PARAMETRIC ANALYSIS ON THE DESIGN OF RF MEMS SERIES SWITCHES

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Abstract

A parametric analysis on the design of RF MEMS series switches is performed. The main design variables were identified and a set of RF MEMS series switches were designed, fabricated and measured. The effect of these design variables on the pull-in voltage (Vp) and the RF performance of the switches is studied and simplified equations for design propose are evaluated and corrected on the basis of experimental results.

Keywords: RF MEMS, Pull-in voltage, Cantilever beam, S-parameters

Introduction

MEMS (Micro Mechanical-Electrical Systems) have experienced a rapid expansion in the last years finding application in many fields of electronics and mechanics. When it goes to radio frequency (RF) applications there are many examples of MEMS devices which found their way into the market. In particular the RF switches have become very successful RF MEMS devices and are broadly used. This fact can be attributed to the good electrical performance of this kind of switches which offer low power consume, high power handling, high linearity, good isolation, and very low insertion loss when compared with the semiconductor alternatives. Anyway not all are roses in the MEMS house, MEMS devices present also some weak points, especially when it goes to the switching time and reliability, but there are many applications where the switching time is not critical, and in recent years there have been done very big improvements on the reliability of MEMS (DeNatale,2003) (Malmqvist, 2010) (Becher, 2002).

There are two main kinds of RF MEMS switches, the shunt capacitive switch and the series switch which can be capacitive or resistive. The work principle of the shunt switch is based on capacitive filtering and thus its band is limited and it is more suitable for applications beyond the

5GHz. On the other hand the series switch in its resistive variant is essentially broadband and is suitable for both, high and low frequencies. There are many constructive variants of the series switch; the switches studied in this work correspond to the implementation presented in figure 1.

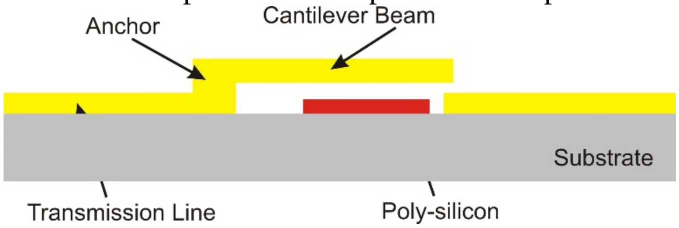

Figure 1. Cross section view of the designed RF MEMS series

The switch is formed by a CPW line which has a cantilever in its center. When no control voltage is applied the cantilever is suspended, there is not ohmic contact and only a very low value parasitic capacitance is formed between the input and the output of the switch, thus there is not signal transmission. When a control voltage is applied the cantilever bends providing ohmic contact and the switch is close.

The design of the MEMS switches is usually performed with the help of 3D electromagnetic and electro-mechanical simulation CADs. These simulations are usually quite time consuming and demand high computational resources. Even when simulations are almost mandatory for the design, the use of simplified design equations is also very valuable because they speeds up the design cycle since the time consuming simulations can be reduced to a minimum, and also give the designer the necessary insight and understanding of the problem for maximizing the performance and better achieve the design target. Thus the design equations should be that rare mix of accuracy and simplicity which allows getting a rather accurate first approach while been enough simple to give the designer the necessary insight for correctly understanding the effect and weight of the key design parameters.

The aim of this work was identifying the key dimensional parameters that should be taken into account when designing a RF MEMS series switch and some simplified design equations. These equations where used in the design of a set of RF MEMS switches. The switches were measured and the experimental data was used to validate and improve the accuracy of design equations.

Switch design variables and equations

The key performance parameters for a RF MEMS include the Pull-in Voltage (Vp), i.e. the minimum control voltage value necessary to move the switch from its natural position, the isolation (blocking state), the input and output return loss (transmission state), and the insertion loss (transmission state). Since the switch is basically a CPW transmission line when in it is closed, the return losses and the insertion loss will mainly depend on the characteristic impedance and the losses of the line which in turns depend on the gap (G) and the width (W), and the length (usually proportional to the length of the cantilever L) respectively. On the other hand the Vp value depends on the actuation area (which is usually proportional to L), the thickness of the cantilever (T), the gap between the cantilever and the control contact (g), and the length of the cantilever (L). For a clearer view of the dimensional parameters please refer to figure 2.

