All-Metal High-Isolation Series and Series/Shunt MEMS Switches

Jeremy B. Muldavin, *Student Member, IEEE*, and Gabriel M. Rebeiz, *Fellow, IEEE*

***Abstract*—This paper presents a novel all-metal series switch with several different pull-down electrode geometries. The switch results in an up-state capacitance of 5–9 fF and an isolation of -25 to -30 dB at 10 GHz. The fabrication process is completely compatible with the standard capacitive (or dc-contact) shunt switch. A dc-40 GHz series/shunt switch is also presented with an isolation of -60 dB at 5 GHz and -42 dB at 10 GHz. This is the highest isolation switch available to-date. The performance is limited by radiation in the CPW lines and not by the series/shunt switch characteristics. The application areas are in high-isolation switches for basestations and satellite systems.**

***Index Terms*—DC contact, high isolation, k-band, x-band, MEMs, 10 GHz.**

I. INTRODUCTION

MICROELECTROMECHANICAL (MEMS) series and shunt switches have been demonstrated from 1–100 GHz for low-loss applications [1]–[5]. Most series switches fabricated using a cantilever-based design which is composed of a stress-balanced Si_3N_4/Al or SiO_2/Al beam (or dual beam as in the case of the Rockwell MEMS switch). On the other hand, the inline series switch of northeastern/analog devices is based on a 5–8 μm-thick gold-plated cantilever [6]. This switch has also shown some outstanding performance, but requires a very special processing gold-plating technique which is very hard to reproduce. All series metal-to-metal contact (dc-contact) switches have an off-state capacitance of 2–8 fF and results in high isolation up to 20–40 GHz. The loss of the series switch is determined by the contact resistance and for a contact resistance of 1–2 Ω, the loss is 0.1–0.2 dB.

The goal of this paper is to introduce a new all-metal series switch which can offer high isolation at 0.1–30 GHz. The switch is based on a fixed-fixed beam approach and, therefore, is not very sensitive to the residual stress in the supporting beam. The advantage of this switch is that it is easy to fabricate and does not require special processing with dielectric beams or a thick low-stress electroplated cantilever. Also, the fabrication process of the novel series switch is compatible with capacitive (or dc-contact) shunt switches, allowing the construction of a high-isolation dc-40 GHz series/shunt switch.

Manuscript received February 21, 2001; revised July 2, 2001. This work was supported by NASA-Jet Propulsion Laboratory and the National Science Foundation. The review of this letter was arranged by Associate Editor Dr. Ruediger Vahldieck.

The authors are with the Radiation Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 49109-2122 USA (e-mail: muldavin@engin.umich.edu; rebeiz@umich.edu).

Publisher Item Identifier S 1531-1309(01)08080-1.

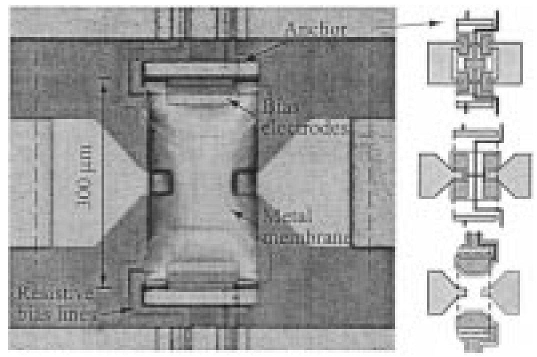

Fig. 1. Photomicrograph of the all-metal MEMS series switch and three different pull-down electrode geometries.

II. ALL-METAL SERIES SWITCH: DESIGN AND MEASUREMENTS

The all-metal series switch is shown in Fig. 1. The series switch is composed of a gold bridge suspended 1.5 μm over the microwave t-line and a 80 μm wide opening is defined in the t-line. The length of the MEMS bridge is 300 μm and the width depends on the t-line gap. In most cases, the width is around 100–120 μm thus ensuring a 10–20 μm overlap with the t-line. The bridge is anchored at both sides and the anchors do not touch the CPW ground planes. The MEMS air bridge is fabricated using a Ti/Au sputter deposition with a total thickness of 9000 Å. Two pull-down electrodes are defined near both anchors of the switch and are connected to the supply voltage using a resistive bias line. When the switch is pulled down, it makes a metal-to-metal contact between the input and output ports. When the switch is in the open position, it offers a low series capacitance and excellent isolation at 0.1–30 GHz. The switch is fabricated using the published techniques described in [5].

