A DC-Contact MEMS Shunt Switch

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***Abstract*—This paper presents the design, fabrication, and performance of a metal-to-metal contact micro-electro-mechanical (MEMS) shunt switch. The switch is composed of a fixed-fixed metal beam with two pull-down electrodes and a central dc-contact area. The switch is placed in an in-line configuration in a coplanar waveguide transmission line. This topology results in a compact dc-contact shunt switch and high isolation at 0.1–18 GHz. The isolation at mm-wave frequencies is limited by the inductance to ground and is −20 dB at 18 GHz. The application areas are in wireless communications and high-isolation switching networks for satellite systems.**

***Index Terms*—Micromachining, radars, RF MEMS, switches, telecommunications.**

I. Introduction

The design of RF MEMS switches has reached a mature level with many dc-contact series [1]–[4] and capacitive shunt [5]–[8] switches available today. The dc-contact series switch provides high isolation at 0.1–26 GHz, while the capacitive contact shunt switch with silicon nitride or silicon dioxide dielectrics provides excellent isolation at 10–120 GHz. In certain cases, a high-dielectric constant material such as SrTiO is used in the capacitive switch resulting in high isolation at 1–10 GHz [9].

An alternative switch is the dc-contact *shunt* switch. This switch can be used in place of a dc-contact series switch for 0.1–20 GHz operation, or in conjunction with a dc-contact series switch so as to provide a very high isolation (−70 dB to −50 dB) and compact series/shunt switch at 0.1–40 GHz [4]. A dc-contact shunt switch was developed by Feng *et al.* with an isolation of −25 dB from 0.25–40 GHz [10]. This letter presents a different design which is suitable for microstrip or CPW transmission lines. The switch has been successfully applied in a dc-26 GHz absorptive switch [11], and the present paper focuses on an accurate equivalent circuit and the effect of the bias lines on the insertion loss.

II. Modeling and Design

The dc-contact shunt switch consists of a fixed-fixed gold beam in an in-line configuration, with two off-center pull-down electrodes and a dc-contact area in the center (Fig. 1). There are two contact points between the switch and two short sections of transmission line which are part of the CPW ground plane. A resistive bias line is attached to each of the two pull-down electrodes.

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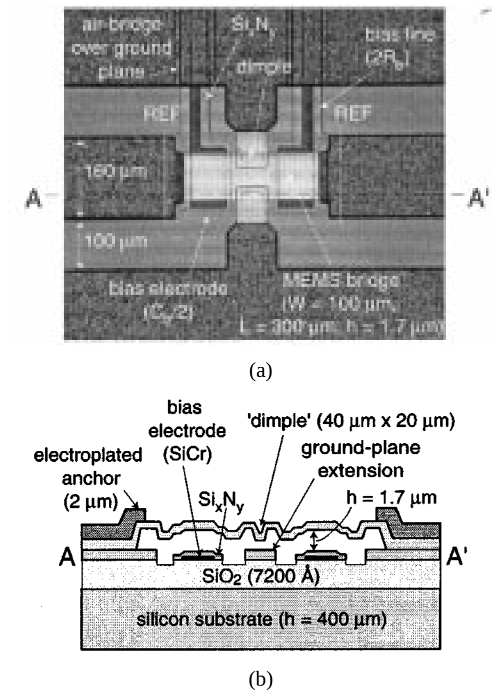

Fig. 1. DC-contact shunt switch. (a) Top view and (b) cross section at plane A–A′.

In the down-state position (isolation state), the switch is modeled as an R_sL circuit, where $R_s = (R_c + R_l)/2$ is the resistance of the switch and L is the inductance to ground; R_c is the contact resistance at the contact points, and R_l is the resistance of the short section of transmission line [Fig. 2(a)]. For the dc shunt switch, the isolation is given by

$$\begin{aligned}|S_{21}|^2 &= (2R_s/Z_o)^2 \quad (\omega L \ll R_s)\\ &= (2\omega L/Z_o)^2 \quad (\omega L \gg R_s). \end{aligned} \tag{1}$$

The maximum isolation is limited by the series resistance to ground, and for $R_s = 0.25\ \Omega$, the isolation is −40 dB. However, it is very difficult to attain this value due to the contact resistance of the switch. In general, dc-contact shunt switches result in an isolation of −28 to −34 dB at 0.1–6 GHz. For $R_s = 1\ \Omega$ and $L = 20$ pH, the isolation is −28 dB at 0.1–4 GHz and gradually decreases to −20 dB at 20 GHz. Equation (1) shows that dc-contact shunt switches which are built using a microstrip design result in poor isolation *above* 10 GHz. This is due to the large via-hole inductance to ground ($L = 40$–80 pH) which is unavoidable in a microstrip design.

