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Vanadium Oxide Thin-Film Variable Resistor-Based RF Switches

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***Abstract*—Vanadium dioxide (VO_2) is a unique phase change material (PCM) that possesses a metal to insulator transition. Pristine VO_2 has a negative temperature coefficient of resistance and undergoes an insulator to metal phase change at a transition temperature of 68°C. Such property makes the vanadium dioxide thin film based variable resistor (varistor) a good candidate in reconfigurable electronics, to be integrated with different RF devices like inductors, varactors, and antennas. Series single-pole single throw (SPST) switches with integrated VO_2 thin films were designed, fabricated and tested. The overall size of the device is 380 µm x 600 µm. The SPST switches were fabricated on a sapphire substrate with integrated heating coil to control VO_2 phase change. During the test, when VO_2 thin film changed from insulator at room temperature to metallic state (low resistive phase) at 80ºC, the insertion loss of the SPST switch was below 3 dB at 10 GHz. And, the isolation of the SPST improved to better than 30 dB when the temperature dropped to 20°C. These tunable characteristics of the RF switch provide evidence for VO_2 as a useful PCM for broad range of applications in reconfigurable electronics.**

***Index Terms*—Vanadium dioxide (VO_2), thin film, varistor, metal-insulator transition, switch, coplanar waveguide (CPW).**

I. Introduction

Vanadium oxides attract researchers' attention recently due to the unique property in metal-insulator transition (MIT) [1, 2] at various temperatures. Since the discovery of MIT in 1959 by Morin [1], the research focus was mainly on VO_x or combined multiphase vanadium oxides. This was due to the limitations in manufacturing technologies to obtain high quality, single phase vanadium oxide thin films. The stable forms of vanadium oxides for microelectronic devices are VO, V_2O_3, VO_2, V_2O_5 and VO_3 [3-10]. Research on electro-chromic and thermo-chromic effects have been studied on VO_x for electro-optical device applications, initiated by Honeywell in 1990s [11]. Since then it had become one of the promising materials in current uncooled IR imager manufacturing. Advancement in thin film deposition such as pulsed laser deposition (PLD) during recent decades provided necessary technologies to lay down single phase vanadium oxide such as VO_2. VO_2 has a constant and stable insulator to metal transition temperature at 68°C and superior resistivity ratio between metallic and insulator phases compared to other forms of vanadium oxides [12-18]. With pure VO_2, such large amplitude change in resistivity provides a good opportunity for researchers in reconfigurable electronics area with simplified device structures. Recently, tunable devices have attracted a lot of attention in electronics in order to build a more versatile systems with fewer devices [19, 20]. Specifically in modern communication systems, the flexibility of reconfigurable RF and microwave electronics will support multiple modes over a wide bandwidth and a variety of communication protocols.

Typical reconfigurable devices include variable capacitors (varactors), variable inductors and variable resistors (varistors). These adaptive devices could allow the engineers to dynamically match the impedance of power amplifiers (PAs), tunable filters, and phase control circuits.

The VO_2 property we used in this article will focus on varistor RF/microwave applications. Currently the resistance change in terms of the MIT has been researched [21-23]. The resistance of VO_2 has been measured in different kinds of experiments. First, the resistance of VO_2 was measured at hydrostatic pressures up to 2GPa and room temperature by using electric-field-induced resistance switching (EIRS) of VO_2 planar-type junctions [24]. Second, the VO_2 was fabricated in number of parallel strip patterns in the varistor, and the resistance of VO_2 thin film has been measured [25]. Third, the resistance of the VO_2 was measured by VO_2 thin film based RF shunt resonator, and the VO_2 thin film was deposited as shunt resistance in this device [26].

In this paper, the study of achieving high quality single phase VO_2 thin film using the pulsed laser deposition technique is presented. SPST device has been used as an example to demonstrate the effect of VO_2 thin film in RF device performance.

