Characteristics of Coplanar Waveguide on Sapphire for High Temperature Applications (25 to 400˚ C)

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***Abstract*— This paper presents the characteristics of coplanar waveguide transmission lines fabricated on R-plane sapphire substrates as a function of temperature across the temperature range of 25 to 400˚ C. Effective permittivity and attenuation are measured on a high temperature probe station. Two techniques are used to obtain the transmission line characteristics, a Thru-Reflect-Line calibration technique that yields the propagation coefficient and resonant stubs. To a first order fit of the data, the effective permittivity and the attenuation increase linearly with temperature.**

I. Introduction

There is an increasing demand for microwave circuits that operate throughout the temperature range of 25 to 650˚C for wireless sensors in aircraft engine performance monitoring, oil drilling, and mining machinery [1], [2]. Wide bandgap semiconductors such as GaN and SiC are expected to operate through 500˚ C [3]. GaN and SiC transistors and circuits are often monolithically fabricated on SiC substrates. Microwave components on high purity 4-H SiC have been shown to have low loss through 500˚ C [4], [5], but most GaN and SiC transistors are fabricated on 6-H SiC, which has been shown to introduce very high loss in microwave transmission lines at elevated temperatures [6]. An alternative substrate for GaN and SiC transistors and circuits is Sapphire, and some research has been reported on GaN contacts formed on an r-plane Sapphire substrate operating 500˚ C [7]. Furthermore, Sapphire is a potential substrate for System in Package (SiP) and System on Chip (SiC) because of its low loss tangent.

Before Sapphire may be used as a substrate for wireless sensors operating at high temperatures, its characteristics and those of transmission lines built on Sapphire must be understood. Prior research on the characteristics of transmission lines on Sapphire as a function of temperature is very limited. Sapphire cavity resonators were used to measure the change in the effective permittivity over the frequency range of 2 to 12 GHz and a temperature range of -100 to +200˚ C [8]. Dielectric resonators were used to measure the permittivity at 60 GHz over the temperature range of -50 to +80˚ C [9], and coaxial probes were used to measure the permittivity from 0.5 to 3 GHz at 600 and 800˚ C [10].

In this paper, the effective permittivity and attenuation of coplanar waveguide (CPW) on r-plane sapphire is measured by three different methods. The measurements are performed over the frequency range of 1 to 50 GHz and the temperature range of 25 to 400˚C.

II. Experimental Technique

A 430 μm thick, r-plane Sapphire substrate is used. The CPW test structures are e-beam evaporated using standard lithography, and they are comprised of 0.025 μm of Ti and 1.4 μm of Au. The CPW center conductor width is 130 μm and the slot width is 60 μm, which results in a characteristic impedance of 50 Ω. The measurements are performed on a unique RF probe station that permits measurements across the temperature range of 25 to 500˚ C [11] and a Vector Network Analyzer. A Thru-Reflect-Line (TRL) calibration was performed at each temperature using a thru line of 5000 μm and delay lines of 5844, 7950, 11000, and 20000 μm [12]. The TRL calibration was implemented with the software package Multical from NIST. The temperature of the wafer chuck was set to the desired temperature and held there for 10 minutes before measurements started to allow the Sapphire substrate temperature to stabilize. Measurements were made from 25 to 400˚C in 50˚ C increments.

A. *Effective Permittivity and Attenuation by TRL Calibration*

Because the TRL calibration routine has more data than necessary to determine the error coefficients for the Vector Network Analyzer, this extra information can be used to determine the propagation constant of the thru line used in the calibration [13]. By using multiple delay lines that are averaged in a weighted manner, a very accurate determination of the attenuation, α, and effective permittivity, ε_{eff}, of the CPW is measured. Therefore, besides using the TRL calibration to set the reference plane for later measurements, it is used to measure the CPW propagation constant.