In the up-state position (insertion-loss state), the switch can be modeled as two short sections of transmission lines (150 μm long) and two capacitors ($C_b/2$) attached to two bias resistors ($2R_b$), as shown in Fig. 2(b). The capacitors represent the coupling between the switch and the pull-down electrodes. The transmission lines have an impedance of 62 Ω with $\epsilon_{eff} = 6.23$,

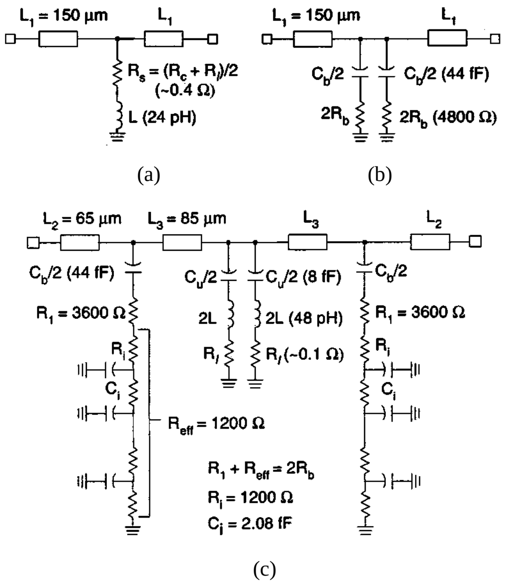

Fig. 2. Simplified model of the dc-contact shunt switch in the (a) down-state position, (b) the up-state position, and (c) accurate up-state model, including distributed bias lines and coupling at the dimples.

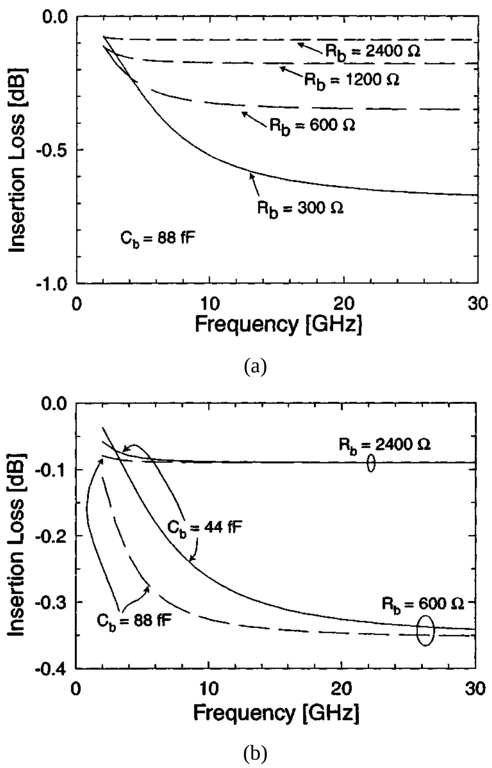

Fig. 3. Calculated insertion loss of the dc-contact shunt switch based on Eq. (2): (a) variation of loss with R_b for $C_b = 88$ fF and (b) variation of loss with C_b for $R_b = 2400\ \Omega$ and $600\ \Omega$.

and a measured attenuation of 0.4 dB/cm at 10 GHz that varies as $\sqrt{f}$.

The insertion loss, as calculated by the simple R–C model in Fig. 2(b) and ignoring the transmission lines, is given by

$$|S_{21}|^2 = \frac{4\left(R_b^2 + 1/(\omega^2 C_b^2)\right)}{(2R_b + Z_o)^2 + 4/(\omega^2 C_b^2)}. \tag{2}$$

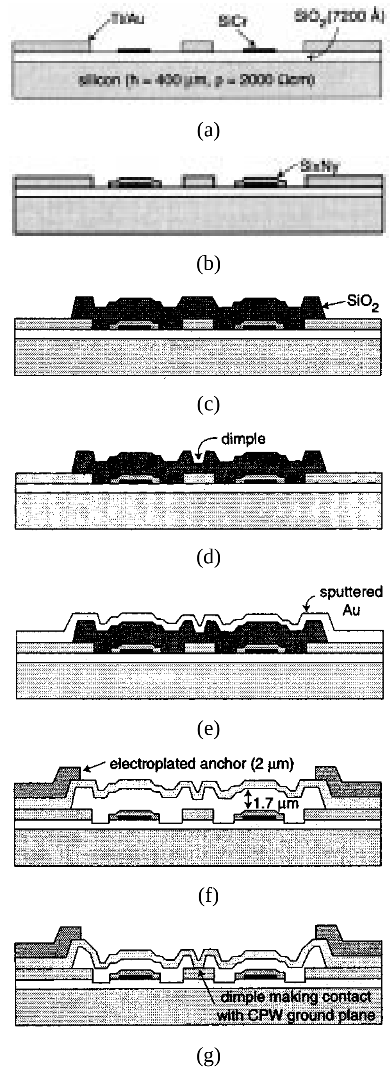

Fig. 4. (a)–(f) Process steps of the dc-contact shunt switch with dimple and bias resistor procedures and (g) switch in the down-state position. The cross sections shown here are the same as in Fig. 1.

The loss of the switch depends strongly on the bias resistance, as shown in Fig. 3(a). An R_b greater than 1200 Ω is required for an insertion loss of less than -0.2 dB. Fig. 3(b) shows that the loss of the switch is not very sensitive to the variation in C_b when the bias resistance R_b is high ($R_b \gg 1/(\omega C_b)$). However, when $1/(\omega C_b)$ becomes comparable to or greater than R_b, the insertion loss becomes a strong function of C_b. This happens for low-resistance bias lines below 1 kΩ.

