An Ultra-low Loss Millimeter-wave Solid State Switch Technology Based on the Metal - Insulator - Transition of Vanadium Dioxide

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Abstract — A new ultra-low-loss and broad band millimeter wave switch technology based on the reversible metal / insulator phase transition of vanadium dioxide has been developed. We report having fabricated series configured, single-pole single-throw (SPST) switches having measured S-parameters from DC to 110 GHz. The on-state insertion loss is 0.2 dB and off-state isolation is 21 dB at 50 GHz. The resulting impedance contrast ratio, Z_{OFF} / Z_{ON}, is greater than 500:1 at 50GHz (i.e. cut-off frequency f_c ~ 40 THz). As a demonstration of the technology's utility, we also present the results of a 2-bit real time delay phase shifter incorporating a pair of VO_2 SP4T switches. This switch technology's high impedance contrast ratio combined with its compactness, ease of integration, and low voltage operation make it an enabler of previously unachievable high-performance millimeter wave FPGAs.

Index Terms — VO_2, Phase Change Switch, Vanadium Dioxide, Low Loss RF Switch, RF-FPGA.

I. INTRODUCTION

Our development of a vanadium dioxide switch is the result of a search for an RF switch with near ideal properties to support the level of switching complexity required to realize a programmable transceiver. Reconfiguration of an RF transceiver requires either bias-gated signal paths or high-frequency switches. While bias-gating (removing active stages by turning off their bias) appears attractive, the MOSFET off-state input and output capacitances are both ~40% of the on-state C_{gs}; hence inactive gain stages and signal paths still provide considerable parasitic loading to the active stages, degrading gain, $F_{\min}$, and IP3. Alternatively, silicon MOS, InGaAs BIFET, and III-V MOS FET switches could be used to isolate inactive stages, removing their loading from the selected circuit. However, an FET's on-resistance is $\sim 1/g_m$, while the sum of all MOSFET off-state capacitances $C_{gs,off}$, $C_{dg,off}$, $C_{s,bulk}$, and $C_{d,bulk}$ are comparable to the on-state capacitance C_{gs}. The FET off/on impedance contrast ratio is thus $g_m / 2\pi f_{signal} C_{gs}$, which is approximately f_T / f_{signal}, thus only ~ 6:1 using 65 nm CMOS at 50 GHz.

Given this poor impedance contrast and the fan in/out required for programmable switched signal paths, present MOSFET switches are insufficient for RF-FPGA's at frequencies exceeding 10GHz. Much better switches are needed. Vanadium dioxide is known to undergo a thermally driven phase transition that results in a resistivity change greater 10^4 over a temperature excursion of a few degrees near 68 °C [i]. Excellent VO_2 films can be produced with a metallic-state sheet resistance in the range of 2 - 5 Ω / □.

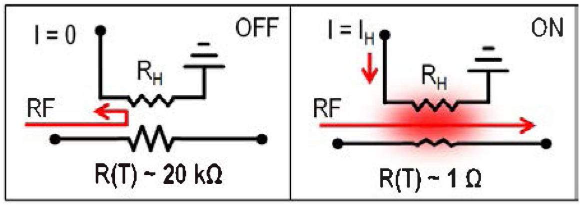

Fig. 1. Schematic of the vanadium dioxide phase change switch.

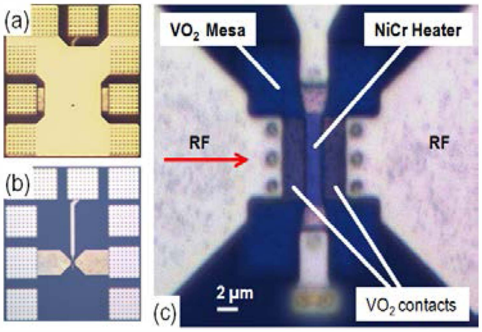

Fig. 2. Top view of the baseline switch test structure (a). GSG probe pads are provided for RF (east / west) as well as for heater bias (north). Views of the switch prior to top metal deposition are shown in (b) and (c).

Switches incorporating VO_2 have been fabricated having an off-state capacitance of approximately 4 fF and on state resistance of about 1 Ω. Such switches yield an impedance contrast ratio exceeding 500:1 at 50GHz (cutoff frequency $f_c = 1/(2\pi R_{on} C_{off})$ ~ 40 THz), enabling high-performance millimeter wave FPGAs.