II. Design of Series Single-Pole Single Throw (SPST) Switch Device

A series single-pole single throw (SPST) switch is designed with the VO_2 thin film. The series SPST switch is implemented in a coplanar waveguide (CPW) transmission line configuration. A coupled line structure is formed in the middle of the signal line of the CPW, with the VO_2 thin-film designed to bridge between input and output signal lines. At room temperature, the VO_2 film acts like an insulator making the

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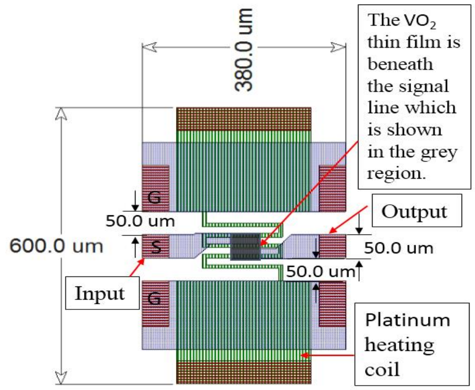
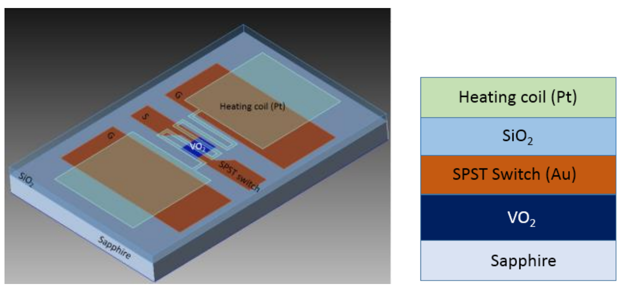
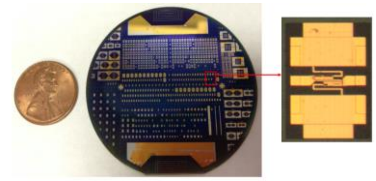


Figure 1. The top view of a VO_2 thin film series SPST switch, showing the coplanar waveguide structure. The VO_2 thin film is beneath the signal line which is shown in the dark region, and this switch has 50 µm width and 10 µm gap between coupled lines.



(a) (b)

Figure 2. (a) The top view of layers of the VO_2 thin film switch; (b) Cross-sectional view showing the platinum (Pt) heating coil on the top layer, then SiO_2, Au, VO_2, and sapphire substrate.



(a)

(b)

Figure 3. (a) The photos of VO_2 thin film series single-pole single throw (SPST) switch. (b) The heating station and temperature controller.

device off. At temperatures above 68°C, the VO_2 film becomes a conductor allowing signal to go through. For better impedance matching, the switch is designed to work with a transmission line characteristic impedance of 50 Ω.

The overall size of the device is 380 µm x 600 µm. The small rectangular dark region in the middle of Figure 1 is the VO_2 thin film layer introduced in the coupling gap of the input/output signal lines. The platinum (Pt) heating coil is introduced on top of the VO_2 thin film using a SiO_2 isolation layer. The heating coil is shown as a meandering line (green in color). The marked G, S, G (stands for Ground, Signal, Ground) in Figure 1 are part of the CPW line conductor, typically made of Au. The layers of the VO_2 thin film switch are VO_2/Au/SiO_2/Pt on a sapphire substrate shown in Figure 2 with the Pt layer as the top layer. The corresponding thicknesses are 0.35 µm for VO_2, 0.5 µm for Au, 0.3 µm for SiO_2, and 0.1 µm for Pt.

III. Experiment

To fabricate the device, the VO_2 layer was first deposited uniformly on the whole wafer using a pulsed laser deposition technique. Then VO_2 was patterned and dry etched to remove unwanted areas. The standard lift-off process was used for Ti/Au thin film layer of ~ 500 nm to fabricate the CPW structure (G, S, G). After that, the functional device was passivated by a layer of 300 nm silicon dioxide by PECVD at 300 °C followed by a thin layer of platinum heating coil on the top.

To obtain pristine VO_2 thin film is critical in tunable device fabrication. A typical VO_2 deposition uses a 248 nm excimer laser, striking a target of vanadium disk, with the laser energy density of 3.5 J/cm^2 at 10 Hz repetition rate. A reactive deposition is performed at a substrate temperature of 500°C in an optimized oxygen partial pressure. In pulsed laser deposition of VO_2, oxygen partial pressure determines the quality of the film. Three different oxygen pressure conditions were studied, which are, 25 mTorr, 35 mTorr and 45 mTorr. Grain size and film composition were compared for these conditions. Samples fabricated on silicon with exactly same deposition conditions were used, for better imaging in a scanning electron microscope. The X-ray diffraction (XRD) is used as another metrology tool to identify the crystal structure of VO_2 film.