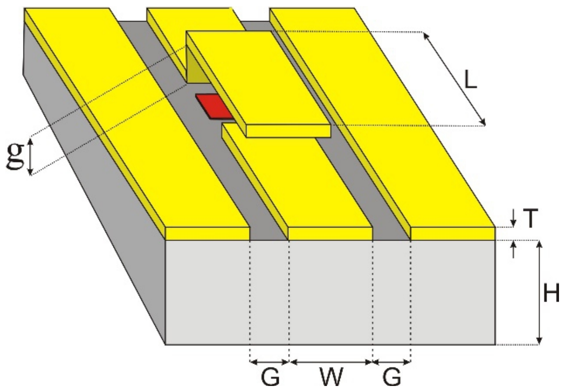

Figure 2.Key design variables for the RF MEMS series switch

Unfortunately, for some of these parameters, the choice is limited to a very narrow set of values fixed by the fabrication process technology. That is the case for example of the metallization thickness T and the cantilever gap g. On the other hand there is a bigger choice on the value of the dimensional parameters G, W and L. Since G and W fixe the characteristic impedance of the transmission line which forms the switch and decide on the return loss as well as on the insertion loss indirectly, then these values should be fixed on the basis of the electrical RF performance. Thus the main design parameter which can be varied relatively free in order to adjust the pull-in voltage is the cantilever length L. Anyway the L value will affect the size and the insertion loss of the switch and thus should be keep as small as possible.

In order to predict the pull-in voltage a relative simple equation is derived and proposed in (Rebeiz, 2003).

$$V_{pull-in} = \sqrt{\frac{8k}{27\varepsilon_0 A} g_0^{\,3}} \qquad (1)$$

In the derivation of equation 1 it was assumed the cantilever is plane (constant g) and has no curling due to residual stress introduced during the fabrication process. While this assumption is rather true in the case of a short cantilever it becomes less accurate when the switch length increases because of stress induced deflection (Nishijima, 2004). Most of the times the residual stress introduced during the fabrication produce the curling of the cantilever (usually the value of g increase while moving through the free end of the cantilever), this effect is more evident for long cantilevers (small g/L ratio) and thus in such cases the equation 1 is less accurate. In order to correct equation 1 it would be necessary to take into account the g variation as a function of the cantilever length. The calculation of this curling profile based on the residual stress is not straight forward and requires simulation. Since it is desired to reduce the simulation effort a simplified approximation is needed. First it is not necessary to take into account for the complete curling profile, and applying the mean value theorem it should be enough to use some kind of mean value in order to correct the equation. Also since the standard deviation of the variations on the g value introduced, for a fixed L, by different processes is small compared with its mean value, if a correction is derived for a "typical" process on the basis of profile measurement, then this correction should be useful for other similar processes. Taking into account the former premises a corrective improvement for equation 1 is derived using the profile measurements (gmax) corresponding to a typical MEMS process using Au/AuCr metallization (figure 3).