II. VANADIUM DIOXIDE

Vanadium dioxide is a thermo-chromic material that undergoes a reversible insulator to metal transition (MIT) at ~ 68°C. The material has found wide use in a variety of applications including solar rejection, optical modulation, and imaging. A crystallographic transformation from a low-temperature monoclinic structure to a high-temperature tetragonal structure alters the nearest neighbor spacing of the vanadium atoms and modifies the band structure, thus yielding the MIT properties [i]. While recent studies indicate that the structural transition may not be the only transformation

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involved, it is certain that the structural change always accompanies the phase change and is reversible [ii,iii]. The MIT has resulted in recorded resistivity differences of 10^5 between the insulator and metallic states for single crystal material. Furthermore, the transition has been measured to take place over as little as 0.1 °C [iv]. Our work developing grain-oriented thin film vanadium dioxide on lattice-matched substrates such as sapphire has led to resistivity differences of $6x10^4$ and transformation widths of 2-4°C[i]. Growth of an un-oriented film on a lattice-mismatched substrate, such as silicon, generally reduces the resistivity difference by one or two orders of magnitude and increases the transformation width to 5-10°C [i]. To obtain the lowest loss switches possible, we have opted to deposit the VO_2 on c-axis oriented sapphire substrates.

III. SWITCH DESIGN & FABRICATION

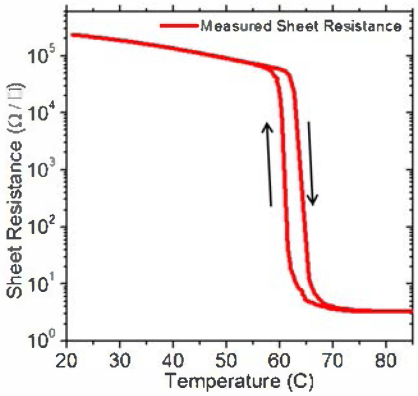

Fig. 4. Measured sheet resistance as a function or temperature for the 600 nm thick VO_2 deposition used to fabricated the switches reported herein.

The basic single-pole single-throw switch is constructed by separating two RF terminals by a series connected VO_2 *thermistor* element having a temperature dependant resistance, R(T) (see Fig. 3b). Placed in close proximity to the thermistor is a nickel chromium (NiCr) resistive heater. In the normally off condition, R(T) ~ 20 kΩ and the switch terminals are well isolated. Application of sufficient heater power results in R(T) ~ 1 Ω. A SPNT switch can be realized by combining the input terminals, *N,* SPST switches. We demonstrate an SP4T switch as discussed later.

Vanadium dioxide films are deposited on 75 mm diameter epitaxial grade c-axis oriented sapphire wafers. Films of approximately 600 to 1000 nm thick provide a sheet resistance of 2 - 5 Ω / □. VO_2 films are deposited over the surface of the wafer using an RF sputtering chamber.

The switches utilize the architecture shown in Fig. 3a. Many transmission line options are available in this wiring environment; we have chosen to use inverted microstrip. This layout provides excellent topside isolation when performing chip-to-chip hybridization. MET3 is used as the ground plane, MET2 is used for DC bias routing, and MET1 is used at the RF signal level. A 50 Ω MET1 transmission line is 1 µm thick x 6 µm wide.

Patterned atop the VO_2 are two ohmic contacts (VMET) separated by a gap, L_g, that form the analog of an FET channel. Deposited over the VO_2 and contacts is a 300nm SiO_2. Patterned on the SiO_2 DC isolation layer and aligned between the VMET contacts is a nominally 50 Ω / □ NiCr thin film resister (TFR) heater having a length, Lh, and width, W. At both ends of the heater's length are ohmic contacts. The VO_2 is patterned to form independent switch mesas, approximately 20 µm X 20 µm. A benzocyclobutene (BCB) dielectric layer covers this stack-up and is nominally 2 µm thick as measured from the substrate surface. A 3-metal layer MMIC process is used provide RF and DC interconnection to the device and provide I/O pads. This wiring environment includes the availability of MIMCAP and TFR structures.

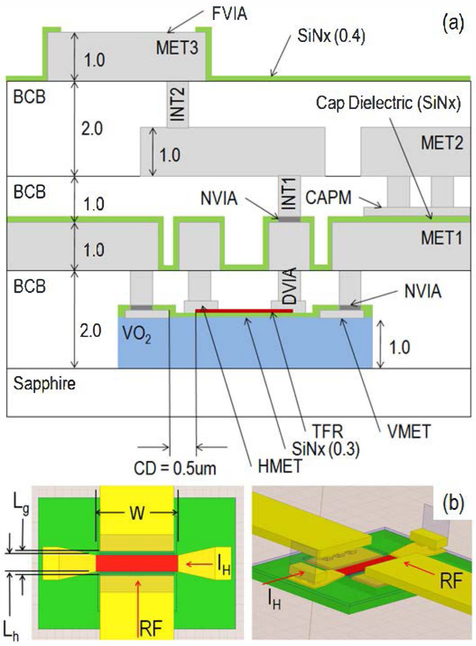

Fig. 3. (a) Schematic cross-section of the VO_2 switch technology showing the switch at the substrate level and 3-metal level interconnects with low loss BCB. (b) Shows the basic switch topology.