The disadvantage of this switch is its higher up-state capacitance, around 6–9 fF, instead of 2–4 fF. Also, when the switch is pulled down, it connects two short stubs (150 μm) to the microwave t-line. These stubs have minimal effect on the operation of the switch up to 30 GHz, but do result in an increase in the reflection coefficient of the switch above 40 GHz (down-state). Still, the design shown in Fig. 1, with its advantages described above, result in an excellent high-isolation switch from dc-26 GHz.

It is important to note that the all metal series switch is compatible with a microstrip implementation. Actually, it is easier to build since the ground plane is not near the anchors of the bridge and the bias lines need not be isolated from the ground plane metal using a nitride layer.

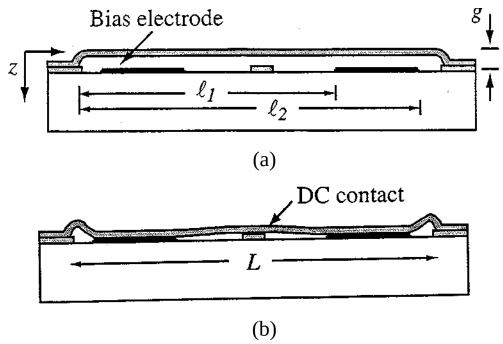

Fig. 2. Illustration of the mechanical geometry of a MEMS series switch: (a) in the up-state and (b) down-state position.

A. Mechanical Modeling

The deflection at the center of a fixed-fixed beam due to a distributed load can be derived from the deflection versus load position for a concentrated load and the principle of superposition [7]. The relation between the deflection and the total force yields the spring constant of the structure. For the electrode geometry of Fig. 2, the spring constant is given by

$$k = \frac{-4t^3 wE(\ell_2-\ell_1)}{L^3(\ell_2-\ell_1)-3L^2(\ell_2^2-\ell_1^2)+3L(\ell_2^3-\ell_1^3)-(\ell_2^4-\ell_1^4)} + \frac{2tw(1-\nu)\sigma(\ell_2-\ell_1)}{L(\ell_2-\ell_1)-\frac{1}{2}(\ell_2^2-\ell_1^2)} \quad \text{[N/m]} \qquad (1)$$

for $\ell_2 - \ell_1 \leq L/2$, where

- L, ℓ_1, and ℓ_2 shown in Fig. 2;
- w width of the bridge;
- t thickness of the bridge;
- σ residual stress;
- E Young's modulus of the membrane;
- ν Poisson's ratio.

The pull-down electrode area is $2(\ell_2 - \ell_1) \times w$. The calculated spring constant in (1) is higher than a center-pulled bridge. The spring constant of a gold bridge with $L = 300$ μm, $w = 140$ μm, $t = 0.9$ μm, $\ell_1 = 205$ μm, $\ell_2 = 260$ μm, and $\sigma = 30$ MPa is $k = 78$ N/m. The pull-down voltage for the case above with a gap height of 1.5 μm is 22 V.

In order to ensure that the bridge contacts well the microwave t-line, we have purposely fabricated the t-line around 4000 Å thicker than the pull-down electrode. Also, as seen in Fig. 1, different pull-down electrodes were used so as to ensure that an electrostatic force is applied around the center of the bridge.

B. Electromagnetic Modeling

The switch of Fig. 1 was modeled using a full-wave EM simulator (Sonnet). The CPW line dimensions are $G/W/G = 96/160/96$ μm. The opening in the CPW line was defined at 80 μm. It was found that the up-state capacitance due to the CPW lines alone for an 80 μm gap is 5 fF. The total capacitance of the bridge is simulated to be 9 fF and the increase is due to the fringing fields between the CPW lines and the bridge structure and the parallel-plate capacitance of the two contact areas in series.

One way to reduce the up-state capacitance is to use a narrow 100 μm long center conductor around the switch. This reduces

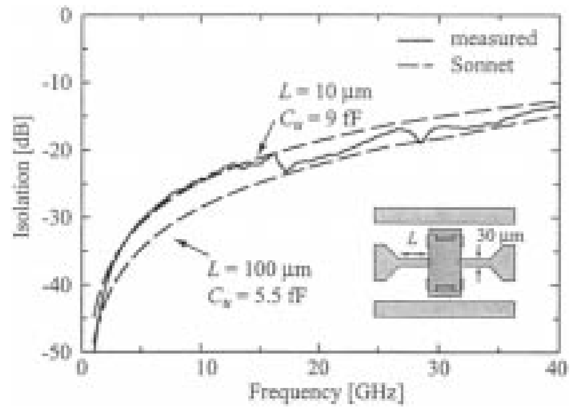

Fig. 3. Measured and simulated isolation of an all metal series MEMS switch. Extending the length of the tapered section to 100 μm increases the isolation by 5 dB.

the fringing capacitance to 3.8 fF and the total capacitance to 5.5 fF, at the expense of a large equivalent series inductance in the t-line. The series inductance increases the reflection coefficient in the down-state position to −20 dB at 26 GHz (Fig. 4). This was not done in our design, but is an excellent way of increasing the isolation by 5 dB. Simulations indicate that it is not advantageous to increase the narrow center conductor length to more than 120 μm since the isolation will be limited by the CPW gap capacitance and the switch parallel-plate capacitance.

