Ka-Band MEMS Switches on CMOS Grade Silicon with a Polyimide Interface Layer

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***Abstract* — For the first time, RF MEMS switches on CMOS grade Si with a polyimide interface layer are fabricated and characterized. At Ka-Band (36.6 GHz), an insertion loss of 0.52 dB and an isolation of 20 dB is obtained.**

I. INTRODUCTION

Over the past ten years, there has been a paradigm shift within the microwave industry towards low cost circuits that provide just enough performance to accomplish the system goals. At the same time, system goals have been shifting towards highly integrated circuits that provide all or most of the system, including the analog, RF, and digital circuits, on a single chip or within a single package, and to circuits that consume less power. Two separate technologies have been developed recently to meet these divergent system goals. The first is MicroElectroMechanical Systems (MEMS) applied to RF/microwave circuits, primarily as switches in phase shifters [1-3]. RF MEMS switches and phase shifters are relatively simple to fabricate, requiring only five mask levels and no ion implantation, MOCVD, or MBE material growth as required for traditional Microwave Monolithic Integrated Circuits (MMICs), which decreases the fabrication cost. In addition, they consume negligible DC power. The second revolutionary technology is the fabrication of MMICs on Si with the relatively recent development of SiGe Heterojunction Bipolar Transistors [4-6] and short gate length CMOS transistors [7] with high f_T and f_{max}. Because standard CMOS processing is used, these circuits are fabricated in large volume on 8 to 12 inch Si wafers, and the monolithic integration of RF and digital circuits is possible.

Although the processing technologies used in RF MEMS circuits does not limit their use to a particular substrate, GaAs [1], quartz/fused glass [2], and High Resistivity Silicon (HRS) [3] have been used because they are low loss substrates for microwave integrated circuits. While Si MMICs can be fabricated on HRS, the major foundries prefer standard CMOS grade Si wafers because of familiarity and availability in large wafer diameter. Fabrication of low loss microwave circuits on CMOS grade Si is difficult because the substrate resistivity is 0.1-20 Ω-cm, depending if a CMOS or BiCMOS process is used, which can cause high losses unless non-standard transmission lines are used [8]. One such promising technique is to use a polyimide interface layer between the Finite Ground Coplanar waveguide (FGC) and the Si wafer to minimize electromagnetic field interaction with the Si substrate as shown in Fig. 1. Such a structure has already been used to demonstrate antennas [9], filters [10], and couplers [11] on CMOS grade Si.

In this paper, we present for the first time the fabrication and characteristics of RF MEMS switches on a CMOS grade Si wafer (substrate resistivity equal 15 Ω-cm) with a polyimide interface layer. The intent of this first attempt to build a MEMS switch on polyimide is to demonstrate the fabrication and operation of the MEMS device. Thus, the FGC and switch design were not optimized for performance on the structure shown in Fig. 1.

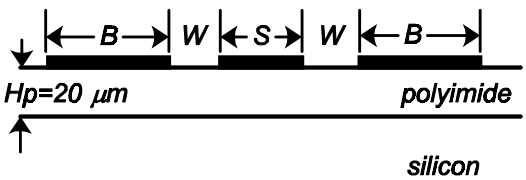

Fig. 1: Schematic of Finite Ground Coplanar waveguide on a Si wafer with a polyimide interface layer.

II. CIRCUIT DESIGN

The circuit is comprised of FGC on a 20 μm thick polyimide layer over the 15 Ω-cm Si wafer. The MEMS switches are doubly anchored cantilever beam capacitive shunt devices with inductive sections, referred to as MEMS LC switches as shown in Fig. 2. Together, the capacitance sections and inductive segments transforms the MEMS structure into a resonant device capable of creating a short circuit to ground over a wide frequency range through the simple adjustment of the dielectric thickness or the inductor layout. The cantilever beam is 650 μm long and 175 μm wide and consists of three capacitive sections separated by two inductive segments. As seen in Fig. 2, FGC is used as the transmission line media. The center strip width (S), the slot width (W), and the ground plane width are 80, 50, and 220 μm, respectively.

The planar configuration of the FGC transmission line makes it possible for the MEMS switch to be placed in a shunt configuration with the cantilever having negligible effects when the device is in the OFF-state (up-position) and then resonate at the specific design frequency when in the device is in the ON-state (down-position). Furthermore, the narrow width of the FGC transmission lines enable the MEMS cantilever to extend over the entire transmission line with no physical contact between the cantilever and the FGC. This enables the MEMS bias to be applied to the cantilever itself while the FGC line is held at ground or a small potential required to bias other electronic components.