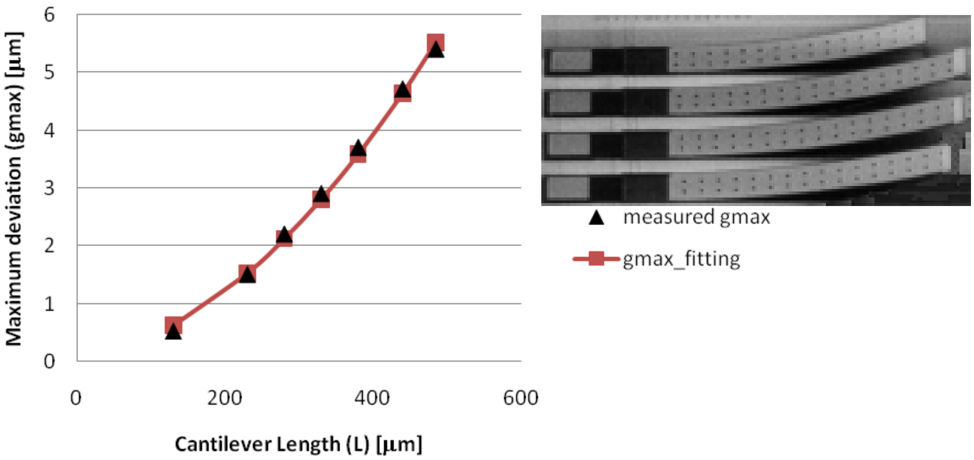

Figure 3. Comparison of the measured and calculated maximum cantilever deviation. Calculation was performed using the proposed second order polynomial fitting. SEM image of a set of test structures (on the top right corner).

A second order polynomial (gmax_fitting) is fitted to the measured profile curling data and an expression for the mean value of the g deviation is derived (eq.2).

$$g\max = 18.5e-6\cdot L^2 + 0.025\cdot L \qquad (2)$$

Where gmax is the maximum gap deviation at the free edge of the cantilever and L is the length of the cantilever in µm.

Then a simplified expression for the mean value of the g deviation (gmean) as a function of the maximum gap deviation (gmax) is derived (eq.3a).

$$gmean = \frac{g\max}{3} \qquad (3a)$$

$$g' = g + \frac{g\max}{3} \qquad (3b)$$

Replacing the constant gap value used in equation 1 by the new corrected g' value (eq.3b) a new improved equation for the calculation of the pull-in voltage is obtained (eq.4)

$$V_{pull-in} = \sqrt{\frac{8k}{27\varepsilon_0 A}\left(g_0 + \frac{18.5e-6\cdot L^2 + 0.025\cdot L}{3}\right)^3} \qquad (4)$$

As previously stated the value of the design variables W and G should be fixed in order to assure the desired RF performance for the switch. The RF MEMS series switch can be modeled using a CPW transmission line plus a parasitic inductance (Ls) and a contact resistance (Rc) (figure 4).

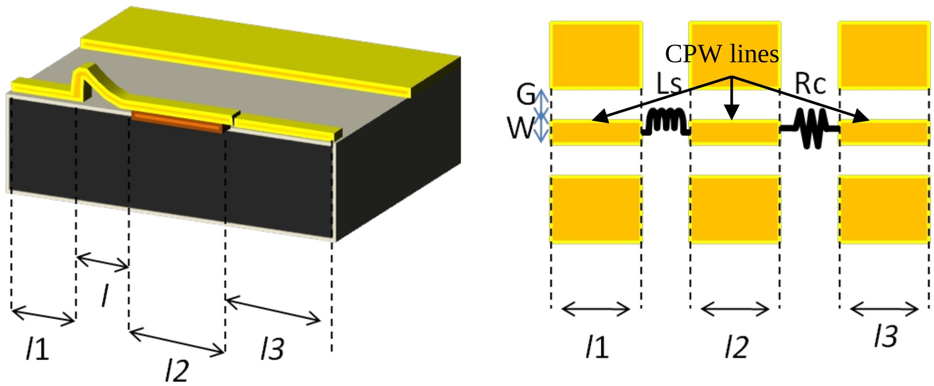

Figure 4. RF MEMS series switch cross section and its equivalent simplified model.