All fabricated devices in this article were tested using swept frequency scattering parameter measurements up to 15 GHz. The return loss (S_{11}) and insertion loss (S_{21}) were obtained for the device while sitting on a temperature controlled stage, and using on-wafer probes. First, each single device was tested at room temperature with external controller set at 20°C. The testing setup is shown in Figure 3. A HP 8720B network analyzer was used for experimental measurements, using a probe station and cascade SP-ACP40-GSG-150-C probes. The probes were placed in the left edge and right edge of the transmission line for the swept frequency S-parameter measurement. Figure 3(a) shows the fabricated VO_2 thin film series single-pole single throw switch on the wafer, and this wafer is a 2" sapphire substrate. Figure 3(b) shows the heating station. A temperature controller is used to heat the wafer and control the temperature of measurement from 20 °C to 100 °C.

IV. Results and Discussions

Figure 4 shows SEM pictures of the VO_2 grain size on

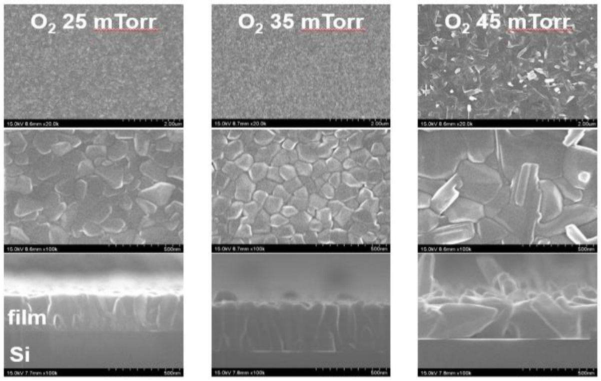


Figure 4. Visual comparison of VO_2 grain size on silicon substrate for each oxygen partial pressure. (Top view: 20k and 100k magnification)

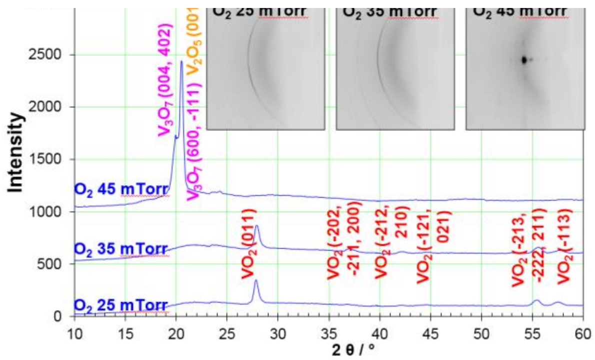


Figure 5. XRD measurement of vanadium oxide thin film of each oxygen condition.

silicon substrate at each oxygen partial pressure. The grain sizes are different in the films processed under different oxygen conditions. The film using 35 mTorr oxygen partial pressure condition has more uniform and finer grains compared to 25 mTorr and 45 mTorr conditions. At 25 mTorr, the grain size is around 250 nm, at 35mTorr condition, the grain size is around 100 nm, and at 45 mTorr condition, the grain size is around 300 ~ 500nm. Figure 5 shows the XRD measurement on each sample. The films formed from 25 mTorr and 35 mTorr partial oxygen pressure conditions is VO_2, but the one from 45 mTorr condition is V_2O_5 instead of VO_2. This result shows the VO_2 thin film can be obtained from oxygen partial pressure of 25 mTorr and 35 mTorr conditions. Therefore, electrical measurements of these conditions are necessary to distinguish further.

The resistivity measurement results of all three conditions on glass substrate are shown in Figure 6, and this figure indicates that vanadium oxide films on glass substrate deposited at 45 mTorr condition has different resistivity vs. temperature properties from other two conditions. Although there's no significant indication on material difference from XRD measurement for 25 mTorr and 35 mTorr cases, the resistivity measurement on both conditions help address the difference. From the measurements, vanadium oxide film with 25 mTorr processing condition has only one order of magnitude change on resistivity from room temperature (20°C) to high temperature (100°C). And the vanadium oxide film deposited at 35 mTorr has as high as three orders of magnitude change compared to two orders of magnitude change at 45