B. *Effective Permittivity by Series Stub*

A CPW short circuit terminated series stub, or spurline filter, and its equivalent circuit are shown in Fig. 1 [14]. Omitting the parasitic reactances of the structure [15], the stub has a transmission minimum when the stub length is an odd multiple of λg/4 where λg is the guided wavelength of the stub, or when the short circuit termination is translated to a series open circuit. A reflection minimum occurs when the stub length is an even multiple of λg/4, or when the short circuit is translated to a series short circuit. Therefore, the effective permittivity may be determined by:

$$\varepsilon_{eff} = \left[\frac{nc}{4Lf_n} \right]^2 \qquad (1)$$

where n is the order of the resonance, c is the velocity of light, L=6492 μm (chosen to have first resonance at 5 GHz), and f_n is the frequency of the minimum for the nth resonance.

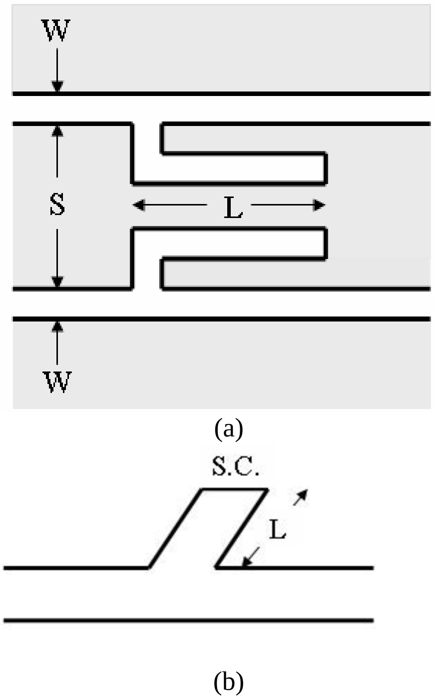

Figure 1: (a) Schematic of short circuit terminated series stub (b) and equivalent circuit.

C. *Effective Permittivity by Shunt Stub*

A CPW open circuit terminated shunt stub and its equivalent circuit are shown in Fig. 2. Omitting the parasitic reactances of the structure, the stub has a transmission minimum when the stub length is an odd multiple of λg/4, or when the open circuit termination is translated to a shunt short circuit at the tee junction. Therefore, the effective permittivity may be determined from (1) [16]. Wirebonds are used at the T-junction to minimize the excitation of the slotline parasitic mode. Stubs of length 6455 and 19365 μm were built with the same strip and slot width as the CPW.

III. RESULTS

The measured attenuation as a function of frequency for each temperature by the TRL technique is shown in Fig. 3. It is seen that the attenuation increases as approximately as $f^{0.5}$, which verifies that the attenuation is conductor loss dominated. It has been reported that the loss tangent of Sapphire is less than 10^{-4} through 80˚ C [9], so this result is expected. It is further seen in Fig. 3 that the attenuation remains low, less than 2 dB/cm at 50 GHz, even for a temperature of 400˚ C.

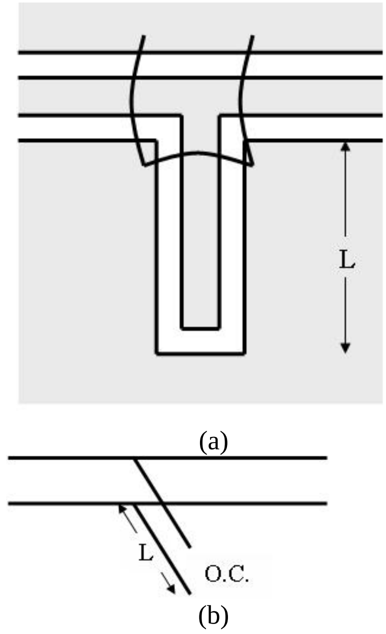

Figure 2: (a) Schematic of open circuit terminated shunt stub and (b) equivalent circuit.

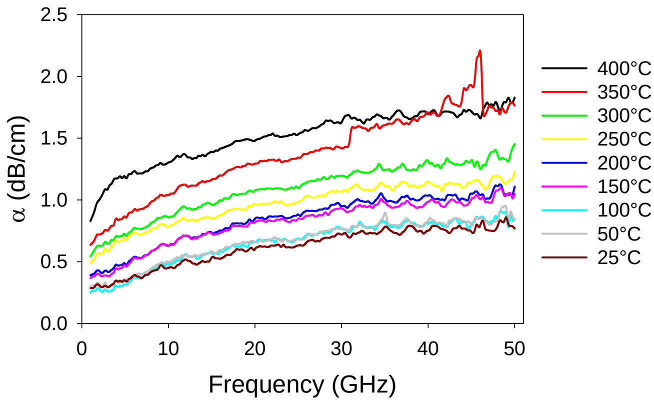

Figure 3: Measured attenuation as a function of frequency by the TRL method.