In order to minimize the losses, the switch should be matched to the impedance of the system (Zo) where it will be used (Zo=50Ω for most of the RF applications). Since the switch model is basically a CPW line, it will be enough matching its characteristic impedance to Zo, this can be easily accomplished by inverting equation 5 (Kumar, 2012) for the determination of W and G.

$$Z_o = \frac{30\pi}{\sqrt{\frac{\varepsilon_r+1}{2}}} \cdot \frac{K'(k)}{K(k)} \qquad (5)$$

Where

$$k = \frac{W}{W+2G} \qquad (6)$$

And

$$\frac{K'(k)}{K(k)} = \begin{cases} \dfrac{\pi}{ln\left(2\frac{1+\sqrt{1-k^2}}{1-\sqrt{1-k^2}}\right)} & for \quad 0 \leq k \leq \frac{1}{\sqrt{2}} \\ \dfrac{ln\left(2\frac{1+\sqrt{k}}{1-\sqrt{k}}\right)}{\pi} & for \quad \frac{1}{\sqrt{2}} \leq k \leq 1 \end{cases} \qquad (7)$$

The contact resistance is a function of the contact area, the quality and material of the surface, the mechanical force applied. For most of the practical applications it can be assumed a value of Rc between 0,5Ω and 1Ω per contact area (Rebeiz, 2003), so choosing a value of 0.75Ω would be a good initial guess for the model. The parasitic inductance Ls is mostly due to the part of the cantilever which remains suspended in air when the switch is actuated, this part of the line will have a smaller capacitance per unit length because the line is suspended in air which has a lower permittivity than the MEMS's substrate, which means it will have a higher characteristic impedance (Z_b) given by equation 8.

$$Z_b = Z_0 \cdot \sqrt{\varepsilon_r} \qquad (8)$$

The short line can then be approximated with a lumped inductance Ls using equation 9 (Rebeiz, 2003).

$$L_S = \frac{Z_b \cdot l. \cdot \sqrt{\varepsilon_r}}{C_0} \qquad (9)$$

A final expression for Ls is obtained by replacing eq.8 into eq.9.

$$L_S = \frac{Z_0 \cdot l \cdot \varepsilon_r}{C_0} \qquad (10)$$

Where *l* is the length of line that remains suspended in air when the switch is activated, in the dielectric constant of the substrate, c_o is the speed of the light, and Z_o is the characteristic impedance of the system.

Having identified all the parameters of the simplified model, and related them to the key design variables it is now possible to determine the values of W, G and L that suits the RF (return loss, insertion loss, etc) and DC (pull-in voltage) design specifications for the switch.

Experimental results:

A set of four RF MEMS series switches, with different cantilever lengths (200µm, 300µm, 400µm, and 500µm respectively, fig. 5) was designed, using the guidelines defined in section II, and fabricated.

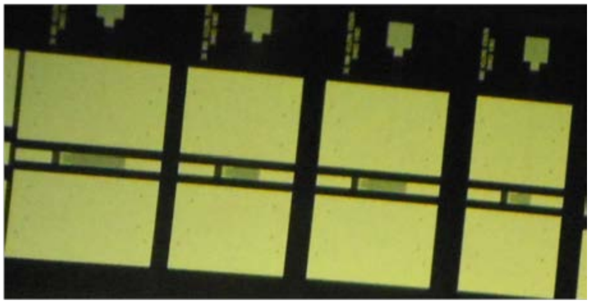

Figure 5. Fabricated switches with different cantilevers lengths (500µm, 300µm, 400µm and 200µm from left to rigth).

The switches were measured for both RF S-parameters and pull-in voltage performance. The measurement set up is presented in figure 6.