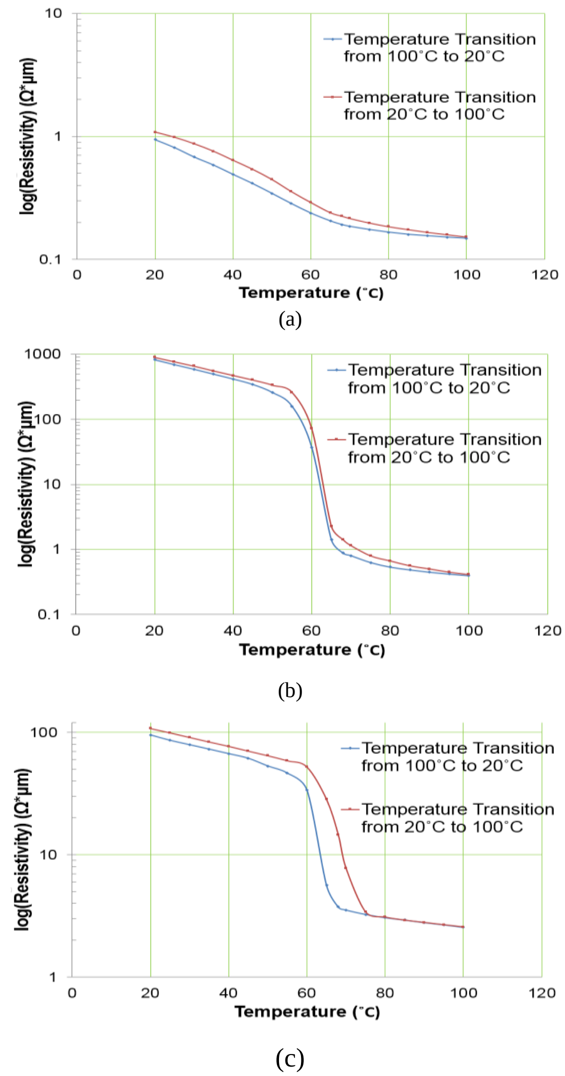


Figure 6. Resistivity measurements of vanadium oxide films on glass substrate deposited at (a) 25 mTorr, (b) 35 mTorr, and (c) 45 mTorr.

mTorr processing condition. From all these analyses, 35 mTorr oxygen partial pressure is chosen as the processing condition for device fabrication due to its highest resistance change in the metal-insulator transition.

Moreover, the measured results show that the resistivity of the VO_2 films is substrate dependent as well. Compared to glass substrate, sapphire substrate has even better phase transition performance with less hysteresis between room temperature and high temperature [26]. Therefore, for the

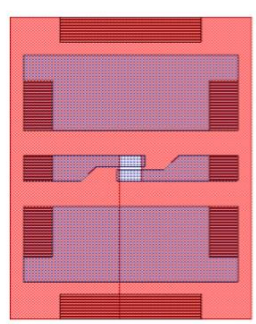


Figure 7. SPST switch without SiO_2 and heating coil Pt layers.

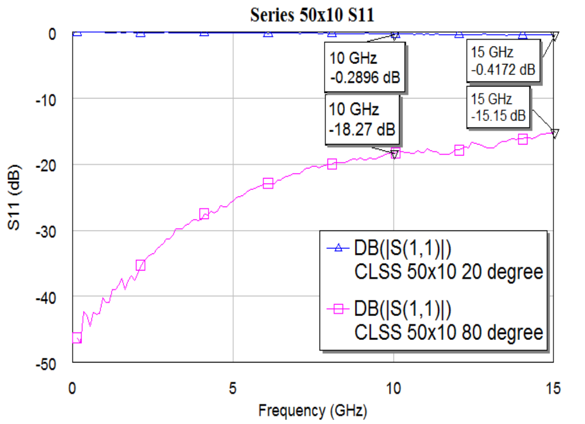


Figure 8. The measured S_{11} of VO_2 coupled line series SPST switch without SiO_2 and heating coil Pt layers at temperatures 20ºC and 80ºC.

