 1.928 + 1.185 \times 10^{-2} \times \text{FREQ} \\ &\quad + 2.3 \times 10^{-4} \times \text{FREQ} \times \text{FREQ} \\ &\quad (\text{FREQ in GHz, RHO is unitless}). \end{aligned} \tag{1}$$

Fig. 4 shows that the use of the empirical RHO equation accurately simulated the measured 69 μm microstrip attenuation factors. These results show that dc measurement of the 1st metal/gold plate microstrip is not enough to fully characterize its loss characteristics at microwave frequencies. Either new theoretical models need to be created, or foundries can use the methods described in this paper to empirically fit parameters which produce modeled data simulating that foundry's particular microstrip construction. The empirical parameters approach is suggested since the microstrip attenuation seems to be the only difference in modeled and measured data. Present CAD models accurately simulate other electrical parameters such as effective permittivity and characteristics impedance. Only the attenuation needs to be empirically modeled, which can be done simply by adjusting RHO. Foundries should keep in mind that this empirical RHO will vary with microstrip width, thickness, metallization proportions, substrate height, and frequency due to the different current distributions for each case. Other transmission lines, such as coplanar waveguide, can be characterized this way in order to obtain more accurate CAD simulations.

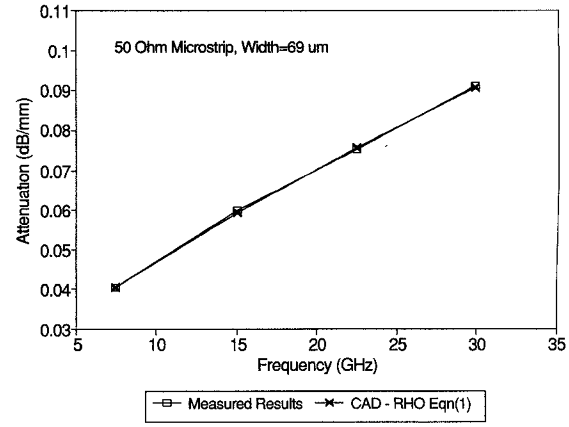

Fig. 4. Accurate modeling of measured attenuation through the use of empirical RHO.

V. CONCLUSIONS

It was shown that the MMIC gold plating process produces microstrip whose attenuation factor was higher than modeled CAD losses at microwave frequencies. This was determined by measuring the Q-factors of 50 Ω microstrip resonators, and comparing the attenuations to CAD models and previously published data. The 1st metal/gold plate losses were 44% higher than CAD models and 38% higher than previously published data for evaporated gold microstrip at 29.9 GHz. The losses of the microstrip were broken into their frequency dependent components to show that the conduction losses dominate the attenuation factor. The 1st metal/gold plate microstrip has multilevels of metal which cause the microstrip's dc resistivity to incorrectly characterize the attenuation in CAD simulations. Empirical bulk resistivities were found for the CAD models so that the higher attenuation caused by the plated microstrip could be properly modeled. This indicates that foundries must characterize each of their transmission line fabrication processes to create empirical design parameters. These results facilitate future CAD design of MMIC's by showing how accurate simulation of microstrip transmission lines can be achieved through proper characterization.

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