Using the data in Fig. 3, the measured attenuation as a function of temperature for two frequencies is shown in Fig. 4. It is seen that, to a first order approximation, the attenuation increases linearly with temperature, which is expected for thin metal lines since, to a first order, metal resistivity increases linearly with temperature. If the metal lines were thicker than three skin depths and the second order model for resistivity as a function of temperature were used, the attenuation would increase at a faster rate. The 1.4 μm thick metal lines are less than three skin depths over most of the frequency and temperature range due to the increasing metal resistivity with temperature. For 5 and 25 GHz, the attenuation increases at a rate of 0.0021 (dB/cm/˚C).

The measured S-parameters of the short circuit terminated series stub at 25 and 400˚ C is shown in Fig. 5. The downward shift in the resonant frequency as temperature increases is seen. It is also seen that the minimums in S_{11} and S_{21} are easily obtained. Using this data and the similar data for the shunt stubs, ε_{eff} is extracted from (1).

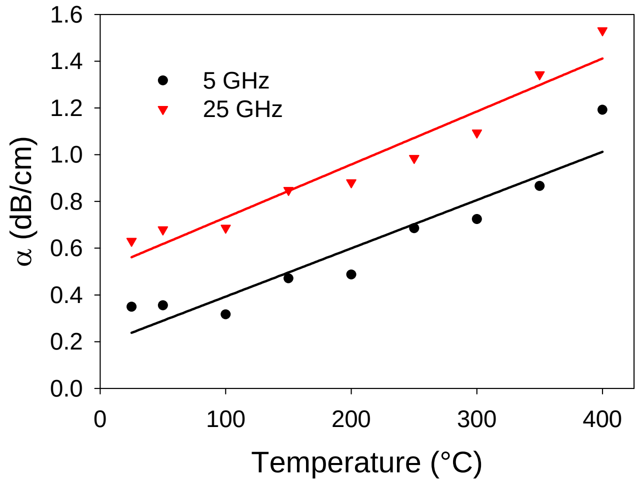

Figure 4: Measured attenuation as a function of temperature.

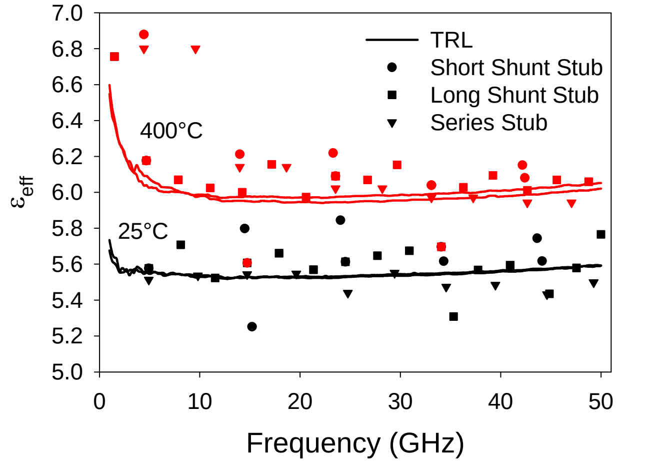

Figure 6: Measured effective permittivity as a function of frequency by three different methods.

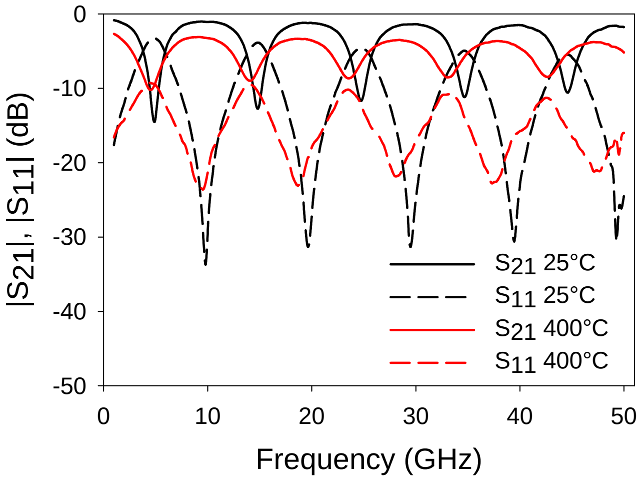

Figure 5: Measured S-parameters of short circuit terminated series stub at 25 and 400˚ C.