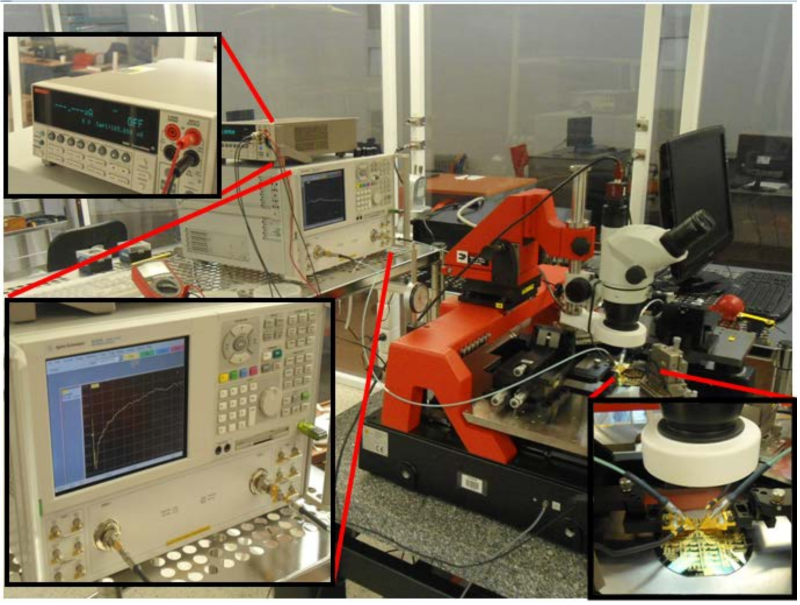

Figure 6. Measurement set-up. DC Source, VNA (Vector Network Analyzer), and probe station.

The pull-in voltage measurements were recorded and compared with the predictions of eq.1 and eq.4.

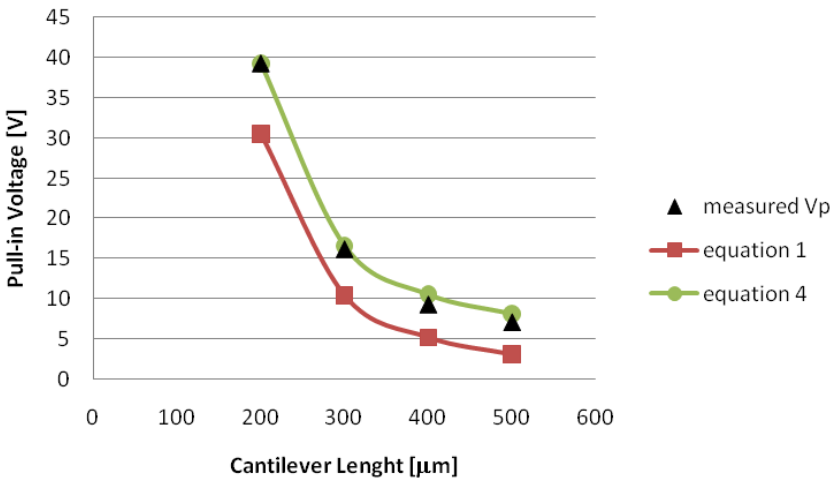

Figure 7. Measured pull-in voltage (black triangles), equation 1 prediction (brown trace), and equation 4 predictions (green trace)

The results show that the new improved equation (eq.4) is sensible more accurate in predicting the pull-in voltage for different L values that the classical model (eq.1).

In order to verify the accuracy of the simplifier model proposed in section II, and validate the design equations adopted, the measured RF performance of the switches was compared to the model predictions for 3 key performance indicators (fig.8), namely the return loss, the insertion Loss and the transmission phase (the prediction of the transmission phase is important if the switch is intended to be used some kind of phase shifters).