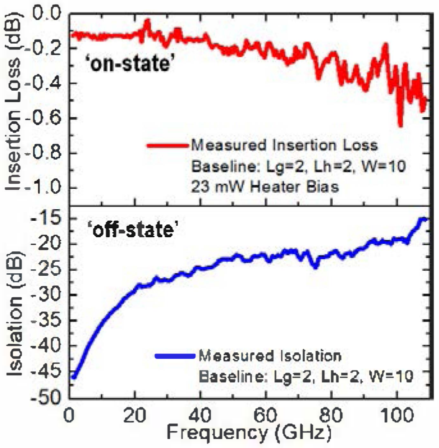

Fig. 5. Transmission properties of the baseline SPST switch measured from 1 to 110 GHz. The red trace represents the on-state performance at 23 mW of heater power while the blue trace was produced with zero heater current (off-state).

IV. RESULTS

Our baseline SPST switch has heater dimensions of W = 10 µm by 2 µm, and a channel with L_g = 2 µm. This switch requires approximately 20 mW of heat to saturated the VO_2 metallic state; or equivalently a bias of about 2V and 8mA. The measured transmission characteristics are shown in Fig. 5. At 50GHz, for device provides 21.5 dB of isolation in the off-state and -0.2 dB of insertion loss in the on-state. Remarkably, at 110GHz, the on-state insertion loss is approximately 0.5 dB while the off-state isolation approaches a respectable 15 dB. In this switch, the off and on state resistance have been measured to be 17 kΩ and 1 Ω respectively. The off-state capacitance extracted from the measurement is 3.5 fF. The on-off and off-on switching delay has been measured to be 2 µs.

As a demonstration of the utility of this switch technology, we fabricated and characterized a 50GHz, 2-bit phase shifter design. The phase shifter is constructed by using two SP4T switches connected with four different lengths of transmission line including a thru, thru + 90°, thru + 180°, and thru + 270°. The results are shown in Fig 6.

V. CONCLUSION

A compact vanadium dioxide switch with a 40THz cut-off frequency has been demonstrated. Furthermore, the switch requires only 8mA at 2 volts for operation which can be easily achieved with CMOS circuitry. The device's utility has been successfully demonstrated with 2-bit true-time-delay circuit.

VI. ACKNOWLEDGEMENTS

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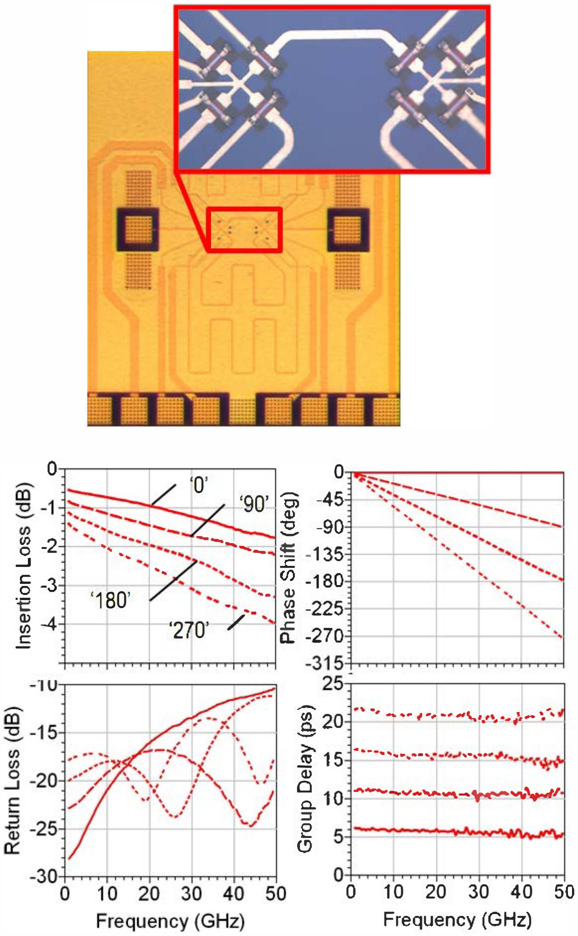

Fig. 6. The top image shows a demonstration 2-bit phase shifter circuit. The internal metal traces have been graphically superimposed over the image for clarity. An exploded image of the SP4T switches is also shown. In the lower image, the phase shifter insertion loss, return loss, phase shift, and group delay are plotted for each of the four phase states.

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