III. MEMS Fabrication and Characterization Procedures

The circuits are fabricated on a 15 Ω-cm Si wafer. Two 10 μm thick layers of PI-2611 polyimide are spun on and and fully cured at 335 C to obtain a final thickness of 20 μm. The MEMS processing starts after a 1 hour, 200 C dehydration bake with the definition of the first level metal consisting of 0.02 μm of Ti and 0.8 μm of Au by lift off processing that defines the FGC lines and posts for the MEMS cantilever. This is followed by 0.13 μm of PECVD grown silicon nitride (Si_3N_4), which is etched back using Reactive Ion Etch (RIE) so that it only covers the FGC lines where the cantilever will be pulled down. The FGC lines, except under the cantilever, and the cantilever posts are then thickened to 1.6 μm by evaporating another 0.8 μm Au. Next, the posts, which support the cantilever, are built up with another 1.5 μm Au and the sacrificial photoresist is defined. To be sure that the tops of the posts are clean, an O_2 RIE is done before the 0.12 μm Au seed layer is sputtered over the wafer. The cantilever is defined with photoresist and the bridge is gold plated to 1.9 μm. The cantilever definition photoresist is stripped and the Au seed layer removed. Finally, the sacrificial photoresist is removed in acetone and a critical dry release system. Electrical testing revealed that there was some sacrificial material remaining under the cantilevers; therefore, an O_2 barrel etch was performed. This removed the material, but also etched approximately 1 μm of polyimide. It is noted that standard MEMS processing was performed on the polyimide interface layer without any changes.

After processing, an optical interferometer and SEM is used to verify processing. The bridge is 3.6 μm above the Si_3N_4, and it is relatively flat with only 1.2 μm of variation across the 650 μm length and 0.4 μm variation across the 175 μm width. An SEM microphotograph of the MEMS switch is shown in Figs. 2 and 3 where the flatness and uniformity can be observed.

A full Thru-Reflect-Line (TRL) calibration was performed using standards fabricated on the wafer. The TRL routine was performed with the NIST software MULTICAL [12]. The measurements were made on an HP 8510C vector network analyzer and an RF probe station. Bias of the MEMS switches was made to the separate bias pad connected to the cantilever while the FGC metal lines were tied to ground. A 30V peak to peak, 1 kHz square wave is used to actuate the switch.

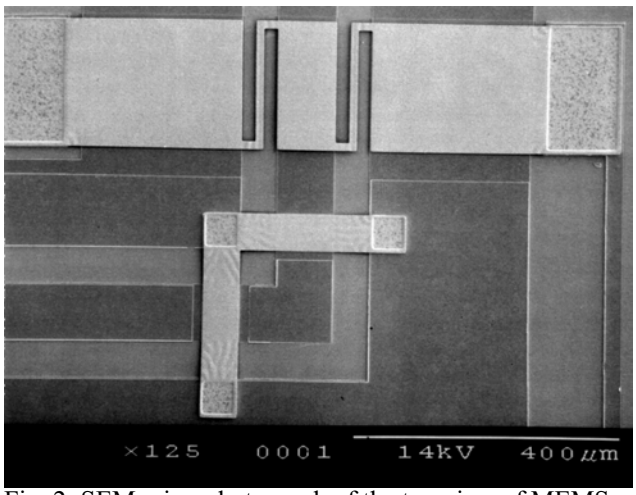

Fig. 2: SEM microphotograph of the top view of MEMS switch on polyimide.

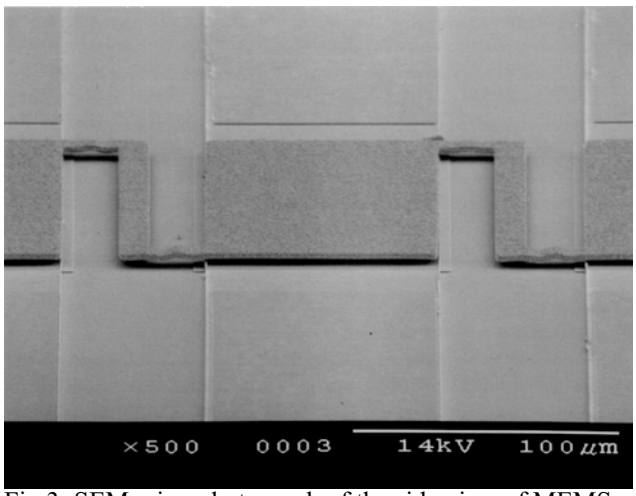

Fig 3: SEM microphotograph of the side view of MEMS switch on polyimide.