For an accurate modeling of the up-state return loss, the capacitive coupling at the dimples and the short sections of transmission lines (Z, L_1, L_2) must be taken into account. Also, the sections of the bias lines *under* the ground plane should also be modeled as distributed R–C networks [Fig. 2(c)]. The expected up-state reflection loss is very low due to the open-circuit effect of the bias resistors, even at mm-wave frequencies.

III. Fabrication and Measurements

The dc-contact shunt switch is fabricated on a 2000 Ω-cm silicon wafer in a CPW configuration with dimensions of 100/160/100 μm, thus allowing operation up to 30 GHz with

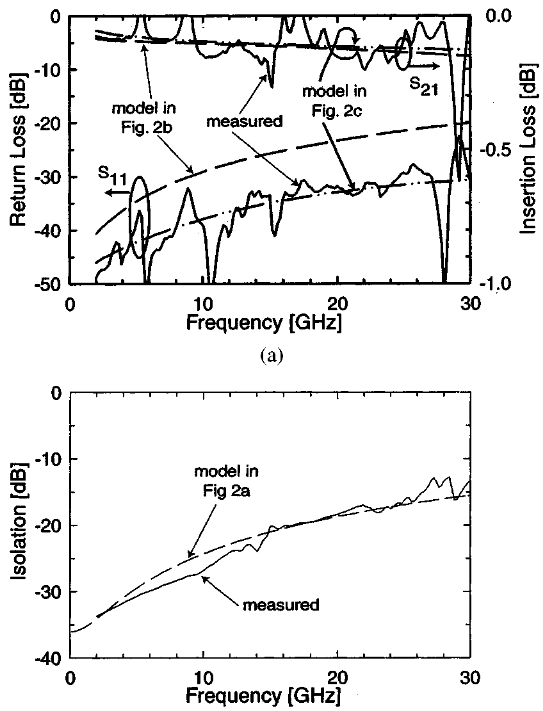

Fig. 5. Measured S-parameters in the (a) up-state position and (b) down-state position for the dc-contact shunt switch.

no radiation. As shown in the fabrication procedure in Fig. 4, a 40 μm $\times$ 20 μm dimple is used at each of the contact areas in order to achieve a low contact resistance. A 1.7 μm-thick PECVD SiO_2 is used as the sacrificial layer. The process results in a nonplanar bridge as seen in Fig. 4(f). The PECVD layer is partially etched (5000–6000 Å) to create the contact dimples. The bridge is fabricated by sputtering 0.8 μm of gold, and is 300 μm long by 100 μm wide. The SiCr pull-down electrodes have dimensions of 100 μm $\times$ 70 μm and are placed 85 μm from the center of the switch. They are connected to 20 μm-wide SiCr bias lines. The sacrificial layer is removed using a buffered HF solution, and the switch is released using a critical point dryer. The contact metal is gold-to-gold, with a contact resistance of 0.6–1.0 Ω per dimple depending on the fabrication run.

The spring constant of an off-set pull-down electrode structure has been derived by Muldavin *et al.* [4]. The measured pull-down voltage was 45–55 V, which results in a spring constant of 79–119 N/m and a residual stress σ of 47–70 MPa. An actuation voltage of 65 V was used so as to result in a large pull-down force and a low contact resistance.

The resistive bias lines are deposited using a SiCr layer with an RF resistivity of 1200 Ω/sq. This results in a resistance of approximately 3600 Ω for each of the two bias lines between the pull-down electrode and the edge of the CPW ground plane. The section of the bias line under the ground plane can be modeled as a 1200 Ω resistor to ground, thus resulting in a total resistance of 4800 Ω between the pull-down electrode and the RF ground. The effective resistance to ground due to the two bias lines combined is therefore 2400 Ω.

The measured S-parameters using the reference planes in Fig. 1 are shown in Fig. 5. In the up-state position, the measured loss is only -0.1 to -0.15 dB up to 30 GHz, and can be fitted with $C_b = 88$ fF and $R_b = 2.4$ kΩ. The insertion loss can be further improved by connecting the two bias electrodes underneath the switch and removing one of the bias lines, thus reducing the coupling loss to the ground plane. The insertion loss in such a case is -0.05 dB using (2), since R_b is now 4.8 kΩ. The measured reflection loss is excellent up 30 GHz due to the high value of R_b. Notice that the complete model of Fig. 2(c) results in an accurate prediction of the return loss.

In the down-state position, the measured response is fitted using $R_s = 0.4\ \Omega$ resulting in an isolation of -34 dB at 0.1–2 GHz. The fitted inductance is 24 pH due to the 130 μm-long transmission line sections between the switch and the CPW ground planes. This results in an isolation of -20 dB at 18 GHz. It is possible to reduce the inductance to 12 pH if a 65 μm CPW gap is used, thereby improving the isolation by about 6 dB above 10 GHz.

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