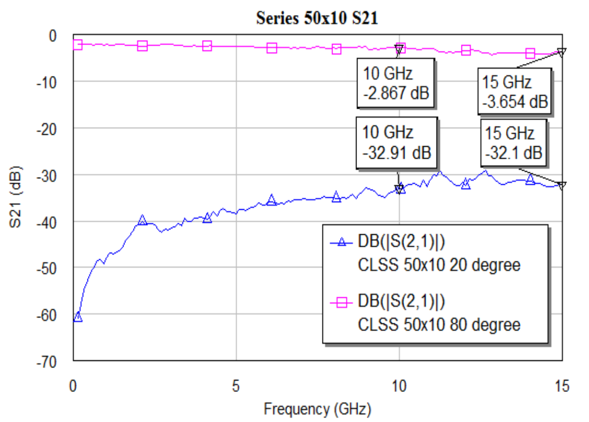


Figure 9. The measured S_{21} of VO_2 coupled line series SPST switch without SiO_2 and heating coil Pt layers at temperatures 20ºC and 80ºC.

better quality, sapphire substrate was selected to fabricate RF devices in this research.

The VO_2 thin film series SPST switch is a multi-layered device. To carefully study VO_2 performance throughout fabrication process, the measurements were separated into two stages. The first stage was to measure the S-parameter only when VO_2 and Au layers were deposited. The Figure 7 shows the structure of SPST without the SiO_2 and Pt heating coil layer. The measured S_{11} is greater than -1 dB at 20 ºC, and it is less than -20 dB at 80ºC shown in Figure 8. The measured S_{21} is less than -30 dB at 20ºC, and it is greater than -4 dB at 80ºC as shown in Figure 9.

When the temperature was at 20ºC, VO_2 acted like an insulator and the RF signal would not pass through the transmission line. When the temperature was increased to 80ºC, the VO_2 acted like a conductor, and most input signal was able to pass through it. The VO_2 thin films series SPST switch showed that the phase transition was achieved by integrating the VO_2 thin film with SPST switch.

The second stage was to measure the S-parameters when VO_2, Au, SiO_2 and Pt layers were deposited. Figure 10 shows the SiO_2 and Pt heating coil layers have been fabricated with the series SPST switch. The measured result of the S_{11} is worsened at 20ºC, and it is below -15 dB at 80ºC as shown in Figure 11. The S_{21} is less than -20dB at 20ºC, and it is greater than -5dB at 80ºC as shown in Figure 12. Compared to the measured S_{11} and S_{21} in the first stage, the measured results of S_{11} with SiO_2 and Pt layers are around 6 dB worse than the measured S_{11} without SiO_2 layer, and the measured results of S_{21} with SiO_2 and Pt layers are around 10 dB worse than the measured S_{21} without SiO_2 layer. Therefore, such experimental results have showed that the addition of SiO_2 has some negative effect on the performance of VO_2. However the XRD measurement on the substrate at this stage shows no sign of VO_2 crystal structure change. Further study will be conducted on understanding the effects of SiO_2 deposition on VO_2.

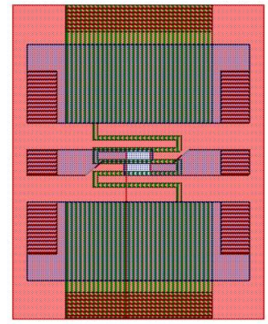


Figure 10. The SPST switch with SiO_2 and heating coil Pt layers.

The commercial microwave frequency simulation tool, AWR from NI was used to import the measured results of the

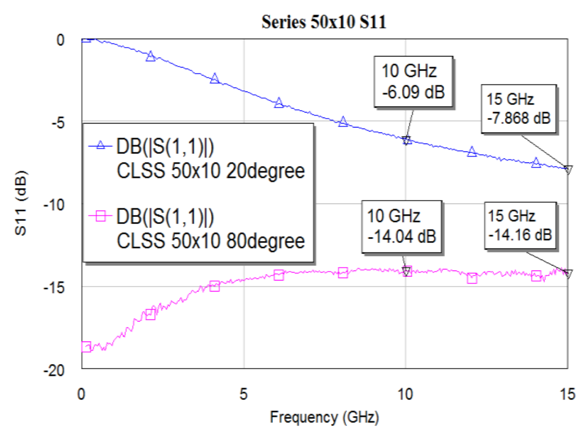


Figure 11. The measured S_{11} of VO_2 coupled line SPST switch with SiO_2 and heating coil Pt layers at temperatures 20ºC and 80ºC.