C. Measurements

The measured response of the switch is shown in Fig. 3. The pull-down voltage was around 40 V and an actuation voltage of 45–50 V was applied. The isolation fits a $C_u = 9$ fF model, and we observe small resonances in the isolation at 20 GHz due to the coupling of the anchor of the bridge with the CPW ground plane. The down-state return loss is better than -20 dB up to 26 GHz, showing that the 150 μm stubs have virtually no effect below 30 GHz. The insertion loss varied between 0.5 dB to 2.0 dB, depending on the fabrication run, and was independent of frequency up to 26 GHz. We were experiencing problems in the removal of the sacrificial layer and this seriously affected the contact resistance (3–5 Ω per contact). If the switch was fabricated in the down-state position, the measured insertion loss was less than 0.1 dB up to 26 GHz, showing that the measured loss in Fig. 4 is due to the contact resistance and not to leakage through the high-resistance bias lines.

The switch was also measured with different electrode geometries (Fig. 1). The electrodes are extended to the center of the bridge to result in an additional pull-down force near the contact area. An actuation voltage of 45–50 V was also used for these electrodes. The isolation decreased by only 2 dB from 1–40 GHz, showing that the up-state capacitance increased to 10 fF. This is a small price to pay for a larger contact force. However, due to processing problems, the switch still resulted in the same contact resistance (3–5 Ω).

III. High-Isolation Series/Shunt Switches

The novel series switch was integrated with a standard CPW capacitive shunt switch to result in a high-isolation series/shunt

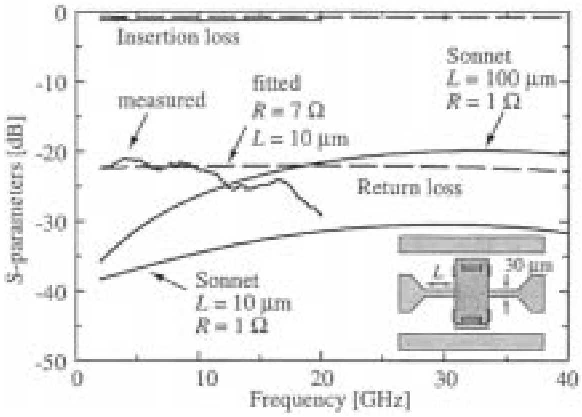

Fig. 4. Measured and simulated S-parameters of an all metal series MEMS switch in the down-state. The high contact resistance dominates the measured response.

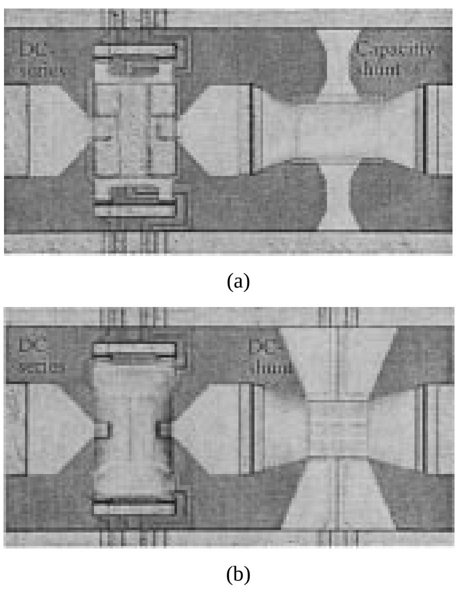

Fig. 5. Photomicrograph of a series/shunt switch with (a) a capacitive shunt switch and (b) a dc-contact switch.

switch (Fig. 5). Both switches are fabricated in exactly the same process steps and the only difference are the anchor connections and bias electrodes. The capacitive shunt switch is 300 μm long, with a width of 100 μm and results in an up-state capacitance of 70 fF and a down-state capacitance of 3.1 pF. The height of the capacitive switch is identical to the series switch (1.5 μm). The pull-down voltage is 18–22 V.