IV. Results

The measured switch insertion loss and up state return loss are shown in Fig. 4 and the measured isolation is shown in Fig. 5. At the resonant frequency of the LC shunt switch of 36.6 GHz, the insertion loss is 0.52 dB, the return loss is 8.7 dB, and the isolation is 20 dB. Because the FGC line was not designed using known design rules for low loss on the polyimide interface [13], 0.35 dB of the insertion loss, which is determined from the measured FGC line attenuation, is attributed to the line and not the switch. The measured scattering parameters were used to determine an equivalent circuit model consisting of a series RLC circuit in

shunt for the switch in the up and down state. In the up state, the circuit parameters are L=25 pH, C=66 fF, and R=0.5 Ω, and in the downstate, L=20 pH, C=580 fF, and R=0.5 Ω. The modeled circuit characteristics are shown on Figs. 4 and 5. The 20 dB isolation is very good considering that the inhomogeneous substrate supports surface wave modes at a lower frequency than if a homogeneous GaAs, HRS, or quartz substrate would, which tends to degrade isolation in RF circuits. The up-state phase characteristics are shown in Fig. 6, where it is seen that the phase is nearly linear across the entire measured frequency band.

V. CONCLUSION

We have presented for the first time the fabrication and characteristics of RF MEMS switches on a CMOS grade Si wafer (substrate resistivity equal 15 Ω-cm) with a polyimide interface layer. Although the FGC and switch design were not optimized for performance on the structure shown in Fig. 1, the switch characteristics are promising with 20 dB of isolation and an insertion loss of 0.52 dB, which can be lowered to 0.17 dB by proper design of the FGC line.

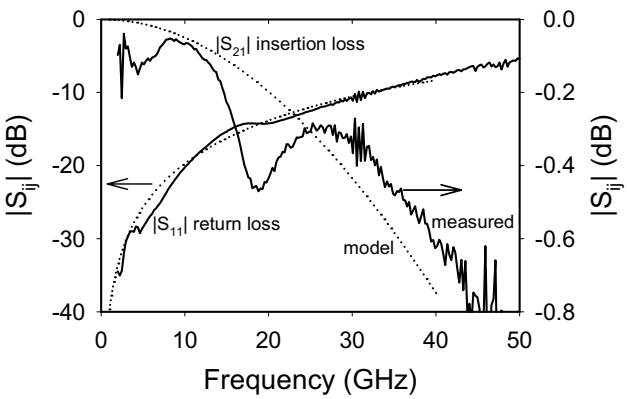

Fig. 4: Measured up-state characteristics of RF MEMS switch.

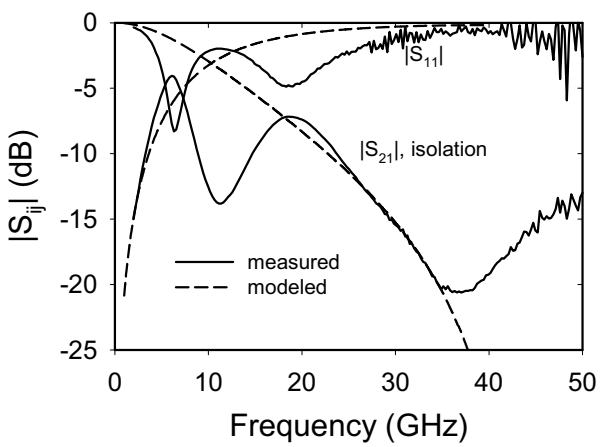

Fig. 5: Measured down-state characteristics of RF MEMS switch.

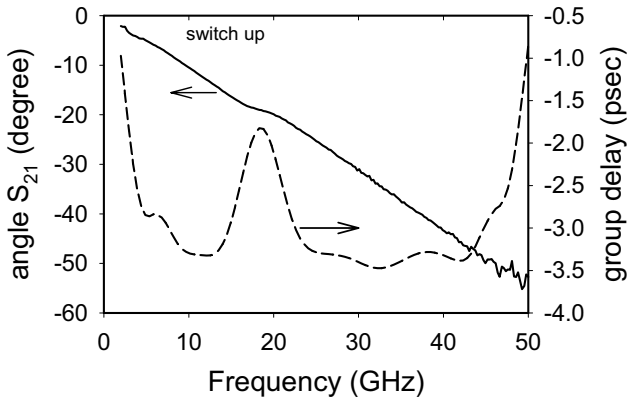

Fig. 6: Measured up-state phase characteristics of RF MEMS switch.