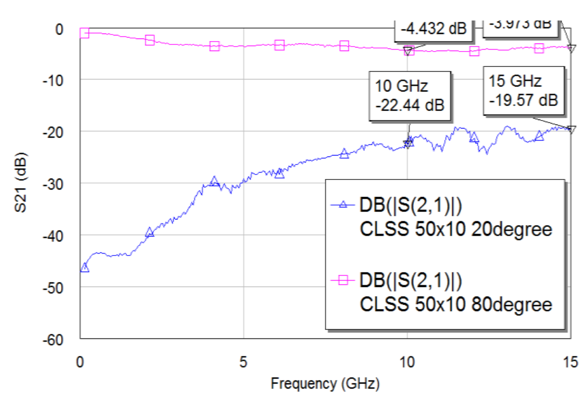


Figure 12. The measured S_{11} of VO_2 coupled line SPST switch with SiO_2 and heating coil Pt layers at temperatures 20ºC and 80ºC.

fabricated device, develop a schematic electrical circuit model, and compute the scattering parameters over the predefined frequency range. Two electrical models were used to find the different resistances of VO_2 at different temperature conditions, 20ºC and 80ºC by matching the S-parameters (S_{11} and S_{21}) of the measured results without the SiO_2 and Pt layers.

The input and output ports of the electrical models are connected with transmission lines in the form of CPW structure. In the electrical model, W is the width of the transmission line, S is the gap between the transmission line and the ground, and L is the length of the transmission line. Based on the design of the devices, W is 50 µm, S is 50 µm, and L is 165 µm.

The electrical model in Figure 13 is used to match the S_{11} and S_{21} at 20ºC. The resistor R_3 in this electrical model is used to determine the resistance of VO_2 thin film varistor and the capacitor C_3 is used to represent the capacitance between the transmission lines. The resistance of VO_2 is around 73.3K Ω, and the capacitance of C_3 is 0.0058pF in the insulating state of VO_2 at 20º C. The capacitors of C_1, C_2 and the resistors of R_1,

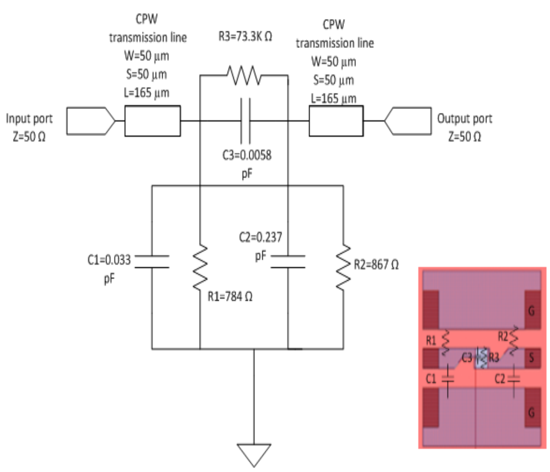


Figure 13. Electrical model matching results for 20ºC.

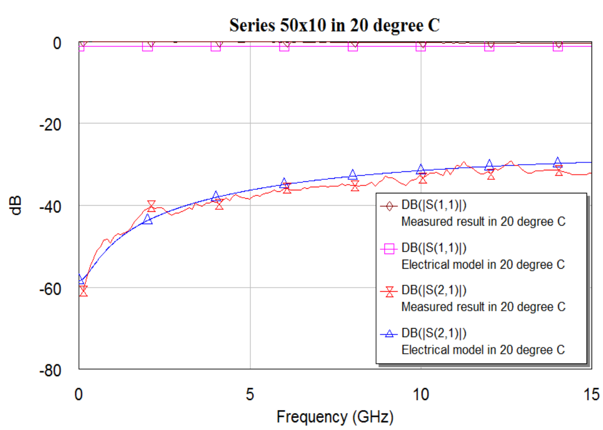


Figure 14. The S_{11} and S_{21} of measured results and S_{11} and S_{21} of electrical model matched at 20 ºC.

R_2 represent the capacitance and resistance between the signal line and ground plan of the CPW structure. The corresponding capacitance of C_1 is 0.033 pF, C_2 is 0.237 pF, and the resistance of R_1 is 784 Ω, and R_2 is 867 Ω based on fabricated device structure. The matched results are shown in Figure 14.