Fig. 6 shows the measured isolation of the series/shunt switch when the series switch is in the up-state position and the shunt switch is in the down-state position. The isolation is better than -40 dB up to 40 GHz. We believe that the intrinsic isolation of the series/shunt is much better than the measured response, but is limited to -35 dB by radiation in the 96/160/96 μm CPW line, even at 10 GHz. The measured insertion loss of the series/shunt switch in the pass-state (series-down, shunt-up) was again given by the contact resistance of the series switch and was 0.5–2 dB depending on the fabrication run. The measured reflection coefficient in the pass-state was less than -15 dB up

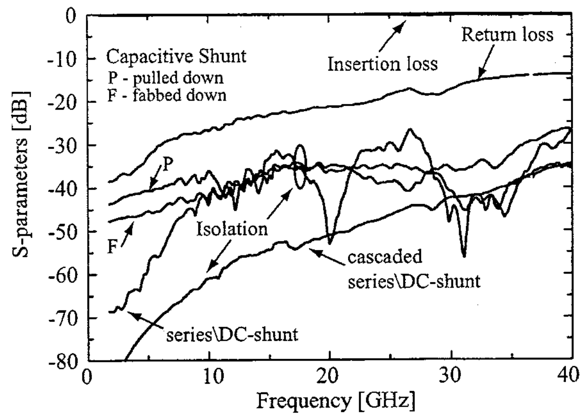

Fig. 6. Measured S-parameters of several MEMS series/shunt switches in the isolation-state and pass-state. The "cascaded" curve shows the isolation of a measured series and shunt S-parameters cascaded in a circuit simulator. The measured insertion loss is for a series/shunt switch with the series switch fabricated in the down-state position.

to 40 GHz and is due to the up-state capacitance of the shunt switch ($C_u = 70$ fF). If the series switch is fabricated down, the reflection loss does not change, but the insertion loss is less than 0.1 dB up to 20 GHz.

The series switch was also fabricated with an inline dc-contact shunt switch. This shunt switch was published in [9] and will not be repeated here. The only difference in the two designs is the measured isolation at low frequencies. The dc-contact shunt switch results in excellent isolation at dc-5 GHz which adds to the isolation of the series switch. The resulting isolation of the series/shunt switch was better than -60 dB up to 5 GHz. The measured insertion loss and reflection coefficient in the pass-state were very similar to the case of a capacitive shunt switch (Fig. 4).

REFERENCES

[1] C. L. Goldsmith, Z. Yao, S. Eshelman, and D. Denniston, "Performance of low-loss RF MEMS capacitive switches," *IEEE Microwave Guided Wave Lett.*, vol. 8, pp. 269–271, Aug. 1998.

[2] R. E. Mihailovich, M. Kim, J. B. Hacker, E. A. Sovero, J. Studer, J. A. Higgins, and J. F. DeNatale, "MEM relay for reconfigurable RF circuits," *IEEE Microwave Wireless Compon. Lett.*, vol. 11, pp. 53–55, Feb. 2001.

[3] D. Peroulis, S. Pacheco, and L. P. B. Katehi, "MEMS devices for high isolation switching and tunable filtering," in *2000 IEEE MTT-S Symp. Dig.*, Boston, MA, June 2000, pp. 1217–1220.

[4] D. Hyman, A. Schmitz, B. Warneke, T. Y. Hsu, J. Lam, J. Brown, J. Schaffner, A. Walston, R. Y. Loo, G. L. Tangonan, M. Mehregany, and J. Lee, "Surface micromachined RF MEMS switches on GaAs substrates," *Int. J. RF Microwave CAE*, vol. 9, pp. 348–361, Aug. 1999.

[5] J. B. Muldavin and G. M. Rebeiz, "High isolation MEMS shunt switches; part 1: Modeling," *IEEE Trans. Microwave Theory Tech.*, vol. 48, pp. 1045–1052, June 2000.

[6] N. E. McGruer, P. M. Zavracky, R. Morrison, S. Majumder, D. Potter, and M. Schirmer, "RF and current handling performance of electrostatically actuated microswitches," in *Sensor Expo*, Cleveland, OH, Sept. 1999.

[7] N. S. Barker, "Distributed MEMS transmission lines," Ph.D. dissertation, Univ. Michigan, Ann Arbor, 1999.

[8] J. B. Muldavin and G. M. Rebeiz, "Nonlinear electro-mechanical modeling of MEMS switches," in *2001 IEEE MTT-S Symp. Dig.*, Phoenix, AZ, June 2001.

[9] ——, "Inline capacitive and dc-contact MEMS shunt," *IEEE Microwave and Wireless Compon. Letters*, vol. 11, pp. 334–336, Aug. 2001.