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REFERENCES

[1] G. L. Tan, R. E. Mihailovich, J. B. Hacker, J. F. DeNatale, and G. M. Rebeiz, "A very-low-loss 2-bit X-band RF MEMS phase shifter," *2002 IEEE MTT-S Int. Microwave Symp. Dig.*, Seattle, WA., June 2-7, 2002, pp. 333-335.

[2] Y. Liu, A. Borgioli, A. S. Nagra, and R. A. York, "K-band 3-bit low-loss distributed MEMS phase shifter," *IEEE Microwave and Guided Wave Letters*, Vol. 10, No. 10, Oct. 2000, pp. 415-417.

[3] B. Pillans, S. Eshelman, A. Malczewski, J. Ehmke, and C. Goldsmith, " Ka-band RF MEMS phase shifters," *IEEE Microwave and Guided Wave Letters*, Vol. 9, No. 12, Dec. 1999, pp. 520-522.

[4] J.-F. Luy, K. M. Strohm, H. E. Sasse, A. Schuppen, J. Buechler, M. Wollitzer, A. Gruhle, F. Schaffler, U. Guettich, and Klaaβen "Si/SiGe MMICs," *IEEE Trans. Microwave Theory and Techniques,* Vol. 43, No. 4, pp. 705-714, April 1995.

[5] J.-S. Rieh, L.- H. Lu, L. P. B. Katehi, P. Bhattacharya, E. T. Croke, G. E. Ponchak, and S. A. Alterovitz "X- and Ku-band amplifiers based on Si/SiGe HBTs and micromachined lumped components," *IEEE Trans. Microwave Theory and Techniques,* Vol. 46, No. 4, pp. 685-694, May 1998.

[6] A. Gruhle and A. Schuppen, "Recent advances with SiGe heterojunction bipolar transistors," *Thin Solid Films*, 294, pp. 246-249, 1997.

[7] K. Yamamoto, T. Heima, A. Furukawa, M. Ono, Y. Hashizume, H. Komurasaki, H. Sato, and N. Kato, "CMOS low-noise/driver MMIC amplifiers for 2.4-GHz and 5.2 GHz wireless applications," 2001 IEEE Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems Dig., Ann Arbor, MI, Sept. 12-14, 2001, pp. 18-22.

[8] G. E. Ponchak, "RF transmission lines on silicon substrates," 29 th European Microwave Conference Dig., Munich, Germany, Oct. 5-7, 1999, pp. 158-161.

[9] A. Bacon, G. E. Ponchak, J. Papapolymerou, N. Bushyager, and M. Tentzeris, "Folded coplanar

waveguide slot antenna on silicon substrates with a polyimide interface layer," *2002 IEEE Int. Symp. on Antennas and Propagation Dig.*, San Antonio, TX, June 16-21, 2002, pp. 432-435.
[10] J. Papapolymerou and G. E. Ponchak, "Microwave filters on a low resistivity Si substrate with a polyimide interface layer for wireless circuits," *2001 IEEE Radio Frequency Integrated Circuits (RFIC) Symposium Dig.*, Phoenix, AZ, May 20-22, 2001, pp. 125-128.
[11] J. Papapolymerou, G. E. Ponchak, and E. M. Tentzeris, "A Wilkinson power divider on a low resistivity Si substrate with a polyimide interface layer for wireless circuits," *2002 IEEE Radio Frequency Integrated Circuits (RFIC) Symposium Dig.,* Seattle, WA, June 2-4, 2002, 483-486.
[12] R. B. Marks, "A multiline method of network analyzer calibration," *IEEE Trans. Microwave Theory and Techniques*, Vol. 39, pp. 1205-1215, July 1991.
[13] G. E. Ponchak, E. Dalton, A. Bacon, J. Papapolymerou, and E. M. Tentzeris, "Measured propagation characteristics of finite ground coplanar waveguide on silicon with a thick polyimide interface layer," *32nd European Microwave Conference Dig.*, Milan, Italy, Sept. 23-27, 2002, pp. 167-170.