Figure 15 shows the other electrical model which is used to match S_{11} and S_{21} at 80ºC temperature. Compared to the electrical model in Figure 13, there is no capacitance between the two transmission lines in the electrical model of Figure 15 because VO_2 becomes conducting when the temperature is increased to 80 ºC and the two transmission lines are connected by the VO_2. In this electrical model, the resistor R_3 represents the resistance of VO_2 in the conducing state, which is around 13 Ω. The capacitors of C_1, C_2 and the resistors of R_1, R_2 represent the capacitance and resistance between the signal line and ground plane of the CPW structure. In this case, the capacitance of C_1 is 0.0165 pF, C_2 is 0.117 pF, and the resistance of R_1 is 300 Ω, and R_2 is 866 Ω. The matched results are shown in Figure 16.

From the matching of the results, the resistance of the VO_2 is 73.3 KΩ at 20ºC and becomes lower resistance of about 13 Ω at the temperature of 80ºC. The resistance ratio is 5600 which is similar magnitude level of VO_2 resistivity ratio

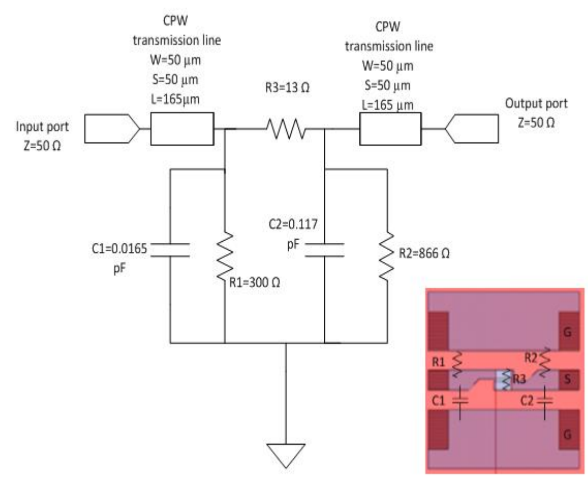


Figure 15. Electrical model matching results for 80ºC.

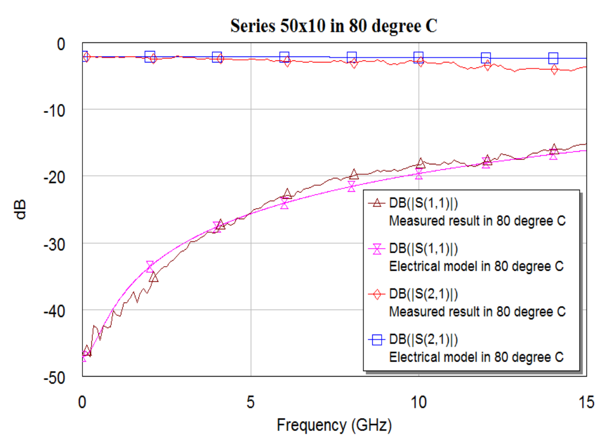


Figure 16. The S_{11} and S_{21} of measured results and S_{11} and S_{21} of electrical model match results at 80ºC.

outlined by Figure 6(b).

V. Conclusion

In this article, the impact of oxygen partial pressure on VO_2 thin film deposition conditions were studied. High quality VO_2 thin films were obtained for the oxygen partial pressure of 35 mTorr. VO_2 thin films exhibited sharp insulator to metal transition at 68ºC, with the resistance of the thin film varistors changing by more than three orders of magnitude. A series single-pole single throw (SPST) switch built using VO_2 thin film showed that the isolation is better than 30 dB at room temperature and the insertion loss is below 5 dB at temperatures above 68ºC. Although VO_2 based switches shows less ideal RF performance compared to RF MEMS switches [27-29], the switching time could be as fast as 5 ns [30-31] compared to 25 µs of a MEMS switches [29] and such devices have no fatigue concern which is typical in RF MEMS switches. In addition, the manufacturing cost could be much lower with such simple device structure.

It's also worth mentioning that the measured results showed that the VO_2 is affected by the subsequent SiO_2 deposition process. Other alternate low temperature passivation layers will be investigated in the future. Other future plans for this research also include study of applications of VO_2 in reconfigurable antennas, varactors, and tunable inductors and ultimately using integrated Pt heating coil to control the SPST switches instead of using external heating source. Standalone devices could have broader applications in reconfigurable electronics.

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