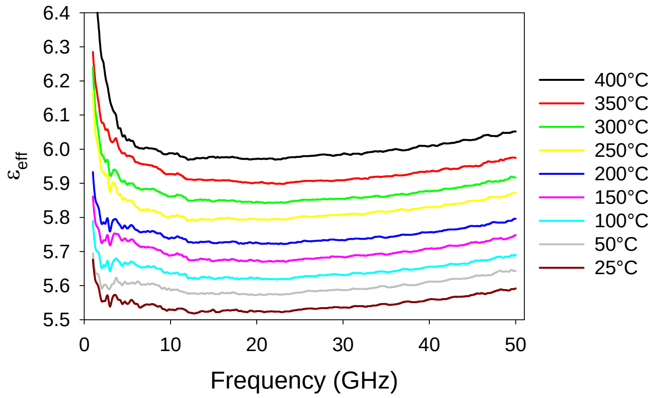

Figure 7: Measured effective permittivity as a function of frequency and temperature by the TRL method.

Figure 6 shows measured ε_{eff} from the TRL calibration, the short circuit terminated series stub, and the two open circuit terminated shunt stubs as a function of frequency for 25 and 400˚ C. The average difference in ε_{eff} for all of the data is less than 3 percent, which indicates the accuracy of the measured ε_{eff}. Figure 7 shows the measured ε_{eff} as a function of frequency and temperature. It is seen that for all temperatures, ε_{eff} has the same variation with frequency, which indicates that there are no physical changes in the CPW lines on Sapphire over the tested temperature range. Finally, Fig. 8 shows the measured ε_{eff} as a function of temperature at 25 GHz. It is seen that ε_{eff} increases linearly with temperature with a slope of 0.0012 /°C. Therefore passive circuit characteristics on Sapphire will not change by more than 8 percent over the 375˚ C temperature range. If the standard approximation, $\varepsilon_{eff}=(\varepsilon_r+1)/2$ where ε_r is the relative dielectric constant, is used for the CPW, it is found that ε_r of the Sapphire is 10 at 25˚ C, 10.2 at 80˚ C, and 11 at 400˚ C. This compares favourably with 9.42 at 25˚ C [9], 9.46 at 80˚ C [9], and 10.5 at 600˚ C [10] reported in the literature.

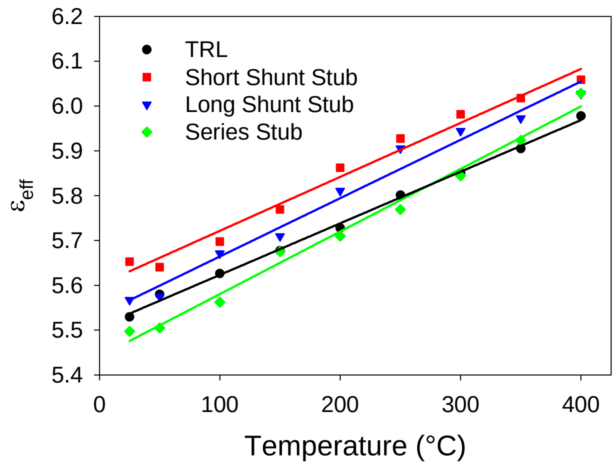

Figure 8: Measure effective permittivity as a function of temperature by three different methods at 25 GHz.

IV. Conclusions

Initial experiments to determine the characteristics of CPW lines on r-plane Sapphire as a function of temperature and frequency have been reported. Three different methods to extract the data showed excellent agreement. The attenuation and effective permittivity increase linearly with temperature for the 375˚ C range. Both the attenuation and the effective permittivity increase at a slow rate. Therefore, Sapphire should be a good high temperature substrate for integrated circuits and packaging at high temperature.

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