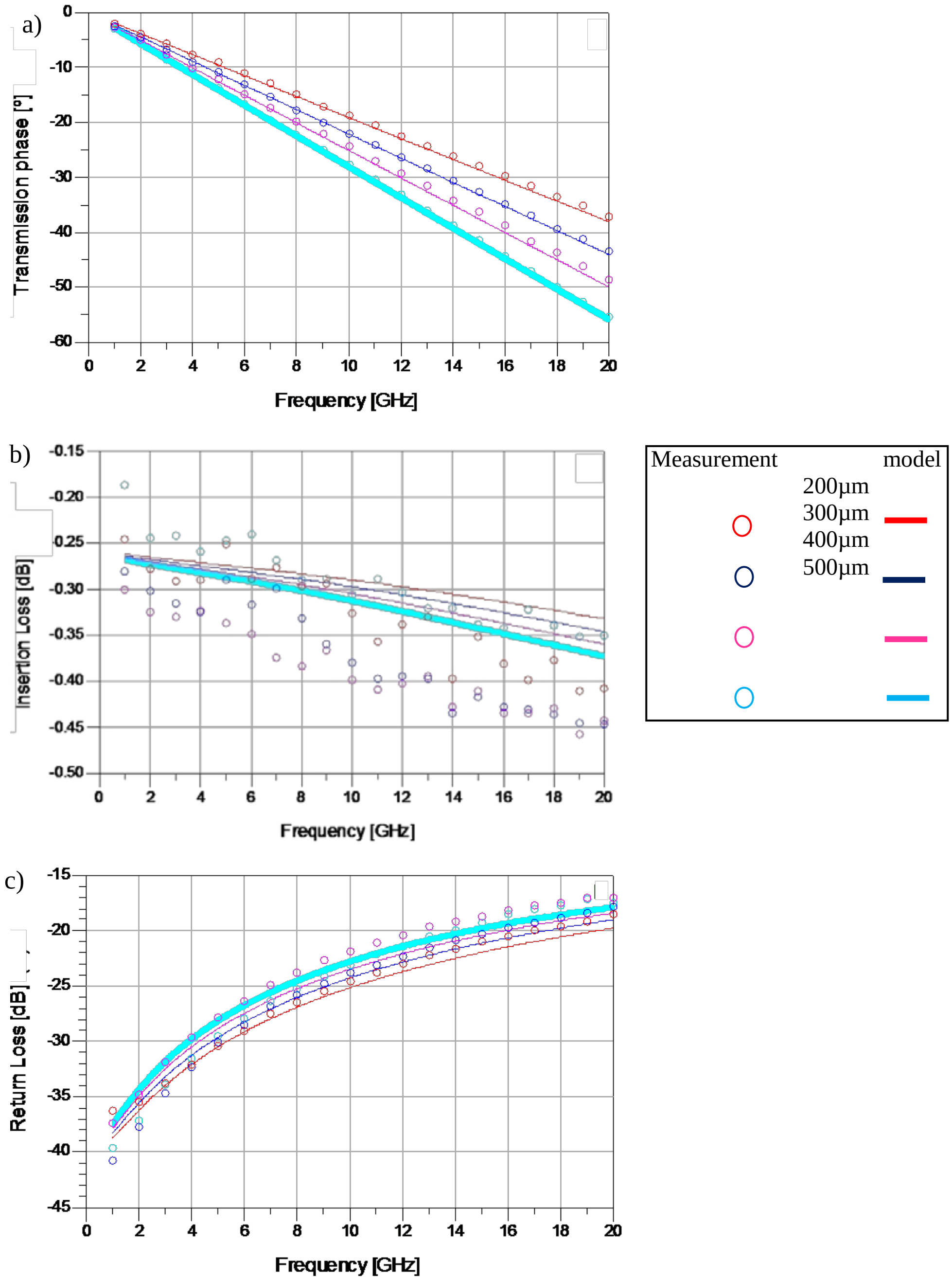

Figure 8. Measured RF performance of the switches vs model predictions for the main three key performance indicators: a) Transmission phase, b) Insertion Loss, and c) Return Loss.

There is good agreement between the measured data and the theoretical predictions, showing the model and the design equations proposed are a reasonable choice and can be a useful tool for speeding up the design cycle.

Conclusion

A set of simplified equations were derived for the design of RF MEMS series switches, and a simplified model was proposed. The equations allow to accurately predicting the pull-in voltage and the key RF performance indicators of the switches. A set of for series switches, with different cantilever lengths, was designed, fabricated and measured. The measured data shows good agreement with the predictions from the derived design equations and the proposed simplified model. The proposed design approach could be a valid tool for speeding up the design of the RF MEMS series switches.

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